Master's Thesis

Quantifying the Economic Value to Building Owners of Retrofitting Residential Structures with Heat Pumps:

A Building-Level Geospatial Approach in Saxony, Germany

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The presented intellectual work of this research thesis is my own. In particular, I have not taken any help of any qualified consultant.

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Every effort has been made in the following analysis to model reality as accurately as possible, however any mischaracterizations regarding building stock morphology, market dynamics or any other topic is entirely a result of oversight for which the author takes full responsibility.

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Glossary of Terms and Abbreviations

ALKIS	Authoritative Real Estate Cadastre Information System
ASHP	Air Source Heat Pump
AWHP	Air to Water Heat Pump
BAFA	Ministry for Economy and Export Control (Bundesministerium für Wirtschaft und Ausfuhrkontrolle)
BEHG	Fuel Emissions Trading Act (Brennstoffemissionshandelsgesetz)
BWP	German Heat Pump Association (Bundesverband Wärmepumpe)
COP	Coefficient of Performance
DWD	German Weather Service (Deutsche Wetter Dienst)
EU ETS I & II	European Union Emission Trading Scheme I & II
EUBUCCO	EUropean BUilding stock Characteristics in a Common and Open system
KfW	German State-Owned Redevelopment Bank (Kreditinstitut für Wideraufbau)
LNG	Liquified Natural Gas
NPV	Net Present Value
SPF	Seasonal Performance Factor
TSO	Transmission Service Operator
UFS	Up Front Subsidy

Explanation on Electronic Resources

Throughout the text, various scripts and data files are referenced. These have been included in the electronic submission along with metadata as a single *dataFiles.zip* file. All programmatic and data resources can be accessed at a later date by contacting the author by email at the contact listed on the title page or by viewing the public github repository at:

https://github.com/samuelsmock/thesisCode.git

Abstract

This paper explores the variance of the net present value (NPV) of heat pump retrofits along several axes including building morphology, regional climate, uncertain future energy markets, and building owner economic expectations for existing residential buildings in Saxony, Germany. Using spatially aggregated tract data from the 2011 German Census and building-level information from the EUropean BUilding Stock Characteristics in a Common and Open System (EUBUCCO) data set, a building-level model was developed which calculates and statistically characterizes NPVs across the entire building stock. This information was then used to evaluate both the efficacy and necessity of public subsidies under numerous possible price trajectories and building owner circumstances. A key result was that a ratio of heat pump electricity tariffs (HPTs) to natural gas prices of roughly 2.4 : 1 is an important tipping point for the effective incentivization of heat pump retrofits in single family homes (SFHs) over 20 years given the regional climate, building stock, and existing upfront subsidies. Two paths towards achieving this market balance were compared: the possibility of legislatively guaranteeing a permanent 28 cent price brake for HPT and a broader energy policy focused on scaling renewable energy sources (RES). The results indicated that it is likely more efficient in terms of the use of public funds to focus on RES scaling in the short run. The time sensitivity and urgency of heat pump rollout was also considered by viewing the expenditure of public funds on heat pump subsidies as its own Marginal Abatement Cost (MAC) over a 0-5 year timeline and a 5+ year timeline. Here, it was found that additional subsidies are not a necessary part of a least cost decarbonization pathway in the short run with the strong caveat that carbon savings from immediate retrofitting projects merit additional public price supports when compared to potential climate damages.

1 Introduction

Major revisions to the German Building Energy ordinance passed in late 2023 as well as numerous statements from public officials have made clear that heat pump adoption constitutes a major plank in Germany's path to decarbonizing its energy system (Federal Ministry for Economic Affairs and Climate Protection, 2023a). While some stringent requirements have already been put into place for new heating systems such as the headline requirement of 65% renewable energy sources for new heating systems, and an eventual prohibition of fossil fuel based heat is slated for 2045, the mid-run strategy for addressing the nearly 75% of the existing building stock with fossil fuel heating hinges on voluntary decommissioning of existing systems, which in turn hinges on an accurate assessment of the net present value (NPV) of heat pump retrofits to understand and quantify the efficacy and necessity of subsidies (German Association of Energy and Water Industries, 2023a; German Federal Government, 2023).

Numerous studies have focused on characterizing the cost and savings profile over time of representative single family and multi-family homes (SFH and MFHs), and have generally focused on terms such as payback period and return on investment, but a spatially aggregated treatment of heat pumps and heat pump subsidies in terms of their economic and climate impact has been somewhat limited, in part due to a lack relevant attribute coverage in available building data. With the advent of more highly modeled building data products, which apply methods like computer vision to satellite imagery to yield broad and accurate coverage on attributes like above ground height and building footprint, the potential exists to more accurately disaggregate census tract-level data on heating systems and building use in a way that can ultimately yield meaningful insights on a whole host of metrics including NPV by deploying the well-understood methods for single structures on a regional, state or even national scales. (Langreder et al., 2022; Malhotra et al., 2022)

Heat pumps have gained considerable traction in recent years and received a particular boost in Germany as a new governing coalition took power in 2021 with decarbonization high on its list of priorities. Leaders from the German Ministry for Economy and Climate Protection have set ambitious goals for heat pumps such as a doubling of the rate of installation to 500,000 per year by 2028 (Federal Ministry for

Economic Affairs and Climate Protection, 2023b; German Heatpump Association, 2023a).

Despite the public push and various new subsidies, the electrification of space heating in Germany is in its very early stages. While over half of new building permits by 2022 cited heat pumps as the main source of space heating, only 3% of existing buildings have a heat pump, placing Germany well behind neighbors such as Austria and France in terms of heat pump rollout (Fassbender, 2023; German Association of Energy and Water Industries, 2023a; Schreurs, 2019). Perhaps the biggest reason for the relatively low adoption rates of heat pumps in Germany to date has been the low cost of natural gas compared to electricity, which has been a phenomenon across Europe over the past decade or more but is particularly pronounced in Germany as can be seen in Figure 1.

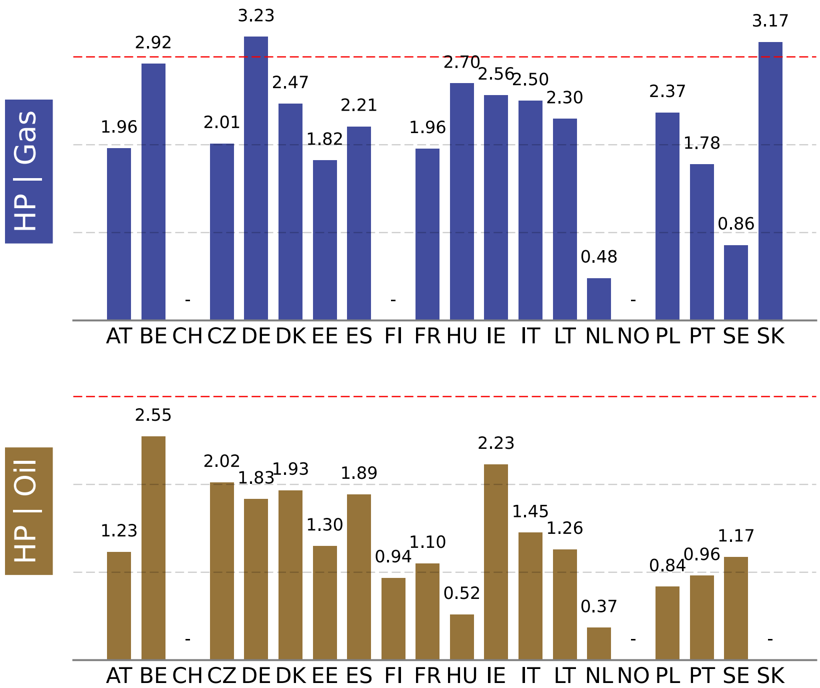

Figure 1: Ratio Peak of Tariff Electricity Prices to Natural Gas and Oil by Energetic Content Across Europe in June, 2022 (Reprinted from: European Heat Pump Association, 2022)

While retrofitting existing fossil fuel heating systems to use heat pumps for the main heating source has historically presented costly difficulties such as the potential requirement for renovations to improve building insulation or new radiators to account for lower system output temperatures, the newest generation of heat pumps feature many models with high output temperatures nearing 60 °C, and can thus provide a lower cost retrofit option when existing infrastructure like radiators are maintained

(German Heatpump Association, 2023b; Heizsparer, 2022; Viessmann, 2023a, 2023b). For this reason, air to water heat pumps dominate the German Heat pump market and are likely to help achieve the goals of climate neutrality that have now been moved forward to 2045. (German Heatpump Association, 2023a; Prognos, Öko-Institut, Wuppertal Institut, 2021).

While technology has advanced and the domestic industry has grown, widescale adoption hinges first and foremost on the micro-economic considerations of building owners as decision takers, which is in turn underpinned by price signals in upfront costs and ongoing energy prices that can incentivize adoption. As will be shown in the pages that follow, historically low-cost natural gas in the last 2 decades have meant that investment in a heat pump has been economically disadvantageous compared to replacing old fossil fuel boilers with newer ones even when future savings are discounted at a relatively low 'risk-off' rate of around 2.8%.

The question of the relative ongoing price of household natural gas and heat pump electricity will emerge as a key consideration for building owner-decision makers with the takeaway result that maintaining a ratio of no more than 2.4 : 1 in the price per kilowatt hour of electricity and natural gas over a 20 year service effectively incentivizes a building owner of a representative SFH in Saxony to replace an old fossil fuel boiler with a heat pump.

While this result already incorporates a discount on future savings, there is an additional psychological effect from the uncertainty of recent energy market volatility that must also be considered. If there is a possibility that relative prices of heat pump electricity tariffs and natural gas might return to historic ratios of 3.5 : 1 or even more, then a building owner faces the prospect of investing into a money-losing improvement that they are locked into for several decades (Federal Statistical Office, 2023a). This points to another result that price stability in the form of guaranteed heat pump tariffs potentially pay double dividends because they send price signals to a theoretical "rational" decision maker with perfect knowledge on future energy costs while also alleviating uncertainty as a deterrent to investment.

Aside from market forces, the value of heat pumps is also heavily influenced by their operating efficiency known as their Coefficient of Performance (COP) or when expressed as a yearly average weighted by usage, the Seasonal Performance Factor (SPF) (German Heatpump Association, 2023b). For air source heat pumps (ASHPs) this is mainly a function of size and outdoor temperature. As building characteristics such as location, size and number of units are needed to determine these metrics of efficiency as well as the rate at which energy savings accumulate over time, the approach taken here is to run the market factors discussed above for all buildings in Saxony. This approach gives insight into how the economic picture varies across regions as well as across different types of buildings.

The results show that different price breakpoints exist for different groups of building owners. Generally, multifamily building owners require cheaper electricity to incentivize heat pumps due to higher upfront costs and generally lower heat loads per square meter and lower operating efficiencies for larger units which drive annual savings down. Similarly, buildings in colder parts of the state are generally less incentivized to adopt ASHPs due to lower efficiencies during the coldest parts of the year. The variance in both dimensions implies that targeted policies in the form of lower heat pump tariffs for multifamily structures or additional incentives for non-air source heat pumps in colder climates could be a consideration for policy makers.

1.1 Policy Background

Numerous policy instruments are currently in force to help spur investment in heat pumps and many more are in various stages of development. Generally, these policies target either upfront costs through subsidies and tax incentives, or ongoing savings through energy market interventions.

1.1.1 European and National Carbon Pricing

While providing a price ceiling for heat pump electricity tariffs is the most obvious means to affect electricity and natural gas price ratios, carbon pricing in the form of direct taxation or emissions permits indirectly serves this same purpose from the other side by adding cost to energy. While some forms of planned carbon pricing are passed directly to consumers, existing carbon pricing schemes only do so in an indirect way (Wettengel, 2019). This section will provide a brief overview of planned and current carbon pricing and environmental levies in Germany and explore their impact on the ratio of electricity and gas prices.

Introduction

The European Union's landmark cap and trade carbon pricing initiative, the Emissions Trading Scheme (ETS) was adopted in 2003 and launched in 2005 (European Comission, 2020). Since then, the ETS has been gradually phased into effect with various sector-based exemptions and slowly decreasing free allocations. A key provision that was negotiated with stakeholders and member states in the original policy was an exemption on the building sector, meaning emissions that take place at the point of combustion for heating homes and businesses are exempted. Generally, this has been interpreted as an effort to prevent placing an undue burden on lower income homeowners and renters, who tend to spend a larger portion of their income on heating (Corbeau and Merz, 2023). While this effort to avoid a regressive effect has worked by initially targeting large, industrial emitters over individuals, it also has meant that carbon prices paid by fossil fuel generators within the power sector has trickled down to consumer electricity costs. It is difficult to quantify what portion of the price paid by consumers is attributable CO2 pricing due in part to the single price settlement structure and temporal variance of the power mix, but an ETS price of 80€ per ton and carbon intensity figures for coal and natural gas, which lie at abt 1.14 and 0.33 kg_{co2}/kWh_{elec} respectively imply a price to emissions intensive producers of between and 3 and 10 cents per kWh, a very significant portion of the settlement price component of end use power. (Carboncredits.com, 2023; International Energy Agency, 2023; Volker Quaschning, 2022)

In 2023, the European Commission approved a measure to set up a separate emissions trading scheme termed ETS 2 to cover buildings, road transportation and small industrial sectors not covered in the existing system (European Comission, 2020; European Commission, 2018). The creation of a separate exchange means that homeowners will not need to compete with large industrial players for carbon credits and will be shielded from market volatility in the original ETS exchange. It also means that natural gas and heating oil will become more expensive for consumers across Europe for the first time because of carbon pricing. It is anticipated to take effect in 2027 with an initial price of 60 € per ton of CO2 (Transport and Environment, 2021).

While Europe-wide carbon pricing in the buildings sector will have to wait until 2027, Germany preempted ETS 2 in 2021 by creating the Fuel Emissions Trading Act (BEHG), which does apply to emissions from the buildings sector (Wettengel, 2019).

Introduction

The system features structured, yearly price increases that are slated to go from 30 €/ton in 2023 to 55-65 €/ton in 2026 (Federal Ministry for Economic Affairs and Climate Protection, 2022). While the carbon price is not paid by customers as a separate line item on their bills, a large portion of the additional cost is passed to them by servicers, which amounts to about 0.6 cents per kWh in 2023 or about 0.2 cents for every 10 €/ton (Burger et al., 2022).

It is currently a matter of policy debate as to what will happen to CO2 pricing in the building sector after 2027. Forecasts from the consulting firm Prognose and the German Heat Pump Association (BWP), seem to suggest the possibility of double coverage of both the BEHG and ETS 2 after 2027, showing CO2 prices over 100 €/ton into the 2030's. This corresponds to an additional 2+ cents per kWh of natural gas or a 15% share of the overall price paid by consumers as seen in Figure 2. (Burger et al., 2022; Langreder et al., 2022)

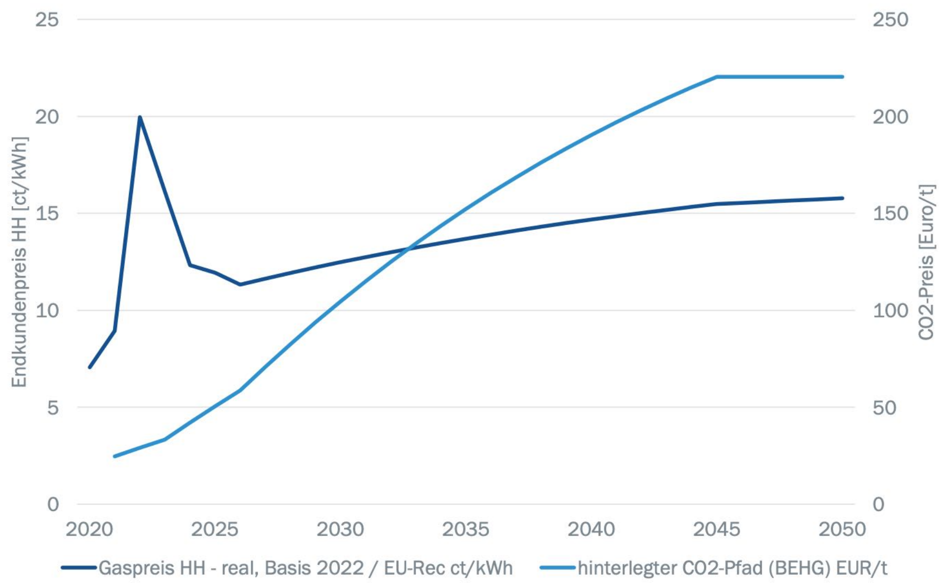

Figure 2: Forecasted Development of Natural Gas and Carbon Prices (2020-2050) (Reprinted from: Langreder et al., 2022)

While carbon pricing initiatives which increase the cost of natural gas and heating oil are beneficial to the adoption of heat pumps, it is worth noting that there is a keen awareness of the potential for regressive effects, and changes of course are always possible. In 2023, for instance the German government placed a pause on a planned increase to the BEHG cost structure due to convulsions in the energy market, and numerous programs such as the German Climate and Transformation special fund

(KTF) exist to reinvest government income from carbon pricing schemes in ways that reduce the burden on citizens. (Federal Ministry for Economic Affairs and Climate Protection, 2022; German Federal Government, 2022)

1.1.2 Upfront Subsidies

The landscape of upfront subsidies for heat pumps has evolved rapidly in recent years, and the ultimate amount of money granted to a project depends on many factors including the scope of renovations, prior state of the building, ownership status and tax situation. The German government grants funds to building owners through the Federal Funding for Efficient Buildings (BEG) program, which can be accessed either through Federal Office for Economic Affairs and Export Control (BAFA) or the state-owned investment and development bank, KfW, which administers the funds as subsidies on repayment of loans (Foerster, 2023). KfW subsidy programs are generally viewed as requiring more involved projects improving overall energy performance, particularly in older buildings, so BAFA-administered subsidies were used as the reference point for upfront subsidies in accordance with the boundary conditions. (Haase and Torio, 2021)

Even within BAFA loans, there is a considerable amount of variation, as different levels of funding are provided in the form of tailored bonuses depending on the type of heat source and what it is replacing. After increases of around 5% for most building classes was approved in January 2023, BAFA now advertises on their website repayment subsidies of between 25 and 35% for most buildings (Martins Breslow, 2023; Ministry for Economy and Export Control, 2023). As there were many variables linked to specific building characteristics already under consideration, the choice was made here to simply analyze upfront subsidies as a binary policy choice at either 0% or 30% of total project cost. The 30% figure was chosen following representative values for SFHs prior to the recent increase and for this reason is likely conservative. Nevertheless, this formulation begins the process of answering the most basic question posed here on the sufficiency of existing upfront subsidies, and the model is intentionally programmed in such a way as to allow sensitivity analyses and a more tailored calculation of upfront subsidy for each building in future research. (German Heat Pump Association, 2023a)

1.1.3 The Heat Pump Tariff and Price Brakes

The Russian invasion of Ukraine in early 2022 set off turmoil in global energy markets. In Germany and much of Europe. This supply crunch affected both natural gas and electricity markets because by 2021 over 15% of electricity supply in Germany came from natural gas driven thermoelectric power plants (Federal Statistical Office, 2023b). Electricity and natural gas prices for households peaked at 0.46 €/kWh and 0.18 €/kWh respectively in late 2022 prompting the German *Bundestag* to enact emergency prices brakes in March 2023 capping household electricity at 40 cents and natural gas at 12 cents up to 80% of prior year usage (German Association of Energy and Water Industries, 2023b). These price brakes for electric power and natural gas were known as the StromPBG and EWPBG and were effective retroactively to the beginning of 2023. (Federal Ministry for Economic Affairs and Climate Protection, 2023b; Federal Ministry of Justice, 2023)

As the price brakes were broadly targeted towards relieving the heating cost burden in the winter of 2022/23, the legislation also included specific language targeting heat pump tariffs (HPTs), capping them at 0.28 €/kWh. This was noteworthy, because the Government was essentially codifying and guaranteeing, if only temporarily, a type of special arrangement between service providers and consumers that historically constituted a discount on grid transmission and service fees mainly due to the fact that the diurnal demand profile of a residential heat pump differs from that of the grid as a whole, with consumption weighed more on nights and weekends. (Pehnt et al., 2023; TGA +E, 2023)

Over the prior decade or so, the industry standards of the these special HPT contracts took shape and averaged a 20-25% discount over peak rates or around 0.22 €/kWh for those customers with a dedicated meter for their heat pump (Esslingen, 2022; Langreder et al., 2022; TGA +E, 2023). While the price brakes enshrined in the StromPBG were already higher than many 12 year contracts being offered by mid 2023 and are at the time of writing only in legal effect until April 2024, the willingness of the government to step into a volatile market to provide certainty got to the heart of what industry analysts have been pointing to as essential to adoption of heat pumps: long term electricity price certainty (Federal Ministry for Economic Affairs and Climate Protection, 2023a; North German Broadcasting, 2023; Verivox, 2023).

The issue of price stability goes hand in hand with calls from industry advocates to also address what they see as the stagnating effects of unequal tax and regulatory treatment of fossil fuel vs electric heat sources. In 2021 for instance the German Heat Pump Association (BWP) asserted that taxes, levies, and fees made up nearly 70% of the end user price paid for electricity, but only 50% for natural gas (Figure 3). While the Renewable Energy levy on electricity (EEG) of 3.5 cents per kWh that was meant to help fund renewable energy development in Germany was terminated in 2022, the question from heat pump advocates has been why taxes ear marked for environmental causes should come from electricity and not natural gas or heating oil if the stated aim of the government is truly to protect the climate and encourage technological transition in the heating sector. (European Heat Pump Association, 2022; German Government, 2022)

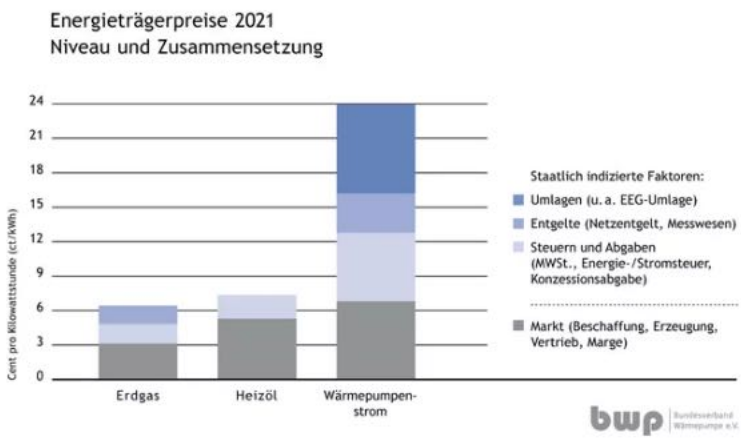

Figure 3: Composition of Electricity and Natural Gas Prices in Germany 2021 (Reprinted from: German Heat Pump Association, 2023)

This general sentiment amongst heat pump advocates has led to calls to make the 28 cent heat pump price brake permanent and to enact changes in tax and energy policy to reach a stable ratio of 2 to 1 in the price of HPT to natural gas on a per kWh basis (European Heat Pump Association, 2022) As will be shown in the following sections, this combination of stability and energy policy favoring affordable electricity would indeed all but guarantee a strong economic incentive for both single family and multifamily buildings to switch to a heat pump. The sensitivity of the NPV of a heat pump investment to energy market prices will be investigated in detail for the German state of Saxony as a case study for the broader goal of identifying tipping points at which heat pumps are effectively incentivized given a variety of other variables such as building characteristic, timeline of installation and expected return on investment.

2 Data Overview

At the highest level, this study sought to calculate NPV and a variety of other policy-relevant terms such as potential carbon emissions reduction of an air-to-water heat pump (AWHP) for each residential structure in Saxony. This approach allows the statistical characterization of economic and climate protection value based on building morphology and market conditions as well as the calculation of certain aggregate statistics like the total cost of a given Subsidy or price guarantee and net impact on emissions reductions.

The task of data set collection, cleaning and preprocessing is an entire subfield of data science unto itself with one major recent contribution coming in 2023 from Milojevic-DuPont et. al. with the EUropean BUilding stock Characteristics in a Common and Open (EUBUCCO) database. Generally, building stock data sets hybridize satellite imagery and ground sampled data such as cadastral, surveying, or census data, and thus completeness is inconsistent and dependent on the practices of local surveying authorities. Building characteristics which cannot be sampled remotely such as age, use (industrial, commercial, residential) number of units, technical energy system characteristics and energy use have widely varying levels of coverage from country to country and even city to city. In the following subsections, the data sources used for NPV modelling in Saxony will be presented with an emphasis on highlighting areas in which data is lacking and the assumptions that were made to provide context and motivation for the methodological workarounds employed in the following section (Bandam et al., 2022).

2.1 Boundary Conditions and Limitations on Data

2.1.1 Geographic

While all the spatial data sets employed here are available for all of Germany, this paper limits the analysis to the state of Saxony. The reason for this was primarily due to limited computational resources and long analysis times, particularly due to the exploratory nature of the modelling where many different price pathways and potential building owner decisions are considered. Limiting the geographic range also makes certain simplifying assumptions cleaner and closer to reality such as the use of relative ratio of gas to oil heating within the state to compute the economic and carbon impacts of heat pump substitution across the entire building stock dataset in the absence of robust fuel type attributes for any individual building.

The geographic extent was further limited only to those 100m grids that featured at least one residential building in the 2011 census. This provided a very rapid way of pairing down the initial set of buildings from around 2.1 million in the raw input EUBUCCO data to around 800,000 within these residential grids and meant that the remaining task of assigning the roughly 700,000 known residential buildings from the 2011 census to the largely unclassified building footprint data set became much more precise. The process of spatially disaggregating census data to the building level is described in section 3.1.3 and the process of pairing down the EUBUCCO building data to the geographic and technical boundary conditions can be viewed by the numbers in
Table 2.

2.1.2 Temporal

The building dataset used here comes primarily from the Digital 3D City Model of the Geobasis Information and Surveying Service of Saxony, and is current as of 2021 (Milojevic-Dupont et al., 2023; State Saxon Authority for Geobasis Information, 2021). The aggregated count of residential buildings on the other hand was collected through on the ground sampling in 2011 (Deutsche Zensus, 2011). For this reason, the process of assigning classifications to buildings was not only a project of filtering non-residential buildings within census enumeration areas, but also one of anticipating and removing buildings built between 2011 and 2021.

This process underpinned two fundamental assumptions in the analysis. The first is simply that a building built before 2011 can be considered a candidate for heat pump install by 2024, which is primarily informed by the practical realities of available data, but also stands to some basic logic that a building that was built in 2011 is likely to be operating on its original heat system and therefore be at least 13 years old and over halfway through its useful service life by 2024 (Famiglietti et al., 2021). Furthermore, Figure 4 indicates that, after removing district heating from the building set, at the very least 90% of the building subset in Saxony probably used oil or gas heating in 2011, as this was the case nationwide and Saxony's heating fuel mix tracks nationwide figures somewhat closely. This means that even if it cannot be shown which buildings are using less common fuel sources such as resistive electric or biomass, it can confidently be said that 9 out of 10 of the identified buildings from 2011 really are burning either heating oil or natural gas for heat. It is also worth noting that in the 2011 snapshot, heat pumps constituted essentially 0% of installed capacity, so there is no risk of errantly considering buildings which already have a heat pump installed. (German Association of Energy and Water Industries, 2023a)

This point about producing aggregate figures in the modelling exercise gets to the heart of a second assumption made in the temporal treatment of known building stock data. If a building within a certain census enumeration grid is misassigned to either a non-residential structure or to one built after 2011, it will be because another building of similar size and building morphology was excluded. This is because the methodology explained in section 3.1.3 places a hard cap on the number of allowed residential buildings of each size category in each grid to the 2011 Census count. For this reason, even if the exact buildings are sometimes misattributed, the overall statistical character of things like total living space for each building type, and the overall effect of outdoor temperatures on heat pump performance in each grid square should be roughly maintained.

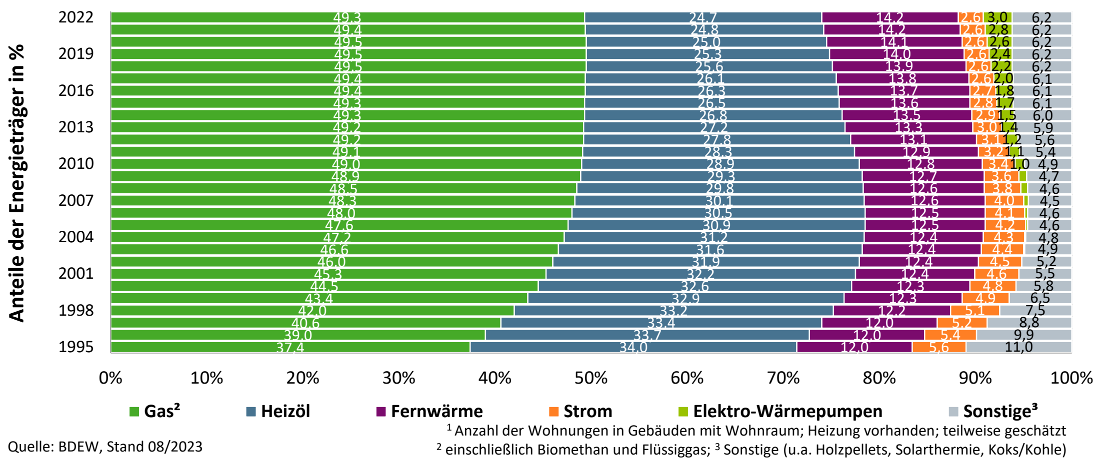

Figure 4: Development of the heating structure of the housing stock in Germany (Reprinted from German Association of Energy and Water Industries, 2023a)

2.1.3 Technical

The previous section on the temporal range of the data sets already mentioned two major limitations on available data having to do with technical heating system characteristics. The first is that while 2011 Census data did collect information on heat delivery systems, it did not collect data on fuel types. Appendix B provides an overview of the 6 categories of heat type provided in the 2011 Census and shows that a large majority (around 79%) of buildings are categorized as "Central Heating." This category encompasses the type of oil and gas boilers that are the main target of analysis, but also incorporates buildings that may already have large central heat pumps or biomass boilers among other fuel types. Single Unit and Single/Multi Room furnaces, which together make up around 12% of the total 2011 building stock are also candidates for heat pumps, although typically these would be substituted with air-to-air heat pumps like the relatively common "mini split" rather than a hydronic system. These buildings are not explicitly excluded as the economics, particularly of monthly savings are not significantly different between air-to-water and air-to-air heat pumps (German Association of Energy and Water Industries, 2023a; German Heatpump Association, 2023b).

The bigger issue posed by the lack of fuel type data is that it is not exactly possible to differentiate between heating oil and natural gas use, the latter of which has a significantly lower emissions intensity (Frost, 2019). While quantifying emissions mitigation potential is secondary to this project, coming up with estimates is important to help evaluate the efficacy of subsidies. For this reason, the assumption was made that across the entire building stock of Saxony, oil and gas boilers would be replaced in rough proportion to their use in 2022, which stood at a ratio of about 60 : 40 in favor of natural gas once district and non-traditional heat sources like wood were removed (German Association of Energy and Water Industries, 2023a). This allowed for the calculation of an effective replacement emissions intensity of around 232 $kgCO_{2\ equiv.}$/kWh for Saxony by weighting the emissions intensities of natural gas and heating oil according to usage, which were taken to be 205 and 272 $kgCO_{2\ eq.}$/kWh respectively (CarbonIndependent.org, 2019).

The dilemma posed to the economic picture by unknown fuel types was a bit more troublesome because yearly savings are such an important term in the NPV equation. To evaluate the extent of the impact in effective price differences in natural gas and heating oil and better constrain the effect this could have on NPV calculations, a long term average of both natural gas prices and heating oil prices was taken for the 11 years leading up to the market volatility of 2022 with a resulting average price of 0.063 €/kWh for natural gas and 67 €/hl for oil (Federal Statistical Office, 2023a). Transforming the heating oil price to a comparable price per unit of chemical energy using a calorific (pre combustion) heat content of 1,060 kWh/hl, yields a remarkably close value for long term average price of 0.063 €/kWh_{oil} (GOK, 2016). While this price is prior to combustion, new oil and gas boilers have both increased in efficiency in tandem with only about a 5% difference between them (Frost, 2019; Viessmann, 2022). While the relative effective price of natural gas and heating oil do tend to diverge in moments of broader energy market turmoil such as occurred in 2022, the long-term tracking of effective prices between heating oil and gas for the useful thermal energy they produce led to the conclusion that the two could be treated as equivalent in the long-term for energy savings calculations. This conclusion is also borne out by the modelling of Pehnt et al., (2023), which project a roughly 10% difference in effective price between heating and oil and natural gas narrowing to near zero over the next two decades (see Figure 6).

With these two simplifying assumptions, the data set of ‘candidate buildings’ that is derived in section 3.1.3, which again, has had district and block heating removed, and effectively only contains buildings older than 13 years old as of 2024, is treated as if they were all burning natural gas in 90% efficient boilers, with a “virtual” emissions intensity of 232 $kgCO_{2\ equiv.}/kWh_{therm}$ post combustion (about 15% higher than actual natural gas to account for the share of heating oil). Consequently, when looking at price pathways, only relative ratios of HPT electricity and natural gas are considered, which is a useful simplification as quoting ratios of HPT price and natural gas has come to be used as a common way of characterizing the energy market as whole (European Heat Pump Association, 2022; German Heat Pump Association, 2023b).

Other boundary conditions placed on the technical domain include an insistence on high output temperature, air-to-water, monobloc heat pumps of a relatively small unit size under 85kWh (or about 1,000 m^2 of living space). Although different heat pump types can have fairly wide variations in performance factors, with geothermal heat pumps for instance regularly providing COPs over 4 in the winter months, air-to-water heat pumps were chosen because their relatively low upfront costs allow for quicker pay off periods, which has in turn propelled them to the top of the heat pump market in Germany, accounting for nearly 87% of installs in 2022 (German Heatpump Association, 2023a).

Similarly, models capable of producing relatively high, 60º C output temperatures were chosen with an eye towards modelling specifically those retrofit options that do not require broader modifications to the buildings heat system, such as piping, radiative bodies, or insulation envelope (Heizsparer, 2022; Viessmann, 2023a). This decision was in part due to the fact that larger renovation projects are subject to different cost structures and subsidies such as those offered by the Reconstruction Loan Corporation (KfW), which place more stringent stipulations on building characteristics than can be effectively modelled with available building stock data (Reconstruction Loan Corporation, 2023)

2.2 Data Sources

The following subsection includes a brief description of all data sources used in the calculation of NPV, energetic totals, and market projections. A selection of the most important spatial and non-spatial data sources is summarized in Appendix A.

2.2.1 Geospatial Data

EUBUCCO Building Stock Data-
For Saxony, building footprint, height, and location came from the EUBUCCO dataset, which in turn was ultimately derived from Geobasis Information and Surveying Service of Saxony (Milojevic-Dupont et al., 2022; State Saxon Authority for Geobasis Information, 2021). The base data set included roughly 2.1 million buildings with only about 7% containing usage data, of which almost all were non-residential, but featured full coverage on height.

2011 German Census Data -
Data from the 2011 German Census, which is the most recent survey for which data is available contains aggregate information on building counts per 100m square across several categories including the number of units and energy delivery system (eg district, central, single unit). Downscaling this information to be used in conjunction

with building-level footprint and height data formed the most important data preprocessing challenge and is detailed in section 3.1.3. (Deutsche Zensus, 2011)

Monthly Average Temperature-
In addition to building data, 30 year average monthly temperature with raster coverage from the German Weather Service (DWD) was used to approximate heat pump performance by way of point sampling outdoor air temperatures (German Weather Service, 2023).

2.2.2 Energy Grid and Market Projections

As will be detailed in section 3, the calculation of NPV requires an approximation of yearly savings between a heat pump installation and a fossil fuel counterfactual case, which in turn requires projecting electricity and fossil fuel prices for at least 20 years corresponding average service life of a new heat pump (Famiglietti et al., 2021). As 2022 reminded the world, the development of energy markets even in the short run is inherently uncertain and subject to unpredictable developments in the geopolitical and technological landscape. Nevertheless, the exercise of forecasting energy prices, even if subconsciously, underpins the decision-making process for both building owners considering an investment in a heat pump and policy-makers considering how to structure market interventions. The approach taken here is to consider 3 potential trajectories that energy prices may take and calculate NPV's across the building stock data set for all three. This allows results to be grouped based on a particular scenario of interest and can be used to model the sensitivity of NPV to price in a dynamic way. Below is a short description of the price models informing the high- and low-end estimates used here.

BWP and Prognos AG
A 2022 short report from the BWP on the economic efficiency of heat pumps quote prices from a power forecast model by the consulting firm, Prognos that shows heat pump tariffs returning to stable levels below the current price brake of 0.28 €/kWh well into 2050 and natural gas prices steadily increasing to over 0.15 €/kWh, in part due to steadily increasing CO2 pricing in the building sector (Figure 2, Figure 5 ; Langreder et al., 2022).

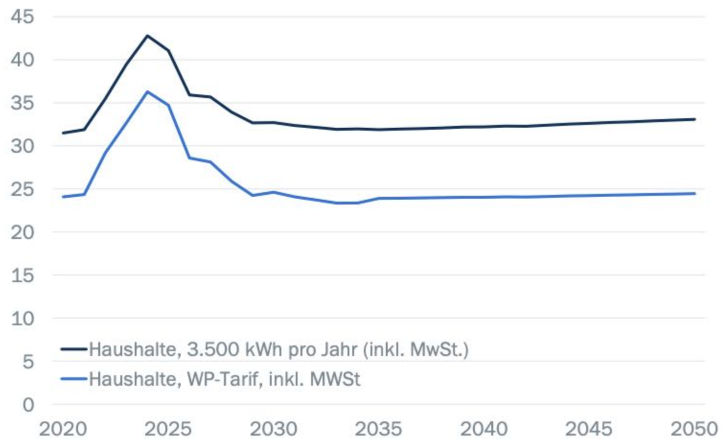

Figure 5: The Prognos Power Market model used in Modelling by the BWP (2020-2050) (Reprinted from Langreder et al., 2022)

Pehnt et. al, (2023) - *Heating with 65% Renewable Energy*

A higher price pathway for electricity and a lower estimate for natural gas prices through 2050 combine to create a less favorable picture for ongoing heat pump savings by Pehnt et al. in their 2023 report, “Heating with 65% Renewable Energy” in the framework of the project, "Building Energy Act and EPBD.” Specifically, this forecast features a continuation of a HPT discount of around 20%, but with more rapidly decreasing peak tariffs and the price paid by heat pump owners for their electricity reaches 0.33-0.35 €/kW by 2044. Natural gas prices are forecasted to run a similar trajectory to the Prognose model and reach 0.16-18 €/kWh by 2044 (Figure 6).

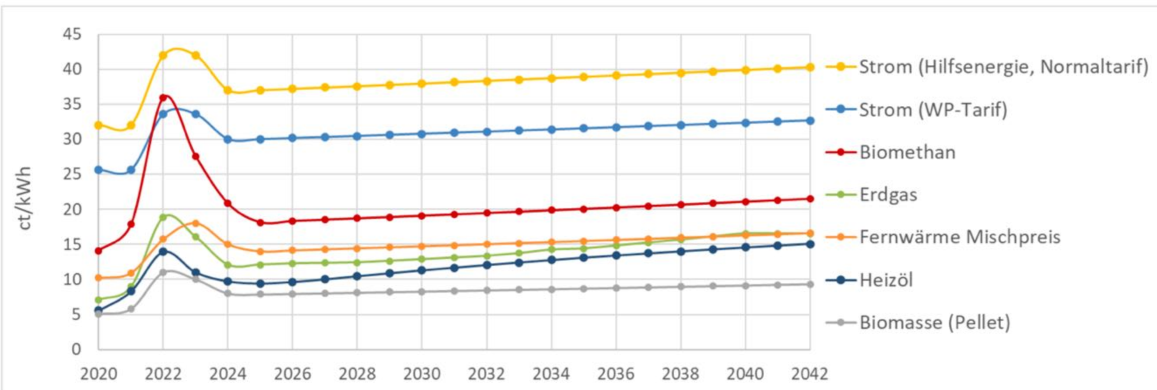

Figure 6: Projection of Various Energy Prices 2020-2042 (Reprinted from Pehnt et al., 2023)

The permanent 28 Cent HPT Price Brake-

A third distinct possible trajectory for heat pump tariffs is one in which peak tariff electricity rise into the 35-40 cent range, but the 28-cent HPT price brake is made permanent either through legislation, agreement with providers, or some combination of the two. Permanent price ceilings for HPT are strongly advocated for by many industry groups such as the German Heat Pump association and could alternatively be pegged at another price point or a steadily increasing rate after the current legislation expires in April, 2024 (Federal Ministry of Justice, 2023; German Heat Pump Association, 2023b).

Synthesized Market Price Pathways

Using the two market models and possible legislative course described above, three energy price pathways were created which are detailed in Figure 7. Generally, the three scenarios can be viewed as going from most favorable to least favorable for heat pump owners.

The first (scn1) can be thought of as pairing aggressive electricity price support in the form of additional changes to taxes and network delivery fees or even direct subsidies for HPTs taking a form rather than price brakes and is paired with tight natural gas market conditions and aggressive carbon pricing. Double coverage of building carbon emissions under ETS2 and BEHG after 2027 resulting in a price jump on natural gas of around a half cent per kWh_{gas} in 2027 is one policy that could be represented here. Even with aggressive carbon pricing, this pathway requires tight market conditions which could be associated for instance with either geopolitical trends or a sluggish phase out of natural gas use for power generation (Deutsche Bundestage, Wissenschaftliche Diesnst, 2023).

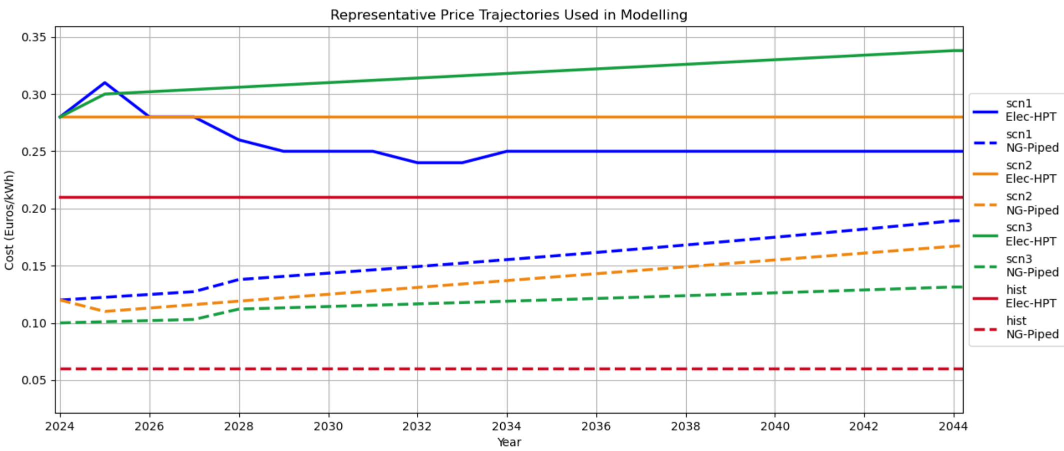

Figure 7: Overview of 3 Potential Price Trajectories for Electricity and Natural Gas

The second price pathway (scn2) is a middle path and pairs a permanent 28 cent HPT with less aggressive carbon pricing and a moderate wholesale natural gas market. Assuming that the historic discount of around 20% for the HPT remained a standard, this trajectory implies peak tariffs rising to at least the 35 cent level so as to be determined by price cap rather than a peak tariff discount, and imagines a carbon pricing trajectory similar to those reflected in the Prognos model (Federal Ministry for Economic Affairs and Climate Protection, 2023a; Ortner et al., 2021).

The third price pathway (scn3) is the worst case for a heat pump investor in 2024. HPTs increase rather quickly and roughly linearly after 2025, reaching 0.34 €/kWh by 2044, a result of an expiring price brake and tight electricity market arising for instance from increasing demand of electricity for green hydrogen production and electromobility (Bavarian Industry Association, 2023; Pehnt et al., 2023). While this scenario reflects the highest pathway for electricity prices, it is worth considering that this trajectory still has a growth rate of only about 0.7% per year after 2025, which is well below target inflation as well as the historic rate of inflation in household energy in Germany, which averaged around 2.9% per year for the period 2010-2021 (Federal Statistical Office, 2023a). This fact underlines some structural changes that can be anticipated in the electricity market throughout the energy transition and is also a valuable insight should policy makers want to consider conceiving a dynamic price brake that could increase over time. Low consumer natural gas prices in this scenario are driven by a return to very low wholesale prices in the European market after 2026, which is predicted by some market forecasts (Cochintu, 2023). Low natural gas prices would also be in line with continuity in German energy and foreign policy which combined to keep natural gas prices low and largely flat even as prices for other energy sources increased over the last decade (Federal Statistical Office, 2023a).

The same energy price was applied to all buildings in the analysis, which is a simplifying assumption, because in reality, contracts over 15,000 kWh/yr typically are discounted by around 15% or more while similarly large natural gas contracts are discounted slightly less at around 5-10% for a similar difference in use (Federal Statistical Office, 2023a). It is not totally clear if a similar dynamic exists in large HPT contracts as does with large natural gas contracts, but the fact that large buildings would in theory have both the factual and counterfactual inputs to their yearly savings discounted even if the discount was not the same was enough to justify this simplifying assumption.

Carbon intensity of power generation

While the chief goal of this project is to investigate heat pump NPVs, understanding the pathways under which heat pump adoption may lead to carbon emissions abatement is key to quantifying the efficiency of public investments in price brakes from a climate perspective. Because heat pumps fundamentally shift heating loads away from physical fuels like natural gas or heating oil towards electricity, this requires a grid-level picture of the power mix both now and in the future. Germany's current power mix puts it behind some neighboring countries in terms of the carbon intensity of power generation. On average Germany produced around 390 $gCO2_{equiv}/kWh_{elec}$ in the first 9 months of 2023, reflecting a bit of a rebound from a relative low in 2020 in part due to the global energy crises of 2022 and subsequent turn back towards domestically available coal resources (Electricity Maps, 2023; European Environmental Agency, 2023).

Nevertheless, the German government has been aggressive in its targets for decarbonizing and scaling its power system. From 2020 on, numerous revisions of the German Renewable Energy Law (EEG) have placed varying target dates for complete decarbonization. Starting first with 2045, the date was then bumped to 2040 and recently to 2035 (Amin, 2022; International Energy Agency, 2023). For the purposes of conservatively modelling carbon savings here, the original date of 2045 for complete decarbonization is used, but is paired with a more rapid decarbonization timeline through 2030 in line with analysis of the European Environmental Agency and the latest goals of reaching 80% renewable energy in the power mix by that date (Appunn and Wettengel, 2022; European Environmental Agency, 2023). The resulting forecast for the carbon intensity of power generation by year can be seen in Figure 7.

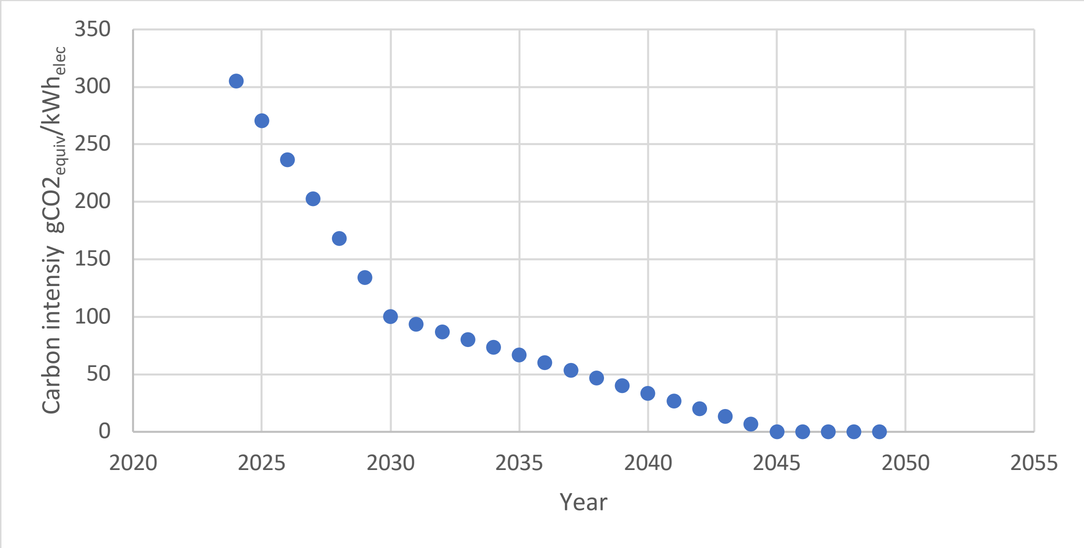

Figure 8: Projection of German Decarbonization Timeline in the Power Sector (2024-2049)

A fair criticism of this model is that the carbon intensity of heat pump electricity should be less than the grid average because they tend to have their load times more heavily weighted towards off peak hours like nights and weekends. However, a conflating factor here is the diurnal variation of renewable sources, with solar for instance being completely unavailable at night. This question requires deeper grid modelling than can be explored here, and the resulting decision to use averages means that computed carbon savings could be on the low end of actual values.

As was outlined in section 2.1.3, a point of comparison for the emissions intensity of oil and gas heating was drawn simply by taking the emissions intensity of heating oil and that of natural gas and weighting them in proportion to their current use in Saxony, with a result of around 236 $kgCO_{2,eq}/kWh_{therm}$ (CarbonIndependent.org, 2019; German Association of Energy and Water Industries, 2023b).

2.2.3 Upfront Cost

For estimating upfront costs, the level of building insulation, type (SFH or MFH) and living area are the main determinants. As is detailed in the section on data limitations, coverage is lacking for both existing heating systems and insulation level, so the overall approach was to focus on scaling upfront costs with living area and to break up the costs per area based on building size classification (MFH or SFH). This approach makes sense as living area translates fairly cleanly to required system capacity (in kW), and the size classification is the best proxy available for installation complexity.

For single family homes, 3 different cost breakdowns from commercial installers were compared, which quoted values ranging from 8,000-15,000 € in equipment costs, and 2,000-6,000 € for the install on a "typical" single family home (Heizungsfinder.de, 2023; Klivatec, 2022; Kloth, 2023). As none of these cost breakdowns mentioned specific living area, sizing factors from the energetic analysis (section 2.2.4) were used to find likely heat pump models for a small and mid-size single family home. Mid points in the range of installation costs quoted in commercial cost breakdowns were then taken as representative, and finally the total was divided by living area. For a 150 m^2 home at a specific heating load capacity of 0.09 kW/m^2, a unit such as the Junkers/Bosch CS7001iAW 12.5 kW with a retail price of around 13,200 € was identified, making the total price around 17,200 with a 4,000 euro installation (heizungsdiscount24.de, 2023). Similarly for a 200 m^2 home, a 17kW unit costing 18,300 € was identified suggesting a price with install of around 22,300 €. The price per square meter in these two scenarios was 114 € and 111 € respectively and were rounded down to 110 €/m^2.

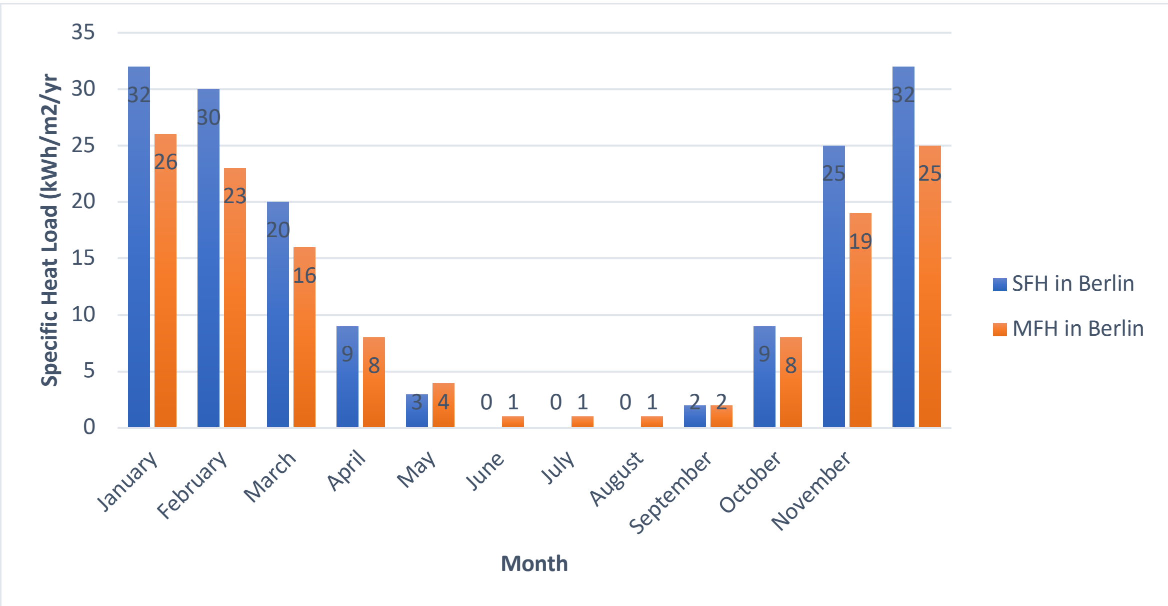

Figure 9: Heat Loads For Modelled Buildings in Berlin (Zangheri et al., 2014)

For multifamily homes, more studies and cost breakdowns focusing on upfront cost were readily available including by (Henning, 2023; Langreder et al., 2022; Schreurs, 2019). These all suggested ranges of 110 -150 €/m^2 for MFHS and a lower required specific capacity for multifamily homes relative to single family homes of around 0.7

kW/m^2. This is consistent with a broad base of findings from Dott et al. (2013), Schlemminger et al., (2022), and Zangheri et al. (2014) showing lower specific heat loads for multifamily homes but a larger initial investment cost arising from more involved installation. A representative value of around 130 €/m^2 was decided on for MFH with 6 units or more by averaging price breakdowns by Schreuers (2019) and Henning (2023). The decision was made to include small apartment buildings within the cost grouping of smaller structures based on the case study of a 420 m^2, 6 unit building in Langreder et al. (2023). A summary of the estimations on upfront costs can be found in *priceDict.csv* in the accompanying files.

2.2.4 Heating Load, Sizing and System Efficiencies

Yearly specific heat loads in kWh/m2/yr are heavily dependent on building characteristics such as insulation, ratio of external wall area to living area and the outdoor climate. As with upfront cost calculations, the spatial data from the German census and EUBUCCO dataset are missing much of the information that would be required to effectively model energy use on a building-by-building basis, so the decision was made to find a reference building, and scale loads based on the average outdoor temperature, which can be readily point sampled from climate data.

In addition to the yearly specific heating load, data on a monthly time frame was desirable in order accurately calculate heat pump SPF by weighing COPs by usage on a monthly basis. A first step in this direction was to identify reference structures in nearly comparable climates. Figures with monthly granularity from Schlemminger et. al. (2022) and Dott et. al. (2013) which studied buildings in Lower Saxony, Germany and Strasbourg, France and ranged from 15 -100 kWh/m^2/yr were the first to be considered but were clearly unrepresentative of likely retrofit candidate buildings as both studies looked at higher performing structures built after 2011. Zangheri et al., (2014), Langreder et al., (2022) and Kloth, (2023) focused on older, or otherwise less energy efficient buildings and cite yearly thermal energy loads in the range of 160 – 200 kWh/m^2/yr for unrenovated single family homes and 130- 160 kWh/m^2/yr for multifamily homes in the same age range and level of insulation. Data from Ortner et al. (2021) and Zangheri et al. (2014), which included SFH and MFH in the same methodology and study location further suggested a roughly 20% difference in yearly specific heating loads between comparable high and low occupancy buildings due to the insulating effect and thermal mass of neighboring apartments and smaller percentage of external facing wall area and windows per unit.

A final input used to create the picture of the heating load for a representative candidate structure was data from the German Association of Chimney Sweeps showing that roughly 70% of oil and gas heaters in Germany were installed between 1990 and 2004 and further that the median age of gas heaters was between 22 and 26 years as of 2021 (Figure 10).

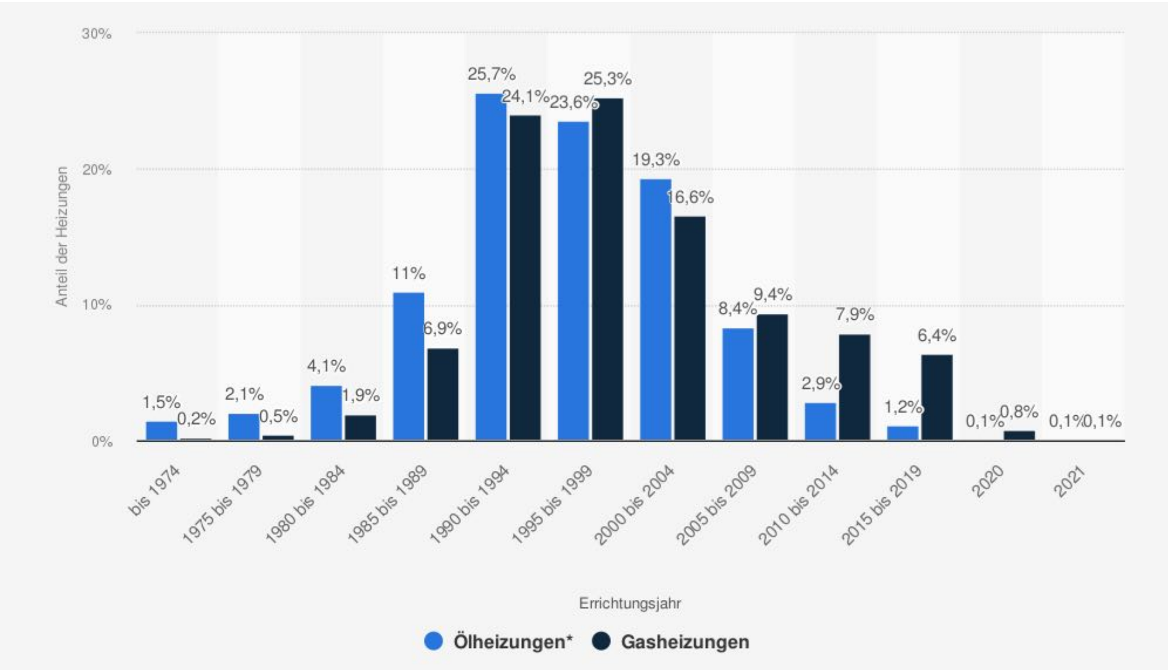

Figure 10: Age Structure of Oil and Gas Heaters in Germany as of 2021 (Reprinted from statista.com citing Federal Association of Chimney Sweeps, 2021)

This data is informative, both for the economic valuation of heat pump installation, which is somewhat altered if existing fossil fuel infrastructure needs to be replaced anyways as well as for getting a picture of the building and heating system characteristics that are missing from building level data sources. Complimenting this age breakdown of heating systems is data from the German Association of the Energy and Water Industry (2022), which further indicates that the median building year for apartments (by unit) is 1970 (Figure 11).

Taking these together, the idea of the representative structure, defined as one with median age, heat system, and insulation level is a building built sometime around 1970 with an oil or gas burner installed in the mid to late 1990's. Looking back at the studies referenced above this matches somewhat closely the 6 unit MFH described in Langreder et al. (2022) built in 1969 -1978 with specific heat loads of around 150 kWh/m^2/yr which in turn matches quite closely a MFH in Berlin modelled by (Zangheri et al., 2014) at 160 kWh/m^2/yr using the EnergyPlus building energy modeler. As Zangheri et al., also included SFH monthly breakdowns, and conformed with the roughly 5 to 4 ratio of specific heat loads between MFH and SFH mentioned above, this study was used as the baseline, and specific heat loads for a given building were scaled in proportion to the difference of mean outdoor to indoor temperature using a formula and rationale highlighted in detail in section 3.2.

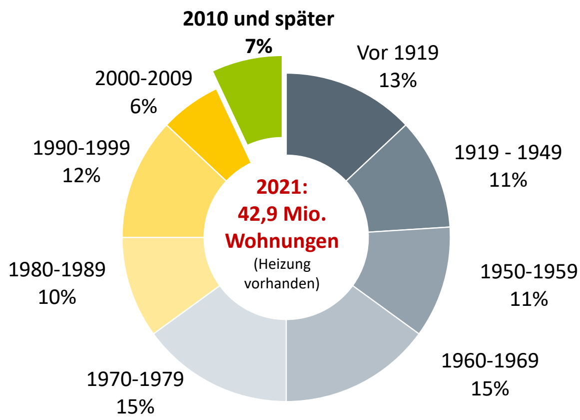

Figure 11: Apartments in Germany by Building Year (Reprinted from the German Association of Energy and Water Industries, 2023a)

COP-

The Coefficient of Performance (COP) is a measure of how much thermal energy per unit of electrical energy can be produced by a heat pump. For ASHPs, this value scales in proportion to outdoor temperature. In this study, the quantitative relationship between outdoor temperature and heat pump performance was synthesized from two studies and an online calculator which all suggested a range of roughly 2.25 to 4 for outdoor temperatures between -15^o and 20^o C (Corberán and Cazorla-Marin, 2018; German Heatpump Association, 2023b; Hirvonen and Sirén, 2017).

The online calculator, provided on the German Heat Pump Association's website allows users to look up seasonal performance at any given average outdoor temperature, which when manually entered is equivalent to COP. The representative models used when consulting this calculator were the same as those used in the upfront cost estimation, namely the Junkers/Bosch CS7001iAW 12.5 kW for SFHs and CS5000AW 38kW for MFHs. Additionally, a high send temperature and low return temperature of 60° and 40°C respectively were selected in line with the assumption of a minimally involved retrofit which makes use of existing heat distribution equipment (Heizsparer, 2022). The resulting curve was placed in a dictionary file (*copDict.csv*) so that the resulting performance could be easily looked up in calculations for NPV and Seasonal Performance Factor. A summary of the COP curve can be seen in Figure 12.

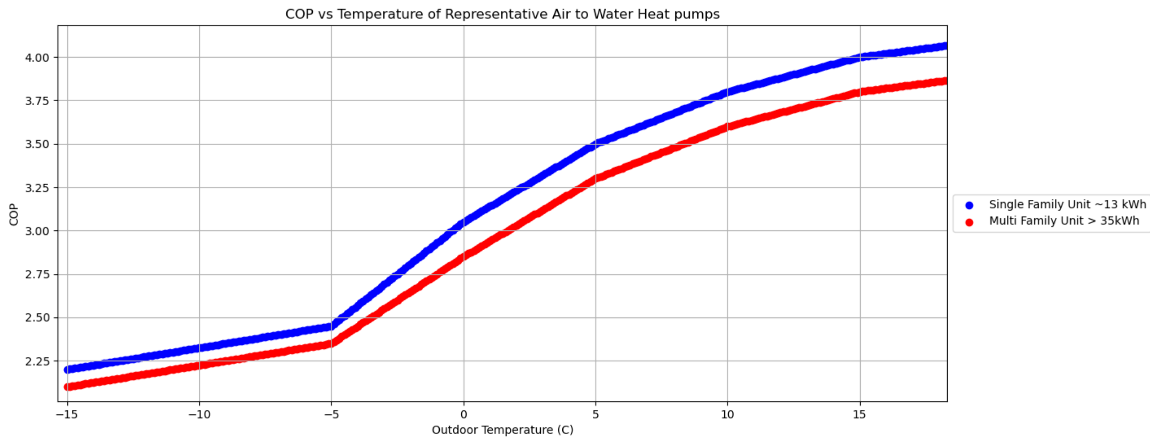

Figure 12: COP to Outdoor Temperature Curve Used in Modelling (synthesized from BWP, 2023b; Corberán and Cazorla-Marin, 2018; Hirvonen and Sirén, 2017)

The Thermal efficiency of both gas and oil heaters were taken to be around 90%, which may be on the high end, particularly for boilers installed in the 1990's, but was chosen to provide a conservative estimate in subsequent energy savings calculations (Arena and Faakye, 2013; United States Department of Energy, 2023).

3 Methodology

The following is a broad overview of how spatial data was combined with the non-spatial characteristics and used to calculate NPV as well as potential emissions savings and subsidy costs among other quantities of interest for policy makers. For the most part, data was preprocessed and analyzed using Python's Pandas and Geopandas data science and geospatial libraries in conjunction with the open-source geospatial software, QGIS.

Methodology

All Python scripts as well as the final output shapefile of roughly 450,000 structures with calculated NPVs are included in the accompanying file set, while intermediate files are available upon request.

3.1 Preprocessing

Figure 13 provides a broad overview of the essential preprocessing task of this project, which was spatially disaggregating (downscaling) heating system and use type data from the 100m census grids to the building level where it could be paired footprint, height and spatial relationship for the eventual modelling task. Additionally, some filtering by area and relationship to neighboring structures was done to remove structures like garages and sheds.

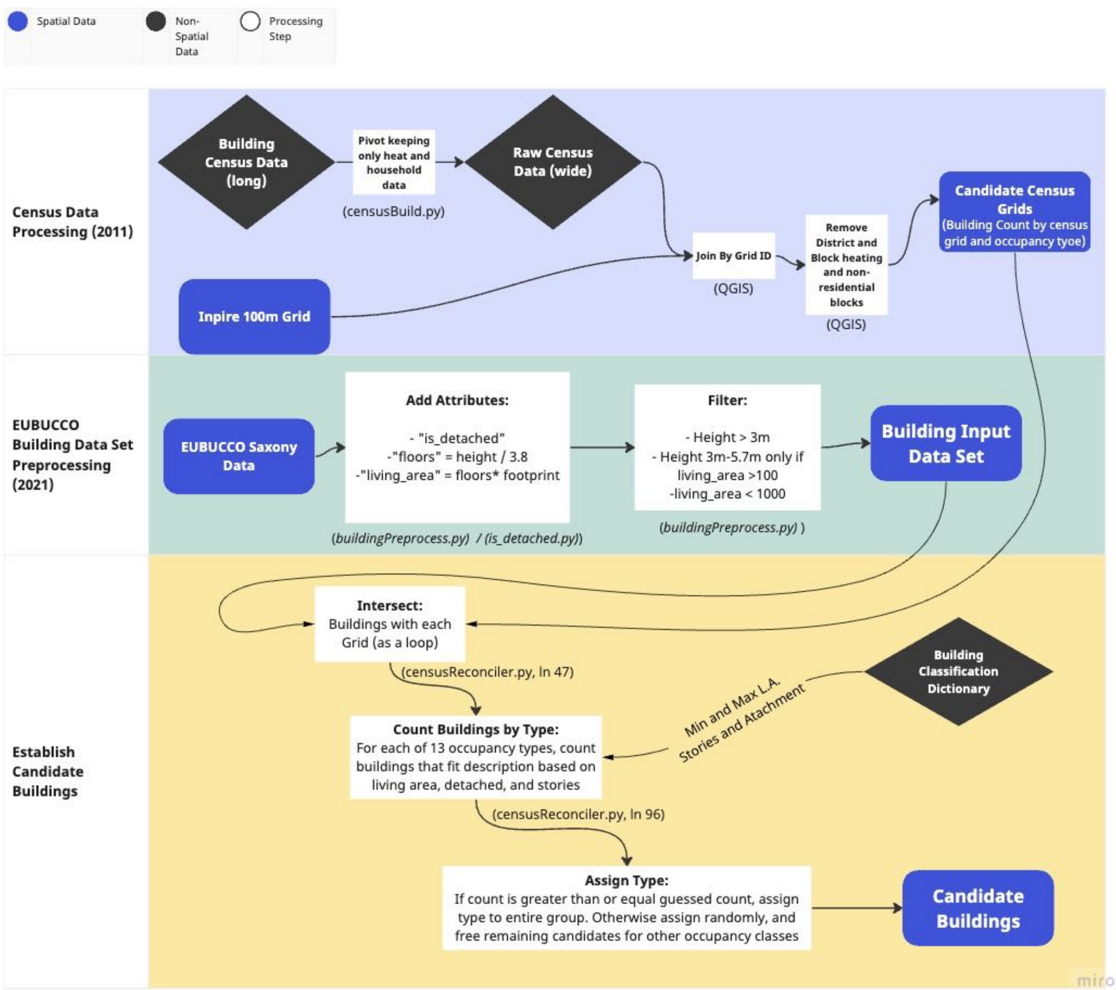

Figure 13: Flowchart Summarizing the Preprocessing used to Determine the Spatial Set of Candidate Structures

3.1.1 Census Data Preprocessing *(censusBuild.py)*-

The German census authority publishes their buildings data in nonspatial spreadsheets with a grid_id ("Gitter_ID_100m") field referring to 100m INSPIRE grids. The data comes in long format with various rows for each grid square corresponding to a variety of attributes ("Merkmal") and their values ("Auspreaugung_Text"). The first step was to filter this data by only those potentially important attributes (originally ['HEIZTYP','GEBAEUDEART', 'GEBTYPBAUWEISE', 'GEBTYPGROESSE']). Explanations of these attributes and English translations of their values can be found in Appendix B

After filtering, this data set was then pivoted on the grid id column using summation as an aggregator function. The result was a data set in wide format with only one entry for each grid square and a large number of columns, one for each possible value of a given attribute (eg heat_district, heat_central, type_row, type_single …) and values reflecting the number of buildings in each grid square. (Deutsche Zensus, 2011)

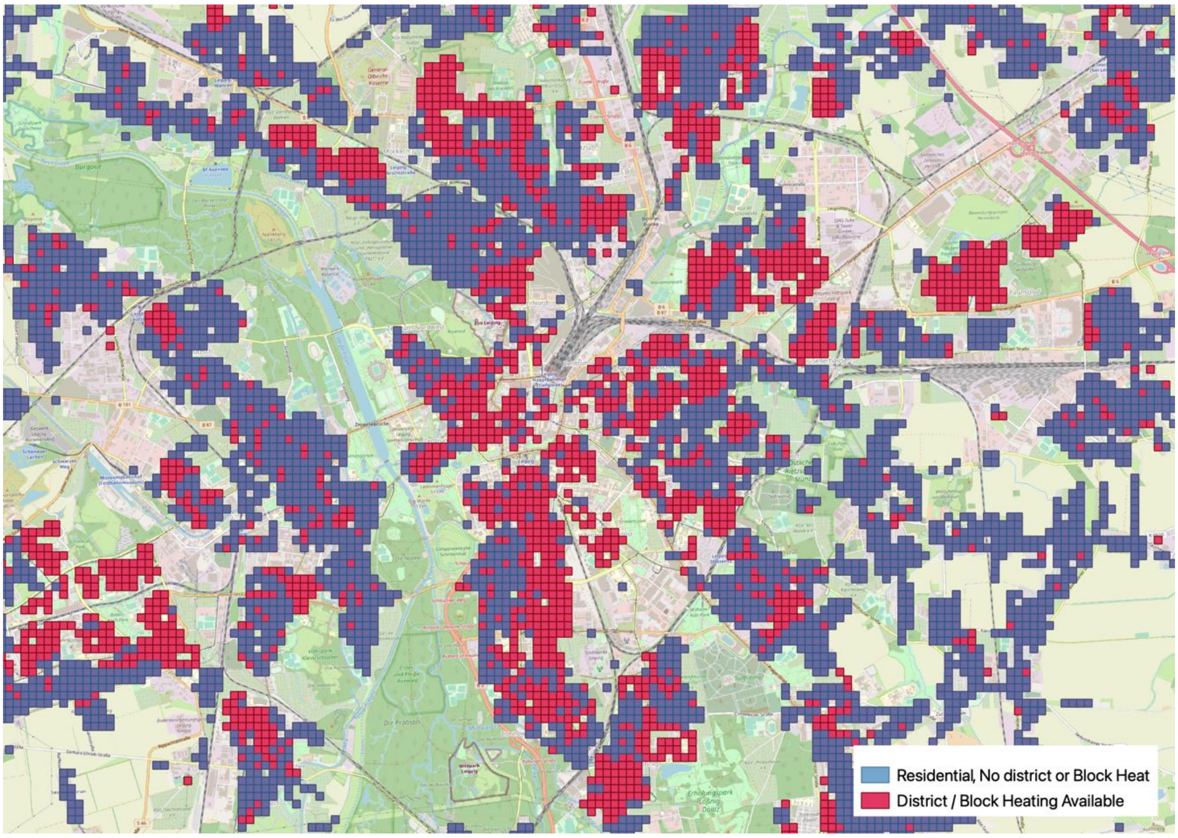

Figure 14: Census Grid Coverage in Leipzig, Germany Showing Areas with at Least One Structure Using District or Block Heating

From here, the filtered and widened building type and heating data could be joined by grid_id (GITTER_ID_100m) to grid data available from the INSPIRE geoportal to get a spatially relevant image of this data (INSPIRE Geoportal, 2023). A basic visualization of this data for the downtown area of Leipzig, Germany in Figure 14 shows that this data set already incorporates many of the important criteria for determining candidate structures. In particular, the grid only has coverage for areas with at least one residential structure built before 2011 and can easily be filtered to exclude areas with available district or block heating.

A further useful piece of information to be taken from the Census grid data is residential building counts. In theory, all four feature categories carried over from the raw data (heat type, building type, construction type, and building size) should sum to the same number of total buildings across all possible attribute values. However, it was found that there was some arginal variation between the 4 different feature types. As building size information (GEBTYPGROESSE) later becomes an important attribute for building use classification, the sum across all values for this attribute was added as a separate column, “residential_count” to the output file (*candidate_grids.shp*), which also had district and block heating grids removed. This is to say that the operational estimate of all buildings in the state come is based on the size attribute.

3.1.2 EUBUCCO Building Data Preprocessing (*buildingsPreprocess.py)*

Preprocessing the building data took place in the *buildingsPreprocess.py* and *is_detached.py* scripts, and consisted principally of adding necessary attributes such as number of floors and living space, information on whether a building is free standing or attached and filtering based on the study boundary conditions using these properties.

The total height of a building was used as a proxy for number of floors, and the methodology was to take a sample of 15 different buildings, both MFH and SFH, and determine the number floors based on observation of windows and other visual attributes using Google Earth Street View (Google, 2023). From this sample, the average number of meters per floor could then be used to estimate number of floors for the whole dataset. Examples of this process including a discussion of its’ limitations can be seen in *Appendix D* and Appendix E. Based on this process the average number of above ground meters per floor was determined to be approximately 3.8m, therefore a modulus operator was used to return a whole number of floors with cutoffs halfway between averages. In this way, any building between 1.9m and 5.7m was considered to be 1 floor, the range of 5.7m to 9.5m was taken as two floors and so on in 3.8 meter increments.

Living area was then taken as simply the building footprint in m^2 times the number of floors. Finished basements, unfinished attics, and unheated common areas such as lobbies and hallways all could introduce error to this approximation, however as discussed above specific heat load estimates are based on sensible heat transfer modelling and to a certain extent already incorporate these types of building structural features, so by the same token, this process was determined to be close enough to reality for modelling purposes.

While conceptually quite simple, determining whether a building was detached or not proved to be operationally difficult for the full building data set of over 2 million total buildings. This is because when Geopandas goes through checking for intersection it checks every other feature for intersection resulting in a $O(n^2)$ complexity which blows up processing power for the large data set (Ashworth, 2022). The solution to this was to define a small search area using a 1-meter buffer around each building, which was used to mask the whole set for each iteration. Spatial indices were also applied to the entire data set to speed up the search for adjacent buildings intersecting the 1m buffer mask in each iteration. Finally, to avoid misclassifying buildings with attached unheated spaces such as sheds or garages, the total area of bordering structures was used for the final proxy of "attached-ness." If the footprint of the attached structure was less than $25m^2$, which roughly corresponds to a large garage, the principal structure was still classified as unattached (see *is_detached.py*).

The filtering step of buildings preprocessing was essentially aimed at removing sheds and garages that could be mistaken for residential structures during census disaggregation. For sheds and garages, visual investigations with Google Earth again revealed building height and footprint area as the best proxies for distinguishing accessory structures from smaller SFHs. Ultimately the rule that buildings must be at least 3m tall and only allowed between 3 and 5.7m height if the building footprint was over 100 m^2, was determined to be the best way to include short, ranch-style homes while excluding sheds and detached garages. For buildings over 5.7m (taken from to be

2 stories or more), there was no limit placed on building footprint as many 2 story SFHs especially in urban areas have rather small footprints (see Appendix E). At the other extreme of building size, 1000 m^2 total living area was chosen as a hard cutoff for buildings to run on heat pumps of 85kW or less, consistent with study boundary conditions and required heat capacities of around 0.09 kW/m^2 for MFHs (Highseer, 2023; Ortner et al., 2021).

The resulting data set was masked by the census grids seen in Figure 14 before being exported to the file, *snEUBUCCOClean.shp.* In the next step the resulting set of 815,048 buildings was further refined using the grid level census data whose total excluding areas ith district heat was 697,543 in the 2011 census. The discrepancy of around 117,000 buildings arises from a combination of building construction between 2011 and 2021 and non-residential buildings in residential census grids. Addressing this discrepancy was the chief aim of the next preprocessing step.

3.1.3 Spatial Disaggregation of Building Counts *(censusReconciler.py)*

Downscaling enumerated Census Data to individual buildings involved assigning total counts in the original building size attribute (GEBTYPGROESSE) to specific buildings within each grid square, while simultaneously rejecting buildings that do not likely fit any of the residential buildings tallied in the 2011 census, and was the approach taken to close the gap of roughly 110,000 buildings described above. By its nature, this was an inexact process, and the general problem of poor building classification coverage is a well-known issue within the geospatial data science field. Some efforts have been made by Bandam et al. (2022) and others to apply advanced techniques such as machine learning to this problem, however the approach taken here favored a deterministic, iterative, and rules-based approach focusing on reasonable assumptions of building characteristics for each size category.

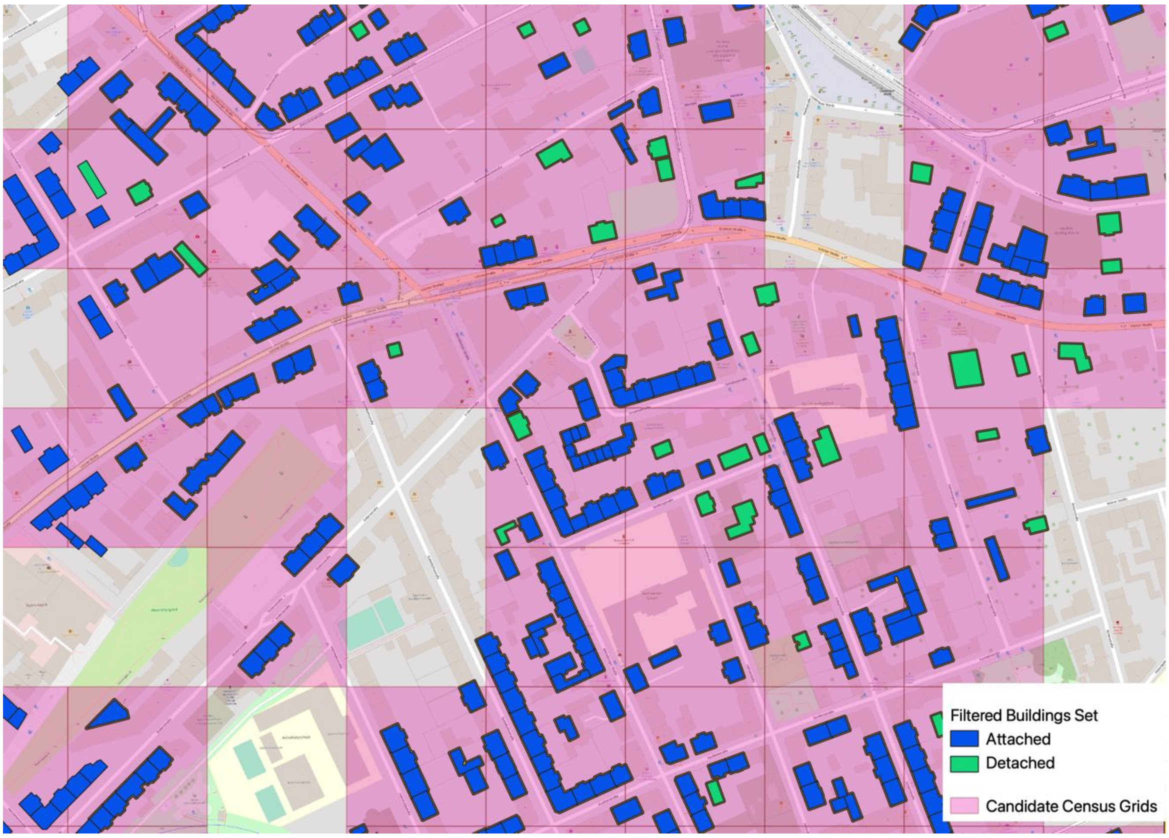

Figure 15: Filtered and Classified Building Set over Candidate Census Grids in Suburban Leipzig

This approach was underpinned by the creation of a building characteristic dictionary (*buildingClassificationDict.csv* in the accompanying file set), which is reproduced in Table 1. This table was populated with likely minimum and maximum living areas, floors and relationship with neighboring buildings for each of the 10 unit types covered in the Census' building size attribute.

name	min_la	max_la	min_floors	max_floors	detached
siz_1_free	80	400	1	3	2
siz_1_semi	80	400	1	3	2
siz_1_row	80	250	2	3	0
siz_2_free	160	600	1	4	1
siz_2_semi	160	600	1	4	2
siz_2_row	160	500	1	5	0
siz_3-6_apart	150	1000	2	8	2
siz_7-12_apart	450	1800	2	15	2
siz_13+_apart	650	10000	3	40	2
siz_other	0	10000	1	40	2

detached: 0 – attached ; 1 – detached ; 2 – ambivalent

Table 1: Building Classification Dictionary (buildingDict.csv)

The python file, *censusDisaggregator.py* is primarily responsible for assigning building counts from the 2011 Census to the buildings data set and works by iterating through each 100m grid and counting the number of buildings that fit the characteristics in the building classification dictionary. If the number of buildings fitting the characteristics of a given building classification is less than or equal to the figure listed in the census, all of them are immediately assigned that classification and the remaining tally is added back to a running list of unidentified buildings. If on the other hand there are fewer entries in the census data than there are matching buildings, the building classification is assigned randomly to the matching buildings set up to the total listed in the census for that grid, and the remaining buildings are assigned back to an internally held list of unclassified buildings in the grid square. Once all classifications are checked a second pass is made where building classifications are ordered from lowest to highest expected living area (as they are listed in Table 1) and assigned likewise to remaining unidentified buildings in the grid in ascending order based on living space. This process repeats for each grid and each classification type as a nested loop, for all of Saxony.

The main advantage of this process is that it places a hard cap on the number of candidate buildings in each category and in each grid square at the number confirmed by the 2011 Census, and generally does a good job at locating these classifications in buildings that could reasonably be the ones counted during actual census data collection. The chief drawback is the risk for mis categorization of buildings, particularly in areas with mixed zoning. However, on this point it should be said that for the purposes of energy use and economic modelling using aggregate spatial statistics, this risk might not be a tremendous problem. If for instance a 350 m^2 grocery store is misclassified as a 400 m^2 MFH, the energy use and the economic situation of the errantly rejected building's owner are still being measured, just by way of another similarly sized building in their immediate vicinity. So, while the resulting candidate buildings data set might not be accurate enough for another purpose such as city planning, this was considered to be adequate for the purposes of modelling aggregate energy consumption and the way in which the economic value of heat pump retrofits is impacted by spatial distribution and building stock makeup.

At this point, a review of the size of the input datasets, and expected number of buildings at each step throughout the preprocessing analysis is helpful. This summary can be seen in Table 2, and shows that of the roughly 697,000 residential buildings in Saxony, about 96,000 or 14% were disqualified because they were in grids with district or block heating, and that roughly 75% or 452,000 of these were successfully associated with a specific building using the method described above.

Table 3 presents the breakdown of identified and unidentified buildings recorded in the 2011 Census data and is presented to give an idea of how representative the 452,000 candidate buildings are of the total building stock in the state. The percentage of buildings of each type identified gives information on which building types are "oversampled." Clearly, the method described above struggled to identify one- and two-unit semi-detached homes (SIZ_1_SEMI and SIZ_2_SEMI). This was likely due to the fact that "attached-ness" was strictly defined by spatial proximity here (in section 3.1.2), but may not have had such a strict definition during on the ground census data collection. In addition, the broad "other" category (SIZ_OTHER), because the rules-based method had little to go on for this category. Apart from these three categories, which together make up less than 15% of the Saxon building stock, all other categories were sampled at between 69 and 81% success rates, meaning relative proportions of these buildings is roughly preserved through preprocessing within a tolerance of around 12%.

STEP OR DATA SET DESCRIPTION	COUNT
TOTAL EUBUCCO BUILDING RECORDS IN SAXONY	2,310,000
NUMBER OF RESIDENTIAL STRUCTURES 2022 (INCLUDES DEVELOPEMENT OUTSIDE OF 2011 CENSUS TRACTS) [1]	842,000
EUBUCCO – TOTAL BUILDINGS IN RESIDENTIAL CENSUS BLOCKS (UNDETERMINED USE)	815,000
CENSUS 2011- RESIDENTIAL BUILDING COUNT (BUILDINGS WITH A RECORDED SIZE ATTRIBUTE)	697,000
CENSUS 2011 -RESIDENTIAL BUILDING COUNT NOT IN DISTRICT OR BLOCK HEATING GRIDS	601,000
EUBUCCO BUILDINGS ASSIGNED A RESIDENTIAL SIZE CLASSIFICATION	452,000
UNIDENTIFIED BUILDINGS WITH A CENSUS RECORD	147,000

Table 2: An Overview of How Census and EUBUCCO Building Records Were Filtered and Compared

[1] (German Association of Energy and Water Industries, 2023a)

RESDENTIAL SIZE CLASS.	IDENTIFIED COUNT (%)	UINIDENTIFIED COUNT (%)
SIZ_1_FREE	244613 (81%)	56583 (19%)
SIZ_1_ROW	21721 (70%)	9422 (30%)
SIZ_1_SEMI	31528 (56%)	28459 (47%)
SIZ_2_FREE	44764 (69%)	20224 (31%)
SIZ_2_ROW	5892 (87%))	935 (13%)
SIZ_2_SEMI	3308 (61%)	2118 (39%)
SIZ_3-6_APART	58477 (83%)	12742 (17%)
SIZ_7-12_APART	22391 (74%)	7779 (26%)
SIZ_13+_APART	3634 (90%)	426 (10%)
SIZ_OTHER	15850 (65%)	8706 (35%)
TOTAL	**452178**	**147394**

Table 3: Break Down of Identified and Unidentified Buildings by Size Classification (Residential)

The average living area by assigned unit count classification will become an important consideration later when seeking to interpret NPV results in a way that is comparable across building type categories. The breakdown of these average living areas is shown in Table 4. Semi-detached one- and two-unit buildings are slightly smaller than their free-standing counterparts. The largest building category of 13+ apartment buildings may seem a bit low, suggesting an average unit size in these building types of no more than 55 m^2 per unit, but on this point, it should be remembered that the exclusion of buildings over 1,000 m^2 most heavily affected this category, bringing the average significantly down from what it was before making this area stipulation. In general, this category should therefore be treated with the most uncertainty, and the decision to include those roughly 3,600 buildings classified as 13+ units but under 1000 m^2 in the rest of the analysis was made mainly to provide a point of comparison for the edge cases and shed light on the financing struggles project developers on these types of buildings may be likely to encounter.

ASSIGNED TYPE	AVERAGE LIVING AREA
SIZ_1_FREE	203
SIZ_1_ROW	204
SIZ_1_SEMI	184
SIZ_2_FREE	233
SIZ_2_ROW	262
SIZ_2_SEMI	220
SIZ_3-6_APART	373
SIZ_7-12_APART	516
SIZ_13+_APART	765
SIZ_OTHER	316

Table 4: Average Living Area by Residential Building Size Classification

3.2 Seasonal Performance and Load Calculation *(spfCalc.py)*

At this point the analysis entered the main modelling phase, the general process of which is visualized in Figure 16. As discussed above, both heat pump performance as measured in the unitless SPF value and specific annual heat load in $kWh_{therm}/m^2/yr$ are a function of average outdoor temperature and building characteristics. The residential size classifications yielded in the downscaling of census data discussed above are used here as the best proxy for building characteristics, and can be seen by distinct values for large vs small buildings in COP values (Figure 12), heat loads (Figure 9), and even upfront installation costs (Appendix F).

To constrain the temperature dependence of these two quantities, a point sample was taken from long term average (1990-2020) monthly temperature data from the German Weather Service for each building and each month and were added to the data set of candidate buildings as column “monthlyAvgTemp” (German Weather Service, 2023). Monthly COP values were then obtained by looking up values in a dictionary of COP values vs outside temperature (*copDict.csv* ; Figure 12).

Figure 16:Flow Diagram of Programmatic Calculations of NPV, Subsidy Cost, and Emissions Reductions

Heating loads were scaled from the reference buildings in Berlin using the basic physical relationship of heat diffusion showing that heat loss across an external wall is proportional to the difference of indoor and outdoor temperature (Equation 1). Therefore two otherwise identical buildings can be compared to each other in terms of heating loads based solely on the ΔT between the sampled outside temperature and the inside set temperature taken to be a constant 20º C (Toledo et al., 2018)t. Monthly difference of indoor/outdoor temperature in Berlin was simply looked up and compared to that of each structure, and the ratio was then applied to the known numbers from energy modelling. This was added to the buildings data set as the column "monthlyAvgLoads." (Zangheri et al., 2014 ; *spfCalc.py*)

$$q = h \cdot \Delta T$$ [2]

Equation 1: Heat Transfer Equation (Toledo et al., 2018)

Finally, monthly COP values were transformed into a single yearly SPF factor by weighting them in proportion to corresponding monthly loads. In addition to their use for yielding SPF, monthly loads scaled by outdoor temperatures and reflecting the building's size were also summed and used to calculate the yearly energy savings term in the NPV calculation.

3.3 Net Present Value *(npvCalc.py)*

Net Present Value can be thought of as the current value to a decision taker of taking an action in comparison to a counterfactual (Davis, 2023). For infrastructure investments such as heat pumps, this is often quite simply expressed as the upfront installation cost plus ongoing savings, discounted relative to the cost of capital. However, as the ongoing savings term references a counterfactual, usually thought of as the cost of either natural gas or heating oil, it also stands to reason that the counterfactual term in the upfront cost, such as the cost to a building owner of eventually replacing one fossil fuel heat system with another should also be included.

The approach taken here was to simply model a wide variety of scenarios for each of the three price pathways, including various subsidy scenarios, installation dates and formulations of lost value from retiring fossil fuel boilers. Operationally this meant that for each building 21 NPV values were actually calculated, each representing a different combination of 3 potential energy price pathways and 7 different mixtures of subsidy, installation date and remaining lifetime of fossil fuel boiler. The advantage of this approach is that it is then easy to look back on modelling results to examine the impact of any variation in any of these inputs.

[2] q: specific heat transfer

h: heat transfer coefficient

ΔT : difference in temperature

3.3.1 Terms of the NPV Equation

As outlined above, the annual cash flow conceptualization of heat pump NPV is essentially a summation of a timeseries where for each year, an installation decision is compared to a counterfactual and the difference in associated costs for that year are discounted and added to the sum before moving on to the next year. For the purposes of this project, a timeframe of 20 years was chosen in line with the average lifetime of modern ASHPs (Naumann et al., 2022). Equation 2 shows the conceptual formulation of the NPV Equation and highlights two additional terms that are sometimes neglected, namely foregone energy cost savings incurred by the building owner if they do not install immediately and a term representing the cost of early retirement of a fossil fuel boiler which can range in quantity from zero if the old fossil fuel boiler is not functioning and irreparable to the entire cost of a new fossil fuel boiler in the edge case where a building owner is replacing a nearly brand new fossil fuel boiler with heat pump. (Haase and Torio, 2021)

$$\begin{aligned} NPV = {} & Yearly\ Savings - \ HP\ Upfrontcost \\ & - Foregone\ Savings - Cost\ of\ Early\ FF\ Retirement \end{aligned}$$

Equation 2: Conceptual Terms of the NPV equation

The “cost of early retirement” can be thought of in a variety of ways, but essentially involves deciding on a useful remaining lifetime of an existing fossil fuel burning boiler and discounting what a new fossil fuel boiler would theoretically cost at that time. Equation 3 clarifies how this works. If t_2, the remaining useful life of a fossil fuel boiler, is taken as 0, the fossil fuel boiler needs replacement *now* and the final term evaluates to simply the cost of a new fossil fuel boiler and the effective upfront cost incurred by an owner is just the *difference* in cost between a heat pump and an equivalent new boiler.

$$NPV = \sum_{i=t1}^{20} \frac{q \cdot A \cdot \left(\eta_{ng} \cdot \epsilon_{ng}(t) - \epsilon_{elec}(t) \div SPF\right)}{(1+r)^i} + \frac{HPI(t)|_{t1}}{(1+r)^{t1}} \sim HP\ investment$$

$$-\sum_{i=0}^{t1} \frac{q \cdot A \cdot \left(\epsilon_{elec}(t) \div SPF - \eta_{ng} \cdot \epsilon_{ng}(t)\right)}{(1+r)^i} - \frac{FFI|_{t2}}{(1+r)^{t2}} \sim counterfactual$$ [3]

Equation 3: Analytical Formulation of NPV Equation

If on the other hand t_2 is taken to be sometime between 0 and 20 years, this term evaluates to how much a new boiler would cost in the future when it would have to be replaced anyways and the discount factor accounts for the value gap between that future time and today. It is also possible to simply ignore this term, which is equivalent to assuming that the existing fossil fuel heater has an infinite remaining useful life. The effective upfront cost in this case is the full cost of a heat pump install.

The first and third terms in Equation 3 are ongoing savings terms. In the most basic case where t_1 is equal to 0 (ie an immediate install), the third term drops out and the only ongoing term is defined by the difference in cost for a unit of thermal (sensible) heat in a home times the homes' yearly energy needs – i.e. the yearly savings. If a homeowner decides to wait sometime between 0 and 20 years, but eventually opts for a heat pump, the third term tallies the savings that the homeowner is missing out on during that time.

The second term in Equation 3 is the standard up front heat pump cost term found in most NPV formulations, but HPI is taken to be a function of time to account for an anticipated drop of about 30% in heat pump installation costs between 2023 and 2028 (European Heat Pump Association, 2022; Pehnt et al., 2023).

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[3] q – specific heat load ($kWh_{therm}/m^2/year$)

A- Living Area

t1 – Years until HP Install

t2 – Fossil Fuel Boiler Useful Life (Years)

HPI(t) – Cost of a Heat Pump, assumed to drop linearly by 30% in 2028 (European Heat Pump Association, 2022)

FFI – Cost of a Fossil Fuel Boiler assumed constant over time (Discounted based on assumed useful life)

ε - Future energy prices of electricity and Natural gas, both in € / kWh

η_{ng} = The thermal efficiency of natural gas boilers taken around 90% (Arena and Faakye, 2013)

SPF- Seasonal Performance Factor HP, defined as kWh_{therm}/kWh_{elec}

In general, every non-constant term in Equation 3 such as energy prices and variable install costs is demarcated by f(t) notation. The sign of the various terms can be confusing, and in practice, final signs where simply checked in the code to insure that they made sense. Broadly speaking, term 1 (yearly savings) should be always positive, term 2 (upfront HP costs) always negative, term 3 (foregone savings) always negative and term 4 (counterfactual FF install costs) always positive.

3.3.2 Considerations on Discount Rate

In classic micro-economics, the discount rate applied to annual cash flows is interpreted as the opportunity cost of capital, or the return of investments that are foregone to provide the capital for the investment under study (Haase and Torio, 2021). In determining an appropriate discount rate for a heat pump investment, the idea of risk matching comes into play, because a suitable discount rate will be one that comes from an investment of a similar degree of risk. As was discussed above, there are multiple interpretations of the risk associated with heat pump installs. Due to market uncertainty, some building owners might say for instance that there is a risk that natural gas will become cheap again and electricity prices will soar, in which case heat pumps could end up being more expensive than fossil fuels. This person may then prefer to put their money into a "risk-on" asset like equities, while another person considering an investment in a heat pump as a sure thing, may be more inclined to compare the rate of return of a heat pump favorably simply if it provides a better return than a "risk-off" investment such as government bonds.

As will be discussed in the results section, even the most pessimistic price pathway yields positive yearly cash flows and while the discount rate itself determines whether the NPV of an investment is positive over a fixed time frame, the high likelihood of positive cash flow combined with the argument made above that for practically all building owners, eventual replacement of their fossil fuel boilers will be necessary both points towards the interpretation that heat pump installs can be fairly thought of as a fairly low risk investment for building owners.

For this reason, the bulk of the analysis is conducted with reference towards low risk German government bonds, which as of august 2023 are yielding an effective rate of around 2.8% on a 20 year note (Finanzagentur, 2023). Similarly to the upfront subsidy, and numerous other input variables, the programmatic models in *npvCalc.py* were written to easily change to discount rate simply by changing a variable value.

While this relatively low discount rate was chosen for modelling runs on the data set, a higher "risk-on" discount rate of 9.2%[4] was also ran on some representative structures to show the change to the economic picture if the psychological effect of uncertainty leads some building owners to look at long term returns in equities markets such as the DE40 as their own personal point of comparison (tradingeconomics.com, 2022).

Finally, for some representative structures, the Internal Rate of Return (IRR) was calculated under the same set of scenarios used to analyze the whole data set by rearranging and numerically solving Equation 3 for NPV(r) = 0. This sheds light on the discussion around fair discount rates by essentially showing the effective rate of return for different groups of homeowners under different market and subsidy conditions. This was carried out in *irrCalc.py* using the fsolve() function from Python's SciPy library due to the temporal discontinuities in NPV in some scenarios. The results of both a higher discount rate and this IRR analysis can be found in section 4.1.3.

3.3.3 Degrees of Freedom in Test Parameters

As was outlined in section 2.2.2, the calculation of NPV for each building considered 3 possible price trajectories as well as a historic baseline of average prices in the period of 2010-2021. In addition to these price pathways, it was desired to capture variance of NPV with respect to installation date, useful life of fossil fuel boiler, and upfront subsidy. These factors were assembled into 7 combinations referred to as test parameters and can be seen in Table 5. NPV values were then ran for every combination of test parameter and price trajectory, which resulted in a 4x7 matrix for each building, which was stored as a two-dimensional data structure in the "npvs" column of the *buildingsFinal.shp* shapefile.

[4] Annualized 20 year return on the DE40 composite through August 2023.

PARAMETER INDEX	TERMSTART	TERMEND	FFBOILERUSEFULLIFE	UPFRONTSUBSIDY
0	0	20	0	0
1	0	20	0	0.3
2	5	25	5	0
3	0	20	10	0
4	0	20	100000000	0
5	0	20	100000000	0.3
6	20	20	100000000	0.3

Table 5: Parameter Sets Used to Investigate NPVs

The parameter sets were chosen to capture a variety of decisions that may be considered desirable or undesirable from a public policy perspective as well as to capture the importance of accounting methods on the psychological perception of heat pump values. Parameter Sets 4 through 6 for instance capture the often-unstated assumption present in some calculations of NPV that the existing fossil fuel boiler would never have to be replaced. Here upfront cost is just the subsidized cost of a new heat pump without reference to heating system replacement as a regular part of building upkeep over time. Parameter sets 0 and 1 are worth particular attention for the roughly 85% of gas heaters in Germany which are over 20 years old and represent the scenario if these heaters are considered to be at the end of their lifecycle (Federal Association of Chimney Sweeps, 2021). Parameter set 2 is one in which a building owner thinks they could "squeeze" another 5 years out of their current fossil fuel heater to wait and see if installation prices come down and may be another group that the government might want to target. Parameter set 6 would represent a homeowner who has no interest in the investment regardless of subsidy and is a good baseline reference for the hidden cost of the status quo in the form of continued personal and national fossil fuel consumption.

3.4 Quantifying Climate and Public Fiscal Impact

While the main focus here was on calculating NPV of heat pump installations to homeowners a few fairly simple extensions of the data set were able to yield the public cost of price support for a given building as well as make an estimate of potential emissions reductions associated with a heat pump install. These figures are useful for policy makers, as they allow the climate impact of heat pump subsidies to be weighed against other climate related priorities in a limited budget, and in so doing can help characterize the efficiency of subsidy intervention.

3.4.1 Cost of Subsidies (*subsidyCostCalculator.py)*

The python file, *subsidyCostCalculator.py* uses much the same framework as *npvCalculator.py* but instead calculates the cost to the public sector of a guaranteed HPT and upfront subsidization of installation costs. Unlike *npvCalculator.py* though, *subsidyCostCalculator.py* only considers one energy price pathway, specifically the situation in which market HPT prices rise relatively quickly to 0.34 €/kWh by 2044 as in scn3, but a 0.28 €/kWh ceiling on HPTs is maintained either through legislation or a negotiated arrangement between government TSOs and customers (Figure 7). Similarly to NPV, one-time expenses incurred by the government in the form of installation subsidies are tallied once, while ongoing cost per kWh associated with a guaranteed HPT are taken as the difference between scn2 and scn3 trajectories, and summed over 20 years

It should be carefully noted that the calculated "Net Present Cost" of price supports which appear in the "subsidyCost" column of *buildingsFinal.shp* is not necessarily the cost to taxpayers as this would depend on the exact nature of how price brakes are negotiated. It is rather said to be simply an "externalized cost" that results in value to the building owner.

3.4.2 Carbon Savings and Efficiency of Intervention

As has been extensively studied with electric vehicles, the potential of heat pumps to decarbonize the heating sector is heavily dependent on the carbon intensity of electric power generation (Knobloch et al., 2020). Section 2.2.2 focused in part on establishing a projection of the decarbonization schedule for the German power system based on current pledges and goals, which was used to calculate yearly emissions reductions under each of the 7 test parameters outlined in Table 5.

Operationally, this consisted of first calculating the additional kWh of electricity that would be consumed in each year by a heat pump which was stored in the "addtnlkwhelec" column. This value was then multiplied by the emissions intensity of power generation for that year (from *priceDict.csv*) and subtracted from the carbon emissions arising from a fossil fuel source for an equivalent amount of sensible heat production. The emissions intensity of a unit of sensible heat by fossil fuel was a weighted average of natural gas and heating oil and was taken from the calculations of section 2.2.2 to be 236 $kgCO_2/kWh_{th,\ ff}$.

4 Results

4.1 Breakdown By Building Type

The following section will present average NPV values across building types for various combinations of future energy market conditions and policy choices. For sscenarios in which some portion of a building owners' NPV ultimately derives from either price support or upfront subsidy, this will be broken down into subsidy value and non-subsidy/ (market) value. In total there are 21 possible combinations between the 3 price trajectories and 7 test parameter sets, and only a handful can be presented here, however all the data needed for any possible combination of interest is available in the 2-dimensional data structure in the "npvs" column of *buildingsFinal.shp.*

Figure 17 provides a good example of how NPV to building owner can be broken down into the component that derives from a market intervention and that which derives from "organic" value gaps in energy markets over the course of a 20-year heat pump lifetime. In this particular situation, the building owner needs to replace their heating system now, and there is no upfront subsidy, but the government or power provider essentially pays the difference between a guaranteed 28 cent HPT and the market price modelled in the high electricity price forecast (scn3 in Figure 7). The orange bar depicting the portion of the average NPV that derives from public support is thus entirely comprised of ongoing electricity price support.

Looking at the graph, it is clear that this situation makes little policy sense for large buildings as the cost of guaranteeing the 28 cent HPT over 20 years becomes larger than the NPV to the building owner over that same time frame. This result may seem surprising at first, but it is actually a meaningful result and arises from the very high upfront cost which is unsubsidized (estimated here to be around 130,000€ for a 1.000 m^2 apartment), rather high net electricity consumption, but relatively low heating requirement per m^2. One dynamic that is not explicitly explored in this part of the analysis is the fact that in large apartment buildings, energy costs are split between the tenants, and the NPV as discussed here is not actually to the building owner but to a group of tenant stakeholders that can be collectively thought of as a virtual building owner, with the big difference that they often do not have decision making power on building energy systems.

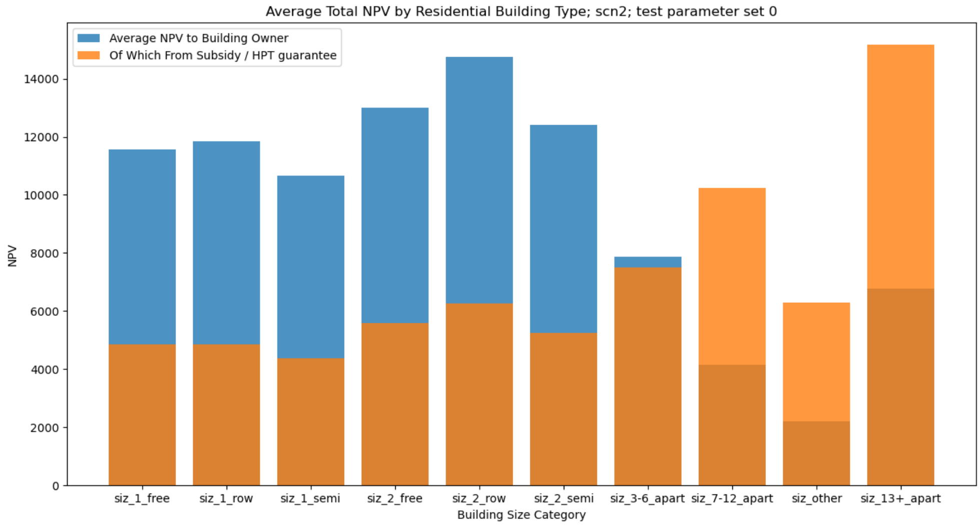

Figure 17: Average Total 20 Year NPV by Residential Building Size
Middle Price Scenario with Guaranteed HPT at 0.28 € (Scenario 2);
No Upfront Subsidy, Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 0)

These distributional effects of energy burden sharing between landlord, building owners and tenants, and the effect of new price dynamics on energy system preferences introduced by heat pumps in multiunit buildings is an interesting economic dilemma studied explicitly by Côté and Pons-Seres de Brauwer (2023), Weber and Wolff (2018) and others, however here it can be simply stated that it is a confounding factor on the very high cost of guaranteeing a HPT for larger buildings and relatively little "building owner" (collective) value derived from it.

A portion of this very high cost of subsidy could also be the from the assumption that the "organic" market rate for a HPT that is set in relation to the peak tariffs is the same for all building types. In discussing this assumption in section 2.2.2, this issue was explained away by saying that a similar (if not equal) large-contract discount in a natural gas burning counter factual would mean that the effect on NPV to the building owner of this dynamic should be minimal, however here the effect could be non-negligible. As a rough point of comparison, if the HPT for a SFH without subsidy would usually be set at 34 cents in this model scenario, then even a 5% bulk discount in heat pump electricity like the one that large buildings have historically gotten on natural gas would translate to a significantly smaller gap between the price brake and the market rate, and a roughly 28% error in the subsidy cost.

For smaller, 1- and 2-unit buildings, the break down shows that about 40% of the NPV or about 5,000 € over 20 years ultimately derives from external price support. In section 5.4 this result will be used to look at the economic efficiency of ongoing price support and compare it to upfront subsidies in terms of their impact on emissions.

Figure 18 visualizes the effects of upfront subsidization as an alternative to ongoing price support and is broadly speaking the current status quo combined with a tight electricity market and abundant supply of natural gas over the next 20 years. In both Figure 17 and Figure 18, peak tariff electricity prices take a high pathway, but in Figure 17, the government intervenes by way of a HPT ceiling and in Figure 18, the government allows prices to go high, relying instead on upfront subsidies. What is immediately clear is that ongoing price support provides significantly more value to building owners than upfront subsidy.

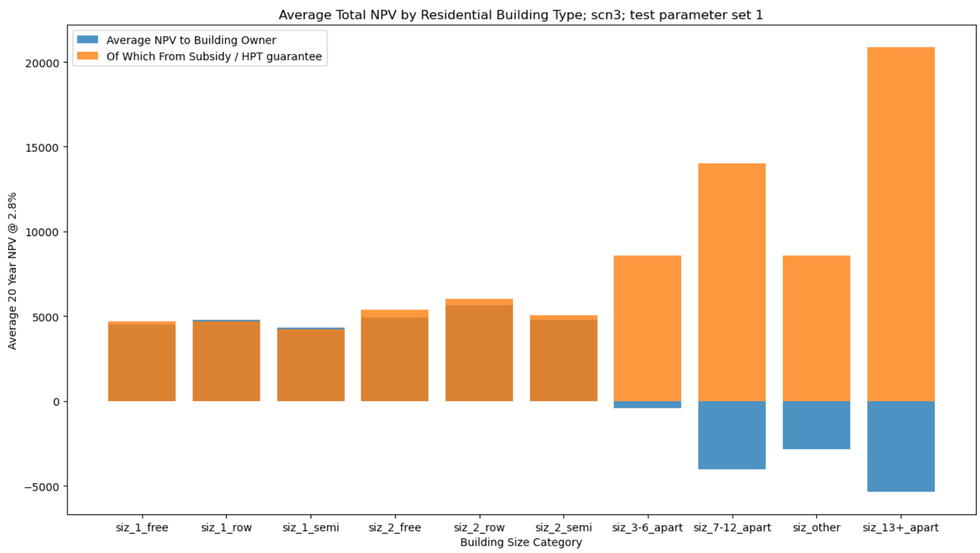

Figure 18: Average Total 20 Year NPV by Residential Building Size
High Electricity Price Scenario with HPT reaching 0.34 €/kWh by 2044 (Scenario 3);
30% Upfront subsidy, Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 1)

Across all one and two unit structure classifications, NPVs with price support (Figure 17) are roughly twice what they are under the upfront subsidy scenario (Figure 18) and

larger buildings experience negative NPVs for their heat pump retrofits, because the upfront subsidy is simply not enough to account for their very high yearly electricity expenditures. It is also interesting to note that for the ongoing price support model, the portion of NPV for smaller structures arising from government subsidy is much lower, and more building owner value is achieved with not that much more public expenditure. This result seems to imply that price ceilings are a more economically effective incentive instrument for small structures, though not for larger ones.
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It is worth reiterating yet again that the discussion above of price pathways 2 and 3 both assume a tight electricity market, the only difference is the government response. Price pathway 1 in contrast was included to capture a trajectory in which broader energy policy is very effective at rapidly scaling renewable energy sources and natural gas kept tight likely through limited investment in new pipelines and LNG facilities.

Figure 19 displays the NPVs associated with this scenario, and the impact of lower market rates for electricity (and higher rates for natural gas) is stark. Across all building types, the NPV to building owners is 2.5 - 4 times higher than with a HOPT price brake only (Figure 17), and higher even than a scenario in which the government provides both upfront subsidy *and* price support (Figure 20). Additionally, the percentage of building owner value coming from market intervention is by far the smallest amongst all scenarios, as the majority of building owner value comes from abundant supply in wholesale markets and robust RES generation.

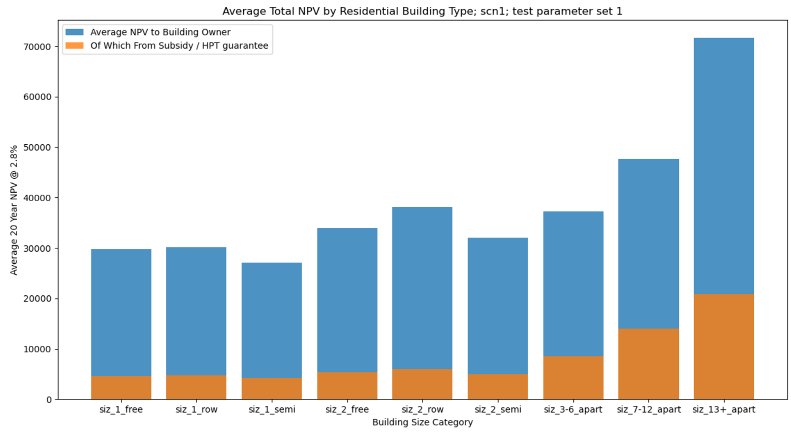

Figure 19: Average Total 20 Year NPV by Residential Building Size
Low Electricity Price Scenario with HPT remaining around 0.24 €/kWh through 2044 (Scenario 1);
30% Upfront subsidy, Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 1)

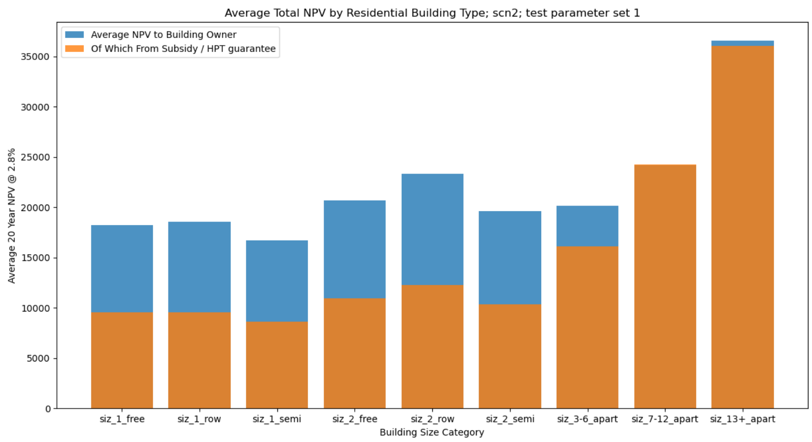

Figure 20: Average Total 20 Year NPV by Residential Building Size
Mid Electricity Price Scenario - 0.28 €/kWh HPT price brake permanent through 2044 (Scenario 2);
30% Upfront subsidy, Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 1)

4.1.1 NPV per m^2

The goal of the previous section was to lay out results that elucidate exactly how building owner value is generated by capturing the relative size of public expenditure and final building owner NPV, including the sign, whether positive or negative. This section reframes these results in terms of NPV per unit of living space to provide a clearer point of comparison between the economic circumstances of building owner. In particular, looking at value per m^2 throws the effects of varying upfront costs, heat loads and geographic distribution of the different building types into sharp relief.

Figure 18 displays one of the key takeaways, which is that for apartment buildings the impact of higher assumed input costs per m^2 outweighs the effect of lower yearly specific heat loads, and results in a lower value per m^2. Due to the assumptions outlined within sections 2.2.3 and 2.2.4 variation between small residential structures and large residential structures is relatively small. This is also an indication that the distribution of building size classes across different climatic zones is uniform enough to have a relatively small impact within one and two-structures. The intermediate value of 3-6 unit structures can be attributed to indications discussed in section 2.2.3 that installation costs per m2 for small apartment buildings are more in line with those of SFHs, but that they nevertheless tend to benefit from thermal mass and the insulation effect of adjacent units in the way that larger apartment buildings do.

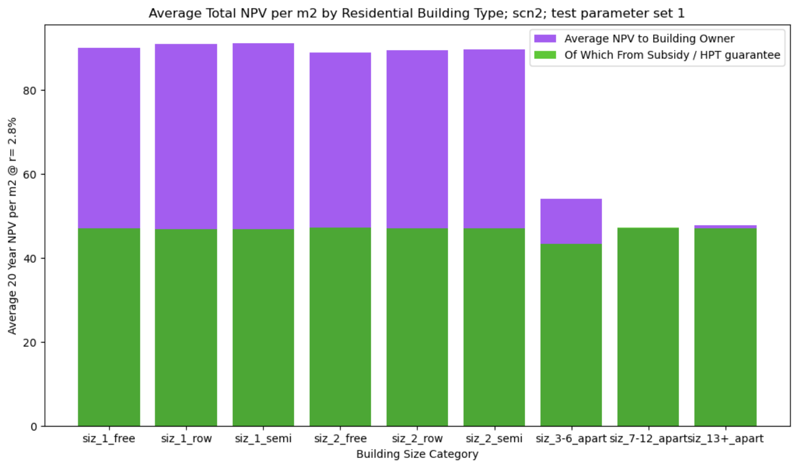

Figure 21 Average Total 20 Year NPV per m^2 by Residential Building Size
Middle Price Scenario with Guaranteed HPT at 0.28 € (Scenario 2);
No Upfront Subsidy, Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 0)

4.1.2 Time Evolution of NPV for a Representative Structure

This section takes a detailed looks at a specific 140 m^2 SFH located outside of Leipzig, Germany to examine the NPV of a heat pump retrofit as a time series for a variety of the energy market projections and test parameters described in section 3.

Figure 22 shows what may be considered the classical formulation of NPV for a heat pump retrofit. It ignores the costs incurred for eventual fossil boiler replacement and thus the owner starts with a strongly negative NPV resulting from the full unsubsidized cost of HP install which slowly pays off over time. It is interesting to note that historic prices have the newly installed heat pump running at a loss which shows how the extremely low prices of natural gas in the period of 2010 to 2021 have made heat pumps untenable as a retrofit option. However, while Scenario 3 does save the homeowner energy every year, it is not enough to justify the upfront cost and results in a negative NPV of around -7,000€ over 20 years. Looking back at the details of price evolution in these scenarios (Figure 7) it can be seen that the ratio of $kWh_{elec} : kWh_{ng}$ lies between 2.6 and 2.8 in this scenario whereas this same ratio ranges between 2.4 and 1.8 in scenario 2. This suggests that with unsubsidized up front cost, a target ratio of electricity to natural gas prices of under 2.4 is required to effectively incentivize private retrofitting with heat pumps.

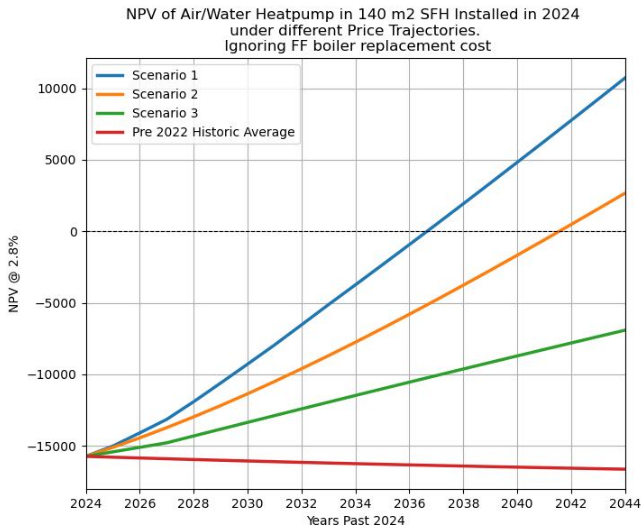

Figure 22: 140m2 SFH NPV: 2024 Install, No Subsidy, Ignoring FF Replacement Costs

Figure 23 shows the effect of adding a 30% upfront subsidy such as those that might be available to a homeowner through the BAFA funding program. The upfront funding is not quite sufficient to cover the homeowner from the risk associated with the market conditions of scn3, however if a slightly higher upfront subsidy of around 35% is used, the the resulting NPV is just about zero . (Federal Office of Economics and Export Control, 2023)

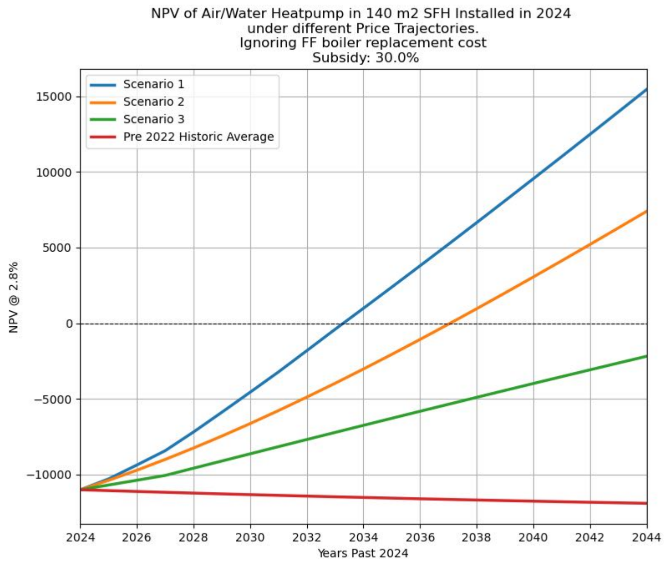

Figure 23: 140m2 SFH NPV: 2024 Install, 30% Subsidy, Ignoring FF Replacement Costs

Figure 24 presents a more complicated picture in which the building owner waits 5 years to install their heat pump and reaps the advantage of a lower installation price as the industry matures, but in return pays more for their heat in the intervening years. It is therefore a good point of comparison with Figure 25, which has otherwise identical parameters. In both scenarios, the building owner considers their fossil fuel boiler at the end of its useful life on the date of decommissioning, though in Figure 26, they have successfully managed to “squeeze” an additional 5 years out of it. Comparing the two it can be seen that under all scenarios (except the historical price comparison) the building owner is slightly better off waiting until 2029 for prices to come down, however if a 30% subsidy or about (4,800 €) is subtracted from the upfront cost in addition to the cost of a fossil fuel boiler in Figure 24, the situation reverses, with the immediate installation winning out by a few thousand euro, though not much more. This would be the case where policy makers at some point remove the upfront subsidy between 2024 and 2029.

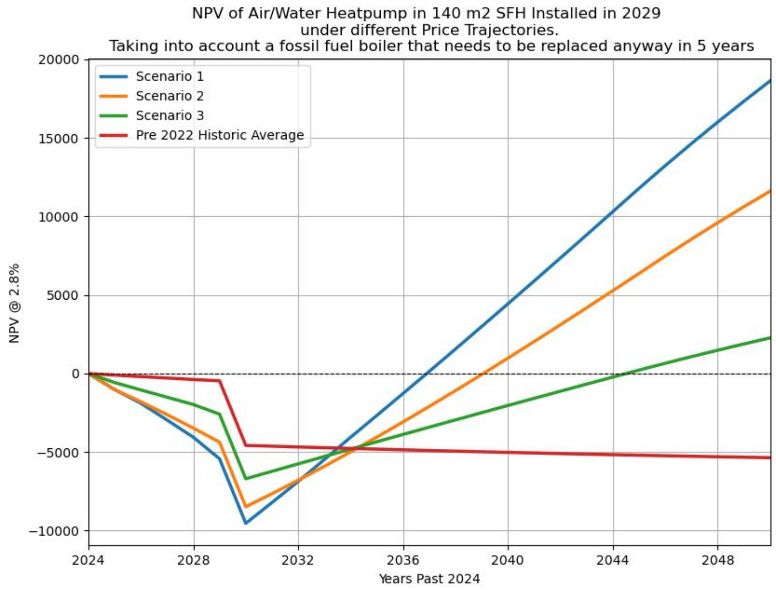

Figure 24: 140m2 SFH NPV; 2029 Install, No Subsidy, Assuming 5 Years left of useful FF life

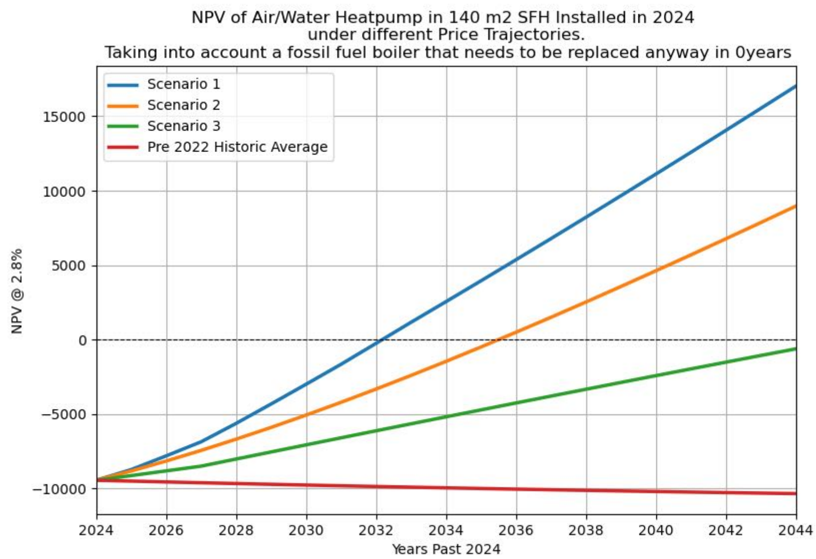

Figure 25: 140m2 SFH NPV; 2024 Install, No Subsidy, FF Replacement Immediately Required

4.1.3 IRR of Representative Structures

Table 6 presents a set of IRR values for the 140 m^2 SFH as well as a 382 m^2 3-6 unit MFH for 6 of the 7 parameter sets listed in

Table 5. It is the result of expressing the NPV expression as a function of discount rate, r and numerically solving for $NPV(r)|_{t=20} = 0$. The details of this are contained in *irrCalculator.py.* IRR values can be useful, because they can be viewed as an effective rate of return for a heat pump investment and allow a very direct comparison to other investment types across various risk tolerances. For instance, if a home owner is in the

rather common situation of having a fossil fuel boiler at the end of its useful life, and is looking at the offer of a 30% upfront subsidy for a heat pump, they could look up their situation in the second row of
Table 6 and find that the roughly 7,000 €[5] after subsidies of additional cost for a heat pump install instead of another fossil fuel boiler would be equivalent to getting a 9.5-26.6% return on that investment, depending primarily on future energy prices.

PARAMETER SET	**140 M2 SFH ; BUILDID 42 ; SPF=3.4** Price scenarios			**382 M2 MFH 3-6 UNIT ; BUILD ID 957656 ; SPF = 3.15** Price scenarios		
	scn1	scn2	scn3	scn1	scn2	scn3
IMMEDIATE INSTALL; 0% SUBSIDY; FF LIFE 0YRS	14.4%	9.6%	2.2%	10.1%	5.5%	-2.8%
IMMEDIATE INSTALL; 30% SUBSIDY; FF LIFE 0YRS	26.6%	19.4%	9.5%	19.8%	13.3%	2.9%
2029 INSTALL; 0% SUBSIDY; FF LIFE 5YRS	12.3%	9.1%	3.2%	11.0%	7.1%	9.0%
IMMEDIATE INSTALL; 30% SUBSIDY; FF LIFE 10YRS	10.0%	6.6%	1.4%	7.0%	3.8%	-1.7%
IMMEDIATE INSTALL; 0% SUBSIDY; FF LIFE INF.	8.0%	4.3%	-2.2%	4.7%	0.9%	9.0%
IMMEDIATE INSTALL; 30% SUBSIDY; FF LIFE INF.	12.3%	7.9%	0.8%	8.3%	4.1%	-3.9%

Table 6: Internal Rates of Return for an Example SFH and MFH

If on the other hand that same homeowner felt they could get another 10 years out of their existing fossil fuel boiler, but are considering retiring it early, that would be equivalent to the fourth row of Table 6 or a 1.5-10% return on investment.

For larger buildings, the impact of initial installation costs on NPV is stronger due to the nature of assumptions made around heat loads and upfront costs in section 2.2.4. This is especially true if there are discontinuities in NPV over time like those that arise if a building owner waits some time before installing (see Figure 24 for example). The last two rows of Table 6 which reflect the assumption that a building owner would

[5] See Figure 25

never need to replace their fossil fuel burner anyways yields unsurprisingly absurd results such as a higher NPV in price Scenario 3 when electricity prices are the highest than in other, more favorable price pathways. This should be viewed as an argument for incorporating the upfront costs of a counter factual in all NPV calculations for energy system investments.

The third row, which also shows this curious inversion of IRR values for MFHs resulting in a better return in the less favorable market condition of price pathway 3 on the other hand should be viewed as a meaningful result, because it simply arises from the fact that larger buildings that wait on heat pump retrofits are losing out on potential savings at a faster rate due to their large living area. A glance at Figure 24 shows how this type of inversion could be possible, as the lost savings of the first 5 years without a heat pump accumulate.

In general, the IRR across all price pathways and installation timelines is considerably less for MFHs than it is for SFHs. This comports with some of the NPV results presented in section 4.1, and could be an indication of stronger impediments to heat pump adoption through retrofitting in MFHs. This will be explored more in the discussion section.

4.2 Geographic Variance

The two main geospatial factors contributing to the average NPV of heat pump retrofits to owners in a particular region are average outside temperature and average living area. Though the study area was relatively limited, the amount of climatic variation even just within Saxony was enough to register a nearly 40% variation across the 13 Saxon *Landkreise* under the more extreme price trajectories. Figure 26 illustrates this variation for one- and two-family structures. In this case, morphological and cost structure differences do not arise as it was assumed that upfront costs and heating load scaled uniformly with living area for all buildings under 6 units. Although the SPF varied only around 8% from the coldest to the warmest parts of the state, the difference in energetic efficiency was amplified due to the additional heat loads arising in colder climates and the larger average living space per house in the more rural and mountainous south and eastern parts of the state.

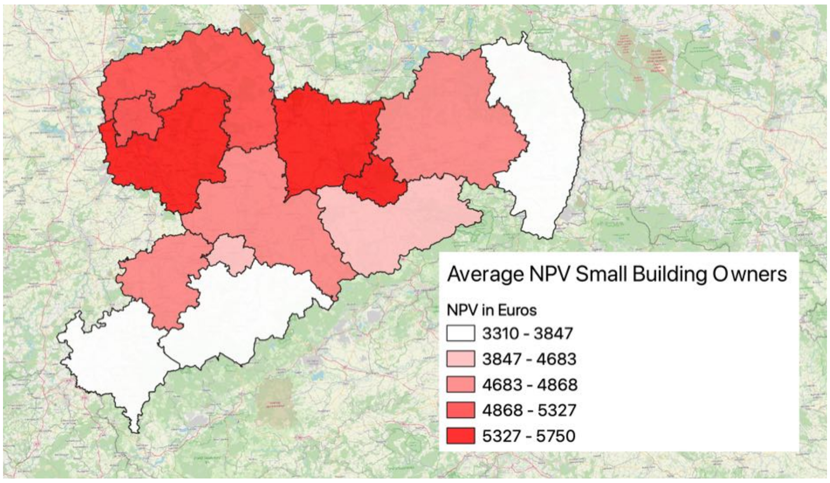

Figure 26: Variation of NPV for One and Two Family Homeowners by Landkreis across Saxony; 2024 Install ; High Electricity Price Pathway (scn3) ; 30% Upfront Subsidy

Figure 27 illustrates the effect of low electricity prices on the same building subset. While one- and two-unit structures in the colder, rural regions still suffer from the lower performance metrics of their AWHPs, their larger average living area and heating loads have shifted in a sense from being a liability to an asset relative to their urban peers. This is because the low electricity costs and high yearly savings dominates the influence of higher upfront costs and even the lower average SPFs. This suggests that rural building owners with their relatively high heating cost burden, have more to gain from heat pumps in a favorable electricity market than their urban counterparts. While NPVs are quite a bit more positive across the board, variation is quite a bit less at around 17% from highest to lowest.

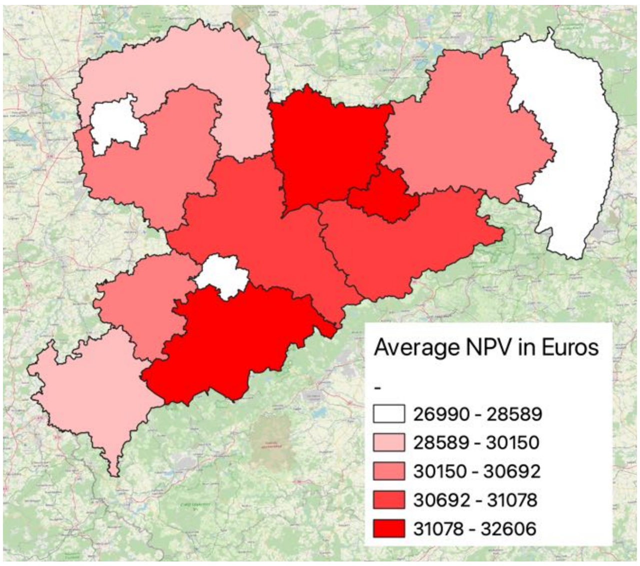

Figure 27: Variation of NPV for One- and Two-Family Homeowners by Landkreis across Saxony; 2024 Install; Low Electricity Price Pathway (scn1); 30% Upfront Subsidy

5 Discussion

At the outset of this project a central question emerged as to what degree uncertainty in the future of energy markets hindered adoption of heat pumps prior to 2023 and how policy moving forward could encourage heat pump retrofits by providing both direct monetary incentives and mitigating the perception of market risk. These can be viewed as two distinct pathways of incentive, one offering hard cash in the form of energy savings to a rational decision maker with total knowledge of the future, and the other as a reassurance to the risk averse decision maker, either by guaranteeing their costs or by providing enough of an upfront subsidy that even in worst-case future energy market conditions, the NPV of a heat pump retrofit would still be positive. It was through this lens that two distinct policy instruments were modelled: the upfront subsidy and the ongoing price guarantee.

5.1 Efficacy of Intervention through Price Guarantees and Upfront Subsidies

Broadly speaking, the results of the modelling conducted above strongly suggest that when taken in isolation, long term price guarantees have a stronger influence on building owner NPV than upfront subsidies across nearly all building types, and environments, and in nearly all metrics. One way this can be seen is by considering two extremes of potential responses to a price pathway that has peak tariffs going to around 42 cents per peak kilowatt hour in 2044 with the HPT trailing it by about a 20% discount factor, as has historically been the case (German Heat Pump Association, 2023b). Under one extreme case, the government continues with current policy providing only upfront subsidies of around 30% as electricity prices go higher. In another, upfront subsidies are cancelled in exchange for a 28-cent price guarantee for HPT perhaps enforced by a willingness on the part of the government to pay the difference if necessary.

Figure 17 and Figure 18 display the effect of these two extreme policies and make clear the point that NPV is more sensitive to ongoing price support than upfront subsidy. For one- and two-unit structures, the total amount of public investment is around 5,000-6,000 €, but the NPV in the 28 cent price brake scheme is roughly double that of the upfront subsidy alone where the entire NPV is essentially made up by public price support, meaning that without the upfront subsidy a heat pump retrofit would essentially be a wash when compared to a new fossil fuel boiler. In numeric terms, this model would suggest that 1 euro invested over 20 years in the form of price support creates about 2.2 euros of NPV to the building owner, while 1 euro invested in the form of an upfront subsidy only produces about 1 euro, with the important caveat that a home owner must be in a position of immediate need for a new heating system, and the assumption that electricity prices are heading in a high direction consistent with price pathway 3.

The other aspect of ongoing price supports is that they provide certainty and should, at least in principle do away with the perceived risk of getting squeezed by a return to a historically high ratio of electricity to gas prices. But while there seems to be an answer here about the marginal rate of exchange between upfront subsidies and ongoing price support in terms of NPV, these two extreme cases still beg the question of the psychological weight that homeowners place on immediate vs ongoing support, perhaps best called their psychological discount rate, which may be different from that found here for the “homo economicus.”

Experiments based on opinion sampling to establish willingness to pay (WTP) for heat pump retrofits such as that by Côté and Pons-Seres de Brauwer (2023) and models which more realistically capture cost burden sharing between tenants and landlords like that of Weber and Wolff (2018), can thus provide an interesting point of comparison to the results discussed above, where the “building owner” is conceived as a monolithic individual who can make decisions based of preordained cash flows. This comparison of true versus perceived value of up front versus ongoing incentives deserves further research, particularly because it seems entirely plausible that when presented with a higher upfront cost, even with the guarantee of disproportionately higher future savings many building owners may not act in a strictly rational way.

5.1.1 The Necessity of Incentives and Rate of Return

In addition to efficacy, this paper also sought to answer the question of whether incentives were even necessary in the first place. In the results section, bar graphs were presented showing the NPV to building owners alongside the cost of subsidies in various price trajectories. As all combinations of price pathway and subsidy/building owner decision parameters involved some kind of intervention, the portion of NPV deriving from incentives were all non-zero. Figure 28 and Figure 29 present the same results but with no incentives of any kind, either upfront or ongoing. In this sense, these figures answer the question of the necessity of incentive while also capturing the profound effect of wholesale electricity markets on the NPV to building owner.

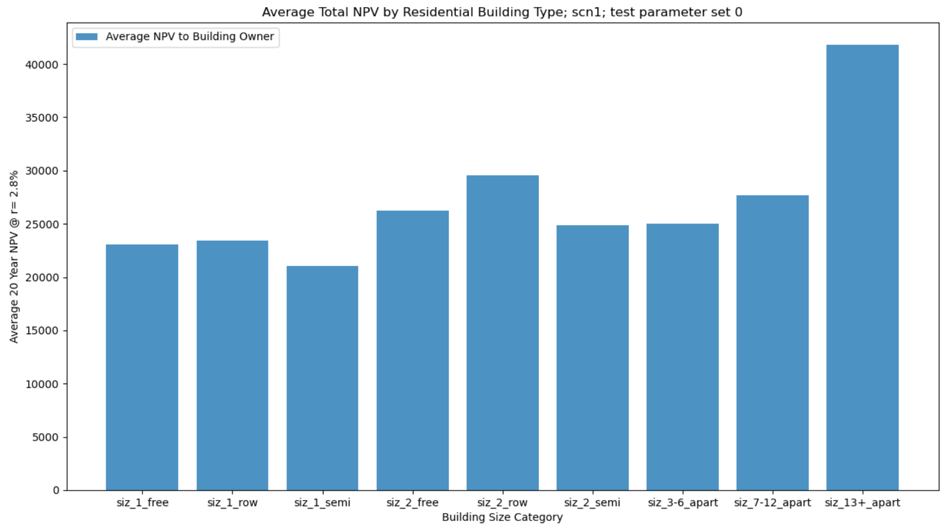

Figure 28: Average Total 20 Year NPV by Residential Building Size without Incentives Low Electricity Price Scenario with HPT remaining around 0.24 €/kWh through 2044 (Scenario 1); Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 0)

Essentially, the ultimate necessity of incentives depends more than anything on what happens to supply in the electricity and natural gas markets. Unsurprisingly, if electricity prices return to ranges seen in 2008-2021, but natural gas remains scarce, the government does not need to be involved in incentivizing heat pump retrofits at all beyond the broader energy policy around renewable scaling and fossil imports needed to achieve this situation. Interestingly, even in the worst case scenario (Figure 29), the investment for small one- and two-unit residential structures, is very nearly break even, and comparing this with the same situation but with a 30% subsidy (Figure 18), indicates that existing subsidies already go beyond what is necessary to achieve a positive NPV even in the worst case price pathway for smaller residential structures, assuming that the building owner needs to replace their boiler immediately and are accepting of the premise that their heat pump retrofit project is a “risk-off” investment and any return over 2.8% is “additional value.”

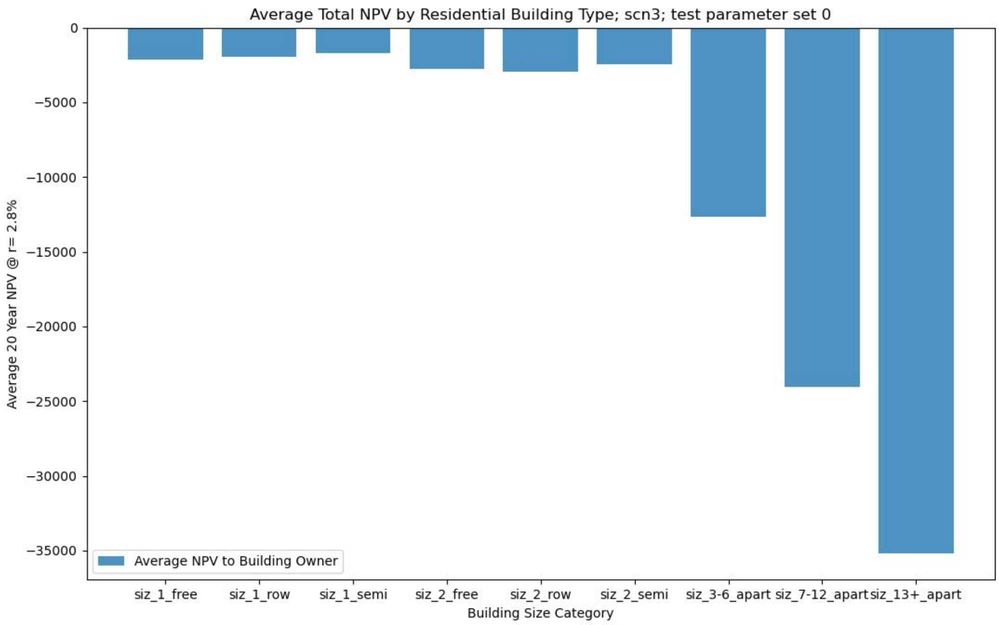

Figure 29 Average Total 20 Year NPV by Residential Building Size without Subsidies High Electricity Price Scenario with HPT reaching 0.34 €/kWh through 2044 (Scenario 3); Immediate Installation, Fossil Fuel Boiler End of Useful Life (Parameter Set 0)

5.2 Sensitivity of NPV to Accounting Practice, Markets, and Decisions

Again, in the discussion of necessity the ideas of risk and return come to the fore. By looking at what can be considered a nearly worst-case scenario price pathway, one is essentially trying to capture the downside risk of the investment.

The results presented here indicate that even to the single-family homeowner with the most cynical view of the risk profile associated with a heat pump retrofit, the roughly 30% existing upfront subsidy already does more than enough to merit the risk. This can be seen for instance in Table 6, which shows that in the worst case price pathway, a 30% subsidy results in a 9.5% IRR for a homeowner requiring a new heating system, beating even the return on the German stock market over the last 20 years (Trading Economics, 2023). So even if all of the above analysis were re-ran for a building owner that considered the cost of their capital to be closer to 9.5% nearly any scenario still results in a positive NPV for a single family home with current subsidy levels.

For most of the above discussions the scenario in which a building owner requires an immediate update has been considered, however in practice heat pumps are probably more often installed when the building owner decides that “it is time” for a new system and not when they find themselves in an emergency situation without heat. For this reason, this model also incorporated early retirement costs to capture this mood, as well as to compare the incentives of installing now or waiting.

Table 6 captures the importance of this type of subconscious accounting decision by showing a roughly 65% decrease in return for an immediate heat pump install simply if a building owner feels they “could have” gotten another 10 years out of their existing heater. This is one argument for incentives that adjust the relative price of electricity and natural gas rather than an upfront subsidy. To this same point, Figure 24 reveals that ongoing subsidies vary significantly from upfront ones in how they incentivize people’s willingness to surrender additional useful years on their existing infrastructure by increasing the penalty incurred in the form of foregone potential savings.

Finally, the results of the analysis show that the strongest influence on NPV, above subsidies or price brakes is the development of wholesale energy markets. While national energy and foreign policy, which influence supply and demand through things like infrastructure, geopolitical, and tariff decisions, are not the focus of this analysis, this fact does imply the existence of a potential third approach. Figure 19 shows the strength of focusing on policy that leads to higher gas prices and lower HPT. If HPT are kept below 28 cents, then heat pumps are a windfall investment across all building types and the relative contribution of public direct investment (here just a 30% upfront subsidy) is very small, less than 10% for small buildings and around 25% for larger buildings. What is of course left out in this picture are the costs associated with rapid scaling of (ideally) renewable generation capacity, competition for power incurred by other electricity-hungry green technologies, and the societal cost borne primarily by those owners and renters who for whatever reason cannot benefit from a heat pump, but still get pinched by the higher natural gas prices that make this price scenario so attractive for heat pumps. The next section will briefly explore this last question before moving on to a look at emissions savings and final thoughts.

5.3 Are Subsidies Targeted to Heat Pumps Progressive or Regressive?

Throughout the many debates over the Building Energy Law, price brakes, and efforts at carbon taxation, German policy makers have been explicit about their concern for the distributional effects of energy price interventions (Federal Ministry for Economic Affairs and Climate Protection, 2022; Meakem, 2023). When it comes to heat pumps and energy efficiency in particular, there is a wide body of research showing that people in lower income brackets and tenants who have little to no control over the energy systems of their buildings tend to be more heavily impacted by high fossil fuel energy prices both because of the larger share of their income going to heating and the fact that they tend to live in less energy efficient buildings (Kröger et al., 2022). The high initial price tag of heat pumps mean that it is very likely that heat pump adoption, even with hefty upfront subsidies, will be more heavily weighted towards the higher end of the income stream at least in the short run, as those who have a harder time affording a costly heat pump investment try to “squeeze” additional years from their existing systems.

This paper has argued in large part that in the absence of any command and control measures such as the outright ban on fossil heating in existing buildings, the most effective way to spur private investment in heat pumps is through tuning the ratio of hpt electricity to natural gas to no more than 2.4:1. While an even lower ratio of 2:1 which has been called for by the EHPA would certainly do even more to hasten the transition to heat pumps, the question remains whether such a market could be regressive by punishing those in society that often do not even have any choice in how their buildings are heated (European Heat Pump Association, 2023).

Kröger et al. (2022) found a year over year increase of around 5.5% in the portion of household income going to natural gas costs for the lowest income decile compared to a less than 1 % increase for the highest decile. This was calculated around the time natural gas hit 12 cents per kilowatt hour in Germany, which was also the ultimate level of the price brake for natural gas in the retroactive law passed in April, 2023. It is difficult to say exactly what HPT contracts were being offered at this time, but the peak tariff around 33 cents at that time would suggest HPT tariffs in the 28 cent range also enshrined in the energy price brake law. This ratio of 2.3:1 of HPT electricity to natural gas implied as a target by existing price brakes and already analyzed by Kröger et. al. in a statistically rigorous way very nearly matches the first 10 years of the middle price pathway (scn3) analyzed here and this concept of foregone savings experienced by a household that chooses not to install a heat pump, or perhaps cannot afford one, provides another data point to place alongside these results.

The first 5 years in Figure 24 visualizes this concept of foregone savings and shows that a 140 m^2 household that is forced perhaps through economic necessity to continue burning natural gas for heat is losing out on about 1,000 €/yr by not having a heat pump in this middle trajectory for the years 2024 -2029. Placing this into a similar statistical context as that considered by Kröger et. al. (2022), this amounts to about 9% of the total after tax equivalent income of the lowest decile, and about 4% for the median.[6]

This result is in a sense similar to various studies showing a roughly two-fold increase in burden as a percentage of household income on the poorest households but is different in that it explicitly incorporates the substitution of electricity for gas as the primary heat source and a specific price ratio thereof.

As price ratios are tuned to effectively incentivize heat pump retrofits for those who have the resources to afford the upfront cost, policy makers should double down on many of the programs that are already in place to shield the lowest income households from high gas prices such as direct payments and perhaps even expand on these with measures such as price brakes targeted at specific income levels (German Federal Government, 2023; Redaktions Netzwerk Deutschland, 2022). Furthermore, providing additional support for owners of MFHs, who tend to have larger barriers to heat pump investments may have additional benefits to tenants who are in general from disproportionately lower income groups. These types of tools a are crucial part of the "double target" of reducing gas consumption while avoiding regressive distributional effects (Corbeau and Merz, 2023)

5.4 Climate Efficiency of Intervention

When analyzing the efficacy of heat pump subsidies, it is important not to lose sight of the overarching goal of the heating transition, which is to realize carbon emissions reductions through fiscal policy. Specifically, the goal of subsidies is to hasten the adoption of lower carbon technologies beyond what would be expected under regular technology shifts in a free market. To this end, this section presents estimates on the

[6] Equivalent income adjusts median household income for household size. Values for equivalent income obtained by working backwards from household gas expenditure and ratios of equivalent income and energy costs. See Appendix G

total emissions reductions of heat pumps vs fossil fuel boilers over 20 years across the building stock dataset for Saxony. These estimates are then used to analyze the economic efficiency of heat pump incentives measured in carbon emissions reductions per 1,000 euros invested either through upfront subsidy or through the public cost of enforcing a ceiling on HPTs.

The goal is to reexamine this question of the necessity of incentives for heat pump adoption by comparing heat pump subsidies as a form of carbon abatement cost with other potential investments in decarbonization such as scaling renewable capacity. To provide a totally different angle of comparison, they will then also be compared to estimates on the social costs of climate damages taken from the rich body of literature in the domain of integrated climate assessment.

5.4.1 Heat Pump Subsidies as a Carbon Abatement Cost

The python script *emissionsCalc.py* calculated 20-year, non-discounted emissions reductions associated with a heat pump install in both 2024 and 2029 for every building in the *candidateBuildings.shp* dataset. The results show that on average, for both SFHs and MFHs under 6 units, a roughly 88% reduction in emissions can be achieved by installing a heat pump in 2024 which corresponds to an average 20 year CO2 savings of around 117 metric tons for the average 1 and 2 unit structure and 169 metric tons for a 3-6 unit MFH. If instead the heat pump is installed in 2029, this emissions reduction drops to around 70% over 20 years, corresponding to around 93 metric tons for an average one- or two-family home and 134 metric tons for 3-6 unit MFHs.

Figure 30, expresses these emissions reduction results divided by the public cost of subsidy calculated in section 3.4.1. The choice of scenarios and timeframes were chosen to capture a binary choice in which policy makers can optionally make the 28 cent HPT price brake permanent to incentivize building owners to switch to a heat pump in 2024 rather than wait 5 years. The other option is to allow energy prices to rise in line with the price pathway of scn3, less incentive for an immediate retrofit, less carbon mitigation, but significantly less subsidy cost. It was obtained by dividing the potential emissions reduction of a heat pump given the planned power sector decarbonization timeline (Figure 8) for each structure by the cost of upfront and ongoing subsidies, then averaging this value across the entire dataset (see *CO2perEuro.py)*.

It is important to recognize that in this process, cash flows are discounted at 2.8% while emissions are not. Therefore, neither the controversial topic of discount rate for future climate damages nor the increased radiative forcing overtime that results from front-loaded emission profiles are considered (Apling et al., 2018; Rennert et al., 2022). Nevertheless, it is a useful point metric to help widen the perspective and weigh heat pump incentives against other climate priorities. The first very striking thing that emerges from this graph is that perhaps surprisingly the economic efficiency in terms of CO2 savings per euro of subsidy is *higher* for 2029 despite lower total emissions reductions in this scenario. The reason for this is twofold: first, due to Germany's relatively high emissions intensity in the power sector in 2024, the efficacy of heat pumps at carbon mitigation will be somewhat undercut until enough renewable generation capacity can be brought online. As a rough point of comparison, the model employed here based on current emissions figures and stated targets does not have Germany's power generation dropping below 100 gC02$_{equiv}$/kWh until 2030, which was already achieved by neighboring France by 2017, mostly because of their heavy use of nuclear power (Electricity Maps, 2023). In this sense, it could be said that the realities of the current energy mix in Germany has built in a 5 -10 year cushion during which time the climate urgency of the heat pump rollout is somewhat lessened.

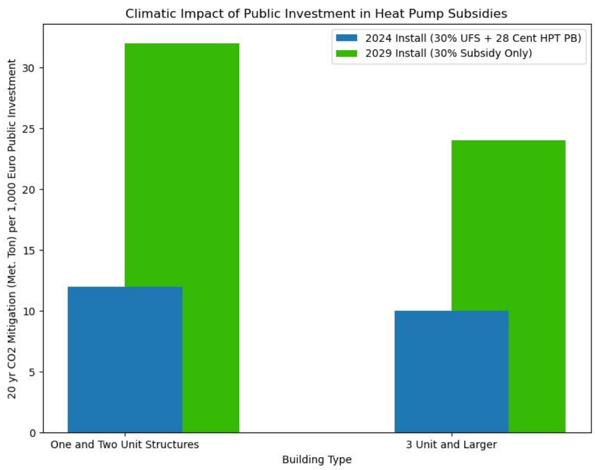

Figure 30: Average 20-Year Carbon Mitigation Achieved per 1,000 € of Public Financing by Replacing a 60/40 mixture of Natural Gas and Heating Oil with Heat Pumps in the Saxon Building Stock (2024-2044 time Horizon)[7]

[7] The 2024 scenario uses the second price pathway, scn2, the 2029 scenario uses the third price pathway, scn3, though the results would be the same for scn2, because in either case there is ongoing price support

The other dynamic here is more strictly economic and results from the anticipated drop of installation costs through 2029 and the discount applied to future subsidy expenditures, which both result in much lower subsidy cost (European Heat Pump Association, 2022). The 2029 model assumed that worst case markets without a price brake with the logic that nearly zero NPVs in this case sends ambivalent incentives, and therefore may cause many building owners who are otherwise interested in a heat pump to forego the investment in the short term. It should be noted, however that if renewable sources can scale fast enough to send market HPTs below 28 cents, then the 2029 scenario presented in Figure 30 would be the same regardless of whether the market took a high path or a low path as the government would have no ongoing costs in either case. The only difference would be significantly higher building owner value in pathway 1.

In other words, if Germany can manage to scale its electricity supply quickly in the next 5 years, it could set a permanent 28 cent price cap on HPT simply to allay market anxiety, but never have to enforce it, as a supply-driven market could result low enough prices long term to keep HPTs that low anyway. This indeed may be one of the most succinct subsidy policy recommendations coming from these models based both on the efficiency of generating building owner value and environmental impact.

This all suggests that there is an economically and scientifically sound argument for placing the timeline for heat pump rollouts in Germany on the 5-10 year time horizon, or in other words that heat pump retrofits are a good mid-to long term pivot, but might not be worth more subsidization than what is already on the table. This is an actionable policy insight especially because the results discussed in section 4.1 indicate that under most likely market trajectories, building owners are not particularly incentivized to invest in a heat pump now rather than waiting 5 or more years, and significantly stronger incentives would need to be on the table to change that.

The flip side of this argument is of course that change takes time, and any added expense associated with larger subsidies now simply means that policy in the future has less ground to cover in terms of adoption. An argument could also be made along similar lines that just because the power sector has a long way to go to decarbonize, does not mean that the heating sector should be short changed. The following two sections will look at both sides of this argument by comparing the carbon impact of subsidies with the marginal abatement costs (MAC) of renewable power scaling and the social costs of carbon emissions (SC-CO2). It should be said that the carbon mitigation impact of subsidies calculated above is not strictly speaking a marginal abatement cost, as that would require deeper modeling on estimates of how many people would retrofit without subsidies or with smaller ones (Guminski, 2021). However, the values calculated above can be seen as something akin to a proper MAC if one essentially assumes that very few people would install a heat pump without the subsidy, and therefore that any subsequent emissions reduction can be traced directly to the subsidy.

5.4.2 Comparison with Costs of Climate Damage and Other Mitigation Initiatives

This section will compare the carbon mitigation efficiency subsidies derived above with values found in literature for the social costs of climate damage, measured as SC-CO2 and the efficiency of other carbon mitigation projects, quantified by MAC. Both of these quantities are usually measured in euros per ton of $CO2_{eq,}$ have wide variation, and can be steeped in controversy, the details of which lie beyond the scope of this research. However, comparison with representative values can result in interesting insights on the priority and premium that should be placed on funding targeted heat pump initiatives in limited public budgets.

	ONE AND TWO UNIT STRUCTURES	**3-6 UNIT MFH**
2024 INSTALL, 30% UPFRONT SUBSIDY + PERMANENT 28 CENT PRICE BRAKE	83 €/ton $CO_{2\ \mathrm{equiv.}}$	90 €/ton $CO_{2\ \mathrm{equiv.}}$
2029 INSTALL, 30% SUBSIDY ONLY	31 €/ton $CO_{2\ \mathrm{equiv.}}$	42 €/ton $CO_{2\ \mathrm{equiv.}}$

Table 7: Cost of Abatement to the Public Sector of Heat Pump Subsidies in 2023 Euros

Table 7 inverts the values of Figure 30 to be expressed in cost per ton of CO2 in 2023 Euros for easy comparison to values cited in the literature. First, comparison to grid scale solar and on shore wind will be made. For a meaningful comparison, MAC must be quoted for a specific emissions reductions amount because the price for each additional unit of abatement tends to increase as the investment becomes larger, hence the term abatement cost "curve" (Guminski, 2021). To find a point of comparison, the total theoretical 20-year emissions reductions of the entire dataset was calculated for a 2029 install. It is subject to debate what degree of penetration is realistic by 2029, however the total was used as a reference value as it is relatively small compared to potential emissions reductions for national RES investments that are often cited in literature. It is also important to keep in mind that the potential emissions reductions which are summarized in Table 8 are for the subset of the entire building stock referred to as "candidate buildings," which consists of only around 450,000 structures, which is already only about 53% of the 2022 Saxon building stock (BDEW, 2023a ; see Table 2). It is therefore not completely outside the realm of what could be expected.

A theoretical upper limit for carbon savings of around 46 MtCO2 over 20 years for the first generation of heat pumps in Saxony was then annualized to arrive at around 2.3 MtCO2 per year for the "first generation" of heat pumps to look up study values such as one by (Misconel et al., 2022), which suggested very low ranges of around 20 €/tCO2 at that abatement level and roughly -40€/tCO2 for solar. This of course may not be the best comparison as we are comparing total abatement values for one state with national numbers, but even if you take the average across an the entire abatement potential for a given technology, this same study suggests values for onshore wind and ground-based solar of around 60-70 €/tCO2 and around 0 €/ton respectively. Similar figures when adjusted for inflation, and currency come from Gillingham, (2018) and Mckinsey & Co., (2007).

It is important to provide many caveats here, as MAC curves can be prone to misinterpretation and are very sensitive to parameters such as the exact substitution occurring, installation costs, inflation, and the timeline of analysis. Here, the figure used for the heat pump subsidy was chosen for reference year 2029, and assumes a "virtual flat" MAC for heat pump subsidies, meaning that unlike physical interventions such as infrastructure development, the government can get the same CO2 reduction per euro invested in subsidies regardless of how many it gives out. It also assumes that heat pumps are replacing oil and gas heating in relatively constant proportion over time while the MAC cited for instance for onshore wind by Misconel et al. (2022) slowly rises towards 100 €/ton as the total abatement rises to 60+ MtCO2, presumably as more emissions intensive sources like coal are phased out.

While all these assumptions can and should be challenged and reexamined in further research, the analysis of the economic efficiency of subsidy in 2024 and 2029, suggests a meaningful result on the dynamic nature of the efficacy of heat pump subsidies from a climate perspective. Namely, the MAC of RES investments are currently lower than those of additional heat pump subsidies or a price brake on HPTs in the short run, but the two are heading in different directions. As more renewable capacity is added it will become more expensive to mitigate carbon emissions in the power sector, but cheaper to do so in the heating sector through heat pump subsidies. The results here seem to indicate that this inversion could happen by 2029 given current targets, so this 5 year timeline during which heat pump retrofits will become amongst the highest-level climate priorities should be in the back of policy makers' thinking.

On the climate damages side, one finds even wider ranges of estimates for the SC- CO2 than for MACs due to compounding uncertainties in the climate system, technological development pathways, civilizational vulnerability, and above all the discount rate that should be applied to future damages arising from CO2 emissions (Moxnes, 2014). The debate over discount rate is perhaps one of the most central to the field of sustainable development, and has ensnared national governments, international climate organizations and Nobel prize winners. The comparison value taken here comes from Rennert et al., (2022), which applied a discount of 2% and the recently developed Greenhouse Gas Impact Value Estimator (GIVE) model to arrive at a value of 188 €/ton[8], which is certainly on the high end relative to mainstream estimates such as the operational value used by the US government of around 55 € /ton. (National Academies of Sciences, Engineering, and Medicine, 2017)
Using this value for SC- CO2 places the urgency and necessity of additional price supports in a different light by indicating that, despite not being the most effective "lever," these measures, and the cost incurred to enact them, are still much less than the damage that would ultimately arise from forgoing the opportunity to spur additional building owners to retrofit their buildings now rather than waiting.

This comparison of the climate efficiency of heat pump subsidies with SC-CO2 and MAC of renewable generation scaling captures the essence of two different approaches

[8] Quoted originally at 185 $ / US ton = 188 € / metric ton using 2022 average exchange rate

to sustainability. In one the focus is on finding the 'least cost decarbonization pathway' in limited public and private budgets and while the other cries out for policy makers to pull any "lever" whose cost is less than the sum of all eventual damages which may befall society. Under the first interpretation, policy makers should leave heat pump subsidies as they are at least until 2029, then consider the addition of new subsidies or price brakes once the power sector has become more decarbonized, while under the other, they should make price brakes permanent immediately and consider even higher subsidies while simultaneously making every possible investment in renewable scaling.

5.5 Heat Pumps as a Driver for Generation Capacity

As was outlined at the outset of this paper, from a physical and engineering perspective, heat pumps are simply the instruments by which thermal heating loads can be shifted from existing physical fuel delivery networks for fossil fuels to the electrical grid, that is the tools to electrify the heating sector. From a climate perspective, it is essential that the increase of demand in electricity for heat pumps is met by new renewable capacity, and furthermore that the heat pump rollout must not impede the retirement of coal generation. That is, if the timing of one or the other is off, there is the potential for counter productive rebounds of carbon emissions (Electric Tranportation Network France, 2020). To this end, this section will present estimates of aggregate additional yearly electricity consumption if the roughly half of the current Saxon building stock represented in the candidate buildings sub set were retrofitted with a heat pump. This will then be used to compare to progress made so far in RES scaling and to look at reasonable timelines for adding that amount of generation capacity.

Measure	Value
Potential 20 year Carbon Savings (2024 - 2044)[9]	46 $MtCO_2$
Additional Required Heat Pump Electricity Consumption per Year	4,400 GWh/yr
Additional Installed Renewable Generation Capacity (@ 15% capacity factor)	3.43 GW

Table 8: Summary of Potential Carbon Mitigation and Required Grid Capacity if 54% of 2022 Building Stock were Retrofitted by 2029

[9] If 53% of buildings were retrofitted by 2029

Discussion

Table 8 summarizes carbon and grid impacts of transitioning all the candidate structures identified above to heat pumps. While the carbon impact required a specific timeframe for calculation and modelled using a hypothetical situation in which the entire data set representing roughly 54% of the Saxon residential building stock are retrofitted by the year 2029, the electricity consumption and generation capacity figures simply reflect the eventual requirements of the switch without reference to a specific year. The estimation of required generation capacity was derived using a mixed onshore wind and ground-based solar capacity factor for Germany of around 15% derived by Kaspar et al. (2019).

The figures indicate that installed capacity in Saxony would roughly need to double from the 3.9 GW of installed capacity as of 2020 by the time that half of buildings in Saxony can run on a heat pump to provide them with 100% renewable energy, not taking into account electrification of other sectors (Federal Ministry for Economic Affairs and Climate, 2021). While the exact timeline for reaching 50% heat pump penetration in the residential sector is not certain, it is clear that only the most aggressive scaling can achieve the robust supply required. It should be said that decarbonization of the nationwide power system which was recently made yet more ambitious with a revised goal of 2035 for carbon neutrality is broadly speaking compatible with the trajectories outlined here. In particular, the goal of scaling onshore wind capacity from roughly 58 GW in 2022 to 115 GW by 2030 nationwide, would likely be felt particularly strongly in Saxony where wind is the largest single RES (VEE Saxony eV, 2021). As a very rough point of comparison, the newest 2030 goals from the federal government would provide enough renewable supply for about 226,000 heat pump retrofits or 27% of the 2022 residential stock if renewable capacity in Saxony scales in line with the national average and the new capacity were split evenly between electro mobility and the heating sector (Amin, 2022; Federal Wind Energy Association, 2023). This is very encouraging, but it of course remains to be seen if these capacity goals can be met, and how new competing demands for electricity shape the market.

5.6 Conclusions and Further Research

The research presented above sought to evaluate the necessity and efficacy of heat pump subsidies within Germany by evaluating 20-year NPVs of heat pump retrofit projects to building owners in Saxony. It attempted to accomplish this by modelling the variability of upfront cost and ongoing savings at the building level and at the intersection of numerous market uncertainties and building owner decisions. The goal was not necessarily to correctly predict the energetic performance or economic situation of each building in isolation, but rather to focus on finding values for the model inputs that were representative of the current building stock as a whole to identify tipping points along different axes at which average NPVs across a building subset becomes positive. The results indicated that existing upfront subsidies in the neighborhood of 30% are already enough to result in positive net present values for small, one- and two-family structures even under pessimistic market outlooks if a risk free discount rate of 2.8% is used. For larger buildings and building owners that expect a higher return on investment, one of two cases must hold. Either the government must step in to set some kind of long-term price ceiling on HPTs while allowing natural gas to rise modestly in price, or the electricity market over the next several decades must be characterized by a surge in supply that outpaces demand growth from the electrification of numerous sectors.

Section 5.4 attempted to shed light on this question of whether additional market interventions are prudent to hasten the adoption of heat pumps by analyzing two scenarios- in the first many more building owners were convinced to install a heat pump in the next several years due to a guaranteed long term HPT below 28 cents and a lasting ratio of HPT electricity to natural gas of around 2.3, while in the other current upfront subsidies are deemed to be sufficient resulting in more building owners waiting 5 or more years for their retrofitting projects. From a public policy perspective, the results indicated somewhat strongly that due to Germany's decarbonization timeline and costs of guaranteeing a 28 cent HPT in the absence of broader energy policy supporting electricity wholesale market supply, the best course of action is to allow a slower rollout focused on the 5+ year time horizon, and therefore to begin more aggressive heat pump measures after 2029. However, the analysis also suggested very strongly that the best thing that policy makers can do now is focus on the rapid scaling of renewable capacity. This was also borne out in section 4.1, which determined that the portion of building owner NPV that ultimately derives from public price supports is by far the lowest when new renewable supply dominates wholesale markets and electricity prices go low enough to keep the "market rate" of HPTs below 28 cents. In this case there is no downside to offering a permanent price brake, and a policy strategy focused on offering a brake with the plan of keeping market prices below the ceiling was strongly endorsed to essentially extend no cost incentives to those building owners that might view heat pumps as a risk due to the possibility of energy prices reverting to their historic levels.

Because so many geospatial, economic, and building morphological variables were already under consideration, this analysis made many assumptions and limitations within the technical realm which further research should investigate. To begin with, only one of many types of heat pump retrofit was considered, namely a swap out of a fossil fuel boiler with an air-to-water heat pump which did not include the provision of domestic hot water or involve any other improvements to the building's energetic performance. In reality of course, building owners have myriad options when it comes to investing in their heating system. Ground source heat pumps (GSHPs) should also be included in further research particularly if a wider range of climatic zones are considered because they function much better at colder temperatures but require considerably more upfront capital and are only feasible in certain types of buildings. Similarly, package installs including rooftop photovoltaic panels could also be added to this model and potentially shed light on how effective tiered subsidy programs are at targeting incentivizing building owners to make larger investments in climate zones where they can have the most potent carbon cutting effect. If this type of analysis were done, subsidies for both rooftop PV and GSHPs should be weighed against the MAC of investments in utility scale renewables because both technologies help lighten the demand strain on grid-delivered electricity.

From a climate perspective, the assumption that the carbon impact of new heat pumps is limited to their substitution of fossil fuels should be rigorously challenged and investigated. In particular, the addition of so many new refrigerants to the consumer market and the corresponding risk of fugitive emissions should be wrapped into a broader lifecycle carbon assessment of heat pumps, which should include the manufacturing, reclamation, as well as the effects of early retirement for otherwise functional fossil fuel infrastructure.

It may also be worth considering certain rebound effects of heat pump retrofits. For instance, more efficient heating systems may cause changes in consumer behavior around thermostats resulting in higher sensible heat loads. Additionally, some configurations of heat pumps allow for cooling functionality which, if utilized, could increase the overall end energy use for indoor climate control, particularly within a country like Germany which has historically gone without space cooling, but is now experiencing increased demand in part because of climate change. The effects on both of these fronts are a form of rebound effect associated with heat pumps as a technology and the results of studies by Kenkmann, (2019) and the Electric Tranportation Network France, (2020) amongst others could be plugged into this model to see for instance how changes in summer heat patterns could influence technology choices and corresponding demand.

In addition, the results of this modelling likely have something to add to the debate around the distributional effects of heat pump subsidies. From the earliest debates around price brakes and other policies effecting the relative cost of natural gas, there has been explicit and fair concern amongst many German policy makers around the fact that the poorest in society have the largest heating burden as a portion of their income to begin with, and as yearly savings start accruing only to those tenants or owners who can afford to live in a building with a heat pump, there is a potential for this to get worse (Federal Ministry for Economic Affairs and Climate Protection, 2022; Meakem, 2023). Partial results on this front emerged in section 4.1.2 when the effects of a building owners' decision to forego a heat pump for 5 years showed "missed savings" of between 400 and 1,200 €/yr for a 140 m^2 house in Leipzig, but more could be done to explore this dynamic at the intersection of the regional socioeconomic picture and the incidence of rural vs urban poverty. These results on lost savings and the impact of a specific electricity to gas price ratio in a world with mixed heat pump coverage could provide a technology specific to results focused on the rigorous statistical treatment of heat burden in general for instance by Kröger et al. (2022).

Heat pump retrofits clearly will play a central role in the broader energy transition in Germany, but their rollout must be coordinated with required changes in the power sector. While heat pump retrofits are already a net positive investment for many building owners under most likely future scenarios, subsidies and price brakes can provide the additional value and confidence to overcome the inertia of aging fossil fuel structure that could in many cases continue to work for many years to come to the detriment of the climate. While this research has brought to light certain considerations on efficiency of intervention through subsidies and attempted to highlight the least cost pathways to decarbonization, it is important to take a step back and recognize that infrastructure change takes time, and at the end of the day the energy transition requires multiple simultaneous shifts under an "all of the above" policy suite. With that perspective, this research should be interpreted as a forceful indorsement of heat pump subsidies and targeted HPT price brakes, even as it has tried to surgically characterize them by their necessity and efficacy.

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Appendix

Type	Source (Year)	Overview
Spatial Data	EUBUCCO (2021) (Milojevic-Dupont et al., 2023)	Building Height, Footprint, and Limited usage (~97% unknown)
	German Census (2011) (Deutsche Zensus, 2011)	100m Inspire Grids, with building count across 6 heat types and 10 size classifications
	(German Weather Service, 2023)	30m raster coverage of long term average outdoor temperature by month (1990-2020)
Future Energy Price	(Langreder et al., 2022)	Based on Prognose Energy Models ; HPT at 0.25 €/ kWh in 2044
	(Pehnt et al., 2023)	Estimates Based on numbers from the German Energy Agency HPT at 0.34 €/ kWh in 2044
	(Federal Ministry of Justice, 2023)	2023 Price brakes, set to expire in April 2024, but with ongoing debate on extension. HPT – 0.28 €/ kWh
Upfront Costs	(Langreder et al., 2022)	111 €/m2 ; Average of 2 MFHs in Germany
	(Schreurs, 2019)	600-1000 €/kW -> 66-110 €/m^2 SFHs in Austria
	(Kloth, 2023)	18,750 € for an “average“ German SFH
Heating Loads and Efficiency	(Langreder et al., 2022)	146 kWh/m^2/yr for 6 unit MFH built in the late 1970s
	(Henning, 2023)	Estimate for 6 Unit MFH of unspecified construction year in Germany ~ 156 kWh/m^2/yr
	(Zangheri et al., 2014)	Based on monthly EnergyPlus modelling in Berlin, Germany 162 kWh/m^2/yr MFH ; 132 kWh/m^2/yr

Appendix A: Overview of Selected Data Sources

Merkmal (Remark or attribute)	AUSPRAEGUNG_TEXT (Values)

HEIZTYP	The heating type characteristic indicates the predominant heating type in the building. 1: District heating (district heating) The building is supplied with heat from a central district heating plant (so-called district heating). 2: Floor heating A floor heating system is a central heating system for all rooms of a closed apartment, where the heating source is usually located within this apartment, e.g. gas boiler. 3: Block heating Block heating is when a block of houses is heated by a central heating system and the heating source is located in or on one of the buildings or in their immediate vicinity (so-called local heating). 4: Central heating In a central heating system, all residential units in a building are heated by a central heating point located within the building (usually in the basement). 5: Single/multi-room furnaces (also night storage heating) Single furnaces (e.g., coal or night storage heaters) heat only one room at a time in which they are located. They are usually permanently installed. A multi-room stove (e.g. tiled stove) heats several rooms at the same time (also through air ducts). 6: No heating in the building or in the apartments.
GEBAUDEART_SYS	The characteristic indicates the type of construction of the building. 1: Detached house Freestanding building, regardless of whether it is a single-family or multi-family dwelling. 2: Semi-detached house Building that is contiguous with exactly one other building, regardless of whether it is single-family or multi-family. 3: Rowed house Building that is built side by side with at least two other buildings, regardless of whether they are single-family or multi-family dwellings. The buildings do not have to be identical in construction; they can also be offset laterally or in height. Row corner buildings are also included. 4: Other building type Any type of building that is not a detached house, duplex, or row house, and any type of occupied dwelling.
GEBTYPBAUWEISE	1: Buildings with living space Structures erected for an extended period of time and intended either wholly or in part for the residential accommodation of households. This also includes administrative or commercial buildings if they contain at least one dwelling used for residential purposes. Buildings with living quarters are divided into residential buildings and other buildings with living quarters. 11: Residential buildings

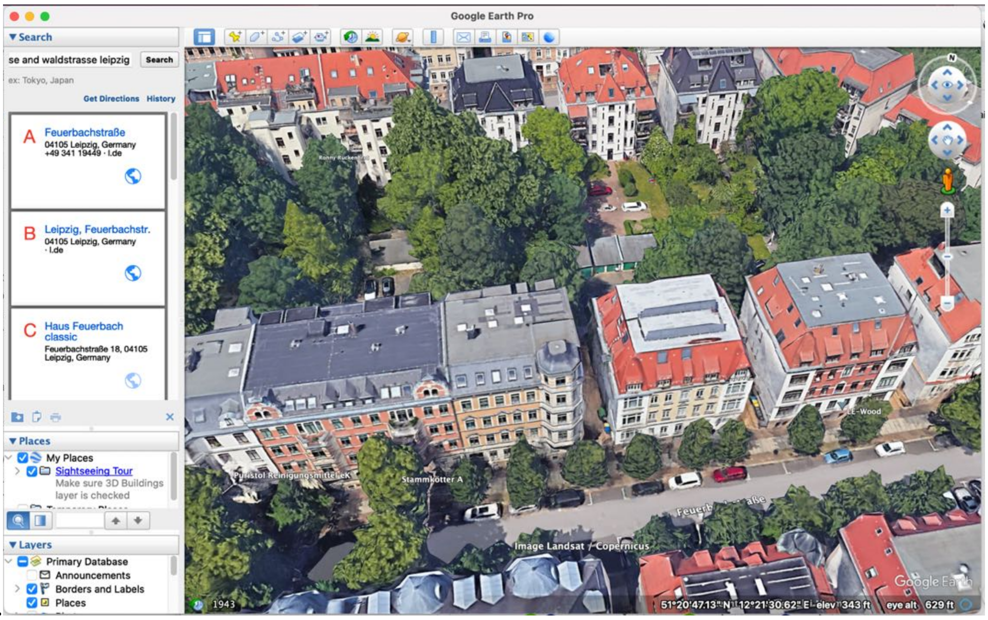
	Buildings in which at least half of the total usable floor area is used for residential purposes. Residential buildings also include dormitories (with own household management of the residents). 111: Residential buildings (excluding dormitories) Buildings in which at least half of the total usable floor area is used for residential purposes (here: excluding dormitories). 112: Dormitories Dormitories are residential buildings that primarily serve the housing needs of specific segments of the population (e.g., student dormitory, retirement home). Residence halls have common areas. Residents of dormitories maintain their own households. 12: Other buildings with living space Buildings in which less than half of the total floor area is used for residential purposes, e.g. because the building contains mainly stores or offices.

Appendix B: The Building Characteristics and Possible Values in English Translation from deepl.com

Heating Type	Definition	Number of Residential Buildings in Saxony	Percent
1: District heating (district heating)	**The building is supplied with heat from a central district heating plant (so-called district heating).**	**50289**	**7.14**
2: Single Unit heating	**A floor heating system is a central heating system for all rooms of a closed apartment, where the heating source is usually located within this apartment, e.g. gas boiler.**	**39903**	**5.66**
3: Block heating	**Block heating is when a block of houses is heated by a central heating system and the heating source is located in or on one of the buildings or in their immediate vicinity (so-called local heating).**	**6923**	**0.98**
4: Central heating	**In a central heating system, all residential units in a building are heated by a central heating point located within the building (usually in the basement).**	**559540**	**79.43**

5: Single/multi-room furnaces (also night storage heating)	Single furnaces (e.g., coal or night storage heaters) heat only one room at a time in which they are located. They are usually permanently installed. A multi-room stove (e.g. tiled stove) heats several rooms at the same time (also through air ducts).	46376	6.58
6: No heating in the building or in the apartments.	No heating in the building or in the apartments.	1387	0.20
Total		704418	100

Appendix C: A summary of Heating Systems and Their Total Count in Saxony 2011 Census (German Census, 2011)

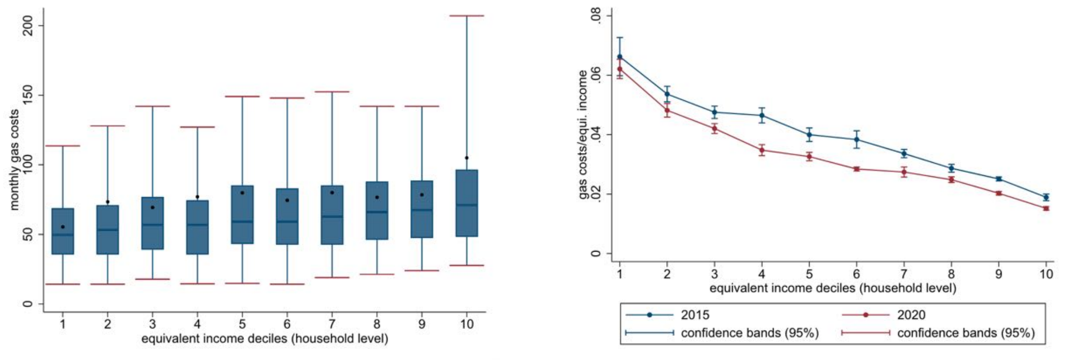


Appendix D: Removing buildings under 3.8m removed the garage, the free standing building was effectively labelled as a 4 floor, while the building in the foreground was misclassified as a 5 story building, missing a garden level apartment

Appendix E Lower limit was set at 3M to include single family homes such as those in the foreground here at 3.11 and 3.09m High respectively

	UPFRONTCOSTPERM2	YEARLYSENSHEATPERM2
SIZ_1_FREE	110	140
SIZ_1_SEMI	110	140
SIZ_1_ROW	110	140
SIZ_2_FREE	110	140
SIZ_2_SEMI	110	140
SIZ_2_ROW	110	140
SIZ_3-6_APART	110	112
SIZ_7-12_APART	130	112
SIZ_13+_APART	130	112
SIZ_OTHER	130	112

Appendix F: A reproduction of energeticTotalsDict.csv



(a) Absolute gas costs along income deciles (b) Relative gas costs along income deciles

Own calculation based on SOEP v37 using the restricted working sample. Fig. (a) shows the monthly gas costs across household income deciles. Boxes indicate the 25^{th} to 75^{th} percentile of the distribution. Whiskers indicate the 5^{th} till 95^{th} percentile. Points represent the mean value and horizontal lines represent the median value. Fig (b) shows the relative gas costs of 2015 and 2020. Confidence bands indicate the 95^{th} percent around the median value and are based on bootstrapped standard errors with 500 replications. Median value by equivalent income decile are shown by the line graph.

Appendix G: Gas Expenditure and Household Income (Reprinted from Kröger et al., 2022)

Declaration Of Authorship

"I do solemnly declare that I have written the presented research thesis by myself without undue help from a second person others and without using such tools other than that specified.

Where I have used thoughts from external sources, directly or indirectly, published or unpublished, this is always clearly attributed. In the selection and evaluation of research materials, I have received support services from following individuals/institutions: Prof. Dr. Paul Lehmann and Jan-Niklas Meier with the Energy and Economics Team in the Faculty of Economic Sciences and Institute for Infrastructure and Resource Management at the University of Leipzig.

The presented intellectual work of this research thesis is my own. In particular, I have not taken any help of any qualified consultant.

I have not directly nor indirectly received any monetary benefit from third parties in connection to this research thesis.

Furthermore, I certify that this research thesis or any part of it has not been previously submitted for a degree or any other qualification at the University of Leipzig or any other institution in Germany or abroad."

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