Empirical Analyses of Market Outcomes regarding Energy Efficiency Valuation and Renewable Energy Investments

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zur Erlangung des Doktorgrades

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“Believe you can and you’re halfway there!”

Theodore Roosevelt

PREFACE

I authored this thesis while working at the Chair for Management Science and Energy Economics at the University of Duisburg-Essen and being part of the Graduate School for Sustainable Energy Systems in Neighborhoods, funded by the Ministry of Culture and Science of the German State of North Rhine-Westphalia.

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CHAPTER ONE

Introduction

„The earth has a fever. And the fever is rising.“

– Al Gore (2007)

Climate change has become a central focus of political and societal concern, ranking as one of the most important global challenges of our time. The global warming associated with climate change poses a growing and potentially irreversible threat to human societies and the planet. Therefore, the broadest possible cooperation of all countries and their participation in an cooperative approach is needed to achieve a rapid and sustainable reduction of global greenhouse gas emissions (UNFCCC, 2015a). Above all, global warming must be limited to preserve a viable environment for future generations (cf. IPCC, 2018). Knowing the link between energy use, CO_2 emissions and climate change, policy makers have enacted several legislative requirements to reduce the energy demand and the usage of fossil fuels.

An international agreement on a reduction in greenhouse gas emissions was legally established for the first time in the Kyoto Protocol of 1997 (UNFCCC, 1997). Almost 20 years later, the member states of the United Nations Framework Convention on Climate Change (UNFCCC) met in Paris and agreed on legally binding climate protection targets. According to the Paris Agreement (UNFCCC, 2015b), the increase in the global average temperature is to be limited to well below 2 °C above pre-industrial levels. Additional efforts are also to be initiated to limit the temperature increase to 1.5 °C above pre-industrial levels.

The climate protection targets agreed in Paris are thereby based on national targets and climate protection measures, which each individual country attempts to fulfil. These nationally determined contributions must be updated and increased every five years from 2025 onwards. Further, all countries were required to submit long-term strategies for low greenhouse gas development by 2020 (cf. BMWk, 2023a).

To meet the objectives of the Paris Agreement, Germany primarily emphasizes the increasing use of renewable energies and an increase in energy efficiency. The German government's ambitious goal is to reach greenhouse gas neutrality by 2045, which is also stipulated in the Federal Climate Protection Act (KSG, 2021). For the existing building stock, which by 2045[1] is also supposed to become climate-neutral, the Energy Efficiency Strategy for Buildings provides an initial necessary framework (BMWi, 2015). This framework was updated and expanded in 2020 by the German government's Long-term Renovation Strategy (BMWi, 2020).

Through a combination of energy savings due to efficiency improvements and the use of renewable energy, the German government aims to reduce the non-renewable primary energy consumption in buildings by around 55 % by 2030 compared to 2008. In 2018, a reduction of around 25 % compared to 2008 was already achieved (BMWi, 2020). The existing policy instruments already reach building owners on a large scale and provide incentives for investments in building's energy efficiency. However, to achieve the ambitious goal of a climate-neutral building stock by 2045, further investments in energy-efficient refurbishments and renewable energy technologies (and especially renewable heat) are necessary.

In this context, the main objective of this thesis is to find empirical evidence for effects of energy efficiency improvements as well as of different heating technologies on real estate sales prices and rents. In addition, regarding renewable energy technologies beyond the aforementioned heating systems, different drivers for the expansion of rooftop photovoltaic (PV) systems are investigated. The focus is on the existing building stock in both the sales and rental housing market, as there are great potentials for energy efficiency improvements (cf. Prognos AG et al., 2017). Additionally, given the country's relatively old building stock[2], the decarbonization of existing buildings must be a priority. Furthermore, the rate of new construction is only just under 0.8 %[3] (own calculations based on Statistisches Bundesamt, 2023a, 2023b), so that a large proportion of the buildings that will be in the stock in 2045 already exist today.

Therefore, the remainder of this introductory chapter gives an overview of the residential building stock as well as the real estate markets in Germany (cf. Chapters 1.1 and 1.2). It also describes the regulatory framework, including the subsidy schemes for energy refurbishments

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[1] The Energy Efficiency Strategy for Buildings is based on an originally planned target achievement by 2050. However, this deadline has been tightened to 2045.

[2] About 63 % of residential buildings were built before the introduction of minimum energy efficiency standards in 1979 (cf. Chapter 1.1 and Chapter 1.3).

[3] Relative to the total stock of residential buildings. For apartments, the new construction rate is only about 0.5 % (BMWi, 2020).

and the regulations on rent increases after renovations (cf. Chapter 1.3), as well as the German energy performance certificates (cf. Chapter 1.4). A short overview on PV installations in Germany together with information on subsidy schemes for rooftop installations follows in Chapter 1.5. Subsequently, the main research questions addressed in this dissertation are presented in Chapter 1.6 while an overview of the structure of this dissertation is given in Chapter 1.7.

1.1 The residential building stock in Germany

The residential building stock in Germany consists of around 19.4 million residential buildings with a total of 3.8 billion m² of living area distributed among 41.7 million apartments[4] (Statistisches Bundesamt, 2022). The vacancy rate is 7.9 % (Statistische Ämter des Bundes und der Länder, 2018a). Approximately 67 % of all residential buildings are single-family homes, while the remaining is evenly split between two-family and multi-family dwellings (dena, 2021).

Overall, the operation of the German building stock accounts for around 35 % of final energy consumption and around 30 % of CO_2 emissions – including emissions from the use of electricity and district heating and from industrial buildings. Direct emissions from buildings in the two sectors *private households* and *commerce, trade, services* “only” account for 15 % of CO_2 emissions (BMWk, 2021). From 2005 to 2020, annual direct and indirect CO_2 emissions of private households in the area of *housing* decreased by about 20 % from 255 million tCO_2 to just below 199 million tCO_2 (UBA, 2023). Thus, to achieve a climate-neutral building stock by 2045, emission reductions of about 8 million tCO_2 per year are necessary.

Since the energy efficiency of buildings depends inter alia on the construction period, Figure 1 shows percentages of residential buildings by year of construction. More than half of all buildings were constructed before 1979 (cf. Statistische Ämter des Bundes und der Länder, 2018b). Currently, almost all residential buildings in Germany are older than ten years, as 95 % were already built before 2012.

The largest proportion of residential buildings was constructed between 1950 and 1979, of which a large part belongs to the so-called post-war buildings of the 1950s, which are characterized by thrift, scarcity of materials and simple construction methods (BauNetz, n.d.). An even larger part (Statistische Ämter des Bundes und der Länder, 2015) is accounted for by

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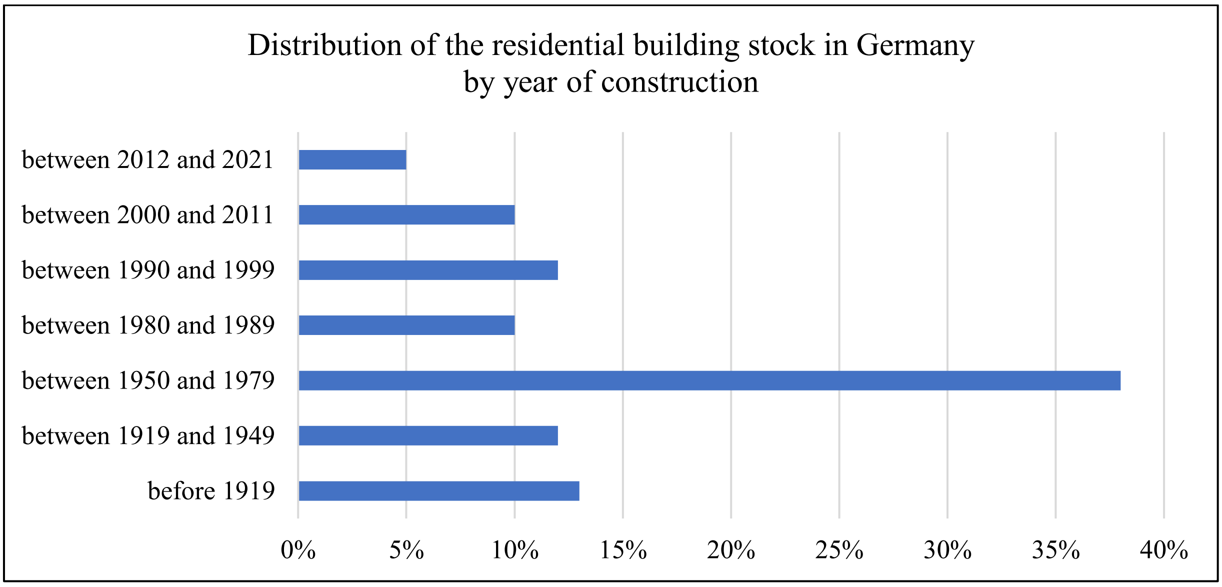
[4] As of 2021. Extrapolation is based on the results of the 2011 building and housing census. The data refers only to dwelling units in residential buildings – dwellings in non-residential buildings are not included.

the industrialized housing construction of the 1970s, which includes the so-called prefabricated buildings (“*Plattenbauten*”) (BauNetz, n.d.).

With the first regulations on energy standards in residential buildings only coming into force in November 1977 (WärmeschutzV, 1977), the overall energy standard of all older buildings can be classified as rather poor, unless substantial energetic retrofits have taken place. As of 2016, only about half of all residential buildings had an insulated exterior wall. At just under 84 %, the highest insulation rate is found for the upper floor ceiling respectively the roof; in contrast, only around 40 % of all basement ceilings are insulated. (Cischinsky and Diefenbach, 2018)



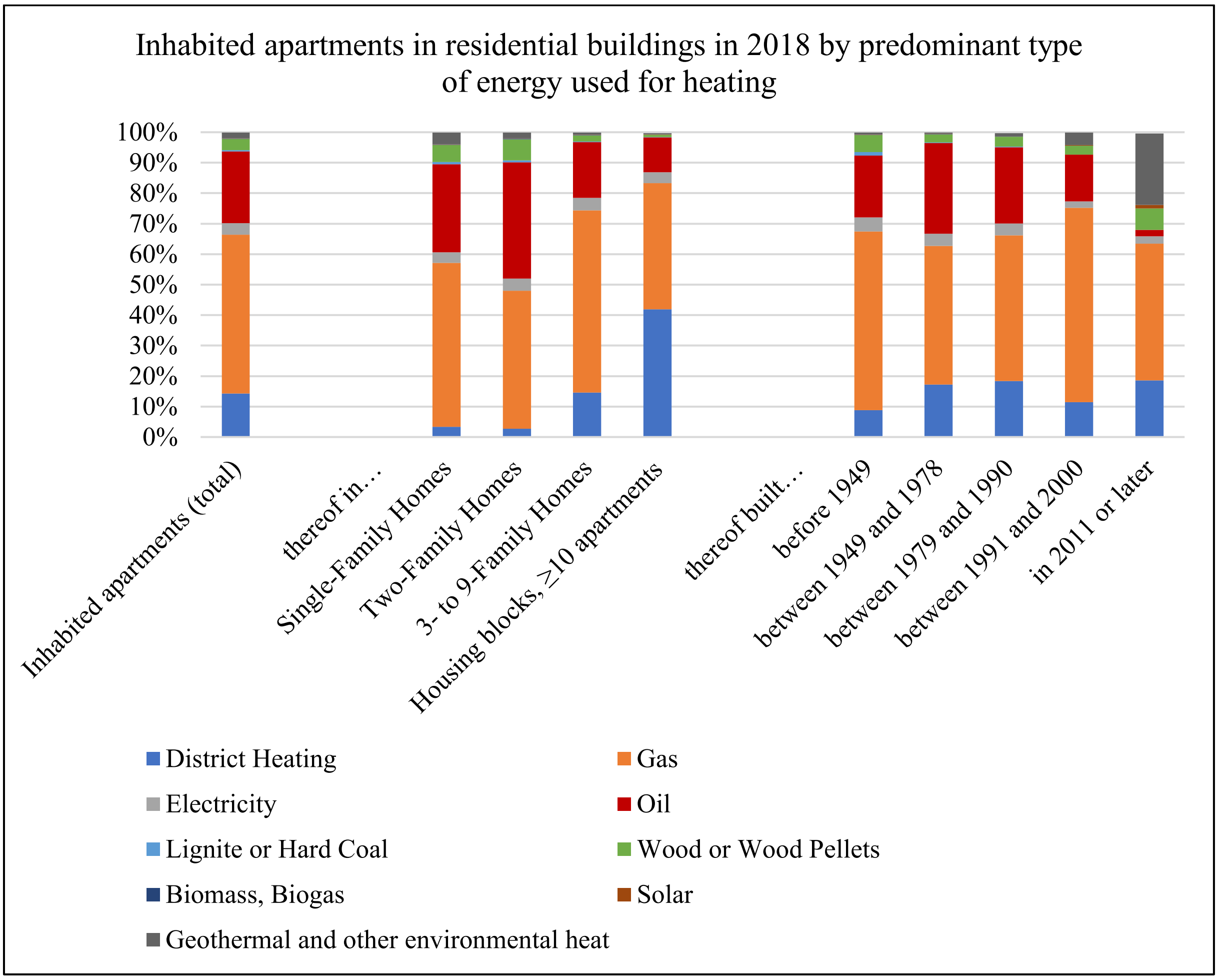
Source: Own illustration based on Statista (2023a).

Figure 1 Distribution of the residential building stock in Germany by year of construction.

These values vary greatly depending on the year of construction. For old buildings built up to 1978, for example, only 45 % of all buildings have exterior wall insulation, whereas the proportion for new buildings built from 2010 onward is over 75 %. This difference is even more pronounced in the case of basement ceiling insulation: only 27 % of old buildings are insulated, compared with 84 % of new buildings (Cischinsky and Diefenbach, 2018). Overall, more than 55 % of all residential buildings in the German housing stock have not been modernized in terms of energy efficiency, or only to a very limited extent (ARGE, 2022).

To achieve a climate-neutral building stock by 2045, retrofitting is therefore necessary – especially in older buildings. For the residential building stock in total, energy-refurbishment rates, however, stagnate at about 1 % per year. For old buildings (up to 1978), the rate is slightly higher with 1.43 %. In comparison, the renewal rates for residential building facades are 2.27 % (in the total building stock), so the difference can be considered a missed opportunity for energy refurbishments. (Cischinsky and Diefenbach, 2018; Kost et al., 2021)

In addition to the building envelope, the type of heating system in combination with the energy source predominantly used for heating also plays an important role in decarbonizing the building stock, as heating accounts for about two-thirds of households CO_2 emissions in the residential sector (Statistisches Bundesamt, 2021). Therefore, Figure 2 shows the predominant type of energy used for heating in 2018 for all inhabited apartments and split by house type and construction period.



Source: Own calculation and illustration based on Statistische Ämter des Bundes und der Länder (2018a).

Figure 2 Inhabited apartments in residential buildings in 2018 by predominant type of energy used for heating.

Overall, most apartments use gas as primary energy source for heating, followed by oil and district heating. Renewable energy sources such as wood pellets, geothermal or environmental heat and solar energy only account for less than 10 % in total. For single-family and two-family homes, the share of district heating is below 5 %, whereas it is more common in multi-family dwelling with 15 % in 3- to 9-family homes and more than 40 % in housing blocks with ten or more apartments. Just like district heating networks, large apartment buildings are often found in conurbations, which explains the high proportion. Nevertheless, gas is still the main energy source used for heating among all house types; for two-family homes this is closely followed by oil with about 38 %.

Looking at the different construction periods, it is noticeable that renewable energies are gaining in importance over time: more than 20 % of all residential buildings constructed in 2011 or later use geothermal or other environmental heat as their primary energy source for heating. The share of electricity used for heating, however, remains almost constant over time. Also more or less constant over time is the share of district heating, with a small dip for the construction years 1991 to 2000, which can certainly be explained by high shares of single-family homes among the new buildings of this period (cf. dena, 2021) but also by the collapse of the German Democratic Republic (DDR) and the associated shift from (lignite-based) district heating to gas heating in eastern Germany, as well as the emerging liberalization of electricity markets (cf. Fernwärme-Info.com, 2023).

1.2 The residential real estate market in Germany

At just under 50 %, Germany has the lowest home-ownership rate[5] of all EU countries (Statista, 2023b). According to the 2018 sample survey of income and expenditure (EVS), around 57.9 % of all households live in rented accommodations with an average living space of 70.5 m² per household. The owner-occupancy rate[6] thus amounts to 42.1 %; the average living area for households living in their owned apartments is 124.5 m² (Statistisches Bundesamt, 2020).

Of all inhabited and rented apartments, 58 % are let by private owners, 23 % by housing and building cooperatives, 15 % by private companies and about 4 % by public institutions (Statistische Ämter des Bundes und der Länder, 2018a). Further, there are substantial regional differences in the rental housing market. Eastern Germany and the city states Berlin, Hamburg and Bremen are characterized by an extensive municipal and cooperative housing stock. In the western states, the ownership structure is characterized by a higher proportion of small private landlords (BMWSB, 2022).

Due to the highly diverse regional population trends in Germany, the housing markets are also showing different development trends. Growing cities and regions have been experiencing rapidly increasing demand for housing for years due to high internal and external migration gains. This housing demand is exacerbated by the reduction in average household sizes in recent

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[5] The home-ownership rate given here represents the ratio of the number of households that have formed residential property to the number of total households under consideration.

[6] In contrast to the home ownership rate, the owner-occupancy rate only includes owner-occupied property.

decades[7]. Moreover, this strong demand for housing is reflected in rising rents and purchase prices for real estate. In contrast, cities and regions with negative population growth are more likely to experience increased vacancy rates, rising per capita costs for public infrastructure and a thinning out of public utilities[8]. (BMWSB, 2022)

The economic situation, infrastructure facilities and links to labor markets also influence regional differences in real estate prices and rents. To illustrate these differences, Figure 3 shows average monthly asking rents[9] for apartments as well as average asking prices for single-family houses in Germany on NUTS3 level[10] in 2014 and 2021. The data originates from Germany's largest real estate internet platform *immobilienscout24.de* and is provided by the RWI – Leibniz Institute for Economic Research as a scientific use file (RWI and ImmobilienScout24, 2022a, 2022b).

Both real estate prices as well as rents vary widely across Germany's subregions. Large metropolitan cities like Munich, Hamburg or Berlin stand out clearly from their surrounding areas. High prices and rents in the metropolitan regions of Munich and Stuttgart are carried far into the surrounding districts, which are also economically strong (cf. BMWSB, 2022). In other regions, such as Dusseldorf and Cologne or Berlin, high prices and rents only extend into the immediate surrounding area. These are followed by rural areas with significantly lower real estate prices and rents.

Looking at price changes over time from 2014 to 2021, it is obvious that both in the rental sector and in the market for single-family homes, prices have risen significantly in all regions. Monthly asking rents increased by up to 75 % in the surroundings of Munich; the average rent increase amounts to 30 %. Asking prices for single-family homes even have risen by more than 150 % in some regions, with an average increase of about 82 %. In contrast to asking rents, existing net basic rents according to the consumer price index have only risen by approx. 10 % from 2014 to 2021 (Statista, 2023c).

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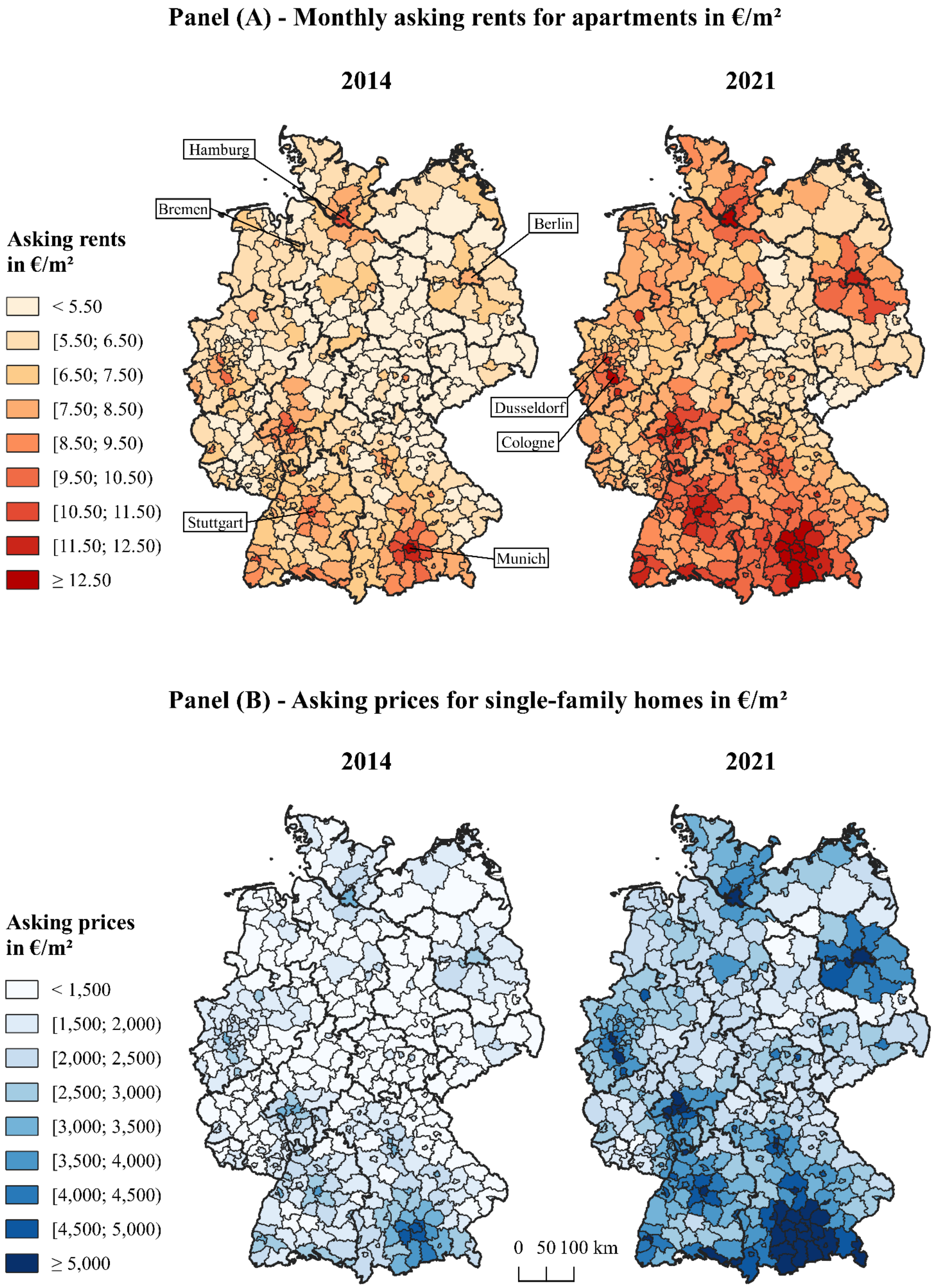
[7] About 75 % of households are one- or two-person households (Statistisches Bundesamt, 2023c).

[8] Public utilities include hospitals, doctors' offices, but also stores for everyday needs.

[9] Net basic rent, excluding costs for energy or other auxiliary costs. Since the rents stated in the real estate advertisements on the internet platform are not necessarily final transaction prices, they are referred to as asking rents.

[10] The territory of the European Union is divided into hierarchical levels using the geographical system NUTS (Nomenclature des Unités territoriales statistiques). NUTS3 regions typically have a population of 150,000 to 800,000 inhabitants, which refers to districts known as *Kreise* or *kreisfreie Städte* in Germany.


Panel (A) - Monthly asking rents for apartments in €/m²

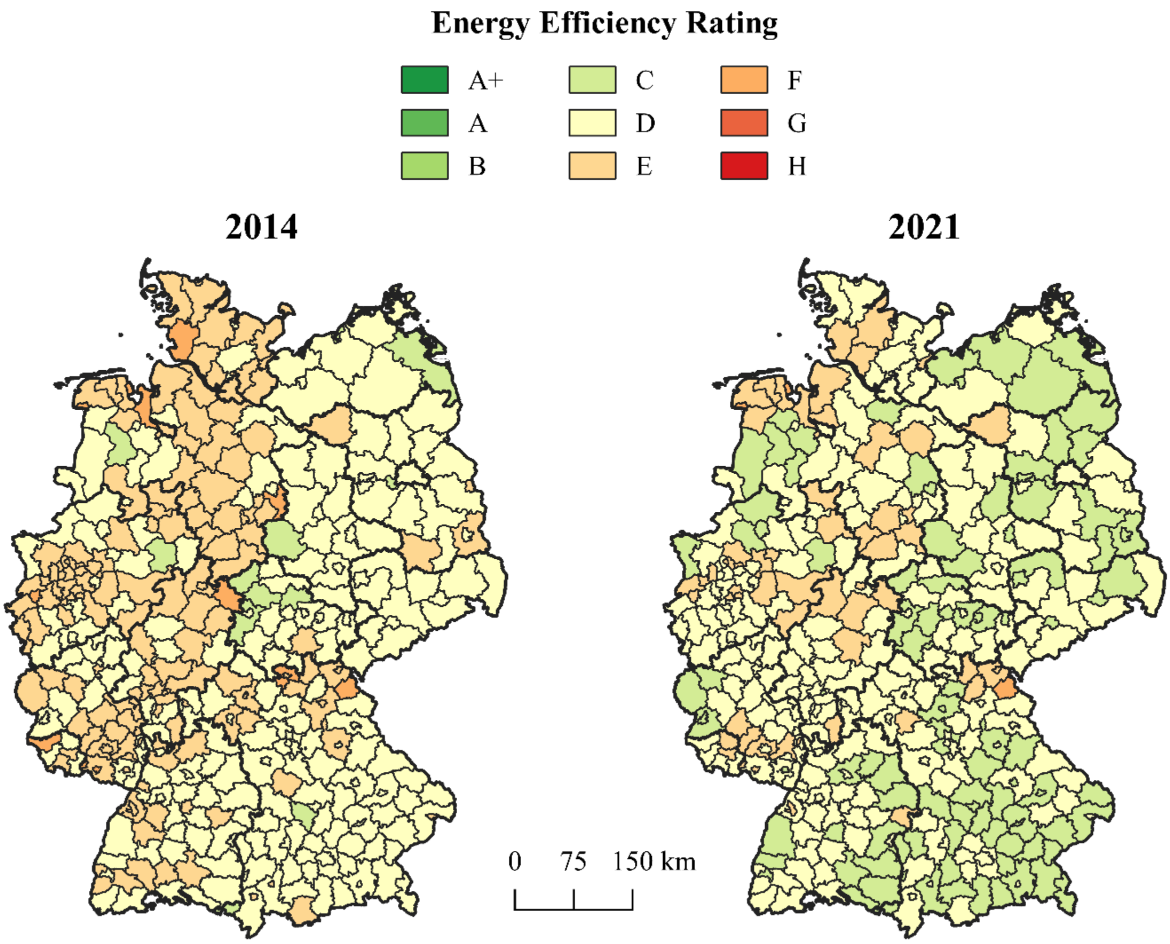
Panel (B) - Asking prices for single-family homes in €/m²

Source: Own calculations and illustrations based on RWI and ImmobilienScout24 (2022a, 2022b).
Map Data: @GeoBasis-DE/BKG 2021.

Figure 3 Monthly asking rents and asking prices for residential real estate in Germany.

Comparable to the divergence observed in regional asking rents, the extent of rent burden ratio in Germany displays significant regional disparities. The average rent burden ratio is 27.2 % of net household income (Statistische Ämter des Bundes und der Länder, 2018a). In large cities, nearly 40 % of households encounter a rent burden ratio exceeding 30 % of their net household income (Holm and Junker, 2019). This situation is generally deemed concerning, as it leaves a relatively limited portion of funds for other essential living expenditures, particularly among individuals with lower earnings (Lebuhn et al., 2017).

Lastly, Figure 4 illustrates the average energy performance in terms of the energy efficiency rating[11] for advertised rental apartments in 2014 and 2021. At the county level, the average apartment offered in 2014 can be generally categorized as D or E ratings, with a few exceptions where a better energy efficiency rating of C, or an even worse rating of F is observed.



Source: Own calculations and illustrations based on RWI and ImmobilienScout24 (2022a).
Map Data: @GeoBasis-DE/BKG 2021.

Figure 4 Average energy efficiency rating of rental apartments advertised on the internet platform immobilienscout24.de in 2014 and 2021.

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[11] The energy efficiency rating in Germany has a scale from A+ (best category = low energy consumption) to H (worst category = high energy consumption). A detailed description of energy performance certificates follows in Chapter 1.4.

Regional differences are also observable: In the northwest of the country, the apartments on offer are on average less efficient compared with offers in most other regions in Germany (indicated by the poorer energy efficiency rating).

Up to 2021, the energy efficiency of all rental apartments on offer has increased on average, so that for most counties, the average apartment on offer in 2021 reaches a C or D rating. Regional differences can still be observed: Both in the northwest and in the middle of Germany, there are still some counties in which the average rental apartments on offer are assigned to class E in the energy efficiency rating.

1.3 Regulatory frameworks

Minimum energy standards for (residential) buildings have been required by law in Germany since the introduction of the Heat Insulation Ordinance (Wärmeschutzverordnung – WSchV) in 1977. In addition to the Heat Insulation Ordinance, the Energy Savings Act (Energieeinsparungsgesetz – EnEG) and the Heating System Ordinance (Heizungsanlagen-Verordnung – HeizAnlV) have also regulated the use of renewable energies and the requirements for the equipment and design of central heating systems using water as a heat transfer medium and for hot water systems. The Heat Insulation Ordinance and the Heating System Ordinance were then replaced by the Energy Saving Ordinance (Energieeinsparverordnung – EnEV) in 2002. The Renewable Energies Heat Act (Erneuerbare-Energien-Wärmegesetz – EEWärmeG) was added in 2009.

As the legal situation became increasingly complex and opaque due to the many laws and constant updates, all rules have been combined in the new Buildings Energy Act (Gebäudeenergiegesetz – GEG) since 2020. An overview including a timeline of the various laws is shown in Figure 5. Currently, the GEG makes several prescriptions for energy refurbishments in existing buildings[12]. These include, on the one hand, various specifications on minimum values for thermal insulation, for example of the top floor ceiling (§47 GEG) or also specifications on the limit values to be complied with for transmission heat losses in the case of conversions (§48 GEG) and extensions (§51 GEG) of the existing building.

On the other hand, the GEG stipulates that owners of buildings may no longer operate their boilers that are fed with a liquid or gaseous fuel and were installed or set up before January 1,

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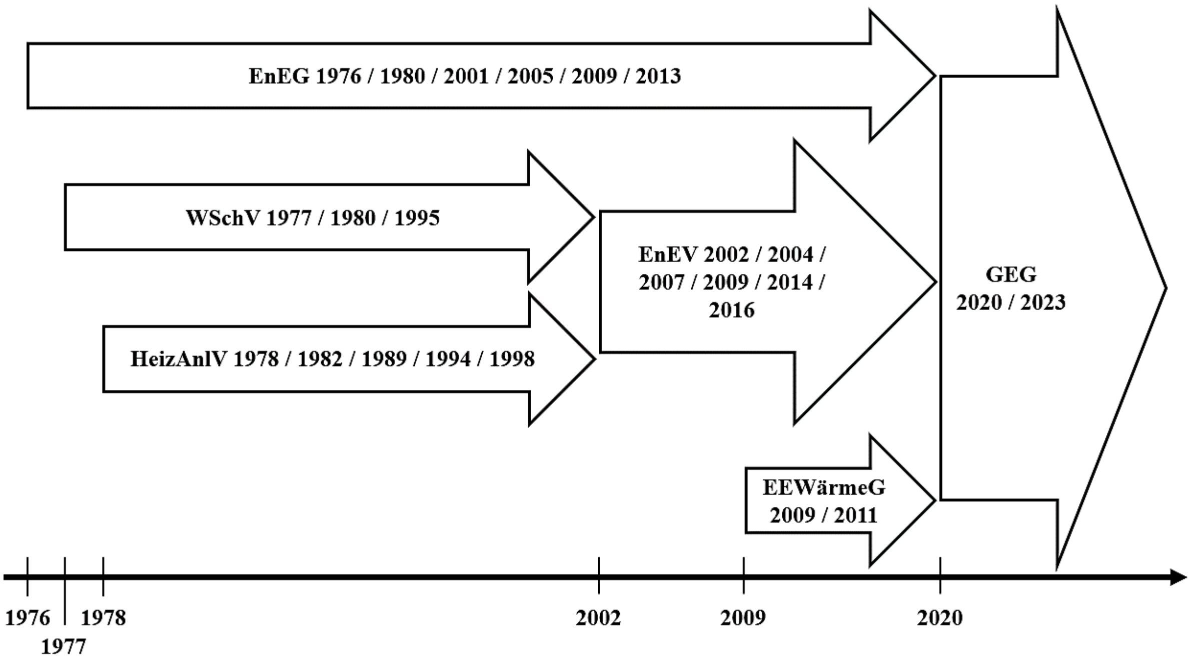
[12] The GEG and its predecessors generally have focused on requirements for newly constructed buildings; however, since these are not the subject of the studies included in this dissertation, the information in this introduction are limited to existing buildings.

1991 (§72 GEG). The same applies to systems that were installed after January 1, 1991, and have been in operation for more than 30 years. There are exceptions for low-temperature boilers and oil-fired boilers as well as heating systems with a rated output of less than 4 kilowatts or more than 400 kilowatts. Furthermore, as of January 1, 2026, boilers fired with fuel oil or solid fossil fuel may only be installed in exceptional cases. One of these exceptions is, for example, that an existing building has been constructed or modified in such a way that the heating and cooling energy demand is covered proportionally by renewable energies (§72 GEG, section 4(3)).



Source: Own illustration.

Figure 5 Development of the Building Energy Law (GEG).

Only recently[13], a tightening of the GEG – the so-called *"Heizungsgesetz"* – was passed by the Bundestag. The amendment stipulates that, from 2024, owners must consistently use renewable energy when installing new heating systems. In concrete terms, this means that from January 1, 2024, as far as possible, every newly installed heating system must be powered by 65 % renewable energy. The GEG proposes several heating alternatives, inter alia the connection to a heating network, the installation of an electric heat pump or the installation of a gas heating system that demonstrably uses renewable gases.

To create financial incentives for energy refurbishments alongside the statutory regulations, there are numerous subsidy programs in Germany. On the one hand, many of the existing programs are available through the *Kreditanstalt für Wiederaufbau* (KfW), and on the other

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[13] As of September 08, 2023.

hand, subsidies are set out in the new Federal Subsidy for Efficient Buildings (BEG) of the Federal Office of Economics and Export Control (BAFA). With the amendment of the GEG, there will also be subsidies for new, climate-friendly heating systems from the government. Details about the amount and income limits are not yet known.

Current BAFA renovation options focus on the building envelope, the systems technology used (excluding heating systems) and the systems for heat generation (i.e., heating technology). The minimum investment volume is €2,000 in each case; the maximum eligible costs are €60,000 per residential unit and calendar year up to a maximum of €600,000 per building (BAFA, 2021a, 2021b).

In case of the KfW, the subsidy consists in low-interest loans (from 0.15 % annual interest rate) for renovation projects of private homeowners. These subsidized loans are available, among other things, for the insulation of the building envelope, the replacement of installed windows, the installation or replacement of a ventilation system or new heating system, and the installation of a PV or solar thermal system. The maximum loan amount is €150,000 per residential unit; a repayment grant of 5 % to 45 % is also provided, depending on the respective energy-efficiency class of the building. (KfW, 2023a)

In addition to subsidies, which are mainly of interest for real estate owners, there are some regulations to protect tenants from excessive rent increases. Throughout its history, the German residential rental market has been subject to diverse pricing controls. However, in response to recent surges in both property sales prices and rental rates, supplementary regulations have been introduced since 2019, primarily directed at fortifying the security of tenants bound by existing lease agreements. Consequently, with regards to investments in property refurbishments, landlords are restricted from entirely transferring the expenses of these enhancements to their present tenants. Following the execution of a modernization project aligned with the specifications outlined in §559 of the German Civil Code (BGB), landlords are permitted to augment the annual rent by a maximum of 8 % of the incurred costs (BGB, 2023).

Moreover, irrespective of the actual amount of the modernization costs, rents may not be increased by more than €3 per square meter of living space over a span of six years, provided the initial rent exceeded €7 per square meter. In instances where the initial rent was lower, the permissible maximum increase is capped at €2. In cases where landlords undertake multiple minor modernization projects in the near future, each warranting a modernization-based rental hike, they are obliged to counterbalance the costs previously claimed over a period of five years (BGB, 2023, Section 559c). Additionally, rents may not generally increase by more than 20 %

within three years and may never exceed a publicly available reference level, the so-called local comparative rent, determined by the municipalities in cooperation with landlord and tenant associations. Post-modernization rent increases yet remain disassociated from these adjustments to the local reference level.

The aforementioned rules for an existing tenancy are overridden in case of new tenancies, where a completely new leasing agreement is established. In these scenarios, property owners can set the new rent at their discretion, without relying directly on the local rent index or the comparative rent. The determination of the price is theoretically open to negotiation with the tenant, subject to the proprietor's prerogative. Notably, no redevelopment, modernization or renovation work is necessary to justify rent increases. The sole constraint imposed on pricing pertains to ensuring that the rental rate for the apartment remains within a 20 % margin in comparison to analogous properties located in the immediate vicinity.

To ensure that the switch to environmentally friendly heating does not overburden tenants and landlords financially, there will be a further modernization levy as soon as the amendment to the GEG comes into force. In concrete terms, this means that the property owner will be allowed to increase the rent, but only if the tenants also benefit financially.

1.4 Energy Performance Certificates

Energy performance certificates (EPCs) in the real estate sector were introduced by many governments around the world with the aim to mitigate information asymmetries regarding the thermal quality of the advertised building between property owners and potential tenants or buyers, respectively. In Germany, EPCs were introduced in 2002, initially with mandatory issuance only for new buildings (EnEV, 2002). From 2008, EPCs were also gradually introduced for existing buildings. The German law included the weak obligation to provide an EPC as soon as a prospective client asks for it; however, this obligation could not be tracked and the missing of an EPC was not subject to legal sanctions (EnEV, 2007).

The mandatory EPC then came into force on May 1, 2014, requiring property owners to disclose the energy consumption per square meter living area of the respective building or apartment offered[14] (EnEV, 2014). To enforce the regulations, high fines for non-compliance were introduced as of May 2015. With these legal modifications, the character of the labeling system changed significantly, from an originally voluntary disclosure of energy information to an

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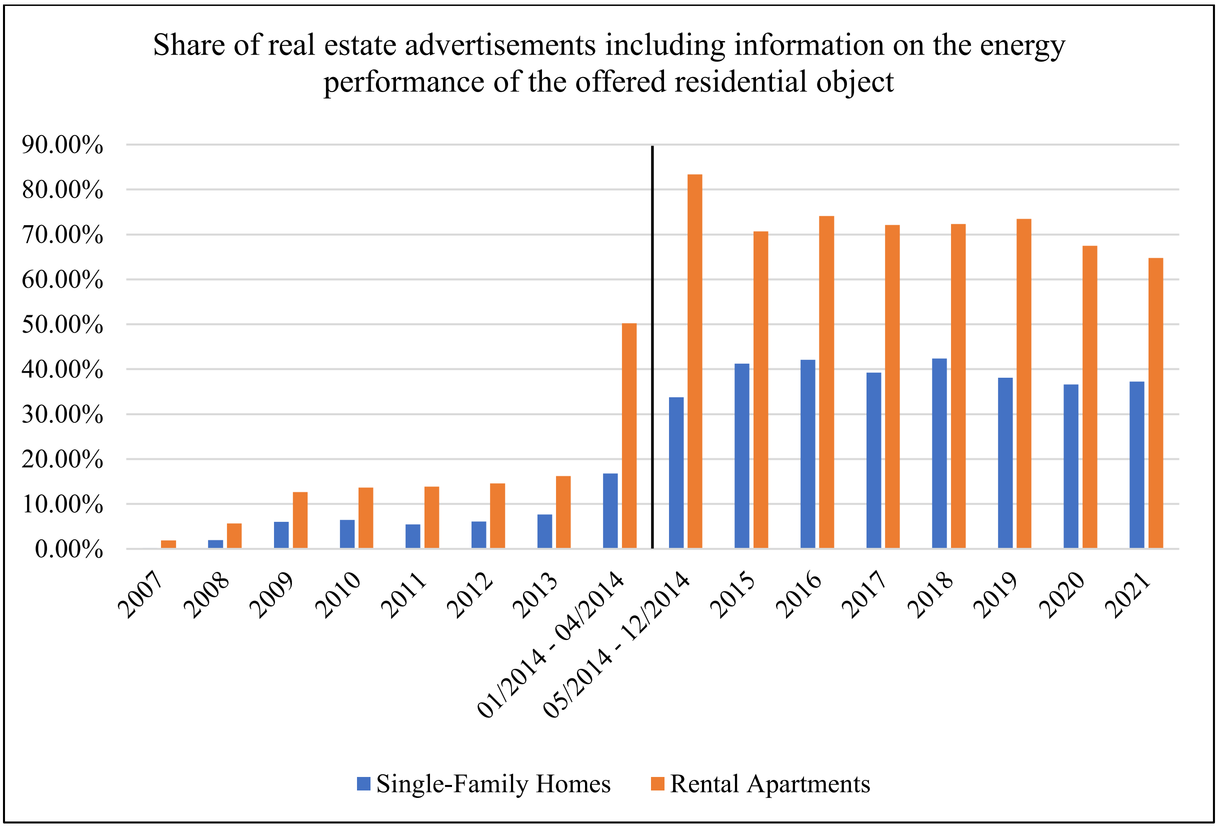
[14] Information from the EPC must already be provided in the exposé or the property advertisement. The certificate must then be handed over to the interested parties during the viewing.

imposed disclosure today (cf. Frondel et al., 2020). Since 2020, the issuance and use of energy certificates have been regulated by the Building Energy Act (GEG, 2020).

Figure 6 shows the share of rental apartments and single-family houses on offer between 2007 and 2021 for which information on the energy performance of the stated object is already included in the online advertisement, either in terms of the energy efficiency rating from A+ to H or the energy consumption in kWh/m²a. Until 2013, less than 20 % of all advertised properties had information on the energy performance disclosed in the online advertisement.



Source: Own calculations and illustrations based on RWI and ImmobilienScout24 (2022a, 2022b).

Figure 6 Real estate advertisements including information on the energy performance of the offered objects.

At the beginning of 2014 – before the stricter regulation came into force in May – the percentages already increased to 50 %, at least for rental apartments. From May 2014 onwards, numbers started to rise, although energy performance measures are still only provided in less than 50 % of the single-family homes on offer. As a fine is usually only due if a valid EPC is not presented at the time of inspection, this could partly explain the low reporting rates. Nevertheless, at least two-thirds of all advertisements for rental apartments already feature information on the energy performance in online advertisements.

In Germany, there are two types of energy certificates: the demand certificate (§81 GEG) and the consumption certificate (§82 GEG). Both types contain basic information about the building, such as the year of construction, the building type and the usable building area, as well as information about the heating system and hot water generation, including the main energy sources used.

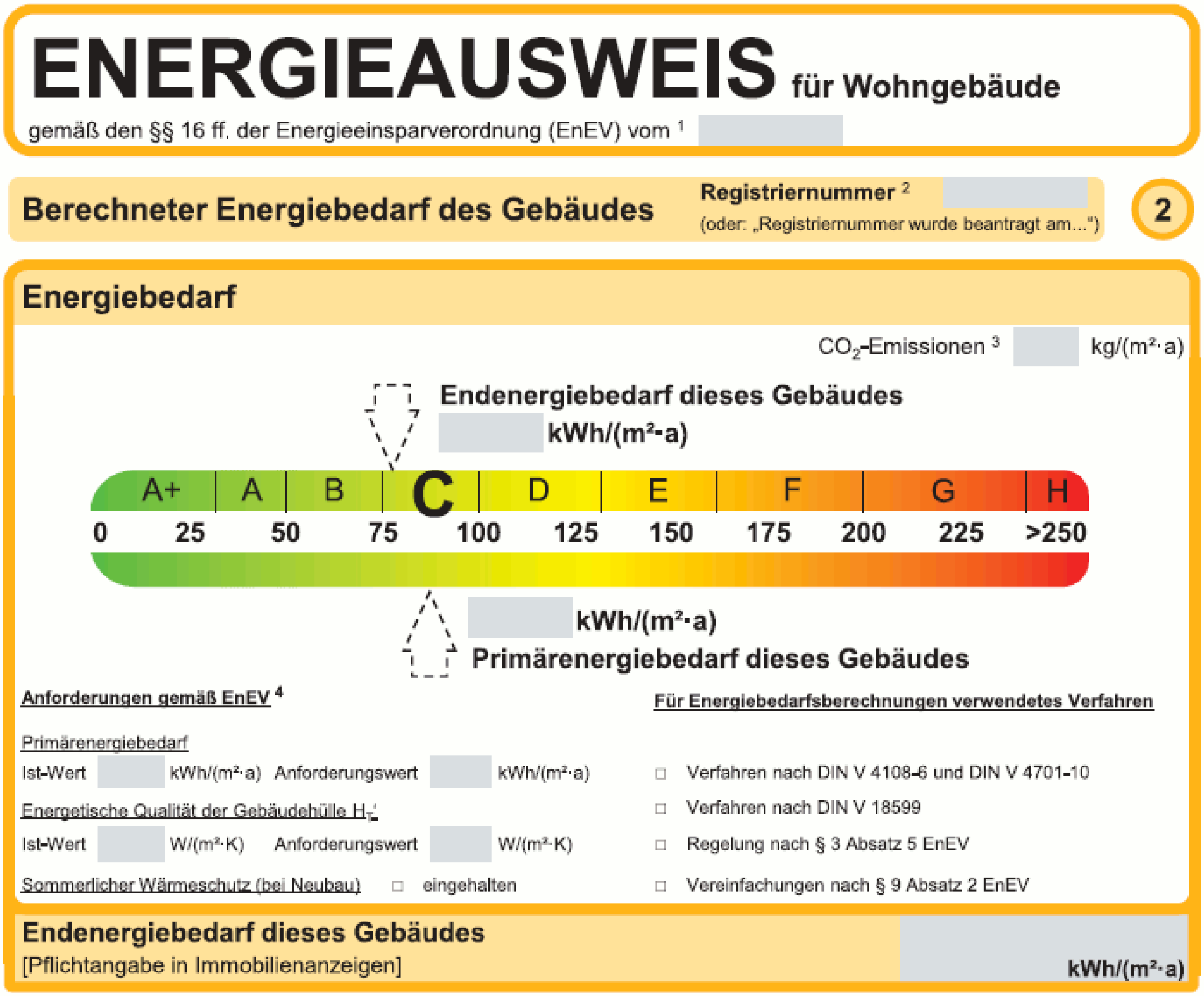
Regarding the demand certificate, the characteristic metrics pertaining to energy demand are derived based on engineering computations. This assessment draws upon technical aspects of the building's structure and heating systems within a standardized framework that includes climate data, user behavior norms, and room temperatures. In case characteristics of the building components are not available from the building documentation, typical values are derived based on year of construction, building type, apartment count, total living space and visual inspection. Consequently, the computed values remain detached from the specific heating and living practices of individual tenants. Nevertheless, it is crucial to emphasize that the accuracy and thoroughness with which the certifying agent gathers data play a pivotal role in shaping these computed values.

Conversely, the consumption certificate necessitates access to consumption data spanning the immediately preceding three years. This data is typically derived from heating cost invoices or similar consumption measurements. Subsequently, characteristic energy consumption values are extrapolated for the entire building. To enhance comparability, these values are subsequently standardized to reflect a nationwide average across Germany, incorporating climatic factors. This standardization process mitigates potential biases arising from climatic variations, thereby ensuring equitable assessments of buildings even in the presence of particularly severe winters. Notably, this approach simplifies the data collection process, making it easier and less prone to errors. It should be noted, however, that the resulting characteristic values are now significantly influenced by the heating and ventilation behavior of the former tenants.

The final energy demand or consumption obtained as result of these computations and the greenhouse gas emissions based on the primary energy demand/consumption are entered in the certificate. Since 2014, the efficiency rating achieved has also been indicated by a color scale from A+ (green) to H (red). An example of a demand certificate is shown in Figure 7.

There are a few rules regarding the choice of the certificate. Buildings with less than five residential units, for which the building application was submitted before November 1, 1977, and which do not meet the requirements of the 1st Heat Insulation Ordinance, must have a demand certificate. In addition, a consumption certificate can only be issued if the heating cost and consumption statements from three consecutive years are complete. The end of this billing period may not be more than 18 months ago. Demand certificates, on the other hand, can be issued for any building and are also used for new buildings as a rule.

The effectiveness of mandatory and voluntary EPCs around the world has been investigated in different studies – with mixed results. EPCs were found to have little impacts on purchase decisions or price negotiations (Watts et al., 2011). Additionally, the design of certain EPCs does not help in understanding the financial implications of energy efficiency (Amecke, 2012), which further limits their effectiveness. On the other hand, Brounen and Kok (2011) show that the EPC creates transparency with regard to the energy efficiency of homes and that consumers include this information in the price of their future homes. Furthermore, the ratings given in EPCs are found to have a positive effect on purchase prices and rents, which is known as the so-called green premium for efficient dwellings (cf. Lyons et al., 2013; Fuerst et al., 2015; Cajias et al., 2019).



ENERGIEAUSWEIS für Wohngebäude

gemäß den §§ 16 ff. der Energieeinsparverordnung (EnEV) vom [1]

Berechneter Energiebedarf des Gebäudes

Registriernummer [2]

(oder: „Registriernummer wurde beantragt am...")

2

Energiebedarf

CO_2-Emissionen [3] kg/(m^2·a)

Endenergiebedarf dieses Gebäudes

kWh/(m^2-a)

A+ A B C D E F G H

0 25 50 75 100 125 150 175 200 225 >250

kWh/(m^2·a)

Primärenergiebedarf dieses Gebäudes

Anforderungen gemäß EnEV [4]

Primärenergiebedarf

Ist-Wert kWh/(m^2·a) Anforderungswert kWh/(m^2·a)

Energetische Qualität der Gebäudehülle H_T'

Ist-Wert W/(m^2·K) Anforderungswert W/(m^2·K)

Sommerlicher Wärmeschutz (bei Neubau) ☐ eingehalten

Für Energiebedarfsberechnungen verwendetes Verfahren

☐ Verfahren nach DIN V 4108-6 und DIN V 4701-10

☐ Verfahren nach DIN V 18599

☐ Regelung nach § 3 Absatz 5 EnEV

☐ Vereinfachungen nach § 9 Absatz 2 EnEV

Endenergiebedarf dieses Gebäudes

[Pflichtangabe in Immobilienanzeigen]

kWh/(m^2·a)

Source: BMVBS, 2014.

Figure 7 Example of an energy performance certificate according to EnEV 2014.

1.5 Solar photovoltaic systems on residential buildings in Germany

With the introduction of the Renewable Energy Sources Act (EEG) in April 2000, the installation of PV systems in Germany started to receive general financial support. From 2007 onwards, annual additions picked up speed; in the years 2010 to 2012, the addition of annually installed capacity of photovoltaic systems in Germany reached a record high – not least due to attractive financial incentives and decreasing prices for installations. After 2012, there was a significant slump and the addition of new capacity in 2013 halved compared to 2012 and continued to fall until 2015. Since 2016, more and more PV systems have been installed annually again; in 2019, the capacity additions again exceeded the level of 2009. (cf. e.g., Statista, 2023d)

As of 2023, Germany has about 2.6 million PV systems with a total installed capacity of 70.6 gigawatts – including both (typically) small-scale rooftop systems and larger ground-mounted installations. In 2022, PV systems in Germany generated about 54.3 million megawatt-hours of electricity, which is an increase of 20 % compared to the previous year. The share of electricity generated by PV also rose to a new high of 11 % of the total electricity fed into a grid that year. (Statistisches Bundesamt, 2023d)

Typical residential rooftop PV systems with an installed capacity of up to 10 kWp[15] account for about 18 % of the total installed capacity (as of 2023). The progression of the net nominal power of these small installations is shown in Figure 8. There is also a sharp increase in installations after 2007; a leveling off in new installations occurred between 2013 and 2017. Since 2018, the annual newly installed capacity has been rising strongly again.

As indicated above, the legal framework conditions for the installation of PV systems and also for remuneration are specified in the EEG, which was fundamentally reformed in 2023. This is associated with some advantages for PV system operators. For example, systems up to 25 kWp are now allowed to feed the maximum electricity production into the public grid (previously, feed-in was capped at 70 %). In addition, new systems commissioned after July 30, 2022, will receive a higher feed-in tariff depending on both the size of the system and the type of feed-in (full feed-in vs. excess feed-in). For a typical residential rooftop system up to 10 kWp, the feed-in tariff is 8.2 cents per kWh for excess feed-in and 12 cents per kWh if all the electricity

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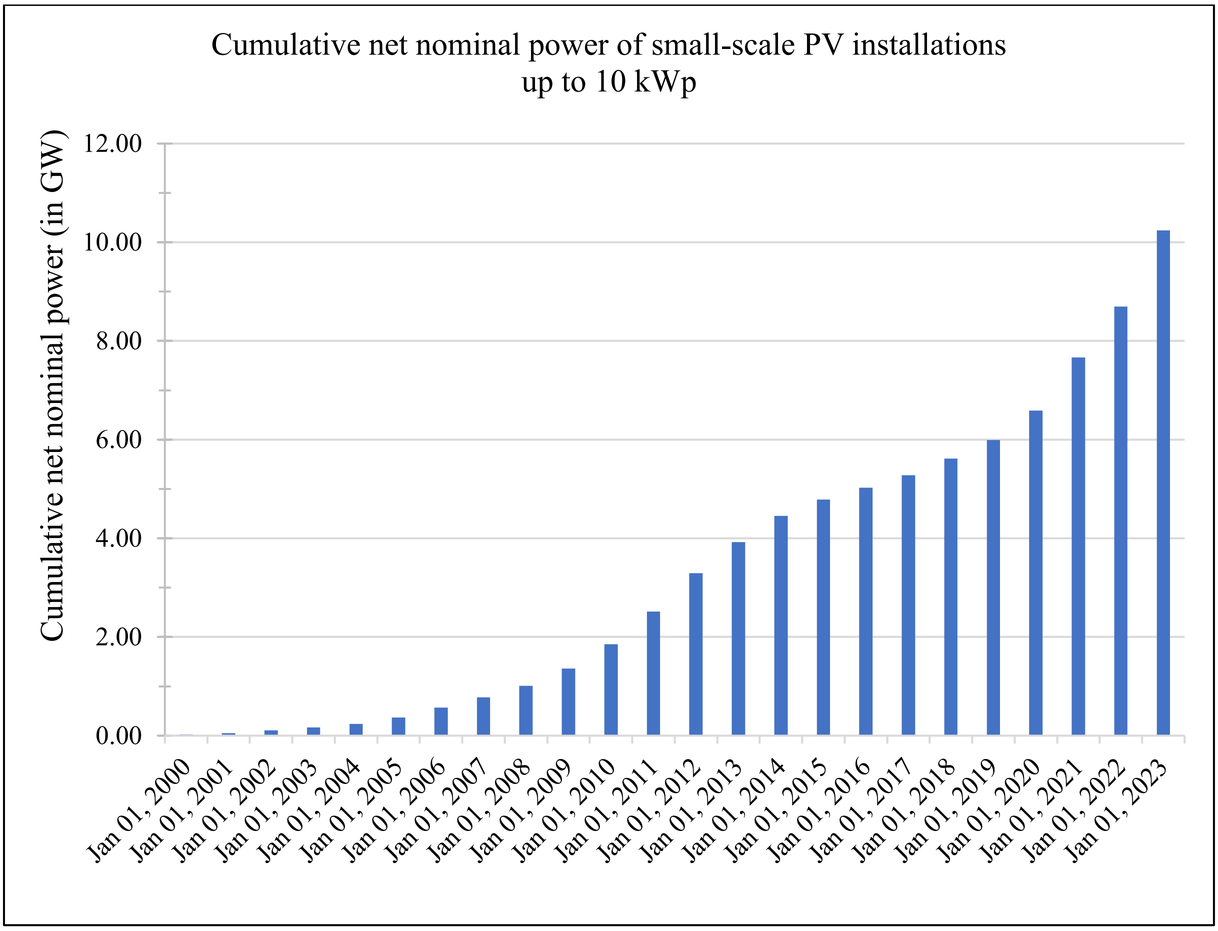
[15] In Germany, most PV systems installed on a single-family house have an installed capacity of 4 to 10 kWp (cf. E.ON, 2023).

generated is fed into the grid (§48(2) EEG, 2023). These support payments apply to newly commissioned solar plants and are guaranteed for twenty years.



Source: Own calculation and illustration based on the MaStR (BNetzA, 2023).

Figure 8 Cumulative net nominal power of small-scale PV installations in Germany.

In addition to the feed-in tariffs, the EEG also stipulates a tenant electricity support payment (§§21, 48a EEG, 2023). This is applied if the PV system is installed on a multi-family house in which several parties live for rent. The so-called tenant electricity model allows the property owner to directly sell the electricity generated by the PV system to the tenants. Until 2017, tenant electricity from PV systems was generally not profitable for landlords and landladies, despite the advantages in terms of charges and levies, partly because tenant electricity models incur significant costs for billing, sales and metering. The tenant electricity support payment is now expected to make tenant electricity more economically attractive (cf. BMWk, 2023b).

Regarding funding and subsidy schemes for PV installations, the KfW offers subsidy programs similar to the funding for energy refurbishments (cf. Chapter 1.3). On the one hand, there are loans with reduced interest rates for private households, companies and public institutions (KfW, 2023c). On the other hand, from September 26, 2023, there is also a new program for owners of owner-occupied residential buildings that subsidizes the installation of PV systems with up to €10,600, provided that an electric car is already registered in the household (KfW, 2023b).

1.6 Research questions

In view of the ambitious goals of climate neutrality in the building sector by 2045 and the resulting need for increased investments in higher energy efficiency and renewable energies, this dissertation contributes to answering key research questions of both methodological and substantive nature.

Given that markets for dwellings are always “local” markets in the sense that demand and supply are matched considering the location of the dwellings, an investigation of such markets using high-resolution data is of great interest. In the past, often challenges due to data availability limitations arose, which is why many studies rely on larger-scale regional data. Yet if high-resolution data can be leveraged, this enables both richer analyses and the identification of location-dependent effects, which in turn supports the development of more precisely targeted policy interventions. Therefore, the studies in this dissertation are based on small-scale grid data. However, this requires the adoption of special computational methods to fully exploit the potential of the data and analyze regional effects. Hence the dissertation addresses the following research question:

> **[RQ 1]** *How can small-scale data be used to examine spatial effects regarding residential building energy use and production and what are viable approaches for incorporating spatial effects into corresponding analyses of housing markets?*

The second question to be addressed points at different estimation methods to capture price effects of energy efficiency:

> **[RQ 2]** *How can the impact of the building’s energy performance on sale prices and rents be modelled adequately?*

As research question number two may already suggest, the type of real estate market plays a major role in the investigation of energy efficiency effects on real estate values. A third research question thus addresses the diversity of real estate markets:

> **[RQ 3]** *To what extent is energy efficiency valued in the markets for residential dwellings and are there differences between the sales and the rental markets?*

Furthermore, in light of the recent regulations aiming at the phase out of carbon-intensive heating systems, the effect of different heating systems on prices and rents is also of interest. Taking a somewhat broader perspective, the fourth research question thus refers to other drivers that may affect the perceived energetic quality of a dwelling and also the adoption of rooftop solar photovoltaic systems:

> **[RQ 4]** *What other factors affect the valuation of the energy performance in real estate sales and rental markets? Are there similar factors influencing the adoption of residential photovoltaic systems?*

Finally, the collection of studies that have been included in this dissertation can be used to provide advice on policy instruments suitable to support the realization of a carbon-neutral building stock. This leads to the fifth and final research question:

> **[RQ 5]** *What policy implications can be derived from the different empirical studies?*

1.7 Thesis structure and overview

The body of this cumulative dissertation is organized into four chapters that comprise individual research papers addressing the research questions raised above. In the following, Chapters 2 – 5 are briefly described in terms of their context, content and methodological approach. Each chapter provides its own references, listed at the end of the chapter. Chapter 6 concludes and discusses the obtained results to answer the research questions raised in the previous section.

Chapter 2:

> ***Estimating the Impact of Energy Efficiency on Housing Prices in Germany: Does Regional Disparity matter?***
>
> *By Lisa Taruttis and Christoph Weber*
>
> *Published in: Energy Economics Vol. 105 (2022), 105750.*
>
> *DOI : https://doi.org/10.1016/j.eneco.2021.105750*

This paper investigates whether energy efficiency improvements are reflected in the property values of German single-family homes, thus identifying potential monetary benefits for homeowners. The research draws on a repeated cross-sectional dataset of over 420,000 individual housing observations at a 1 km^2-grid level from 2014 to 2018 and thereby distinguishes between urban and rural regions to explore potential heterogeneity in effects.

First, a hedonic regression model in its common semi-logarithmic form is applied to examine energy efficiency effects on single-family house prices. Second, a non-parametric analysis is conducted to provide energy efficiency premiums for different levels of energy efficiency. Third, a nonlinear specification representing a total-cost-of-ownership perspective is used to calculate an energy efficiency value-to-cost ratio for comparing the increase in housing values with the initial investment costs and future energy cost savings. Lastly, the impact of housing shortage and purchasing power per capita on energy efficiency premiums (EEPs) is analyzed.

The study finds a positive relationship between energy efficiency and housing prices. A 100 kWh/m^{2}a increase in energy efficiency leads to an average price increase of 6.9 %. However, regional disparities exist, with larger cities showing weaker effects compared to other urban areas while significantly stronger impacts are observed in rural regions. Housing shortage and higher purchasing power per capita contribute to lower energy efficiency premiums in certain areas. The results also indicate that the energy efficiency effect on housing prices has become increasingly important in rural regions over time.

Chapter 3:

Inefficient Markets for Energy Efficiency? – The Efficiency Premium Puzzle in the German Rental Housing Market

By Lisa Sieger and Christoph Weber

Published in: Energy Policy Vol. 183 (2023), 113819.

DOI: https://doi.org/10.1016/j.enpol.2023.113819

Following the third methodological approach of Chapter 2 by applying a nonlinear hedonic pricing model to compare rental premiums with estimated energy cost savings, the paper contained in Chapter 3 investigates energy-efficiency effects in the residential rental market in Germany. Employing a cross-sectional dataset from 2014 to 2020, comprising about 845,000 apartment listings for rent in North Rhine-Westphalia, Germany, the study aims to examine whether energy efficiency is adequately reflected in basic rents (i.e., the rental price to be paid to the landlord without utility and other auxiliary costs) and whether there are premiums for different heating technologies.

The study finds that energy-efficient apartments obtain a premium in the rental market; however, the premium is rather small. The expected energy cost savings based on the German energy performance certificate (EPC) exceed the observed rental premiums for energy efficiency by a factor of three to seven, depending on the type of EPC – this is referred to as the *energy efficiency valuation gap*. Additionally, apartments with outdated heating technologies are rented at a discount of up to 9.2 % compared to those with efficient heating systems. Replacing such technologies with greener alternatives can lead to increased attractiveness and higher rental income for landlords. Finally, different mechanisms explaining the energy efficiency valuation gap are discussed, taking both the supply and demand side into account.

Chapter 4:

> ***Investigating Inefficiencies in the German Rental Housing Market: The Impact of Disclosing Total Costs on Energy Efficiency Appreciation***
>
> *By Lisa Sieger*
>
> *HEMF Working Paper No. 05/2023, Essen 2023.*
>
> *Revised version published in: Energy & Buildings Vol. 312 (2024), 114183*
>
> *DOI: https://doi.org/10.1016/j.enbuild.2024.114183*

In the qualitative discussion of Chapter 3, information bias is mentioned as one possible reason for market inefficiencies. Chapter 4 empirically checks on this assumption by exploring the market (in)efficiency regarding energy efficiency in the German rental housing market. The study considers the split incentives between landlords and tenants and evaluates the potential for underinvestment in energy refurbishments. Drawing on a total of 3,900,000 observations from 2014 to 2021, a hedonic pricing model combined with a total-cost-of-use perspective is estimated to evaluate market inefficiencies related to energy efficiency in the rental housing market. Further, applying a moderation analysis, effects of information disclosure on energy efficiency premiums are investigated, focusing on advertisements that provide varying levels of information, including basic rents, warm rents, and explicit heating costs.

Results point to existing inefficiencies in the market for energy efficiency in the German rental housing sector. Energy cost savings resulting from energy improvements exceed the increases in basic rent, leading to lower warm rents. However, nearly efficient markets are observed in high-income neighborhoods and for already energy-efficient apartments. Moreover, the research highlights that providing warm rent information alone does not significantly impact tenants' appreciation of energy efficiency. However, disclosing explicit heating costs in addition to warm rents increases the willingness-to-pay for more efficient apartments by approximately 50 %. The effects of information disclosure further vary across different types of EPCs.

Chapter 5:

Disentangling Small-Scale Solar Photovoltaic Adoption: A Spatial Analysis of Decision Factors and Localized Interactions in Germany

By Tobias Stein, Lisa Sieger and Christoph Weber

HEMF Working Paper No. 06/2023, Essen 2023.

Link: https://ssrn.com/abstract=4605917

While Chapters 2 to 4 mainly focus on the valuation of energy efficiency in the housing markets, Chapter 5 contributes to the investigation of investments in renewable energy technologies. It examines the spatial patterns and determinants driving the adoption of small-scale solar photovoltaic (PV) systems at the local level in Germany. Drawing on a unique dataset of installed PV systems in Germany for 2020 together with micro-level sociodemographic and economic data on a 1 km²-grid level, this study employs spatial econometric models to assess spatial dependence and interactions at a highly localized level.

Results show a robust positive correlation between the number of larger PV systems (up to 100 kWp) and the adoption of smaller residential PV installations (up to 10 kWp), emphasizing the importance of considering larger systems in adoption estimations. Furthermore, positive impacts are found for purchasing power, higher shares of one- and two-family homes as well as solar irradiation while negative impacts of the unemployment rate and a high household density on the adoption of small-scale PV systems underline previous findings in the literature.

The results also highlight the relevance of choosing appropriate neighborhood sizes when investigating adoption dynamics. As neighborhood size increases, spatial autoregressive effects become more pronounced. However, the influence of spillover effects diminishes with larger distances, peaking at a radius of 8 km, emphasizing the importance of high-resolution spatial data to avoid underestimating such effects.

CHAPTER TWO

Estimating the Impact of Energy Efficiency on Housing Prices in Germany: Does Regional Disparity Matter?

by Lisa Taruttis and Christoph Weber

This article was published in Energy Economics, Vol. 105, Taruttis, Lisa, and Christoph Weber, Estimating the Impact of Energy Efficiency on Housing Prices in Germany: Does Regional Disparity Matter?, 105750, Copyright Elsevier (2022).

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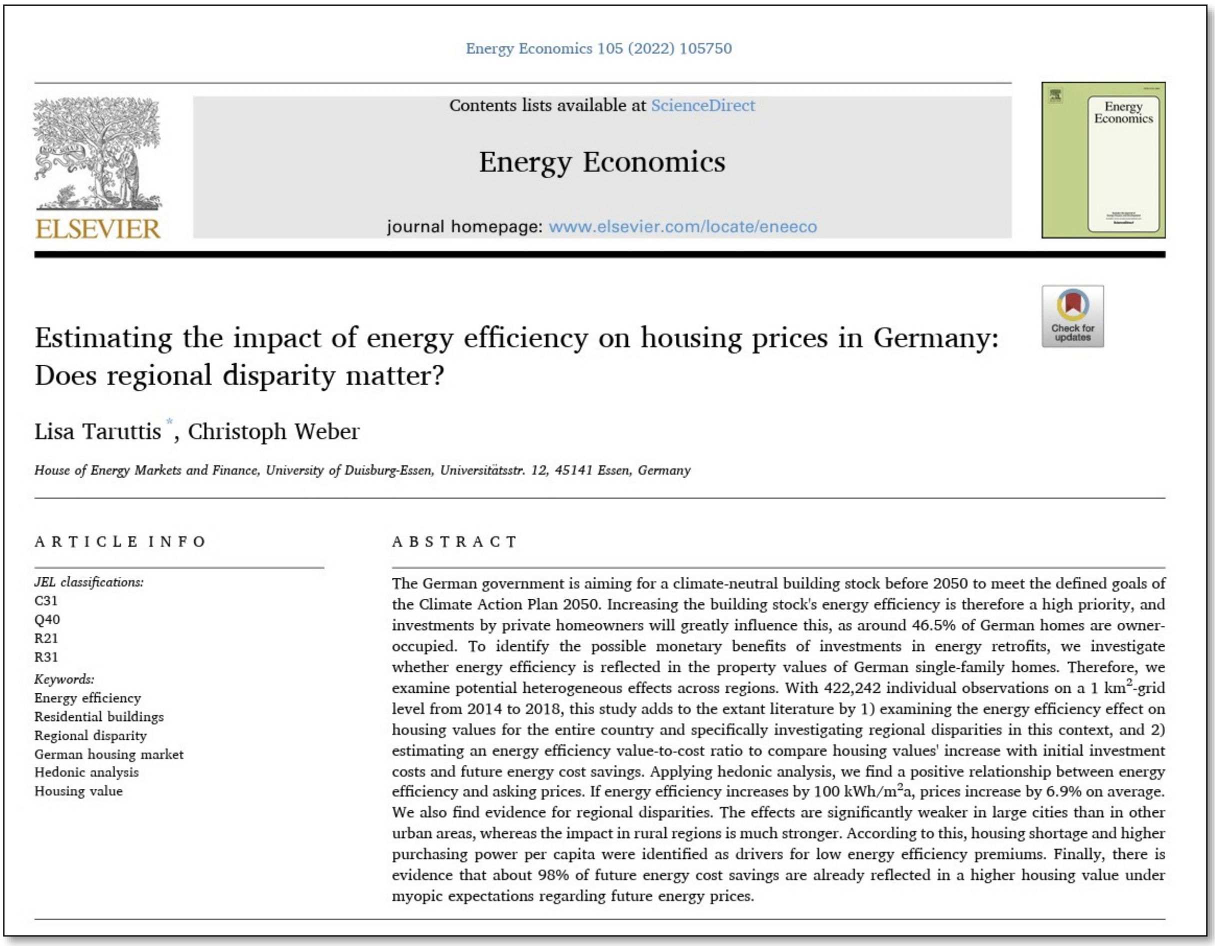

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Estimating the impact of energy efficiency on housing prices in Germany: Does regional disparity matter?

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ARTICLE INFO

JEL classifications:
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R31

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German housing market
Hedonic analysis
Housing value

ABSTRACT

The German government is aiming for a climate-neutral building stock before 2050 to meet the defined goals of the Climate Action Plan 2050. Increasing the building stock's energy efficiency is therefore a high priority, and investments by private homeowners will greatly influence this, as around 46.5% of German homes are owner-occupied. To identify the possible monetary benefits of investments in energy retrofits, we investigate whether energy efficiency is reflected in the property values of German single-family homes. Therefore, we examine potential heterogeneous effects across regions. With 422,242 individual observations on a 1 km^2-grid level from 2014 to 2018, this study adds to the extant literature by 1) examining the energy efficiency effect on housing values for the entire country and specifically investigating regional disparities in this context, and 2) estimating an energy efficiency value-to-cost ratio to compare housing values' increase with initial investment costs and future energy cost savings. Applying hedonic analysis, we find a positive relationship between energy efficiency and asking prices. If energy efficiency increases by 100 kWh/m^2a, prices increase by 6.9% on average. We also find evidence for regional disparities. The effects are significantly weaker in large cities than in other urban areas, whereas the impact in rural regions is much stronger. According to this, housing shortage and higher purchasing power per capita were identified as drivers for low energy efficiency premiums. Finally, there is evidence that about 98% of future energy cost savings are already reflected in a higher housing value under myopic expectations regarding future energy prices.

Abstract

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Keywords: Energy efficiency, residential buildings, regional disparity, German housing market, hedonic analysis, housing value

JEL Classifications: C31, Q40, R21, R31

1 Introduction

In Germany, about 35 % of final energy consumption and about one-third of CO_2 emissions are related to the building sector[1] (Federal Ministry for Economic Affairs and Energy, 2015). Thus, dwelling stock's decarbonization is the key to meeting the goals implemented in the Climate Action Plan 2050 (Federal Ministry for the Environment, Nature Conservation, Building, and Nuclear Safety, 2016). Realizing this goal requires doubling the energy refurbishment rate from about 1 % to 2 % yearly, as most of the dwelling stock that will exist in 2050 is already built. Investments by private homeowners will greatly influence the decarbonization process, as around 46.5% of all dwellings are owner-occupied (Destatis, 2019).

Especially for owners of single-family homes, investing in energy-efficient retrofits may nevertheless seem too costly compared to their monetary benefits. Example calculations show payback periods of up to 22 years, with a mean payback period clearly below the typical service life of most components (Holm et al., 2015). Also, there is evidence that investments in energy efficiency are improperly capitalized into housing prices (cf. Olaussen et al., 2019; Olaussen et al., 2017), which may also discourage homeowners from investing in retrofits.

The "German Energy Act for Buildings" (GEG, 2019) was passed by the German parliament in June 2020 to increase renovation rates and accelerate the decarbonization process. The new bill is intended to be less bureaucratic, more balanced, and easier to understand, in that it unifies the national energy standards for buildings (WEKA Redaktion, 2020) by combining the previous Energy Savings Act (EnEG, 2013), the Energy Saving Regulation (EnEV, 2015), and the Renewable Energy Heat Act (EEWärmeG, 2008). In November 2019, the German Federal Government also approved the "Bundesförderung für effiziente Gebäude" —a federal funding for efficient buildings (Klimakabinett der Bundesregierung, 2019). With this scheme, about 20 % of the investment costs for energy-efficient renovations are tax-deductible over three years so that the taxable income can be reduced by about €8,000 for investment costs of about €40,000.

While savings due to less energy consumption are relatively predictable, comprehensive evidence on returns on energy-efficiency investments for the German real estate market is lacking. Cajias and Piazolo (2013) found a 0.015 % increase in a building's total return if energy consumption decreases by 1 % using 2,630 observations obtained from the German Investment Property Database (IPD). Kholodilin et al. (2017) compared energy efficiency capitalization in

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[1] depending on delimitation.

selling prices and rents for the Berlin apartment market and found positive effects. Also, for the German rental market, Cajias et al. (2019) found that energy-efficient rental units are rented at a premium. However, comprehensive evidence of the returns on investments in the energy efficiency of single-family homes across Germany remains missing.

To identify potential monetary benefits for private homeowners of single-family homes who invest in the improved energy efficiency of their buildings, we investigate whether energy efficiency is reflected in the property value of single-family homes across Germany. We apply hedonic regression to a repeated cross-sectional dataset containing both individual housing observations and socioeconomic data at a 1 km²-grid level from 2014 to 2018. Furthermore, we examine potential heterogeneous effects across urban and rural regions. Additionally, we compare potential monetary benefits with initial investment costs and annual energy cost savings using a tailored non-linear least squares estimator.

This study makes two major contributions to the extant literature on investments' returns in energy-efficient retrofits for owner-occupied dwellings. First, we examine the energy efficiency effect on housing values for the entire country on a smaller spatial scale and specifically investigate regional disparities here. Second, we estimate an energy efficiency value-to-cost ratio by comparing housing value increases to the expected investment costs for energy efficiency improvements. Unlike most studies that use energy efficiency ratings (on a scale from A+ to H) obtained from dwellings' Energy Performance Certificates (EPCs) as a measure of efficiency, we use the final energy consumption in kWh/m²a to provide more granular results. Finally, we contribute to the literature by providing energy efficiency premiums (EEPs) for different levels of energy efficiency by undertaking a non-parametric analysis.

The remainder of this paper is organized as follows. Section 2 overviews previous research in this field at the intersection of energy, housing, and regional economics. Section 3 outlines the econometrical approach, followed by Section 4, which describes the datasets used. Section 5 presents the results, before Section 6 gives a discussion and concludes.

2 Related Literature

Dinan and Miranowski (1989) were among the pioneers who investigated whether fuel savings resulting from energy-efficient retrofits are capitalized into housing prices. Using a hedonic price model for the Des Moines, Iowa housing market, they found evidence for the positive effects of energy efficiency on real estate values in this area. In a European context, Brounen and Kok (2011) were the earliest to report evidence of a price premium for green-labeled dwellings in residential markets in the Netherlands. Furthermore, Kok and Jennen (2012) evaluated the financial implications of energy efficiency in the Dutch market for commercial real estate and found positive effects on rents for A-, B-, or C-labeled buildings.

Various studies for several countries followed, including Deng et al. (2012) investigating the “Green Mark” program in Singapore, Aroul and Hansz (2012) examining the housing market in Frisco and McKinney in Texas, Kahn and Kok (2014) evaluating the effects in the Californian housing market, and Fuerst and Shimizu (2016) analyzing housing data for the Tokyo metropolitan area in Japan. All these studies focused on the price effects of different eco-labels, both mandatory and voluntary. They all found that green buildings were sold at a premium compared to non-labeled homes.

In contrast to these studies, Feige et al. (2013) did not focus on the price effect of eco-labels but on the effects of individual sustainability attributes of residential buildings for the Swiss housing market. They found that the environmental performance of buildings had significant positive price effects. Fuerst and Warren-Myers (2018) combined research on eco-labels and sustainable building characteristics for the housing and rental market in the Australian Capital Territory, where energy efficiency ratings are mandatory. Their analysis confirmed that both eco-labels and dwelling features had significant positive effects on transaction prices and rents.

EPCs’ impact on transaction prices for several EU countries, including Austria, Belgium, and France, was examined in a study mandated by the European Commission (Lyons et al., 2013). Numerous studies for different European countries have also followed, e.g., Cajias and Piazolo (2013) for Germany, Hyland et al. (2013) and Stanley et al. (2016) for the Irish real estate and rental market, Högberg (2013) and Cerin et al. (2014) for single-family houses in Sweden, Fuerst et al. (2015) for sale prices of residential properties in England, and Fuerst et al. (2016a; 2016b) for residential markets in Wales and Finland. Furthermore, Jensen et al. (2016) examined the Danish housing market with a focus on effects related to the coming into force of the EU requirement to display EPCs, while Chegut et al. (2016) focused on green premiums in affordable housing in the Dutch housing market. More recent studies were also conducted by Khazal and Sønstebø (2020) for the Norwegian rental market and Civel (2020) for the French housing market.

Other studies also investigated the impact of energy efficiency on housing values in southern European countries, for example, Ramos et al. (2015) for Portugal, and De Ayala et al. (2016) and Marmolejo-Duarte and Chen (2019) for Spain. Moreover, Taltavull et al. (2017) contributed to Eastern Europe, as they focused on the apartment market in Bucharest. All the above-mentioned European studies found a positive impact of energy efficiency on real estate prices of about 2 % to 10 % and about 6.5 % for rental markets.

In contrast to most studies, Murphy (2014), Olaussen et al. (2019; 2017), and Fregonara et al. (2017) only found small or negligible effects of energy labels on the prices of dwellings. However, Olaussen et al. (2017) suggested that energy labels are correlated with the expected energy consumption, and that positive price effects are therefore driven by the dwellings' energy performance and not by the energy label itself. Wahlström (2016) not only found positive effects of energy consumption on transaction prices, but also a strong willingness to pay for housing features that reduce energy consumption.

Unlike many European countries, the German residential market has a high share of rented accommodations. Against this background, Kholodilin et al. (2017) explored the Berlin real estate market and examined the effects of sales and rents. Following most studies, they found that energy efficiency is well capitalized into sale prices. In the rental sector, however, the future value of energy cost savings is 2.5 times above tenants' implicit willingness to pay. A more recent study by Cajias et al. (2019) investigated the energy efficiency effect on rental values using a sample of over one million observations across 403 local markets in Germany from 2013 to 2017. Furthermore, the study examined the link between energy-efficiency ratings and the time-on-market. Results suggest that energy-efficient apartments are rented at a premium, and that efficient dwellings are more liquid due to shorter marketing periods compared to their inefficient counterparts. The study is limited to newly built apartments and recently renovated flats that are advertised as "like new."

Nevertheless, the ownership rate in Germany remains around 46.5 %, so energy-efficiency impacts on real estate values are particularly imperative to homeowners. We believe that no study has recently comprehensively examined these effects across Germany. Our study therefore aims to fill this gap. Moreover, we provide a detailed comparison of the increase in value with the observed costs for energy-efficiency improvements using a novel nonlinear regression model specification. To further address the problem of low refurbishment rates, we focus on existing single-family homes under all conditions listed for sale.

3 Econometric Approach

Subsequently, we specify two econometric approaches to investigate the EEP size. First, we design a conventional hedonic pricing model that is extended for an in-depth analysis of regional disparities. In the second approach, we develop a novel, nonlinear model that agrees with a total-cost-of-ownership (TCO) framework. It enables us to compare our findings to engineering-economic estimates of cost savings and investment costs for energy-efficiency improvements.

3.1 Hedonic Pricing Model

To identify energy efficiency effects on prices for German single-family homes, we estimate a hedonic pricing model in the sense of Lancaster (1966), Rosen (1974), and Brown and Rosen (1982) to control for price differences caused by quality differences other than energy consumption. We use a common semi-logarithmic specification, where the logarithmized price per square meter living space of dwelling *i* in neighborhood *k* and district *d* at time *t* is described by the following equation:

$$lnPRICE_{ikdt} = \alpha + \beta ENERGY_i + \gamma \boldsymbol{D}_i + \delta \boldsymbol{N}_{kt} + \mu_t + \tau_d + \nu_{dt} + \varepsilon_{ikdt} \qquad (1)$$

Our main variable of interest—$ENERGY_i$—describes the specific energy consumption for heating of dwelling i, measured in kWh/m²a. Vector $\boldsymbol{D}_i$ contains several hedonic characteristics, such as living space[2], lot size[3], year of construction[4], the type of heating system, and numbers of rooms and floors. Furthermore, different factor variables are included, which indicate condition and quality of the property, and a dummy that indicates whether dwelling i was renovated after the year 2000. $\boldsymbol{N}_{kt}$ describes the object's neighborhood structure based on 1 km²-grid cells. The vector comprises various socio-economic characteristics, including population density and purchasing power per capita, both logarithmized, and unemployment rate and proportion of foreigners. It also contains information on the predominant building type within the neighborhood. Finally, μ_t are quarterly year dummies for Q3/2014 through Q4/2018 (with reference group Q2/2014), τ_d are regional fixed effects at district (NUTS3[5]) level, ν_{dt} are combined fixed effects for time and region, and ε_{ikdt} is the error term of the regression. We report cluster-robust standard errors to correct for spatial and temporal correlation between subdivisions (Cameron and Miller, 2015).

In the first step, we estimate the above-developed specification, checking for the fixed effects' relevance by contrasting estimates, including the full specification with a specification that

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[2] With dummy variables in 10 m² steps, starting at 55m² to capture non-linear effects.

[3] In 50 m² steps, starting at 40 m².

[4] In 10-year steps from 1850 to 1949, and 5-year steps from 1950 onwards.

[5] The territory of the European Union is divided into hierarchical levels using the geographical system NUTS (Nomenclature des Unités territoriales statistiques). NUTS3 regions typically have a population of 150,000 to 800,000 inhabitants, which refers to districts known as Kreise or kreisfreie Städte in Germany.

includes only the single effects μ_t and τ_d and, furthermore, a simple model without any fixed effects. We expect the coefficients for $ENERGY_i$ to be negative as we include energy consumption in our regression. Thus, for energy efficiency, higher consumption is associated with less efficient buildings. Due to the semi-logarithmic specification, coefficients for $ENERGY_i$ can be interpreted as semi-elasticities and therefore give us the monetary surplus in approximately $100 \cdot |\beta|\%$ for a one-unit decrease in energy consumption.

In a second step, we estimate the regression as described by Eq. (1) using ordinary least squares and interact our main variable of interest with a variable *DTYPE* that describes the district type. The categorical variable *DTYPE* captures regional disparities so that we can analyze the moderating effect of region types on the EEP. The variable *DTYPE* describes the effects for independent large cities (kreisfreie Großstädte), densely populated rural areas and sparsely populated rural areas in contrast to urban areas (städtische Kreise). Hence, we add the term $\beta(ENERGY_i \times DTYPE_i)$ to the specification of Eq. (1).

The *DTYPE* definition is based on an indicator for different regional types according to their settlement structure at the NUTS3 level (INKAR), provided by the Federal Institute for Research on Building, Urban Affairs, and Spatial Development (2019).

Figure A 1 shows the spatial distribution of these district types. ANOVA testing indicates that statistically significant differences between the groups are present ($F = 825.65$, $p < 0.001$), and we hence test the hypothesis that disparities across regions exist regarding energy efficiency influence on single-family house prices.

In the third step, to further understand why the effects differ across regions, we save demographic information for a second-stage regression, where in the first stage, we estimate the energy efficiency premium for each of the 401 German NUTS3 regions by interacting our variable of interest with τ_d (see Eq. (2)). *EEP_d* is then generated by computing[6] $1 - exp(\beta_d)$. We use this newly constructed variable as dependent variable and add neighborhood demographics as given by Eq. (3) to analyze variations across space. *lnPOPULATION* is the logarithmized population density, *lnPURCHPOWER* describes the logarithmized purchasing power per capita, *UER* is the unemployment rate, and *FOREIGN* describes households' share with foreign household head. We further focus on two predominant building types: *TYPE1*

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[6] The coefficients β_d can be interpreted as semi-elasticities. To get rid of this, we transformed the estimates by computing exp(β_d)-1. Further, as described earlier, our coefficient β_d is assumed to be negative, as we captured the effect of energy consumption on house prices instead of the effect of energy efficiency. However, a premium is usually associated with positive values. We therefore multiplied by [-1]. Overall, we got [-1]*[exp(β_d)-1], which can be truncated to 1-exp(β_d).

refers to the share of 1–2 family homes in homogenous street sections in district d and $TYPE7$ to the proportion of industrial and commercial buildings.

$$lnPRICE_{idt} = \alpha + \beta_d(ENERGY_i \times \tau_d) + \gamma\boldsymbol{D}_i + \mu_t + \varepsilon_{idt} \tag{2}$$

$$\begin{aligned} EEP_d = \varphi_0 + \varphi_1 lnPOPULATION_d + \varphi_2 lnPURCHPOWER_d + \varphi_3 UER_d \\ + \varphi_4 FOREIGN_d + \varphi_5 TYPE1_d + \varphi_6 TYPE7_d + \varepsilon_d \end{aligned} \tag{3}$$

Finally, we run various subsample regressions to check our results' robustness, e.g., by controlling for housing shortage. To do so, we interact[7] our variable of interest with housing supply, estimated as advertisements per 1,000 residents. We further perform a non-parametric analysis, as given by Eq. (4), to estimate an EEP for different levels of energy efficiency. In this specification, vector $\boldsymbol{E}_{b(i)}$ includes a set of variables for different levels of energy consumption b to allow for a more flexible functional form. These variables are generated by (1) estimating 1st to 99th percentiles of energy consumption and (2) calculating an optimal bandwidth of energy consumption using a kernel-density estimator[8] and classifying observations in the corresponding bins.

$$lnPRICE_{ikdt} = \alpha + \beta_k\boldsymbol{E}_{b(i)} + \gamma\boldsymbol{D}_i + \delta\boldsymbol{N}_{kt} + \mu_t + \tau_d + \nu_{dt} + \varepsilon_{ikdt} \tag{4}$$

3.2 Total cost-of-ownership-based approach

To compare the increase in housing value—due to improved energy efficiency—with both cost savings and investment costs needed for energy refurbishments, we additionally estimate a second model, as given by equations (5) and (6), using a non-linear least squares estimator. We also use robust standard errors to control for heteroskedasticity.

This model directly reflects that energy consumption translates (almost) proportionally[9] into the operating costs for the house. In a TCO approach (cf. e.g. Ellram, 1993), we hence expect energy consumption to contribute linearly to housing cost (left-hand side of Eq. (5)).[10]

$$\ln\left(PRICE_{ikt} + \tilde{\beta}ENERGY_i\right) = \tilde{\alpha} + \tilde{\gamma}\boldsymbol{D}_i + \tilde{\delta}\boldsymbol{N}_{kt} + \mu_t + \varepsilon_{ikt} \tag{5}$$

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[7] In the specification as given by Eq. (1).

[8] We used the "dpik" function of the "KernSmooth"- package in R (cf. Matt Wand et al., 2021).

[9] Small non-linearities may occur due to degressive heating fuel prices or through higher efficiencies of larger heating systems. Yet price changes and efficiency improvements will hardly exceed small single-digit percentages.

[10] Another term used widely synonymously to total-cost-of-ownership approach is life-cycle costing (e.g. Gluch and Baumann, 2004).

This formulation reflects that (heating) energy is an input in producing housing amenity, namely a heated dwelling[11]. Hence, energy efficiency is not to be treated as an attribute of the building, but rather the corresponding costs are part of the total cost of ownership associated with a home of given characteristics $\boldsymbol{D}_i$ and $\boldsymbol{N}_{kt}$. For the estimation, we rearrange Eq. (5) terms to obtain the housing price as dependent variable on the left-hand side:

$$PRICE_{ikt} = -\tilde{\beta} ENERGY_i + exp\big(\tilde{\alpha} + \tilde{\gamma}\boldsymbol{D}_i + \tilde{\delta}\boldsymbol{N}_{kt} + \mu_t + \varepsilon_{ikt}\big) \qquad (6)$$

The coefficient $\tilde{\beta}$ in Eq. (6) is then expected to be positive—the lowering impact on housing prices in Eq. (6) is contained in the negative sign obtained after rearranging the terms. This coefficient $\tilde{\beta}$ can directly be interpreted as the monetary impact on total property costs in euro per unit decrease in energy consumption, since both housing prices and energy consumption are normalized to the square meters of living space.

From this cost-based perspective, $\tilde{\beta}$ reflects the average price per unit of energy multiplied by a factor reflecting the present value of the annual heating cost over the building's lifetime. This multiplier may be determined using Eq. (7), and it describes the monetary increase in housing value per euro decrease in annual energy costs. Using this multiplier, we can easily compare the investment costs required to achieve a given level of energy cost savings with an increase in housing values. Concurrently, the values determined for this energy multiplier can be compared with rental multipliers, which are often used by practitioners to evaluate the prices for rented buildings.

$$energy\ multiplier = \frac{\tilde{\beta}}{average\ energy\ price\ for\ heating}\ [a] \qquad (7)$$

Obviously, this TCO-based approach emanates from a rather straightforward model of home buyers as maximizers of intertemporal utility (or wealth). There is a long-standing debate as to whether consumers will actually invest in energy-efficiency improvements if there is a positive net present value (NPV) of resulting energy savings. The lack of investments, even if energy cost savings exceed the required investment costs, is known as the "energy paradox" introduced notably by Jaffe and Stavins (1994). Here, the *Household Energy Efficiency Upgrade Model* by Carroll et al. (2020) tries to explain the underlying mechanisms for investment failures. According to their study, imperfect information, especially regarding future energy cost savings and potential monetary benefits, can induce less implementation of energy efficiency measures.

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[11] Cooling and air conditioning are so far rather exceptional in German residential buildings.

In our analysis, based on housing market data, the question is not on the implementation of energy efficiency measures but on their valuation in a (subsequent) property transaction. Therefore, using a TCO-based approach is defendable.

Nonetheless, some limitations of the implemented approach exist. In our TCO perspective, we ignore other operating costs of the property (besides energy costs) or possible interest charges from loans granted. However, since we are interested only in returns on energy efficiency, this does not affect our analysis' outcomes. Furthermore, we do not distinguish between structure and land values when estimating housing values. We refrained from doing so for the following reasons. Land values vary substantially within districts and even within small neighborhoods, so that—due to data constraints—a distinction will be simply impossible.

Nevertheless, to account for differences in land values, at least between metropolitan and less populated areas, we estimate Eq. (6) for subsamples according to *DTYPE*. Also, anecdotical as well as empirical evidence suggests that higher-valued homes are often built in more expensive regions and vice versa (at least within subsamples), which makes a separation of land and structure value error-prone. Finally, we expect that homeowners who invest in energy-efficient refurbishments try to increase the total value (structure plus land), as they will not necessarily divide into land and construction prices when determining asking prices if the property is sold, especially not for private sales on the internet.

4 Data

Our dataset combines micro-level information on prices and characteristics of buildings with population and neighborhood characteristics at the 1 km²-grid level. These grids are assigned to the four different district types, as given in Figure A 1. *Large cities* are defined as independent cities with over 100,000 citizens. *Urban areas* describe counties with a population density of over 150 inhabitants per square kilometer, and counties where over half of the population lives in medium-sized or large (non-independent) cities[12] that also have a population density above 150 inh/km². In contrast, counties with over 50 % of the population living in medium-sized or large (independent) cities and a population density below 150 inh/km², and counties with less than 50 % of the population living in medium-sized or large cities that have a population density of at least 100 inh/km² are referred to as *densely populated rural areas*. All other counties are

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[12] Medium-sized cities are defined in German statistics as cities with a population between 20,000 and 99,999, whereas large cities have more than 100,000 inhabitants (Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2019).

characterized as *sparsely populated rural areas* (for a detailed description, see Federal Institute for Research on Building, Urban Affairs, and Spatial Development (2019)).

4.1 Building Data from ImmobilienScout24

Information on the prices and characteristics of residential houses was extracted from the RWI-GEO-RED dataset (B. Boelmann et al., 2019), which is based on data provided by the internet platform ImmobilienScout24 (IS24). The data is available from 2007, but as we are interested in energy efficiency, we restricted the dataset to advertisements that were placed from May 2014. We use this specific cutoff because, on May 1, 2014, a new revision of the Energy Saving Regulation (EnEV, 2014) was established, which declared the energy performance certificate for buildings obligatory for sellers. By restricting the dataset, we diminish the probability of selection bias[13].

Furthermore, we removed outliers based on 1st and 99th percentiles of asking price, living space and lot size, and excluded all observations with missing values for main variables, e.g., energy consumption, asking price, and living space. For all factor variables that indicate condition, etc., we added the level "unknown" for missing values to avoid losing too many observations due to control variables. We focus on existing single-family homes constructed between 1850 and 2010 and on houses that are neither used as holiday homes nor already let.

Although our data lack information on final transaction prices, several reasons abound to assume that it is suitable for our analysis. With about 1.2 million new advertisements monthly, IS24 is the biggest internet platform for real estate listings in Germany with a self-reported market share of about 50 % of all offered dwellings for sale or rent (Georgi and Barkow, 2010; De Meulen et al., 2014).

Moreover, Dinkel and Kurzrock (2012) examined whether asking prices quoted on IS24 were significantly above real transaction prices for owner-occupied dwellings. Using six districts of Rhineland-Palatinate as a case study, they found confirming evidence for this question, but differences between those prices did not vary systematically among property types. A uniform or stochastic yet uncorrelated markup on transaction prices, however, will not affect the estimation results in any case when estimating a hedonic pricing model (Bauer et al., 2015).

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[13] It is likely that only sellers of efficient buildings placed information about the energy performance of the dwelling in their offers in the time before this declaration was mandatory (Frondel et al., 2020; Kholodilin et al., 2017).

Furthermore, Lyons (2019) showed that hedonic indices based on listing prices capture final transaction prices even when market conditions are volatile.

Regarding the investigation of energy-efficiency effects, a minor drawback of the RWI-GEO-RED data arises. Information on the main energy sources used for heating and on primary energy consumption are lacking. Nonetheless, the dataset also has two major advantages. First, final energy consumption or final energy demand, respectively, is given and can be used instead of categorical variables from A+ to H. Second, information about the type of EPC is included, which allows for better comparability of the given values. EPCs based on energy consumption measurements, i.e., so-called "consumption certificates," show about 25 % lower values compared to EPCs based on a (calculated) "energy requirement" (Verbraucherzentrale, 2018). We can therefore control for variation due to different EPCs.

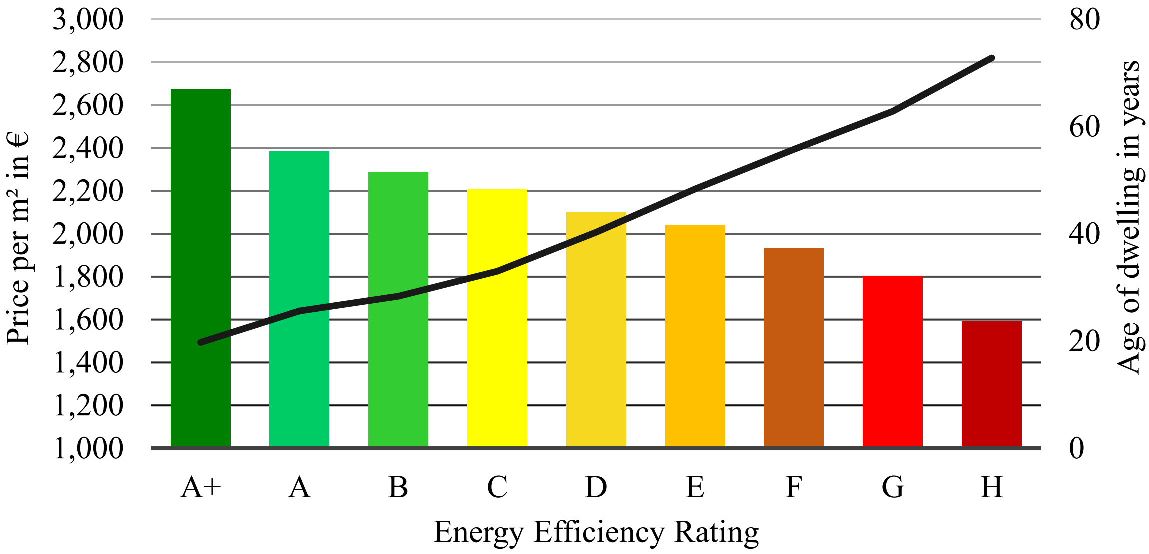
4.2 Socioeconomic data from microm Micromarketing-Systeme and Consult GmbH

Socio-economic characteristics on a 1 km²-grid level were taken from the RWI-GEO-Grid dataset (RWI and microm, 2020), which is based on data provided by microm Micromarketing-Systeme and Consult GmbH—a market research firm specializing in regional analysis (microm-Micromarketing-Systeme und Consult GmbH, 2019). Adding to inhabitants' number, our dataset includes total purchasing power, unemployment rate, and households' share headed by foreigners. We also use information about the predominant building type within a grid cell to describe the neighborhood where an offered dwelling is located. The data is available from 2009 to 2017 and is merged with the housing data with a one-year lag. Thus, our final sample includes 422,242 observations from May 2014 to December 2018, distributed over 69,597 grid cells.

4.3 Descriptive Statistics

While energy-efficient homes are, on average, more expensive than inefficient ones, they tend to be younger, likely to be in better overall condition, and may have a newer heating system or other special features. Figure 1 shows the relationship between asking prices, energy efficiency, and the age of dwellings. The bars' height describes the average price per square meter, the colors indicate the energy efficiency ratings, and the black line shows the mean object age. In our sample, an average "D"-rated single-family home, for example, was constructed in the

1980s, has a mean energy consumption of 116 kWh/m²a, and is offered for €2,100 per square meter of living space.



Source: Authors' calculation and illustration based on IS24 and microm.

Figure 1 Average asking price and age by category of the energy efficiency rating.

Table 1 presents summary statistics for the main hedonic and socio-economic variables included in our regression model. The median dwelling in our dataset has a final energy consumption for heating of 151 kWh/m²a, which corresponds to the upper end of an E-rating; the average energy consumption even corresponds to an F-label. Prices range from €195 to €7,390 per square meter living space, which serves as a strong indicator of a mixed ad portfolio that includes dwellings in all price classes. In our sample, the average dwelling is offered for €1,984 per square meter, which is mostly related to E or F-rated objects.

When examining socio-demographic characteristics—especially the maximum population density of 20,923—it is noteworthy that this information is provided per 1 km²-grid cell and that uninhabited grids are ignored. Average population density per square kilometer amounts to 1,702 inhabitants; the minimum is 11 (due to data privacy reasons).

Table 2 provides the summary statistics grouped by *DTYPE*. Half of all the advertised dwellings in our sample are located in urban areas, whereas the other half is almost evenly distributed over large cities and densely and sparsely populated rural areas. While no major differences between the area types regarding energy consumption for heating, property age, and living space exist, houses in rural areas have a significantly larger property size on average but are also significantly less expensive than those in urban and large cities.

Table 1 Descriptive statistics of main variables.

Variable	N	Mean	SD	Min	Max	Median	unit
Price	422,242	1,984	994	195	7,390	1,809	€/m²
Energy consumption	422,242	168	87	5	600	151	kWh/m²a
Age	406,755	50	28	10	170	46	2020 = 1
Living space	422,242	155	52	60	420	144	m²
Lot size	422,242	673	436	45	3,500	600	m²
Rooms	422,242	6	2	1	25	5	
Hits	422,242	2,354	2,709	1	350,316	1,586	
Advertisement duration	422,242	1.68	2.02	0.03	18.30	1.00	months
Population[a]	422,242	1,702	1,600	11	20,923	1,205	inh/km²
Purchasing power[b]	422,242	23,303	3,900	11,302	63,273	22,733	€/inh
Unemployment rate	422,242	4.99	3.24	0.00	37.48	4.35	%
Share of foreigners	422,242	6.91	5.78	0.00	72.14	5.56	%

[a] avg. number of inhabitants per 1 km²-grid cell. Only inhabited grid cells are included in the calculation, which is why the numbers are much higher than population densities measured at the city or any larger level.

[b] measured as total purchasing power per 1 km²-grid cell divided by total population per 1 km²-grid cell.

Source: Authors' calculation based on IS24 and microm.

Following the definition of the four different district types, the average population size in large cities is about three times higher than in densely populated rural areas and almost twice as high as in urban areas. Average purchasing power per capita is also larger in urban compared to rural regions.

Table 2 Main hedonic characteristics across regions – mean values (standard deviations in parentheses).

	DTYPE			
	Large city	**Urban area**	**Rural, dens. pop.**	**Rural, spars. pop.**
No. of obs.	70,778	213,402	75,994	62,068
%	16.76	50.54	18.00	14.70
Price	2,656 (1,087)	2,020 (944)	1,662 (836)	1,488 (750)
Energy consumption	166 (82)	171 (88)	167 (87)	158 (85)
Age	52 (27)	50 (28)	49 (30)	48 (31)
Living space	151 (52)	158 (52)	153 (51)	151 (50)
Lot size	534 (354)	631 (403)	763 (462)	866 (506)
Population[a]	3,097 (2,132)	1,686 (1,405)	1,078 (1,019)	934 (938)
Purchasing power[b]	24,805 (4,434)	23,903 (3,818)	22,051 (3,213)	21,060 (2,739)

[a] avg. number of inhabitants per 1 km²-grid cell. Only inhabited grid cells are included in the calculation, which is why the numbers are much higher than population densities measured at the city or any larger level.

[b] measured as total purchasing power per 1 km²-grid cell divided by total population per 1 km²-grid cell.

Source: Authors' calculation based on IS24, microm and INKAR.

One main factor directly related to energy efficiency is the installed heating system. Houses using heat pumps are, on average, the most efficient dwellings in our sample, while heating by stove induces the highest energy consumption measures followed by oil and night storage heating (cf. Table A 1). However, improvements in the energy efficiency are visible for retrofitted dwellings of all construction periods (cf. Table A 2). In our dataset, about one-fourth of all advertised dwellings were renovated after 2000, and evidence suggests that, at least in some cases, sustainable energy systems, such as solar panels, wood pellet heating, or heat pumps, were installed during modernization.

Another factor that is at least indirectly related to the energy efficiency measure is the EPC type. In our sample, buildings with consumption certificates are, on average, 42 years old, while those certified based on requirement certificates were built approximately 15 years earlier. Thus, our data match the legal requirements for different types of EPCs in Germany. Consumption certificates are only permitted for buildings that are either built from 1977 onwards, already meet the EnEV Heat Insulation Ordinance of 1977 (e.g., due to renovations), or have over five residential units (which is not the case when examining single-family homes). Newly constructed houses[14] and older dwellings that do not meet the 1977's Heat Insulation Ordinance need a requirement certificate.

Dwellings certified by consumption display an average energy consumption of 129 kWh/m²a, while those certified by requirement show a mean energy demand of 203 kWh/m²a. Also, our data agrees with the statement of the consumer association (Verbraucherzentrale, 2018) that consumption certificates report significantly lower energy consumption than requirement certificates. In our sample, about 52 % of all buildings were certified by requirement, and the other 48 % were certified by consumption.

5 Empirical Results

5.1 Main Results

Table 3 presents the main regression results for Eq. (1). To highlight the importance of including spatial fixed effects to control for omitted-variable bias, we also provide the results for our basic OLS specification without any fixed effects (Column (1)). Column (4) shows the results, including an interaction term between our main variable of interest and *DTYPE*. A Cook's distance filter is applied in all regressions using a cutoff at 4/N.

Expectedly, we find negative effects of energy consumption on asking prices for single-family homes. These effects are statistically significant at the 0.1 % level in all specifications. Estimates can be interpreted as semi-elasticities. If energy consumption decreases by 100 kWh/m²a, the price per square meter for single-family homes in Germany increases, on average, by approximately 6.9 % (see Column (3)). Furthermore, houses with less efficient or more

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[14] The regulation is effective from May 2014, so dwellings that were built after this date are defined as "newly constructed."

costly heating systems, such as electric heating, night storage heating, or heating by stove, are sold at a discount of up to 17.8 % compared to houses with gas heating. Floor and solar heating, however, induce price premiums of 1.4% and 3.9%, respectively, compared to heating by gas[15]. Additionally, if a dwelling was last renovated in 2000 or later, the price will be 2 % higher, on average, compared to earlier and non-renovated homes.

Table 3 Main regression results for Eq. (1), full dataset.

Dependent variable:	**OLS**			
lnPrice (€/m²)	**(1)**	**(2)**	**(3)**	**(4)**
Energy consumption	-0.0808 ***	-0.0693 ***	-0.0690 ***	-0.0627 ***
(in 100 kWh/m²a)	[0.0018]	[0.0013]	[0.0013]	[0.0016]
Effect of energy consumption compared to urban areas (reference category) in:				
Large cities				0.0504 ***
				[0.0026]
Densely pop. rural areas				-0.0363 ***
				[0.0026]
Sparsely pop. rural areas				-0.0517 ***
				[0.0033]
Heating system, reference: Gas heating				
CHP	-0.0342 *	-0.0373 †	-0.0374 *	-0.0294
	[0.0133]	[0.0194]	[0.0187]	[0.0179]
Electric heating	-0.1138 ***	-0.1289 ***	-0.1307 ***	-0.1304 ***
	[0.0092]	[0.0073]	[0.0070]	[0.0069]
Self-contained central	-0.0606 ***	-0.0586 ***	-0.0607 ***	-0.0619 ***
heating	[0.0094]	[0.0082]	[0.0074]	[0.0075]
District heating	0.0089	-0.0052	-0.0049	-0.0019
	[0.0088]	[0.0069]	[0.0068]	[0.0066]
Floor heating	0.0410 ***	0.0141 **	0.0139 **	0.0147 **
	[0.0059]	[0.0050]	[0.0046]	[0.0046]
Wood pellet heating	0.0702 ***	7.01e-04	7.24e-04	-3.34e-04
	[0.01004]	[0.0098]	[0.0093]	[0.0092]
Night storage heating	-0.1062 ***	-0.1315 ***	-0.1308 ***	-0.1319 ***
	[0.0095]	[0.0074]	[0.0072]	[0.0072]
Heating by stove	-0.1470 ***	-0.1761 ***	-0.1780 ***	-0.1750 ***
	[0.0094]	[0.0073]	[0.0068]	[0.0067]
Oil heating	0.0127 *	-0.0162 ***	-0.0160 ***	-0.0176 ***
	[0.0055]	[0.0041]	[0.0038]	[0.0038]
Solar	0.0701 ***	0.0347 *	0.0386 *	0.0325 †
	[0.0142]	[0.0165]	[0.0170]	[0.0170]
Heat pump	0.0308 ***	-0.0058	-0.0075	-0.0059
	[0.0081]	[0.0065]	[0.0063]	[0.0063]
Central heating	-0.0086 *	-0.0176 ***	-0.0179 ***	-0.0180 ***
	[0.0037]	[0.0027]	[0.0025]	[0.0025]
Unknown	0.0084 †	-0.0140 ***	-0.0144 ***	-0.0144 ***
	[0.0046]	[0.0035]	[0.0033]	[0.0033]
Last renovated in 2000	0.0142 ***	0.0197 ***	0.0205 ***	0.0206 ***
or later	[0.0026]	[0.0021]	[0.0019]	[0.0019]

(continues next page)

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[15] Excluding the heating type regressor in our baseline model led to similar results as shown in Column (1).

Table 3 – continued.

House type, reference: Semi-detached				
Detached	0.0238 ***	0.0485 ***	0.0480 ***	0.0483 ***
	[0.0035]	[0.0027]	[0.0026]	[0.0026]
Terraced	-0.0579 **	0.0054	0.0104	0.0075
	[0.0199]	[0.0198]	[0.0197]	[0.0217]
Rowhouse - middle	-7.50e-04	0.0011	-2.03e-04	3.68e-04
	[0.0049]	[0.0037]	[0.0036]	[0.0035]
Rowhouse - end	0.0075	0.0012	8.44e-04	2.68e-04
	[0.0055]	[0.0040]	[0.0039]	[0.0039]
Bungalow	0.0432 ***	0.0812 ***	0.0805 ***	0.0774 ***
	[0.0053]	[0.0040]	[0.0039]	[0.0038]
Facilities, reference: Normal				
Simple	-0.0706 ***	-0.0783 ***	-0.0762 ***	-0.0769 ***
	[0.0062]	[0.0047]	[0.0044]	[0.0044]
Sophisticated	0.1131 ***	0.0993 ***	0.0996 ***	0.1015 ***
	[0.0033]	[0.0025]	[0.0023]	[0.0023]
Deluxe	0.1904 ***	0.1834 ***	0.1857 ***	0.1903 ***
	[0.0102]	[0.0085]	[0.0074]	[0.0074]
Unknown	0.0289 ***	0.0350 ***	0.0356 ***	0.0355 ***
	[0.0028]	[0.0021]	[0.0020]	[0.0020]
Condition, reference: Well kept				
1st Occupancy after	0.1764 ***	0.1361 ***	0.1372 ***	0.1386 ***
reconstruction	[0.0114]	[0.0108]	[0.0106]	[0.0102]
Like new	0.0392 ***	0.0523 ***	0.0574 ***	0.0592 ***
	[0.0039]	[0.0032]	[0.0030]	[0.0029]
Reconstructed	0.0760 ***	0.0613 ***	0.0610 ***	0.0633 ***
	[0.0055]	[0.0046]	[0.0044]	[0.0044]
Modernized	0.0354 ***	0.0357 ***	0.0360 ***	0.0369 ***
	[0.0037]	[0.0031]	[0.0030]	[0.0030]
Completely renovated	0.0367 ***	0.0412 ***	0.0403 ***	0.0408 ***
	[0.0062]	[0.0058]	[0.0054]	[0.0054]
Needs renovation	-0.1330 ***	-0.1520 ***	-0.1508 ***	-0.1525 ***
	[0.0039]	[0.0030]	[0.0029]	[0.0028]
By arrangement	-0.0736 ***	-0.0632 ***	-0.0626 ***	-0.0608 ***
	[0.0140]	[0.0115]	[0.0110]	[0.0108]
Dilapidated	-0.2682 ***	-0.3012 ***	-0.2993 ***	-0.3095 ***
	[0.0186]	[0.0369]	[0.0386]	[0.0388]
Unknown	-0.0345 ***	-0.0409 ***	-0.0408 ***	-0.0403 ***
	[0.0028]	[0.0021]	[0.0020]	[0.0020]
Population density (log)	0.0960 ***	0.0735 ***	0.0734 ***	0.0728 ***
	[0.0017]	[0.0013]	[0.0012]	[0.0012]
Purchasing power per	1.7740 ***	1.2060 ***	1.2139 ***	1.2079 ***
capita (log)	[0.0134]	[0.0129]	[0.0123]	[0.0125]
Predominant building type in neighborhood, reference: Mixed development				
1-2 Family homes,	-0.0549 ***	-0.0338 ***	-0.0335 ***	-0.0342 ***
homogenous street section	[0.0040]	[0.0031]	[0.0030]	[0.0029]
1-2 Family homes,	0.0418 ***	0.0058	0.0049	0.0056
non-homogenous street section	[0.0062]	[0.0044]	[0.0042]	[0.0041]
3-5 Family homes	0.1813 ***	0.1385 ***	0.202 ***	0.1206 ***
	[0.0154]	[0.0206]	[0.0156]	[0.0156]
6-9 Family homes	-0.0077	0.0186	0.0238	0.0234
	[0.0147]	[0.0247]	[0.0242]	[0.0234]
Housing block, 10-19 households	0.3164 ***	0.0937 **	0.1023 **	0.1137 ***
	[0.0133]	[0.0329]	[0.0242]	[0.0293]

(continues next page)

Table 3 – continued.

Housing block, ≥ 20 households	0.2233 ***	0.0338 †	0.0395 *	0.0424 *
	[0.0173]	[0.0194]	[0.0191]	[0.0181]
Industry/trade	0.1769 ***	0.1095 **	0.1162 **	0.1145 **
	[0.0198]	[0.0340]	[0.0428]	[0.0417]
Cellar and guest WC	*yes*	*yes*	*yes*	*yes*
No. of floors and rooms	*yes*	*yes*	*yes*	*yes*
Living space & lot size cat.	*yes*	*yes*	*yes*	*yes*
Construction period cat.	*yes*	*yes*	*yes*	*yes*
Unemployment rate	*yes*	*yes*	*yes*	*yes*
Share of foreigners	*yes*	*yes*	*yes*	*yes*
Fixed Effects:				
Time (quarterly year)	*no*	*yes*	*yes*	*yes*
Region (NUTS3)	*no*	*yes*	*yes*	*yes*
Time×Region	*no*	*no*	*yes*	*yes*
Adj. R-squared	0.6722	0.7827	0.7867	0.7899
RMSE	0.2922	0.2377	0.2333	0.2316
Observations	422,242	422,242	422,242	422,242

Note: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, † $p < 0.1$.
Source: Authors' calculations based on data from IS24, microm and INKAR.

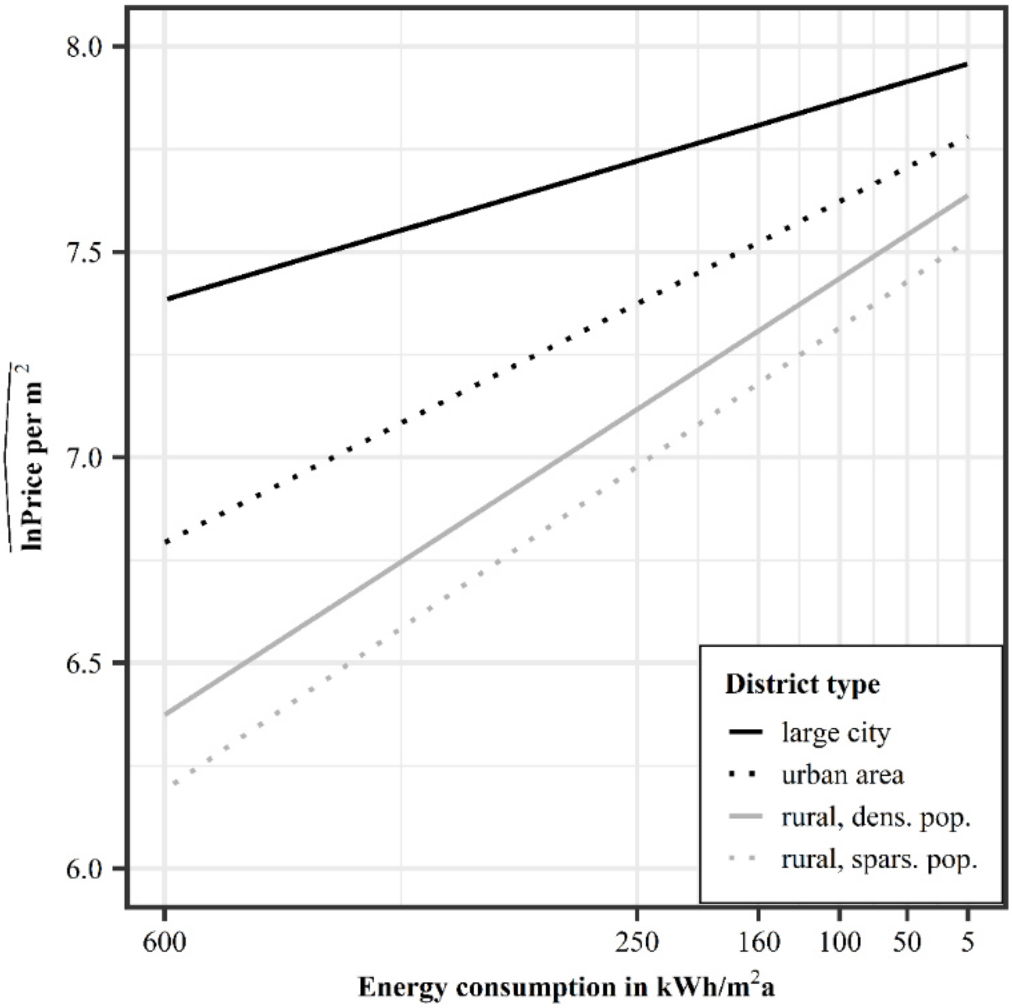
All other intrinsic housing characteristics show expected outcomes. Detached homes are sold at a premium of approximately 4.8 % compared to semi-detached homes. Furthermore, prices of homes with sophisticated or deluxe facilities are about 10 % or 18.5 % higher, respectively, than prices for homes with normal facilities. Also, homes that were completely renovated or advertised as 1^{st} occupancy after reconstruction are more expensive than those promoted as well kept. In contrast, single-family homes that needed renovation are sold at a discount of 15 % on average. Coefficient plots for living space and lot size categories, as well as for construction periods are shown in the appendix (cf. Figure A 2).

Purchasing power per capita also has a statistically significant effect on prices for single-family homes in Germany. If purchasing power increases by 1 %, asking prices increase, on average, by 1.2 %. Surprisingly, houses in a neighborhood with housing blocks or industry and trade as predominant building types are sold at a premium compared to houses located in a mixed development. For an industry/trade neighborhood, this effect may compensate for the price-dampening effect of the lower (residential) population density in such areas, so the net effect is certainly smaller, if not negative. The positive price effect of housing blocks in the neighborhood is particularly pronounced when no region fixed effects were included—it partly captures the effect of metropolitan areas or proximity to the city center. Houses in a neighborhood with mostly 1–2 family homes in homogeneous street sections are, however, sold at a discount of approximately 3.4 %, presumably these are homes in suburbs.

In this context, we investigate the effects across regions according to the four defined district types. If energy consumption decreases by 100 kWh/m²a, prices for single-family homes in urban areas increase, on average, by 6.3 %. In independent large cities, the effect is about 5.0

percentage points weaker, so the price premium for improvements of 100 kWh/m²a is only 1.3 %. Also, we find 3.6 and 5.2 percentage points stronger effects in densely and sparsely populated rural areas, respectively, compared to urban regions.

Figure 2 illustrates the energy efficiency effects on fitted values for the logarithmized price per m² living space across regions, holding everything else constant. We find similar slopes for impacts in both types of rural areas. In contrast, the slope for the effect in large cities is much flatter, and the slope for urban areas lies in between. This also points to diverse effects and ANOVA testing supports the importance of differentiating across regions with F = 1,522.5; $p < 0.001$.



Source: Authors' calculation and illustration based on IS24, microm and INKAR.

Figure 2 Effect plot: Energy consumption on fitted values across district types.

Note: One step on the x-axis refers to two steps in the energy efficiency rating: 5 to 50 kWh/m²a corresponds to an A+ or A rating; 50 to 100 kWh/m²a corresponds to an B or C rating and so on. The last step from 250 to 600 kWh/m²a corresponds to G-rated dwellings. The plot was created using the ggplot2-package in R. Fitted values were smoothed using the "lm"-method in geom_smooth().

To further investigate why the effects differ between urban and rural areas, Table 4 shows the results for the second stage of the two-stage regression, given by Eq. (3). Interpretation of these results is straightforward—positive estimates imply increasing effects on EEPs; negative estimates show decreasing impacts on EEPs.

Purchasing power per capita has negative, statistically significant effects on energy efficiency premiums. If purchasing power per capita on the NUTS3 level increases by 1%, the EEP decreases by $\varphi_2/100 = 0.0024$ units or 0.24%, respectively. Negative impacts can also be found for an increasing share of foreigners and industrial and commercial buildings. The latter, however, is statistically non-significant.

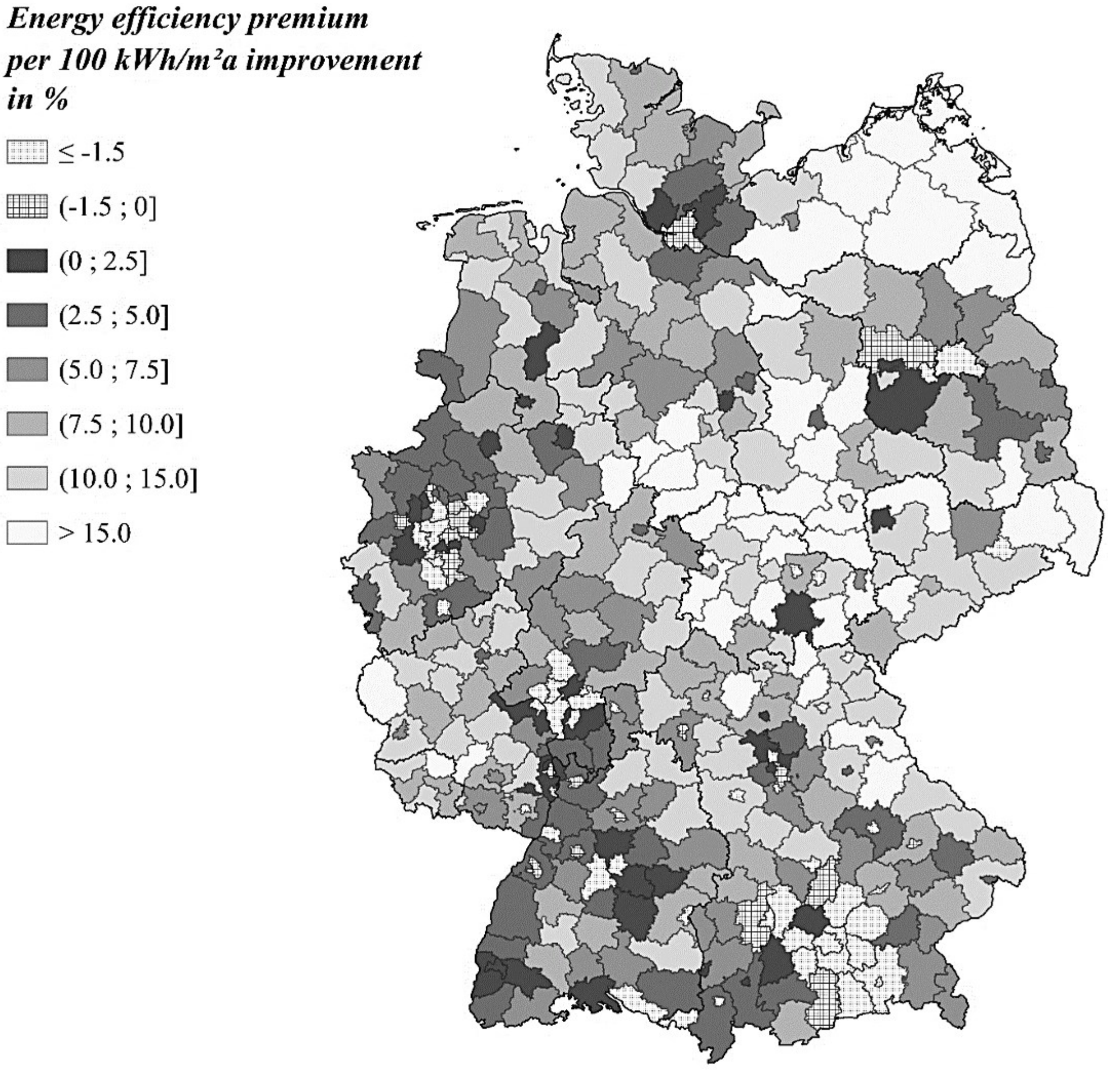
Table 4 Effects of demographics on EEP.

Dependent variable: EEP$_d$	
Total population (log)	0.0040
	[0.0043]
Purchasing power per capita (log)	-0.2457 ***
	[0.0340]
Unemployment rate in %	0.0023 †
	[0.0014]
Share of foreigners in %	-0.0026 **
	[9.67e-04]
Share of industry/trade buildings in %	-0.0023
	[0.0020]
Share of 1-2 Family homes, homogenous street section in %	0.0014 ***
	[2.97e-04]
Intercept	0.7472 ***
	[0.1357]
Adj. R-squared	0.5984
RMSE	0.0420
Observations	401

Note: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, † $p < 0.1$.
Source: Authors' calculations based on IS24 and microm.

Also, an increasing share of 1–2 family homes in homogenous street sections implies increasing EEPs. If the share of 1–2 family homes increases by 1 %, the EEP increases by 0.0014 units or 0.14 %, respectively. Positive effects can also be found for an increasing unemployment rate and total population; however, the latter is statistically non-significant.

Figure 3 illustrates the energy efficiency premiums for each of the 401 NUTS3 regions, resulting from first stage. In some large cities and their surrounding counties, negative premiums can be found for a 100 kWh/m²a improvement of energy efficiency. However, these effects are miniscule and statistically non-significant in most regions. Largest positive premiums can be found in more rural districts, e.g., in the North-East of Germany.



Source: Authors' calculation and illustration based on IS24 and microm. Map Data: @GeoBasis-de/BKG 2019.

Figure 3 Energy efficiency premium across NUTS3 regions.

5.2 Different price effects for different levels of energy efficiency

For further investigations, we first split our sample according to EPC types since this is indirectly linked to the performance of a building (cf. 4.3). Results are shown in Table A 3. Energy efficiency impact on real estate prices in the dwellings' subsample with requirement certificates is more than twice the size of the effects in the other subsample. One explanation for such differences could be that the energy consumption listed in consumption certificates heavily depends on the individual behavior of former inhabitants, which probably indicates the expected energy costs. This uncertainty is then reflected in a lower willingness to pay for energy efficiency. When considering regional disparities, we observe the same pattern as for the full dataset (cf. Table 3, Column (4)), with only one exception: in the consumption certificate subsample, we find negative effects of energy efficiency on housing prices in large cities. These results therefore agree with previous (negative) EEPs found at the district level.

In the next step, we investigate the EEPs separately for each category from A+ to H of the energy efficiency rating. Results are shown in Table 5. For A+ to C-rated buildings, which have a stated energy consumption of max. 100 kWh/m²a, we find no statistically significant effects of energy efficiency improvements on housing prices. For less efficient buildings in categories D to H, price premiums of about 6.8 % can be found for a reduction in energy consumption by 100 kWh/m²a. These results are statistically significant at the 0.1 % level.

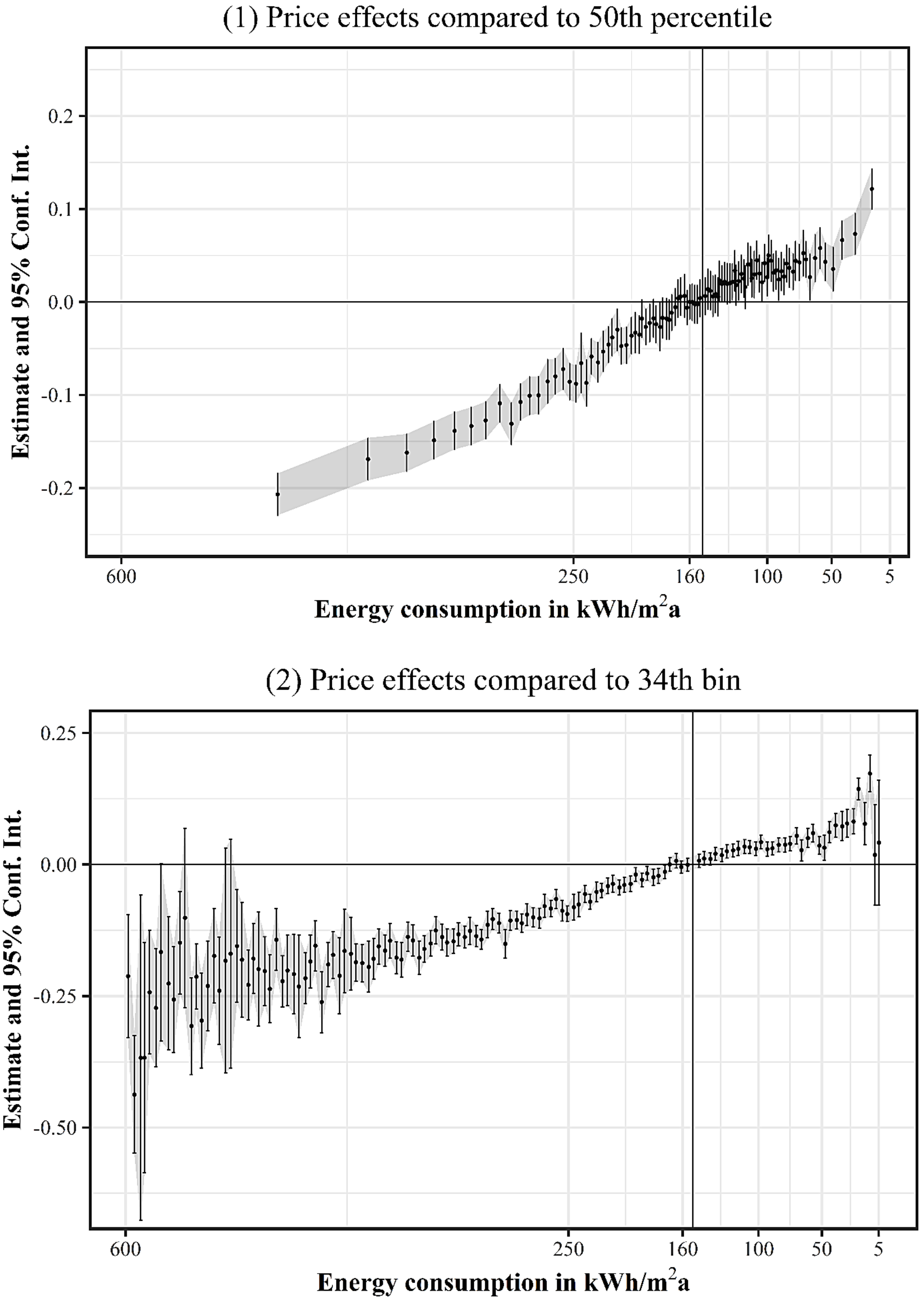
Table 5 Effects of energy consumption for categories of the energy efficiency rating.

Dependent variable: lnPrice (€/m²)	**Categories**							
	A+	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Energy consumption	-0.0017	-0.0063	0.0141	-0.0088	-0.0433 ***	-0.0660 ***	-0.0568 ***	-0.0675 ***	-0.0457 ***
(in 100 kWh/m²a)	[0.0738]	[0.0174]	[0.0187]	[0.0148]	[0.0131]	[0.0117]	[0.0105]	[0.0111]	[0.0030]
Fixed effects:									
Time (quarterly year)	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Region (NUTS3)	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Time×Region	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Adj. R-squared	0.9262	0.9073	0.8451	0.8238	0.8038	0.8140	0.8250	0.8278	0.8293
RMSE	0.1081	0.1303	0.1678	0.1819	0.1998	0.2044	0.2121	0.2191	0.2349
Observations	5,243	10,529	29,365	50,423	70,550	66,062	67,469	54,599	68,002

Note: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.5$.
All regressions include variables for structural and neighborhood characteristics as given in our baseline model. Time FEs are on the quarterly-year level; regional FEs are on NUTS3 level.
Source: Authors' calculations based on IS24, microm and INKAR.

We finally estimate two different non-parametric specifications, as given by Eq. (4), to obtain insights into the price effects for various levels of energy efficiency. Figure 4 illustrates the outcomes. Plot (1) shows price effects for percentiles of the energy consumption compared to the median. The most efficient dwellings (1st percentile) are sold at a premium of over 10 % compared to dwellings with energy consumption of 151 kWh/m²a (median), whereas the least efficient dwellings are sold at a discount of about 20 %.

More granular results are illustrated in Plot (2), which shows coefficients for different bins that were chosen based on the optimal bandwidth obtained from a kernel-density estimation. In contrast to specification (1), the distribution of bins now follows the distribution of energy consumption (c.f. Figure A 3). The reference groups are dwellings assigned to the 34th bin with an average energy consumption of 150 kWh/m²a. Unsurprisingly, we find more fluctuating results at both distribution ends; however, the overall pattern remains similar to Plot (1): more efficient dwellings are sold at a premium, whereas less efficient ones are sold at a discount.



Source: Authors' calculation and illustration based on IS24, microm and INKAR.

Figure 4 Resulting coefficients for non-parametric specification.

5.3 Housing shortage—Driver for regional disparities?

Differences in market conditions probably impact effect sizes for the defined district types. Living space is already becoming scarce in wealthier urban regions. We thus examine whether the weaker effects of energy efficiency on real estate prices in large independent cities are mainly driven by these shortages. Therefore, we define housing supply as advertisements per 1,000 inhabitants based on the NUTS3 level and month.

The advertisement-to-inhabitant ratio is the lowest in large cities. On average, 0.5 advertisements per 1,000 inhabitants are available online. One reason might be that the overall share of single-family homes in large independent cities is quite lower in other regions. In urban areas, approximately 0.9 advertisements per 1,000 residents are online. The numbers of advertisements per 1,000 inhabitants in densely and sparsely populated rural areas, however, exceed the previous numbers by far and are 1.5 and 1.7, respectively. Figure A 4 shows the distribution of (log) housing supplies across regions. We generate three subsamples using quantiles $Q_{1/3}$ and $Q_{2/3}$ of housing supply as cutoffs and run subsample regressions. Table 6 shows the results.

Table 6 Main regression results for housing supply subsamples.

Dependent variable:	**Housing supply**					
lnPrice (€/m²)	**1st tercile**	**2nd tercile**	**3rd tercile**	**1st tercile**	**2nd tercile**	**3rd tercile**
Energy consumption	-0.0473 ***	-0.0678 ***	-0.0861 ***	-0.0584 ***	-0.0623 ***	-0.0755 ***
(in 100 kWh/m²a)	[0.0016]	[0.0018]	[0.0023]	[0.0019]	[0.0020]	[0.0031]
Effect of energy consumption compared to urban areas (reference category) in:						
Large cities				0.0280 ***	0.0296 **	0.0268
				[0.0027]	[0.0091]	[0.0230]
Densely pop. rural areas				-0.0317 ***	-0.0241 ***	-0.0114 **
				[0.0064]	[0.0031]	[0.0039]
Sparsely pop. rural areas				-0.0214 *	-0.0343 ***	-0.0229 ***
				[0.0096]	[0.0040]	[0.0044]
Fixed Effects:						
Time (quarterly year)	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Region (NUTS3)	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Time×Region	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Adj. R-squared	0.7415	0.7435	0.7463	0.7427	0.7460	0.7468
RMSE	0.2141	0.2290	0.2427	0.2136	0.2279	0.2425
Observations	138,000	137,898	137,947	138,000	137,898	137,947

Note: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.
All regressions include variables for structural and neighborhood characteristics as given in our baseline model. Time FEs are at the quarterly-year level; regional FEs are at the NUTS3 level.
Source: Authors' calculations based on IS24, microm and INKAR.

In the 1st tercile subsample (with a tight housing supply), we find weaker effects of energy efficiency on asking prices than in the 2nd tercile with medium supply and the 3rd tercile with larger housing supply (Columns (1)–(3)). Statistically significant differences across regions within these subsamples remain. Energy efficiency effect on housing prices is weaker in large independent cities than in urban areas for all subsamples. In the 1st tercile subsample, the effects are slightly stronger in the sparsely populated compared to densely populated rural areas. Otherwise, the pattern is similar to results for the full dataset. Nonetheless, these results should be carefully interpreted. For example, the average housing supply in urban areas in the 1st tercile subsample is 0.59, while the average for large cities is 0.46. Therefore, different effect sizes may still be driven by differences in market conditions.

Including an interaction term between our main variable of interest and the (log) housing supply in our regression (Eq. (1)) also suggests that a large housing supply positively impacts the effect size of energy efficiency on housing prices. If supply increases, the energy consumption coefficient decreases, which induces an increasing impact of energy efficiency on housing prices (Table 7). More precisely, energy efficiency matters less if the housing supply is tight. Therefore, the hypothesis that housing shortages detrimentally affect the energy efficiency effect size can be confirmed.

Table 7 Impact of housing supply on effect size.

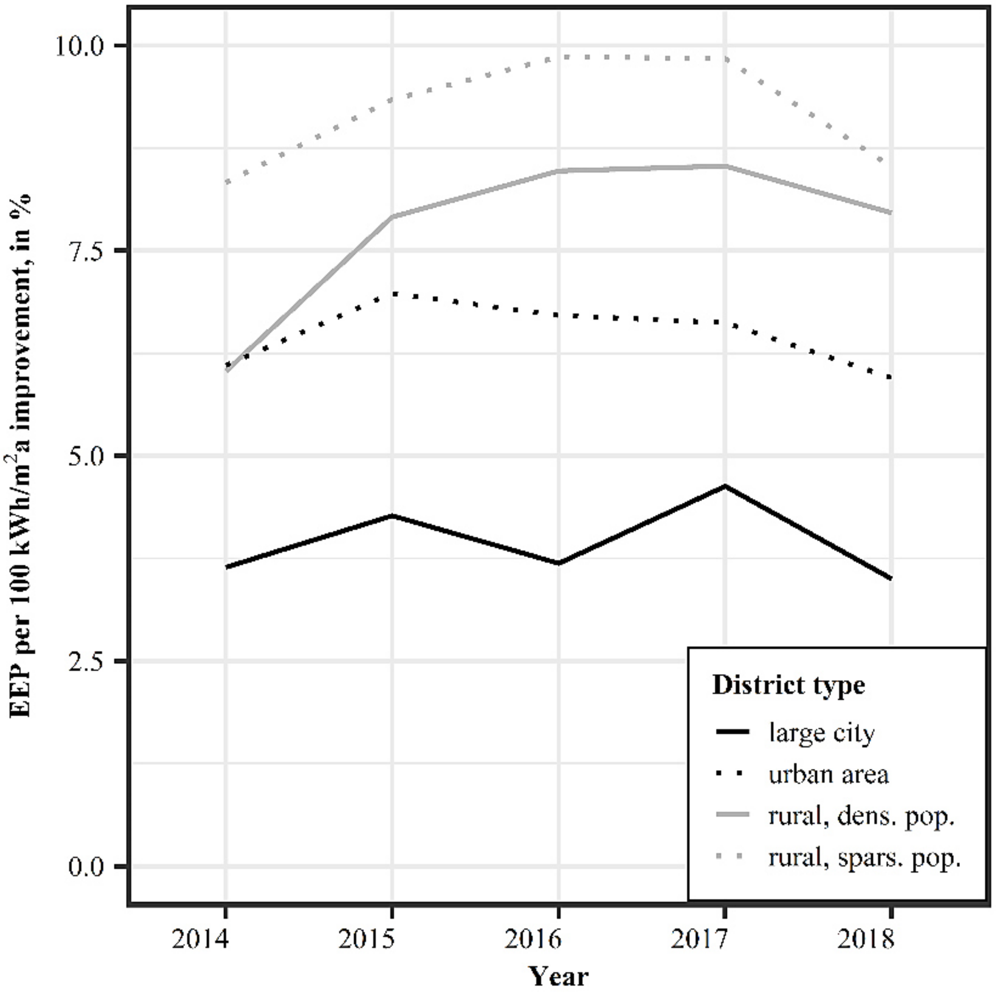
Dependent variable: lnPrice (€/m²)	**Full sample**
Energy consumption (in 100 kWh/m²a)	-0.0723 *** [0.0014]
Housing supply (log)	0.0833 *** [0.0043]
(log) Housing supply×Energy consumption	-0.0692 *** [0.0021]
Fixed Effects:	
Time (quarterly year)	*yes*
Region (NUTS3)	*yes*
Time×Region	*yes*
Adj. R-squared	0.7752
RMSE	0.2380
Observations	413,845

Note: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05.

Variables for structural and neighborhood characteristics are included as in our baseline specification, except of population density.

Source: Authors' calculations based on IS24, microm and INKAR.

Since housing supply was slightly decreasing over the sample period, we additionally compare the relative energy efficiency impact across time, focusing on 2014 to 2018. Figure 5 shows the courses for all regions. Effect sizes are increasing in all areas from 2014 to 2015. In urban areas, we observe a downward trend beginning in 2015, whereas in rural areas, both densely and sparsely populated, we still observe increasing energy efficiency premiums till 2017. In large cities, there is a downward trend from 2015 to 2016, followed by another upward trend. Finally, decreases in effect sizes are found in all areas from 2017 to 2018. However, in both rural areas, we observe stronger effects in 2018 compared to 2014, although the housing supply was tighter in the latter. This trend might be explained through increasing environmental awareness, so that, in case of this hypothesis being true, we would expect even stronger effects over the next years, since ecological attitudes and behaviors have gained importance in our society. Nevertheless, we find slightly lower effects in 2018 compared to 2014 in large cities and rural areas.



Source: Authors' calculation and illustration based on IS24, microm and INKAR.

Figure 5 Impact of energy efficiency across time.

5.4 Monetary benefits, energy cost savings, and required investment costs

Our results show that investments in energy-efficient retrofits generate monetary benefits, and that effects are heterogeneous across regions. But how large is the expected surplus compared to actual heating cost savings? And how is this related to the sellers' investment costs for energy efficiency improvements? For example, a complete refurbishment of a single-family home, which generates energy savings of about 60 %, can be realized with investments of €277 per square meter living space (co2online gemeinnützige GmbH). In our sample, a 60 % reduction in the mean energy consumption is equal to an average energy savings of approximately 100 kWh/m²a with a needed total investment of about €43,200 or €2.77 per annual kWh saved.

To explain more about the housing value impacts of heating cost savings from energy efficiency improvements, Table 8 shows the main regression results for the non-linear least squares estimation (Eq. (6)). Also, the corresponding energy multipliers (Eq. (7)) are shown that can be used to calculate a monetary surplus per one euro decrease in annual energy costs. We assume that the mean energy price for heating energy will be €6.50 per 100 kWh (cf. Federal Ministry for Economic Affairs and Energy, 2020) when calculating the multipliers.

The results can be interpreted as follows. If energy consumption decreases by 100 kWh/m²a, the asking price for single-family homes located in large cities increases by 136,23 €/m². This corresponds to a total value increase of about €20,570 for an average single-family home in the subsample of large cities and a multiplier of 20.96. The monetary benefit per one euro decrease in annual energy costs is then given by 1[€/a]*20.96[a] = €20.96. Our computed energy multiplier agrees with the rent multipliers indicated in recent market reports (cf. DZ BANK AG, 2019).

The obtainable minimum (average) value increase is €19,320[16] when the dwelling is in sparsely populated rural areas. In urban areas, the monetary benefit is, on average, €22,250. In contrast to the OLS specification, where strongest effects are found in rural areas, the monetary benefit in densely populated rural regions now lies between those in cities and urban areas. This analysis thus nuances Model 1 in that the relative importance of energy efficiency increases for dwellings in rural areas but the absolute impact reduces.

Table 8 Non-linear least squares regression results with corresponding multipliers.

Dependent variable: Price (€/m²)	**NLS**			
	Large city	**Urban area**	**Rural, dens. pop.**	**Rural, spars. pop.**
Energy consumption	136.23 ***	140.85 ***	138.08 ***	127.95 ***
(in 100 kWh/m²a)	[4.1077]	[1.8318]	[2.8284]	[2.6583]
# Iterations to convergence	5	6	6	5
Achieved convergence tolerance	6.495e-07	2.616e-06	1.665e-06	8.826e-06
	Corresponding multiplier			
	20.96	21.67	21.24	19.68

Note: Robust standard errors in brackets. *** p < 0.001, ** p < 0.01, * p < 0.05.
Variables for structural and neighborhood characteristics, as well as time-dummy variables, are included. Subsamples were used for estimation.
Source: Authors' calculations based on IS24, microm and INKAR.

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[16] The average living space in sparsely populated areas is 151 m². The corresponding value increase is 127.95 €/m²*151 m² = 19,320.45 €.

The found price premiums represent only 46 % to 51 % of the total investment costs given in the example above. Hence, investment costs of about €20,000 remain or, put differently, almost half of the required investment costs are not reflected in higher housing values. According to theory, discounted energy cost savings should correspond with investment costs. When assuming a long service life of 25 years, an interest rate of 1.86 % (cf. Deutsche Bundesbank), energy costs of €0.065 per kWh, and an average living space of 155 m², the NPV is €19,997 and thus matches roughly the value increase in the housing market but not the original investment costs. However, this depends fully on the assumptions made.

Table 9 gives a more detailed overview of energy savings depending on the chosen (single) renovation measure. The shown mean energy savings result from a field experiment on energy refurbishments for residential buildings (co2online gemeinnützige GmbH, 2015). According to this study, homes with a mean energy consumption of about 156 kWh/m²a can achieve mean energy savings of 10 % to 30 % with single renovation measures. Also, investment costs of these single renovation measures are partly capitalized into housing prices. The potential increase in housing values covers only about 86 % of the average investment costs, depending on location and on whether investment costs are at the upper or lower end of the given range. Furthermore, government funding for new technologies and energy refurbishments is excluded, which may induce better coverage.

Table 9 Investment costs, energy savings, and monetary benefits, depending on different renovation measures.

Measure	Avg. energy savings in %	Avg. energy savings in kWh/m²a	Avg. investment costs in €	Monetary benefit in €	Inv. covered by benefit in %
Heating boiler exchange	15	23.4	6,000 - 9,000	4,700 – 5,100	52 – 85
Boiler exchange + solar	30	46.8	12,000 - 18,000	9,300 – 10,300	52 – 86
New windows	10	15.6	500 - 1,000 each	3,100 – 3,400	depends on # windows
Roof insulation	11	17.2	5,000 - 20,000	3,400 – 3,800	17 – 76

Note: Mean savings are related to buildings with an average energy consumption of 156 kWh/m²a. The monetary benefit is calculated for a single-family home with living space of 155 m² based on mean energy savings in kWh using results given in Table 8. The range for investments covered by monetary benefit in % is calculated by dividing the highest monetary benefit by the lowest avg. investment costs as well as the lowest benefit by the highest inv. costs.
Source: Authors' illustration based on (co2online gemeinnützige GmbH, 2015; Effizienzhaus-online; Energieheld).

Instead of comparing potential monetary benefits with investment costs, we additionally compare the increase in housing values to the value of the stated energy savings. We still assume a useful life of 25 years, interest rate of 1.86 %, and energy costs of €0.065 per kWh. An average single-family home then saves energy costs of around €236 yearly after installing a new boiler[17]. Depending on location, the value increase is, on average, 21 times higher and thus far exceeds these annual energy cost savings. The exemplary NPV of energy costs saved is €4,684, so that about 98 % of these energy cost savings are already reflected in the higher asking price. This further indicates that the monetary value of energy efficiency improvements tends to be adequately reflected in house prices—under the assumption of "myopic" expectations of homeowners—that is, more or less constant energy prices in the future.

6 Discussion and conclusion

Increasing buildings' energy efficiency is a key factor in reducing CO_2 emissions in Germany to achieve the targets defined in the Climate Action Plan 2050. As the ownership rate in Germany is at least 46 %, private homeowners will greatly influence investments in energy refurbishments of existing properties. To identify monetary benefits for owners of single-family homes who invest in such energy retrofits, we constructed a repeated cross-sectional dataset from 2014 to 2018, which includes over 420,000 individual housing observations with full hedonic characteristics and various socio-economic characteristics on a 1 km^2-grid level.

Using a hedonic pricing model in a common semi-logarithmic specification, we found evidence that energy-efficient dwellings are sold at a price premium. Our results thereby confirm the findings of most previous European and international studies. Estimated effect sizes are also in the same range. Contrary to Wahlström (2016), we found that the price impact of energy consumption is still highly significant when excluding all other energy-related variables from our regression. However, these results are in line with Chegut et al. (2016), and also with many other studies that do not control for those heating-related features at all (i.e., Cajias et al., 2019; Kholodilin et al., 2017). Nevertheless, including information about the heating type is still of importance as evidenced by Hahn et al. (2018).

Furthermore, we found that the surplus for improved energy efficiency differs across regions. In large independent cities, a decrease in energy use by 100 kWh/m^2/year causes a 1.3 % increase in asking prices per square meter, whereas in sparsely populated rural areas, a price premium of 11.4 % can be achieved. When investigating the effects in relative terms, we therefore highly recommend a distinction between urban and rural areas, as we find that the capitalization of energy efficiency is more important in the latter. This is in line with findings by Hyland et al. (2013) who also found higher price effects in rural compared to urban areas

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[17] Savings in kWh/a: 156 kWh/m^2a * 155 m^2 * 15 % = 3,627 kWh/a.
Annual monetary savings: 3,627 kWh/a * 0.065 €/kWh = 235.76 €/a.

for the residential real estate market in Ireland. In absolute terms, however, effects are similar across regions. These results underline and generalize the findings of Civel (2020), who focuses on housing markets in two different regions in France and draws the same conclusion.

There are reasons to assume that differences across regions arise due to different market conditions. On the one hand, there is evidence that EEPs are lower in high-income districts. This leads to the hypothesis that energy efficiency probably does not matter to homebuyers in these regions since high energy costs are not considered problematic. Therefore, notably, Carroll et al. (2020) emphasized that energy costs matter rather than energy consumption. They investigated the treatment effects of a change from energy consumption labels to energy cost labels and found higher EEPs in the treatment group but only when analyzing real transaction prices instead of list prices. Thus, they conclude that treatment effects are demand-side driven.

Through our analysis, which is based on list prices, we cannot fully distinguish whether the effects are demand-side or supply-side driven. However, evidence abounds that housing shortage influences effect sizes. In regions where housing supply is tight, the effects of energy efficiency on house prices are significantly smaller than in other regions. These results also agree with negative EEPs found in some large cities, which have the lowest housing supply in our sample (< 0.2 advertisements per 1,000 inhabitants). Moreover, our findings are consistent with those of Cajias et al. (2019), as they too found lower effects in Germany's 'Top 7' markets[18] compared to effects in secondary markets. We therefore conclude that housing shortage, together with higher purchasing power per capita, can be identified as drivers for lower EEPs.

Furthermore, stronger effects of energy efficiency on asking prices were found for dwellings with requirement certificates compared to dwellings certified based on the energy consumption of the previous owner. These results confirm findings of Wahlström (2016), as she also found that potential buyers of new homes tend to base their expectations of future energy use on energy-related characteristics rather than just on the previous owner's energy consumption.

Additionally, our results suggest that environmental aspects have become increasingly important for housing prices over our sample period, but only in rural regions. The effects on asking prices were larger in 2018 compared to 2014. If this pro-environmental valuation continues or even increases[19] in our society, we might expect the energy efficiency effect on housing prices to increase further over the next few years, which can probably increase the

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[18] Berlin, Dusseldorf, Hamburg, Cologne, Frankfurt, Munich and Stuttgart. All 7 cities face housing shortage.

[19] E.g., due to the impact of the Fridays for Future movement.

willingness-to-pay for energy refurbishments. In urban and metropolitan areas, these effects might be offset by increasing housing scarcity.

When examining the investment costs for energy refurbishments, we find that costs for single measures, such as the installation of a new heating system, are capitalized into housing prices by about 86 %. For a complete refurbishment with an improvement of the energy performance by 60 %, the monetary benefit only accounts for up to 51 % of initial investment costs. However, government funding is excluded here and might induce better coverage of needed investments. Furthermore, there might be some co-benefits of refurbishments besides energy cost savings, e.g., regarding comfort or reliability.

On the one hand, our results differ slightly from Civel's (2020), as he found that green premiums in absolute values fully correspond to the required investments for energy refurbishments. Civel (2020) argues that a Bertrand-like competition among sellers prevents them from charging more for increased energy efficiency than they actually spent on renovations. However, regarding Germany, with a tight housing supply in many areas, it is likely that it is needless for owners to improve energy efficiency before selling, because there are still enough potential buyers. So, even sellers of inefficient homes can request high purchase prices, making EEPs seem rather small.

On the other hand, our energy multiplier is in the same range as the one given by Kholodilin et al. (2017). For mean energy costs of 8 eurocents per kilowatt hour, they found that a one-euro reduction of yearly energy costs relates to a house price increase of €15.5. Since we assume the mean energy price for heating with 6.5 eurocents per kilowatt hour to be slightly smaller, our estimated house price increase for a one-euro reduction in yearly energy costs amounts to approximately €20. However, this premium decreases by €3 to €4 when assuming the same price for heating as Kholodilin et al. (2017).

Finally, from a buyer's perspective, the extra price for efficient homes can be explained by discounted energy (cost) savings, at least if low discounting rates and myopic assumptions regarding fuel prices are assumed. Obviously, about 98 % of energy cost savings are already reflected in higher housing values when assuming a useful life of 25 years.

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Appendix

Table A 1 Type of heating and corresponding mean energy consumption.

Type of heating	N		Mean energy consumption in kWh/m²a
	total	in %	
CHP	341	0.08	107
Electric	3,543	0.84	168
SCC	5,219	1.24	177
District	4,676	1.11	127
Floor	16,691	3.95	102
Gas	36,750	8.70	153
Pellet	836	0.20	139
Night storage	3,203	0.76	186
Stove	10,302	2.44	225
Oil	19,813	4.69	192
Solar	155	0.04	88
Heat pump	3,414	0.81	51
Central	265,413	62.86	170
Unknown	51,886	12.29	176

Source: Authors' calculation based on IS24.

Table A 2 Energy consumption by selected construction periods and modernization status.

Construction period	**Modernized after 2000**	**N**	**Mean energy consumption in kWh/m²a**	
Between 1850 and 1859	*no*	450	248	
	yes	225	169	(-79)
Between 1900 and 1909	*no*	10,318	239	
	yes	4,673	200	(-39)
Between 1950 and 1954	*no*	12,346	237	
	yes	5,072	191	(-46)
Between 1955 and 1959	*no*	16,447	235	
	yes	6,725	193	(-42)
Between 1960 and 1964	*no*	21,821	229	
	yes	8,872	191	(-38)
Between 1965 and 1969	*no*	20,650	216	
	yes	8.714	182	(-34)
Between 1970 and 1974	*no*	27,171	188	
	yes	11,352	170	(-18)
Between 1975 and 1979	*no*	24,829	169	
	yes	10,692	151	(-18)
Between 1980 and 1984	*no*	19,993	144	
	yes	8,546	135	(-9)
Between 1985 and 1989	*no*	14,059	138	
	yes	5,515	128	(-10)
Between 1990 and 1994	*no*	18,589	132	
	yes	6,151	125	(-7)
Between 1995 and 1999	*no*	28,238	111	
	yes	7,414	105	(-6)

Source: Authors' calculation based on IS24.

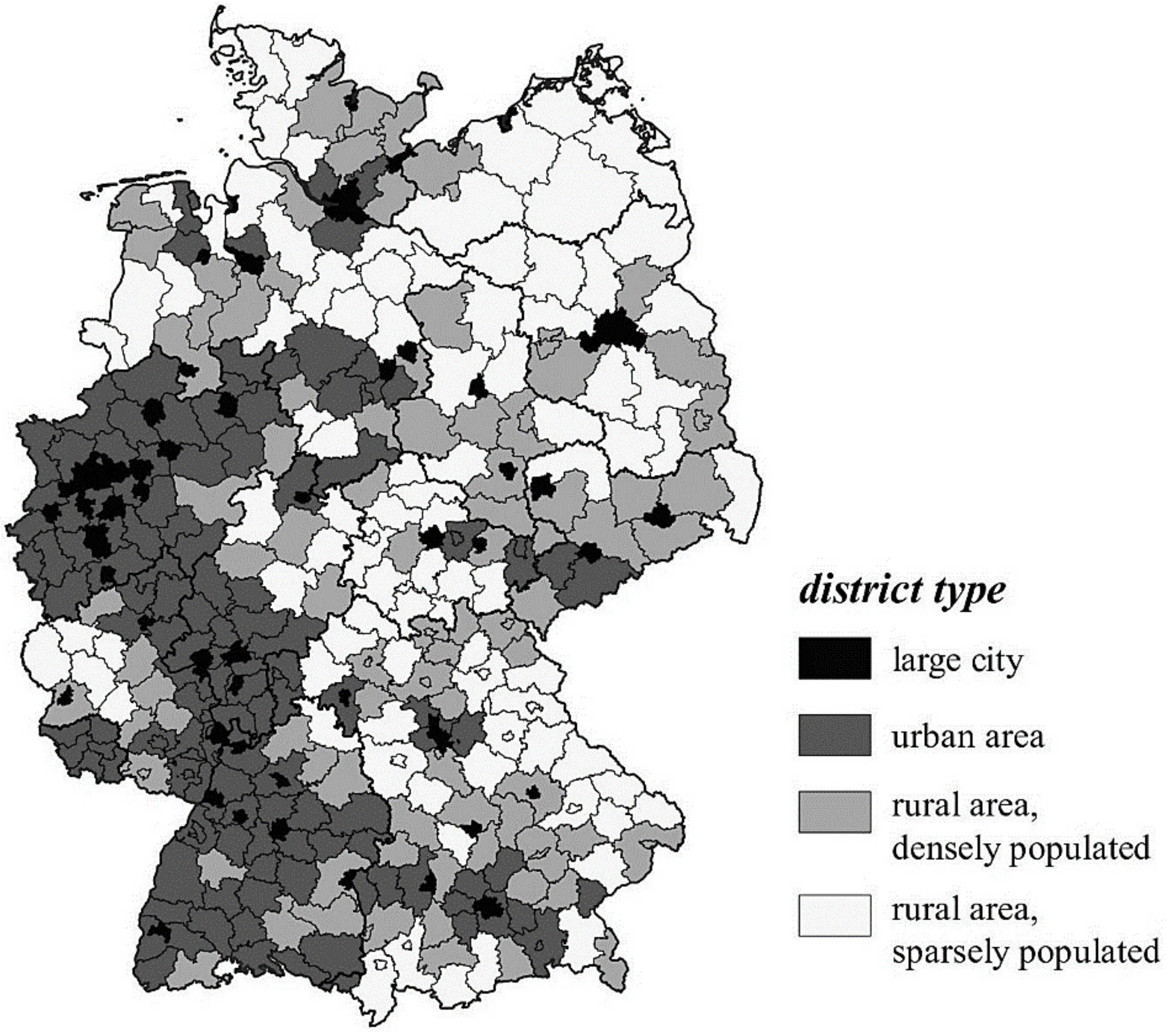
Table A 3 Regression results for EPC subsamples.

Dependent variable: lnPrice (€/m^2)	**Type of EPC**			
	Consumption certificate	**Requirement certificate**	**Consumption certificate**	**Requirement certificate**
Energy consumption	-0.0322 ***	-0.0789 ***	-0.0298 ***	-0.0729 ***
(in 100 kWh/m^{2}a)	[0.0023]	[0.0015]	[0.0029]	[0.0019]
Effect of energy consumption compared to urban areas (reference category) in:				
Large cities			0.0532 ***	0.0422 ***
			[0.0049]	[0.0031]
Densely pop. rural areas			-0.0322 ***	0.0330 ***
			[0.0061]	[0.0031]
Sparsely pop. rural areas			-0.0466 ***	-0.0488 ***
			[0.0064]	[0.0037]
Fixed Effects:				
Time (quarterly year)	*yes*	*yes*	*yes*	*yes*
Region (NUTS3)	*yes*	*yes*	*yes*	*yes*
Time×Region	*yes*	*yes*	*yes*	*yes*
Adj. R-squared	0.7822	0.7953	0.7842	0.7978
RMSE	0.2169	0.2365	0.2159	0.2351
Observations	200,881	221,361	200,881	221,361

Note: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05.

All regressions include variables for structural and neighborhood characteristics. Time FEs are on a quarterly-year level; regional FEs are on NUTS3 level.

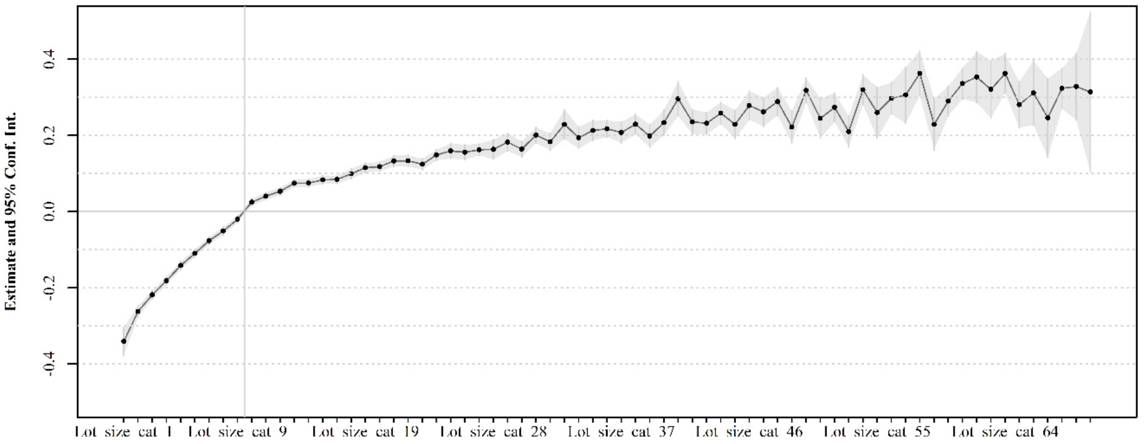
Source: Authors' calculations based on IS24, microm and INKAR.



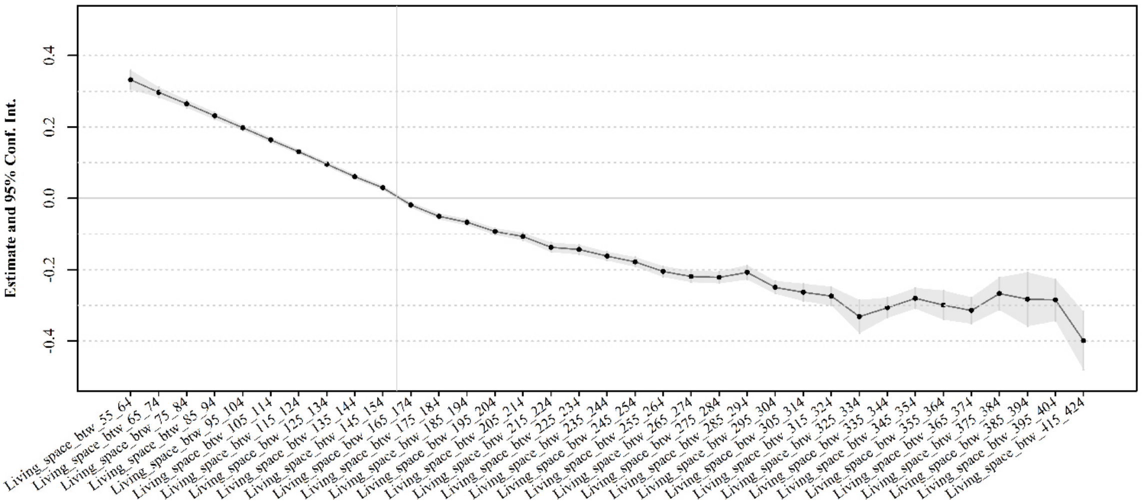
Source: Author's illustration based on INKAR. Map Data: @GeoBasis-de/BKG 2019.

Figure A 1 Regional distribution of district types in Germany.

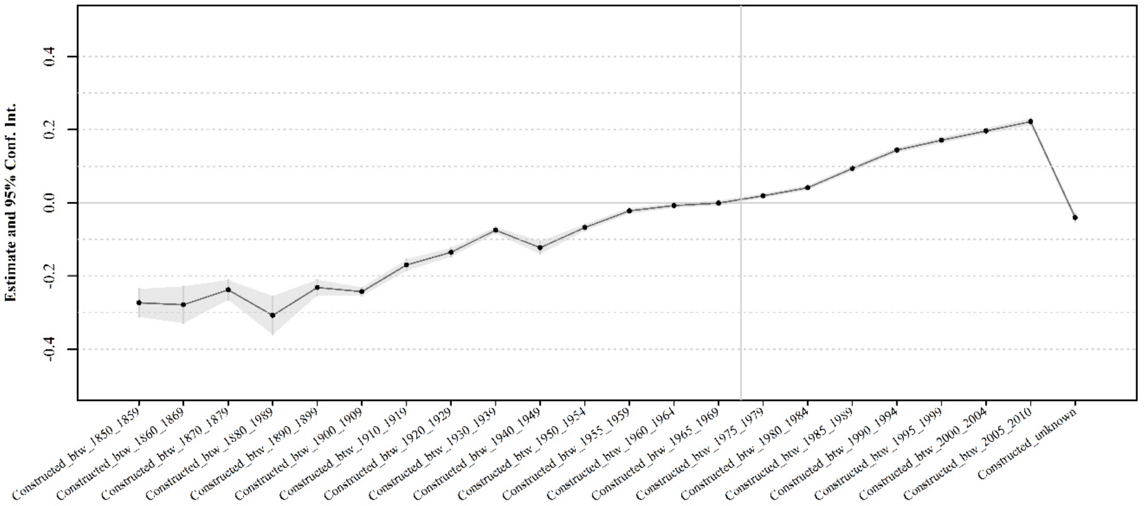
(1) Price effects of lot size categories, compared to 490-539 m²



(2) Price effects of living space categories, compared to 155-164 m²



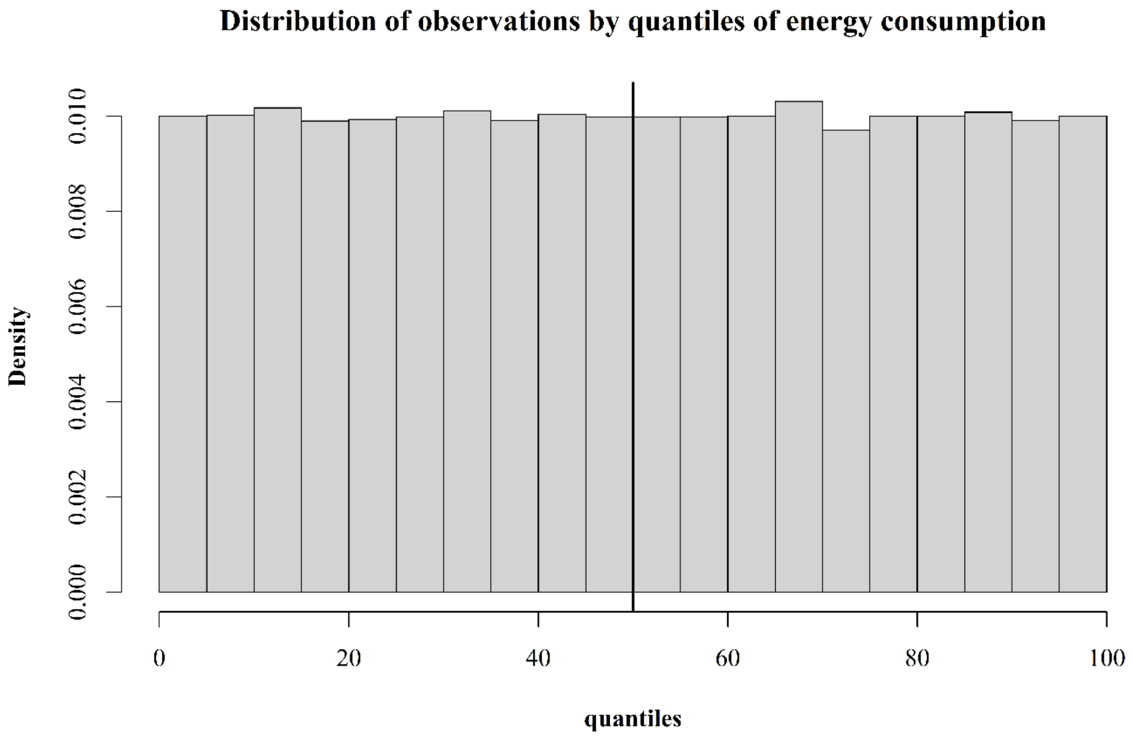
(3) Price effects of construction periods, compared to 1970-1974

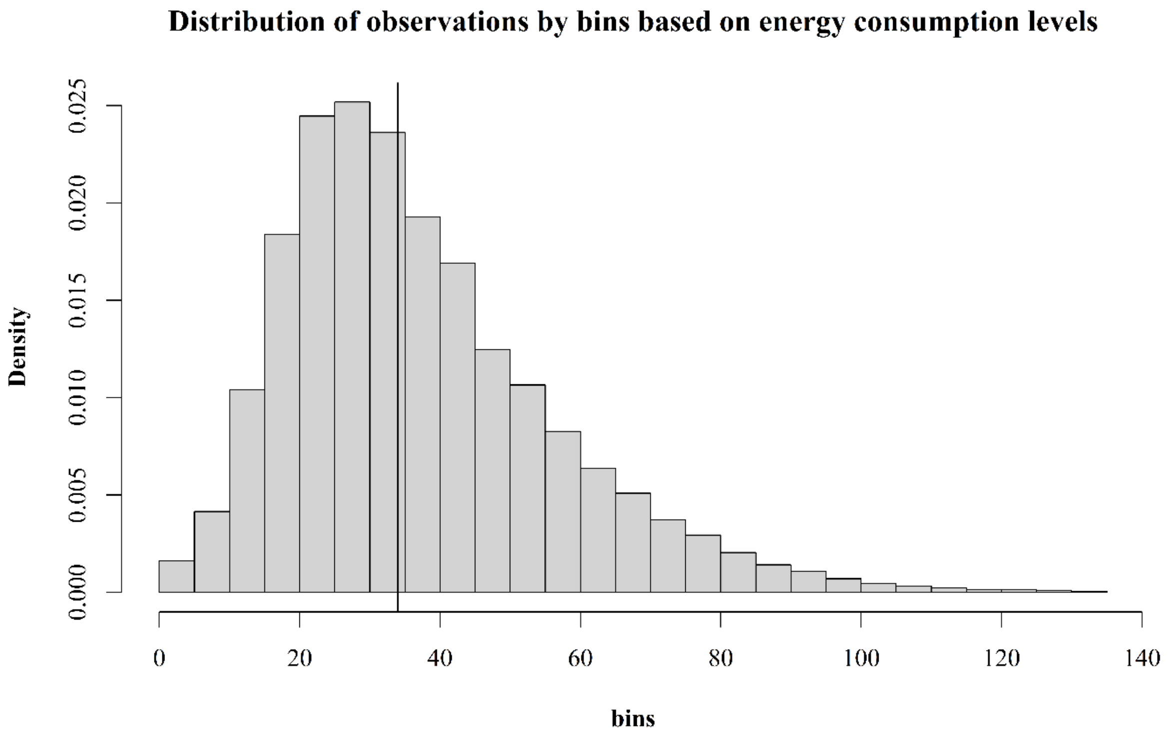


Source: Authors' calculation and illustration based on IS24, microm and INKAR

Figure A 2: Coefficient plots for living space, lot size and construction period.

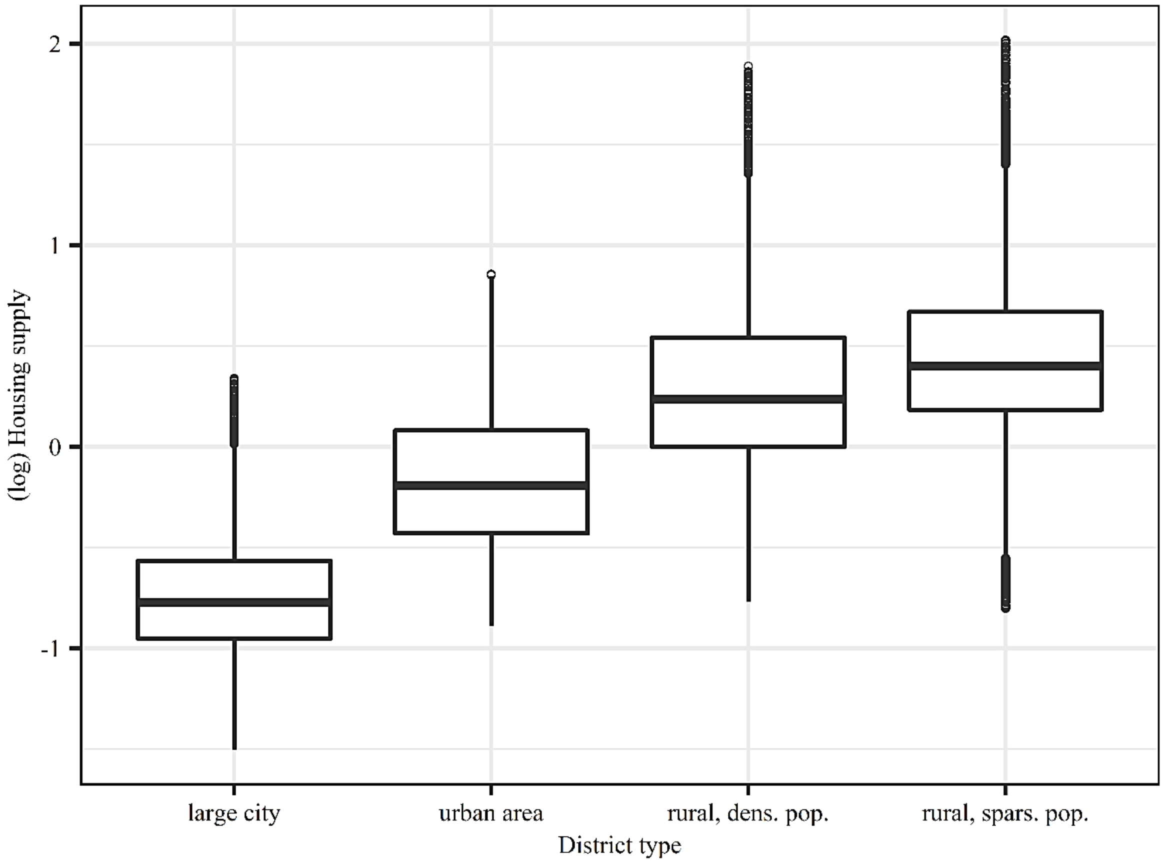
Note: Plots relate to regression results in Column (4) of Table 3.





Source: Authors' calculation and illustration based on IS24.

Figure A 3 Distribution of observations by quantiles respectively bins-based energy consumption for non-parametric specifications in Eq. (4).



Source: Authors' calculation and illustration based on IS24, microm and INKAR.

Figure A 4 Distribution of (log) housing supply across regions.

DECLARATION OF INTEREST

None

FINANCIAL DISCLOSURE

We certify that no party having a direct interest in this research's results supporting this article has or will confer a benefit on us or on any organization with which we are associated. Also, we certify that all financial and material support for this research (e.g., NIH or NHS grants) and work are clearly identified in the manuscript's title page.

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CHAPTER THREE

Inefficient Markets for Energy Efficiency? – The Efficiency Premium Puzzle in the German Rental Housing Market

by Lisa Sieger and Christoph Weber

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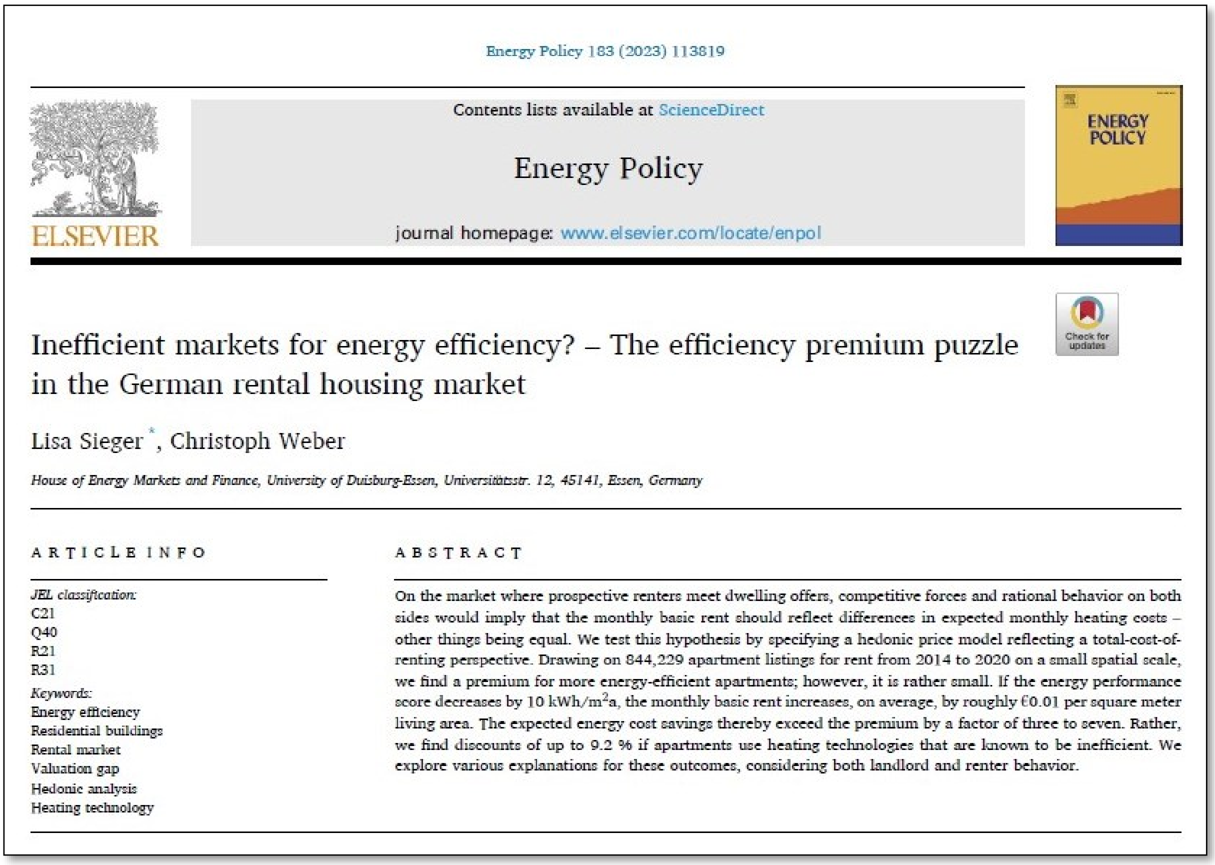

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Inefficient markets for energy efficiency? – The efficiency premium puzzle in the German rental housing market

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ABSTRACT

On the market where prospective renters meet dwelling offers, competitive forces and rational behavior on both sides would imply that the monthly basic rent should reflect differences in expected monthly heating costs – other things being equal. We test this hypothesis by specifying a hedonic price model reflecting a total-cost-of-renting perspective. Drawing on 844,229 apartment listings for rent from 2014 to 2020 on a small spatial scale, we find a premium for more energy-efficient apartments; however, it is rather small. If the energy performance score decreases by 10 kWh/m^2a, the monthly basic rent increases, on average, by roughly €0.01 per square meter living area. The expected energy cost savings thereby exceed the premium by a factor of three to seven. Rather, we find discounts of up to 9.2 % if apartments use heating technologies that are known to be inefficient. We explore various explanations for these outcomes, considering both landlord and renter behavior.

Abstract

On the market where prospective renters meet dwelling offers, competitive forces and rational behavior on both sides would imply that the monthly basic rent should reflect differences in expected monthly heating costs – other things being equal. We test this hypothesis by specifying a hedonic price model reflecting a total-cost-of-renting perspective. Drawing on 844,229 apartment listings for rent from 2014 to 2020 on a small spatial scale, we find a premium for more energy-efficient apartments; however, it is rather small. If the energy performance score decreases by 10 kWh/m²a, the monthly basic rent increases, on average, by roughly €0.01 per square meter living area. The expected energy cost savings thereby exceed the premium by a factor of three to seven. Rather, we find discounts of up to 9.2 % if apartments use heating technologies that are known to be inefficient. We explore various explanations for these outcomes, considering both landlord and renter behavior.

Keywords: Energy efficiency, residential buildings, rental market, valuation gap, hedonic analysis, heating technology

JEL Classifications: C21, Q40, R21, R31

1 Introduction

In view of ambitious pledges for climate neutrality, a focus on the decarbonization of the dwelling stock is key as buildings account for 21 % of total Greenhouse gas emissions and for 31 % of CO_2 emissions (IPCC, 2022). This requires investments in energy refurbishments, which can relate to both the building envelope and the installed heating system. When looking at rental markets, the so-called landlord-tenant dilemma (Ástmarsson et al., 2013; Bird and Hernández, 2012) has been identified as a key impediment. Incentives for more energy efficiency are split among landlords and tenants, as the latter benefit from improvements due to lower energy bills while the first must pay for refurbishments[1]. Therefore, an investment in energy efficiency is only profitable for landlords, when it can be refinanced through increased basic rents[2].

Some evidence has been put forward that investments in energy efficiency are not enough capitalized into rental incomes, implying that landlords do not have incentives to invest (Ambrose, 2015; Hope and Booth, 2014) – at least as long as their flats are still rented out quickly and generate rental income. Rising energy prices and the introduction of CO_2 pricing for heating, as done recently e.g., in Germany, might exacerbate this dilemma, as heating costs are usually borne entirely by tenants and landlords are not affected by higher energy bills (Groh et al., 2022).

Further, März et al. (2022) find a higher willingness-to-pay (WTP) of tenants for more visible features (e.g., guest toilet, fitted kitchen) compared to higher energy efficiency. Therefore, landlords with limited financial resources are more likely to invest in these visible improvements. However, to our knowledge, the rental premiums for different heating technologies have not been investigated so far – albeit these are more tangible characteristics than energy efficiency ratings.

Replacing inefficient and environmentally unfriendly heating technologies with greener alternatives could yet be worthwhile for landlords. The federal support for efficient buildings (BEG EM, 2022) promotes both the optimization of existing heating systems and the replacement of old oil or night storage heaters with new heat pumps or renewable energy heating systems. The maximum subsidy rate, e.g., for heat pumps, is up to 40 % and the maximum limit of eligible costs is €60,000 per residential unit.

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[1] At least in a framework, where tenants pay the energy bills (which is the case in Germany). For detailed information, see Appendix C.

[2] Basic rent describes the net cold rent without including any auxiliary costs (like heating or other utility costs).

Correspondingly, the core objective of this paper is to gather detailed empirical insights into the financial valuation of both energy efficiency and heating technologies in view of identifying promising policy interventions. We thereby use a detailed dataset on rental offers in the largest German federal state and investigate two key issues relevant for implementing net zero carbon strategies in rented dwellings: 1) are direct monetary benefits for renters through increased energy efficiency adequately reflected in the basic rents? 2) are there premia for different heating systems as tangible and visible features related to decarbonization? Both aspects have important implications for decarbonization policies – as they may point at pitfalls for (so-called first-best) policy instruments traditionally advocated by economists and at potentials for interventions targeting behavioral biases. Based on our empirical results, we discuss the drivers that contribute to the observed (too) low market valuations for energy efficiency in the rental market.

This study draws on a cross-sectional dataset from 2014 to 2020 with 844,229 individual apartment listings for rent in North Rhine-Westphalia (NRW). Data is georeferenced at a 1 km^2 grid level which enables us to control for small-scale differences in neighborhood structure. We reformulate a hedonic-pricing model which determines the value of different apartment attributes to align with a total-cost-of-use perspective and estimate the resulting specification via nonlinear least squares. It allows us to compare our estimates with engineering-economics findings of cost savings. This enables us to conclude not only on the existence of a market premia for energy efficiency but to investigate the existence of a significant bias compared to a fair valuation based on saved heating costs.[3]

Our results reveal that energy efficiency is capitalized into rents; however, the premium is rather small. Expected energy cost savings based on the indications of the energy performance certificate (EPC) exceed rental premiums observed for basic rents by a factor of three to seven. We further find that flats with heating technologies considered inefficient are rented at a discount of up to 9.2 % compared to flats with gas heating – all else equal. Replacing such (inefficient) heating technologies with greener alternatives therefore not only leads to less CO_2 emissions, but also to increased attractiveness of the apartment and thus to significantly higher rental income. These findings raise questions regarding market efficiency – in the sense of the

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[3] We refer here to the concept of fair valuation as used in the finance literature (e.g., Hull, 2022), i.e., a valuation that is in line with actual market prices.

Efficient Market Hypothesis[4] (cf. Fama, 1991, 1970) which stipulates that market prices should reflect all available information.

The remainder of this paper is organized as follows. Section 2 provides an overview of related literature. Sections 3 and 4 describe the data and empirical approach. Section 5 reports regression results. Further, Section 6 discusses empirical results and different channels for inefficiencies and provides some limitations of our study. Finally, Section 7 concludes and gives policy implications.

2 Related Literature

Findings on the impact of energy efficiency on real estate sales prices are well established in the extant literature. To quantify effects of energy efficiency on prices, most studies either compare labeled with non-labeled dwellings (Brounen and Kok, 2011) or estimate impacts based on the energy efficiency rating[5] or on the energy performance score (EPS) of the building (Högberg, 2013). Many studies focus on owner-occupied dwellings (e.g., Aroul and Hansz, 2012) or private rental buildings[6] (e.g., Fuerst et al., 2016), but there are also studies on office buildings (Eichholtz et al., 2010; Newell et al., 2014) and affordable housing (Chegut et al., 2016). Results are available for various countries, inter alia USA (Kahn and Kok, 2014), Germany (Taruttis and Weber, 2022), Sweden (Cerin et al., 2014), Italy (Bisello et al., 2020) and Australia (Fuerst and Warren-Myers, 2018). All studies find positive effects on housing prices of up to 10 %.

Additionally, Myers (2019) reports that home buyers pay attention to energy costs and that a large share of the net-present value of fuel expenditures is actually capitalized into real estate prices, indicating the importance of including energy prices in this type of analysis. For a more detailed comparison of studies on effects of energy efficiency on sales prices, see Cespedes-Lopez et al. (2019), Wilkinson and Sayce (2020), and Copiello and Donati (2021).

Evidence for energy-efficiency effects on rents or rental income, respectively, in the extant literature is much sparser – mostly due to a lack of sufficient data, but also due to less importance of rental compared to sales markets in many countries. Hyland et al. (2013) were

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[4] This hypothesis has been brought up and intensively tested in the context of the finance literature on asset pricing. In the context of real estate markets, inter alia Myers (2019) and Taruttis and Weber (2022) take up this perspective. Although this hypothesis may be linked to the debate on the energy efficiency gap (e.g., Jaffe and Stavins, 1994; Allcott and Greenstone, 2012), there are some salient differences – notably in the debate on the energy efficiency gap, the reference is a (not directly observable) societally optimal level of energy efficiency investments.

[5] E.g., on a scale from A to G.

[6] Houses, which are directly sold as ready-to-let.

among the first to consider the impact of energy efficiency not only on sales but also on rental prices. They examine the Irish real estate market and find positive effects for both sales and rents; however, effects are stronger in the sales segment with a green premium of about 9 % compared to a green rent premium of 1.9 %.

Cajias and Piazolo (2013) report results in a same range for the German residential market. Further, in a similar framework, Kholodilin et al. (2017) also find that energy efficiency is capitalized into rents in the Berlin housing market. In a more recent study, März et al. (2022) investigate the residential rental market in the German city of Wuppertal, using small-scale spatial data. Their results show a positive rental premium as well; however, it appears to be rather small especially in relation to other (visible) apartment characteristics. Additionally, Groh et al. (2022) use a semi-log specification for a hedonic-price model on similar data and conclude that the monetary benefit resulting from rent increases is clearly not enough to offset the costs of retrofitting measures. Further, Galvin (2023b, 2023a) investigates the sales and rental market and estimates effects for pre-war and post-war apartments and finds that the market mostly fails to reward energy efficiency for property owners, buyers and tenants.

Besides the many studies on the effects of energy efficiency on sales and rental prices, there are hardly any studies that examine the influence of different heating technologies on the respective prices. Using detailed Finnish register data, Harjunen and Liski (2014) investigate how heating technologies capitalize into house values and thereby focus on electric versus district heating only. They find evidence that houses equipped with district heating will sell at a premium of roughly €20,000, which corresponds to the capitalized value-difference in the cost of using the two technologies.

For the German residential real estate market in 2015, Hahn et al. (2018) examine price impacts of distinct types of heating technologies and mainly focus on whether the green premium of energy efficiency is outweighed by a "brown discount" if certain types of heating systems are used. They thereby distinguish between three baskets: "standard technologies", "green technologies" and "brown technologies".

They find that the discount for "brown technologies" is larger compared to the premium for "green technologies". Further, they find larger effects in the sales compared to the rental market and conclude that rental markets respond more gently towards heating technology features. They also note that energy efficiency effects should only be interpreted together with impacts of different heating technologies.

The focus on the relative premium for energy-efficient or green rentals in the extant literature leaves yet open the question on the actual valuation gap for energy efficiency in rental offers. By applying a total-cost-of-use perspective, we add to the extant literature by immediately comparing the rental premia for energy efficiency both to the actual cost savings for renters and to the (potential) cost of energy retrofit investments for landlords. According to Ambrose (2015) and Hope and Booth (2014), inter alia the lack of direct financial incentives deter private landlords from investing in energy efficiency measures.

Our empirical setting offers moreover the possibility to investigate effects related to fuel price changes – which point at the potential impact of increased carbon taxes. Due to our detailed dataset, we are also capable to estimate price effects for various individual heating technologies which, to our knowledge, so far have only been assessed in a very limited manner (cf. Hahn et al., 2018; Harjunen and Liski, 2014).

On the market where prospective renters meet the dwelling offers, competitive forces and rational behavior on both sides would imply that the monthly basic rent should reflect (with opposite sign) differences in expected monthly heating costs – other things being equal. Since the empirical findings contradict this hypothesis, we additionally discuss the potential channels for explaining these inefficiencies in view of identifying policy instruments to close the valuation gap – or to foster ambitious decarbonization objectives by taking behavioral biases into account and thereby also add to the extant literature.

3 Data

Our dataset combines data from three sources, representing neighborhood-level population characteristics and micro-level information on apartments entering the market for rent. The first database, *RWI-GEO-RED* (RWI and ImmobilienScout24, 2021), provides micro-level information on asking rents for apartments advertised on the internet platform *ImmobilienScout24.de*, which is the largest in Germany with a self-reported market share above 50 %. It contains information on a variety of apartment characteristics such as living area, type, and condition of the apartment, and features like having a garden, balcony, or kitchen. A full set of variables is given in Table 1.

The second dataset, *RWI-GEO-GRID* (RWI and microm, 2020), offers socio-economic characteristics such as population density, purchasing power, and unemployment rate, compiled at the level of 1 km² grids. The data originates from *microm Micromarketing-Systeme und*

Consult GmbH, a market research company specializing in regional analysis (microm-Micromarketing-Systeme und Consult GmbH, 2019).

Table 1 Overview of variables included in our model.

Variable	Description	Unit/Values
$\mathbf{Rent_{indt}}$	monthly basic rent of apartment *i* in neighborhood *n* and district *d* at time *t*	€/m²
$\mathbf{EPS_i}$	Energy performance score, based on EPC	10 kWh/m²a
contained in vector $\boldsymbol{X_i}$		
HEATING	Factor variable, indicating the heating system of apartment *i*	13 factors in total; Reference: gas.
TYPE	Factor variable, indicating the type of apartment *i*	11 factors in total; Reference: flat.
FACILITIES	Factor variable, indicating the facilities of apartment *i*	5 factors in total; Reference: normal.
CONDITION	Factor variable, indicating the condition of apartment *i*	9 factors in total; Reference: well kept.
FLOORS_BUILD	Factor variable, indicating the number of floors of the building in which apartment *i* is located	1 to 3 (Ref.), 4 to 6, 7 to 10, more than 10, unknown
ROOMS	Factor variable, indicating the number of rooms of apartment *i*	1, 2 (Ref.), 3, 4, 5 and more
BALCONY	Factor variable, indicating the appearance of a balcony in apartment *i*	yes, no (Ref.), unknown
GARDEN	Factor variable, indicating the appearance of a garden in apartment *i*	yes, no (Ref.), unknown
KITCHEN	Factor variable, indicating the inclusion of a kitchen in apartment *i*	yes, no (Ref.), unknown
CONSTRUCTED	Factor variable, indicating the construction period of apartment *i*	5-year steps, start at 1900; Reference: 1961-1970
LIVINGAREA	Factor variable, indicating the living area of apartment *i*	10 m² steps, start at 20; Reference: 60-70 m²
MOD2000	Dummy variable, indicating whether apartment *i* was renovated in 2000 or later	yes, no (Ref.)
contained in vector $\boldsymbol{N_{nt}}$		
log(PURCHPOWER)	Purchasing power per capita	€1,000 per capita
log(POPULATION)	Population density	1,000 inhabitants per km²
UER	Unemployment rate	%
FOREIGN	Share of households with foreign household head	%
Fixed Effects		
$\boldsymbol{\tau_d}$	Regional fixed effects on NUTS3 level	53 regions in total; Reference: DUS
$\boldsymbol{\mu_t}$	Time fixed effects on quarterly-year level	27 time periods in total; Reference: Q1/2015

Source: Authors' illustration.

The third database, *INKAR*, is provided by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR 2019) and gives an indicator for different regional types according to their settlement structure at so-called NUTS3 level (401 counties in

Germany)[7]. Georeferencing in the first two datasets is provided in terms of 1 km² grids and NUTS3 regions which enables a matching of the three data sources.

After clearing the data from outliers and implausible values and further focusing on existing buildings that were at least 10 years old[8] at the time of advertisement, but built no earlier than 1900, our final dataset consists of 844,229 observations from May 2014 to December 2020 distributed over 10,050 grid cells. We use the specific cut-off in May 2014, as – according to the EnEV regulation (EnEV, 2014) – this is the date from which the disclosure of energy performance certificates has become mandatory in online advertisements. By limiting the dataset this way, we reduce the likelihood of selection bias related to the disclosure of information about the building's energy performance.

3.1 Summary statistics – overall

Table 2 gives an overview of descriptive statistics for all numerical variables. Apartments are rented for an average of 6.92 €/m² with a standard deviation of 1.91 €/m². A mean EPS of 140 kWh/m²a corresponds to E-labeled[9] apartments on a scale from A+ to H; however, even the most efficient apartments in the sample only achieve an A-label. The least efficient apartments, nevertheless, correspond to an H-label. The mean age of the advertised apartments is 56 years. Furthermore, the average apartment has a living area of 67 m² and is likely to be rented out after being online for 25 days.

Table 2 Summary statistics, full dataset.

	Unit	**Mean**	**St. Dev.**	**Median**
Basic rent	€/m²	6.92	1.91	6.47
Energy performance score	kWh/m²a	140	47	134
Living area	m²	67	20	65
Age	years	56	22	56
Duration of advertisement	days	25	32	15
Population density	inh/km²	4,804	3,404	4,037
Unemployment rate	%	10.02	4.64	9.82
Share of households with foreign household head	%	14.63	7.54	13.69
Purchasing power per capita	€/inh	21,623	3,946	20,925

Source: Authors' calculations based on RWI-GEO-GRID and RWI-GEO-RED.

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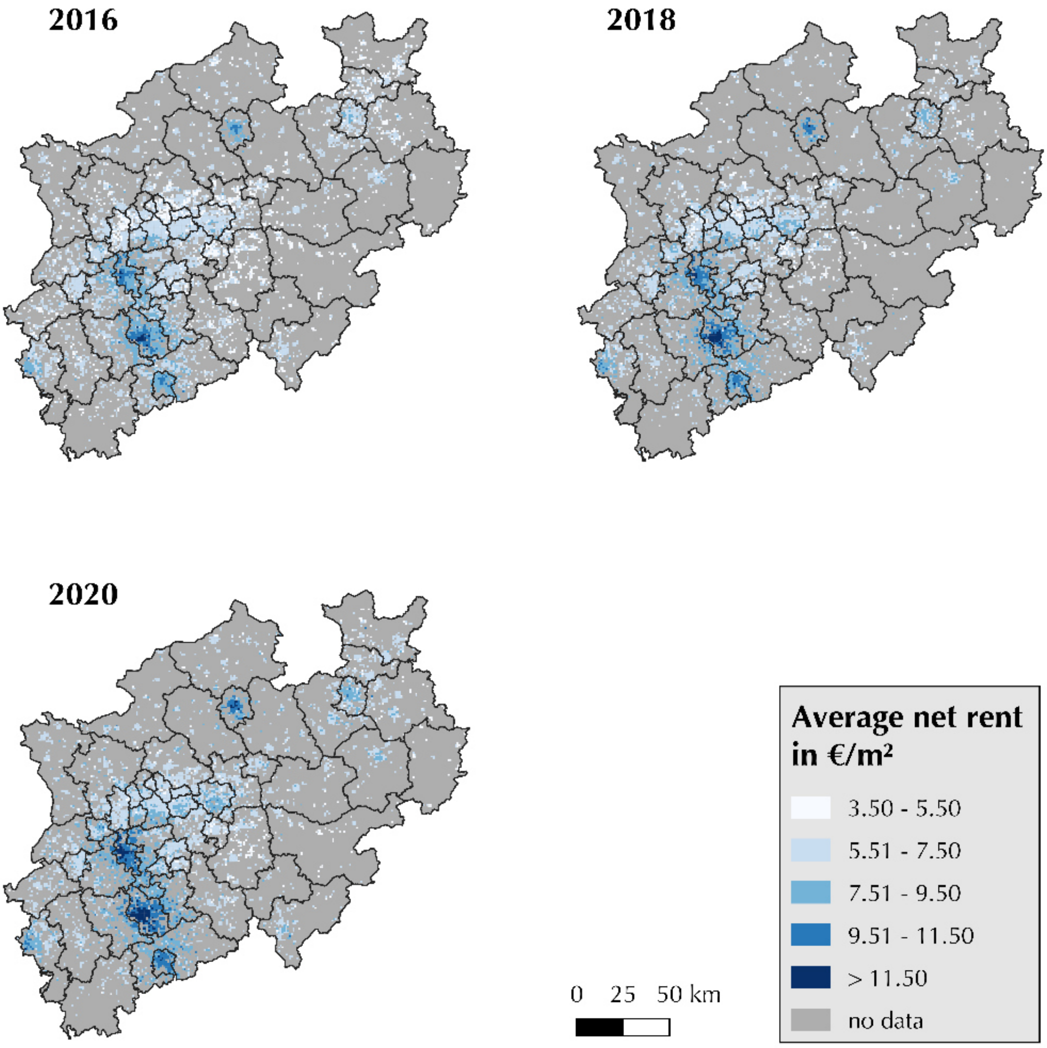
[7] The territory of the European Union is divided into hierarchical levels using the geographical system NUTS (Nomenclature des Unités territoriales statistiques). NUTS3 regions typically have a population of 150,000 to 800,000 inhabitants, which refers to districts known as Kreise or kreisfreie Städte in Germany.

[8] As we are interested in effects of energy retrofits, we focus on existing buildings only.

[9] Energy labels and corresponding energy performance scores are shown in Figure A 1.

Population density is given per 1 km² grid cell and amounts to 4,804 on average. Large numbers can be explained by the grid structure – the area of uninhabited grid cells corresponding, e.g., to large forest or water areas, is not considered when calculating the population density. Accordingly, unemployment rates, shares of households with a foreign household head, as well as purchasing power per capita are also given at the 1 km² grid level. The latter amounts to a median of about €21,000. Average unemployment rate is 10 % and the share of foreign-headed households averages 14.6 %.

The distribution of offers and corresponding average basic rents per square meter living area across NRW on grid level over time is shown in Figure 1. It is noticeable that average basic rents increased overall between 2016 and 2020. Highest average basic rents can mainly be found in the southern half of NRW, whereas the lowest ones appear in the Ruhr region and more rural areas (cf. Figure A 2).



Source: Authors' calculation and illustration based on RWI-GEO-RED. Map Data: @GeoBasis-de/BKG 2019.

Figure 1 Average basic rent per square meter living area on grid level over time.

Percentages of different heating technologies[10] with corresponding mean energy performance scores and mean age of the apartment are illustrated in Table 3. More than half of all advertised apartments have a central heating system; self-contained central heating (SCC) systems are installed in 12.7 % of all advertised dwellings. Gas and district heating follow with slightly below 6 % each.

Heating by stove and SCC are by far the most inefficient technologies in our sample with mean EPS of 158 kWh/m²a or 155 kWh/m²a, respectively. Oil heating follows with 149 kWh/m²a. With an average EPS of only 92 kWh/m²a, solar heating is the most efficient technology in our sample; however, as we only have 25 observations, this needs to be handled with appropriate care. Lastly, apartments with floor heating are the youngest with, on average, 33 years. The highest mean age of 66 years can be found for apartments with SCC as implemented heating technology.

Table 3 Percentages of heating technologies with mean energy performance scores and age.

Heating type	**Observations**	**Age (in years)**	**Energy performance score (in kWh/m²a)**	
	(in %)	**Mean**	**Mean**	**St. Dev.**
Gas heating	5.98	54	139	48
CHP [a]	0.06	50	131	56
Electric Heating	0.34	59	122	50
SCC[b]	12.72	66	155	50
District heating	5.69	56	126	42
Floor heating	1.40	33	114	41
Wood pellet heating	0.01	55	131	48
Night storage heating	0.99	61	121	44
Heating by Stove	0.12	60	158	63
Oil heating	1.53	53	149	43
Solar	0.0002	51	92	25
Heat pump	0.04	59	111	47
Central heating	55.06	54	139	46
unknown	16.06	59	144	47

[a]Combined Heat and Power; [b]Self-contained central heating.

Source: Authors' calculations based on RWI-GEO-RED.

3.2 Summary statistics – Subsamples

To demonstrate variations in socioeconomic characteristics at grid level, Figure 2 illustrates the population density for 2018. Dusseldorf and Cologne as well as most large cities located in the Ruhr region show high population densities. Furthermore, urban centers and agglomerations

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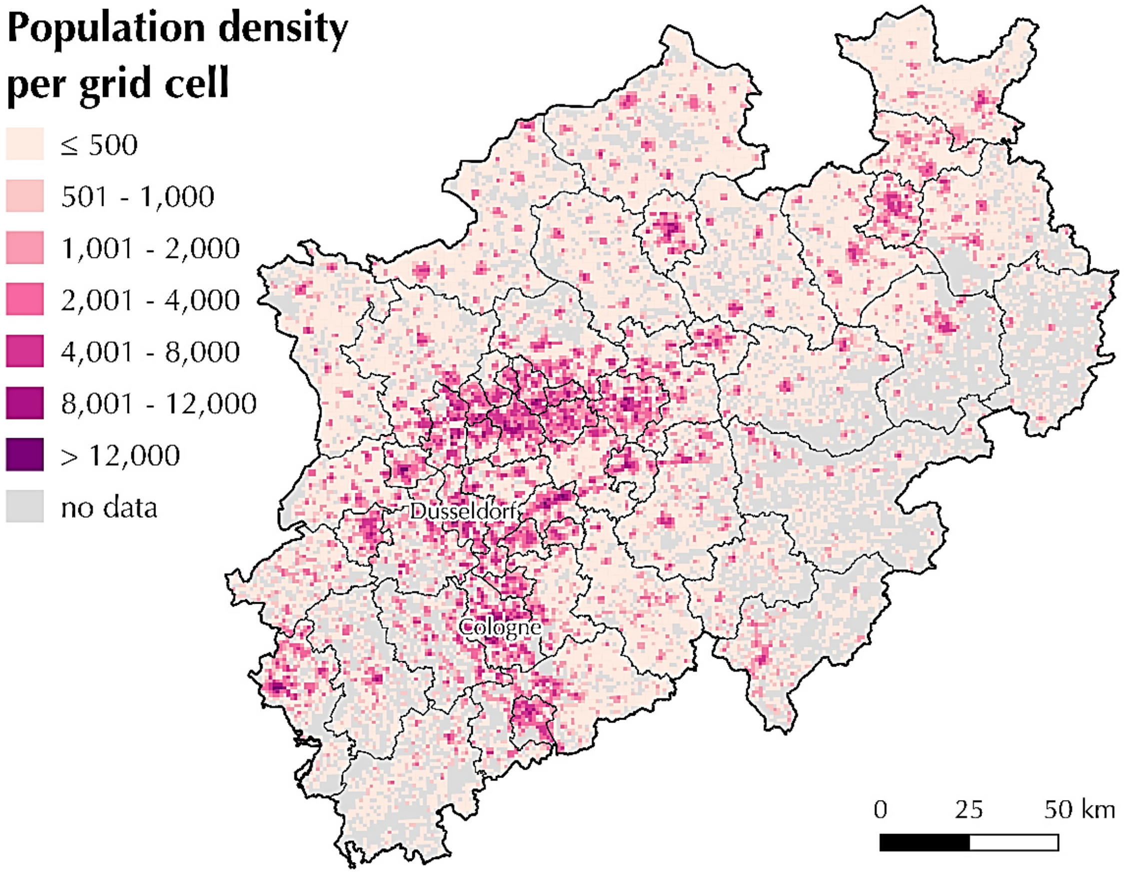
[10] The categorization of heating technologies is taken from the rental advertisements. It is partly based on the energy source, but partly also on other features.

can be clearly identified. When comparing Figures 1 and 2, overlaps in the grid cells can be spotted: Rentals are found primarily where population densities are high.

Furthermore, the EPCs deserve closer attention, as there are two types of EPCs in Germany – demand certificates and consumption certificates. Due to different assessment methods, both types provide different indications on the energy efficiency of a building – the first is calculated using engineering estimates based on technical building data; the latter is based on average consumption data of the last three years. This can result in varying expectations of new tenants in terms of energy costs, which in turn can lead to different WTP for energy efficiency (cf. Taruttis and Weber, 2022).



Source: Authors' calculation and illustration based on RWI-GEO-GRID. Map Data: @GeoBasis-de/BKG 2019.

Figure 2 Population density per 1 km² grid cell (2018).

Summary statistics are given in Table A 1. In our sample approximately 30 % of all apartments are certified based on (calculated) demand; the other 70 % are labeled based on (observed) consumption. No major differences occur in terms of living area and advertisement duration. Moreover, the difference in average basic rents between subsamples only amounts to €0.14. Nonetheless, apartments with demand certificates are, on average, 4 years older and the mean EPS is 14 kWh/m²a higher compared to apartments in the subsample of consumption certificates. This is in line with the statement of the German Consumer Association that the final energy performance score indicated in demand certificates is higher than in consumption certificates[11] (Verbraucherzentrale, 2022).

Lastly, summary statistics over time are shown in Table 4. Most flats were advertised in 2015, least flats in 2018. Rental prices increased from 6.47 €/m² in 2014 to 7.66 €/m² in 2020. Means of living area and age have remained constant, while the mean EPS decreased by 10 kWh/m²a.

Table 4 Summary statistics over time.

	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Observations	113,790	176,326	134,300	107,256	72,953	117,982	121,622
In %	13.48	20.89	15.91	12.71	8.64	13.98	14.41
Basic rent	6.47	6.48	6.69	6.86	7.17	7.39	7.67
	(1.77)	(1.73)	(1.75)	(1.88)	(1.95)	(1.93)	(2.07)
Energy performance score	145	143	144	139	139	136	135
	(47)	(47)	(48)	(47)	(48)	(47)	(46)
Living area	69	69	68	68	66	66	66
	(20)	(20)	(20)	(20)	(19)	(19)	(20)
Age	57	56	56	55	56	56	56
	(23)	(23)	(22)	(23)	(22)	(22)	(22)
Duration of advertisement	23	32	23	23	27	21	25
	(26)	(42)	(26)	(28)	(35)	(29)	(32)

Note: St. Dev. In parentheses.
Source: Authors' calculations based on RWI-GEO-RED.

4 Empirical Approach

As appartements are diverse and may differ by numerous characteristics, their prices are most appropriately modelled using the hedonic pricing approach in the sense of Lancaster (1966) and Rosen (1974). This approach characterizes apartments as a bundle of attributes and assigns prices to each attribute. It hence allows to explicitly investigate effects of energy efficiency and effects of different heating technologies on rents while controlling for other building and neighborhood characteristics. Specifically, we combine this hedonic approach with a total-cost-of-use (TCU) framework (cf. Ellram, 1993) to validate our results against engineering-economic estimates of heating cost savings and relate those to investment costs for energy refurbishments.

As energy efficiency by itself does not provide direct utility to tenants, we stipulate that the tenants' WTP for energy efficiency should reflect the impact of energy efficiency on total expenditures in (informationally) efficient markets rather than being a hedonic attribute

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[11] This issue is also referred to as the "prebound effect" and has already been discussed in the literature (cf. notably Sunikka-Blank and Galvin, 2012).

affecting the basic rent[12]. The total cost of renting a property for the tenant generally equals the sum of basic rent and auxiliary costs that cover heating and other utility costs, e.g., garbage disposal, road cleaning and winter service. Electricity costs mainly depend on tenants' behavior and their own appliances and equipment and are separately billed to tenants in Germany; therefore, they are not considered here[13]. Other auxiliary costs are neither adjustable by landlords nor by tenants, which is why we focus on heating costs and basic rents only. The expected total costs can then be written as:

$$E(Total\ Costs_{ie}) = Rent(X_i, N_i) + E(P_e * EPS_i) \tag{1}$$

The basic rent thereby depends on hedonic (*X*), and neighborhood (*N*) characteristics of apartment *i*. Expected energy costs are given by the price for heating energy (P_e) multiplied by the energy performance score (*EPS*) measured in energy units as a proxy for the expected quantity of energy used. P_e further depends on the source of heating energy, and the *EPS* may vary according to the type of EPC. This equation implies that improved energy efficiency directly impacts the tenants' total costs and that their WTP per unit of improvement of energy efficiency directly corresponds to the energy price[14]. Under this hypothesis, the landlord-tenant dilemma is absent at least on the market for new rentals, since an improvement in energy efficiency would translate into a corresponding increased WTP on the basic rent – other things being equivalent. Consequently, under these assumptions of frictionless markets with perfect information, energy efficiency investments are profitable for landlords if the savings in energy costs provide a sufficient payback.

To capture possible market imperfections, we may replace the energy price in Eq. (1) by an empirical parameter β. Describing the impact of hedonic and neighborhood characteristics on apartment rents by a widely used semi-logarithmic specification then leads to the following relationship giving the costs for renting apartment *i* in neighborhood *n* and district *d* at time *t*:

$$ln\ (Rent_{indt} + \beta EPS_i) = \alpha + \gamma \boldsymbol{X}_i + \delta \boldsymbol{N}_{nt} + \mu_t + \tau_d + \varepsilon_{indt} \tag{2}$$

The left-hand side of Eq. (2) now directly reflects that changes in the energy performance linearly impact the heating costs (other things being equal) - and consequently also the total

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[12] Assuming that there is no systematic bias or systematic measurement error in the energy performance score. A systematic bias as notably suggested by Sunikka-Blank and Galvin (2012) would require the use of specific statistical techniques. We leave such an extension to further research.

[13] The exception are costs related to electric heating systems which obviously depend on the building energy efficiency and are therefore considered here as part of the gross rent. Yet this is relevant for about 5 % of all households in Germany.

[14] In case of full information.

costs for living in an apartment. This expression thus indicates that (heating) energy is an input for the creation of a household service, namely a heated dwelling. Therefore, rather than treating energy efficiency as an attribute of the dwelling, the corresponding cost is part of the total cost associated with living in an apartment of given characteristics $\boldsymbol{X}_i$ and $\boldsymbol{N}_{nt}$. We rearrange terms in Eq. (2) to obtain the monthly basic rent, measured in euro per square meter of living area, as dependent variable on the left-hand side and estimate Eq. (3) using nonlinear least squares:

$$Rent_{indt} = -\beta EPS_i + exp\,(\alpha + \gamma \boldsymbol{X}_i + \delta \boldsymbol{N}_{nt} + \tau_d + \mu_t) + \varepsilon'_{indt} \tag{3}$$

EPS_i is the main explanatory variable of interest and provides a measure of the energy performance[15] of apartment i in 10 kWh/m²a. Heating type information is included in vector $\boldsymbol{X}_i$. This vector also contains various hedonic characteristics, such as living area, number of rooms as well as different indicators for comfort and quality of the apartment; vector $\boldsymbol{N}_{nt}$ includes neighborhood characteristics on grid level, e.g., (log) population density and (log) purchasing power per capita.

To control for omitted variable bias, we add regional[16] fixed effects τ_d on NUTS3 level, which is equivalent to counties in North Rhine-Westphalia, and seasonal (i.e., quarter-yearly) fixed effects μ_t to our model. Finally, ε'_{indt} is the error term of the regression for which we report cluster-robust standard errors to correct for temporal and spatial correlation between subdivisions (Angrist and Pischke, 2008).

The coefficient β is expected to be positive because the lowering impact of energy consumption/demand on rents is already included in the negative sign after rearrangement. Interpretation is straight forward: if the energy performance score decreases – and energy efficiency thus increases – by 10 kWh/m²a, the monthly basic rent increases by β euro per square meter. Based on the estimated coefficient $\gamma_{heating}$, the relative impact of a specific heating technology on rents compared to apartments with gas heating is given by approximately 100 * $\gamma_{heating}$ % since in that part we use a semi-log specification where estimated parameters correspond to semi-elasticities.

We start our analysis by estimating a baseline model in which we include only our main variable of interest and all hedonic characteristics, first without and then with the installed heating technology indicator. Next, we gradually add neighborhood characteristics, seasonal and

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[15] Based on the measured energy consumption or the engineering estimate of the energy demand for heating, respectively.

[16] Thereby, we adhere to what the old adage already defines: the three most important determinants of real estate valuation are "location, location, location" (Eichholtz et al., 2010).

regional fixed effects to our regression. By gradually adding more variables, or omitting relevant variables in earlier stages, we simultaneously test the sensitivity of the effect of energy efficiency on rental prices.

To check the robustness of our results, we additionally run subsample regressions according to regional types and years of advertisement. A detailed analysis is further done for EPC types and different heating technologies. We thereby create comparable results to those previously found for owner-occupied single-family homes (cf. Taruttis and Weber, 2022).

Finally, we calculate an energy multiplier M_e as given by Eq. (4) to easily compare rental premia with energy cost savings and corresponding investment costs that are required to achieve a specific level of energy efficiency.

$$M_e = \frac{12 \times \beta}{P_e} \tag{4}$$

Our multiplier describes the monetary increase in yearly basic rents per one euro decrease in annual energy costs given that the EPS is measured in annual energy consumption/demand per square meter. The average energy price for heating (P_e) is thereby computed as a weighted average based on the shares of energy carriers used for heating.[17]

5 Results

5.1 Main regression analysis

Regression results for our model as denoted by Eq. (3) are given in Table 5[18]. Column (1) shows the baseline specification without fixed effects, neighborhood characteristics and energy-related controls other than energy performance. A factor variable indicating the installed heating system is added in column (2), neighborhood characteristics in column (3). Finally, time-fixed effects on quarterly-year level are added in column (4) and regional-fixed effects on NUTS3 level in column (5). Further, to control for heteroskedasticity, reported standard errors are clustered on grid level.

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[17] We have also tested a regression specification with the parameter β being replaced by specific values per heating-type. The main effect for gas heating was yet rather similar and for other heating types results were difficult to interpret – notably for infrequent heating types. Therefore, we subsequently focus on the average β.

[18] We refrain to include the exact p-values for the regression coefficients directly in the table to improve readability and since most of them are anyhow very close to zero. Yet they are available from the authors on request.

If the EPS decreases by 10 kWh/m²a, the monthly basic rent increases, on average, by roughly 0.01 €/m². These results do not vary much between different specifications as estimates marginally increase when including other energy-related variables and neighborhood characteristics and decrease again slightly below €0.01 when including fixed effects.

The overall difference in effects between the baseline specification in column (1) and the full model in column (5) only amounts to €0.0005 per 10 kWh/m²a. Results are significant at the 0.1 %-level in all specifications. Furthermore, if an apartment was renovated in 2000 or later, rents are approximately 1.4 % higher compared to non- or earlier renovated dwellings. Other intrinsic dwelling characteristics show expected outcomes.

Impacts of different heating technologies compared to gas heating are substantial albeit diverse. Apartments with night storage heating are rented out at a discount of about 7 %, regardless of the chosen specification, with results being significant at the 0.1 %-level. Effects of electric heating and heating by stove are also more or less constant among specifications and show a discount of 3.8 % to 4.6 % and 5.1 % to 6.2 %, respectively. Furthermore, apartments with SCC or heat pumps are also rented out at a discount compared to apartments with gas heating. For the full model (column (5)), these discounts amount to 1.2 % or 2.7 %, respectively.

For apartments that are connected to district heating, results show a discount in all specifications without regional-fixed effects. But as regression diagnostics indicate the full model to be the most reliable one, apartments with district heating report a small rent premium of 0.4 % compared to gas heated apartments. Buildings that are advertised with the use of CHP or central heating, as well as flats with floor or wood pellet heating also show premia of up to 0.7 % and up to 3.3 %, respectively. Moreover, apartments with solar heating show a premium, too; however, as there are only few observations, results need to be interpreted with appropriate care. Overall, gas heating turns out to be preferred over other conventional heating systems, whereas innovative heating systems with lower carbon footprint like CHP or wood pellet heating are rented out at a premium.

An exception to the rule are yet dwellings with heat pumps which rent out at a discount although such heatings are expected to play a major role in the decarbonization strategies of the German government. This might be as well due to a limited number of observations or a possible fear of prospective tenants (because of their lack of knowledge) that a heat pump will be too expensive because of the related electricity costs.

Table 5 Main regression results for Eq. (3) – full sample.

Dependent Var.: Basic rent in €/m²	**NLS (1)**	**(2)**	**(3)**	**(4)**	**(5)**
Energy performance score	0.0101***	0.0112***	0.0139***	0.0092***	0.0096***
(in 10 kWh/m²a)	[0.0004]	[0.0004]	[0.0003]	[0.0003]	[0.0002]
Heating system, reference: gas heating					
CHP		0.0315**	0.0314***	0.0276***	0.0071*
		[0.0109]	[0.0062]	[0.0060]	[0.0035]
Electric heating		-0.0464***	-0.0389***	-0.0382***	-0.0437***
		[0.0043]	[0.0030]	[0.0030]	[0.0022]
SCC		-0.0029*	-0.0122***	-0.0087***	-0.0115***
		[0.0013]	[0.0010]	[0.0010]	[0.0008]
District heating		-0.0206***	-0.0057***	-0.0060***	0.0039***
		[0.0015]	[0.0012]	[0.0011]	[0.0009]
Floor heating		0.0689***	0.0345***	0.0309***	0.0329***
		[0.0023]	[0.0017]	[0.0017]	[0.0013]
Wood pellet		-0.0328*	0.0154	0.0142	0.0281***
		[0.0149]	[0.0125]	[0.0115]	[0.0044]
Night storage		-0.0705***	-0.0714***	-0.0698***	-0.0695***
		[0.0026]	[0.0020]	[0.0019]	[0.0015]
Heating by stove		-0.0575***	-0.0624***	-0.0554***	-0.0513***
		[0.0061]	[0.0044]	[0.0042]	[0.0028]
Oil heating		0.0279***	0.0097***	0.0096***	0.0037**
		[0.0023]	[0.0018]	[0.0017]	[0.0013]
Solar		0.0788*	0.0756*	0.0833**	0.0357***
		[0.0380]	[0.0328]	[0.0274]	[0.0053]
Heat pump		-0.0746***	-0.0271***	-0.0164*	-0.0270***
		[0.0092]	[0.0068]	[0.0068]	[0.0033]
Central heating		0.0248***	0.0085***	0.0109***	0.0046***
		[0.0011]	[0.0008]	[0.0008]	[0.0006]
Last renovated in 2000 or later	0.0035***	0.0015*	0.0018**	0.0146***	0.0137***
	[0.0008]	[0.0008]	[0.0006]	[0.0006]	[0.0004]
Neighborhood characteristics					
Population density			0.0749***	0.0751***	0.0407***
			[0.0003]	[0.0003]	[0.0003]
Purchasing power per capita			0.8497***	0.8870***	0.3534***
			[0.0021]	[0.0021]	[0.0022]
Unemployment rate			-0.0041***	-0.0011***	-0.0019***
			[0.0001]	[0.0001]	[0.0001]
Share of households with			0.0102***	0.0088***	0.0017***
foreign head			[4.24e-06]	[3.74e-05]	[3.36e-05]
Constant	1.8270***	1.8191***	-7.3496***		
	[0.0015]	[0.0018]	[0.0215]		
Condition, Facilities. Apt. Type	*yes*	*yes*	*yes*	*yes*	*yes*
Balcony, Garden, Kitchen	*yes*	*yes*	*yes*	*yes*	*yes*
No. of rooms, floors	*yes*	*yes*	*yes*	*yes*	*yes*
Living area	*yes*	*yes*	*yes*	*yes*	*yes*
Construction period	*yes*	*yes*	*yes*	*yes*	*yes*
Season FE (quarterly-year)	*no*	*no*	*no*	*yes*	*yes*
Region FE (NUTS3)	*no*	*no*	*no*	*no*	*yes*
Pseudo-R²	0.302	0.312	0.612	0.636	0.784
RMSE	1.594	1.583	1.190	1.152	0.888
Observations	844,229	844,229	844,229	844,229	844,229

Note: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Pseudo-R² is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE is in €/m².

Source: Authors' calculations based RWI-GEO-RED and RWI-GEO-GRID.

5.2 Detailed Analysis

Results for the EPC and heating type subsamples are presented below. The results of the robustness checks for the annual and regional subsamples are included in Appendix B.

5.2.1 EPC-type Subsamples

Regression results for subsamples by EPC-types are shown in Table 6. Both regressions still include all control variables and fixed effects. In the consumption subsample, coefficients for the energy performance score are only slightly smaller compared to the full model. If energy consumption decreases by 10 kWh/m²a, monthly basic rents increase on average by 0.008 €/m². In the demand subsample, however, effects are twice as large: If energy demand decreases by 10 kWh/m²a, monthly basic rents increase on average by 0.016 €/m².

Table 6 Regression results for EPC type subsamples.

Dependent Var.: **Basic rent in €/m²**	**EPC subsamples** **Demand certificate**	**Consumption certificate**
Energy performance score (in 10 kWh/m²a)	0.0163*** [0.0004]	0.0075*** [0.0003]
Season FE (quarterly-year)	*yes*	*yes*
Region FE (NUTS3)	*yes*	*yes*
Pseudo-R²	0.772	0.792
RMSE	0.901	0.875
Observations	240,545	603,684

Note: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Only estimates of interest are shown; however, all control variables were included in the regression. Full results, analogous to main regression results in Table 5 are presented in Table A 2. Pseudo-R² is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE is in €/m².

Source: Authors' calculations based RWI-GEO-RED and RWI-GEO-GRID.

5.2.2 Heating-technology Subsamples

Three different subsamples based on the installed heating technology were constructed. "Standard" includes flats with central heating, gas heating and floor heating. "Dirty" describes inefficient and environmental unfriendly technologies, namely night storage heating, oil heating, heating by stove and SCC. Lastly, solar heating, CHP, heating pumps, wood pellet and district heating belong to the "Green" subsample (cf. Hahn et al., 2018). Further, all samples were again split according to the EPC, as previous results show large differences between both types of certificates. Regression results are shown in Table 7.

Energy efficiency effects on basic rents are largest in the standard subsample for both certificate types. If the energy performance score decreases by 10 kWh/m²a, the basic rent increases, on average, by 0.008 €/m^2 when the apartment has a consumption certificate and by 0.02 €/m^2 if it has a demand certificate. The latter is only slightly larger compared to effects in the green subsample; however, results in the green subsample are negative yet insignificant, if the apartment has a consumption certificate.

Table 7 Regression results for heating technology subsamples.

	Heating technology subsamples					
	Standard		**Dirty**		**Green**	
Dependent Var.: Basic rent in €/m^2	**Demand certificate**	**Consumption certificate**	**Demand certificate**	**Consumption certificate**	**Demand certificate**	**Consumption certificate**
Energy performance score	0.0206***	0.0082***	0.0091***	-0.0051***	0.0178***	-0.0023
(in 10 kWh/m^{2}a)	[0.0005]	[0.0004]	[0.0008]	[0.0008]	[0.0022]	[0.0015]
Season FE (quarterly-year)	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Region FE (NUTS3)	*yes*	*yes*	*yes*	*yes*	*no*	*no*
Pseudo-R^2	0.751	0.776	0.778	0.790	1.10	1.07
RMSE	0.958	0.934	0.878	0.861	0.724	0.679
Observations	144,404	382,726	48,348	81,327	10,875	38,079

Note: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Only estimates of interest are shown; however, all control variables were included in the regression. Standard-technology subsample includes Central, Floor, and Gas. Dirty-technology subsample includes Oil, Stove, SCC and Night storage. Green-technology subsample includes CHP, Solar, Pump, Pellet and District. Pseudo-R^2 is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE is in €/m^2.
Source: Authors' calculations based RWI-GEO-RED and RWI-GEO-GRID.

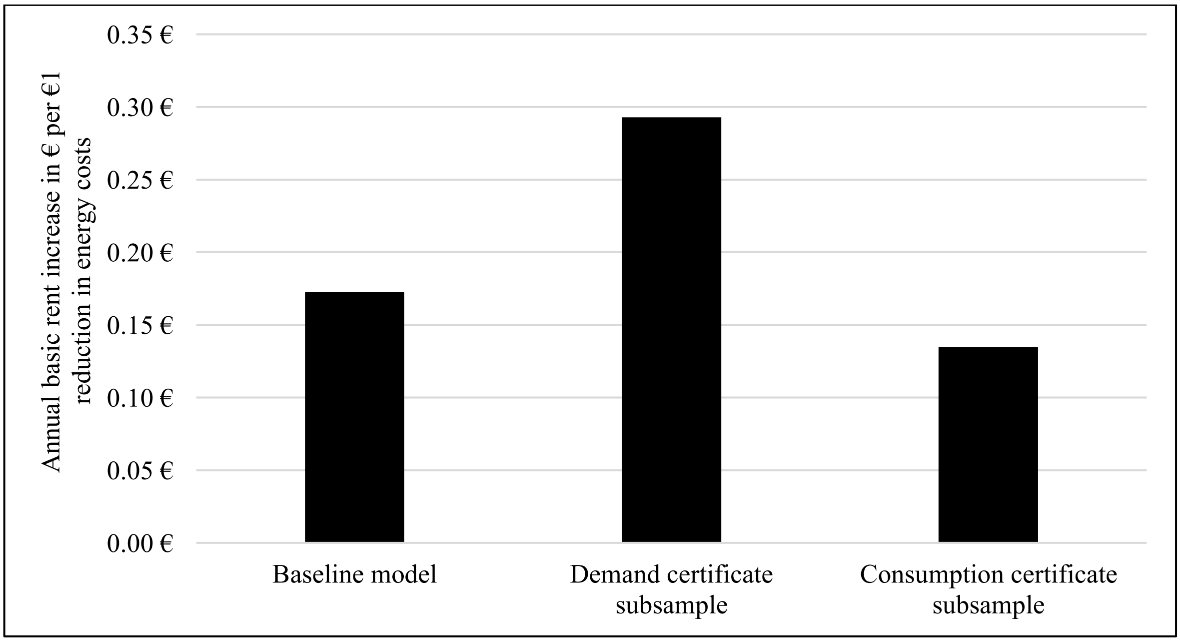
Contrary, in the dirty subsample, we even find statistically significant negative effects for apartments with consumption certificates. We therefore tentatively conclude that efficiency improvements don't pay back as long as such inefficient technologies are installed. Nevertheless, even in the dirty technology subsample, effects are positive and significant if the flat has a demand certificate; however, effects are more than two times smaller compared to the standard technology subsample.

5.3 Energy multiplier

As an indicator for the size of rental benefits compared to corresponding energy cost savings, we calculate an energy multiplier as given by Eq. (4). Since energy bills usually must be paid on a yearly basis, the multiplier also shows yearly basic rent increases. The energy price for heating used to calculate the multiplier is the weighted average energy price over the whole sample period; it amounts to 0.067 €/kWh. More detailed prices for different energy carriers over time according to the Federal Ministry for Economic Affairs and Energy (BMWi, 2020) are shown in Figure A 3.

Figure 3 illustrates the multiplier for our baseline model in comparison with results for the EPC-type subsamples. In our baseline model, one euro decrease in annual energy costs translates into yearly basic rent increases of €0.17. More promising results are found in the demand certificate subsample, where the rental benefit for the weighted average energy price amounts to €0.29. In the consumption certificate subsample, however, the reduction in energy costs of one euro translates into a benefit of only €0.13.

Based on empirical data of actual renovations, the Arbeitsgemeinschaft für zeitgemäßes Bauen (ARGE, 2022, p. 60) indicates a range of 100 €/m² up to 680 €/m² of additional investment costs[19] for energy retrofits, depending on the initial condition and the target standard of the building. A frequently advocated target efficiency is the E100 level[20], which implies an improvement in the energy performance score by about 125 kWh/m²a.[21]. The energy-related costs for reaching the E100 level amount to approximately 140 to 290 €/m² (ARGE, 2022, p. 60). However, it is difficult to state exact costs, since the actual costs depend on many factors, especially on the building under consideration.



Source: Authors' calculation and illustration.

Figure 3 Annual basic rent increases per €1 reduction in energy costs.

Note: The weighted average energy price for heating of 0.067 €/kWh was used for calculations.

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[19] Values relate to multi-family buildings – not to single apartments – constructed between 1948 to 1979, assuming an unrenovated building.

[20] The "Efficiency House 100" – E100 – is a fictitious building that reaches exactly 100 % of the permissible energy demand according to the EnEV (2009). The calculated permissible energy demand varies for each building (e.g., depending on the building geometry); there is no fixed value in kWh/m²a.

[21] Own calculations. According to IWU (2015), a newly built multi-family house with gas heating constructed between 2010 and 2015 meeting the EnEV (2009) standard has a primary energy demand of 123 kWh/m²a (p. 116). For the unrenovated multi-family houses under consideration (constructed between 1949 and 1978), a (consumption adjusted) primary energy demand of 248 kWh/m²a is indicated (p. 113). Improving the energy performance of the building to meet the E100 level corresponding to the standard of the EnEV (2009), implies therefore a reduction in the energy performance score by 125 kWh/m²a.

Nevertheless, these rough measures can be used for comparison. To reach this E100 efficiency level, energy-related investment costs for the average building in our dataset (six apartments of 67 m^2 each) range between €56,000 and €116,500. It should be noted, however, that these costs only apply if the building is to be refurbished anyway: in fact, the investment costs given only refer to the additional costs for the extra energy retrofit measures.

Improvements of 125 kWh/m^2a result in annual energy costs savings of 8.38 €/m^2 (at energy prices of €0.067 per kWh) and in annual basic rent increases of only 1.13 €/m^2 (consumption certificate) to 2.46 €/m^2 (demand certificate). At first glance, this leads to very long payback periods. In other words, with 1.13 to 2.46 €/m^2 higher rental income and six apartments of 67 m^2 each, landlords can invest about €9,000 respectively €20,000 if they accept standard payback periods of 20 years. This is far below the €56,000 to €116,500 required for this six-family dwelling based on the rough number stated above. Yet the monetary advantage for tenants clearly exceeds that of landlords by a factor of three to seven – depending on the EPC. From a tenant's point of view, these improvements sum up to energy savings of about €46 per month for an average apartment of 67 m^2 living area.

A simple heating system replacement can also help to reduce CO_2 emissions. A relatively inexpensive alternative is to switch from gas-fueled central heating to district heating – assuming that the building can be connected to an existing district-heating network. The costs for connection and for disposal of the old system amount to about €15,000 for smaller multi-family buildings (Verbraucherzentrale, 2023). With a payback period of 10 and 20 years, respectively, and an interest rate of 2 % p.a., the monthly additional costs amount to €138 or €76.

With an average apartment size of 67 m^2 and the six apartments per building as assumed above, a rent increase of only about 0.34 €/m^2 respectively 0.19 €/m^2 is necessary to fully recover the investment costs through additional monthly rental income. This is yet higher than the 0.4 % to 0.8 % premium observed in the market for dwellings with district heating – which corresponds to 0.028 €/m^2 or 0.056 €/m^2 for the average apartment. In general, an increase in monthly rental income of about 0.02 €/m^2 [0.01 €/m^2] is needed per €1,000 investment costs to recover investments over a period of 10 [20] years at a 2 % interest rate in the considered multi-family house with six apartments of 67 m^2 each.

6 Discussion

6.1 Discussion of empirical results

In our study, we find an average rental premium for ‘greener’ dwellings corresponding to a monthly rental increase of 0.01 €/m² when improving the energy efficiency by 10 kWh/m²a. For the mean apartment in our dataset, this corresponds to an increase of about 0.14 %. Our analysis hence confirms results of previous studies regarding the existence of rental premiums for ‘greener’ dwellings, although the extant literature mostly shows improvements from D to A labels which corresponds to an improvement of about 70 to 100 kWh/m²a. Our study reports monthly rental increases of about €0.07 to €0.10 per square meter or approximately 1.4 %, respectively, for this range.

Cajias et al. (2019) found rents to increase by 1.4 % on average, drawing on data for the whole German residential rental market. These results are therefore in line with the premium found in our study. März et al. (2022) also confirm these results and report a 0.17 % increase in rents per 10 kWh/m²a improvement in energy efficiency for Wuppertal – a city that is also located in NRW. This results in 1.2% to 1.7% rent increases for improvements from D to A. Moreover, our findings are in line with studies that use data from outside Germany, e.g., Fuerst et al. (2020) find slightly smaller and Khazal and Sønstebø (2020) somewhat larger effects.

Drawing only on German pre-war apartments with demand certificates, Galvin (2023b) found monthly basic rent increases of 0.09 %, corresponding to an increase of €0.55 for each reduced kWh/m²a. Adjusting the premium to the average square meter of living space in this study, it amounts to roughly 0.07 €/m² for an improvement of 10 kWh/m²a. Thus, the effect is about four times larger than the effect that we find in the demand certificate subsample. For post-war apartments constructed between 1946 and 2009, the author found monthly rental premia of €0.07 to €0.44 per reduced kWh/m²a (Galvin, 2023a). Normalized to the average living space, the premia amount to 0.009 €/m² or 0.06 €/m², respectively, for improvements of 10 kWh/m²a. Our results are also in this range.

Going beyond the confirmation of existing results, we directly compare the premium for higher energy efficiency to the benefits for tenants in terms of resulting energy cost savings. With our novel specification based on total-cost-of-use, we show that the latter exceed the rental premium by a factor of three to seven based on estimated average energy prices for heating of €0.067 per kWh. For refurbishments leading to energy improvements of about 125 kWh/m²a, roughly approximated calculations thus result in a deficit between initial investments and additional rental income of about €36,000 to €107,000 for an average multi-family building with six apartments.

Based on these empirical observations of market results, incentives for energy efficiency improvements for landlords are very limited so that the landlord-tenant dilemma is relevant even in the case of new rentals. Our results point also in the same direction as those by Kholodilin et al. (2017). For a reduction in energy costs of €1, they find rental prices in Berlin to increase by €0.23 at energy prices of €0.08 per kWh, so that energy cost savings exceed rental premiums roughly by a factor of four.

The impacts of different installed heating technologies on rents turn out to be substantial. For night storage heaters and SCC, negative premia for the apartments are observed (e.g., -0.96 % or -1.16 % for SCC in the demand or consumption certificate subsample, respectively), which are in line with the bad reputation of these technologies among the general public. On the other hand, positive rental premia are found for apartments with more sustainable heating technologies, such as district, wood pellet or solar heating (e.g., +0.82 % or +0.39 % for district heating). These "revealed"[22] preferences of renters induce an incentive for renovation for landlords which in turn may result in positive environmental side-effects. Besides these premia, also the change in the sign of the energy efficiency premia in the heating technology subsamples points in the same direction: by moving from "dirty" heating technologies to standard ones, the landlord can also obtain a positive instead of a negative premium on energy efficiency – at least if the apartment has a consumption certificate.

Overall, rent increases of only 0.01 to 0.02 €/m² are necessary to offset €1,000 in investment costs in the average building in our sample (6 flats, cf. above). According to our empirical results, a switch from SCC to district heating (if possible) enables the landlord to invest roughly €12,000 to €13,000 with a standard payback-period of 20 years. Taking available financial support for district heating into account, the investment will be profitable for the property owner in many cases.

Our detailed results complement the more general results of Hahn et al. (2018), who find a positive premium for apartments with "green" technologies and a negative premium for flats with inefficient heating systems, each compared to apartments with either standard heating technologies or no given information about the heating system. Thereby, our analysis underlines the importance of including the individual heating technologies in comparison to considering

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[22] As we use offer data, the preferences are not „revealed" in a strict sense. Yet the pricing of such hedonic attributes by the landlords is likely to reflect the actual preferences of renters in the actual market equilibrium if rental offers are not negotiated.

different technology baskets, because even within the "green" technologies there are significant differences in the found effect sizes.

Results of our EPC type subsample regressions point at another behavioral effect that needs to be considered when designing decarbonization strategies for rental dwellings. The energy efficiency premium in the demand certificates subsample is twice as large as in the consumption subsample, even though average rents only differ by 0.14 €/m². Similar results were found when examining effects on single-family house prices across Germany (Taruttis and Weber, 2022) and Sweden (Wahlström, 2016). We conclude that the higher premium results from a higher perceived reliability of the stated energy performance score given in demand certificates. The energy performance reported in consumption certificates indeed depends strongly on the individual behavior of former residents, at least in the case of small buildings, where statistical averaging does not prevail. Given the limited predictive power for own energy costs, tenants may accordingly exhibit a lower WTP for energy efficiency.

6.2 Drivers for the energy efficiency valuation gap

Our results suggest that substantial market inefficiencies for energy efficiency in the residential rental market exist. Various mechanisms, both on the supply and demand side, may be invoked to explain these inefficiencies. Subsequently, we discuss qualitatively these potential market imperfections in view of both potential policy implications and directions for further empirical research.

On the supply side, we identify four major potential drivers for the observed gap. First is a potential stickiness of rental prices within a building or a quarter. Accordingly rental prices for historical renters serve as anchor points for fixing new rents, so that these align on the preexisting rents and do not reflect the full value of refurbishments. Corresponding empirical evidence has been reported in particular for private landlords (cf. Haufe, 2017). Such behavior may also be enforced by the second mechanism which are regulatory limits to price increases . For existing rental contracts, rent increases after refurbishments are limited by German law (notably in the Civil Law (BGB) §559). Such clauses do not apply to new rental contracts, yet there are restrictions on rents above the local comparative rent – at least in selected urban areas.

A third potential driver might be a shift of refurbishment costs into auxiliary costs. However, this should typically be prevented by regulation. Finally, portfolio management strategies may play a role. Larger real estate companies may avoid directly charging refurbishment cost – as refurbishment is applied as part of the portfolio management on a regular basis and discrimination of renters according to their current refurbishment status is not perceived as appropriate in view of longer-term customer relationship management.

On the demand side, we also identify four potential drivers that may induce a persistent energy efficiency valuation gap. A first strand is related to non-anticipation of energy cost differences as energy-related financial literacy is generally limited (e.g., Blasch et al., 2021). This, together with time pressure (e.g., due to a high number of applicants when viewing apartments), might lead to several implications: lack of information in general, assumption that heating cost mostly depend on the energy source or lack of correct evaluation of information.

A second strand is associated with biased information. On the one hand, there is an information bias when advertisements only indicate aggregate auxiliary costs instead of a detailed description of heating and other utility costs or if the landlords opportunistically decide to suppress heating cost information for low-efficiency buildings[23]. In this case – and in combination with time pressure and limited energy-related financial literacy – a biased valuation of energy efficiency may result. On the other hand, there might be a bias towards tangible features. This is in line with the observed higher premia for more sustainable heating technologies and penalties for technologies that are known to be inefficient. Also, the present bias put forward in behavioral economics may be invoked as renters may overvalue the immediately perceivable basic rent compared to future heating energy costs (cf. Galvin, 2023c). Loss aversion may also play a role as tenants possibly fear negative side effects of energy refurbishments, notably moisture.

Further, there might be limited saving incentives for tenants as energy costs within a building are only partially allocated according to metered consumption. This German regulation is roughly in line with physical causality yet biases the perceived link between heating control settings and energy costs.

Another mechanism refers to a potential lack of trust in available information. This may apply to the EPSs, and we find some empirical evidence for such an effect as the valuation of energy efficiency is higher for apartments with a demand-based EPC compared to those with consumption-based EPC.

Beside these market-related drivers for the observed valuation gap also statistical explanations could be envisaged, notably some bias related to omitted variables. We cannot fully exclude such an effect, yet the same methodology applied to a similar dataset for single-family-home

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[23] In the database, fields for both aggregate auxiliary costs and heating costs are available but there are a lot of missing values.

sales has not provided any evidence of omitted variable bias (Taruttis and Weber, 2022). There our methodology leads to results that are in line with findings by Myers (2019) and others (e.g., Copiello and Donati, 2021), namely that energy cost savings are actually capitalized to a large extent into real estate prices, i.e., there is no obvious valuation gap for energy efficiency.

6.3 Limitations

Our study is subject to certain limitations mainly regarding the dataset used. First, it only shows asking rents; however, available empirical evidence indicates that these are often in line with final transaction prices (cf. Olaussen et al., 2021; Thomschke, 2015). Second, the given asking rents only reflect the distribution of advertised rents that households encounter when looking for a rental apartment via digital apartment ads. Rents from existing tenancies are not captured. Yet investigating issues of informational efficiency of markets should be done based on actual market transactions and not based on legacy contracts, possibly concluded based on a different information set.

Third, data is dependent on owners' accuracy and honesty in presentation and description of the apartments. But owners incur substantial reputation risk by providing wrong information to potential renters. Fourth, there could be a self-selection bias towards younger users, as elderly people are sometimes not familiar with internet platforms. In addition, a self-selection bias towards private providers is conceivable (Wittowsky et al., 2020) which may underestimate results because private lessors are likely to assign lower rents (cf. Khazal and Sønstebø, 2020).

An additional limitation arises regarding the energy source for heating. We cannot distinguish, whether central or floor heating systems have gas, oil, or district heating as main energy source. The same holds for SCC. In the face of rising energy prices for heating in Germany, this might be a valuable information for prospective tenants that impacts their WTP. Further, this information would make calculations of energy savings much more precise.

7 Conclusion and Policy Implications

Based on a novel methodological approach and a very rich empirical dataset, we reach the conclusion that there is no efficient pricing of energy efficiency in the German rental market. We use a cross sectional dataset for 2014 to 2020 covering Germany’s most populated federal state North Rhine-Westphalia including more than 840,000 apartment listings for rent distributed over 10,050 1 km^2-grid cells. As we specify our model in a total-cost-of-use perspective, we are capable of computing an energy multiplier to directly compare rental premia with energy-cost savings. It reports annual basic rent increases per one euro reduction in energy costs by taking actual price for heating energy into account.

Although energy-efficient apartments are found to be rented out at a premium, this market premium is rather small and expected energy cost savings exceed the market premium by a factor of three to seven – depending on the type of the Energy Performance Certificate. Even if the interplay between drivers on the supply and demand side of rental markets deserves further detailed investigations, our results point at important policy implications in view of ambitious decarbonization strategies: if behavioral patterns in the rental market remain consistent over time, our results imply that a simple application of first-best instruments for decarbonization is likely to induce very limited effects.

Even with higher prices for fossil fuels induced by carbon taxes or carbon certificate costs, prospective renters will continue to substantially undervalue the benefits of improved building energy performance. Accordingly, the financial incentives for landlords to invest in energetic-retrofit measures remain insufficient – even when disregarding the classical landlord-tenant dilemma[24].

The fact that the rental premium differs according to the type of EPC highlights the role of trustworthy and relevant information. Overall, our results indicate that the informational efficiency of existing disclosure rules for energy performance information is insufficient. But given the observed differences in the valuation gap between the EPC subsamples, the perceived value of the information obviously matters. A straight-forward remedy would then be to impose a mandatory disclosure of energy performance in monetary terms in EPCs or in the rental advertisements. Alternatively, just explaining the categories in more detail could already help to establish higher premia in the markets (Carroll et al., 2016; Pommeranz and Steininger, 2021) and to consequently induce higher incentives for landlords to renovate. The implementation of such an obligation yet necessitates more detailed analyses.

Another, more indirect approach to foster energy efficiency may be derived from the substantial discounts observed for apartments with dirty heating technologies. These results suggest that salient energetic features are at least as relevant as the actual energetic performance for the pricing of rented dwellings. Correspondingly, an alternative approach to foster energy efficiency could be to support the installation of new heating technologies, preferably parallel to improving the overall energy efficiency of a dwelling. This will enable landlords to reap

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[24] As we are analyzing new leases, the landlord-tenant dilemma does not apply since the investment should have been made prior to the advertisement.

additional rental benefits which imply a better profitability of energy-retrofit investments. Heating technology subsample-regression results support this recommendation, as tenants are not willing to pay for higher energy efficiency if flats have dirty, i.e., inefficient and environmental unfriendly technologies (at least if the apartment has a consumption certificate). Yet in view of deep decarbonization strategies, the switch to standard heating technologies is not sufficient – and thus corresponding support mechanisms are likely not to deliver appropriate environmental benefits.

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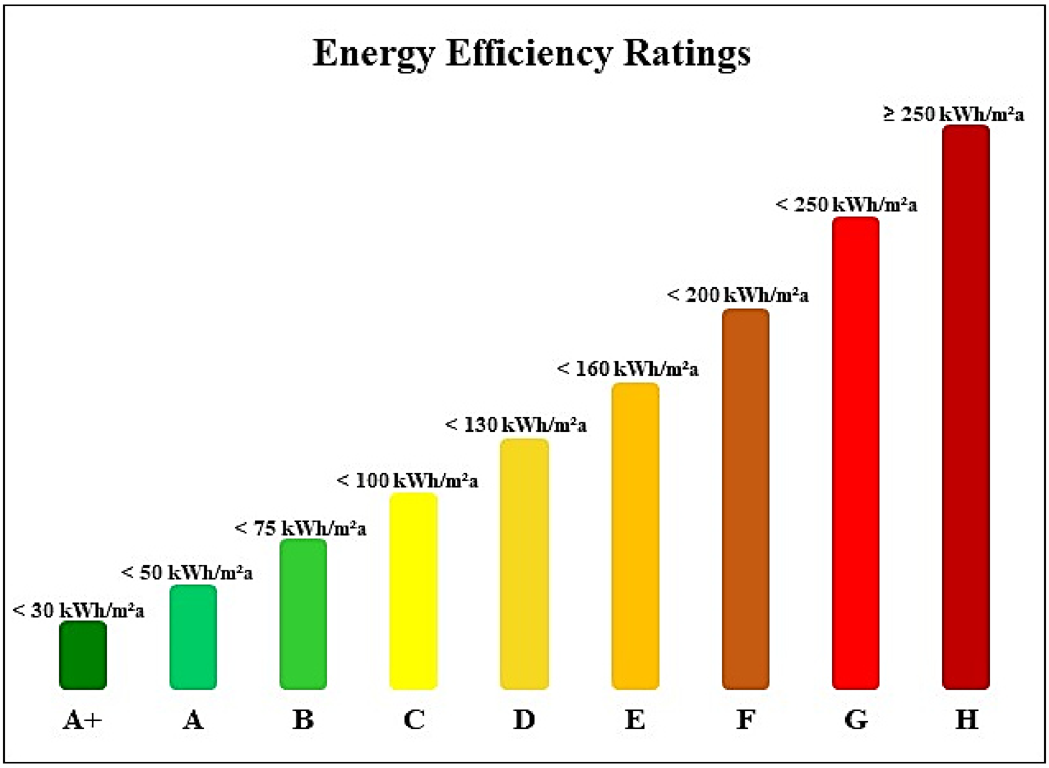
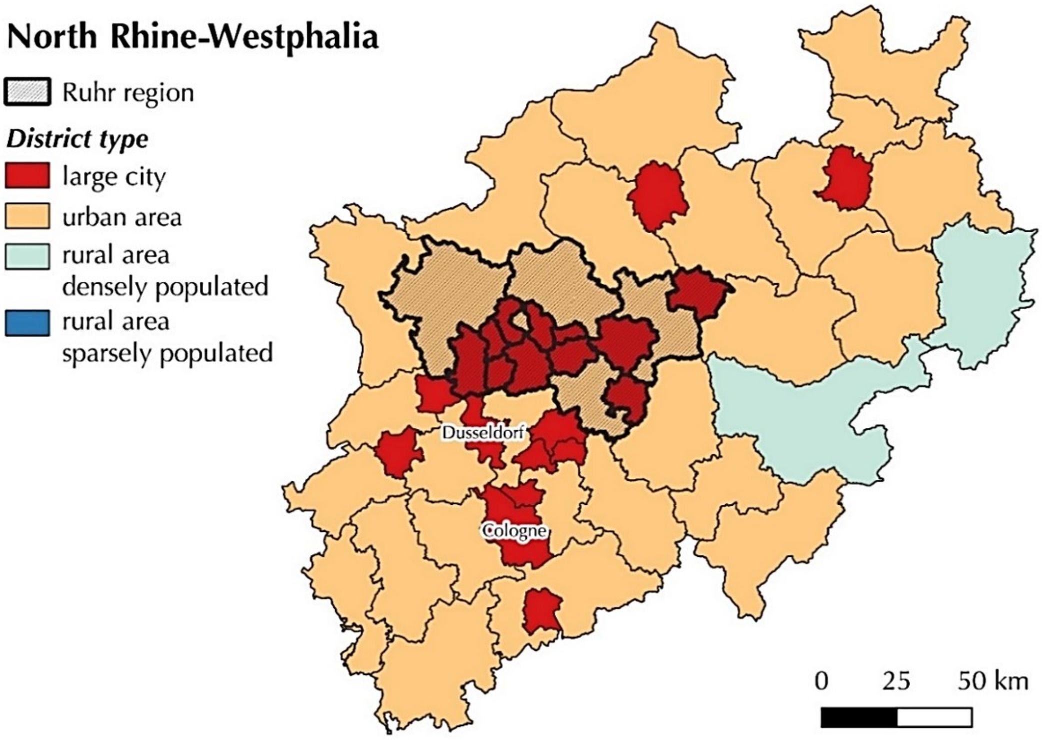
Appendix A: Additional figures and results



Source: Authors' own depiction.

Figure A 1 Energy efficiency ratings with corresponding energy performance scores.



Source: Authors' illustration based on INKAR. Map Data: @GeoBasis-de/BKG 2019

Figure A 2 Map of North Rhine-Westphalia showing the district types according to INKAR.

Table A 1 Summary statistics for EPC subsamples.

	No. of obs.	**Mean**	**St. Dev.**	**Median**
Panel A. Demand certificate				
Basic rent	240,545	7.02	1.89	6.58
Energy performance score	240,545	150	57	143
Living area	240,545	68	20	66
Age	240,545	59	21	58
Duration of advertisement	240,545	25	33	15
Panel B. Consumption certificate				
Basic rent	603,684	6.88	1.92	6.40
Energy performance score	603,684	136	42	132
Living area	603,684	67	20	65
Age	603,684	55	23	55
Duration of advertisement	603,684	25	32	15

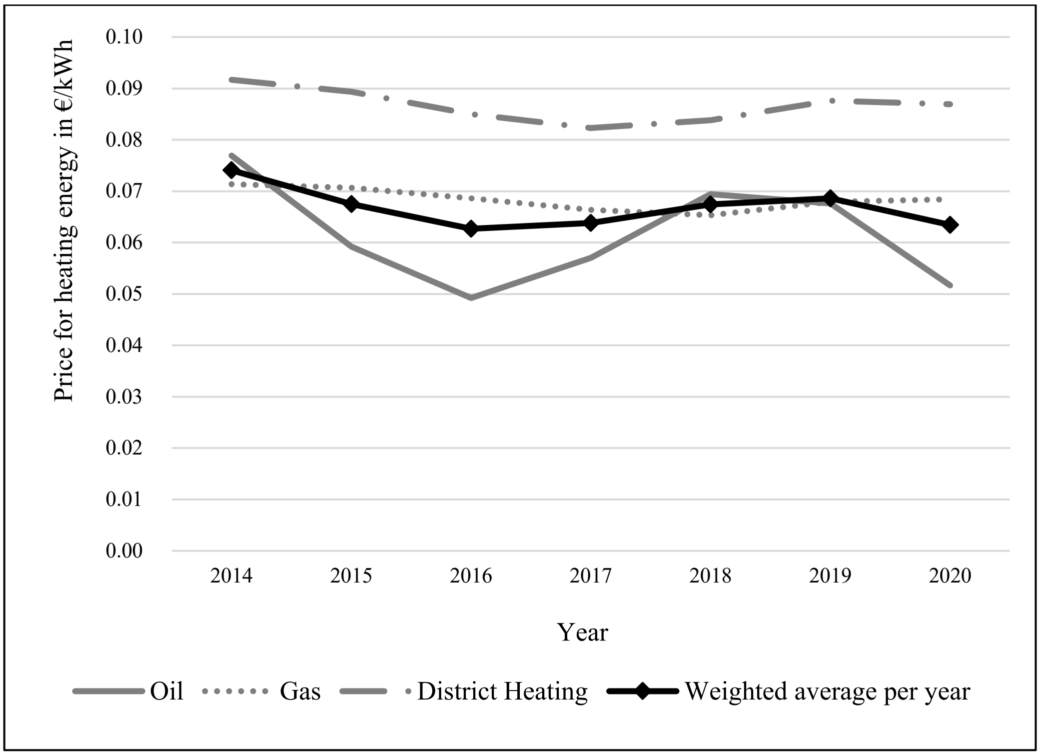
Source: Authors' calculations based on RWI-GEO-RED.

Table A 2 Regression results for EPC type subsamples – full table.

	EPC subsamples	
Dependent Var.: Basic rent in €/m^2	**Demand certificate**	**Consumption certificate**
Energy performance score (in 10 kWh/m^2a)	0.0163***	0.0075***
	[0.0004]	[0.0003]
Heating system, reference: gas heating		
CHP	-0.0018	0.0073
	[0.0057]	[0.0046]
Electric heating	-0.0563***	-0.0379***
	[0.0035]	[0.0028]
SCC	-0.0096***	-0.0156***
	[0.0014]	[0.0009]
District heating	0.0082***	0.0039***
	[0.0018]	[0.0010]
Floor heating	0.0421***	0.0270***
	[0.0025]	[0.0015]
Wood pellet	0.0149*	0.0330***
	[0.0062]	[0.0060]
Night storage	-0.0680***	-0.0723***
	[0.0026]	[0.0019]
Heating by stove	-0.0648***	-0.0451***
	[0.0037]	[0.0041]
Oil heating	0.0066**	0.0017
	[0.0025]	[0.0015]
Solar	0.0298***	0.0334***
	[0.0089]	[0.0088]
Heat pump	-0.0273***	-0.0252***
	[0.0067]	[0.0038]
Central heating	0.0094***	0.0004
	[0.0013]	[0.0007]
Last renovated in 2000 or later	0.0113***	0.0138***
	[0.0009]	[0.0005]
Neighborhood characteristics		
Population density	0.0381***	0.0424***
	[0.0005]	[0.0003]
Purchasing power per capita	0.3374***	0.3629***
	[0.0041]	[0.0026]
Unemployment rate	-0.0022***	-0.0016***
	[0.0001]	[0.0001]
Share of households with foreign head	0.0017***	0.0016***
	[0.0001]	[0.395e-3]
Condition, Facilities. Apt. Type	*yes*	*yes*
Balcony, Garden, Kitchen	*yes*	*yes*
No. of rooms, floors	*yes*	*yes*
Living area	*yes*	*yes*
Construction period	*yes*	*yes*
Season FE (quarterly-year)	*yes*	*yes*
Region FE (NUTS3)	*yes*	*yes*
Pseudo-R^2	0.772	0.792
RMSE	0.901	0.875
Observations	240,545	603,684

Note: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Pseudo-R^2 is estimated using the ‘rsquare’-function from the ‘modelr’-package in R (Version 4.1.2). RMSE is in €/m^2.

Source: Authors’ calculations based RWI-GEO-RED and RWI-GEO-GRID.



Source: Authors' calculation and illustration based on BMWi (2020).

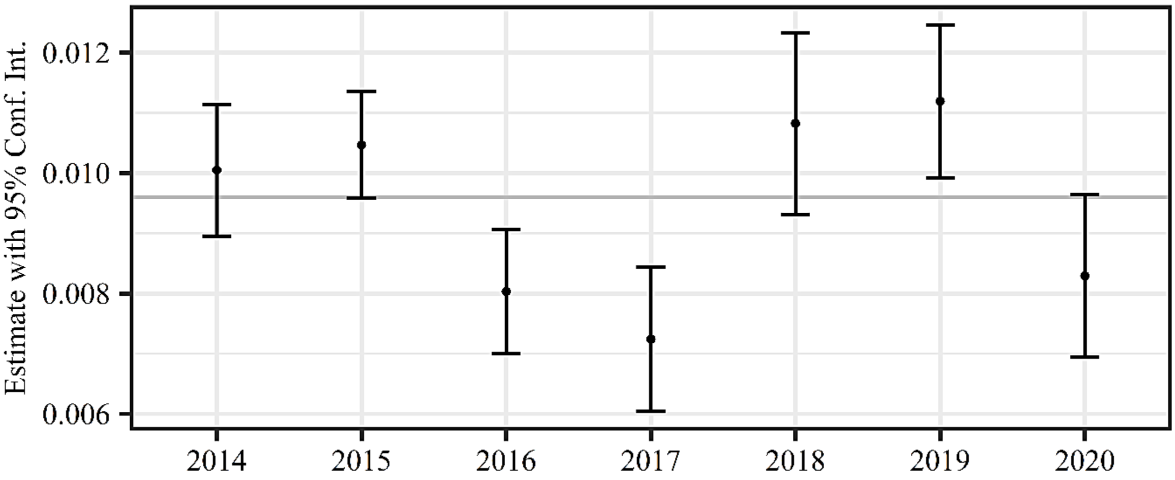
Figure A 3 Prices for heating energy over time.

Note: The weighted mean price was calculated based on the shares of energy carriers used in our data set.

Appendix B: Robustness Checks

Yearly Subsamples

Figure B 1 illustrates regression results differentiated by time. Again, all control variables and regional fixed effects were included in all regressions. Seasonal-fixed effects only relate to quarters of the year with reference Q1. Overall, the impact of energy efficiency on rents only slightly varies over time. Effects were strongest in 2019, with an increase in basic rents by 0.011 €/m² if energy efficiency improved by 10 kWh/m²a. The lowest rental premium of only 0.007 €/m² was found in 2017. Further, effects are larger than average effects in 2014 and 2015 as well as 2018 and 2019 on the one hand, and lower than average effects in 2016, 2017 and 2020 on the other hand.



Source: Authors' calculations and illustration based RWI-GEO-RED and RWI-GEO-GRID.

Figure B 1 Estimate and 95% Conf. Int. for the energy performance score in yearly subsample regressions.

Note: Dependent var.: Basic rent in €/m². All control variables except for 'Balcony', 'Garden' and 'Kitchen' were included in the regression. The grey horizontal line shows the average effect of the energy performance score on basic rents as reported in Table 5 column (5).

Regional Subsamples

With an increase of energy efficiency by 10 kWh/m²a, monthly basic rents increase on average by €0.012 in large cities and €0.008 in urban areas, both per square meter. On the other hand, when differentiating between the Ruhr area and other regions in NRW, the impact of energy efficiency on basic rents is almost 70 % larger for districts outside the Ruhr region: If the energy performance score decreases by 10 kWh/m²a, monthly basic rents increase on average by 0.017 €/m². Corresponding results for the regional subsamples are given in Table B 1.

Table B 1 Regression results for different regional subsamples.

Dependent Var.: Basic rent in €/m²	**District type subsamples**		**Area subsamples**	
	Large city	**Urban area**	**Ruhr area**	**other**
Energy performance score	0.0122***	0.0079***	0.0100***	0.0168***
(in 10 kWh/m²a)	[0.0004]	[0.0004]	[0.0003]	[0.0005]
Season FE (quarterly-year)	*yes*	*yes*	*yes*	*yes*
Region FE (NUTS3)	*no*	*no*	*no*	*no*
Pseudo-R²	0.657	0.566	0.491	0.634
RMSE	1.224	0.952	0.828	1.294
Observations	544,567	296,070	399,064	445,165

Note: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Only estimates of interest are shown; however, all control variables were included in the regression. Pseudo-R² is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE is in €/m². *Large cities* are defined as independent cities with more than 100,000 citizens. *Urban areas* describe districts with a population density larger than 150 inh/km² and districts, where more than half of the population lives in middle-sized (betw. 20,000 and 99,999 citizens) or large (non-independent) cities that have a population density above 150 inh/km² as well.

Source: Authors' calculations based RWI-GEO-RED and RWI-GEO-GRID.

Disparities in the valuation of energy efficiency can be found across different regional types. Notably, effects are stronger in large cities compared to urban areas. At first sight, this is in sharp contrast with results obtained in several other studies (cf. Cajias et al., 2019; Civel, 2020). However, our estimates show direct monetary impacts rather than relative impacts. As basic rents are higher on average in large cities, a higher impact in absolute terms may be consistent with a lower impact in relative terms. Regarding the observed valuation gap for energy efficiency, our findings yet point in the opposite direction than the earlier results: we find that the valuation gap is lower in large cities than in urban areas whereas the conventional semi-log specification suggests the opposite.

A case apart are the smaller impacts of energy efficiency on basic rents found in the Ruhr region compared to all other regions in NRW. Similar results were found for sales prices (Taruttis and Weber, 2022). These results indicate a weaker link between energy efficiency in the Ruhr region than elsewhere. This could be a consequence of a lower WTP for energy efficiency of prospective tenants, as a larger proportion gets government subsidies for renting and heating cost.

Appendix C: Background Information on energy bills in the German Rental Market

In Germany, heating energy bills are paid in almost every case by the tenants themselves based on their own energy consumption. Heating costs are then obviously dependent on the main energy carrier used and the corresponding prices. In case of electric heating, tenants receive their electricity bill directly from their electricity provider; the landlord is not involved therein.

If the building is equipped with central heating, tenants receive a heating bill from their landlord or directly from the energy supplier. Landlords are obliged to charge 50% to 70% of the energy cost based on consumption. The remaining 30% to 50% are allocated using a distribution key like the dwelling area. It is also possible to have 100% consumption-based billing. In any case, tenants can influence their annual energy costs to a certain extent. This consumption-based billing of heating energy costs does not provide landlords with a direct incentive to improve the energy efficiency of their apartments, as they do not benefit from energy savings. Accordingly, costs for efficiency improvements can only be compensated by a higher basic rent.

Recently, the Fuel Emissions Trading Act (BEHG) has entered into force in Germany (since January 1, 2021). It includes a CO_2 tax on oil and gas which amounts to €25 per ton of CO_2 for 2021 and will be steadily increased until 2025. There is currently a great debate about who will have to pay for the additional heating costs due to this CO_2 tax in future. From January 2023, the payment will probably be split between tenants and landlords. An often-discussed option is to determine the shares depending on the efficiency of the apartment. The German government is thus relying on a price mechanism to accelerate energy-efficient renovations. Landlords are to be given additional incentives to implement efficiency-enhancing measures, while tenants in inefficient apartments are to be relieved at the same time.

DECLARATION OF INTEREST

None

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We certify that no party having a direct interest in this research's results supporting this article has or will confer a benefit on us or on any organization with which we are associated. Also, we certify that all financial and material support for this research (e.g., NIH or NHS grants) and work are clearly identified in the manuscript's title page.

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CHAPTER FOUR

Investigating Inefficiencies in the German Rental Housing Market: The Impact of Disclosing Total Costs on Energy Efficiency Appreciation

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Abstract

Energy efficiency and renewable energy are key pillars of the energy transition that is high on the political agenda of governments in face of the climate crisis. Germany, however, is underperforming in its emissions reduction goals. There is still room for improvement, especially in the building sector – but this is often associated with high upfront investments. There is evidence that the market for energy efficiency in the German rental housing market is inefficient, resulting in underinvestment. To investigate these inefficiencies, this study estimates a hedonic pricing model combined with a total-cost-of-use perspective based on the observation of warm rents for a sample of 3,903,473 rental offers from 2014 to 2021. In a "perfect world", the effect of the energy performance score given in energy performance certificates as an indicator of energy consumption or demand, respectively, is expected to be zero, as corresponding costs are already included in the warm rent. If the coefficient is significantly different from zero, it can be interpreted as measure for inefficiencies. The study further investigates whether disclosing heating costs in real estate advertisements could lead to a better appreciation of energy efficiency in the rental market and thus contribute to closing the information gap. Results show that the market for energy efficiency is indeed inefficient; however, the disclosure of full information can help to overcome these inefficiencies. These results lead to several important policy implications.

Keywords: energy efficiency, rental housing market, information asymmetry, hedonic pricing

JEL-Classification: C31, Q40, R21, R3

1 Introduction

Energy efficiency and renewable energies are crucial for the energy transition, which is high on the policy agenda of governments and organizations around the world in the face of the climate crisis. Germany, however, is underperforming in its emission-reduction goals (UBA, 2020). With 35 % of end-energy use and about one third of CO_2 emissions (BMWi, 2021), the building stock provides high opportunities for emission reductions. However, low renovation rates and a lack of investment in sustainable heating technologies prevent this potential from being sufficiently exploited to date. Thus, increasing the refurbishment rates from about 1 % to 2 % per year is necessary to reach a climate-neutral building stock by 2045 (Luderer et al., 2021).

As Germany has one of the largest shares of rented accommodations across Europe, incentives for energy refurbishments are split among property owners and tenants (Gillingham et al., 2012). Landlords or landladies, respectively, invest in higher energy efficiency while tenants profit from lower energy bills[1]. Consequently, private investments in energy improvements to existing buildings may still lag behind the optimal level (Allcott and Greenstone, 2012; Gerarden et al., 2017), leading to the so-called energy efficiency gap (Jaffe and Stavins, 1994).

The German government has already passed a law making energy refurbishments mandatory in certain cases to a prescribed minimum extent (GEG, 2022). However, this law currently applies almost exclusively when the owner of the building changes. Further, a CO_2 price for heating energy, among others, was introduced in 2021. From January 2023, the additional costs arising from this CO_2 pricing scheme must be shared between the two parties in private leases. The worse the energy quality of the respective building, the higher the share of costs to be borne by the landlord or landlady (CO2KostAufG, 2023). In the case of inefficient buildings, the property owner thus may consider renovating the apartment.

Even if new incentives for energy refurbishments are created, especially through the sharing of CO_2 costs, it plays a major role whether the required investment costs can be covered by additional rental income. There is evidence that energy efficiency is still not enough capitalized into rents so that no further incentives are created for property owners to invest (Ambrose, 2015; Groh et al., 2022; Hope and Booth, 2014). To overcome these inefficiencies in the market for energy efficiency (Sieger and Weber, 2023), one proposal is to adjust policies regarding the mandatory disclosure of information (Frondel et al., 2020; Myers, 2020).

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[1] In Germany, it is common for tenants to pay the costs for their energy consumption directly to the energy supplier.

In this context, two hypotheses are proposed and tested in this study:

[H 1] The market for energy efficiency in the German rental housing market is inefficient, even if warm rents are disclosed.

[H 2] The disclosure of heating costs in (online) real estate advertisements can help to close the information gap und thus to overcome these inefficiencies.

The first hypothesis is tested by estimating a hedonic pricing model combined with a total-cost-of-use (TCU) perspective, as already implemented in Sieger and Weber (2023). Using the warm rent as dependent variable and additionally including a measure for the energy performance of the respective apartment, arising inefficiencies in the market for energy efficiency can be examined. In a "perfect world", the impact of the energy performance score as indicator for energy consumption or demand, respectively, on the warm rent is expected to be zero, as corresponding costs are already included in the warm rent. If the effect of the energy performance score on warm rents is significantly different from zero[2], there is evidence for inefficiencies in this market.

To evaluate whether the disclosure of heating costs can help to close the information gap, a moderation analysis is conducted, making use of the rich dataset with almost 4,000,000 individual apartment observations for the time period 2014 to 2021. Thereby, a distinction is made between advertisements that (a) only report basic rents, (b) report an overall warm rent – consisting of basic rent, heating costs and other auxiliary costs – and (c) those that also provide explicit information on heating costs.

A review of the extant literature reveals several groups of studies that estimate a so-called *green premium* for efficient buildings. The first strand examines the effects of labeled vs. non-labeled homes (e.g., Aroul and Hansz, 2012; Bloom et al., 2011; Brounen and Kok, 2011) in either the sales (Högberg, 2013; Taruttis and Weber, 2022) or rental (Fuerst et al., 2020; März et al., 2022) segment of real estate markets. These label effects are mostly found to be positive, leading to higher sales prices for houses or higher rental incomes for property owners, respectively. Overall, effects are found to be larger in the sales sector (cf. Hyland et al., 2013).

Only small or negligible label effects were found by Olaussen et al. (2017) and Wahlström (2016). However, they still find effects of single efficiency measures, which is a second strand in the existing literature. For instance, Feige et al. (2013) investigated the Swiss rental housing market and found significantly positive price effects of the environmental performance of the

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[2] This applies for both negative and positive effects. The first implies financial advantages for tenants, the latter results in financial advantages for the property owners.

respective building. Further, Fuerst and Warren-Myers (2018) combined research on the pure label effect with investigations on sustainable building characteristics and also found positive effects on sales prices and rents for both features.

In addition, a third strand of literature captures energy efficiency differences in apartment buildings for sale vs. rent, addressing the split-incentives in multi-family buildings. For instance, Broberg and Egüez (2018) examine the efficiency of the housing stock in Sweden, where it is common that heating costs are included in the apartment rent so that there are no incentives for tenants to actively control their heating and ventilation behavior. Further, differences in energy efficiency measures between rental and owner-occupied properties were investigated for Ireland (Petrov and Ryan, 2021) and Germany (Singhal et al., 2023). Both studies find no significant divergence in the energy quality of properties according to the mode of tenure in the market of apartments.

Finally, a recent study by Galvin (2023b) compares effects on apartments for rent and sale in the period 01/2019 to 12/2021 and thereby focuses on buildings that were built between 1800 and 1945. The study further excludes all observations that have consumption certificates and thus focuses on buildings that were certified by energy demand. The author finds that only the sales market compensates owners of pre-war apartments who first renovate and then sell their houses. All other actors – owners who either renovate and then rent out or renovate and live in – suffer shortfalls.

The present study takes an in-depth look at an issue that lies at the crossroads of these different research directions: the impact of the different types of information presented to (potential) tenants. Thereby, it makes several important contributions to the extant literature. First, it examines the market efficiency of the German rental housing market in regards of energy efficiency by considering the total costs of renting and living in an apartment rather than relying on basic rents only. Second, it analyzes different moderating effects for the valuation of energy efficiency and thus explores options to close the information gap. Finally, this study distinguishes between different kinds of energy performance certificates (EPCs), leading to compelling outcomes that have important policy implications.

Results suggest that there are inefficiencies in the market for energy efficiency leading to advantages for tenants. In addition, reporting warm rents does not automatically result in a better appreciation of energy efficiency. The market valuation for higher energy efficiency standards only increases when the exact heating costs are disclosed in addition to the warm rent in the online advertisement.

The remainder of this paper is organized as follows. Section 2 discusses some theoretical considerations for the influence of energy efficiency on basic and warm rents. Building on this, the empirical approach and data used are described in Section 3. Sections 4 and 5 report and discuss the empirical results. Finally, Section 6 concludes and gives some important policy implications.

2 Theoretical Considerations

The willingness-to-pay (WTP) for a specific apartment can be described as a function of the apartment's structural (x) and locational (n) attributes:

$$WTP = f(x,n) \tag{1}$$

From a renter's perspective, this WTP refers to total expenditures rather than just basic rent. The (expected) total costs of renting and living in a property for the tenant thus equals the sum of basic rent and auxiliary costs that cover heating, electricity, and other utility costs. They can be written as:

$$E[TotalCosts_{ie}] = BasicRent(X_i, N_i) + E[P_e \cdot eps_i] + Utility_i + Electricity_i \tag{2}$$

The basic rent thereby depends on hedonic (X_i) and neighborhood (N_i) attributes of apartment *i*. Expected heating costs are given by the price for heating energy (P_e) multiplied by the energy performance score (eps_i) of the respective apartment which is measured in energy units and is used as a proxy for the expected quantity of energy used. $Utility_i$ costs include other than energy and electricity costs, e.g., garbage disposal, road cleaning and maintenance as well as winter services. These costs are passed through by landlords and landladies and are hence neither (directly) adjustable by themselves nor by tenants. Finally, $Electricity_i$ costs[3] depend mainly on tenants' behavior and the appliances they use. In Germany, they are paid directly to the electricity provider and are not included in the so-called warm rent, so that these costs are not included in the analyses of this study. Therefore, the expected warm rent can be written as:

$$E[WarmRent_{ie}] = BasicRent(X_i, N_i) + E[P_e \cdot eps_i] + Utility_i \tag{3}$$

Parallel to electricity costs, it is also common in Germany for heating costs to be paid on the basis of measured consumption. In the case of rented apartments, this usually involves a 30/70

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[3] Costs for electric heating are already included in expected heating costs.

key, i.e., 30 % of the energy costs of the apartment building are apportioned to the individual tenants (e.g., according to the size of the apartment and the number of people living in it) and the remaining 70 % consists of the tenants' individual consumption (measured by metering devices on all heaters). Accordingly, tenants can influence their own heating costs through appropriate heating and ventilation behavior.

If a dwelling is now renovated to make it more energy efficient, the energy performance score will decrease, so that the (expected) heating costs will also decrease if prices remain the same and tenants' behavior does not change. As a result of the consumption-based billing, this refurbishment creates monetary benefits for the tenant. Consequently, the basic rent could be increased to keep the total-cost-of-use at the same level while making the energy-related refurbishment profitable for the property owner.

According to the Efficient Market Hypothesis (EMH), first proposed by Fama (1970), prices reflect all available information. The term *efficient market* was originally developed for the stock market in particular, but as time went on, the concept has been generalized to other markets such as the real estate market (Sunjo and Yilmaz, 2017). In the vein of this hypothesis[4], the market for energy efficiency in the rental market is to be considered efficient if basic-rent increases balance out with heating-cost savings after energy retrofits, given that information on the energy performance score and/or expected heating costs are given in the property advertisement, i.e., full information is provided for the prospective tenant.

Table 1 gives an overview of possible changes in basic and warm rents as well as heating costs after an energy retrofit has taken place, and the energy performance score has decreased. As previously described, utility costs are not adjustable so that they will not change in the context of an energy refurbishment. The expected heating costs will decrease by $P_e \cdot \Delta eps_i$ as long as prices stay constant, and the tenants do not change their ventilation and heating behavior after the renovation.

Case (A) describes the worst case[5], in which the basic rent does not change at all after the energy refurbishment. The entire advantage lies with the tenants, so that investments in higher energy efficiency are not profitable for the property owner. Case (B) also has disadvantages for landlords or landladies; however, they generate more rental income than before the renovation, so that part of the investment costs can be refinanced. Case (C) shows an efficient market, where the increase in basic rents corresponds to the decrease in expected heating costs. Thus, tenants

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[4] In its semi-strong form, where all publicly available information are reflected in the price.

[5] The possibility of decreasing basic rents after renovations is not considered.

receive a better energy standard for which they adequately compensate the property owner. Finally, the last case (D) shows an inefficient market again in which the increase in basic rents exceeds the reductions in heating costs. In this case, energy efficiency is over-proportionately valued. From the landlord's point of view, the investment costs can be amortized most quickly in case (D).

Table 1 Changes in heating costs and possible changes in rents after energy refurbishments.

Heating Costs (HC)	+	Basic Rents (BR)	=	Warm Rents (WR)		
$\Delta HC = E[P_e \cdot \Delta eps_i] < 0$		$\Delta BR = 0$		$WR_{after} = WR_{before} + \Delta HC$	↓	(A)
		$0 < \Delta BR < \lvert\Delta HC\rvert$		$WR_{after} = WR_{before} + \Delta BR + \Delta HC$	↓	(B)
		$\Delta BR = \lvert\Delta HC\rvert$		$WR_{after} = WR_{before}$	-	(C)
		$\Delta BR > \lvert\Delta HC\rvert$		$WR_{after} = WR_{before} + \Delta BR + \Delta HC$	↑	(D)

Notes: The arrows indicate whether warm rents increase or decrease, depending on the change in basic rents. $\Delta HC = E[P_e \cdot \Delta eps_i]$ denotes the expected change in heating costs if prices stay the same before and after energy-efficiency improvements, with $\Delta eps_i < 0$. ΔBR is expected to be ≥ 0, as a decrease in basic rents after refurbishments does not seem plausible. Columns marked in red report market inefficiencies with advantages for tenants after refurbishment. Yellow indicates market inefficiencies with advantages for property owners. Green stands for an efficient market.
Source: Own illustration.

The amount of heating cost savings and thus possible rent increases depends not only on the energy price but also on the extent of the refurbishment. Buildings with a poor initial performance typically have greater savings potential than buildings that are already more energy efficient.

3 Empirical approach and data

The research approach in this paper is twofold. In the first part, I examine in more detail whether there are inefficiencies in the market for energy efficiency. The focus here is on the submarket where the total costs, i.e., the warm rents, are given in the advertisement[6] (referred to as "submarket warm"). I also distinguish between advertisements that 1) only provide information on the overall warm rent and 2) additionally provide full information on the heating costs.

In the second part, I examine the entire rental market (i.e., both submarkets "cold" and "warm") and investigate whether the disclosure of total costs helps to overcome information asymmetries and thus better evaluate the energy efficiency of an advertised dwelling in order to minimize inefficiencies in the market for energy efficiency.

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[6] In contrast to advertisements that only provide information on the basic rent (referred to as "submarket cold").

3.1 Total-cost-of-use (TCU) perspective

The first model is based on a standard hedonic regression model in its common semi-logarithmic form going back to Lancaster (1966) and Rosen (1974) to control for price differences due to different apartment and neighborhood characteristics. However, I combine the model with a TCU perspective, as previously implemented in Sieger and Weber (2023), to be able to compare the results with engineering-economic estimates of heating cost savings. For a detailed model description see Sieger and Weber (2023).

To measure inefficiencies in the market for energy efficiency, I use the warm rent as a proxy for the total costs of use. I further subtract the expected heating costs – computed as the energy performance score (eps_i) multiplied by an empirical parameter β_1 – to test whether there is a specific effect of the heating costs beyond the warm rent. The costs for renting apartment *i* in neighborhood *n* at time *t* can then be described by the following equation:

$$ln(WarmRent_{int} - \beta_1 eps_i) = \alpha + \gamma \boldsymbol{X}_i + \delta \boldsymbol{N}_{nt} + \mu_t + \varepsilon_{int} \tag{4}$$

In this specification, the coefficient β_1 provides an indication on the inefficiency in the market for energy efficiency – in a “perfect world” with a fully efficient market it would be zero, as the warm rent then fully captures the impact of the energy performance on the total cost of use (cf. case (C) in Table 1).

If the coefficient is positive, the market is inefficient with benefits from improved efficiency accruing (partly) to tenants. If the energy performance score decreases, heating costs should decrease as well. With a positive coefficient, the overall warm rent will also decrease, which means that the basic rent does not increase up to the limit of energy cost savings and consequently investments are less profitable for property owners (cf. cases (A) and (B) in Table 1). If the coefficient is negative, the financial advantage would be on the landlord’s or landlady’s side, as the energy efficiency is then valued higher than the current heating price (cf. case (D) in Table 1).

To obtain the monthly warm rent in euro per square meter of living area as dependent variable on the left-hand side, I rearrange the terms in Eq. (4) and estimate Eq. (5) using nonlinear least squares:

$$WarmRent_{int} = \beta_1 eps_i + exp\,(\alpha + \gamma \boldsymbol{X}_i + \delta \boldsymbol{N}_{nt} + \mu_t) + \varepsilon'_{int} \tag{5}$$

The main variable of interest – eps_i – is the energy performance score for heating of apartment i measured in 10 kWh/m²a. Vector $\boldsymbol{X}_i$ includes all other apartment characteristics, while neighborhood characteristics are contained in vector $\boldsymbol{N}_{nt}$. Finally, μ_t are time-fixed effects on quarterly-year level and ε'_{int} is the error term of the regression for which I report cluster-robust standard errors to correct for temporal and spatial correlation between subdivisions (Angrist and Pischke, 2008). An overview of the full set of control variables is given in Table A 1 in the appendix. Interpretation of the coefficient β_1 is straight forward: if the energy performance score decreases – and energy efficiency thus increases – by 10 kWh/m²a, the monthly warm rent decreases by β_1 euro per square meter.

I start the analysis by estimating the regression as given by Eq. (5) for the "submarket warm" sample as well as for subsamples according to the disclosure of explicit heating costs. I further test the robustness of the results by excluding newly built apartments to focus on energy retrofits only and additionally excluding all observations that have at least one "unknown" factor variable. Finally, I check for different income levels, different energy efficiency levels, different (basic) rent levels, different heating and fuel types used for heating and also different types of EPCs.

Since the nature of the data does not allow for a comparison of inefficiencies between the "cold" and "warm" submarkets, I instead estimate the impact of energy efficiency on basic rents for both submarket samples. I thereby use the model as specified in Sieger and Weber (2023) (cf. Eq. (6)). The coefficient β_2 is then expected to be positive given that the lowering effect of an increasing energy performance score on basic rents is already included in the negative sign. Interpretation now changes to: if the energy performance score decreases – and energy efficiency thus increases – by 10 kWh/m²a, the monthly basic rent increases by β_2 euro per square meter.

$$BasicRent_{int} = -\beta_2 eps_i + exp\,(\alpha + \gamma \boldsymbol{X}_i + \delta \boldsymbol{N}_{nt} + \mu_t) + \varepsilon'_{int} \tag{6}$$

3.2 Moderation analysis

To investigate a possible moderating effect of information disclosure on the valuation of energy efficiency, two dummy variables are created. Using the full sample, the first dummy, $basic\_only_i$, discriminates between the submarkets "cold" and "warm", taking a value one if only basic rents are disclosed and zero otherwise (Eq. (7)). Using the subsample "warm", the second dummy, $warm\_only_i$, is constructed, taking the value one, if only warm rents are disclosed and zero if explicit heating costs are disclosed (Eq. (8)).

$$basic\_only_i = \begin{cases} 0, & warm\ rent\ disclosed\ (submarket\ "warm") \\ 1, & only\ basic\ rent\ disclosed\ (submarket\ "cold") \end{cases} \tag{7}$$

$$warm\_only_i = \begin{cases} 0, & exact\ heating\ costs\ disclosed \\ 1, & only\ warm\ rent\ disclosed \end{cases} \tag{8}$$

I then implement a traditional hedonic model in its semi-logarithmic form and use the high-dimensional fixed effects (HDFE) method developed by Guimarães and Portugal (2010) and Gaure (2013), among others, to control for possible omitted variable bias due to unobservable geographical and locational conditions[7]. Furthermore, I focus on relative effects of energy efficiency on basic rents, so that the model allows to directly compare results for the full market with results for the submarket “warm” sample.

In a first step, I examine the full rental market to test whether the disclosure of warm rents has positive effects on the valuation of energy efficiency, compared to only providing basic rents in the online advertisements. To estimate the moderating effect, the dummy $basic\_only_i$ as well as an interaction between the dummy and the energy performance score $eps_i \times basic\_only_i$ are included in the regression. The equation thus takes the following form:

$$\begin{aligned} ln(BasicRent_{insdt}) &\\ &= \alpha + \beta_3 eps_i + \beta_4 basic\_only_i + \beta_5 (eps_i \times basic\_only_i) + \gamma \boldsymbol{X}_i \\ &+ \delta \boldsymbol{N}_{nt} + \mu_t + \tau_s + \nu_d + \rho_n + \varepsilon_{insdt} \end{aligned} \tag{9}$$

μ_t again describes time-fixed effects on a quarterly-year level; τ_s, ν_d, ρ_n are regional-fixed effects on state, district and neighborhood level, respectively. eps_i was scaled prior estimation, so that the main effect for $basic\_only_i$ can be interpreted for mean levels of energy efficiency.

In this specification, the coefficients β_3 and $(\beta_3 + \beta_5)$ report semi-elasticities: a one-unit change in eps_i results in a $100 \cdot \beta_3$ percent change in basic rents for $basic\_only_i$ equal to zero, i.e., warm rents are disclosed. Otherwise, the change in basic rents amounts to $100 \cdot (\beta_3 + \beta_5)$ percent.

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[7] An inclusion of such high numbers of fixed effects was not possible for the nonlinear model due to computational power.

In a second step, the submarket “warm” is examined, to test whether the disclosure of explicit heating costs provides further positive effects on the valuation of energy efficiency, compared to only disclosing overall warm rents. The approach and interpretation are analogous to the first moderation analysis; however, the dummy $warm\_only_i$ and the interaction $eps_i \times warm\_only_i$ are now included in the regression. The equation for the second moderation analysis is thus given as:

$$\begin{aligned} ln(BasicRent_{insdt}) \\ &= \alpha + \beta_6 eps_i + \beta_7 warm\_only_i + \beta_8 (eps_i \times warm\_only_i) + \gamma \boldsymbol{X}_i \\ &+ \delta \boldsymbol{N}_{nt} + \mu_t + \tau_s + \nu_d + \rho_n + \varepsilon_{insdt} \end{aligned} \tag{10}$$

I additionally run subsample regressions according to the type of EPCs to check for heterogeneous effects. Thereby, the full sample as well as the submarket “warm” subsample are used to test for the disclosure of warm rents as well as full information.

In a last step, I also add the dummy $\beta_9 warm\_only_i$ as well as the interaction $\beta_{10}(eps_i \times warm\_only_i)$ to Eq. (5) and re-estimate the model using nonlinear least squares. Since the effect of the energy performance score on the warm rent is still linear, interpretation of the moderation effect is straight forward. If the coefficient $\widetilde{\beta_1}$ for eps_i is statistically significantly different from zero, it reports the remaining inefficiencies even when full information is disclosed. If $warm\_only_i = 1$ and β_{10} is also statistically significantly different from zero, this coefficient shows additional inefficiencies when only overall warm rents are provided in the advertisement.

3.3 Data

Micro-level information on asking rents of flats advertised on the internet platform *ImmobilienScout24.de* are provided by *RWI-GEO-RED* (RWI and ImmobilienScout24, 2022). The dataset contains information on basic rents as well as on a variety of apartment characteristics and special features. Additionally, for most observations, utility costs and at least some information on heating costs are reported. The data is georeferenced in terms of 1 km^2 grids. For limitations that arise with this dataset, see Sieger and Weber (2023).

Socio-economic characteristics, compiled at the level of 1 km^2 grids as well, are provided by *RWI-GEO-GRID* (RWI and microm, 2022). The data originates from microm Micromarketing-Systeme und Consult GmbH, a market research company specializing in regional analysis. Both datasets were merged based on georeference and year[8]. After clearing the data from duplicates and outliers based on 1st and 99th percentiles of all numeric variables and applying a Cook's Distance filter with cutoff 4/N, the final dataset consists of 3,903,473 observations from May 2014[9] to December 2021 distributed over 55,733 grid cells across Germany. Descriptive statistics of all numeric variables are presented in Table 2.

Statistics are shown for the submarket "cold", where only basic rents are given, as well as for the submarket "warm", where warm rents are reported. For the latter, there are also separate statistics displayed for subsamples according to the disclosure of explicit heating costs as well as differences between these subsamples. A flow chart explaining the generation of submarkets and subsamples is given in Figure A 1. An overview of all factor variables is given in Figures A 2 to A 5 in the appendix.

A comparison of the "cold" and "warm" submarkets indicates that the first shows cheaper basic rents, but it also has older and less efficient buildings. An average flat is offered for €7.83 per square meter of living area and shows an energy performance score of 135 kWh/m²a (which is equal to energy efficiency class E). In terms of living area and selected neighborhood characteristics, differences are rather small.

Within the "warm" submarket, a distinction between subsamples according to the disclosure of heating costs reveals some interesting insights. Overall, flats are on average advertised for 8.16 €/m²; however, there are large differences across subsamples. When heating costs are fully disclosed (subsample B), the basic rent only amounts to 7.50 €/m² which is even less than in the "cold" submarket sample. When there is no disclosure of explicit heating costs and only the overall warm rent is given, the basic rent amounts to 8.74 €/m², resulting in a difference of 1.24 €/m². The difference between subsamples in terms of the overall warm rent is slightly smaller with 1.07 €/m².

Average heating costs per square meter can only be calculated for the subsample that reveals full information. These costs amount to 1.14 €/m²/months. Nonetheless, Figure 1 shows the conditional probability of estimated monthly heating costs across subsamples. Using subsample B, monthly heating costs were regressed on the (monthly) energy performance score: $HeatCost_i \sim \alpha + \beta eps_i + \varepsilon_i$.

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[8] The socio-economic data was merged to the real estate data with a one-year lag.

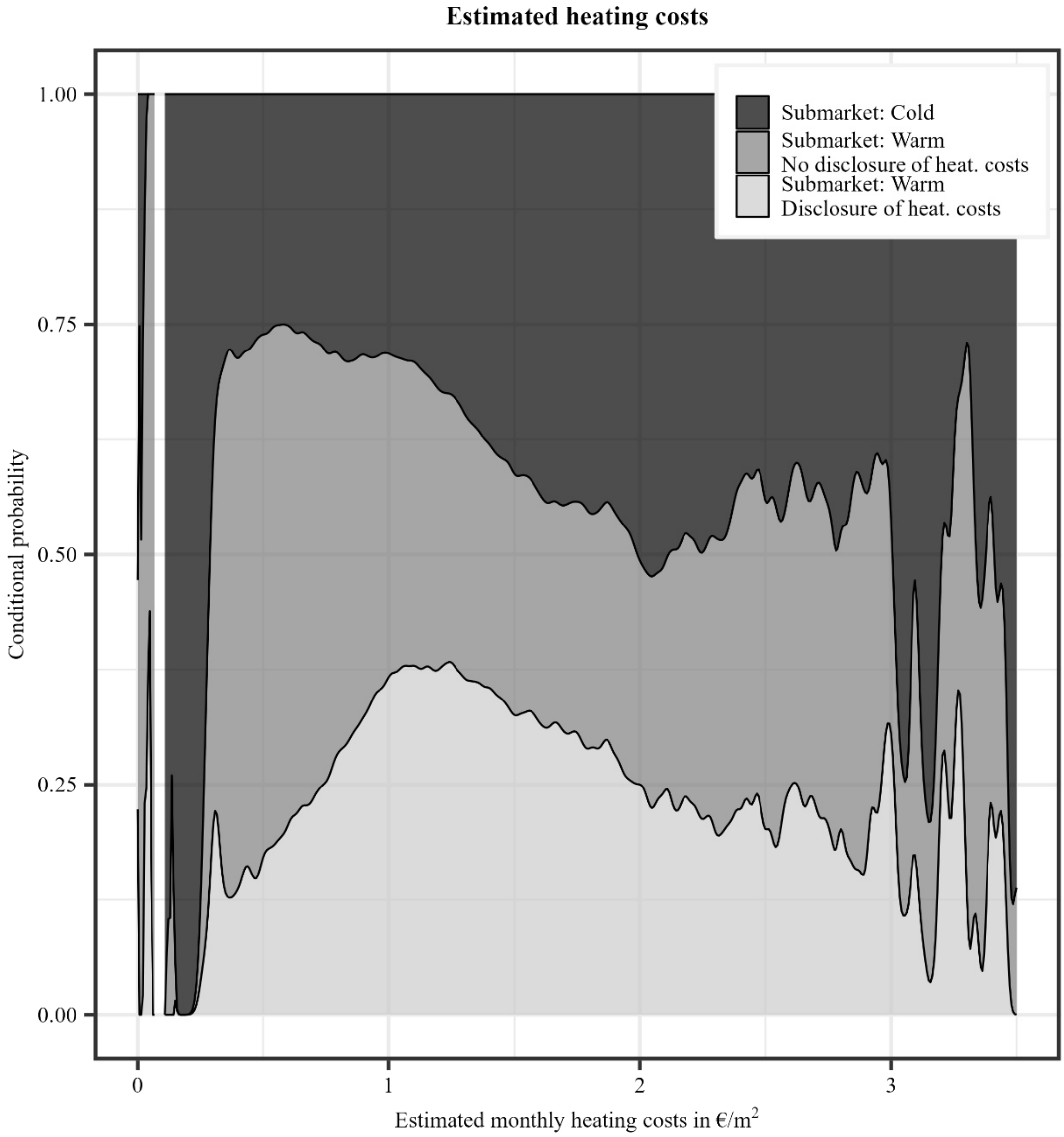
[9] I use the specific cut-off because this is the date from which energy performance certificates must be mandatorily disclosed in online advertisements. By limiting the dataset this way, I reduce the likelihood of selection bias related to the disclosure of information about the building's energy performance.

Table 2 Descriptive statistics.

	Submarket					
	“Cold”	**“Warm”**			**Difference[c]:**	
			Subsample A:	**Subsample B:**	**Subs. B – Subs. A**	
Variable	**Full submarket**	**Full submarket**	**No disclosure of heating costs**	**Disclosure of heating costs**	**Diff.**	**t**
Basic rent	7.82	8.16	8.74	7.50	-1.24***	374.73
(in €/m^2/month)	(2.81)	(3.10)	(3.30)	(2.70)		
Warm rent[a]		10.76	11.26	10.19	-1.07***	297.35
(in €/m^2/month)		(3.31)	(3.59)	(2.86)		
Heating costs[b]				1.14		
(in €/m^2/month)				(0.35)		
Energy performance score	135.31	116.00	110.70	121.99	11.29***	-202.32
(in kWh/m^{2}a)	(60.62)	(50.36)	(49.29)	(50.89)		
Living area	66.66	68.21	70.74	65.36	-5.368***	213.16
(in m^2)	(23.74)	(23.13)	(25.28)	(20.06)		
Age	60.21	50.80	47.69	54.32	6.63***	-191.68
(in years)	(30.90)	(31.68)	(34.63)	(27.56)		
Population density	5,140	4,935	4,698	5,204	506***	-117.91
(in inh/km^2)	(4,158)	(3,852)	(3,784)	(3,911)		
Unemployment rate	8.47	7.94	6.80	9.23	2.43***	-559.96
(in %)	(4.24)	(4.07)	(3.66)	(4.12)		
Households with foreign	13.50	12.45	12.07	12.88	0.81***	-87.79
head (in %)	(8.38)	(8.33)	(8.28)	(8.37)		
Purchasing power	21,833	22,021	22,912	21,015	-1,807***	418.38
(in €/inh)	(3,907)	(4,223)	(4,424)	(3,736)		
Observations N	663,385	3,240,088	1,719,127	1,520,961		
in %	16.99	83.01				
		100.00	53.06	46.94		

Notes: St. Dev. in parentheses. [a] Warm rent consists of basic rent plus auxiliary costs plus heating costs. [b] Only given in Subsample B. [c] t-tests for equality of means assume unequal population variances. This was determined using the Welch Two Sample t-test with its alternative hypothesis: true difference in means between group 0 and group 1 is not equal to 0.
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Using the resulting $\alpha = 44.17$ €/month as fixed costs and $\beta = 0.04502$ €/kWh/month as variable costs, heating costs were estimated for all subsamples. The conditional probability of having low monthly heating costs (< 1 €/m^2) is highest in subsample A, where overall warm rents are provided but exact heating costs are not disclosed. Contrary, the probability of monthly heating costs above 2 €/m^2 is highest in the submarket “cold” sample. Overall, heating costs are still very similar, so that price differences in warm rents should mainly be driven through price differences in basic rents.



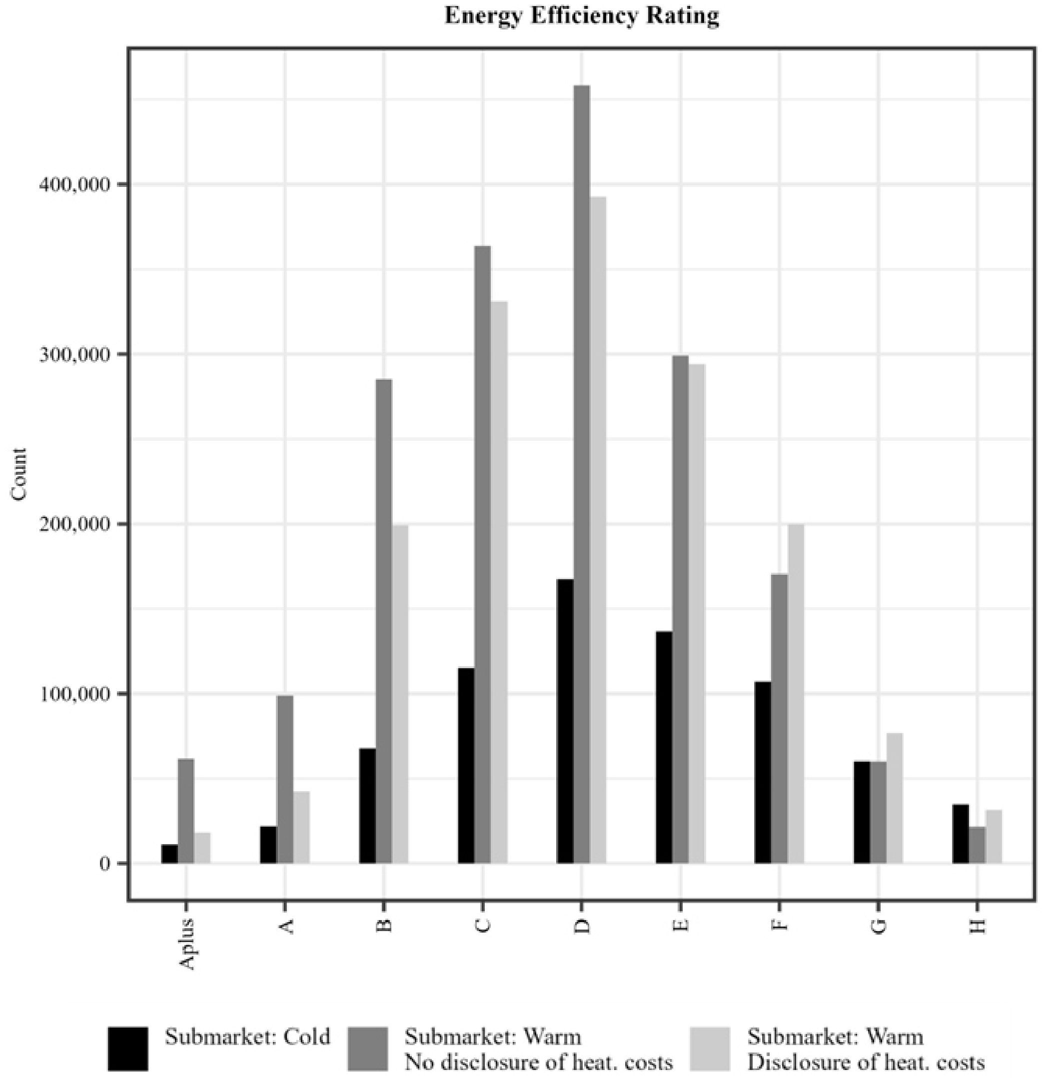
Source: Own calculation and illustration based on RWI-GEO-RED.

Figure 1 Conditional probability of estimated heating costs across subsamples.

Note: The plot was created using the ggplot2-package in R. Probability density estimation was done using geom_density().

Additionally, the distribution of energy efficiency ratings across submarkets and subsamples is illustrated in Figure 2. Overall, most apartments fall into the reference category D. The most efficient buildings (categories A+, A and B) are mostly found in the warm submarket with no disclosure of heating costs. This might be related to newly built apartments, as they are most likely to be efficient with no references for heating costs e.g., from previous tenants. It is further in line with the estimated probability of low monthly heating costs. However, this could also be a result of strategic self-selection, if the buildings that are (very) good on paper according to the energy rating are relatively worse off in terms of heating costs and vice versa.

A high share of least efficient apartments (categories G and H) either belongs to the cold submarket or to the subsample with full information disclosed. Given the overall lower percentage of observations in the cold submarket, the shares in the least efficient categories are overproportioned. Again, this is in line with the estimated probability of higher monthly heating costs and could also be a result of self-selection.



Source: Own calculation and illustration based on RWI-GEO-RED.

Figure 2 Distribution of energy efficiency ratings.

Finally, it is worth looking at differences across types of the EPC as there is evidence that the valuation of energy efficiency differs across EPCs (Galvin, 2023a; Sieger and Weber, 2023; Taruttis and Weber, 2022). Table 3 reports descriptive statistics across EPC types for the full sample as well as both subsamples in the warm submarket. Basic rents as well as overall warm rents (in the submarket "warm") are higher for flats that have a demand-based certificate (*Bedarfsausweis*) compared to consumption-based certificates (*Verbrauchsausweis*).

Table 3 Descriptive statistics for different types of the energy performance certificate.

	Demand-based certificate			**Consumption-based certificate**		
		Submarket “warm”			**Submarket “warm”**	
	Full subsample	**Disclosure of heating costs**	**No disclosure of heating costs**	**Full subsample**	**Disclosure of heating costs**	**No disclosure of heating costs**
Basic rent	9.10	8.33	10.22	7.58	7.07	8.05
(in €/m^2/month)	(3.37)	(2.99)	(3.58)	(2.73)	(2.42)	(2.91)
Warm rent		10.92	12.75		9.80	10.56
(in €/m^2/month)		(3.18)	(3.90)		(2.59)	(3.20)
Heating costs		1.10			1.16	
(in €/m^2/month)		(0.35)			(0.35)	
Energy	112.53	116.48	92.11	122.81	124.80	119.44
performance score	(66.69)	(61.38)	(59.35)	(43.31)	(44.36)	(40.94)
(in kWh/m^{2}a)						
Age	45.25	49.67	34.73	56.14	56.69	53.78
(in years)	(34.87)	(31.20)	(36.06)	(29.30)	(25.19)	(32.18)
1st occupancy	14.71	7.46	25.25	0.84	0.60	1.08
(in %)						
Observations N	1,339,230	512,330	549,796	2,564,243	1,008,631	1,169,331

Note: St. Dev. in parentheses.
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Furthermore, there are differences of about 10 kWh/m^{2}a regarding the energy performance score of the advertised apartments – with it being lower if the apartment is certified based on demand. Even larger differences are found in the subsamples, where only total costs but no heating costs are disclosed: While apartments show an average energy performance score of 120 kWh/m^{2}a when certified based on consumption, flats only report an average of 92 kWh/m^{2}a when certified based on demand. However, about one fourth of all flats in the latter subsample are advertised as 1st occupancy. Better energy efficiency, higher rents as well as the non-disclosure of heating costs can thus be explained by the fact that the building was most likely newly built.

On the other hand, 1st occupancy rates in the consumption-based certificate subsample are quite low and can probably be explained mainly by incorrect entries made by landlords on the internet platform. Moreover, buildings with demand certificates and no disclosure of heating costs are on average approximately 20 years younger than those with consumption certificates. A significant part of this difference might yet be explained by the first-time rentals; the rest corresponds to the difference observed in the samples with disclosed heating costs.

4 Empirical Results

4.1 Are markets for energy efficiency inefficient?

Main regression results for the TCU approach in the warm submarket are displayed in Table 4. Overall, monthly warm rents increase [decrease] on average by 0.008 €/m² if the energy performance score increases [energy efficiency increases] by 10 kWh/m²a. The installed heating system also plays a role when it comes to pricing. For example, if the advertised flat is connected to district heating, its warm rent is on average 3.96 % higher compared to similar flats with gas heating. Furthermore, flats that were modernized in 2010 or later rent out at a premium of about 1.2 %.

The coefficients for the energy performance scores are slightly smaller in both subsamples but remain positive and statistically significant. Somewhat larger differences can only be found for the valuation of oil compared to gas heating with effects being larger in subsample B. Excluding newly built apartments leads to slightly larger effects in subsample A; however, no differences in the valuation of energy efficiency can be found in the full sample and subsample B (cf. Table A 2).

Overall, the positive β_1-coefficients point to inefficiencies in the valuation of energy efficiency. As previously described, the coefficients should be zero (or at least not statistically significant) if the market for energy efficiency was efficient. Nonetheless, all effects appear to be rather small compared to actual energy cost savings for improvements of 10 kWh/m²a. At average energy prices for heating[10] of 0.0871 €/kWh, the expected monthly heating cost savings would be approximately 0.07 €/m². As warm rents only decrease by less than 0.01 €/m², large parts should be already included in higher basic rents resulting in higher rental income for property owners.

By excluding all observations with some missing attribute values from the regression, a robustness check may be performed – this excludes distortions resulting from the deliberate omission of some values by property owners for hidden reasons. In such a case, the inclusion of these observations may lead to biased results. Some data may, of course, also be missing due to (inadvertently) incorrect entries by the landlord or landlady. These observations can usually be included in the regression without causing any problems.

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[10] Weighted average during study period.

Results for the robustness checks – with newly built apartments being either included or excluded – are shown in Table A 3. Sample size is reduced by almost 80 % when excluding all observations with missing values. Nonetheless, effects of the energy performance score on warm rents are still positive in all regressions and only slightly differ compared to the previous results. The decrease in monthly warm rents remains less than 0.01 €/m^2 for improvements of 10 kWh/m^{2}a in all specifications.

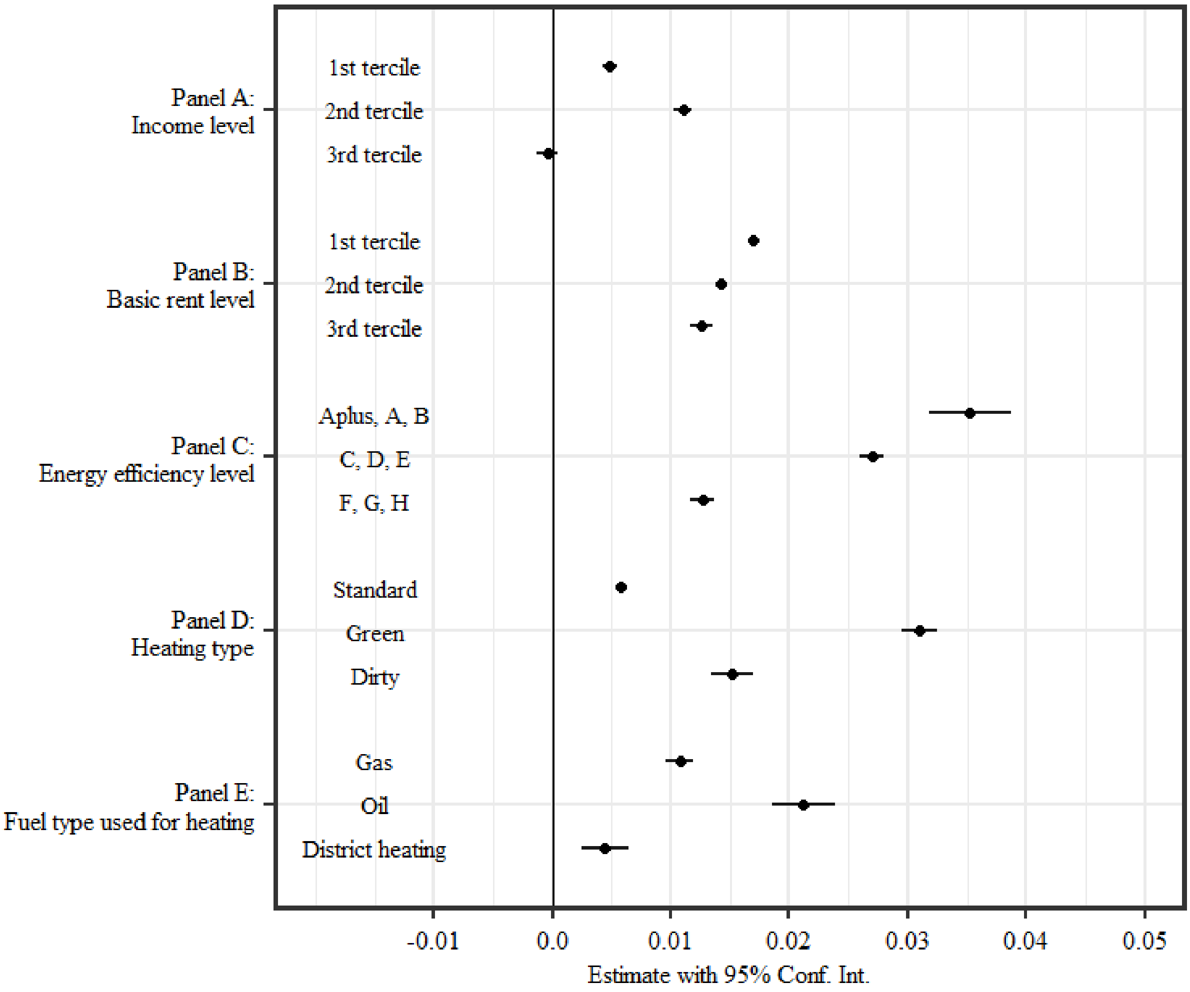
Table 4 Main regression results in TCU model – submarket “warm”.

	Submarket “warm” **Newly built apartments included.**		
Dependent Var.: WarmRent in €/m^2/month	**Full submarket**	**Subsample A: No disclosure of exact heating costs**	**Subsample B: Disclosure of exact heating costs**
Energy performance score	0.0077 ***	0.0061 ***	0.0060 ***
(in 10 kWh/m^{2}a)	[0.0002]	[0.0003]	[0.0003]
Selected heating system, reference: gas heating			
District heating	0.0396 ***	0.0404 ***	0.0327 ***
	[0.0005]	[0.0007]	[0.0007]
Oil heating	0.0095 ***	0.0050 ***	0.0156 ***
	[0.0008]	[0.0011]	[0.0014]
Floor heating	0.0450 ***	0.0461 ***	0.0412 ***
	[0.0005]	[0.0006]	[0.0009]
Central heating	0.0096 ***	0.0124 ***	0.0062 ***
	[0.0004]	[0.0005]	[0.0006]
Last renovated in 2010 or later	0.0119 ***	0.0125 ***	0.0081 ***
	[0.0002]	[0.0003]	[0.0004]
Controls for___included?			
Apartment characteristics	*yes*	*yes*	*yes*
Neighborhood characteristics	*yes*	*yes*	*yes*
Season FE (quarterly-year)	*yes*	*yes*	*yes*
RMSE	1.68	1.76	1.56
Pseudo-R^2	0.741	0.759	0.702
Observations	3,240,088	1,719,127	1,520,961

Notes: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Pseudo-R^2 is estimated using the ‘rsquare’-function from the ‘modelr’-package in R (Version 4.1.2). RMSE in €/m^2. All apartment and neighborhood characteristics included in the regression are listed in Table A 1.

Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Besides checking the robustness of the results, I also test for heterogeneity in the sample. I therefore estimate different subsample regressions; results are illustrated in Figure 3 and further provided in Table A 4. Panel A shows estimates for varying income levels in the neighborhoods. In the 1st and 2nd tercile subsamples, the effect of the energy performance score on monthly warm rents are positive; however, effect size is twice as large in the 2nd tercile than in the 1st tercile subsample. For the highest income tercile, the coefficient becomes slightly negative and statistically insignificant. In high-income neighborhoods, the market for energy efficiency thus seems to be efficient.



Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Figure 3 TCU results for subsample regressions.

Note: Corresponding results are reported in Table A 4.

In Panel B, results are given for different basic rent levels. Effects are found to be larger than in the full sample; however, there are no differences between the 2nd and 3rd tercile subsample and only slightly higher effects in the 1st tercile subsample. Panel C focuses on variations across energy efficiency ratings. Roughly 60 % of all advertised flats either have a C-, D- or E-label, which corresponds to an energy performance score of 75 kWh/m²a to 160 kWh/m²a.

Within this subsample, monthly warm rents decrease on average by 0.03 €/m² when the energy performance score decreases by 10 kWh/m²a. Effects are less than half the size for flats with higher energy performance scores. In the subsample with the most efficient apartments, the effect of the energy performance score on warm rents is the highest with a coefficient of 0.05 €/m². This might be explained due to already very low energy performance measures so that there is a kind of (psychological) "saturation effect" regarding energy efficiency which induces a zero WTP from tenants for further improvements in energy efficiency.

A similar conclusion can be drawn for results of different heating systems, as shown in Panel D. If the flat is equipped with a sustainable heating system (cf. "green" technology), effect sizes are larger compared to those in both other subsamples. Thus, the WTP might be lower for additional improvements in energy efficiency when sustainable heating technologies are already implemented – although this is not economically rational in a total-cost-minimization perspective.

Somewhat contrary results are, however, found among different fuel types used for heating (Panel E). If flats are connected to district heating, monthly warm rents only decrease by 0.003 €/m^2 when energy efficiency is improved by 10 kWh/m^{2}a. Apartments that use gas or oil as primary energy source for heating show effects of the energy performance score on monthly warm rents of about 0.01 €/m^2 or 0.02 €/m^2, respectively.

Lastly, I check for heterogeneous results among flats with different EPCs. Results are shown in Table 5. On the one hand, I find positive and statistically significant effects in the consumption-based-certificate subsample. If energy efficiency is improved by 10 kWh/m^{2}a, monthly warm rents decrease on average by 0.02 €/m^2. Thus, the market for energy efficiency again turns out to be inefficient.

Table 5 Regression results in TCU model for EPC type subsamples.

	EPC Subsamples	
Dependent Var.: WarmRent in €/m^2/month	**Demand-based**	**Consumption-based**
Energy consumption	-0.0114 ***	0.0240 ***
(in 10 kWh/m^2/a)	[0.0004]	[0.0003]
RMSE	1.86	1.56
Pseudo-R^2	0.744	0.721
Observations	1,062,126	2,177,962

Notes: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Pseudo-R^2 is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE in €/m^2. All apartment and neighborhood characteristics are included in the regression, including newly built apartments and all observations including the factor "unknown".
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID

On the other hand, effects are negative in the demand-based-certificate subsample. Accordingly, energy-efficiency improvements as indicated by the demand-based EPC are apparently over-proportionally valued in the market. As only asking prices are observed, it is likely that property owners overestimate the impact of energy efficiency improvements as reflected in the demand-based EPC. Actual heating costs apparently decrease less with better energy performance scores than expected according to the EPC – which results in increasing warm rents in this case.

4.2 Can the disclosure of total costs and exact heating costs help overcome information asymmetries and thus lead to a better valuation of energy efficiency?

Before testing the disclosure of more information as a moderator for the effect of the energy performance score on basic and warm rents, I rather estimate the original nonlinear model (cf. Eq. (6)) separately for both submarkets “cold” and “warm” to see whether differences occur in the estimated effects. I also run separate subsample regressions according to the EPC as prior results suggest that the effects of the energy performance score differ strongly across subsamples. Results are reported in Table 6.

Table 6 Results for basic rents in TCU model for submarket "cold" vs. submarket "warm".

	Full sample		**Demand-based EPC subsample**		**Consumption-based EPC subsample**	
	Submarket:		**Submarket:**		**Submarket:**	
Dependent Var.: BasicRent in €/m²/month	**Cold**	**Warm**	**Cold**	**Warm**	**Cold**	**Warm**
Energy performance score (in 10 kWh/m²/a)	0.0044 *** [0.0003]	0.0166 *** [0.0002]	0.0202 *** [0.0005]	0.0296 *** [0.0003]	-0.0066 *** [0.0005]	0.0048 *** [0.0002]
Last renovated in 2010 or later	0.0139 *** [0.0007]	0.0229 *** [0.0003]	0.0116 *** [0.0010]	0.0450 *** [0.0023]	0.0134 *** [0.0009]	0.0139 *** [0.0003]
Controls for___included?						
Apartment characteristics	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Neighborhood characteristics	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Season FE (quarterly-year)	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
RMSE	1.51	1.52	1.57	1.69	1.44	1.41
Pseudo-R²	0.711	0.758	0.716	0.760	0.704	0.738
Observations	663,385	3,240,088	277,104	1,062,126	386,281	2,177,962

Notes: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Pseudo-R² is estimated using the ‘rsquare’-function from the ‘modelr’-package in R (Version 4.1.2). RMSE in €/m². All apartment and neighborhood characteristics are included in the regression, including newly built apartments and all observations including the factor “unknown”.
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

For the full sample, effects are four times larger in the submarket “warm” compared to the submarket “cold”. If the energy performance score decreases – and energy efficiency thus increases – by 10 kWh/m²a, the monthly basic rent increases on average by 0.004 €/m² in the “cold” and by 0.017 €/m² in the “warm” submarket. Therefore, energy efficiency is more appreciated when warm rents are reported in the online advertisement. Furthermore, apartments that were renovated in 2010 or later are rented out at a premium of roughly 2.3 %, if warm rents are disclosed in the online advertisement, and at a premium of only 1.4 %, if only basic rents are reported – both compared to non-renovated flats.

Similar patterns arise for the EPC-type subsamples. Energy efficiency is again more appreciated when warm rents are disclosed. However, in the demand-based certificate subsample, effects only slightly differ between the “cold” and “warm” submarkets, but effect sizes are generally much larger. If energy efficiency improves by 10 kWh/m^2a, basic rents increase on average by 0.02 €/m^2 in the “cold” and by 0.03 €/m^2 in the “warm” submarket. In the consumption-based certificate subsample, I yet even find negative effects when only basic rents are reported in the advertisement. Overall, effect sizes are much smaller compared to the full sample and the demand-based EPC subsample.

Results for the first moderation analysis, investigating effects of a disclosure of warm rents compared to only providing information on basic rents, are shown in Table 7. The non-disclosure of warm rents already impacts the basic rent of the advertised apartment. The effect is negative yet mostly statistically insignificant for all OLS specifications (columns (1) to (3)) and also when including time fixed effects. Once regional fixed effects are included, the coefficients turn positive and statistically significant.

Table 7 Moderation-analysis results in semi-log model: Disclosure of warm vs. basic rents.

	Full sample – both submarkets combined						
Dependent Var.: Ln(BasicRent) in €/m^2/month	**(1)** **OLS 1**	**(2)** **OLS 2**	**(3)** **OLS 3**	**(4)** **FE 1**	**(5)** **FE 2**	**(6)** **FE 3**	**(7)** **FE 4**
Energy performance score	0.0026 ***	0.0024 ***	-0.0023***	-0.0020***	-0.0018***	-0.00176***	-0.0017***
(in 10 kWh/m^2/a)	[0.0003]	[0.0003]	[0.0002]	[0.0002]	[0.0002]	[0.0001]	[0.0001]
Basic_only = 1	-0.0028	-0.0026	-0.0056*	-0.0049*	0.0028	0.0107 ***	0.0104 ***
(only basic rent given)	[0.0030]	[0.0030]	[0.0022]	[0.0022]	[0.0021]	[0.0016]	[0.0013]
Energy performance score	-0.0011**	-0.0013***	0.0012 ***	0.0012 ***	0.0008 **	0.0002	0.0002
× basic_only	[0.0004]	[0.0004]	[0.0002]	[0.0002]	[0.0002]	[0.0002]	[0.0001]
Controls for___included?							
Heating type	*no*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Apartment characteristics	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Neighborhood charact.	*no*	*no*	*yes*	*yes*	*yes*	*yes*	*yes*
Seasonal FE (quarterly-year)	*no*	*no*	*no*	*yes*	*yes*	*yes*	*yes*
Regional FE (county)	*no*	*no*	*no*	*no*	*yes*	*yes*	*yes*
Regional FE (district)	*no*	*no*	*no*	*no*	*no*	*yes*	*yes*
Regional FE (neighborhood)	*no*	*no*	*no*	*no*	*no*	*no*	*yes*
RMSE	0.26	0.25	0.18	0.18	0.17	0.14	0.12
Adj.-R^2	0.436	0.439	0.727	0.732	0.758	0.820	0.868
Observations	3,903,473	3,903,473	3,903,473	3,903,473	3,903,473	3,903,473	3,903,473

Notes: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. RMSE in log(€/m^2). All apartment and neighborhood characteristics included in the regression are listed in Table A 1.
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

In the full model (column (7)), apartments with an average energy performance score are rented at a premium of roughly 1 %, when no information on warm rents are disclosed. In other words, the lack of knowledge of the tenants is already exploited in the form of higher basic rents. The impact of a non-disclosure on the effect of the energy performance score, however, is rather small. If overall warm rents are provided in the online advertisement ($basic\_only_i = 0$), monthly basic rents increase on average by 0.17 % if the energy performance score decreases by 10 kWh/m^{2}a. For the non-disclosure, this effect decreases to 0.15 %; however, the moderating effect is statistically insignificant. This means that no statistically significant differences arise regarding the appreciation of energy efficiency.

A different picture emerges when looking at the submarket “warm”. Results for the second moderation analysis, including a dummy for only providing overall warm rents in comparison to the additional disclosure of exact heating costs, are reported in Table 8. The non-disclosure of additional information ($warm\_only_i$ = 1) leads to higher monthly basic rents, confirming the full sample results.

Table 8 Moderation-analysis results in semi-log model: Disclosure of exact heating costs vs. warm rents.

	Submarket “warm”						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Dependent Var.: Ln(BasicRent) in €/m^2/month	**OLS 1**	**OLS 2**	**OLS 3**	**FE 1**	**FE 2**	**FE 3**	**FE 4**
Energy performance score	0.0002	-0.0001	-0.0037***	-0.0034***	-0.0029***	-0.0023***	-0.0024***
(in 10 kWh/m^2/a)	[0.0003]	[0.0003]	[0.0002]	[0.0002]	[0.0002]	[0.0002]	[0.0001]
Warm_only = 1	0.0270 ***	0.0243 ***	-0.0007	0.0005	0.0253 ***	0.0350 ***	0.0284 ***
(only warm rent given)	[0.0040]	[0.0039]	[0.0029]	[0.0030]	[0.0023]	[0.0014]	[0.0010]
Energy performance score	0.0054 ***	0.0057 ***	0.0030 ***	0.0029 ***	0.0023 ***	0.0011 ***	0.0012 ***
× warm_only	[0.0004]	[0.0004]	[0.0003]	[0.0003]	[0.0003]	[0.0002]	[0.0001]
Controls for___included?							
Heating type	*no*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Apartment characteristics	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Neighborhood charact.	*no*	*no*	*yes*	*yes*	*yes*	*yes*	*yes*
Seasonal FE (quarterly-year)	*no*	*no*	*no*	*yes*	*yes*	*yes*	*yes*
Regional FE (county)	*no*	*no*	*no*	*no*	*yes*	*yes*	*yes*
Regional FE (district)	*no*	*no*	*no*	*no*	*no*	*yes*	*yes*
Regional FE (neighborhood)	*no*	*no*	*no*	*no*	*no*	*no*	*yes*
RMSE	0.25	0.25	0.18	0.18	0.17	0.14	0.12
Adj.-R^2	0.457	0.460	0.736	0.740	0.747	0.829	0.877
Observations	3,240,088	3,240,088	3,240,088	3,240,088	3,240,088	3,240,088	3,240,088

Notes: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. RMSE in log(€/m^2). All apartment and neighborhood characteristics included in the regression are listed in Table A 1.
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Effects of the energy performance score on basic rents are negative in all specifications (except the first OLS in column (1)) and becoming statistically significant as soon as all control variables are included in the model. The monthly basic rent of apartments for which full information on warm rents and exact heating costs are provided increases on average by 0.24 % for energy efficiency improvements of 10 kWh/m^{2}a. This premium decreases to 0.12 %, when only warm rents are provided. The lack of information for tenants thus leads to a reduction in the rent premium for property owners by 50 %.

Including the moderation effect in the nonlinear model additionally provides information on these differences in direct monetary terms. The remaining inefficiencies in the market for energy efficiency for apartments with fully disclosed information on warm rents and exact heating costs amount to an average of 0.005 €/m²/month. When exact heating costs are not provided in the advertisement, additional inefficiencies of 0.004 €/m²/month occur (Table 9).

Table 9 Moderation-analysis results in TCU model: Disclosure of exact heating costs vs. warm rents – Effect on warm rents.

Dependent Var.: WarmRent in €/m²/month	**Submarket "warm"** **Full submarket**
Energy performance score (in 10 kWh/m²a)	0.0053 *** [0.0003]
Warm_only = 1	-0.2070 *** [0.0050]
Energy performance score × warm_only	0.0039 *** [0.0004]
RMSE	1.68
Pseudo-R²	0.742
Observations	3,240,088

Notes: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Pseudo-R² is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE in €/m². All apartment and neighborhood characteristics are included in the regression, including newly built apartments and all observations including the factor "unknown".
Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Finally, I test both moderation effects across EPC types. Results are shown in Table A 5. In the submarket "warm" sample, using the disclosure of exact heating costs as moderator again, I find a decrease of the rent premium of about 0.1 percentage points in both subsamples when exact heating costs are not disclosed. However, the overall effect size is much larger in the subsample with demand-based certificates compared to the consumption-based certificate subsample – which is in line with results reported in Table 5.

Contrary to full sample results (cf. Table 7) statistically significant moderation effects of the disclosure of warm rents compared to only providing basic rents are found, with differences arising across subsamples. While providing information on warm rents is beneficial for property owners of flats with consumption-based certificates, it results in slight disadvantages for landlords or landladies of demand-based certified flats (as indicated by the negative coefficient for the interaction term). Nonetheless, main effects of energy efficiency on basic rents are again twice the size in the demand-based certificate subsample.

5 Discussion

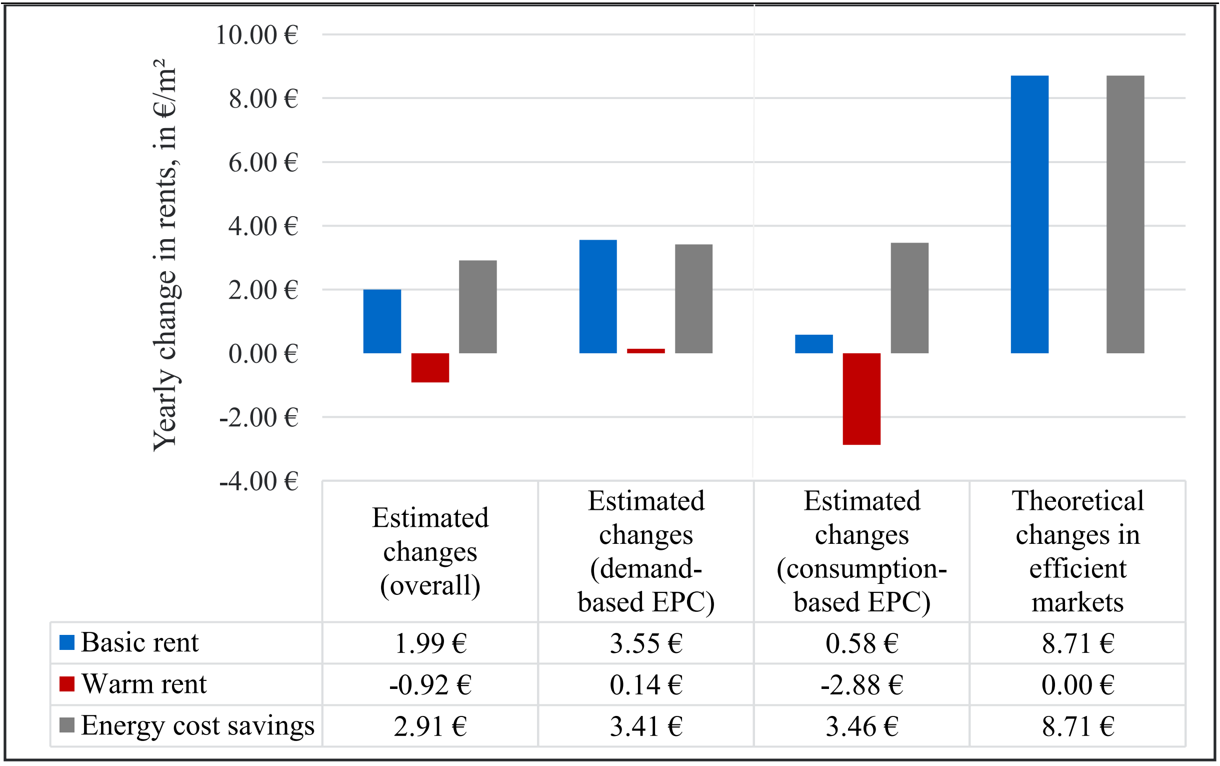
Since the estimated effect sizes are generally small in all regressions, Figure 4 provides the changes in yearly basic rents (cf. Table 6, submarket "warm"), yearly warm rents (cf. Table 4, "Full submarket", Table 5) and resulting energy cost savings in euro per square meter of living area in the case of a full refurbishment, i.e., an improvement of about 100 kWh/m²a. Additionally, theoretical energy cost savings and changes in basic and warm rents are shown in case of efficient markets.

In the submarket "warm", regression results show that basic rents increase on average by 1.99 €/m² per year after a full energy refurbishment has been carried out. If the dwelling has a demand-based EPC, the yearly basic rent increase amounts to 3.55 €/m²; if it has a consumption-based EPC, the surplus is only 0.58 €/m². The expected annual heating cost savings after such refurbishment are approximately 8.71 €/m², computed based on a heating energy price of 0.0871 €/kWh – the weighted average price for heating energy in the study period.

Given the regression results for basic rents, the expected heating cost savings should hence lead to a decrease in warm rents by 6.72 €/m² (5.16 €/m² for demand-based EPCs; 8.13 €/m² for consumption-based EPCs) – assuming that auxiliary costs remain unchanged. However, in sharp contrast, regression results show a decrease in warm rents by an average of only 0.92 €/m² per year. For demand-based EPCs, apartments even show an increase in warm rents of 0.14 €/m² per year; for consumption-based EPCs, yearly warm rents decrease by 2.88 €/m².

Taking it the other way round, if the 8.71 €/m² energy cost savings are offset against the 0.92 €/m² (consumption: 2.88 €/m²) lower warm rent, then around 7.79 €/m² (consumption: 5.83 €/m²) should remain as additional income for the property owner in the form of higher basic rents. However, this is obviously not the case, as the basic rent increase is a factor of four (consumption: five) lower. In the demand-based EPC subsample, this factor only amounts to about 2.5.

The regression results regarding the warm rent are contrary to those by Weber and Wolff (2018). They find that energy cost savings in rentals do not offset the additional costs that were charged after a renovation has taken place. Only in the demand-based EPC subsample, the estimated basic rent increase is greater than the empirically observed energy cost savings, resulting in a small increase in the warm rent. The remaining results are yet in line with findings of Kholodilin et al. (2017) and Sieger and Weber (2023) – both studies also find that expected energy cost savings for the (future) occupant exceed the monetary benefit for the owner by a factor of four or three to seven, respectively.



	Estimated changes (overall)	Estimated changes (demand-based EPC)	Estimated changes (consumption-based EPC)	Theoretical changes in efficient markets
🟦 Basic rent	1.99 €	3.55 €	0.58 €	8.71 €
🟥 Warm rent	-0.92 €	0.14 €	-2.88 €	0.00 €
⬛ Energy cost savings	2.91 €	3.41 €	3.46 €	8.71 €

Source: Own illustration based on estimation results shown in Table 4, Table 5 and Table 6.

Figure 4 Theoretical and estimated change in yearly rents per m² living area for improvements in the energy performance score of 100 kWh/m²a.

The results obtained in the present analysis yet indicate that actual energy cost savings are significantly lower than those theoretically calculated. This may be attributed to the so-called rebound effect (Greening et al., 2000)[11]. Theoretically, basic rents should increase by the same amount as energy cost savings if the market is efficient (right-hand side in Figure 4. However, regression results only report energy cost savings of 2.91 €/m² per year (left-hand side in Figure 4), resulting from the increase in basic rents and decrease in warm rents.

This can be explained by tenants changing their heating and ventilation behavior to the extent that they heat more than before the refurbishment, for example, and thus save less energy than initially assumed. Similar results were found in Aydin et al. (2017) and Peñasco and Anadón (2023). A further explanation for parts of the observed gap between expected and observed energy cost savings could be that the calculated values are overly optimistic regarding the technical energy savings of the implemented measures (Sunikka-Blank and Galvin, 2012). This would obviously also lead to an overestimation of the potential energy cost savings.

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[11] An alternative explanation is that the energy performance scores given in the EPC do not provide an exact measure of the heating energy use attributable to the building. This may notably be a consequence of individual user behavior having a substantial stochastic impact on the actual energy consumption which forms the basis of the consumption-based EPCs.

Furthermore, large differences across EPC-type subsamples are found. One possible explanation, especially for the higher valuation of energy efficiency in the demand-based EPC subsample, may be that, compared with consumption certificates, market participants have a higher level of trust in the technically calculated values.

Finally, providing information on exact heating costs leads to a better valuation of energy efficiency in all samples. This is in line with results of prior studies that evaluated whether monetary values instead of energy performance measures in certificates leads to higher premia for more efficient homes (Carroll et al., 2020; Carroll et al., 2016; Myers et al., 2022; Pommeranz and Steininger, 2021).

6 Conclusion and policy implications

The decarbonization of the dwelling stock is high on the policy agenda of the German government in order to reduce GHG emissions and achieve the stated emission-reduction goals. However, low monetary incentives, especially in the rental market, are slowing down energy refurbishments. By estimating a modified hedonic pricing model and using offering data from Germany's largest real estate internet platform as well as micro-level neighborhood information, this study evaluated the (in)efficiencies in the valuation of energy efficiency in the German rental housing market. Taking advantage of the rich dataset with 3,903,473 observations from 2014 to 2021, a moderation analysis further revealed that the valuation of energy efficiency varies for different levels of provided information in the advertisement.

Overall, the market for dwelling energy efficiency is found to be inefficient with potential monetary benefits arising for tenants. Energy cost savings due to energy improvements usually exceed basic rent increases, resulting in lower overall warm rents. Nearly efficient markets were only found in subsamples with high-income neighborhoods If the advertised apartments are certified by energy demand, overall warm rents are even found to increase when energy efficiency is improved.

Furthermore, including information on warm rents in the online advertisements does not lead to a higher valuation of energy efficiency in comparison to only providing basic rents. However, once information about exact heating costs is included, the premium for better energy efficiency standards increases by 50 %. These effects also vary across apartments with different types of energy performance certificates.

Two main policy implications can be derived from these results. First, a mandatory indication of heating costs in either energy performance certificates or online real estate advertisements could lead to a better valuation of energy efficiency, resulting in a higher willingness-to-pay from tenants for more efficient apartments and thus to higher rental income for property owners, that can be invested in energy retrofits.

Second, further research on the different (German) EPC types is needed to better understand the major differences between the samples and to identify their actual information content. This might help to get a more coherent picture of the interplay between technical improvements, behavioral changes and stochastic effects and to fully exploit the information potential of these certificates in future. On that basis, a transition towards a more standardized approach should be envisaged to develop more realistic energy ratings (Galvin, 2023a).

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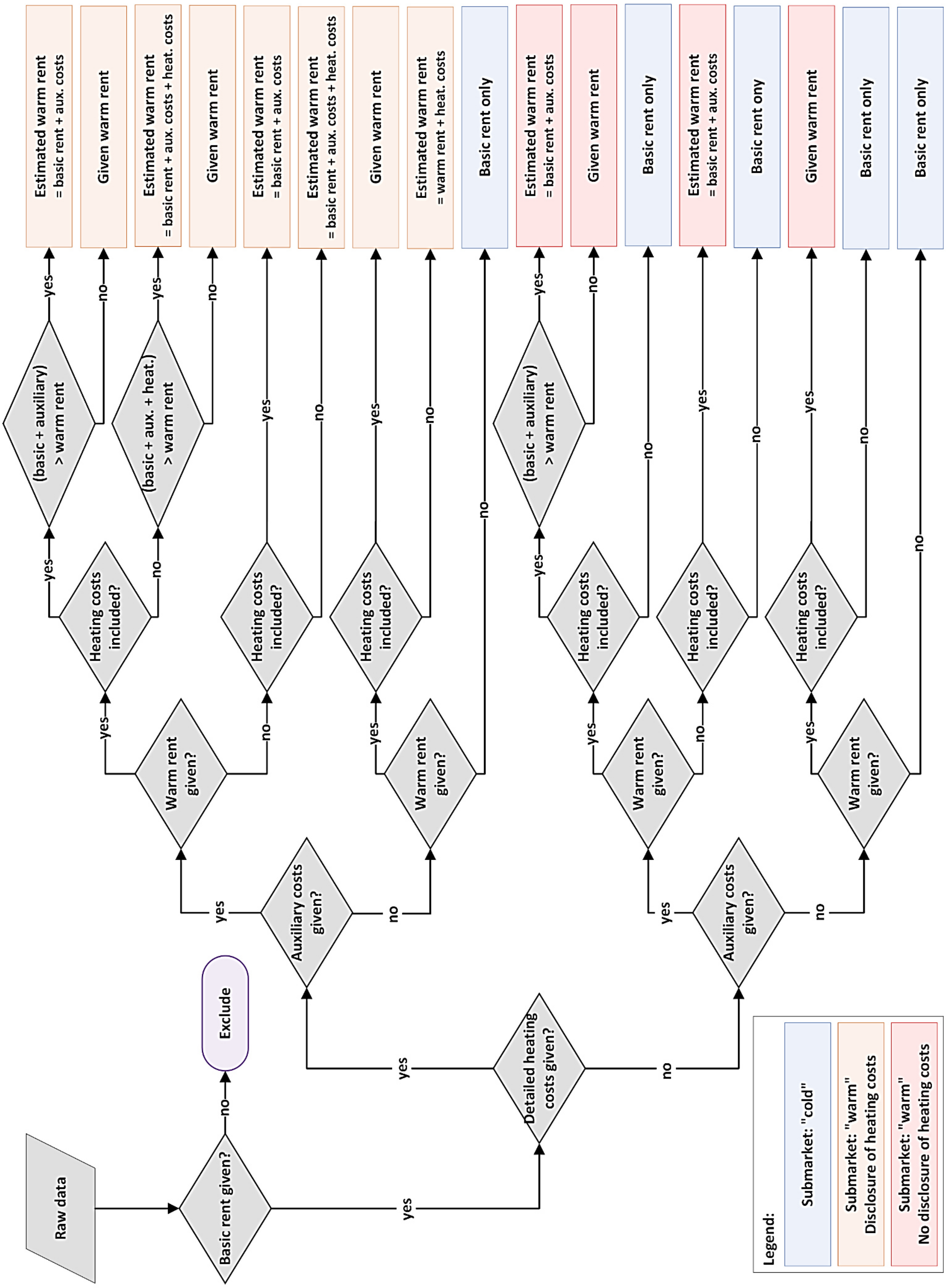
Appendix

Table A 1 Overview of variables included in the regression model.

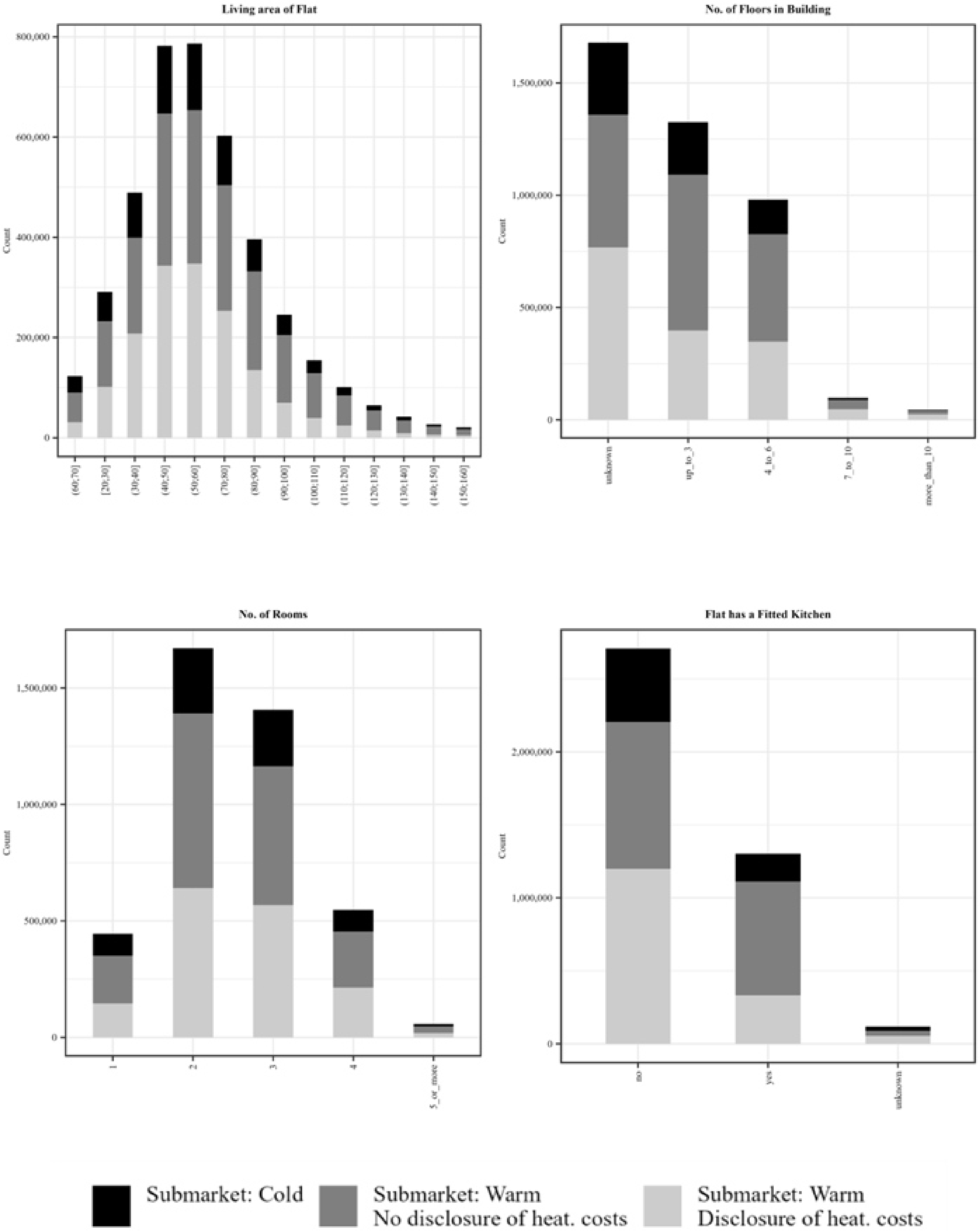
Variable	Description	Unit/Values
$\boldsymbol{WarmRent_{int}}$	Monthly total warm rent of apartment *i* in neighborhood *n* at time *t*	€/m²
$\boldsymbol{BasicRent_{int}}$	Monthly basic rent of apartment *i*	€/m²
$\boldsymbol{eps_i}$	Energy performance score as indicated in the EPC	10 kWh/m²a
HEATING	Factor variable, indicating the heating system of apartment *i*	CHP, ELECTRIC, SCC, DISTRICT, FLOOR, PELLET, NIGHT STORAGE, STOVE, OIL, GAS (Ref), SOLAR, PUMP, CENTRAL, unknown
TYPE	Factor variable, indicating the type of apartment *i*	ATTIC, RAISED GROUND FLOOR, FLAT (Ref), MAISONETTE, PENTHOUSE, SOUTERRAIN, WITH TERRACE, OTHER, unknown
FACILITIES	Factor variable, indicating the facilities of apartment *i*	SIMPLE, NORMAL (Ref), SOPHISTICATED, DELUXE, unknown
CONDITION	Factor variable, indicating the condition of apartment *i*	NEW, 1st OCC after reconstruction, LIKE NEW, RECONSTRUCTED, MODERNIZED, WELL KEPT (Ref), RENOVATED, NEEDS RENOVATION, BY ARRANGEMENT, unknown
FLOORS_BUILD	Factor variable, indicating the number of floors of the building in which apartment *i* is located	1 to 3 (Ref), 4 to 6, 7 to 10, more than 10, unknown
ROOMS	Factor variable, indicating the number of rooms of apartment *i*	1, 2 (Ref), 3, 4, 5 and more
BALCONY	Factor variable, indicating the appearance of a balcony in apartment *i*	yes, no (Ref), unknown
GARDEN	Factor variable, indicating the appearance of a garden in apartment *i*	yes, no (Ref), unknown
KITCHEN	Factor variable, indicating the inclusion of a kitchen in apartment *i*	yes, no (Ref), unknown
CONSTRUCTED	Factor variable, indicating the construction period of apartment *i*	5-year steps, starting at 1900; Ref. = constr. betw. 1961 and 1970
LIVINGAREA	Factor variable, indicating the living area of apartment *i*	10 m² steps, starting at 20; Ref. = 60 to 70 m²
HOTWATER	Factor variable, indicating whether the energy used for producing hot water is included in eps	yes, no (Ref), unknown
MOD2010	Dummy variable, indicating whether apartment *i* was renovated in 2010 or later	yes, no (Ref)
PURCHPOWER	Purchasing power per capita	€1,000 per capita
POPULATION	Population density	1,000 inhabitants per km²
UER	Unemployment rate	%
FOREIGN	Share of households with foreign household head	%
$\boldsymbol{\tau_s}$	Regional fixed effects on state level	16 states (*Bundesländer*)
$\boldsymbol{\nu_d}$	Regional fixed effects on NUTS3 level	401 NUTS3 regions
$\boldsymbol{\rho_n}$	Regional fixed effects on neighborhood level	55,733 neighborhoods
$\boldsymbol{\mu_t}$	Time fixed effects on quarterly-year level	27 Time periods from Q2/2014 to Q4/2021

Source: Own illustration.



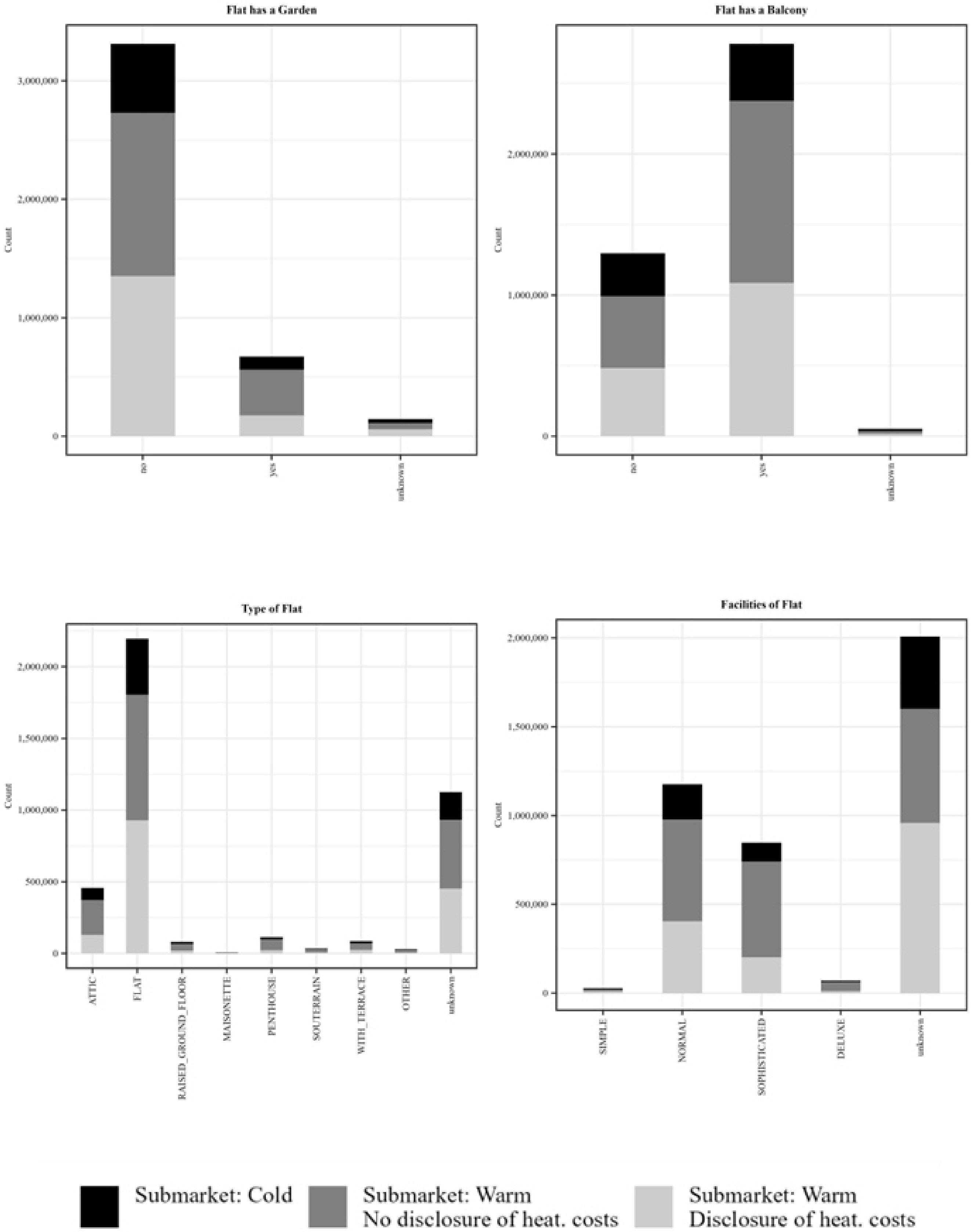
Source: Own illustration.

Figure A 1 Variable selection and classification of submarkets and subsamples.



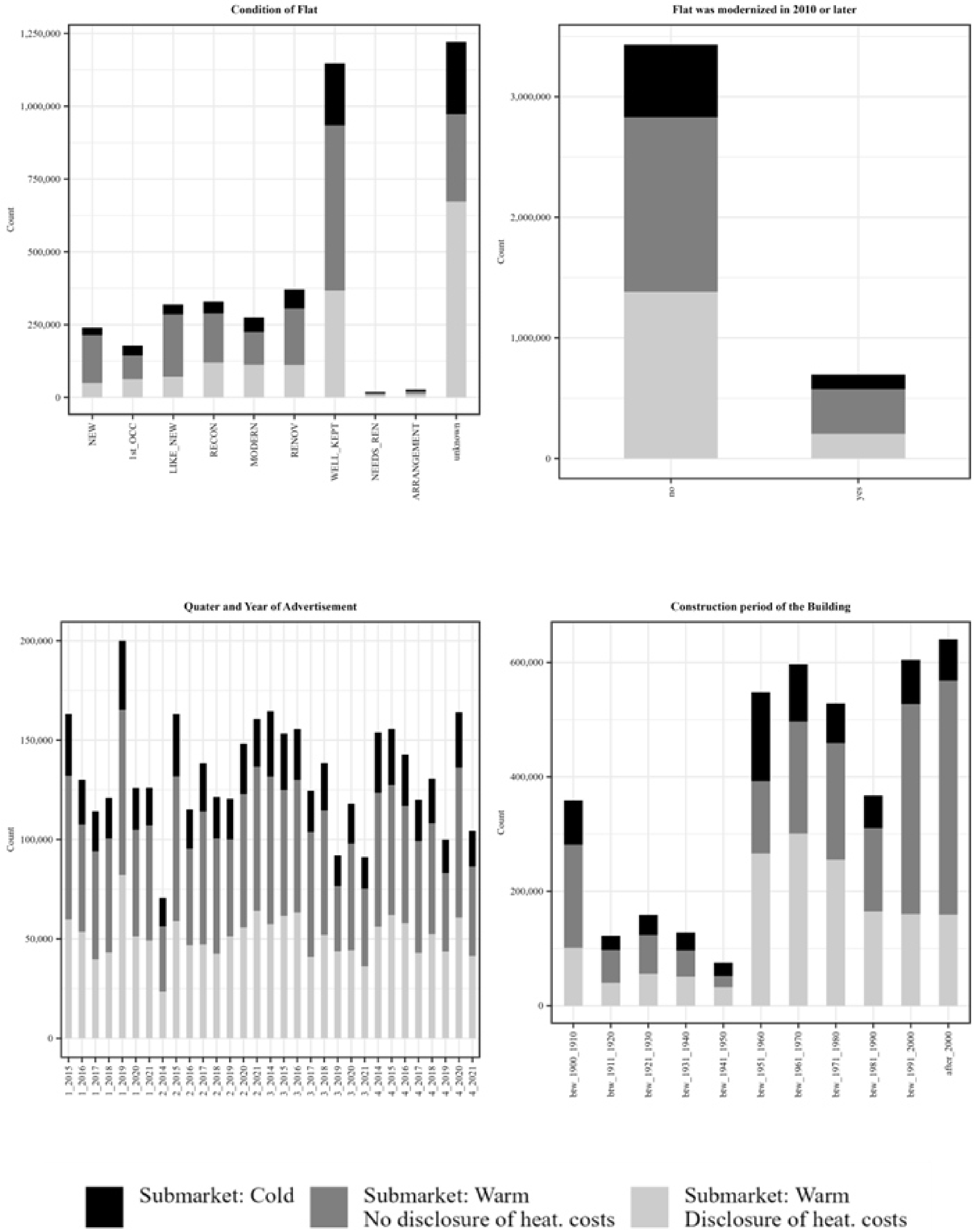
Source: Own calculation and illustration based on RWI-GEO-RED.

Figure A 2 Distribution of different factor variables (1).



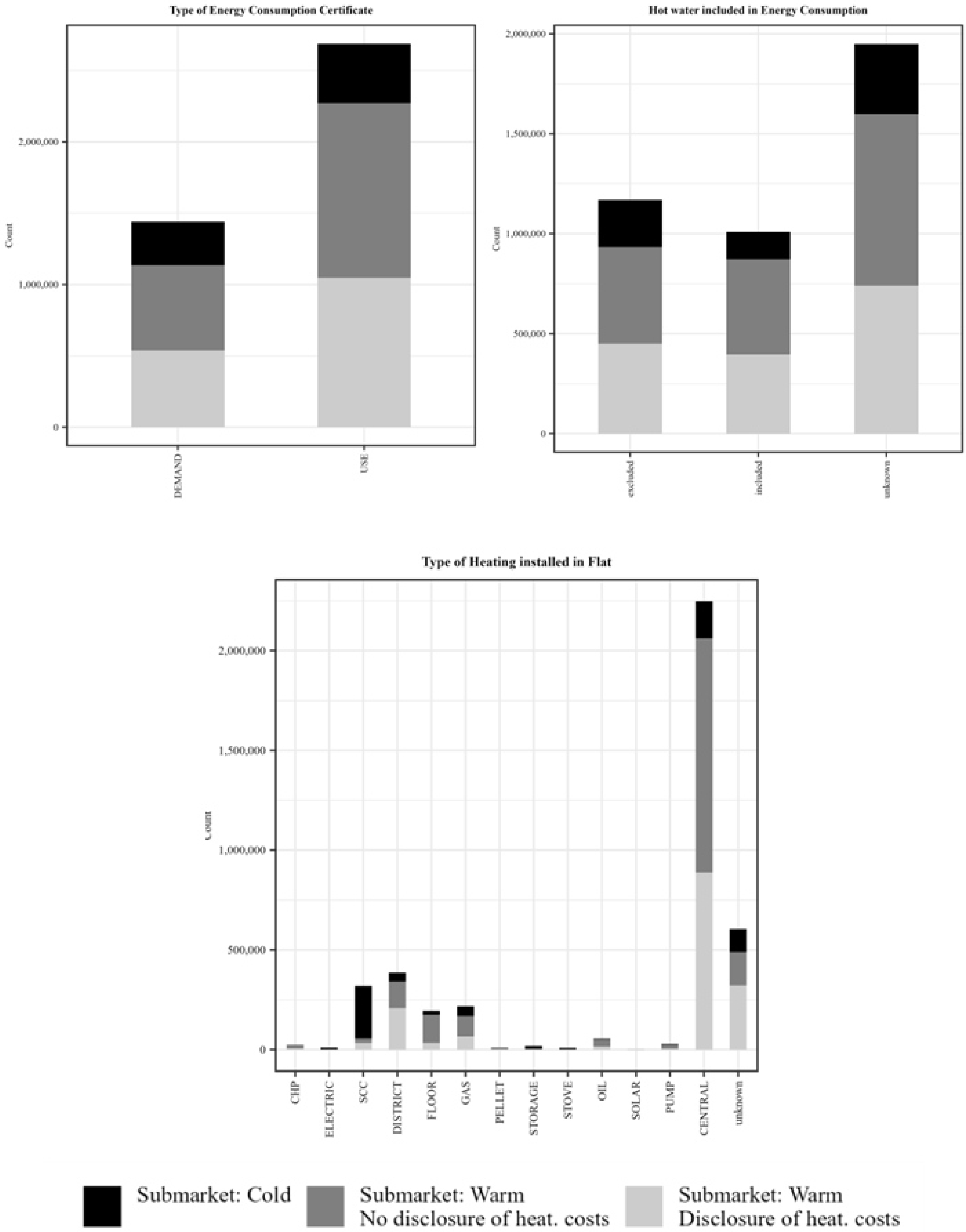
Source: Own calculation and illustration based on RWI-GEO-RED.

Figure A 3 Distribution of different factor variables (2).



Source: Own calculation and illustration based on RWI-GEO-RED.

Figure A 4 Distribution of different factor variables (3).



Source: Own calculation and illustration based on RWI-GEO-RED.

Figure A 5 Distribution of different factor variables (4).

Table A 2 Main regression results in TCU model – newly built apartments excluded.

Dependent Var.: WarmRent in €/m²/month	**Submarket "warm"** **Newly built apartments excluded.** **Full submarket**	**Subsample A: No disclosure of exact heating costs**	**Subsample B: Disclosure of exact heating costs**
Energy performance score	0.0077 ***	0.0066 ***	0.0059 ***
(in 10 kWh/m²a)	[0.0002]	[0.0003]	[0.0003]
Selected heating system, reference: gas heating			
District heating	0.0372 ***	0.0386 ***	0.0300 ***
	[0.0005]	[0.0007]	[0.0007]
Oil heating	0.0076 ***	0.0033 **	0.0145 ***
	[0.0008]	[0.0010]	[0.0014]
Floor heating	0.0555 ***	0.0563 ***	0.0604 ***
	[0.0006]	[0.0007]	[0.0011]
Central heating	0.0076 ***	0.0103 ***	0.0053 ***
	[0.0004]	[0.0005]	[0.0006]
Last renovated in 2010 or later	0.0090 ***	0.0091 ***	0.0068 ***
	[0.0002]	[0.0003]	[0.0004]
Controls for___included?			
Apartment characteristics	*yes*	*yes*	*yes*
Neighborhood characteristics	*yes*	*yes*	*yes*
Season FE (quarterly-year)	*yes*	*yes*	*yes*
RMSE	1.65	1.72	1.53
Pseudo-R²	0.726	0.748	0.684
Observations	3,044,367	1,567,674	1,476,693

Notes: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Pseudo-R² is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE in €/m². All apartment and neighborhood characteristics included in the regression are listed in Table A 1.

Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Table A 3 Robustness checks in TCU model – unknown factors excluded from regression.

	Submarket “warm” **Factors = “unknown” excluded.** **Newly built apartments included.**		
Dependent Var.: WarmRent in €/m²/month	**Full submarket**	**Subsample A: No disclosure of exact heating costs**	**Subsample B: Disclosure of exact heating costs**
Energy performance score	0.0071 ***	0.0065 ***	0.0065 ***
(in 10 kWh/m²a)	[0.0005]	[0.0007]	[0.0008]
RMSE	1.64	1.66	1.58
Pseudo-R²	0.724	0.729	0.717
Observations	620,189	393,330	226,859

	Submarket “warm” **Factors = “unknown” excluded.** **Newly built apartments excluded.**		
Dependent Var.: WarmRent in €/m²/month	**Full submarket**	**Subsample A: No disclosure of exact heating costs**	**Subsample B: Disclosure of exact heating costs**
Energy performance score	0.0083 ***	0.0083 ***	0.0071 ***
(in 10 kWh/m²a)	[0.0005]	[0.0007]	[0.0008]
RMSE	1.63	1.65	1.57
Pseudo-R²	0.720	0.728	0.711
Observations	591,803	371,667	220,136

Notes: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Pseudo-R² is estimated using the ‘rsquare’-function from the ‘modelr’-package in R (Version 4.1.2). RMSE in €/m². All apartment and neighborhood characteristics included in the regression are listed in Table A 1.

Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Table A 4 Regression results in TCU model for different subsamples.

Panel A: Income levels

Dependent Var.: WarmRent in €/m²/month	**1st tercile**	**2nd tercile**	**3rd tercile**
Energy performance score	0.0048 ***	0.0110 ***	-0.0004
(in 10 kWh/m²a)	[0.0003]	[0.0004]	[0.0004]
RMSE	1.34	1.61	1.95
Pseudo-R²	0.580	0.630	0.714
Observations	1,080,055	1,080,011	1,080,022

Panel B: Basic rent levels

Dependent Var.: WarmRent in €/m²/month	**1st tercile**	**2nd tercile**	**3rd tercile**
Energy performance score	0.0169 ***	0.0142 ***	0.0126 ***
(in 10 kWh/m²a)	[0.0002]	[0.0002]	[0.0005]
RMSE	0.72	0.87	1.95
Pseudo-R²	0.248	0.205	0.561
Observations	1,085,520	1,078,884	1,075,684

Panel C: Energy efficiency levels

Dependent Var.: WarmRent in €/m²/month	**A+, A, B**	**C, D, E**	**F, G, H**
Energy performance score	0.0352 ***	0.0270 ***	0.0127 ***
(in 10 kWh/m²a)	[0.0018]	[0.0005]	[0.0005]
RMSE	1.91	1.59	1.59
Pseudo-R²	0.763	0.712	0.721
Observations	658,798	2,049,579	531,711

Panel D: Heating types

Dependent Var.: WarmRent in €/m²/month	**Standard**	**Green**	**Dirty**
Energy performance score	0.0058 ***	0.0310 ***	0.0152 ***
(in 10 kWh/m²a)	[0.0003]	[0.0008]	[0.0010]
RMSE	1.71	1.69	1.54
Pseudo-R²	0.736	0.779	0.734
Observations	2,302,318	367,538	98,973

Panel E: Fuel type

Dependent Var.: WarmRent in €/m²/month	**Gas**	**Oil**	**District Heating**
Energy performance score	0.0108 ***	0.0212 ***	0.0044 ***
(in 10 kWh/m²a)	[0.0006]	[0.0014]	[0.0010]
RMSE	1.78	1.73	1.82
Pseudo-R²	0.734	0.741	0.802
Observations	507,199	80,001	315,005

Notes: Cluster-robust standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. Pseudo-R² is estimated using the 'rsquare'-function from the 'modelr'-package in R (Version 4.1.2). RMSE in €/m². All apartment and neighborhood characteristics are included in the regression, including newly built apartments and all observations including the factor "unknown". Exception 1: Heating type information were excluded in Panel D. Standard-technology subsample includes Central, Floor, and Gas. Dirty-technology subsample includes Oil, Stove, SCC and Night storage. Green-technology subsample includes CHP, Solar, Pump, Pellet and District (cf. Hahn et al., 2018). Exception 2: Panel E only includes observations from 2019 to 2021 since the fuel type is only provided from 2019 onwards.

Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

Table A 5 Moderation-analysis results in semi-log model: EPC-type subsamples.

	Full sample – both submarkets combined		**Submarket "warm"**	
Dependent Var.: Ln(BasicRent) in €/m^2/month	**Demand**	**Consumption**	**Demand**	**Consumption**
Energy performance score	-0.0026 ***	-0.0012 ***	-0.0034 ***	-0.0017 ***
(in 10 kWh/m^2a)	[0.0001]	[0.0001]	[0.0002]	[0.0001]
Basic_only = 1	0.0068 ***	0.0103 ***		
	[0.0020]	[0.0012]		
Energy performance score	-0.0004 *	0.0006 ***		
× basic_only	[0.0002]	[0.0002]		
Warm_only = 1			0.0362 ***	0.0265 ***
			[0.0016]	[0.0010]
Energy performance score			0.0009 ***	0.0010 ***
× warm_only			[0.0002]	[0.0002]
Controls for___included?				
Heating type	*yes*	*yes*	*yes*	*yes*
Apartment characteristics	*yes*	*yes*	*yes*	*yes*
Neighborhood characteristics	*yes*	*yes*	*yes*	*yes*
Seasonal FE (quarterly-year)	*yes*	*yes*	*yes*	*yes*
Regional FE (county)	*yes*	*yes*	*yes*	*yes*
Regional FE (district)	*yes*	*yes*	*yes*	*yes*
Regional FE (neighborhood)	*yes*	*yes*	*yes*	*yes*
RMSE	0.12	0.12	0.12	0.12
Adj.-R^2	0.880	0.863	0.891	0.870
Observations	1,339,230	2,564,243	1,062,126	2,177,962

Notes: Cluster-robust standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. RMSE in log(€/m^2). All apartment and neighborhood characteristics included in the regression are listed in Table A 1.

Source: Own calculations based on RWI-GEO-RED and RWI-GEO-GRID.

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CHAPTER FIVE

Disentangling Small-Scale Solar Photovoltaic Adoption: A Spatial Analysis of Decision Factors and Localized Interactions in Germany

by Tobias Stein, Lisa Sieger and Christoph Weber

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Abstract

The existence of spatial patterns in the adoption of small-scale solar photovoltaic (PV) systems is widely accepted in the academic literature. The diffusion of these systems depends on decisions of heterogenous units, often households, that form their decision based on unit characteristics and attitudes, the built environment, economic and physical factors, as well as peer effects. When including several of these factors, many studies use macro-level datasets, which have a limited ability to capture ‘real’ small-scale spatial patterns. Using data on a 1 km² grid level for Germany, we identify spatial patterns of adoption while also controlling for highly localized explanatory variables. Spatial dependence is estimated and tested with spatial econometric models. Using this set of small-scale data, we show that spatial clustering affects the adoption of residential PV systems, which is increasing with larger neighborhood sizes. Further, the presence of large-scale PV installations has strong direct and also indirect, i.e., spillover effects on the adoption of rooftop PV installations. Finally, spillover effects from defined neighborhoods are found to become statistically insignificant with larger distances, promoting the use of such small-scale data.

Keywords: Solar PV adoption, Spatial econometrics, Adoption behavior, Energy transition

JEL-Classification: C31, Q28, Q55, R12

1 Introduction

The presence of spatial patterns in the adoption of small-scale photovoltaic (PV) systems has received widespread recognition in the academic literature (e.g., Balta-Ozkan et al., 2015; Dharshing, 2017; Müller and Rode, 2013). This diffusion process depends on decisions made by a variety of actors, typically households, with their choices being shaped by a complex interplay of system characteristics, the built environment, economic factors, individual preferences, and the influence of peer behavior (Alipour et al., 2021). While different studies have attempted to capture a variety of these determinants, the use of macro-level datasets often leads to limitations in capturing the complex and 'authentic' spatial patterns that determine adoption dynamics at the small spatial scale (Alipour et al., 2021).

In this study, we therefore shift the focus to the use of small-scale raster data to identify spatial spillover effects underlying the adoption of rooftop PV installations. To shed light on the latent spatial dependence, we employ spatial econometric models that allow for a more accurate estimation of the comprehensive spatial relationships – and thus enable better predictions of future penetrations and the resulting impacts on the distribution grids. The inclusion of socioeconomic information at a small spatial scale further allows to control simultaneously for differences in neighborhoods.

We thus examine (1) the influence of neighborhood-specific factors associated with the socioeconomic status and the built environment, and (2) the impact of spatial interaction effects on the adoption of residential solar PV systems, both at a standardized 1 km² grid level. Spatial interaction effects comprise spatial endogenous effects resulting from the adoption of solar PV systems in adjacent neighborhoods as well as spatial spillover effects resulting from driving factors in these surrounding neighborhoods.

This paper focuses on PV systems with a capacity of up to 10 kWp, following the research of Balta-Ozkan et al. (2015) and Dharshing (2017). However, in contrast to prior studies we expand the analysis by incorporating the impact of larger PV systems on the adoption of these smaller ones into our spatial regression modelling. Moreover, we calculate sensitivities across various neighborhood sizes, ultimately highlighting spillover effects within different spatial contexts.

We employ data from Germany as a case study, where there has been a significant increase in usage of PV systems in recent years. At present, Germany has 2.6 million PV systems with a total installed capacity of 70.6 GW (Statistisches Bundesamt, 2023). However, further expansion is required as the Renewable Energy Sources Act (EEG) 2023 sets an expansion target of 215 GW for PV by 2030, roughly tripling the installed capacity over the next eight years compared to the expansion status at the end of 2022 (UBA, 2023).

Therefore, our paper makes three major contributions to the extant literature. First, we examine drivers for the adoption of small-scale PV installations while also controlling for regional differences in adopter characteristics and settlement structure at a standardized and very local level. We thereby investigate whether spatial autoregressive effects persist if similarities in socioeconomic factors are controlled for – and thus point at actual neighborhood interactions. Second, we extend previous findings by controlling for the influence of large-scale systems on the adoption of small-scale residential PV. Third, we test the sensitivity of the results to different cutoff distances in the definition of neighborhoods to determine the radius at which the spillover effects disappear.

The study is organized as follows. Section 2 provides a brief literature review, focusing on relevant empirical studies. Section 3 discusses some theoretical considerations regarding direct and indirect effects of different drivers for the adoption of residential PV. Section 4 then outlines the methodological approach as well as the data and data processing together with descriptive statistics. Empirical results are presented in Section 5 and further discussed in Section 6. Finally, Section 7 concludes.

2 Literature review

Analyzing the adoption of residential PV systems has gained much attention in recent years; however, modeling technology diffusion across households has a long tradition in economics since Bass (1969). Most research focuses on Germany (e.g., Arnold et al., 2022; Baginski and Weber, 2019; Müller and Rode, 2013; Rode and Müller, 2021, 2016), the United States (e.g. Bollinger and Gillingham, 2019; Graziano et al., 2019; Irwin, 2021; Kwan, 2012) and the United Kingdom (e.g. Alderete Peralta et al., 2022; Balta-Ozkan et al., 2015; Collier et al., 2023; Snape, 2016), but there are also studies investigating inter alia China (Zhao et al., 2017), Australia (Lan et al., 2020; Li et al., 2023; Zander, 2021), Switzerland (Baranzini et al., 2018; Thormeyer et al., 2020), Japan (Zhang et al., 2011), Sweden (Mundaca and Samahita, 2020; Palm, 2017, 2016; Palm and Lantz, 2020), and Belgium (Groote and Verboven, 2019). Further, there are various strands of literature in this field, of which research on regional spillovers and spatial dependencies in technology diffusion (e.g., Copiello and Grillenzoni, 2017; Curtius et al., 2018), as well as on the sociodemographic and economic characteristics of PV adopters (e.g., Dharshing, 2017; Moerkerken et al., 2023; Zhang et al., 2023b) are most important to our study.

Prior research generally confirms that predictors of adoption behavior can be categorized as either individual, social, or informational (Alipour et al., 2020). Moreover, numerous studies indicate that geographic characteristics, which include inter alii sunshine hours (Lamp, 2023) and solar irradiation but also spatial spillovers – both within (Rode and Weber, 2016) and even between counties (Fadly and Fontes, 2019) – or peer effects (e.g. Bollinger and Gillingham, 2012; Graziano and Gillingham, 2015; Steadman et al., 2023; Wolske et al., 2020) play crucial roles in explaining the diffusion of residential PV systems. We subsequently focus on a review of key quantitative studies. For a qualitative analysis resulting in a comprehensive review of further drivers and barriers to technology adoption, see Balcombe et al. (2013); for a theoretical framework examining psychological and social determinants of interest in residential PV systems, see Wolske et al. (2017).

Rode and Weber (2016) concentrate their research on spatial components and investigate whether localized imitation is a driver for technology adoption. For more than 500,000 household PV systems installed in Germany through 2009, they employ an epidemic diffusion model, dating back on Bass (1969) and Geroski (2000), to control for spatial and temporal heterogeneity. The authors find that imitative adoption behavior is highly localized, with its effects decreasing with increasing distance in a predefined radius of 0.5 km, 1 km, 4 km and 10 km, respectively. There is no influence found for a radius larger than 1 km. Irwin (2021), Kim and Gim (2021), and Kosugi et al. (2019) also show spillover effects to be largest within the 15 nearest neighbors, within a 0.5 km radius or within a 1 km radius, respectively.

Based on econometric analysis, Schaffer and Brun (2015) investigate small-scale PV adoption in Germany as well, with more than 820,000 observations registered between 1991 and 2012. The authors find different effects between counties, which they partly explain by varying solar irradiation. However, they state that neighborhood effects such as the house density, the homeownership rate and the purchasing power per capita have greater influence on adoption rates. Similar results were found in various studies (e.g., Balta-Ozkan et al., 2015; Kosugi et al., 2019; Kucher et al., 2021).

Rode and Müller (2021) further explore the micro-level variation of peer effects in household PV adoption. By using geocoded data for Germany up until 2010 and panel data to construct a discrete choice model, they find evidence supporting causal peer effects that are strongest within up to 200 m. Nevertheless, these effects diminish over time and are found to be larger in regions with low economic activity – suggesting that regionally different promotion and support may be necessary. Moreover, Balta-Ozkan et al. (2021) examine effects of various factors on the spatial patterns of PV adoption at a local level in the UK while also considering peer effects. They employ a geographically weighted regression model to corroborate the presence of peer effects and report regional differences in the influential factors.

A comprehensive review of studies is provided by Alipour et al. (2021, 2020). They state that „limited quality sample size has been a major drawback for many researchers, leading to few well-structured models developed to date, and weakly supported conclusions on causal relationships“ (Alipour et al., 2021, p. 484). Additionally, the authors criticize that most studies only focus on the years when financial incentives were introduced, with the phase-out years rarely being considered.

In addition, the empirical studies in the current literature that emphasize the spatial dimension of residential solar adoption have a major limitation. The low spatial resolution of the data used limits the ability to capture spatial characteristics and measure spatial interaction effects for small-scale PV system adoption. Multiple studies considered areas ranging in size from 288 km² (Müller and Trutnevyte, 2020) to 1,809 km² (Balta-Ozkan et al., 2015). Studies that utilize high-resolution spatial data often limit their observation frame to individual cities without looking at influences of the surrounding areas (e.g., Kosugi et al., 2019) or only look at spatial effects without the inclusion of additional explanatory variables (Rode and Müller, 2021; Rode and Weber, 2016). To our knowledge, there is only one recent study that accounts for such small spatial scales while also controlling for additional explanatory variables: Zhang et al. (2023a) explore spatial effects for over 13,000 neighborhoods in the Netherlands, each with an average size of 2.59 km².

Furthermore, it is often argued that observational learning through the visibility of solar panels is one of the main mechanisms behind the spatial interaction effects. However, studies often limit these visible effects to small-scale residential PV systems while not considering the visible effects of larger PV systems. Thus, spatial interaction effects may be underestimated (Zhang et al., 2023a).

We therefore add to the extant literature in different ways. First, we create a unique dataset by using socioeconomic data at a standardized 1 km² grid level combined with geocoded PV data on an individual level. By employing a Spatial Durbin Model (SDM), we are able to capture both spatial spillover as well as spatial autoregressive effects. Second, we include large installations in our analysis to account for visible effects of these PV systems. Third, we apply different cutoff distances in the definition of neighborhoods to test the sensitivity of results regarding the spatial spillover effects. Finally, we draw on data from 2014 and 2020, and thus take two specific years with reduced financial incentives into account.

3 Drivers for PV adoption – theoretical considerations

The installation of a PV system on a building can be conceptualized as an individual discrete choice (cf. e.g., McFadden, 2001; Train, 2009) usually made by the building owner and potentially influenced by social interactions (cf. e.g., Brock and Durlauf, 2001). At the same time, the PV installation represents an investment which provides returns through feed-in compensations or through avoided costs for purchases from the electricity grid/retailer or both. The utility V_j of such a binary adoption choice $\omega_j \in \{0,1\}$ may then be written in general terms as

$$V_j(\omega_j) = m_j\left(\pi_j(\omega_j, x_j)\right) + n_j(\omega_j, x_j, \omega_{-j}, x_{-j}) + \varepsilon_j. \tag{1}$$

The individual utility is thereby composed of a monetary part m_j which is a (monotonously increasing) function of the profit $\pi_j(\omega_j, x_j)$, depending in turn on the adoption decision ω_j as well as on characteristics of both the building and its owner summarized in the vector x_j. Profit may be determined through a net present value calculation:

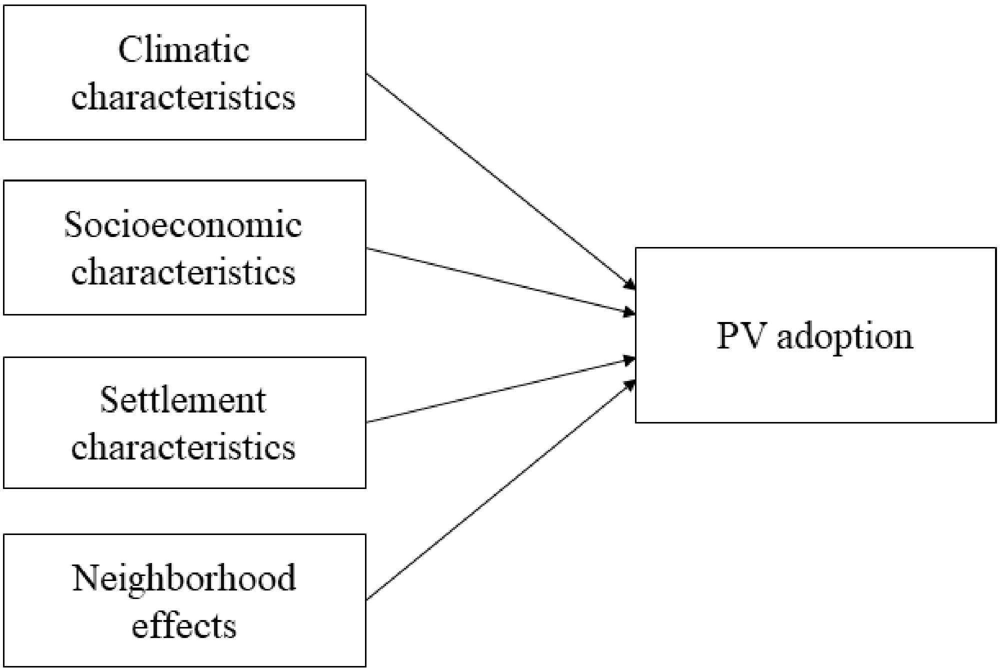
$$\pi_j(\omega_j, x_j) = -I_j + \sum_{t=1}^{T} \frac{1}{\left(1+\delta_j\right)^t} O_{j,t} = -I_j + b(T, \delta_j)\bar{O}_j \tag{2}$$

with I_j the initial investment cost, δ_j the discount rate and $O_{j,t}$ the operational cash flows per year. These may be replaced by an appropriately weighted average $\bar{O}_j$ multiplied by the present value factor $b(T, \delta_j)$ which depends on the useful lifetime T and the discount rate δ_j.

Besides the direct monetary benefits there may be other, often non-monetary advantages of PV adoption which are summarized in the term n_j and where we also hypothesize a dependence on individual characteristics x_j, on adoption decisions of other individuals ω_{-j} (aggregated in a decision vector) and on the characteristics of these other individuals x_{-j}. Besides these (in principle) observable utility components there is also an unobservable stochastic component ε_j.

In detailed studies on adoption behavior, various, often rather detailed behavioral models have been used for investigation (cf. Alipour et al., 2020). However, when it comes to large data sets on PV adoption (as available for Germany), the level of detail regarding the individual adoption decisions remains limited and information on the characteristics of the buildings and decision makers are only available at the neighborhood level. In this setting, the individual decisions may be aggregated to the neighborhood level by defining the PV adoption rate as a dependent variable, corresponding to the share of buildings with a small-scale PV installation on the roof.

For explaining this adoption rate, the available information may then be classified according to the four categories indicated in Figure 1.



Source: Own illustration.

Figure 1 Drivers for PV adoption.

Each category includes various influencing factors that may affect both the monetary and the non-monetary utility components driving the adoption of residential PV installations. At the level of neighborhoods, we may then consider direct effects on adoption, which describe the impact of an influencing factor in a given (focal) neighborhood on the adoption of PV in the same neighborhood. But additionally indirect effects may arise, which encompass impacts of an influencing factor of a neighboring region on the PV adoption in the focal neighborhood. All factors considered in this study, including the expected direct and indirect effects, are summarized in Table 1.

In the category of *climatic characteristics,* the annual solar irradiation is a key physical driver for the profitability of PV systems, since it has direct effects on the electricity production and, consequently, the operational cash flows generated by a PV installation. Indirect effects of solar irradiation are yet implausible since the radiation in neighboring regions has no impact on the profitability and also no transmission channel for indirect impacts on the adoption of PV systems seems likely.

Table 1 Expected direct and indirect effects of the drivers for PV adoption.

Category	**Influencing factor**	**Direct effects**	**Indirect effects, i.e., spillover effects**
Climatic characteristics	Solar irradiation	positive: the higher the solar irradiation, the higher the profitability of the system	no effects
Socioeconomic characteristics	Purchasing power per household	positive: with higher income it is easier to bear large investments	positive: network effects
	Unemployment rate (UER)	negative: high UER is associated with higher income risk	negative: spillover of income risk from neighborhoods
	Old-age-dependency ratio	negative: for a relatively older population long-term investments might not be profitable. Moreover, future expected incomes tend to be lower due to retirement	no effects
Settlement characteristics	Share of 1- and 2-family homes	positive: residential PV installations are common on individual houses and are not complicated by the landlord-tenant dilemma or by issues of co-propriety	positive: network effects
	Household density	negative: high household densities are related to a high share of multi-family buildings, which has direct negative impacts on the available roof size for PV installations	positive: network effects negative: if seen as indicator for settlement structure, it has opposite effects of the share of 1- and 2-family homes
Neighborhood effects	PV adoption rate in surroundings	-	positive: effects due to visibility of systems and network effects
	No. of large-scale PV systems	positive: effects due to visibility of systems	positive: effects due to visibility of systems

Source: Own illustration.

Regarding *socioeconomic characteristics*, two key influencing factors are the purchasing power per household and the unemployment rate, both related to the wealthiness of a neighborhood. High purchasing powers are correspondingly expected to have positive direct effects, as investments are less restricted by borrowing constraints (which would translate into higher discount rates and thus lower investment profitability). For the unemployment rate, a negative correlation with the (unobservable) wealthiness is likely, and moreover a higher unemployment rate is also an indicator of increased income risk – which in turn will induce a higher preference for liquidity and thus lower propensity to invest. Especially the latter transmission channel suggests that there may also be indirect effects of the same (negative) sign, as income risk is also dependent on unemployment rates beyond the immediate neighborhood.

Additionally also network effects (cf. Bollinger and Gillingham, 2012; Manski, 1993) may lead to indirect effects reinforcing the direct effects. Thereby two transmission channels are potentially relevant. First, social networks among adopters and potential adopters which lower the (non-monetary) costs of finding information and assessing adoption choices. Or put differently: in existing social networks, people can talk about (the advantages of) rooftop PV systems if someone starts to deal with the topic. Second, supplier-customer networks which not only channel information but are also enablers of adoption – as most homeowners will rely on craftsmen for the actual installation works – so their absence would increase the cost of adoption. Both types of networks tend to cover areas which extend beyond the immediate neighborhood yet fade out with larger distances. But especially social networks are only partly correlated with physical proximity and could also induce indirect effects over longer distances.

A further relevant socioeconomic factor is the age structure of the population. The old-age dependency ratio[1], i.e., the share of the population aged 65 years and older in relation to the population aged 20 to 64, is used here to describe this socioeconomic characteristic of a neighborhood. Evidence regarding the effect of different age groups is rather mixed in the literature (cf. Alipour et al., 2020); however, we expect that a high old-age-dependency ratio has negative direct effects on the adoption of residential PV. The older the population, the higher the discounting of the (more distant) future given that it may exceed the individual lifespan. Correspondingly it becomes less profitable to make long-term investments such as installing PV systems. Also expected future incomes are lower due to retirement, inducing also more severe credit constraints. Given that these are impacts at the level of the individual profitability, we assume that there are no spillover effects of the old-age-dependency ratio from neighboring regions.

Regarding the settlement structure, we retain two potential drivers for the adoption of small-scale PV. First, the share of one- and two-family homes is considered relevant as the installation of PV systems on individual houses is not complicated by the landlord-tenant dilemma or by

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[1] The old-age dependency ratio is easy to interpret and commonly applied in the literature (cf. Breidenbach et al., 2022). In a time series, this indicator maps the process of demographic aging of the population (VDSt, FachAG-Bevölkerung, Unterarbeitsgruppe Demografie, 2011).

issues of co-propriety. Moreover, positive network effects also tend to emerge based on this factor – if there are other areas with high shares of one- and two-family homes in the vicinity, this provides opportunities for information networks as well as supplier-customer networks as described above.

A second relevant factor regarding the settlement structure but linked also to socioeconomic characteristics is the household density, i.e., the number of households per 1 km², which is related to the wealthiness of the population but also reflects the settlement structure in the specific grid cell[2]. When controlling for the settlement structure (cf. above), we expect the direct effect of household density still to be negative, as higher population densities are then an indication of rather confined dwelling space in larger multi-family buildings or smaller individual houses. This comes along with a more limited roof area available for PV installations. Regarding indirect effects, different transmission channels may be envisaged. On the one hand, positive network effects may be strengthened given the higher population density. On the other hand, the negative direct effect also implies that the probability for strong information and supply networks decreases inducing also a negative indirect impact.

The last category depicted in Figure 1 are *neighborhood effects*. Besides the spillover effects of influencing factors from the neighboring regions as discussed before, there are usually two channels of action discussed in the literature. One is the visibility of PV systems (cf. e.g., Rode and Müller, 2021). If people see a lot of PV systems in their own neighborhood and in the surrounding area, this could be a trigger for them to become involved in the issue. Another channel are the aforementioned network effects. The visibility argument provides a strong case to include spatial lags of the dependent variable into the specification, whereas the network effects could also be captured as spillovers from explanatory variables in neighboring cells.

A second relevant neighborhood effect is the total number of large-scale PV systems with a capacity of more than 10 kWp and up to 100 kWp. For these, the same arguments of visibility and network effects apply as for the small-scale units which are in the focus of the analysis. The existence of such larger PV system is an indication for not purely residential neighborhoods, yet their impact may be similar if not more pronounced than for small-scale systems.

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[2] This illustrates that settlement characteristics and socioeconomic characteristics of the population do not evolve independently one from another. The classification of the characteristics may therefore be considered to some extent as arbitrary, yet it is useful to distinguish more household and more building related characteristics.

4 Methodological approach and data

Following inter alia Zhang et al. (2023a), Müller and Trutnevyte (2020), Kosugi et al. (2019) and Dharshing (2017), we use a spatial econometric approach to capture the impact of different socioeconomic and neighborhood characteristics, as well as spatial spillovers on the adoption of residential PV systems. We thereby distinguish between the use of a Spatial Autoregressive Model (SAR), Spatial Error Model (SEM) or Spatial Durbin Model (SDM). Model selection and specification are described in Sections 4.1 and 4.2. Contrary to the previously mentioned studies, we use raster data that consist of 125,441 standardized 1 km² grid cells rather than pre-defined spatial units (e.g., counties, cities, postal code zones). This approach not only allows for a more flexible choice of neighboring units, but also for the investigation of highly localized effects.

4.1 Spatial model specification and selection

Two approaches are commonly used to select spatial econometric models: the specific-to-general approach and the general-to-specific approach (cf. Elhorst, 2010; Florax et al., 2003). We apply a mix of both approaches and first adopt the specific-to-general approach to determine whether the non-spatial model should be extended to a SAR or SEM. Later, we employ a general-to-specific approach to test whether the SDM should be simplified to either SAR or SEM. We perform a series of tests to identify the optimal spatial econometric models for our cross-sectional data. A description of variables included in the regression model is given in Section 3.

4.1.1 Specific-to-general approach

The specific-to-general approach starts with a non-spatial linear regression model, estimated by ordinary least squares (OLS). It is assumed that the dependent variable in one spatial unit (i.e., grid cell)[3] manifests itself independently of its expression in neighboring spatial units (cf. Elhorst, 2010). The baseline equation takes the form:

$$Y = \alpha + \beta X + \varepsilon \tag{3}$$

where Y is a $N \times 1$ vector consisting of observations on the dependent variable – in our case, the adoption rate of PV systems up to 10 kWp – for each unit i in the data. X is a $N \times K$

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[3] In the following we will only refer to grid cells even if the described models can be used with other spatial units too.

dimensional matrix of observations on K exogenous (explanatory) variables, i.e., the solar irradiation and different socioeconomic factors, for all i grid cells. The corresponding $K \times 1$ vector of parameters is denoted by β while α is the associated intercept parameter. Finally, ε is an $N \times 1$ vector of error terms for the regression.

Spatial data often violate the standard assumptions of OLS models, which assume independency between observations. Using a Moran's I test (Moran, 1950), the assumption of no autocorrelation in the residuals can be tested. If this hypothesis is rejected, the OLS model can be extended to models incorporating spatial autocorrelation. Since Moran's I does not provide any guidance on whether to extend the OLS model to SEM or SAR, standard (Anselin, 1988) and robust (Anselin et al., 1996) Lagrange multiplier (LM) tests can be conducted.

In spatial autoregressive models, the value of the dependent variable in one grid cell is assumed to be influenced by the dependent variables of neighboring grid cells. The neighborhood structure is defined by the non-negative spatial matrix W of known constants displaying the spatial arrangement of the grid cells used in the dataset. The SAR model can be written as:

$$Y = \alpha + \rho WY + \beta X + \varepsilon \tag{4}$$

where ρ denotes the spatial autoregressive parameter of the dependent variable Y that measures the interdependence across grid cells. Interpretation in case of PV adoption is as follows: the PV adoption in grid cell i is dependent on different exogenous variables X in grid cell i, such as the solar irradiation, and also on spillover effects of the PV adoption in neighboring grid cells, as given by ρWY.

The SEM specification, on the other hand, is dealing with the interactions between the residuals of the spatial units. Here, a spatial autoregressive specification is used to allow for spatial dependence in the model's disturbances. Thus, a certain disturbance in a single grid cell is expected to have an impact on the disturbances of neighboring grid cells according to a spatial weights matrix. The neighborhood matrix is the same as in the SAR model. The SEM is formulated as follows:

$$Y = \alpha + \beta X + u, \qquad with\, u = \lambda Wu + \varepsilon \tag{5}$$

where Wu describes the impact of spatially correlated disturbances and λ is the corresponding spatial autocorrelation coefficient, whereas ε represents an independently and identically distributed error term with zero mean and a constant variance σ^2. A statistically significant estimate for λ thus indicates that there is a spatial correlation in the disturbances of the PV adoption; however, it is not captured by the included exogenous variables.

Both, the SAR and SEM are estimated by maximum likelihood estimation (MLE)[4]. The two-step estimation procedure consists of a numerical optimization of the spatial error parameters first, and second, of a parameter estimation for β by generalized least squares (GLS).

4.1.2 General-to-specific approach

If the LM-test results reject the OLS in favor of SAR and SEM, the next step is to test if an SDM can be reduced to SAR and SEM.[5] For this purpose, an SDM is set up, which takes the following form:

$$Y = \alpha + \rho WY + \beta X + \theta WX + \varepsilon \qquad (6)$$

where ρ has the same definition as in the SAR model, while θ represents a $K \times 1$ vector of coefficients of spatially lagged exogenous variables, i.e., it captures the influence of inter alia socioeconomic variables of grid cell j on the PV adoption in the focal grid cell i, and β remains a vector of parameters for the exogenous variables. The SDM model is also estimated by MLE.

The results of the SDM are utilized to conduct a Likelihood Ratio (LR) test to evaluate the two hypotheses: $\boldsymbol{H_0}: \theta = 0$ and $\boldsymbol{H_0}: \rho\beta + \theta = 0$. The first hypothesis examines whether the SDM can be simplified to SAR, whereas the second hypothesis examines the possibility of simplifying to SEM. Based on test results, there are four possible outcomes (cf. Burridge, 1981): First, if both hypotheses are rejected based on the LR tests, then the use of the SDM is preferred for the data at hand. Second, if $\boldsymbol{H_0}: \theta = 0$ cannot be rejected through LR while the LM test results point towards SAR, then the SAR model should be used. Third, if $\boldsymbol{H_0}: \rho\beta + \theta = 0$ cannot be rejected via LR, while the LM test results point towards SEM, then a SEM is the most appropriate model for the data. Finally, if neither of these conditions is satisfied, a SDM should be used to account for both SAR and SEM arguments. Figure 2 illustrates the relationship among the various spatial econometric models examined in this study.

In the presence of a spatially lagged variable WY or/and WX, the point estimates should not be interpreted in the way they are in the usual linear model framework. In spatial regression models

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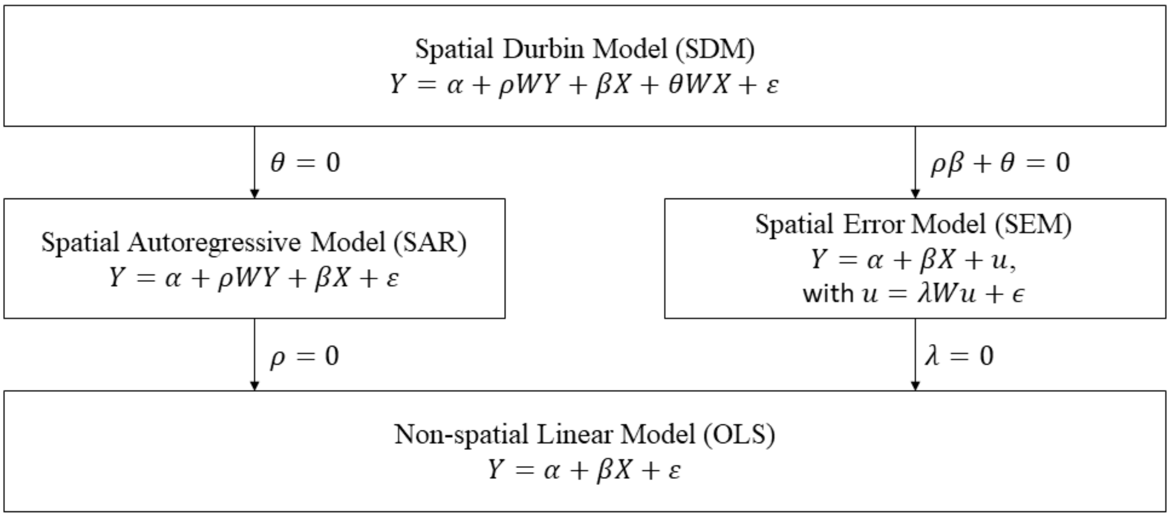
[4] While MLE is the most commonly used method for estimation of SAR/SEM SDM, other methods like quasi-maximum likelihood, Bayesian Markov Chain Monte Carlo (MCMC), semiparametric models, and GMM could also be used as alternatives.

[5] If the LM-test does not reject the null hypothesis, a calculation of an OLS model including spatially lagged explanatory variables can be used to test if $\theta = 0$. If this is also rejected, OLS remains the most appropriate model, and it is not desirable to make further generalizations.

point estimates are used to calculate overall multiplier effects because they can potentially affect the entire sample. LeSage and Pace (2009) show that impact measures should be used that distinguish between direct effects and indirect effects. Direct effects are defined as a measure of the effect of changes in the independent variable $\boldsymbol{X}_i$ in the same grid cell i on the dependent variable Y_i, including feedback effects that arise from the change from $\boldsymbol{X}_i$ on Y_j in the system of spatially dependent regions. The indirect effects deal with the impact of changes in the independent variables of neighboring grid cells $\boldsymbol{X}_j$ on the dependent variable in grid cell i (i.e., Y_i) – which mainly describes the spillover effects (LeSage and Pace, 2009). In an OLS and SEM, the β coefficients correspond to the direct effects, and the indirect effects are zero (Elhorst, 2010).



Source: Own illustration based on Elhorst (2010).

Figure 2 Comparison of the different spatial model specifications.

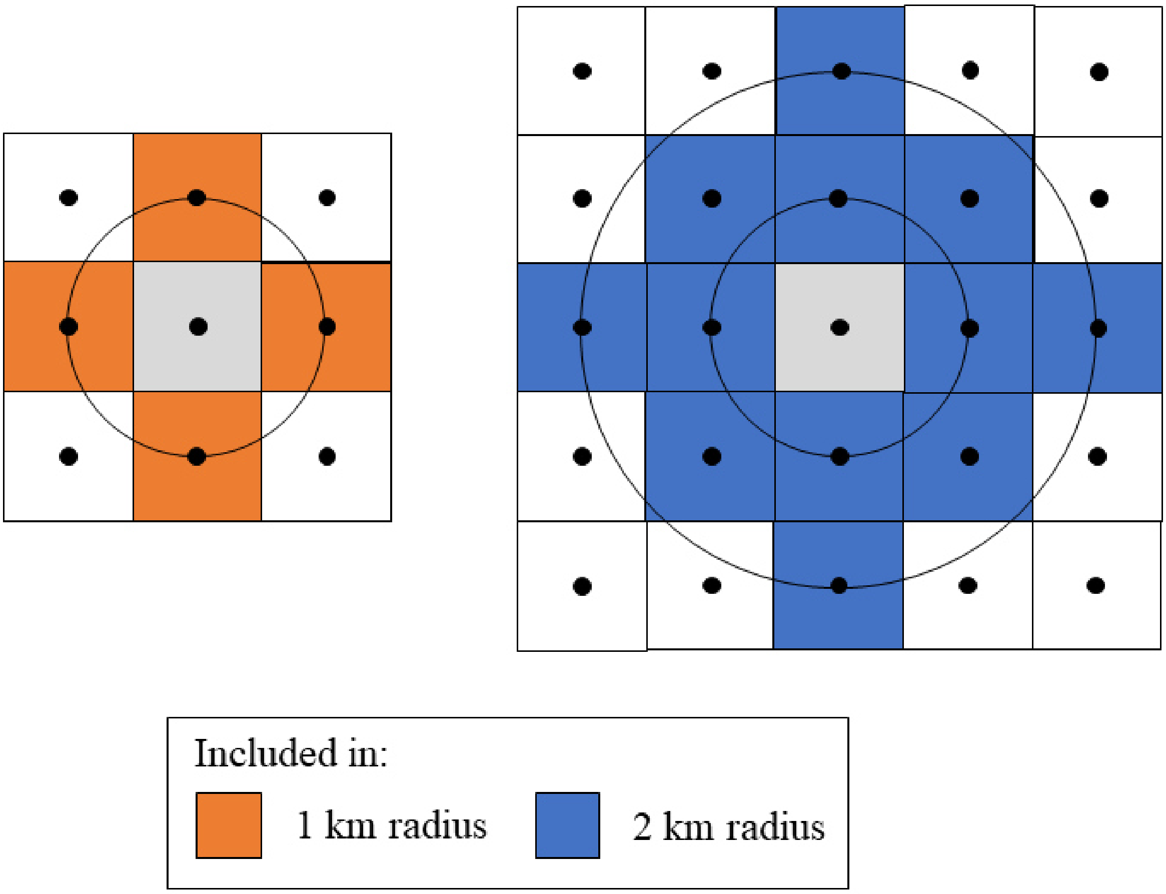
4.2 Spatial weights

W is a $N \times N$ non-negative, non-stochastic and symmetric spatial weights matrix, reflecting the spatial structure of the units in our sample. It is utilized on several occasions in this spatial econometric study. It is employed to compute the spatial lag, examine spatial autocorrelation, and importantly, compute the Jacobian determinant in the MLE. It generally takes the form:

$$W_{i,j} \begin{cases} > 0, & if\ i\ and\ j\ are\ neighbors \\ = 0, & otherwise \end{cases} \tag{7}$$

By convention, the diagonal elements of the weights matrix are set to zero, as units cannot be their own neighbors while all non-zero elements of the matrix reflect neighboring units. Further, the weights matrix is row-standardized such that the elements of each row sum up to one. This facilitates the interpretation of operations with the weights matrix as an averaging of neighboring values (Anselin and Bera, 1998).

Several methods exist to define the neighbors, e.g., based on distance (i.e., all spatial units within a specific radius are neighbors) or contiguity (i.e., all spatial units that either share a border or a single point are neighbors). We use a spatial weights matrix based on distance to define the neighborhood, i.e., all grid cells whose centers are within a certain radius are counted as neighbors. With an increasing radius, the number of (possible) neighbors thus increases. Figure 3 illustrates the number of (possible) neighbors within a 1 km and 2 km radius.



Source: Own illustration.

Figure 3 Neighbors within a 1 km and 2 km radius.

Higher order matrices, i.e., matrices using a larger cutoff distance (or a larger radius respectively), can be constructed analogously[6]. In this way, we can test the sensitivity of our results, especially with regard to the spillover effects. With larger distances and a higher number of neighbors, spillover effects are assumed to decrease. Since we apply a row standardization

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[6] LeSage (2014) shows that the concept of neighbors in spatial weights matrices may be extended to regions or grid cells that are not in direct vicinity.

to unity, the same weight is assigned to each neighbor when estimating spillover effects. Thus, with an increasing number of neighbors, the value of each weight decreases[7].

All benchmark analyses are performed using a radius of 1 km, which is the smallest possible radius that generates neighbors in our data. We then gradually expand the radius in 1 km steps up to a radius of 10 km. Additionally, a radius of 15 km is tested to account for even larger distances[8].

4.3 Data

Our dataset combines information on PV systems with socioeconomic data on a small spatial scale. The PV data originates from the "**Ma**rkt**St**ammdaten**R**egister (MaStR)" and is obtained from the **B**undes**NetzA**gentur (BNetzA, 2021). The data is georeferenced at an individual level. The socioeconomic data (RWI-GEO-GRID) is obtained from microm Micromarketingsysteme and Consult GmbH, a research firm specializing on regional analysis and is provided by the RWI – Leibniz-Institute for Economic Research (RWI and microm, 2022). Georeference is given at a 1 km² grid level. Finally, yearly information on solar irradiation per 1 km² grid cell are downloaded from the Open Data Server of the German Weather Service (DWD, 2023).

After assigning the individual PV systems to the 1 km² grid cells and removing outliers based on the 0.5 and 99.5 percentiles, the final dataset consists of 2×125,441 observations (i.e., grid cells[9]) for 2014 and 2020. Table 2 reports descriptive statistics for the year 2020, which is used for all benchmark estimations. Descriptive statistics for 2014 that are used for a robustness check, are shown in Table A 1.

The variable to be explained is the adoption rate of small-scale PV systems, given as the ratio of the number of PV systems with a capacity up to 10 kWp[10] to the number of houses. We normalize the number of PV systems to the number of houses to abstract from different settlement structures and to describe the degree of saturation regarding PV installations. The adoption share is (loosely) bounded from above by a maximum share of one, which corresponds

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[7] We additionally tested a weights matrix based on inverse-distance where the weight of each neighbor decreases with distance, i.e., spatial units that are farther away have a smaller weight and thus a smaller impact on the focal spatial unit. Results are available on request.

[8] The average commuting distance in Germany is about 16.9 km (BBSR, 2022), and the average radius of a NUTS3 region in Germany, which is often used as a spatial unit in other studies (e.g., Dharshing, 2017; Schaffer and Brun, 2015) is roughly 16.8 km. Our largest distance is therefore still somewhat smaller.

[9] PV systems were summed up at grid level.

[10] The PV systems under investigation were limited to a capacity of up to 10 kWp, which 1) corresponds to a common rooftop system for one- to two-family homes, 2) is used as a limit for specific regulations (cf. §48 Section 2 EEG, 2017) and 3) is also a commonly used threshold in the literature (cf. Balta-Ozkan et al., 2015; Dharshing, 2017). The lower bound is set to 0.1 kWp to remove outliers, such as small pocket systems.

to one PV system per building[11]. The PV adoption rate averages 0.09, i.e., 9 % of all houses have a small-scale PV system installed. The maximum of 1.86 shows that there are rare cases, in which there are more PV systems than houses, e.g., since several PV systems are installed on one roof. Nevertheless, only 38 grid cells out of 125,441 have a PV adoption rate above 100 %. The solar irradiation only shows small variations across grid cells and amounts, on average, to 1,171 W/m². The minimum is about 1,040 W/m² whereas the maximum is 1,320 W/m². Despite the small variation, clear regional differences can be identified. Solar irradiation is stronger in the southern and eastern parts of Germany (cf. Figure A 1).

Three factors are considered when describing the socioeconomic characteristics of the respective neighborhood. The purchasing power per household ranges from €22,500 to €72,400, with an average household income of €48,800. The average unemployment rate amounts to about 4 %[12]. Finally, the old-age dependency ratio represents the ratio of persons aged 65 years and older to 100 persons from 20 to 64 years. It ranges from 17 to 70, with an average of 39.9.

For the settlement structure, we mainly look at the share of one- and two-family homes. On average, each grid cell has 128 houses, of which about 70 % are one- or two-family homes. Contrary to solar irradiation, the number of houses as well as population and household densities, i.e., the number of inhabitants or households per 1 km², show large ranges between minimum and maximum values, pointing at huge differences in settlement structures. Also, very high numbers of population densities occur (in contrast to official federal statistics), as only inhabited grid cells are included and grid cells with forest and water areas, for example, are excluded for calculations.

Finally, additionally to the small-scale PV installations, there are also on average 3.23 large-scale PV systems installed per grid cell, referring to systems between 10 and 100 kWp. The maximum amounts to 24 systems, the median is 2 systems. As large-scale installations require more space compared to small-scale systems, they are often found in more rural regions but also in some densely populated areas such as Berlin[13] (cf. Figure A 2).

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[11] An adoption rate of 100 % means that all houses have an installed PV system. However, in some rare cases, there may be more PV systems than houses, e.g., if installations have been put up on large garages or if more than one PV system has been installed on one roof.

[12] The unemployment rate (UER) is slightly lower than the one reported in official statistics, because we calculate the simple average over all grid cells and do not weight the UER with the number of inhabitants per grid. This “cell-based” averaging may also distort other averages compared to the numbers reported in official statistics.

[13] These may be larger installations on shopping malls, etc.

Table 2 Descriptive statistics for the year 2020. (n = 125,441)

Variable	Mean	Std. Dev.	Min	Max	Median
PV adoption rate, i.e. No. of PV ≤ 10 kWp/No. of houses	0.09	0.10	0.00	1.86	0.06
Solar irradiation, in W/m²	1,171.24	59.36	1,042.00	1,318.61	1,162.40
Purchasing power per household, in €	48,788.62	8,625.33	22,534.39	72,392.13	48,599.57
Unemployment rate, in %	4.07	2.19	0.00	20.15	3.67
Old-age dependency ratio	39.90	8.73	17.48	70.62	38.69
No. of houses	127.64	176.33	2.00	1,038.00	54.00
Share of one-, two-family homes, in %	69.68	20.68	2.04	100.00	73.22
Population density, inhabitants/km²	454.96	815.62	12.00	7,262.00	145.00
Household density, households/km²	224.10	414.67	10.00	3,928.00	69.00
No. of large-scale PV systems, > 10 kWp and ≤100 kWp	3.23	4.10	0.00	24.00	2.00

Notes: Descriptives for 2014 are reported in Table A 1 in the appendix. The old-age dependency ratio represents the ratio of persons of retirement age (here: 65 years and older) to 100 persons of working age (here: from 20 to 64 years). Values are based on inhabited 1 km² grid cells only.
Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.

To have a closer look at the regional distribution of small-scale PV installations across Germany, Figure 4 illustrates this regional distribution for the year 2020. Grey spots represent grid cells without small-scale PV systems, whereas white spots denote areas with no population at all[14]. Grid cells with installed PV systems are indicated in yellow to red, with darker colors indicating a higher number of installations. Large regional differences in the distribution of small-scale PV installations can be observed. We find large clusters of grids with high PV adoption rates at the southern and south-eastern border of Germany in Bavaria and Baden-Wurttemberg. Another cluster is located in the north of the largest federal state in terms of population, North Rhine-Westphalia, at the border to Lower Saxony. In northern and especially eastern Germany, on the other hand, we find lower adoption rates, with the exception of the Berlin region, the northern part of Schleswig-Holstein and the southern part of Saxony.

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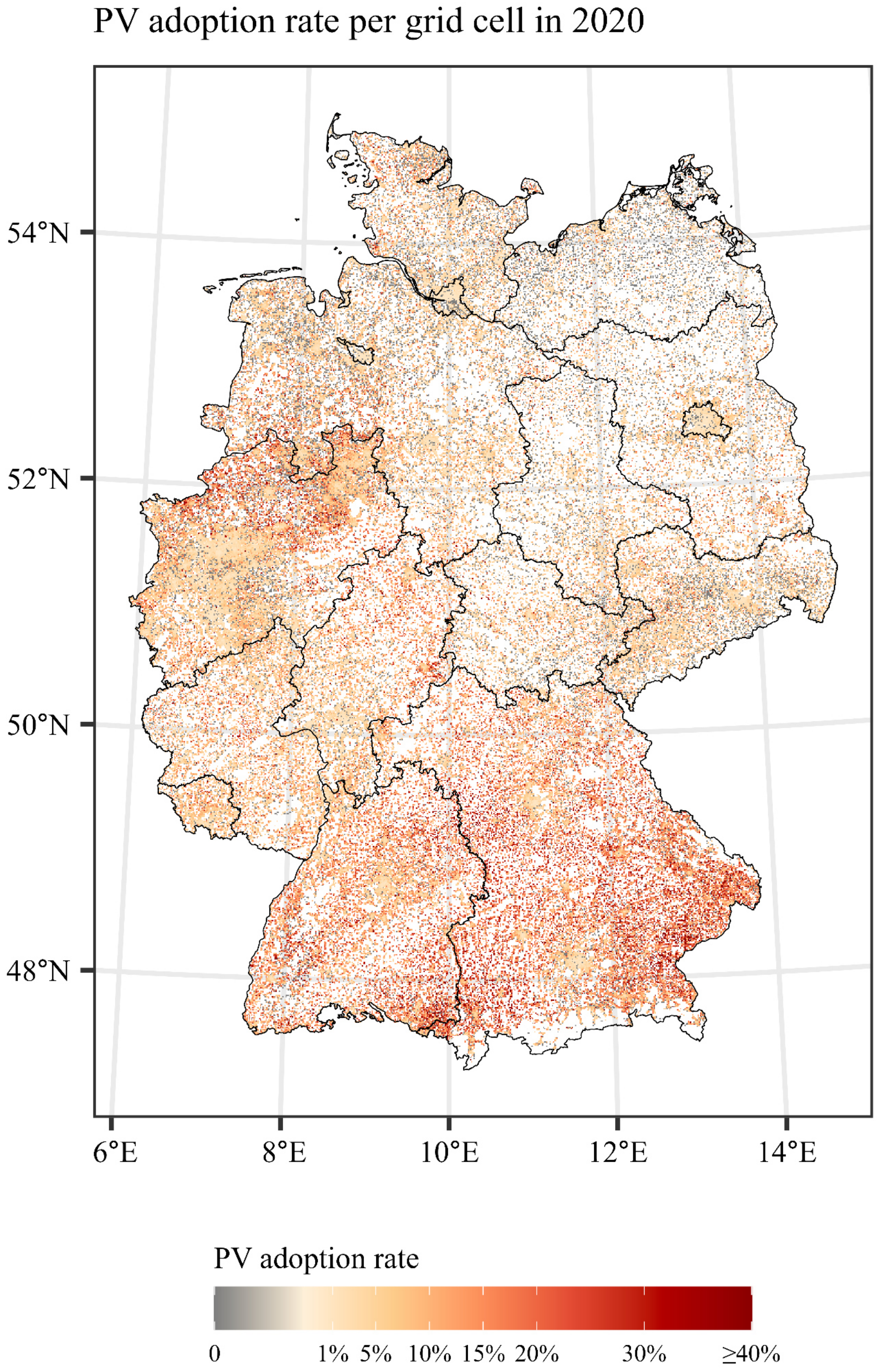
[14] These could either be water or forest areas, or the grid cell was either anonymized due to data security constraints (if a grid has less than 10 households, it will be removed from the analysis) or removed as an outlier.



Source: Own illustration based on MaStR and RWI-GEO-GRID. Map Data: @GeoBasis-DE/BKG 2021

Figure 4 Regional distribution of small-scale PV adoption rates in Germany, 2020.

5 Results

Regression results for the non-spatial OLS with data for 2020 are reported in Table 3. Results reveal that the main physical driver, the solar irradiation, has a positive and significant effect on PV adoption rates.

Table 3 Main regression results for the non-spatial OLS model.

Dependent Variable: **PV adoption rate**	**OLS**
Solar irradiation	0.0003 ***
	[4.41e-06]
Purchasing power	0.0006 ***
(in €1,000)	[3.35e-05]
Unemployment rate	-0.0044 ***
	[0.0001]
Old-age dependency ratio	-0.0010 ***
	[2.98e-05]
One-, two-family homes	0.0004 ***
	[1.40e-05]
Household density	-3.30e-05 ***
	[7.14e-08]
No. of large-scale PV	0.0039 ***
	[6.38e-05]
Constant	-0.3144 ***
	[0.0060]
Adj.-R²	0.1981
Observations	125,441

Notes: Standard errors in brackets. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.
Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.

Regarding the socioeconomic drivers, evidence is rather mixed. While the purchasing power per household shows positive effects, the old-age dependency ratio as well as the unemployment rate show negative effects on the adoption rate of small-scale PV systems. However, these effects are in line with the expected effects described in Section 3. Also, for the settlement and neighborhood characteristics, mixed effects are found. The share of one- and two-family homes as well as the number of large-scale PV systems between 10 and 100 kWp have positive impacts on the adoption of small-scale PV, whereas household density has a negative impact, in line with expectations. Nevertheless, the OLS explains only a small part of the variance, so that the relatively small R^2 already indicates a rather poor model fit.

For the model selection, we first tested for spatial correlation in the OLS by calculating Moran's I (Moran, 1950). Test results are presented in Table 4. The positive value points to spatial dependence of the OLS residuals between neighboring grid cells. Following the specific-to-general approach, we then employed the LM and robust LM tests to evaluate the null hypothesis of no spatial dependence against alternatives of spatial error and spatial lag dependence, respectively.

All LM test results are statistically significant, thus rejecting the null hypotheses of no spatial dependence. Accordingly, the non-spatial OLS regression is inappropriate and may lead to biased estimates because the spatial forces driving photovoltaic expansion are not limited to the 1 km² grid cells but are likely to spill over into nearby neighborhoods. The OLS model is therefore rejected in favor of SAR and SEM.

Table 4 Tests for OLS extension.

Tests for spatial dependence in the OLS regression:	
Morans's I for residuals	54.8 ***
LM (error)	3,003.3 ***
robust LM (error)	1,770.5 ***
LM (lag)	4,102.8 ***
robust LM (lag)	2,870.0 ***

Notes: *** p <0.001, ** p <0.01, * p <0.05.
Source: Own calculations.

5.1 Spatial model specification

Spatial regression results for the SAR, SEM and SDM using a cutoff distance of 1 km are presented in Table 5. Compared to the OLS results, the signs of the coefficients do not change when incorporating spatial models; however, the magnitude of all β-estimates in the SAR and SDM (except of solar irradiation) decrease. In the SEM, however, β-estimates are comparable to those in the non-spatial OLS. Also, the positive and significant spatial effects of λ and ρ in all models suggest the existence of spatial dependence between neighboring grid cells. The coefficient ρ is slightly larger in the SAR compared to the SDM; however, as the latter also controls for spatial spillovers of the exogenous variables, less unobserved autocorrelation is left to be captured by ρ.

According to the general-to-specific approach, we conducted two LR tests to determine whether the SDM can be simplified towards SAR or SEM. Both test statistics were positive and significant. Thus, it can be inferred that the null hypotheses have to be rejected, indicating that the SDM should not be restricted to either a SAR or a SEM. Thus, the SDM is the best model to fit our data and will therefore be used for the following interpretation and analyses.

Table 5 Spatial regression results using a cutoff distance of 1 km.

	SAR	**SEM**	**SDM**	
Dependent Variable: **PV adoption rate**	β	β	β	θ
Solar irradiation	0.0003 ***	0.0004 ***	0.0003 ***	
	[4.43e-06]	[5.11e-06]	[4.47e-06]	
Purchasing power (in €1,000)	0.0005 ***	0.0006 ***	0.0002 **	0.0003 ***
	[3.36e-05]	[3.70e-05]	[6.11e-05]	[6.75e-05]
Unemployment rate	-0.0036 ***	-0.0045 ***	-0.0011 ***	-0.0022 ***
	[0.0001]	[0.0002]	[0.0003]	[0.0003]
Old-age dependency ratio	-0.0008 ***	-0.0010 ***	-0.0003 ***	-0.0004 ***
	[2.89e-05]	[3.29e-05]	[5.65e-05]	[6.33e-05]
One-, two-family homes	0.0003 ***	0.0003 ***	0.0002 ***	0.0002 ***
	[1.38e-05]	[1.43e-05]	[1.51e-05]	[1.95e-05]
Household density	-2.89e-05 ***	-3.14e-05 ***	-2.26e-05 ***	-9.19e-06 ***
	[6.93e-07]	[7,40e-07]	[8.32e-07]	[1.11e-06]
No. of large-scale PV	0.0032 ***	0.0030 ***	0.0022 ***	0.0036 ***
	[6.27e-05]	[6.49e-05]	[6.66e-05]	[8.14e-05]
Constant	-0.2619 ***	-0.3226 ***	-0.2502 ***	
	[0.0061]	[0.0068]	[0.0064]	
Lambda		0.1584 ***		
		[0.0028]		
Rho	0.1746 ***		0.1523 ***	
	[0.0027]		[0.0027]	
LR (error)			3,335.4 ***	
LR (lag)			2,359.9 ***	
Log-likelihood	131,655.5	131,167.7	132,835.4	
Observations	125,441	125,441	125,441	

Notes: Standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. For SDM, β-estimates show coefficients for the independent variables; θ-estimates show coefficients for the spatially lagged independent variables. Data for 2020 is used in all regressions.
Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.

The positive and significant autoregressive parameter ρ in the SDM indicates that there is still a significant level of spatial autocorrelation, even when controlling for spatial spillovers of e.g., socioeconomic factors. This provides evidence of spatial endogenous effects at grid level on the adoption of small-scale PV systems. Hence there is more than network effects induced by socioeconomic or settlement factors – although the available data do not enable us to disentangle the impact of PV visibility from the network effects related to actually installed PV systems (notably supplier networks).

As the interpretation of point estimates may lead to erroneous conclusions (cf. Section 4.1), Table 6 provides corresponding impact measures that are used for the interpretation of direct and indirect effects. The indirect effect (and also the total effect, i.e., the sum of direct and indirect effects) of solar irradiation is excluded, as we suggest that there are no logical reasons to believe that solar irradiation from neighboring spatial units has any additional impact on the PV adoption rate in the focal unit.

Table 6 Impact measures of the SDM.

	Direct	Indirect	Total
Solar irradiation	0.0003 ***		
Purchasing power (in €1,000)	0.0002 ***	0.0004 ***	0.0006 ***
Unemployment rate	-0.0013 ***	-0.0026 ***	-0.0039 ***
Old-age dependency ratio	-0.0003 ***	-0.0005 ***	-0.0009 ***
One-, two-family homes	0.0003 ***	0.0002 ***	0.0005 ***
Household density	-2.35e-05 ***	-1.40e-05 ***	-3.75e-05 ***
No. of large-scale PV	0.0024 ***	0.0044 ***	0.0068 ***

Notes: *** p <0.001, ** p <0.01, * p <0.05.
Source: Own calculations.

As expected, solar irradiation has a positive direct effect on the PV adoption rate. If the solar irradiation increases by one unit, the PV adoption rate is likely to increase by 0.03 percentage points on average. The purchasing power per household also shows the expected outcomes. Increasing the average purchasing power per household by €1,000 is associated with a projected increase of 0.02 percentage points in the adoption rate of small-scale PV systems. Indirect effects, indicating the wealthiness of the surrounding neighborhood, are double in size.

Conversely, the unemployment rate shows expected negative coefficients. If the unemployment rate increases by one percentage point, the PV adoption rate is expected to decrease by 0.13 percentage points. Again, indirect impacts are larger than direct impacts, indicating that the overall unemployment rate in the surrounding area is more important than the unemployment rate in just the local grid cell – at least within a radius of 1 km.

Negative effects are also found for the old-age dependency ratio. A one-unit increase is indicative of a 0.03 percentage point decrease in the PV adoption rate. Contrary to our expectation, we also find significant indirect effects within a 1 km radius. By 2045, the old-age dependency ratio is expected to increase by about 11 points (Destatis, 2023). Other things remaining equal, this would imply a reduction in the PV adoption rate by a mere 0.33 percentage points.

Furthermore, direct and indirect effects of the share of one- and two-family homes on the PV adoption rate are positively correlated as expected: a one percentage-point increase in the share of one- and two-family homes in the focal neighborhood indicates an increase in the PV adoption rate of on average 0.03 percentage points. A one percentage-point increase in the share of one- and two-family homes in the defined neighborhood is related to an additional increase in the PV adoption rate of 0.02 percentage points.

The household density serves as a proxy for a high degree of urbanization, which is associated with a larger number of multi-family buildings that rarely have PV installations in Germany. The direct and indirect effects are thus expected and also found to be opposite to the effects of the share of one- and two-family homes. Thereby, direct impacts are larger (negative) than indirect impacts.

Finally, a positive effect on the PV adoption rate can also be found for the number of large-scale PV systems. If the number of large-scale PV systems in the focal neighborhood increases by one unit, it is associated with a PV-adoption-rate increase of 0.0024, i.e., 0.24 percentage points. With an increase of 0.44 percentage points in the adoption rate, the indirect impact and thus the spillover effect of an increase in the number of large-scale PV systems in neighboring units is even larger than the direct effect.

5.2 Variations in neighborhood size

To check the sensitivity of our results regarding the size of the defined neighborhood, we estimate the SDM using increasing cutoff distances of up to 15 km. Thereby, possible changes in the significance of direct and indirect effects might be detected. Further, the changing influence of endogenous spatial autoregressive effects will be examined. Direct effects and indirect effects are illustrated in Figure 5. Corresponding regression results are given in Tables A 2 and A 3 in the appendix.

On the one hand, all direct effects, are statistically significant at least at the 5 % level, regardless of the cutoff distance used in the regression. On the other hand, indirect or spatial spillover effects of the share of purchasing power per household, unemployment rate, old-age dependency ratio as well as one- and two-family homes become insignificant[15] with increasing distances. The spillover effects of large PV systems and the household density, however, remain statistically significant at the 0.1 % level in all specifications. Looking at the log-likelihood as a goodness-of-fit measure, a radius of 8 km yields the best results for our data. With larger distances beyond this threshold, the log-likelihood starts decreasing again.

With increasing cutoff distances, the positive direct effects of solar irradiation and the number of large-scale PV systems are decreasing. Contrary, the spillover effects of the number of large-scale systems are increasing with rising cutoff distances and this effect largely overcompensates the decrease in the direct effect. This suggests that the visibility (and possibly also the network effects) of (large) PV systems do not only impact the immediate neighborhood, but also affects adoption decisions in a wider area.

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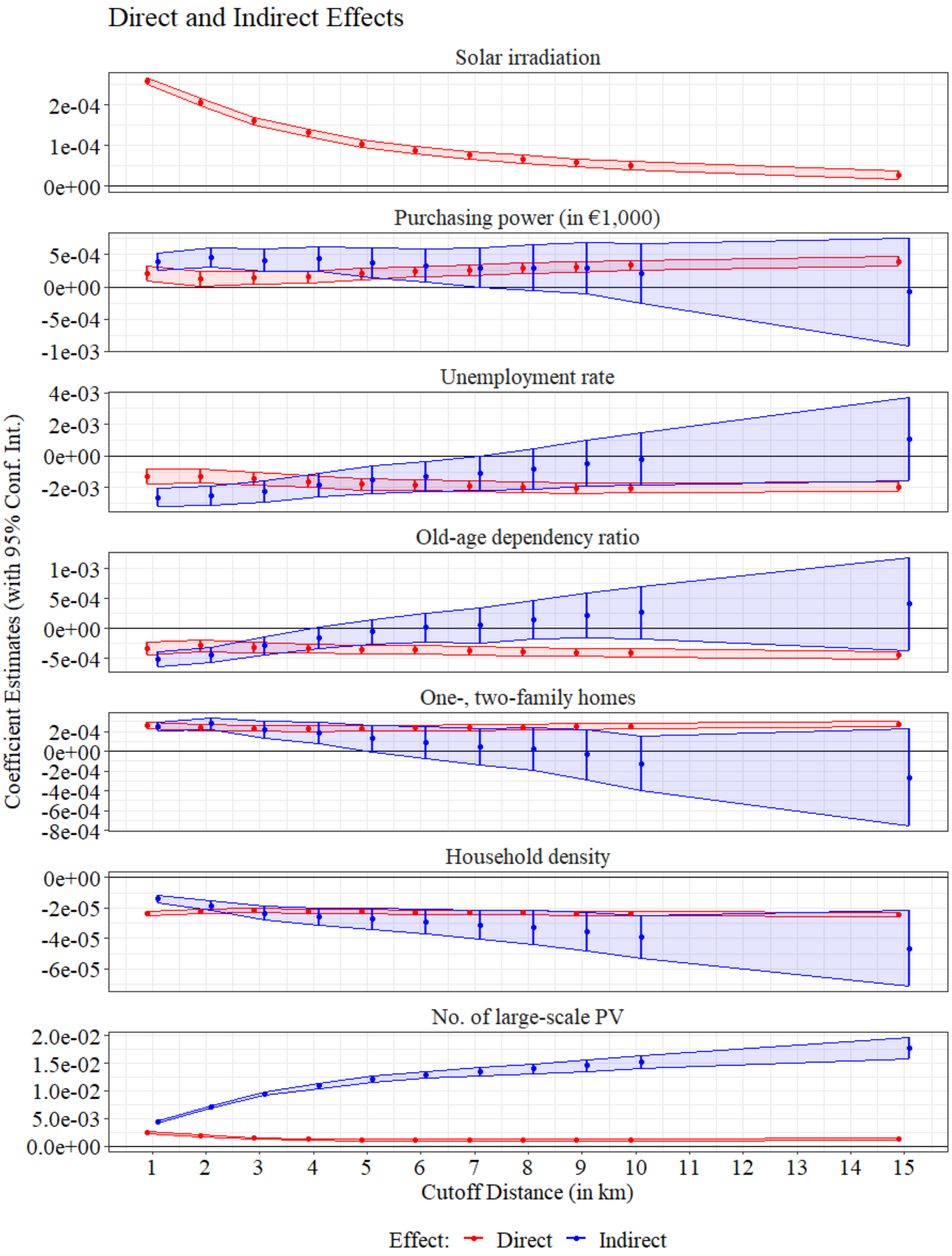
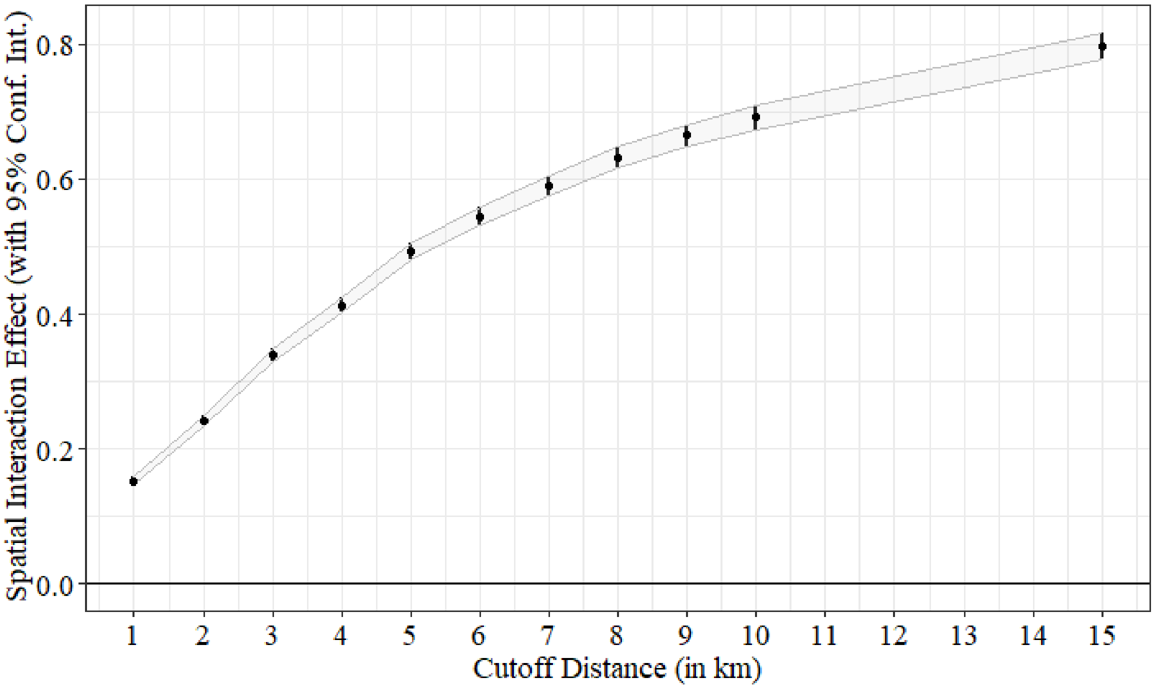
[15] As soon as the coefficients with the 95% Conf. Int. cross the zero line (cf. Figure 5), they become statistically insignificant at the 5 % level.



Source: Own calculation and illustration based on MaStR, DWD and RWI-GEO-GRID.

Figure 5 Direct and indirect effects of all exogenous variables for different cutoff distances.

This finding corresponds to the results obtained for the autoregressive parameter ρ. Also, this parameter increases with distance (cf. Figure 6), indicating spatial spillovers of the adoption of small-scale PV systems in neighboring regions even over distances above 10 km and when controlling for socioeconomic and settlement factors.



Source: Own calculation and illustration based on MaStR, DWD and RWI-GEO-GRID.

Figure 6 Spatial interaction effect for different cutoff distances.

For the socioeconomic factors themselves, i.e., purchasing power per household, unemployment rate and old-age dependency ratio, results are substantially different. The magnitude of direct effects tends to increase slightly with larger cutoff distances whereas the magnitude of spillover effects decreases. For both purchasing power and unemployment rate, the indirect effects become insignificant when the cutoff distance exceeds a radius of 6 km. In the case of the old-age dependency ratio, the spillovers already become statistically insignificant for distances of 4 km and more. As the best fit in terms of log-likelihood is obtained for a cutoff distance of 8 km, we tentatively conclude that spillovers for socioeconomic factors are rather irrelevant – and that their presence at smaller cutoff distances rather constitutes an artefact which results from the omission of far-ranging indirect effects of (small and large) PV installations.

Regarding the settlement structure, similar patterns emerge for the share of one- and two-family homes. As for the socioeconomic factors, its indirect effect decreases at higher cutoff distances, becoming insignificant from a radius of 5 km onwards. For the household density, both direct and indirect effects remain significant across the different regression specifications, with the magnitude of indirect effects even increasing with higher cutoff distances. “Rurality”, which broadly corresponds to large areas with low household density, hence, seems to have a substantial positive effect – other things being equal – on the adoption of PV systems.

5.3 Robustness of results

To test the robustness of our results, we additionally use data for 2014 and re-estimate the SDM for a cutoff distance of 1 km. Results for the SDM regression and corresponding impact measures are given in Table 7. The autoregressive parameter ρ is slightly lower compared to the results for 2020, yet remains positive and statistically significant, indicating endogenous spatial spillovers between neighboring grids. The minor decrease in the parameter value may be related to the fact that there were generally fewer PV installations in 2014 than in 2020 and spillover effects due to the visibility of other installations in neighboring regions have been correspondingly lower.

Table 7 SDM regression results and impact measures, using a cutoff distance of 1 km and data from 2014 .

Dependent Variable:	SDM		Impact measures		
PV adoption rate	β	θ	**Direct**	**Indirect**	**Total**
Solar irradiation	0.0002 ***		0.0002 ***		
	[4.81e-06]				
Purchasing power	0.0003 ***	-0.0001 *	0.0003 ***	-0.0001	0.0002 ***
(in 1,000 €)	[6.63e-05]	[7.35e-05]			
Unemployment rate	-0.0005 *	-0.0025 ***	-0.0006 **	-0.0029 ***	-0.0035 ***
	[0.0002]	[0.0002]			
Old-age dependency ratio	-0.0002 ***	-0.0001 *	-0.0003 ***	-0.0002 **	-0.0005 ***
	[5.77e-05]	[6.52e-05]			
One-, two-family homes	0.0001 ***	0.0001 ***	0.0002 ***	0.0001 ***	0.0003 ***
	[1.40e-05]	[1.80e-05]			
Household density	-2.00e-05 ***	-7.59e-06 ***	-2.07e-05 ***	-1.16e-05 ***	-3.23e-05 ***
	[7.86e-07]	[1.05e-06]			
No. of large-scale PV	0.0028 ***	0.0038 ***	0.0031 ***	0.0046 ***	0.0077 ***
	[6.99e-05]	[8.51e-05]			
Constant	-0.1613 ***				
	[0.0063]				
Rho	0.1468 ***				
	[0.0028]				
Log-likelihood	138,887.4				
Observations	125,441				

Notes: Standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. For SDM, β-estimates show coefficients for the independent variables; θ-estimates show coefficients for the spatially lagged independent variables.

Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.

With the exception of purchasing power, old-age dependency ratio and the number of large-scale PV systems, all direct effects are slightly smaller in 2014 compared to 2020. The direct effects of purchasing power and large-scale PV systems on the adoption rate of small-scale installations, are on the contrary larger in the regression with data of 2014 – which suggests that

PV adoption at that time was more driven by higher income classes and the presence of large "pilot" installations. For the spillover effects, rather similar patterns arise exempt for the unemployment rate: indirect effects are slightly smaller in 2014 compared to 2020. The indirect effect of purchasing power per household, even becomes statistically insignificant when using data of 2014. Overall, changes in effect sizes appear to be rather limited. Accordingly, the results are robust to changes in the year under consideration.

6 Discussion

Estimation results reveal that the adoption of residential solar PV systems is influenced by a combination of local factors, such as socioeconomic characteristics, settlement structure as well as features describing the physical environment. Moreover, there's an observable impact from spillover effects. Similar to numerous studies, we incorporate solar irradiation as an explanatory variable in the category of *climate characteristics*. Since solar irradiation varies geographically, areas with greater solar irradiation can generate more electricity from the same system size (and cost), leading to improved economic viability. This is found to have positive and significant effects on the adoption of residential PV installations. Our results are thus in line with Balta-Ozkan et al. (2015), Balta-Ozkan et al. (2021), Copiello and Grillenzoni (2017), Schaffer and Brun (2015) and Collier et al. (2023), among others.

Regarding the *socioeconomic characteristics* of the respective neighborhood, we find positive and statistically significant direct effects for purchasing power that were also reported inter alia in Zhang et al. (2023a), Dharshing (2017) and Irwin (2021). This is in line with expectations, as higher-income households tend to have fewer financial constraints and a higher willingness to bear risk for new investments such as installing PV systems. These results are contrary to those of Balta-Ozkan et al. (2015), who found insignificant impacts of income on the diffusion of residential solar PV systems in the UK.

Besides positive direct effects, we additionally find statistically significant indirect impacts of purchasing power on PV saturation – at least when limiting neighborhood sizes to a radius of 6 km or less. These results are contrary to those of Zhang et al. (2023a), as they report insignificant indirect impacts drawing on data of about 13,000 neighborhoods in the Netherlands (and using a cutoff distance of 3.5 km). The significant indirect effects in our study may be explained by network effects that are not limited to the own neighborhood in a 1 km² grid and that are not captured by existing PV installations (cf. below). So these are probably information networks in the sense that there is more talk and discussion about the merits of sustainable technologies, which reduces uncertainties e.g., about possible payback periods (cf. Bollinger and Gillingham, 2012). Another explanation is the increased probability of a larger fraction of high-income residents in the area if the average income in the surrounding area is also higher. The effect thus reflects some spillover in the overall economic situation of the neighborhood.

The consistent (negative) effects of the unemployment rate further support this hypothesis. Elevated unemployment within a neighborhood often correlates with lower rates of homeownership and, consequently, reduced disposable income. Additionally, there's a direct connection with the number of welfare recipients, showing an inverse relationship with the percentage of the population that earns an income. These factors have also been explored in other studies (e.g., Baginski and Weber, 2019; Thormeyer et al., 2020; Zhang et al., 2023a), which discover negative impacts associated with the proportion of welfare recipients and positive impacts linked to an increasing prevalence of homeownership and income-earning individuals in the population. Consequently, these outcomes align with the negative effects we have identified concerning increasing unemployment rates.

Regarding effects of age on the adoption of residential PV installations, there is mixed evidence in the extant literature (cf. Alipour et al., 2020). Contrary to most studies that use shares of different age groups, we align with studies on the demographic transition and include the old-age dependency ratio in our analysis (cf. Section 3). This leads to negative and significant direct effects in all model specifications. As a result, PV adoption rates decrease when the ratio of people aged 65 and over to people aged 20 to 64 increases, i.e., the population becomes proportionately older. A negative effect of the share of people aged 65 and older was also found in Bollinger and Gillingham (2012), Dharshing (2017) and Zhang et al. (2023a); however, all studies also report negative effects for younger age groups, leading to an inconclusive or non-linear effect of age on the adoption of residential solar PV.

A factor describing the *settlement structure* of the neighborhood is the share of one-and two-family homes. Some studies also use the share of detached houses or single-family houses only; however, effects are comparable as all of these factors describe the built environment in a neighborhood. Similar to Kucher et al. (2021), Müller and Rode (2013), Dharshing (2017), Balta-Ozkan et al. (2015) and Collier et al. (2023), among others, we find positive direct and indirect effects in all specifications; however, the spatial spillovers for this variable become insignificant with cutoff distances beyond 4 km.

The impact of household density, serving as a representation of urbanization, follows a similar pattern. In regions with elevated household density, the adoption of PV systems tends to be lower (e.g., Balta-Ozkan et al., 2015; Bollinger and Gillingham, 2012; Collier et al., 2023; Kucher et al., 2021; Kwan, 2012). This might be attributed to a greater prevalence of apartments, a particularly significant factor in urban settings – albeit this is in principle already controlled for ex negative by including the share of one- and two-family houses as explanatory variables. Hence it is rather attributable to smaller available rooftop spaces in high-density neighborhoods, which reduces the profitability of PV installations. This prevails also in the indirect effects indicating that household density in the surroundings does not induce strong positive network effects as hypothesized in Section 3.

Finally, *neighborhood effects* are captured inter alia by the impact of large-scale PV installations on the adoption of residential rooftop PV. To our knowledge, this has not received attention in the existing literature (cf. Zhang et al., 2023a). It is often argued that peer effects mainly work through the visibility of other PV installations (Bollinger and Gillingham, 2012; cf. Rode and Müller, 2021). The strong positive direct and indirect effects of large-scale PV plants that we find in all models supports this visibility argument. Concurrently, it implies that the inclusion of large solar installations is crucial, even when studying the distribution of smaller installations.

Neighborhood effects are also captured by the autoregressive parameter ρ. As the size of this coefficient is dependent on inter alia the weights matrix used and also the chosen cutoff distances, it is not directly comparable to other studies. With an increasing distance, we find that the autoregressive parameter ρ also increases. The effect depicts spillovers of the adoption of small-scale PV systems in the surrounding neighborhood on the adoption rates in the focal neighborhood and thus is an indicator for the effect of visibility of these systems.

The increase in spatial autocorrelation underscores the enduring importance of PV system visibility beyond small neighborhoods and points to the conclusion that not only neighborhoods but also supply and information networks matter. This also underlines the increasing indirect effects of large-scale PV systems with increasing distances. Contrarily, indirect effects and thus spillover effects of almost all other variables become insignificant when neighborhood size is increased. This aligns with results from studies using coarser data, yet any estimate of spillovers related to visibility and network effects will be blurred if coarse data is used – as then there is a broad range of distances between individual units belonging to contiguous neighborhoods, e.g., in a range between less than 1 km up to 40 km, if two regions of 20 km diameter are next to each other.

7 Conclusion

Based on a Spatial Durbin Model and a novel dataset at a standardized 1 km² grid cell level, we investigate the adoption of residential solar PV systems in Germany for the year 2020. Thereby, we not only consider socioeconomic as well as geographic factors at a small spatial scale; we also examine spatial spillovers for different neighborhood sizes and investigate the effect of large-scale solar PV systems up to 100 kWp on the adoption of installations up to 10 kWp. Our results reveal that the number of large-scale PV systems has strong positive effects on the adoption of residential PV installations, indicating that an inclusion of such systems is crucial for estimating adoption effects. It further indicates that the installation of large systems in neighborhoods with low adoption rates may foster the installation of residential PV.

Additionally, the autoregressive parameter increases with increasing neighborhood sizes, pointing to relevant spatial effects e.g., due to the visibility of small-scale PV systems, even beyond the immediate neighborhoods. However, spillover effects of other explanatory factors become insignificant with larger distances. Given these differentiated findings, we strongly recommend the use of high-resolution spatial data to avoid the blurring of different types of spillover effects when using coarser data.

Nevertheless, there are several limitations to this study. First, system prices and subsidies are found to be important drivers of PV diffusion, both of which are not included in our study. This is, however, related to the use of cross-sectional data for a single year on which we base our analysis. As spatial price variations are hardly observable, we have excluded these factors from the regression. Second, a minor drawback is the lack of information on the share of owner-occupied homes as this is also found to have significant influence on the adoption of residential PV systems (e.g., Zhang et al., 2023a). Nonetheless, as previous research consistently points to the same outcome, the inclusion of this factor would probably not have led to new findings.

Finally, as we employ cross-sectional data, unobserved time-invariant effects that occur during dynamic technological diffusion processes are not captured in our analysis. However, we leave this for future research, as our initial objective has been to examine the merits of small-scale raster data with combined adoption, socioeconomic and settlement variables to assess the impact of neighborhood effects on the penetration of residential solar PV installations when controlling for multiple other factors.

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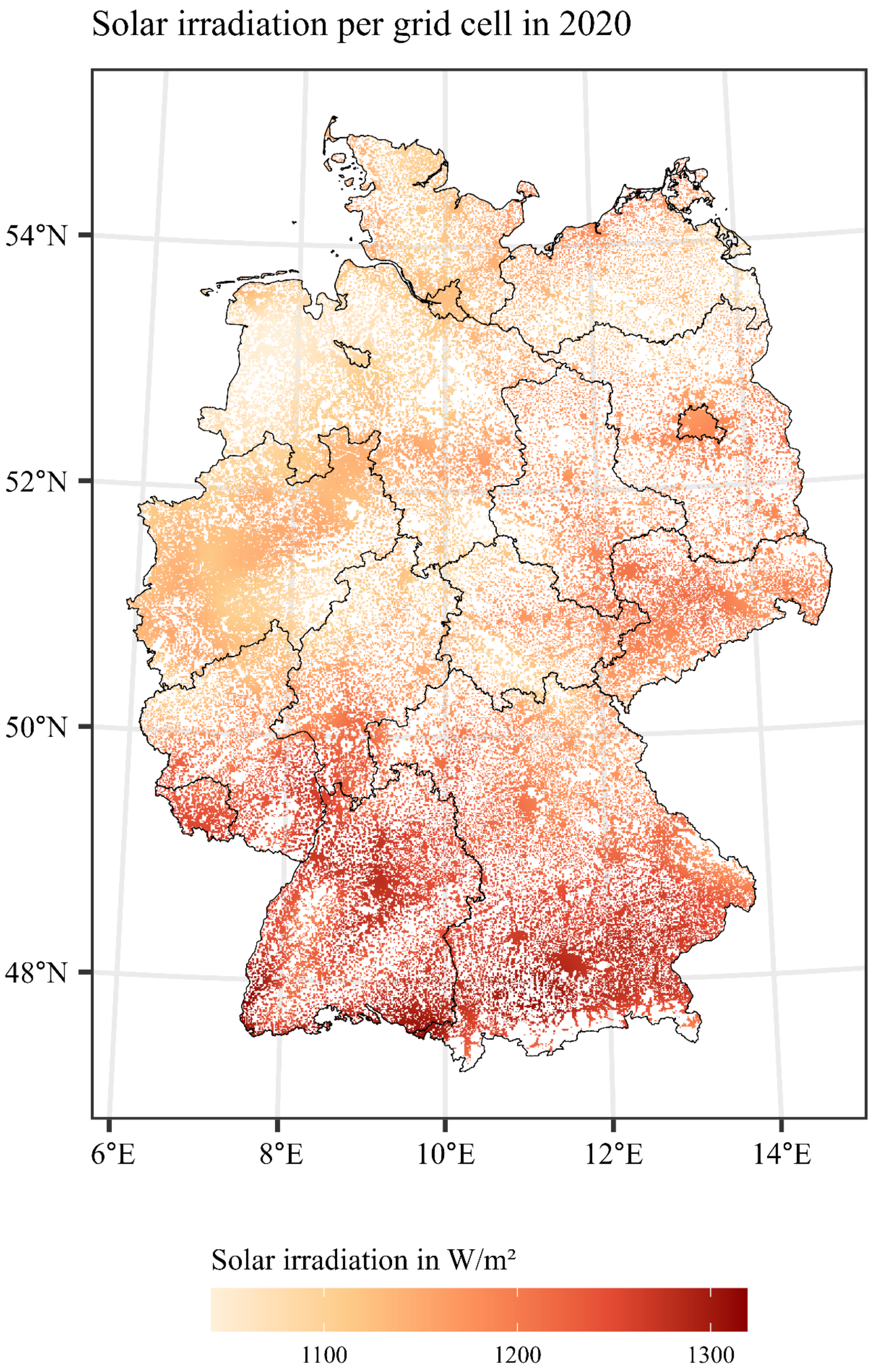
Appendix

Table A 1 Descriptive statistics for the year 2014. (n = 125,441)

Variable	Mean	Std. Dev.	Min	Max	Median
PV adoption rate, i.e. No. of PV ≤ 10 kWp/No. of houses	0.07	0.09	0.00	4.00	0.04
Solar irradiation, in W/m²	1,074.69	50.80	936.70	1,224.00	1,069.00
Purchasing power per household, in €	44,939.86	7,704.12	22,338.10	71,515.86	44,809.51
Unemployment rate, in %	4.73	3.01	0.00	20.00	4.11
Old-age dependency ratio	36.19	7.64	17.28	70.24	35.33
No. of houses	120.86	167.93	2.00	1,032.00	50.00
Share of one-, two-family homes, in %	67.44	21.08	1.91	100.00	70.77
Population density, inhabitants/km²	444.27	791.77	12.00	6,998.00	143.00
Household density, households/km²	221.48	411.75	10.00	3,873.00	67.00
No. of large-scale PV systems, > 10 kWp and ≤100 kWp	2.79	3.69	0.00	24.00	1.00

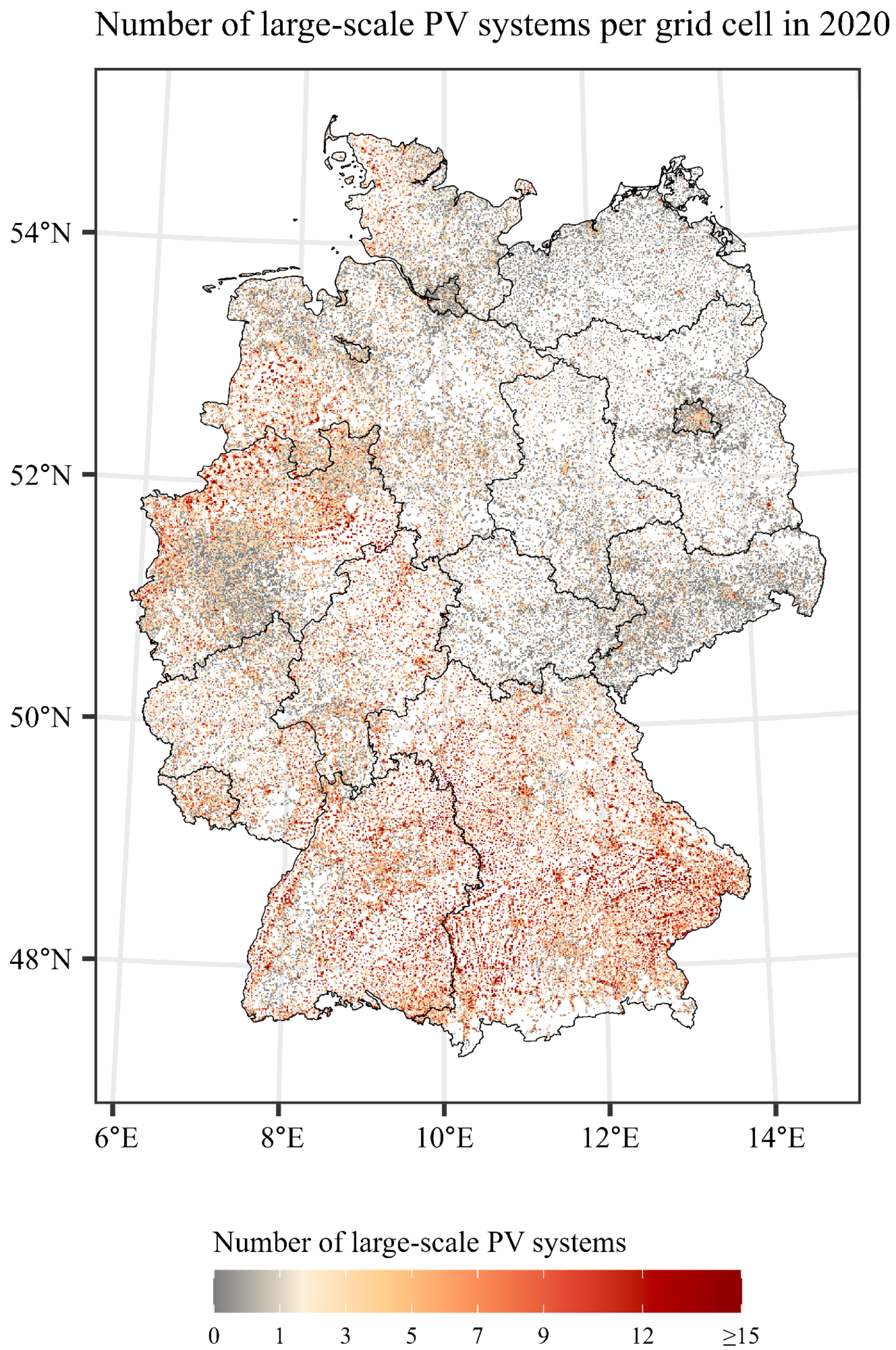
Notes: The old-age dependency ratio represents the ratio of persons of retirement age (here: 65 years and older) to 100 persons of working age (here: from 20 to 64 years). Values are based on inhabited 1 km² grid cells only.

Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.



Source: Own illustration based on DWD (2023). Map Data: @GeoBasis-DE/BKG 2021

Figure A 1 Regional distribution of solar irradiation in 2020.



Source: Own illustration based on MaStR and RWI-GEO-GRID. Map Data: @GeoBasis-DE/BKG 2021

Figure A 2 Regional distribution of large-scale PV systems across Germany, 2020.

Table A 2 SDM-regression results for cutoff distances of 2 km to 6 km.

Dependent Variable: **PV adoption rate**	**2 km**	**3 km**	**4 km**	**5 km**	**6 km**
β-estimates:					
Solar irradiation	0.0002 ***	0.0002 ***	0.0001 ***	0.0001 ***	8.78e-05 ***
	[4.56e-06]	[4.67e-06]	[4.76e-06]	[4.86e-06]	[4.92e-06]
Purchasing power	0.0001	0.0001 **	0.0001 **	0.0002 ***	0.0002 ***
(in €1,000)	[5.66e-05]	[5.06e-05]	[4.75e-05]	[4.52e-05]	[4.39e-05]
Unemployment rate	-0.0012 ***	-0.0014 ***	-0.0016 ***	-0.0018 ***	-0.0018 ***
	[0.0002]	[0.0002]	[0.0002]	[0.0002]	[0.0002]
Old-age dependency	-0.0003 ***	-0.0003 ***	-0.0003 ***	-0.0004 ***	-0.0004 ***
ratio	[4.96e-05]	[4.32e-05]	[4.02e-05]	[3.81e-05]	[3.70e-05]
One-, two-family	0.0002 ***	0.0002 ***	0.0002 ***	0.0002 ***	0.0002 ***
homes	[1.51e-05]	[1.50e-05]	[1.49e-05]	[1.48e-05]	[1.48e-05]
Household density	-2.14e-05 ***	-2.12e-05 ***	-2.14e-05 ***	-2.20e-05 ***	-2.24e-05 ***
	[8.13e-07]	[7.85e-07]	[7.72e-07]	[7.63e-07]	[7.58e-07]
No. of large-scale PV	0.0015 ***	0.0012 ***	0.0010 ***	0.0010 ***	0.0009 ***
	[6.72e-05]	[6.75e-05]	[6.77e-05]	[6.78e-05]	[6.79e-05]
Constant	-0.2038 ***	-0.1573 ***	-0.1315 ***	-0.1051 ***	-0.0891 ***
	[0.0068]	[0.0073]	[0.0077]	[0.0082]	[0.0085]
θ-estimates:					
Purchasing power	0.0003 ***	0.0002 ***	0.0002 **	9.43e-05	2.57e-05
(in €1,000)	[6.93e-05]	[6.88e-05]	[6.96e-05]	[7.17e-05]	[7.37e-05]
Unemployment rate	-0.0017 ***	-0.0011 ***	-0.0005	0.0001	-0.0004
	[0.0003]	[0.0003]	[0.0003]	[0.0003]	[0.0003]
Old-age dependency	-0.0003 ***	-9.35e-05	3.86e-05	0.0001 *	-0.0002 **
ratio	[6.22e-05]	[6.10e-05]	[6.19e-05]	[6.44e-05]	[6.66e-05]
One-, two-family	0.0002 ***	7.37e-05 *	1.70e-05	-4.77e-05	-8.86e-05 *
homes	[2.50e-05]	[3.00e-05]	[3.36e-05]	[3.70e-05]	[3.92e-05]
Household density	-9.36e-06 ***	-8.66e-06 ***	-6.57e-06 ***	-3.17e-06	-1.11e-06
	[1.38e-06]	[1.59e-06]	[1.75e-06]	[1.92e-06]	[2.04e-06]
No. of large-scale PV	0.0052 ***	0.0061 ***	0.0061 ***	0.0058 ***	0.0054 ***
	[0.0001]	[0.0001]	[0.0002]	[0.0002]	[0.0002]
Rho	0.2420 ***	0.3386 ***	0.4123 ***	0.4930 ***	0.5448 ***
	[0.0038]	[0.0048]	[0.0056]	[0.0065]	[0.0071]
Log-likelihood	134,166.1	135,104.3	135,537.1	135,864.4	135,997.18
Observations	125,441	125,441	125,441	125,441	125,441

Notes: Standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. β-estimates show coefficients for the independent variables; θ-estimates show coefficients for the spatially lagged independent variables. Data for 2020 is used in all regressions.

Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.

Table A 3 SDM-regression results for cutoff distances of 7 km to 10 km and 15 km.

Dependent Variable: **PV adoption rate**	**7 km**	**8 km**	**9 km**	**10 km**	**15 km**
β-estimates:					
Solar irradiation	7.57e-05 ***	6.53e-05 ***	5.75e-05 ***	5.05e-05 ***	2.82e-05 ***
	[4.98e-06]	[5.04e-06]	[5.09e-06]	[5.14e-06]	[5.30e-06]
Purchasing power (in €1,000)	0.0003 ***	0.0003 ***	0.0003 ***	0.0003 ***	0.0004 ***
	[4.30e-05]	[4.22e-05]	[4.18e-05]	[4.12e-05]	[4.00e-05]
Unemployment rate	-0.0019 ***	-0.0020 ***	-0.0020 ***	-0.0020 ***	-0.0020 ***
	[0.0002]	[0.0002]	[0.0002]	[0.0002]	[0.0002]
Old-age dependency ratio	-0.0004 ***	-0.0004 ***	-0.0004 ***	-0.0004 ***	-0.0005 ***
	[3.62e-05]	[3.56e-05]	[3.51e-05]	[3.48e-05]	[3.37e-05]
One-, two-family homes	0.0002 ***	0.0002 ***	0.0002 ***	0.0003 ***	0.0003 ***
	[1.47e-05]	[1.47e-05]	[1.47e-05]	[1.47e-05]	[1.46e-05]
Household density	-2.26e-05 ***	-2.30e-05 ***	-2.32e-05 ***	-2.34e-05 ***	-2.46e-05 ***
	[7.53e-07]	[7.48e-07]	[7.45e-07]	[7.43e-07]	[7.33e-07]
No. of large-scale PV	0.0010 ***	0.0010 ***	0.0010 ***	0.0011 ***	0.0012 ***
	[6.78e-05]	[6.78e-05]	[6.78e-05]	[6.78e-05]	[6.74e-05]
Constant	-0.0762 ***	-0.0671 ***	-0.0596 ***	-0.0507 ***	-0.0268 *
	[0.0088]	[0.0091]	[0.0094]	[0.0097]	[0.0108]
θ-estimates:					
Purchasing power (in €1,000)	-2.98e-05	-7.12e-05	-0.0001	-0.0002 *	-0.0003 ***
	[7.57e-05]	[7.81e-05]	[8.06e-05]	[8.32e-05]	[9.41e-05]
Unemployment rate	0.0007 *	0.0009 **	0.0012 ***	0.0013 ***	0.0018 ***
	[0.0003]	[0.0003]	[0.0003]	[0.0003]	[0.0003]
Old-age dependency ratio	0.0002 ***	0.0003 ***	0.0003 ***	0.0004 ***	0.0004 ***
	[6.87e-05]	[7.13e-05]	[7.38e-05]	[7.64e-05]	[8.70e-05]
One-, two-family homes	-0.0001 **	-0.0001 ***	-0.0002 ***	-0.0002 ***	-0.0003 ****
	[4.09e-05]	[4.27e-05]	[4.43e-05]	[4.57e-05]	[5.05e-05]
Household density	5.44e-07	2.44e-06	3.47e-06	4.08e-06	1.01e-05 ***
	[2.13e-06]	[2.22e-06]	[2.32e-06]	[2.41e-06]	[2.76e-06]
No. of large-scale PV	0.0050 ***	0.0046 ***	0.0042 ***	0.0040 ***	0.0026 ***
	[0.0002]	[0.0002]	[0.0002]	[0.0002]	[0.0003]
Rho	0.5900 ***	0.6321 ***	0.6646 ***	0.6913 ***	0.7977 ***
	[0.0076]	[0.0081]	[0.0085]	[0.0089]	[0.0102]
Log-likelihood	136,078.1	136,098.7	136,057.1	136,005.7	135,862.2
Observations	125,441	125,441	125,441	125,441	125,441

Notes: Standard errors in brackets. *** p <0.001, ** p <0.01, * p <0.05. β-estimates show coefficients for the independent variables; θ-estimates show coefficients for the spatially lagged independent variables. Data for 2020 is used in all regressions.

Source: Own calculations based on MaStR, DWD and RWI-GEO-GRID.

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CHAPTER SIX

Conclusion

The present dissertation is built on four academic papers. Chapters 2 to 4 investigated the residential real estate sales and rental markets in Germany to gain insights mainly into the valuation of energy efficiency but also on effects of different heating technologies on sales prices and rents. Chapter 5 evaluated drivers for the adoption of rooftop solar photovoltaic systems in Germany – also with high spatial resolution. In the following, the main findings regarding the research questions identified in Chapter 1.6 are summarized.

Chapter 6.1 discusses the methodological contributions of this dissertation addressing the first two research questions regarding spatial analysis, small-scale data and methods to capture energy efficiency effects in housing markets. The contributions to the substantive research questions three and four, addressing the varying valuations of energy efficiency and different factors affecting both these valuations and the expansion of residential solar PV installations are reviewed in Chapter 6.2. Finally, Chapter 6.3 points at policy implications with a focus on the achievement of a climate-neutral building stock as targeted in the fifth research question.

6.1 Methods to examine spatial effects and capture energy efficiency impacts on property valuation using small-scale data

[RQ 1] *How can small-scale data be used to examine spatial effects regarding residential building energy use and production and what are viable approaches for incorporating spatial effects into corresponding analyses of housing markets?*

Using small-scale spatial data, sometimes also referred to as micro-level data, has numerous advantages when applying micro-econometric approaches to analyze e.g., regional effects. These types of data offer a high level of granularity, allowing to investigate economic phenomena at a much finer scale and also to better capture and analyze the heterogeneity that exists within larger aggregates. It also enables to account for local variations and varying effects across different regional types (cf. Chapters 2 and 3) and further to identify spatial patterns and relationships across space (cf. Chapter 5).

There are several ways to capture spatial effects and incorporate them into regression analysis. One easily applicable option is to include regional or area-specific fixed effects (FEs) at different spatial levels in the regression to account for unobserved heterogeneity or differences across geographic regions. FEs are a type of dummy variable that control for variations in the dependent variable that are specific to each region and not captured by the observed independent variables (e.g., due to regional policies, cultural differences or geographic characteristics). These dummies essentially create a separate intercept term for each geographic region. This allows the model to capture and control for the average differences in the dependent variable across regions, while focusing on the relationships between the independent variables and the dependent variable within each region.

This fixed-effects approach is mainly used in Chapters 2, 3 and 4. The first two studies thereby include FEs on county level, which is equivalent to NUTS3 regions in Germany. Chapter 2 thus includes 401 FEs; Chapter 3 includes 55 FEs, as the analysis is based on one federal state only. Chapter 4 extends this method and applies a so-called high-dimensional fixed effects (HDFE) approach where the regression not only includes FEs on county (401), but also on state (16) and neighborhood (55,733) level. In doing so, the model is able to control for unobserved heterogeneity on different spatial scales. After estimation, robust standard errors that account for the clustering of observations within entities were calculated for each model as this is crucial for accurate inference.

One disadvantage of the fixed-effects approach is that no spatial relationships or spatial spillover effects, respectively, can be calculated. However, the exclusion of such effects might lead to biased results, especially in the case of adoption processes, since according to Tobler's First Law of Geography, "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970, p. 236).

To incorporate these spatial spillover effects, Chapter 5 uses special regression techniques that involve the use of a spatial weights matrix. This matrix defines the spatial relationship between observations based on proximity. A distance-based contiguity matrix with different cutoffs is used to create spatial lag or spatial error terms. This accounts for the potential influence of nearby observations on each other.

There are several spatial regression techniques that include a spatial weights matrix – in Chapter 5, three common model specifications for the estimation of (global) spillover effects were tested: the Spatial Autoregressive Model (SAR), the Spatial Error Model (SEM) and the Spatial Durbin Model (SDM). SAR models explicitly incorporate spatial dependencies by including a spatial lag term in the regression equation. This term represents the weighted average of the dependent variable in neighboring observations. In case of PV adoption, it controls for visibility effects of small-scale installations in neighboring regions on the adoption of small-scale PV systems in the focal neighborhood. In a SEM, the spatial dependence is attributed to the error term, because the disturbances are assumed to be spatially correlated. The corresponding spatial parameter lambda allows to account for the dependence of the error values of one region on the errors in other regions connected to it. In context of PV adoption, lambda controls for unobserved spatial clusters which may include, for example, a clustering of craftsmen that work in the solar industry. The SDM includes a spatial lag term and a spatially lagged independent variable and thus captures the direct and indirect spatial effects of both the dependent variable and the independent variables. The most appropriate model – the SDM in case of Chapter 5 – is then selected based on Lagrange Multiplier and Likelihood Ratio tests.

Both approaches (FE and SDM) are valuable tools for handling spatial dependencies and regional heterogeneity; however, they serve slightly different purposes and have specific advantages depending on the research context. Using the SDM, it is possible to account for how changes in the independent variables in neighboring regions influence the dependent variable in the focal region. In context of PV adoption, the influence inter alia of large-scale PV systems in surrounding neighborhoods on the adoption of small-scale installations in the focal neighborhood can be investigated as the existence of such large installations is assumed to positively affect the adoption of residential PV systems in surrounding areas.

In contrast, the FE approach typically only accounts for region-specific differences in intercepts, without directly considering spatial interactions. Regarding the investigation of real estate markets, the use of FEs thereby allows to control e.g., for price differences across regions and also for regionally different regulatory frameworks (such as the *“Mietpreisbremse”*, which only applies in cities with tight housing markets).

Furthermore, the SDM explicitly considers the idea of spatial spillovers, which is not adequately captured by the FE approach and also can help to test and quantify the degree of spatial dependence in the data. This is particularly useful for assessing whether spatial interactions play a significant role in explaining the variations in the dependent variable. In context of PV adoption, the interest lies almost exclusively on these spatial spillovers to capture regional dependences underlying adoption processes.

Using spatial econometric models like the SDM can also be useful for the investigation of real estate markets as prices in one region might also be influenced by prices (e.g., Can, 1990) or other environmental conditions (such as air quality) (e.g., Anselin and Lozano-Gracia, 2008; Won Kim et al., 2003) in neighboring regions. Nevertheless, as the focus in Chapters 2 to 4 is on energy efficiency rather than on spatial spillover effects, the use of FE is sufficient. Furthermore, the estimation of spatial weights matrices used in spatial econometric models requires precise geolocations of the units, i.e., buildings or apartments, under consideration.

Furthermore, the real estate data used was only available in aggregated form on the basis of the 1 km²-grid cells, so that a calculation could not have been performed without additional assumptions of the location within a grid cell. Additionally, if there is a strong theoretical reason to believe that the relationship between the independent and dependent variables is uniform across all regions, the FE approach might be more appropriate. It's also suitable when the primary interest is in controlling for region-specific differences that are constant over time. Moreover, this approach provides a straightforward and thus simpler interpretation of region-specific intercepts.

While both approaches have their advantages, they also come with certain limitations. First, the inclusion of spatial weights matrices and large numbers of FEs is computationally demanding and requires good programming skills and/or a lot of working memory. Second, especially the SDM introduces additional complexity to the regression analysis, notably when there are multiple spatial lags and additional independent variables. This complexity can make the model more challenging to estimate and interpret. Third, regarding the FE approach, there might be a loss of information when including a large number of fixed effects, as the model captures the average differences across regions but might not fully account for within-region variations. Lastly, both approaches require a large number of georeferenced data so that different challenges arise if data availability is limited.

[RQ 2] *How can the impact of the building's energy performance on sale prices and rents be modelled adequately?*

A widely used approach in the field of housing economics is the so-called hedonic pricing model, which is applied to estimate the implicit values of various attributes or characteristics of a house or apartment that contribute to its market price. This model is based on the idea that a house's price can be understood as the sum of the values attributed to its different characteristics, such as location, size, number of rooms, and other amenities. Further, in a multi-attribute case, the market outcome reflects the market equilibrium across the different preferences of the demand side and the different cost functions of the supply side (cf. Rosen, 1974).

Chapters 2, 3 and 4 apply different specifications of this hedonic pricing model. In Chapter 2, it is first implemented in a common semi-logarithmic form where the logarithmized price per square meter of living area is explained by a number of (linear) independent variables. A similar specification is also used in the HDFE approach in Chapter 4. The estimated coefficients can then be interpreted as semi-elasticities and thus indicate a percentage change in the house price (or rent, respectively) for each one-unit change in the main independent variable of interest.

In the second part of Chapter 2, the hedonic pricing model is combined with a total-cost-of-ownership (TCO) perspective. Rather than treating the energy performance as an attribute of the building, it was added to the righthand-side of the equation, reflecting that (heating) energy is an input in producing housing amenity, i.e., a heated dwelling. The corresponding costs are thus a part of the TCO associated with a house of the given characteristics (on the lefthand-side of the equation). After rearranging the model, it has to be estimated via nonlinear least squares.

The resulting coefficient for the energy performance score can directly be interpreted as monetary impact on the total property costs in euro per one-unit decrease in the energy performance score. This cost-based perspective can then be used to compare the increase in housing values with engineering-economic estimates of energy cost savings and needed investment costs for energy refurbishments. It is also possible to calculate an energy multiplier that gives the monetary benefit per one-euro reduction in energy costs, taking current energy prices for heating into account.

Chapters 3 and 4 both build on this second approach; however, as the focus is on rents rather than sales prices, it is more of a total-cost-of-use (TCU) perspective. Chapter 3 thereby draws on basic rents and estimates the monetary benefit for property owners, i.e., an increase in basic rents, for improvements in the energy efficiency of the building. Contrary, Chapter 4 takes the given overall warm rent as dependent variable so that the coefficient for the energy performance score is expected to be zero, as energy costs should already be included in the warm rent. If the coefficient differs from zero, it indicates inefficiencies (in monetary terms) in the market for energy efficiency.

One major advantage of the nonlinear compared to the linear specification is the ability to directly compare the premiums with energy cost savings and investment costs for energy refurbishments while taking actual energy costs for heating into account. Yet, the hedonic pricing approach in general also has its limitations. First, it only identifies correlations but does not establish causal relationships. Second, the accuracy of the model relies on the quality of data collected. Missing or inaccurate data can affect the reliability of the results. As all studies are based on offering rather than transaction data, some inaccuracies cannot be ruled out. In addition, more accurate analyses could be made possible with precise consumption data, e.g., through smart meters linked to properties via georeference. An additional availability of regional price data for energy sources would further allow a better inclusion of actual heating costs.

Third, the use of nonlinear least squares requires the choice of realistic starting values for each coefficient. If these values are not well chosen, the model may not converge. In addition, compared to linear models, the inclusion of FEs in a nonlinear model is computationally intensive as a dummy variable for each geographical unit has to be included in the model (compared to categorical variables that may be included in linear models).

6.2 Factors affecting the energy performance valuation and the expansion of residential photovoltaic systems

[RQ 3] *To what extent is energy efficiency valued in the markets for residential dwellings and are there differences between the sales and the rental markets?*

The valuation of energy efficiency is investigated in Chapters 2, 3 and 4 so that the main contribution to the third research question is given in the first three studies of this dissertation. To directly give a short answer: Yes, energy efficiency is valued differently in sales and rental markets.

In the German real estate sales market (cf. Chapter 2), single-family homes are sold on average at a premium of roughly 6.9 % if the energy efficiency improves by 100 kWh/m²a. At heating energy prices of 0.065 €/kWh (the weighted average energy price during the study period), the monetary benefit per one-euro reduction in yearly energy costs amounts to approximately €20. The estimated premium only represents about 50 % of total investment costs that are needed for the corresponding improvements in energy efficiency, meaning that about half of the required costs are not reflected in higher property values. Nevertheless, roughly 98 % of (discounted) energy cost savings are reflected in a higher housing value when assuming constant energy prices and a useful life of 25 years.

In the German rental housing market, apartments are rented out at an average surplus in monthly basic rents of only 1.4 % if the energy efficiency improves by 100 kWh/m²a (cf. Chapter 3). If full information on overall warm rents and explicit heating costs are provided in the online advertisement of the respective apartment, the premium increases to 2.4 % (cf. Chapter 4).

Relative effects in the rental market are thus about three to five times smaller compared to effects in the sales market. Furthermore, estimated energy cost savings after energy-efficiency improvements (based on average energy prices for heating of 0.067 €/kWh) exceed the increase in basic rents by a factor of three to seven – depending on the energy performance certificate of the building – resulting in financial advantages for tenants (cf. Chapter 3).

One potential reason for differences in the valuation of energy efficiency are varying market conditions. There is evidence that housing shortage is a driver for varying effects across regions at least in the sales market (cf. Chapter 2). If the market is tight, i.e., there is a low number of advertisements in a specific region, then the effects of energy efficiency on housing prices are weaker compared to less tight markets. However, the "tightness" of sales and rental markets may also vary within a region so that these differences might influence the varying valuations of energy efficiency across markets.

Another possible reason for different valuations might be the split-incentives problem. In owner-occupied housing, the property owner directly benefits from improvements in energy efficiency due to lower energy bills and improved thermal comfort. In rental housing, however, property owners have to pay for energy refurbishments while tenants profit from the made improvements due to lower energy costs – at least if the energy costs are borne by the tenants on the basis of their own consumption.

To further analyze this dilemma in the rental market, Chapter 4 investigated inefficiencies that are found in the market for energy efficiency. The results confirm that there are financial advantages for tenants when renting a more efficient apartment. However, there are differences in the effects depending on the amount of information on the individual price components of the apartment already provided in the real estate advertisement. While it is no different whether only the basic rent or an inclusive warm rent (basic rent plus utilities plus heating costs – without an explicit breakdown of the price components) is indicated, the effects of energy efficiency on the basic rent are almost twice as large if explicit information on heating costs is also provided in addition to the warm rent.

[RQ 4] *What other factors affect the valuation of the energy performance in real estate sales and rental markets? Are there similar factors influencing the adoption of residential photovoltaic systems?*

Besides the tightness of real estate markets, as described above, a major factor that directly affects the valuation of energy efficiency in the real estate sales and rental markets is the type of EPC. The two types of EPCs in Germany are based on different calculation principles (cf. Chapter 1.4), which sometimes leads to significant differences in the energy performance score given by these certificates. In both the sales and rental market, effects of energy efficiency on prices and rents, respectively, are found to be larger if the respective dwelling is scored based on demand rather than consumption (cf. Chapters 2, 3 and 4).

For an energy efficiency improvement of 100 kWh/m²a, housing prices increase on average by 3.22 % if the building has a consumption certificate and by 7.89 % if it has a demand certificate (cf. Chapter 2). For analogous refurbishments, monthly basic rents increase by 1.1 % for consumption-certified dwellings and by 2.3 % for demand-certified dwellings (cf. Chapter 3). If warm rents and explicit heating costs are provided in the online advertisements, the premiums increase to 1.7 % and 3.4 % respectively (cf. Chapter 4).

Furthermore, the type of heating and the energy source of heating, respectively, also have impacts on the valuation of energy efficiency, at least in the rental market. The effect of energy efficiency on basic rents is larger in subsamples of apartments that have standard heating systems such as central, gas or floor heating. Effects on basic rents are significantly smaller (and even negative for consumption-certified dwellings), if the apartment is equipped with dirty heating technologies like oil, stove or night storage heating (cf. Chapter 2). Regarding effects on overall warm rents, similar results were found in Chapter 3. The more environmentally friendly the heating system and energy source for heating, the less inefficiencies can be found in the market for energy efficiency, i.e., the discrepancy between energy cost savings and the increase in basic rents becomes smaller.

Another factor influencing the valuation of energy efficiency is the initial efficiency level of the respective building. In the sales market, effects of energy efficiency on housing prices are largest for single-family houses with an energy efficiency rating of class E to G with corresponding energy performance scores of 160 kWh/m²a to 250 kWh/m²a. Furthermore, effects are statistically insignificant for more efficient homes of categories A+ to C with energy performance scores under 100 kWh/m²a, indicating that there is no willingness-to-pay for additional energy efficiency in already efficient homes (cf. Chapter 2).

Similar patterns arise in the rental housing market. In a subsample of the most efficient apartments (categories A+ to B), effects of energy efficiency on overall warm rents are largest compared to subsamples with less efficient apartments, i.e., with increasing energy efficiency, the warm rents of the most efficient apartments show a large decrease due to decreasing heating costs. This corresponds to low increases in basic rents which again implies a low (or zero) willingness-to-pay from tenants for further improvements in energy efficiency (cf. Chapter 4).

The disclosure of detailed information on heating costs in online advertisements also influences the valuation of energy efficiency in rental markets (cf. Chapter 4). The disclosure leads to decreasing information asymmetries between property owners and prospective tenants. Providing information on overall warm rents (without the explicit disclosure of heating costs) compared to only providing information on basic rents, however, has no statistically significant effects on the valuation of energy efficiency.

Regarding the influence of neighborhood characteristics, especially the purchasing power per capita, the studies in Chapters 2 and 4 found mixed evidence on the valuation of energy efficiency. In the real estate sales market, the energy efficiency premium is found to be lower in high-income districts. This suggests that poor energy efficiency may not be a significant factor for homebuyers in these regions, either because they do not seem to view high energy costs as a concern or because they are willing to invest in energy improvements after they purchase the home (cf. Chapter 2).

On the other hand, the market for energy efficiency in the German rental market seems to be efficient in high-income neighborhoods, i.e., the increase in basic rents equals the decrease in energy costs, so that property owners are adequately compensated for energy improvements (cf. Chapter 4). The effects are thus exactly the opposite in the rental market compared to the sales market. One possible explanation for the reverse effects in the rental market is that efficient apartments often come along with significantly higher basic rents and prospective tenants are not aware that this higher rent can be offset by energy cost savings. Therefore, if the income is rather (below) average and prospective tenants are not aware of this mechanism, they might tend to rent the less efficient apartment with lower basic rents.

There is an associated strand in the literature that deals with so-called *energy poverty* (cf. e.g., Burlinson et al., 2018; Porto Valente et al., 2022; Thomson et al., 2017). Various studies show that, especially in the rental segment, poorer households bear the relatively higher costs – whether for energy costs per se due to poorly insulated houses (e.g., Chen and Feng, 2022) or for rent increases after major renovation projects (e.g., Platten et al., 2022). Drivers for energy poverty especially of low-income households thereby include a lack of understanding of the economic benefits of energy conservation as well as a lack of energy education (Hernández and Bird, 2010). This is in line with the more general hypothesis that *the poor pay more,* which may be traced back in the social sciences at least to Caplovitz (1967).

Besides effects on the valuation of energy efficiency, the purchasing power also has a strong influence on the adoption of residential solar PV systems. The higher the purchasing power per household, the higher the adoption rate of PV installations up to 10 kWp (cf. Chapter 5). One explanation is that rooftop systems are mostly installed on (mostly owner-occupied) one- and two-family homes, of which the occupancy correlates positively with higher income. In addition, the installation of such a system involves high initial costs, which are easier to bear for high-income households than for low-income families.

Finally, regional factors are found to have effects on both, the valuation of energy efficiency in real estate sales and rental markets (cf. Chapters 2 and 3), and also on the adoption of residential solar PV systems (cf. Chapter 5). The relative effects of energy efficiency on house prices, estimated with a semi-logarithmic hedonic pricing model, are larger in rural compared to urban areas. Once the effects are estimated in monetary terms using the nonlinear specification, the impact of energy efficiency on both sales prices and basic rents is found to be larger in urban compared to more rural areas. Since house prices and basic rents tend to be higher on average in large cities and urban areas compared to more rural regions, a greater absolute impact may align with a lower relative impact.

Further, spatial spillover effects play a major role in the adoption of residential solar PV systems. Thereby, not only characteristics of the surrounding neighborhoods (e.g., the built environment and the number of large-scale PV installations) have an impact on the expansion, but also endogenous spillover effects as expressed by the autoregressive parameter rho. These include, above all, the expansion and associated visibility of small-scale PV installations in neighboring regions (cf. Chapter 5). Spillover effects, however, decrease with increasing neighborhood sizes with influences peaking at a radius of 8 km.

Some limitations regarding the transferability of results to other countries may arise. The focus of all studies is on Germany, i.e., in particular the different effects of energy efficiency on house prices and rents across subsamples of different EPCs cannot be directly transferred, as this depends on the design of the certificate. Furthermore, the rental sector is much more important in Germany than in many other (European) countries, which means that transferability is limited here as well. It should also be noted that heating costs in Germany are usually paid according to individual consumption and are not included as a lump sum in the warm rent, as is often the case in the USA. Nevertheless, the results of Chapters 2 and 3 are still in line with results from other countries (e.g., Fuerst et al., 2020; Khazal and Sønstebø, 2020).

6.3 Policy implications to help achieving a climate-neutral building stock

[RQ 5] *What policy implications can be derived from the different empirical studies?*

The results of Chapters 3 and 4 suggest that no efficient market for energy efficiency in the German rental housing market emerges. Chapter 2 also points to some inefficiencies in the real estate sales market for single-family homes, as future cost increases due to climate mitigation are not factored into pricing. In both the real estate sales and rental market, the financial incentives for energy-efficiency improvements provided through higher sales prices or basic rents are thus currently often insufficient. Especially in rental markets, the estimated monetary benefit for higher energy efficiency falls well short of the expected energy cost savings. As a result, there is little to no incentive to invest in higher energy efficiency, which is likely to remain the case even as CO_2 prices increase. Without additional incentives and subsidy programs or even legal obligations the energy-related refurbishment rates are therefore unlikely to be sufficient to achieve the German climate-neutrality target.

To minimize inefficiencies, it is important to reduce information asymmetries between tenants and landlords/landladies or buyers and sellers. In this vein, the different valuation of energy efficiency in relation to the types of EPC is a reason to reconsider the design of the certificates. These certificates were originally introduced to reduce information asymmetries between buyers and sellers or tenants and landlords/landladies, but this appears to work to varying degrees with the different designs of the certificates. Since trust in demand certificates appears to be better than in consumption certificates, a standardization of certificates could be explored to address this discrepancy. Additionally, including a measure for the expected heating costs in the real estate advertisement in addition to the energy performance certificates may help to further reduce information asymmetries and increase the willingness-to-pay for higher energy efficiency (cf. Chapter 4).

In addition to improving energy efficiency, installing or switching to sustainable heating technologies can also help to reduce the CO_2 emissions in the building sector. Since results suggest that energy efficiency only plays a minor role as long as inefficient heating technologies are installed (cf. Chapter 3), a focus on heating system replacements (as already implemented in the GEG for a few technologies) should be maintained or even expanded.

Furthermore, it is crucial to consider social inequalities when deriving policy implications. High-income households are generally willing to pay more for energy-efficient rental housing (cf. Chapter 4). However, in the rental sector, lower-income households often reside in less energy-efficient apartments. These apartments, though, are precisely the ones that should receive attention. Instead of providing energy cost subsidies to socially disadvantaged households, one alternative could be to increase rent subsidies based on the energy efficiency rating of the apartment. This approach would allow low-income households to move into more energy-efficient apartments without requiring additional financial assistance. However, attention must be paid to ensuring that inequalities are not further exacerbated and that funds are distributed equitably. A precise design would therefore have to be very well elaborated and is therefore left open for future research.

Implementing such a measure alone may not directly enhance the energy efficiency of apartments. Nonetheless, the decreased demand for inefficient apartments could incentivize more property owners to invest in making their properties more appealing in the market by improving their energy efficiency.

Finally, the expansion of residential solar PV installations for renewable electricity generation can also contribute to the mitigation of CO_2 in the building sector, if the installations are used e.g., for the generation of renewable heat[16]. As inter alia the visibility of large PV installations increases the adoption of small rooftop PV installations (cf. Chapter 5), promoting large-scale (municipal) projects in areas with few installations could positively influence the private development.

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[16] e.g., by combining PV with a battery storage as well as a heat pump.

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OWN CONTRIBUTION

Title: Estimating the Impact of Energy Efficiency on Housing Prices in Germany: Does Regional Disparity matter?

Authors: Lisa Taruttis and Christoph Weber

Contribution: Lisa Taruttis executed the conceptualization, data research, model implementation and model computation and prepared most of the manuscript. Christoph Weber supervised the conceptualization and reviewed and edited the manuscript. Both authors read and approved the final manuscript.

Title: Inefficient Markets for Energy Efficiency – The Efficiency Premium Puzzle in the German Rental Housing Market

Authors: Lisa Sieger and Christoph Weber

Contribution: Lisa Sieger executed the conceptualization, data research, model implementation and model computation. Christoph Weber participated in the interpretation of estimation results and expanded the discussion section. The manuscript was drafted by Lisa Sieger and reviewed and edited by Christoph Weber. Both authors read and approved the final manuscript.

Title: Disentangling Small-Scale Solar Photovoltaic Adoption: A Spatial Analysis of Decision Factors and Localized Interactions in Germany

Authors: Tobias Stein, Lisa Sieger and Christoph Weber

Contribution: Lisa Sieger and Tobias Stein executed the conceptualization and data research. Tobias Stein mainly executed model implementation and model computation. Lisa Sieger prepared large parts of the manuscript. Christoph Weber participated in the conceptualization and interpretation of estimation results. The manuscript was reviewed and edited by all authors. All authors also read and approved the final manuscript.

Title: Investigating Inefficiencies in the German Rental Housing Market: The Impact of Disclosing Total Costs on Energy Efficiency Appreciation

Authors: Lisa Sieger

Contribution: Lisa Sieger is the sole author of this paper.

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ERKLÄRUNG ZUR SELBSTSTÄNDIGEN ANFERTIGUNG

Eidesstattliche Erklärung zu § 14 Abs. 1 Nr. 6

Ich gebe folgende eidesstattliche Erklärung ab:

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbständig ohne unzulässige Hilfe Dritter verfasst, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt und alle wörtlich oder inhaltlich übernommenen Stellen unter der Angabe der Quelle als solche gekennzeichnet habe.

Die Grundsätze für die Sicherung guter wissenschaftlicher Praxis an der Universität Duisburg-Essen sind beachtet worden.

Ich habe die Arbeit keiner anderen Stelle zu Prüfungszwecken vorgelegt.

Bochum, 25.10.2023

Lisa Sieger