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Inefficient markets for energy efficiency – empirical evidence from the German rental housing market

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by

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Abstract

Improving the energy efficiency of residential buildings is of paramount importance to reduce CO_2 emissions and hence to achieve a climate-neutral building stock – the objective of the German government for 2045. Thereby, a focus on the existing building stock is needed, as regulations for new buildings are already quite tight in terms of energy efficiency, and a large proportion of the dwelling stock of 2045 already exists today. For the important segment of rental housing, split incentives are often invoked as an impediment for energy-related investments. Yet this implicitly takes the tenant-landlord relationship as given. On the market where prospective renters meet the dwelling offers, competitive forces and rational behavior on both sides would imply that the monthly net rent should reflect (with opposite sign) differences in expected monthly heating costs – other things being equal. We test this hypothesis by specifying a hedonic price model that reflects this gross-cost-of-renting perspective and applying it on a detailed dataset including dwelling and neighborhood characteristics. As a case study, we use data for the German state of North Rhine-Westphalia, which implies that variations in regulatory and meteorological conditions are small, while large socioeconomic differences across subregions exist (e.g., in terms of purchasing power or unemployment rates). Drawing on 844,229 observations from 2014 to 2020 on a small spatial scale, we find a premium for more efficient apartments; however, it is rather small. The expected energy cost savings exceed the premium by approximately a factor of six. Rather, we find large discounts if apartments use heating technologies that are known to be inefficient. The paper explores various explanations for these outcomes, considering both landlord and renter behavior as well as institutional settings.

Keywords : Energy efficiency; residential buildings; hedonic analysis; rental market

JEL-Classification : C21, Q40, R21, R31

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1. Introduction

Decarbonization of the dwelling stock in order to reduce greenhouse gas emissions is key to achieving the goals implemented in the Climate Protection Act [1]. Since the existing building stock in Germany accounts for a large share of CO_2 emissions and final energy consumption, increasing the refurbishment rates is necessary to achieve a climate-neutral building stock by 2045. This involves investments in energy refurbishments, which can relate to both the building envelope and the installed heating system. Given the large proportion of rented accommodations in Germany, the so-called landlord-tenant dilemma [2,3] arises here. 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 have to pay for refurbishments. Therefore, an investment in energy efficiency is only profitable for landlords, when it can be refinanced through increased net rents.

Nevertheless, there is evidence that investments in energy efficiency are not enough capitalized into rental incomes, so that no incentives are created for landlords to invest [4,5] as long as their flats are still rented out quickly and generate rental income. The newly introduced CO_2 pricing for heating might exacerbate this dilemma, as heating costs are usually borne entirely by tenants and landlords are not affected by higher energy bills. In addition, März et al. [6] 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.

Moreover, the literature to date agrees that a so-called green premium exists – for both ownership and rentals. However, the number of studies that estimate a direct (monetary) rental premium of specific energy efficiency improvements is rather low. Furthermore, to our knowledge, evidence for effects of heating systems on rents is still missing – albeit these are more tangible characteristics than energy efficiency ratings.

We therefore contribute to the existing literature in two ways. First, by investigating the effect of different installed heating technologies on rental offers and second, by estimating what is usually labelled as tenants' WTP for higher energy efficiency in direct monetary terms. Thereby, we additionally provide an energy multiplier that shows rental benefits per 1€ reduction in energy costs, depending on the actual energy price for heating. The latter allows for a discussion of this so-called tenants' WTP in view of rising energy prices. We follow the established convention (cf. e.g. [6,7]) to use the term WTP for the estimated rental price effects of energy efficiency although we use offer data. Under the assumption of efficient information processing in the markets and in the absence of other market distortions, this may be justified. Yet given our empirical findings, we come to question this efficiency hypothesis. Consequently, we also contribute to the research in the field by discussing various explanations for the observed discrepancies, considering both landlord and tenant behavior as well as institutional settings.

This study draws on a cross-sectional dataset from 2014 to 2020 with 844,229 observations for North Rhine-Westphalia (NRW) – the most populated state in Germany with considerable differences in population structure. Data is georeferenced at a 1km² grid level which enables us to control for small-scale differences in neighborhood structure. We use a traditional hedonic pricing model that aligns with a total-cost-of-use (TCU) perspective and is estimated via nonlinear least squares. It allows us to compare our estimates with engineering-economics findings of cost savings.

The reminder of this paper is as follows. Section 2 provides related literature in this field of energy and real estate economics. Section 3 gives background information on regulatory aspects in the German residential rental market and also focuses on split incentives (i.e., the so-called landlord-tenant dilemma) in relation to the newly introduced CO_2 tax. Finally, a short description of why we use NRW as a case study is given here. Section 4 then describes our empirical approach, followed by Section 5 that provides information about our data used. Sections 6 and 7 show and discuss empirical results while Section 8 concludes.

2. Previous research

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 [8] or estimate impacts based on the energy efficiency rating[1] or on the energy performance score (EPS) of the dwelling [9]. Thereby, they address different mandatory or voluntary energy labels, e.g. the Energy Performance Certificate (EPC) [10] that is mandatory in Europe, the Energy Star [11] that is voluntarily used mainly in the USA, the optional Green Mark Program [12] in Singapore, as well as LEED [13] and BREEAM [14] that are both also voluntarily used worldwide.

Many studies focus on owner-occupied dwellings [15] or private rental buildings[2] [16], but there are also studies on office buildings [17,18] and affordable housing [19]. Results are available for various countries, inter alia USA [20], Germany [21], England [10] and Ireland [22,23], Sweden [24], Finland [25] and Denmark [26], the Netherlands [8], Spain [27,28], Italy [29], Japan [30,31] and Australia [32]. All studies find positive effects on housing prices of up to 10%. Contrary to these studies, Olaussen et al. [33] and Wahlström [34] only find small or negligible effects of the label itself on prices, but also state that sustainable housing attributes have positive price impacts. For a more detailed comparison of studies on effects of energy efficiency on sales prices, see Cespedes-Lopez et al. [35], Wilkinson and Sayce [36], as well as Copiello and Donati [37].

Evidence for energy-efficiency effects on rents or rental income, respectively, can also be found in the extant literature, although not as frequently. Hyland et al. [22] were 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 [38] report results in a same range for the German residential market. Further, in a similar framework, Kholodilin et al. [7] also find that energy efficiency is capitalized into rents in the Berlin housing market. In a more recent study, März et al. [6] 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.

Further, Fuerst et al. [39] examine the residential market in the UK and find that B-rated and C-rated units are rented out at a premium of 4% and 3% to 5%, respectively, both compared to D-rated apartments (on a scale from A to G). Cajias et al. [40], however, report smaller effects for the German residential market with an expected rent premium of 1.4% for A-rated apartments

[1] E.g., on a scale from A to G.
[2] Houses, which are directly sold as ready-to-let.

compared to D-rated units (on a scale from A+ to H). Both studies additionally investigate the relationship between energy efficiency and time-on market and find a negative correlation.

Moreover, setting the focus on the disclosure of EPCs, Dressler and Cornago [41] as well as Bian and Fabra [42] report positive effects of energy efficiency on rents for the Brussels and Spanish residential rental market, respectively. They further show that there are penalties for average energy-efficient dwellings when EPCs are not disclosed in advertisements.

Contrarily to most studies, Feige et al. [43] report an unexpected negative relationship between energy efficiency ratings and rental prices for the Swiss residential market. However, they mainly focus on investigating effects of building's individual sustainability attributes on rents rather than effects of labels or the EPS and still find that there is a positive link between rental levels and environmental performance of the building.

In a similar framework, Im et al. [44] focus on evaluating the adoption of different energy-efficient upgrades in U.S. residential buildings (both single-family homes and multi-family buildings) and its impact on rents. Using propensity score matching and conditional mean comparison methods, they find relative impacts on rental prices of 6% to 14.1%, depending on location and type of building. However, evidence is not clear regarding the relationship between the height of the premium and the capital investment needed for the respective efficiency measure.

A more recent work of Khazal and Sønstebø [45] examines the residential rental market in Norway. By applying a hedonic multilevel approach on information from about 400,000 rental contracts, the authors find that green apartments are rented out at a premium of 3.3% compared to non-green units. This effect increases with higher EPC bands. They additionally distinguish between professional and nonprofessional lessors and report that the first assign higher rents compared to the latter.

Overall, most studies agree that there is a rent premium for efficient buildings. However, since the relative impact appears to be rather small, the question arises whether investments in energy retrofits are profitable for landlords, as their tenants take the advantage of lower energy bills[3]. According to Ambrose [4] and Hope and Booth [5], inter alia the lack of direct financial incentives deter private landlords from investing in energy efficiency measures.

We therefore add to the extant literature by estimating an energy multiplier that shows direct monetary benefits per one euro decrease in yearly energy costs. Thus, we can directly compare energy cost savings for tenants with rental premiums for landlords. This multiplier further depends on the energy price for heating so that effects that are caused due to price changes can be discussed. Moreover, studies that investigate the impact of different heating technologies on rents are scarce and, to our knowledge, only exist for the real estate sales market (cf. [46,47]). By taking these into account, we also contribute to the literature.

Further, on the market where prospective renters meet the dwelling offers, competitive forces and rational behavior on both sides would imply that the monthly net rent should reflect (with opposite sign) differences in expected monthly heating costs – other things being equal. Since this does not appear to be the case, these results point to inefficient markets for energy efficiency. By discussing different channels for these inefficiencies, we contribute significantly to the existing literature as well.

[3] At least in a framework, where tenants pay the energy bills (which is the case in Germany).

3. The German residential rental sector, regulatory aspects, and the landlord-tenant dilemma

3.1 The residential rental market in Germany

Germany has the lowest home ownership rate and thus the largest proportion of tenants among all EU countries [48]. According to the sample survey of income and expenditure (EVS) 2018, around 57.9% of all households in Germany live in rented accommodations with an average living space of 70.5m^2 per household [49].

Overall, Germany has about 19.8 million residential rental apartments. More than half of these dwellings use gas as primary source for heating, followed by district heating with about 22% and oil by 18%. At least 4% have electric heating and the remaining share is accounted for by other, both fossil and renewable energy sources [50, table 12]. Of all inhabited rental apartments, about 58% are being rented out by private owners; 23% are let by housing and building cooperatives, 15% by private companies and about 4% by public institutions [50, table 8].

The average rent burden ratio[4] in Germany is 27.2% of net household income [50, table 19]; however, this strongly varies across regions. In large cities, about 40% of households face a rent burden ratio of more than 30% of their net household income [51] which is generally considered to be problematic, because this leaves relatively little money available for other living expenses, especially for people with lower incomes [52].

3.2 Rent increases in view of modernizations and the standard local comparative rent

The German residential rental market has always been subject to various price regulations. Following the recent increases in dwelling sales prices and rents, additional regulations have been introduced since 2019 aiming mostly at the protection of tenants with existing rental contracts. Therefore, when it comes to investments in retrofits, landlords are not permitted to pass on the costs of refurbishments in full to their current tenants. After a completed modernization corresponding to the terms of paragraph 559 of the German Civil Code (BGB), landlords may increase the annual rent by up to 8% of the costs incurred.

In addition, irrespective of the actual amount of the modernization costs, rents may not be increased by more than €3 per square meter of living space within a six-year period if the initial rent was higher than €7 per square meter, otherwise the maximum increase is €2. If landlords carry out several smaller modernizations in the near future, for each of which they claim a modernization rent increase, they must offset the costs that have already been claimed within a five-year period (BGB, Section 559c) [53]. Furthermore, 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; rent increases after modernization are yet not linked to these rent adjustments to the local reference level.

The above rules for an existing tenancy are overridden in case of a new tenancy, as a completely new leasing agreement is concluded. The landlords are free to set the new rent to any level they deem appropriate. The price does not directly have to be based on the local rent index or the comparative rent but can theoretically be negotiated with the tenant at will. Also, no

[4] gross (cold) rents/net household income.

redevelopment, modernization or renovation work is necessary to increase rents. The only limitation to pricing is that the apartment may not exceed rents of equivalent properties in the close neighborhood by more than 20%.

3.3 Consumption-based energy bills, CO_2 pricing and the landlord-tenant dilemma

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 net 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. Additional heating costs due to this CO_2 tax are to be borne 100% by tenants. This may result in significant disadvantages for tenants in apartments with oil (and gas) heating compared to apartments with better energy performance and 'greener' heating alternatives. Landlords, however, will again have no direct incentives to replace old heating systems with more sustainable ones, as they will not suffer any disadvantage as a result of this CO_2 tax by passing the costs on to their tenants [54].

Therefore, it is likely that this newly introduced CO_2 pricing mechanism will enforce the so-called landlord-tenant dilemma (cf. [2,55]). It describes the circumstance in rental markets that energy-saving investments are not made because landlords cannot achieve a long-term return on their investments, while tenants would benefit from the energy savings achieved through the renovation. Landlords thus base their willingness-to-invest in energy efficiency on achievable rental values which are net of utility costs as these are also (typically) covered by tenants.

3.4 Consumption-based vs. demand-based energy performance certificates

To be able to evaluate the energy condition of buildings, the Building Energy Act (GEG) prescribes energy certificates in most cases. They contain general information about the house, the heating fuels used, and the building's energy characteristics. Newer certificates for residential buildings also list an energy efficiency class from A+ to H, similar to electrical appliances.

In Germany, there are two types of EPCs – demand certificate (*Bedarfsausweis*) and consumption certificate (*Verbrauchsausweis*). Due to different calculation methods, both types evaluate energy efficiency of a building differently. 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. [21]). According to the German Consumer Association, the final energy consumption indicated in demand certificates is about 25% higher than in consumption certificates [56].

In case of the demand certificate, characteristic values for energy demand are determined mathematically based on year of construction, building documents (building type, address, number of apartments and total living space), technical building and heating data and under standardized framework conditions (climate data, user behavior, room temperature). Calculated values are therefore independent of individual heating and living behavior of tenants but are strongly dependent on how precisely and elaborately the person issuing the certificate collects the data.

The consumption certificate requires consumption data for the last three years. Characteristic values for energy consumption of the entire building are then determined from heating cost bills or other suitable consumption measurements and are converted accordingly to a Germany-wide average value using climate factors so that, for example, particularly harsh winters do not lead to a worse rating of the building. With this method, data collection is usually much simpler and less prone to error. However, characteristic values now heavily depend on individual heating or ventilation behavior of former tenants.

3.5 Case study: North Rhine-Westphalia

North Rhine-Westphalia (NRW) is the most populated state in Germany with about 17.4 million inhabitants. Accordingly, it has the highest number of existing buildings [57]. In NRW, we predominantly find urban areas and very densely populated cities, such as the Ruhr region, Dusseldorf, and Cologne. According to the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), only two districts can be described as densely populated and none as sparsely populated rural areas (see Figure A 1) [58].

These urban structures and high population densities favor rental housing. This is also reflected in the homeownership rate, which is lower than the Germany average [59]. In terms of vacancy rates, NRW is at a similar level to national average at 8.1% [60] and the rent burden ratio is also only one percentage point above national level at 28.2% [61]. Therefore, NRW is suitable as a case study to investigate effects of energy efficiency on rents. Further, by looking at one federal state only, we limit the occurrence of weather and climate inequalities.

4. Research Approach

Our empirical strategy follows the hedonic pricing approach in sense of Lancaster [62] and Rosen [63] to explicitly investigate effects of energy efficiency as well as effects of different heating technologies on rents while controlling for other building and neighborhood characteristics. In addition, we combine this hedonic approach with a total-cost-of-use (TCU) framework (cf. [64]) 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 (i.e., gross rent) in (informationally) efficient markets rather than being a hedonic attribute affecting the net rent. The total cost of renting a property for the tenant generally equals the sum of net rent and auxiliary costs that cover heating and other utility costs, e.g., garbage disposal, road cleaning and maintenance, 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.[5] Other auxiliary costs are neither adjustable by landlords nor by tenants, which is why we focus on heating costs and net rents only. The expected total costs can then be written as:

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

Net 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 willingness to pay per unit of improvement of energy efficiency directly corresponds to the energy price[6]. 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 willingness to pay on the net rent - other things being equivalent. Consequently, under these perfect information assumptions, energy efficiency investments are profitable for landlords if the savings in energy costs provide a sufficient payback.

In order 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*:

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

The left-hand side of Eq. (2) now directly reflects that energy consumption contributes linearly to the total costs for renting 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 an apartment of given characteristics $\boldsymbol{X}_i$ and $\boldsymbol{N}_{nt}$. We rearrange terms in Eq. (2) to obtain the monthly net rent, measured in euro per square meter of living space, as dependent variable on the left-hand side and estimate Eq. (3) using nonlinear least squares:

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

EPS_i is the main explanatory variable of interest and gives the energy consumption for heating in 10kWh/m^{2}a of apartment *i*. Heating type information are included in vector $\boldsymbol{X}_i$. This vector also contains various hedonic characteristics, such as living space, 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., population density and purchasing power per capita. The full set of (control) variables included in our regression is given by Table 1.

[5] 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.
[6] In case of full information.

Table 1 Overview of variables included in our regression

Variable	Description	Unit/Values
$\boldsymbol{Rent_{indt}}$	monthly net rent of apartment *i* in neighborhood *n* and district *d* at time *t*	€/m²
$\boldsymbol{EPS_i}$	Energy consumption for heating	10 kWh/m²a
contained in vector $\boldsymbol{X_i}$		
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*	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
LIVINGSPACE	Factor variable, indicating the living space of apartment *i*	10 m² steps, starting at 20; Ref. = 60 to 70 m²
MOD2000	Dummy variable, indicating whether apartment *I* was renovated in 2000 or later	yes, no (Ref)
contained in vector $\boldsymbol{N_{nt}}$		
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	%
$\boldsymbol{\tau_d}$	Regional fixed effects on NUTS3 level	53 NUTS3 regions in total; Ref. = DUS
$\boldsymbol{\mu_t}$	Time fixed effects on quarterly-year level	27 Time periods in total from Q3/2014 to Q4/2020; Ref. = Q1/2015

Authors' illustration.

To control for omitted variable bias, we add regional fixed effects τ_d on NUTS3-level, which is equivalent to counties[7] in North Rhine-Westphalia, and seasonal (i.e., quarterly-year) 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 ([66]).

The coefficient β is expected to be positive because the lowering impact of energy consumption on rents is already included in the negative sign after rearrangement. Interpretation is straight forward: if energy consumption decreases – and energy efficiency thus increases – by 10kWh/m²a, the monthly net rent increases by β euro per square meter. The relative impact of a specific heating technology on rents compared to apartments with gas heating is given by approximately $100 \cdot \gamma_{heating}$ %.

We start our analysis by estimating a baseline model in which we include only our main variable of interest as well as all hedonic characteristics, first without and then with the installed heating technology indicator. Next, we gradually add neighborhood characteristics as well as seasonal and 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. Since energy consumption varies by EPC types, we additionally run subsample regressions to control for these differences.

Finally, we calculate an energy multiplier M_e as given by Eq. (4) to easily compare rental premiums with energy cost savings and corresponding investment costs that are required to achieve a specific level of energy efficiency. Our multiplier describes the monetary increase in yearly net rents per €1 decrease in annual energy costs given that the EPS is measured in annual energy consumption 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.

$$M_e = \frac{12 \times \beta}{P_e} \; [a] \tag{4}$$

As there is evidence that effects may differ across regions (cf. [6,21,65]), we furthermore estimate subsample regressions according to pre-defined district types (cf. Figure A 1), focusing on large cities and urban areas, as well as for the Ruhr region, in contrast to other regions in NRW.

5. 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* [66], provides micro-level information on asking rents of apartments advertised on the internet platform *ImmobilienScout24.de*. It contains information on a variety of apartment characteristics such as living space, type, and condition of the apartment, and features like having a garden, balcony, or kitchen. Georeferencing is provided in terms of 1km² grids and NUTS3 regions.

[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.

Some limitations arise with this dataset. First, it only shows asking rents; however, they are often in line with final transaction prices (cf. [67,68]). Second, given asking rents only reflect the distribution of advertised rents that households encounter when looking for a rental apartment via digital apartment ads on ImmobilienScout24. Rents from existing tenancies are not captured by this data source. Third, data is dependent on owners' accuracy and honesty in presentation and description of the apartments. Fourth, there could be a self-selection bias towards private providers or younger users, as elderly people are sometimes not familiar with internet platforms [69]. Therefore, results might be underestimated, as private lessors are likely to assign lower rents (cf. [45])

The second dataset, *RWI-GEO-GRID* [70], offers socio-economic characteristics such as population density, purchasing power, and unemployment rate, compiled at the level of 1km^2 grids. The data originates from *microm Micromarketing-Systeme und Consult GmbH*, a market research company specializing in regional analysis [71]. The third database, *INKAR* [58], is provided by the *Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR)* and gives an indicator for different regional types according to their settlement structure on NUTS3-level.

5.1 Data processing

Initially, we cleared the real estate data from duplicates[8] and further filtered it the following way. First, advertisements that do not have information about net rent, living space and georeference were removed. Second, dwellings with a stated energy consumption below 5kWh/m^{2}a, and buildings younger than ten years (measured from the year of advertisement) were excluded. Third, outliers based on 1st and 99th percentiles of net rent per m^2, living space and energy consumption for each year were also removed. Furthermore, we focus on existing apartments built no earlier than 1900. Lastly, we exclude advertisements that were online for more than one year (365 days), had no hits or missing information about number of rooms[9].

For all hedonic characteristics, we add dummy or factor variables for each level (see Table 1) to account for nonlinearities and add the level "unknown" to not lose too many observations. We relevel all variables to mean or median level, so that all factors can be interpreted in contrast to apartments with mean or median values. After clearing the real estate data, socio-economic data was merged with a one-year lag. Grids with no information[10] on population density or purchasing power were removed in advance. Lastly, before analyzing, we apply a cook's distance filter with cutoff 4/N.

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 [74] – this is the date from which energy performance certificates must be mandatorily disclosed 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.

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[8] We used the indicator for duplicated objects that was included in the dataset as generated by RWI. For further information see [72,73].

[9] Only 9 observations.

[10] Due to data security reasons, grids with less than 10 inhabitants or less than 5 households are anonymized. Moreover, there are also uninhabited grids, for example through large bodies of water or forest areas.

5.2 Descriptive Statistics

Table 2 gives an overview of descriptive statistics for all numeric variables; information on absolute and percentage values for all factor variables included in our model are given in the appendix (see Table A 1). Apartments are rented for an average of €6.92 per square meter living space with a standard deviation of €1.91 and a maximum of €19.00, both per square meter. Mean energy consumption of 140kWh/m²a corresponds to E-labeled apartments on a scale from A+ to H; however, even the most efficient apartment advertised for rent can only be assigned to an A-label. The least efficient apartment, nevertheless, corresponds to an H-label.

Mean age of advertised apartments is 56; minimum and maximum are given at 10 and 120 years, respectively, due to data restrictions. Furthermore, the average apartment has a living space of 67m² and is probably rented out after being online for 25 days. Roughly 60% of all apartments in our dataset have a balcony; information is missing for about 8.5%. Contrary, only 14.4% of all apartments come with a garden and approximately 13.5% have a built-in kitchen. The majority has two or three rooms and is in buildings with up to three floors. Additionally, about 22% of all apartments in our dataset were modernized in 2000 or later.

Population density is given per 1km² grid cell and amounts to 4,804 on average. The maximum of 20,165 can thus be explained by the grid structure – the area of uninhabited grids due to large forest or water areas is not considered when calculating population density. Accordingly, unemployment rate, share of households with a foreign household head, as well as purchasing power per capita are also given at the 1km² grid level. The latter amounts to a median of about €21,000, with a minimum of €10,400 and a maximum of €46,600. Average unemployment rate is 10% and the share of foreign-headed households averages 14.6%.

Table 2 Descriptive statistics, full dataset

Variable	Unit	Mean	St. Dev.	Min	Max	Median
Net rent	€/m²	6.92	1.91	3.85	19.00	6.47
Energy consumption	kWh/m²a	140	47	42	320	134
Living space	m²	67	20	23	152	65
Age	years	56	22	10	120	56
Duration of advertisement	days	25	32	1	365	15
Population density	inh/km²	4,804	3,404	16	20,165	4,037
Unemployment rate	%	10.02	4.64	0.00	26.29	9.82
Share of households with foreign household head	%	14.63	7.54	0.00	77.09	13.69
Purchasing power per capita	€/inh	21,623.39	3,946.62	10,416.77	45,564.72	20,925.66

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

The distribution of offers and corresponding average net rents per square meter living space across NRW on grid level over time is shown in Figure 1. First, it is noticeable that offers are predominantly found in the Ruhr region as well as on the "Rhine line" from Dusseldorf over Cologne to Bonn, and around Münster in the northern part of NRW. The second observation is that average net rents increased overall between 2016 and 2020. Highest average net rents can mainly be found in the southern half of NRW, whereas the lowest ones appear in the Ruhr region and more rural areas.

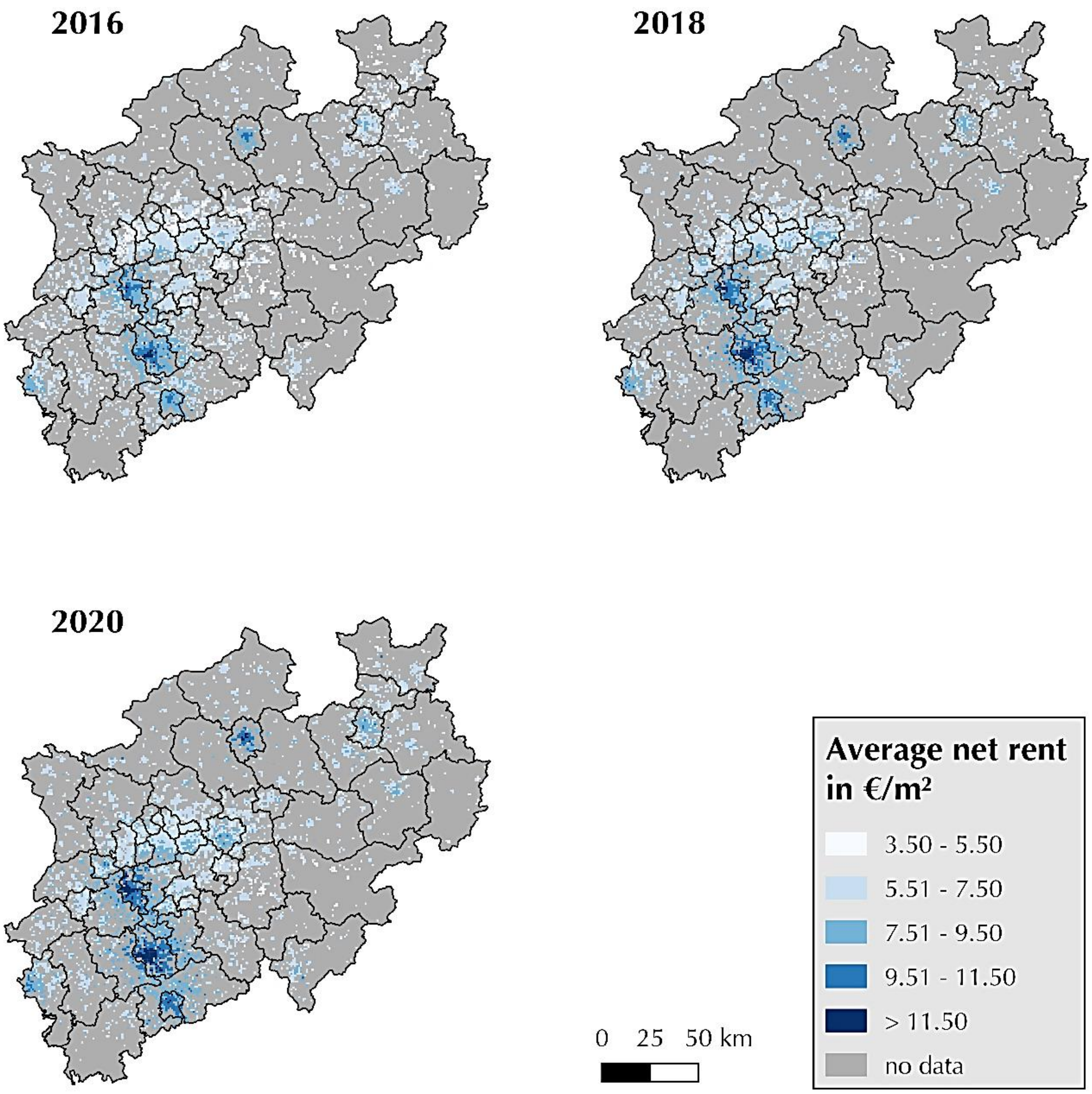

Figure 1 Average net rent per square meter living space on grid level over time
Authors' calculation and illustration based on RWI-GEO-RED. Map Data: @GeoBasis-de/BKG 2019.

To additionally evaluate differences across regions, Table 3 shows summary statistics for the Ruhr region compared to other districts, with Dusseldorf and Cologne (DUS/CGN) being reported separately. About 6% of all observations can be attributed to DUS/CGN; the rest is evenly distributed over the Ruhr region and all other districts, although the first is much smaller in terms of area. Overall, the Ruhr region shows lowest average net rent and living space, as well as the oldest average building age. Only in terms of energy consumption, there are no great differences across regions.

Table 3 Main characteristics across regions – mean values (Std. Dev. in parenthesis)

Variable	Ruhr region		Others*		DUS/CGN	
No. of obs.	399,064		393,280		51,885	
%	47.27		46.58		6.15	
Net rent	6.10	(1.16)	7.33	(1.96)	10.10	(1.86)
Energy consumption	142	(48)	139	(47)	142	(46)
Living space	65	(17)	70	(21)	69	(24)
Age	60	(21)	52	(22)	56	(23)
Population density	4,662	(2,724)	4,524	(3,535)	8,034	(5,056)
Unemployment rate	11.98	(4.25)	8.24	(4.21)	8.36	(4.50)
Share of households with foreign household head	14.86	(7.76)	13.85	(7.09)	18.70	(7.67)
Purchasing power per capita	19,899.44	(2,9724.26)	22,814.82	(3,862.22)	25,851.97	(4,548.66)

Note: *Others include all districts that are neither Dusseldorf or Cologne, nor are assigned to the Ruhr region. Authors' calculations based on RWI-GEO-GRID and RWI-GEO-RED.

As illustrated in Figure 1, the average net rent is highest in DUS/CGN with €10.10 per square meter; the other regions are approximately on NRW level. This pattern is also reflected in the average purchasing power per capita. With under €20,000 per inhabitant, it is lowest in the Ruhr region and highest in DUS/CGN with almost €26,000 per capita. Population density per 1km² grid cell is also highest in the latter and amounts to 8,034 inhabitants.

Summary statistics across different regional types according to INKAR are given in Table A 2. Roughly 64.5% of advertised apartments are in large cities, about 35% in urban areas. The last 0.5% can be found in densely populated rural areas; however, there are only two districts in NRW defined as rural. Differences across regions arise in terms of almost all numeric variables. Sorting from large cities over urban areas to rural areas, the average rental apartment becomes larger, cheaper, and more efficient. However, advertisements also stay online for about 5 to 7 days longer on average. The youngest apartments can be found in urban areas; on average, they are built about 10 years later than in large cities.

Tables 2 and 3 demonstrate that there are large variations in all socioeconomic characteristics at grid level. To further illustrate these variations and show the distribution across NRW, Figure 2 shows the population density per 1km² grid cell for 2018. Purchasing power per capita on grid level is illustrated in Figure A 2. DUS/CGN as well as most large cities located in the Ruhr region have high population densities. Furthermore, urban centers and agglomerations can be clearly identified. When comparing Figures 1 and 2, overlaps can be spotted in the grid cells: Rentals are found primarily where population densities are high.

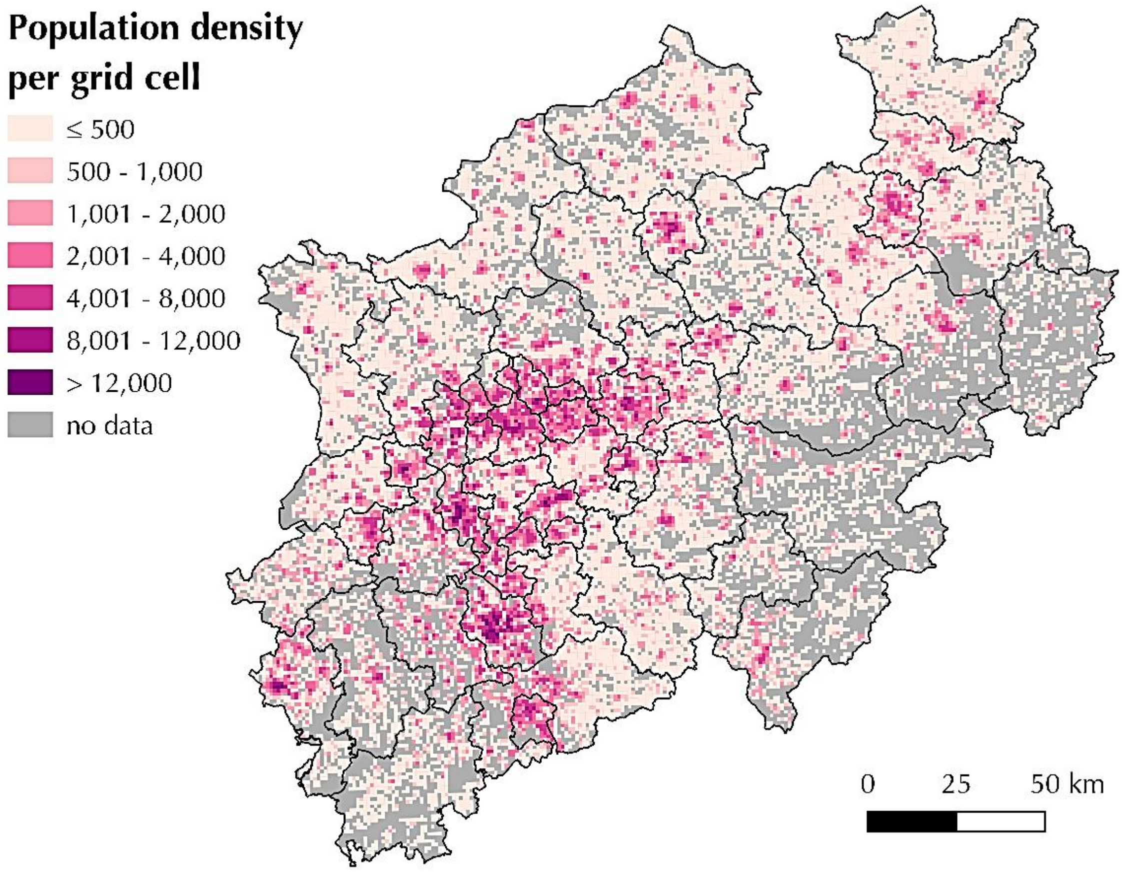

Figure 2 Population density per 1 km² grid cell (2018)
Authors' calculation and illustration based on RWI-GEO-GRID. Map Data: @GeoBasis-de/BKG 2019.

As we are not only interested in effects of energy efficiency on net rents but also in impacts of the implemented heating technology, Figure 3 illustrates percentages of different heating technologies with corresponding mean energy consumption and mean age of the apartment. More than half of all advertised apartments have a central heating system. One limitation of our dataset arises here, as we cannot distinguish, whether these systems have gas, oil, or district heating as main energy source. The same holds for self-contained central heating (SCC) systems, which are implemented in 12.7% of all advertised dwellings. Gas and district heating follow with slightly below 6% each. For roughly 135,600 apartments, no information on the heating system is given.

Heating by stove and SCC are by far the most inefficient technologies in our sample with mean energy consumptions of 158kWh/m²a or 155kWh/m²a, respectively. Oil heating follows with 149kWh/m²a. With an average energy consumption of only 92kWh/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.

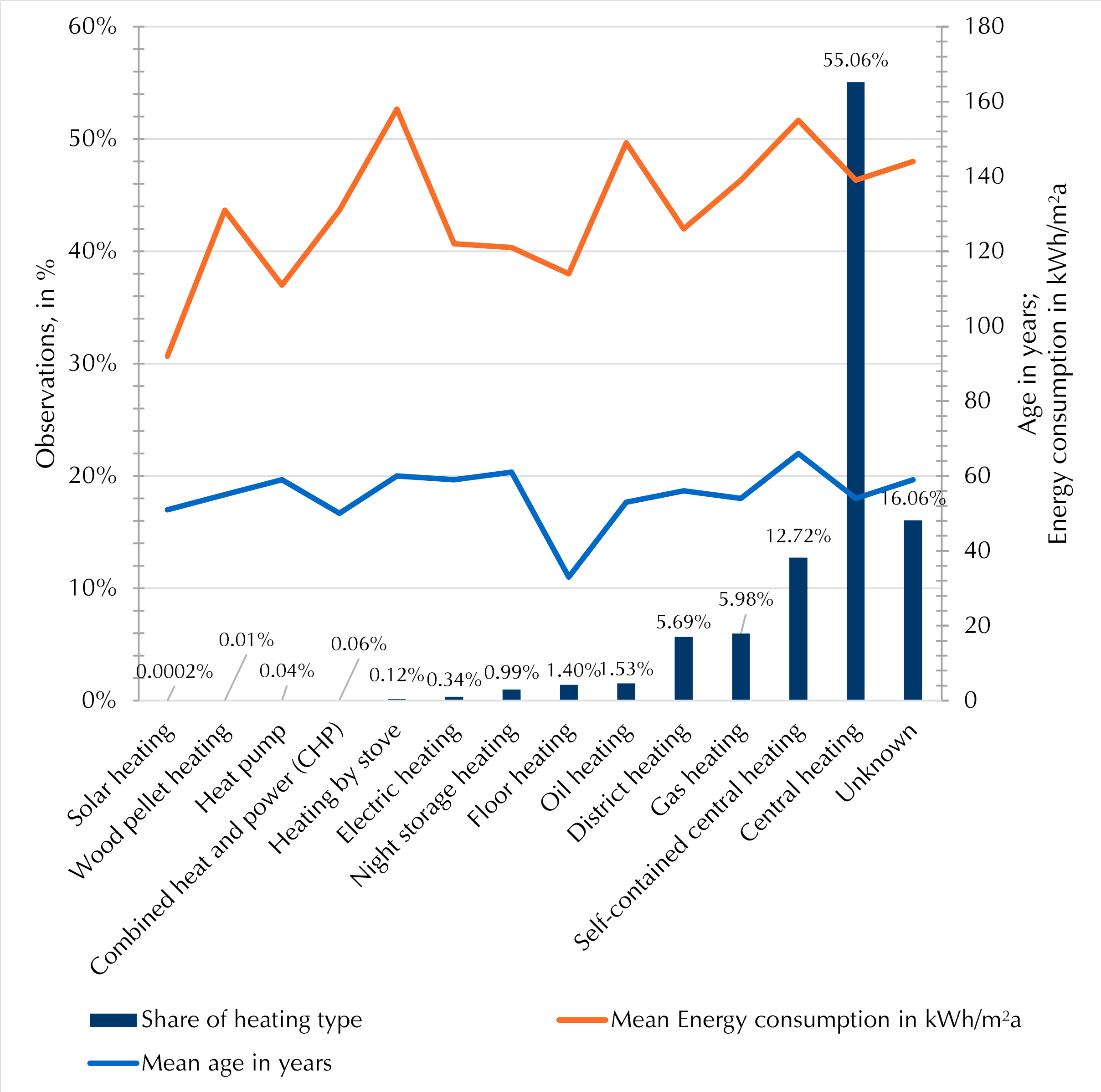

Figure 3 Percentages of heating technologies with mean energy consumption and age
Authors' calculations based on RWI-GEO-RED.

Finally, a distinction between apartments with demand certificates in contrast to apartments with consumption certificates is needed, as this is indirectly correlated with the given EPS (cf. Section 3). Summary statistics are given in Table 4. 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 space and advertisement duration. Moreover, the difference in average net rents per square meter between subsamples only amounts to €0.14.

Nonetheless, apartments with demand certificates are, on average, 4 years older and the mean EPS is 14kWh/m²a higher compared to apartments in the subsample of consumption certificates. Nevertheless, these differences in energy consumption only amount to about 10% and are therefore not as large as indicated by the German Consumer Association in [56].

Table 4 Summary statistics for EPC subsamples

Variable	No. of obs.	Mean	St. Dev.	Min	Max	Median
Demand certificate						
Net rent	240,545	7.02	1.89	3.85	19.00	6.58
Energy consumption	240,545	150	57	42	320	143
Living space	240,545	68	20	23	152	66
Age	240,545	59	21	10	120	58
Duration of advertisement	240,545	25	33	1	365	15
Consumption certificate						
Net rent	603,684	6.88	1.92	3.85	19.00	6.40
Energy consumption	603,684	136	42	43	320	132
Living space	603,684	67	20	23	152	65
Age	603,684	55	23	10	120	55
Duration of advertisement	603,684	25	32	1	365	15

Authors' calculations based on RWI-GEO-RED.

6. Results

6.1 Main regression analysis

Regression results for our model as denoted by Eq. (1) are given in Table 5. Column (1) shows the baseline specification without any fixed effects, neighborhood characteristics as well as energy-related controls other than energy consumption. A factor variable indicating the installed heating system is added in column (2) and 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; asterisks indicate significance at the 0.1/1/5-percent level, respectively.

If energy consumption decreases by 10kWh/m^{2}a, the monthly net rent increases, on average, by roughly €0.01 per square meter living space. These results do not vary much between different specifications as estimates marginally increase when including other energy-related variables as well as neighborhood characteristics and decrease again slightly below €0.01 when including fixed effects. However, the difference in effects between baseline specification in column (1) and full model in column (5) only amounts to Δ€0.0005. Results are significant at the 0.1%-level in all specifications.

Impacts of different heating technologies compared to gas heating as reference are more 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. Further, apartments with self-contained central heating or heat pumps as well as those with no information about the installed heating system 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%, 2.7% or 0.9%, respectively.

Table 5 Main estimation results

Dependent Var.:	NLS				
Net rent in €/m²	(1)	(2)	(3)	(4)	(5)
Energy consumption	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]
Unknown		-0.0498 ***	-0.0324 ***	-0.0257 ***	-0.0085 ***
		[0.0013]	[0.0010]	[0.0010]	[0.0008]
Last renovated in	0.0035 ***	0.0015 *	0.0018 **	0.0146 ***	0.0137 ***
2000 or later	[0.0008]	[0.0008]	[0.0006]	[0.0006]	[0.0004]
Apartment type, reference: flat					
Attic flat	-0.0251 ***	-0.0255 ***	-0.0175 ***	-0.0165 ***	-0.0134 ***
	[0.0008]	[0.0008]	[0.0006]	[0.0006]	[0.0005]
Raised ground floor	0.0621 ***	0.0624 ***	0.0268 ***	0.0269 ***	0.0123 ***
	[0.0023]	[0.0023]	[0.0017]	[0.0017]	[0.0012]
Maisonette	-0.0096	-0.0044	0.0376 ***	0.0358 ***	0.0578 ***
	[0.0116]	[0.0115]	[0.0074]	[0.0069]	[0.0035]
Penthouse	0.0357 ***	0.0347 ***	0.0267 ***	0.0284 ***	0.0200 ***
	[0.0017]	[0.0016]	[0.0012]	[0.0012]	[0.0009]
Souterrain	0.0393 ***	0.0380 ***	0.0581 ***	0.0567 ***	0.0566 ***
	[0.0059]	[0.0059]	[0.0038]	[0.0036]	[0.0023]
With terrace	0.0120 ***	0.0144 ***	0.0105 ***	0.0021	0.0049 **
	[0.0032]	[0.0032]	[0.0023]	[0.0023]	[0.0016]
Other	-0.0224 ***	-0.0243 ***	-0.0510 ***	-0.0507 ***	-0.0515 ***
	[0.0030]	[0.0029]	[0.0022]	[0.0022]	[0.0016]
Unknown	-0.0199 ***	-0.0108 ***	0.0022 ***	0.0046 ***	0.0067 ***
	[0.0006]	[0.0006]	[0.0005]	[0.0005]	[0.0004]

(Continued on next page)

Table 5 continued

Dependent Var.:	NLS				
Net rent in €/m²	(1)	(2)	(3)	(4)	(5)
Facilities, reference: normal					
Simple	-0.0924 ***	-0.0933 ***	-0.0942 ***	-0.0867 ***	-0.0445 ***
	[0.0026]	[0.0026]	[0.0021]	[0.0021]	[0.0014]
Sophisticated	0.1256 ***	0.1242 ***	0.0821 ***	0.0831 ***	0.0779 ***
	[0.0009]	[0.0009]	[0.0007]	[0.0007]	[0.0005]
Deluxe	0.2290 ***	0.2257 ***	0.1623 ***	0.1626 ***	0.1628 ***
	[0.0037]	[0.0037]	[0.0026]	[0.0025]	[0.0018]
Unknown	0.0208 ***	0.0258 ***	0.0248 ***	0.0291 ***	0.0247 ***
	[0.0007]	[0.0007]	[0.0006]	[0.0006]	[0.0004]
Condition, reference: well kept					
1st Occupancy after reconstruction	0.1320 ***	0.1341 ***	0.1038 ***	0.1003 ***	0.0900 ***
	[0.0015]	[0.0015]	[0.0011]	[0.0011]	[0.0008]
Like new	0.0405 ***	0.0394 ***	0.0435 ***	0.0429 ***	0.0445 ***
	[0.0016]	[0.0016]	[0.0012]	[0.0011]	[0.0009]
Reconstructed	0.0946 ***	0.0946 ***	0.0679 ***	0.0637 ***	0.0481 ***
	[0.0017]	[0.0017]	[0.0013]	[0.0013]	[0.0010]
Modernized	0.0373 ***	0.0372 ***	0.0273 ***	0.0223 ***	0.0210 ***
	[0.0011]	[0.0011]	[0.0009]	[0.0008]	[0.0007]
Completely renovated	0.0627 ***	0.0626 ***	0.0346 ***	0.0343 ***	0.0284 ***
	[0.0010]	[0.0010]	[0.0007]	[0.0007]	[0.0006]
Needs renovation	-0.0350 ***	-0.0325 ***	-0.0348 ***	-0.0333 ***	-0.0406 ***
	[0.0028]	[0.0028]	[0.0022]	[0.0021]	[0.0015]
By arrangement	-0.0245 ***	-0.0255 ***	-0.0307 ***	-0.0252 ***	-0.0234 ***
	[0.0028]	[0.0028]	[0.0021]	[0.0020]	[0.0015]
Unknown	-0.0301 ***	-0.0195 ***	0.0006	0.0019 **	0.0010 *
	[0.0008]	[0.0008]	[0.0006]	[0.0006]	[0.0005]
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 w/ foreign head			0.0102 ***	0.0088 ***	0.0017 ***
			[4.24e-06]	[3.74e-05]	[3.36e-05]
Constant	1.8270 ***	1.8191 ***	-7.3496 ***	-7.7966 ***	-1.8700 ***
	[0.0015]	[0.0018]	[0.0215]	[0.0209]	[0.0229]
Controls for ___ included?					
Balcony, Garden, Kitchen	*yes*	*yes*	*yes*	*yes*	*yes*
No. of rooms, floors	*yes*	*yes*	*yes*	*yes*	*yes*
Living space	*yes*	*yes*	*yes*	*yes*	*yes*
Construction period	*yes*	*yes*	*yes*	*yes*	*yes*
Fixed Effects included?					
Time (quarterly year)	*no*	*no*	*no*	*yes*	*yes*
Region (NUTS3)	*no*	*no*	*no*	*no*	*yes*
Convergence tolerance	8.98e-06	3.88e-07	1.14e-06	7.04e-07	9.17e-06
RMSE	1.594	1.583	1.190	1.152	0.888
Log-Likelihood	-1,591,555.92	-1,585,443.44	-1,344,405.44	-1,317,353.22	-1,097,605.66
AIC	3,183,233.83	3,171,034.88	2,688,966.89	2,634,914.43	2,195,523.32
BIC	3,183,944.25	3,171,896.69	2,689,875.29	2,636,125.64	2,197,340.13
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. Authors' calculations based on RWI-GEO-RED and RWI-GEO-GRID.

For apartments that are connected to district heating, results show a discount in all specifications without regional fixed effects. But as regression diagnostics assume 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.

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 characteristics show expected outcomes, e.g., apartments advertised as simple are rented out at a discount, whereas those advertised as sophisticated or deluxe are promoted with premia of up to 16.3%, both compared to flats advertised as normal. Further, for 1st occupancy after reconstruction, tenants must pay 9% higher rents in comparison to apartments that are well kept. On the other hand, flats that need renovation are advertised at a discount of on average 4%. Up to a certain point, rents per square meter also increase with higher living space; however, large flats show a small discount. Moreover, compared to buildings that were built between 1961 and 1970, all other apartments show slightly higher rents.

Interpretation of neighborhood characteristics, especially population density and purchasing power, is not straight forward, as we estimate our model via nonlinear least squares. Nonetheless, all controls have significant influence on net rents at the 0.1%-level. Higher unemployment rates show negative impacts on rents, whereas population density, purchasing power per capita as well as a higher share of households with foreign household heads report positive effects.

6.2 EPC type subsamples

Main regression results for subsamples across EPC types are shown in Table 6. Both regressions still include all control variables and fixed effects. In the consumption subsample, coefficients for energy consumption are only slightly smaller compared to the full model. If energy consumption decreases by 10kWh/m^{2}a, monthly net rents per square meter increase on average by €0.008. In the demand subsample, however, effects are double in size: If energy consumption decreases by 10kWh/m^{2}a, monthly net rents increase by €0.016 per square meter on average.

The impact of different heating technologies on net rents also differs across subsamples. The discount for apartments with electric heating and heating by stove, again compared to gas-heated apartments, is larger in the demand subsample with 5.6% and 6.5%, respectively, compared to 3.8% and 4.5% in the consumption subsample. On the other hand, flats with SCC or night storage heating face larger deductions in the latter. Apartments that are connected to district heating, as well as those equipped with floor or wood pellet heating show positive effects on net rents, with coefficients being larger in the demand subsample for the first two technologies and smaller for the last one mentioned.

Table 6 Main regression results for EPC type subsamples

Dependent Var.: Net rent in €/m²	EPC subsamples	
	Demand certificate	Consumption certificate
Energy consumption	0.0163 ***	0.0075 ***
(in 10 kWh/m²a)	[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]
Unknown	-0.0123 ***	-0.0045 ***
	[0.0015]	[0.0009]
Fixed Effects included?		
Time (quarterly year)	*yes*	*yes*
Region (NUTS3)	*yes*	*yes*
Convergence tolerance	2.91e-07	5.32e-07
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. Results are available upon request. Authors' calculations based RWI-GEO-RED and RWI-GEO-GRID.

6.3 Regional subsamples

Table 7 gives results for different regional subsamples. Control variables and time fixe effects are included in all regressions; however, regional fixed effects are excluded. We first split our dataset in district type subsamples according to INKAR (cf. Figure A 1) and thereby focus on large cities and urban areas. Energy efficiency has slightly weaker impacts on monthly net rents in the latter. With an increase of energy efficiency by 10kWh/m²a, monthly net rents increase on average by €0.012 in large cities and €0.008 in urban areas, both per square meter.

Coefficients for different heating technologies also vary across regions. Large disparities arise for CHP and solar heating, which show positive and significant effects in the city and insignificant effects in the urban subsample. Furthermore, in both subsamples, flats connected to district heating report small discounts compared to gas-heated apartments; however, this is in line with our baseline model without regional fixed effects (see Table 5 column (4)). Moreover, flats equipped with oil heating surprisingly still report positive coefficients compared to flats with gas heating. In urban areas, this premium amounts on average to 1.3%.

Table 7 Main regression results for different regional subsamples

Dependent Var.: Net rent in €/m²	District type subsamples		Regional subsamples	
	Large city	Urban area	Ruhr region	other
Energy consumption	0.0122 ***	0.0079 ***	0.0100 ***	0.0168 ***
(in 10 kWh/m²a)	[0.0004]	[0.0004]	[0.0003]	[0.0005]
Heating system, reference: gas heating				
CHP	0.0347 ***	0.0052	0.0062	0.0186 **
	[0.0088]	[0.0061]	[0.0054]	[0.0070]
Electric heating	-0.0338 ***	-0.0458 ***	-0.0090 **	-0.0455 ***
	[0.0039]	[0.0038]	[0.0030]	[0.0042]
SCC	-0.0067 ***	-0.0112 ***	-0.0011	-0.0183 ***
	[0.0013]	[0.0013]	[0.0012]	[0.0013]
District heating	-0.0056 ***	-0.0130 ***	0.0099 ***	0.0123 ***
	[0.0015]	[0.0016]	[0.0012]	[0.0017]
Floor heating	0.0294 ***	0.0315 ***	0.0574 ***	0.0299 ***
	[0.0024]	[0.0020]	[0.0024]	[0.0019]
Wood pellet	0.0033	0.0355 *	0.0569 ***	0.0026
	[0.0177]	[0.0138]	[0.0097]	[0.0170]
Night storage	-0.0728 ***	-0.0588 ***	-0.0324 ***	-0.0655 ***
	[0.0024]	[0.0030]	[0.0020]	[0.0031]
Heating by stove	-0.0559 ***	-0.0571 ***	-0.0069	-0.0922 ***
	[0.0055]	[0.0060]	[0.0038]	[0.0063]
Oil heating	0.0057 *	0.0129 ***	0.0191 ***	0.0055 **
	[0.0024]	[0.0021]	[0.0023]	[0.0020]
Solar	0.1130 ***	0.0489	0.0513 *	0.0809 **
	[0.0319]	[0.0328]	[0.0231]	[0.0313]
Heat pump	-0.0324 ***	0.0110	-0.0134 **	-0.0147
	[0.0087]	[0.0104]	[0.0046]	[0.0127]
Central heating	0.0133 ***	0.0012	0.0330 ***	0.0001
	[0.0011]	[0.0011]	[0.0010]	[0.0011]
Unknown	-0.0214 ***	-0.0357 ***	0.0009	-0.0261 ***
	[0.0013]	[0.0013]	[0.0011]	[0.0014]
Fixed Effects included?				
Time (quarterly year)	*yes*	*yes*	*yes*	*yes*
Region (NUTS3)	*no*	*no*	*no*	*no*
Convergence tolerance	8.05e-07	9.87e-06	2.83e-06	2.60e-06
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 regressions. Results are available upon request. Authors' calculations based on RWI-GEO-RED, RWI-GEO-GRID and INKAR.

We also divided our dataset into two additional regional subsamples to compare the Ruhr region with all other parts of NRW (including Dusseldorf and Cologne). The impact of energy efficiency on net rents in the Ruhr region subsample is on the same level as for NRW. Effects, however, are larger for districts outside the Ruhr region: If energy consumption decreases by 10kWh/m²a, monthly net rents there increase on average by €0.017 per square meter.

Large differences across subsamples and also compared to our baseline model can be found for apartments equipped with electric heating. In the Ruhr region, these apartments only face rent discounts of about 0.9% compared to gas-heated flats, whereas the discount in the other regional subsample, as well as in the baseline model, and EPC type subsamples reaches up to 5.6%. Further, effects for SCC are insignificant in the Ruhr region, while flats with SCC report statistically significant discounts of about 1% in all other regressions. Lastly, central heating – regardless of the main energy source – seems to have a positive image in the Ruhr region, as these flats show rent premia of 3.3% compared to apartments that were advertised with gas heating.

6.4 Energy multiplier

To get a better understanding of how large or small rental benefits are compared to corresponding energy cost savings, we calculate an energy multiplier as given by Eq. (4). Since energy bills usually have to be paid on a yearly basis, the multiplier also shows annual net rent increases. Figure 4 illustrates this multiplier for our baseline model (column (5) in Table 5) as well as for EPC type subsample regressions. The y-axis shows the annual net rent increase in euro per €1 decrease in energy costs for different energy prices (x-axis). Corresponding multipliers for regional subsamples are given in Table A 3.

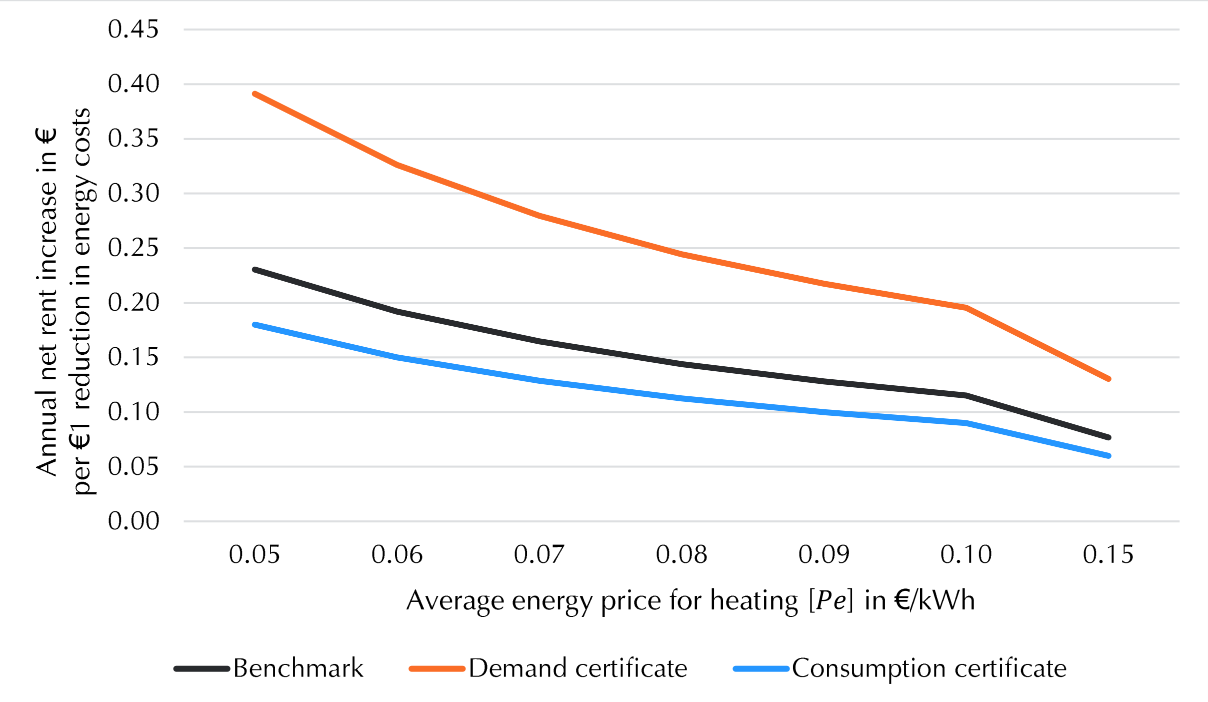

Figure 4 Annual net rent increases per €1 reduction in energy costs for different energy price levels
Authors' calculation and illustration.

According to the Federal Ministry for Economic Affairs and Energy (BMWi)[11], the mean energy price for heating oil and gas was approximately €0.068 per kWh in 2019; prices for district heating were slightly higher with €0.088 per kWh [75]. At these energy prices, our baseline model finds yearly net rent increases of €0.13 to €0.16 per €1 decrease in annual energy costs. More promising results can only be found in the demand certificate subsample, where about one-third of energy costs savings can be capitalized into higher net rents. Due to supply constraints and

[11] Now Federal Ministry for Economic Affairs and Climate Action (BMWk).

the CO_2 tax that has been introduced, energy prices are expected to rise in future. With increasing prices, however, the WTP of tenants for higher energy efficiency decreases even further – other things being equal.

The German Energy Agency assumes that energy-related investment costs[12] amount to 230€/m² for improvements of approximately 160kWh/m²a (which corresponds to an improvement from G-label to B-label). An upgrade from G-label to D-label (improvement of about 100kWh/m²a) is reported to be less expensive at 80€/m² [76]. However, it is difficult to state exact costs, since the actual costs depend on many factors, especially on the building under consideration. Nevertheless, these rough measures can be used for comparison. 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 refurbishment measures.

Improvements of 100kWh/m²a result in annual energy costs savings of 7€/m² (for energy prices of €0.07 per kWh) and in annual net rent increases of only 1.15€/m². At first glance, this leads to very long payback periods. In other words, with 1.15€/m² higher rental income and six apartments of 67m² each (average apartment in our dataset), landlords can invest about €9,200 if they accept standard payback periods of 20 years. This is far below the €32,000 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 six. From a tenant's point of view, these improvements sum up to energy savings of about €40 per month for an average apartment of 67m² living space.

7. Discussion

7.1 Discussion of empirical results

Our analysis supports results of previous studies in that there is a rental premium for 'greener' dwellings. We find a monthly rental increase of €0.01 per square meter of living space when improving the energy efficiency by 10kWh/m²a. For the mean apartment in our dataset, this corresponds to an increase of about 0.14%. The extant literature mostly shows improvements from D- to A-labels which corresponds to an improvement of about 70 to 100kWh/m²a. Our study reports monthly rental increases of about €0.07 to €0.10 per square meter living space or approximately 1.4%, respectively, for this range.

Cajias et al. [40] 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. [6] also confirm these results and report a 0.17% increase in rents per 10kWh/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., [39] find slightly smaller and [45] somewhat larger effects).

Nonetheless, the premium for higher energy efficiency observed in the market is rather small compared to the benefits for tenants in terms of resulting energy cost savings. The latter exceeds the rental premium by a factor of six when assuming energy prices for heating to be €0.07 per kWh. Based on these empirical observations of market results, incentives for energy efficiency improvements for landlords are very limited which suggests the relevance of the landlord-tenant

[12] Values relate to multi-family buildings – not to single apartments.

dilemma. Our results however differ somewhat from Kholodilin et al. [7]. 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.

In view of increasing energy prices for heating due to the newly introduced CO_2 tax in Germany, our multiplier suggests the WTP of tenants for more efficient apartments may decrease even further. One possible explanation is that tenants are unaware about cost savings in more energy efficient apartments. In anticipation of higher bills for energy costs due to increasing prices, they are more likely willing to save additional rental expenses, as the rent burden ratio is already at a very high level. Reporting energy savings in monetary terms in EPCs or even explaining the categories in more detail could help to increase the WTP ([77–79]) and to consequently induce higher incentives for landlords to renovate.

Investigating the effects of different installed heating systems (in comparison to gas heating) on rents additionally reveals some important findings. The bad reputation of night storage heaters and SCC results in lower WTP for the apartment. Installing a new heating system, preferably parallel to improving the overall energy efficiency of a dwelling, however, results in a better profitability of energy-related investments for landlords.

Additionally, results of our EPC type subsample regressions point to underlying effects that need to be considered when evaluating energy efficiency benefits. Tenants' WTP in the demand certificates subsample is twice as large as in the consumption subsample, even though average rents only differ by €0.14 per square meter. Similar results were already found when examining effects on single-family house prices across Germany [21] and Sweden [80]. We conclude that the higher WTP results from a higher perceived reliability of the stated energy performance score given in demand certificates. The energy consumption 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 apply. Given the limited predictive power for own energy costs, a lower WTP for energy efficiency is comprehensible.

Lastly, 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. This seems to be quite the opposite of results that were found in several other studies (cf. [40,65]). However, our estimates show direct monetary impacts rather than relative impacts, so that a moderate decrease in relative terms may align with a higher impact in absolute terms as net rents are on average higher in large cities. A case apart are the smaller impacts of energy efficiency on net rents found in the Ruhr region compared to all other regions in NRW. Similar results were found for sales prices as well [21].

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. An alternative hypothesis is that the large property companies as well as municipally owned companies (which both are over-proportionally represented in the Ruhr region, cf. Figure A 3) apply a more portfolio-oriented pricing strategy which puts less focus on the current energy efficiency status of the buildings but aims to maintain stable rental prices within the portfolio even when energy-efficiency retrofits are undertaken.

7.2 Reasons for market inefficiencies

Our results – mainly that the inferred WTP for energy efficiency is far lower than the expected energy cost savings – suggest that substantial market inefficiencies for energy efficiency in the residential rental market exist. Various mechanisms, both on the supply and the demand side, may be invoked to explain these inefficiencies. Subsequently, we provide a qualitative discussion of these potential mechanisms; however, an empirical validation is left for future research.

On the supply side, we identify four major potential reasons for these perceived inefficiencies. First is the stickiness of rental prices within a building or a quarter. This means that, given rental prices for historical renters, new rents align on these and do not reflect the full value of refurbishments. Corresponding empirical evidence has been reported in particular for private landlords (cf. [81]). This may also be related to the second mechanism which are regulatory limits to price increases. For existing rental contracts, rent increases after refurbishments are limited (see Chapter 3). 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 mechanism might be a shift of refurbishment costs into auxiliary costs. However, this should typically be prevented by regulation. Last but not least 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 current refurbishment status is not seen as opportune.

On the demand side, we again perceive four types of effects that may explain market inefficiencies. A first strand is related to non-anticipation of energy cost differences as energy-related financial literacy is generally limited (e.g.[82]). 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 carrier 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[13]. 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: renters may overvalue the immediately perceivable net rent compared to future heating energy costs. 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.

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

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 EPCs.

In a market perspective, there are yet opportunities to exploit the emerging inefficiencies – both on the part of tenants and landlords. Tenants may benefit from the inefficiencies by renting energy efficient homes. On the other hand, landlords can overprice inefficient buildings as a consequence of tenants' undervaluation of energy efficiency. An obvious remedy against these inefficiencies would be to provide more reliable and applicable information.

8. Conclusion

To achieve a climate-neutral building stock by 2045, increasing refurbishment rates are a key factor. Since Germany has the highest share of tenants across all EU countries, energy refurbishments in the rental housing stock are particularly important. Thereby the so-called landlord-tenant dilemma yet comes into play because costs and benefits are usually split between the two actors in rental relationships. Investments in energy efficiency are therefore only appealing and profitable for landlords if investment costs can be refinanced by increasing rental income (i.e., net rents).

We investigate the rental market in Germany's most populated federal state North Rhine-Westphalia using a cross sectional dataset for 2014 to 2020. With more than 840,000 individual observations distributed over 10,050 1km^2-grid cells, we explore tenants' WTP for energy efficiency and also for different heating technologies. Thereby we furthermore focus on different regional subsamples as well as on effects across dwellings with different types of EPCs. In addition, to easily compare rental premia with energy cost savings, an energy multiplier is computed. It reports annual net rent increases per €1 reduction in energy costs.

Efficient apartments are found to be rented out at a premium; however, it is rather small. Expected energy cost savings thereby exceed tenants' WTP for energy efficiency by a factor of six. Rather, we find large discounts if apartments use heating technologies that are known to be inefficient. Further, results differ across regions which leads to varying payback periods for landlords. Lastly, different mechanisms for emerging market inefficiencies were discussed; however, empirical assessment is left for further research.

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Appendix

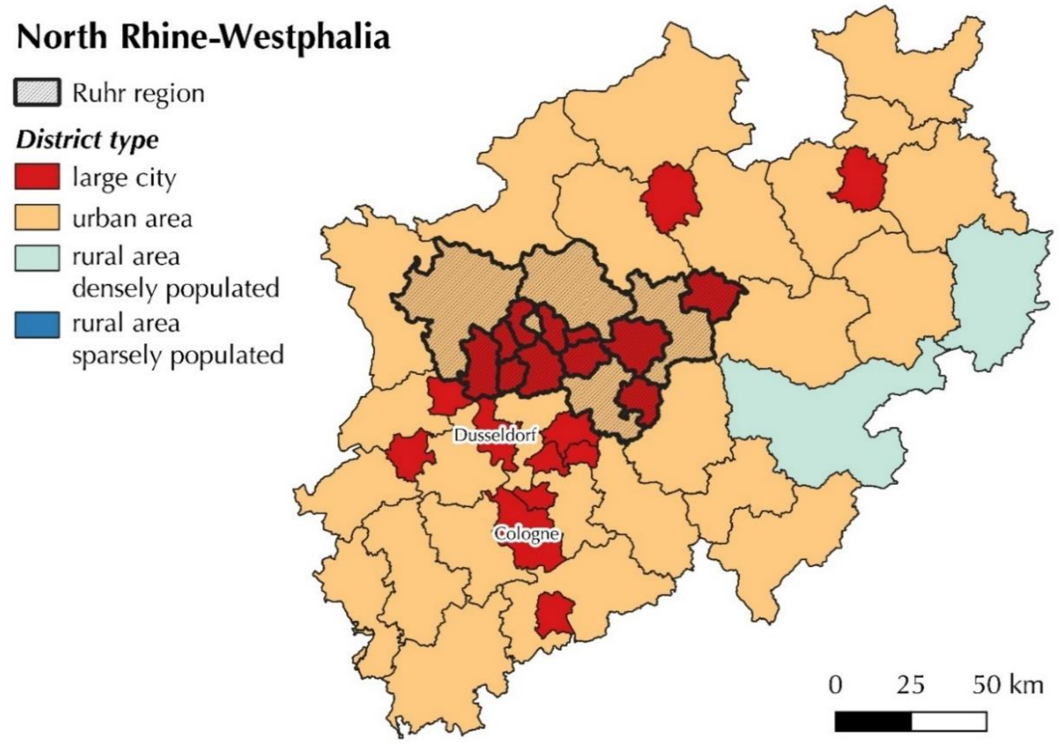


Figure A 1 Map of North Rhine-Westphalia showing the district types according to INKAR
Authors' illustration based on INKAR. Map Data: @GeoBasis-de/BKG 2019

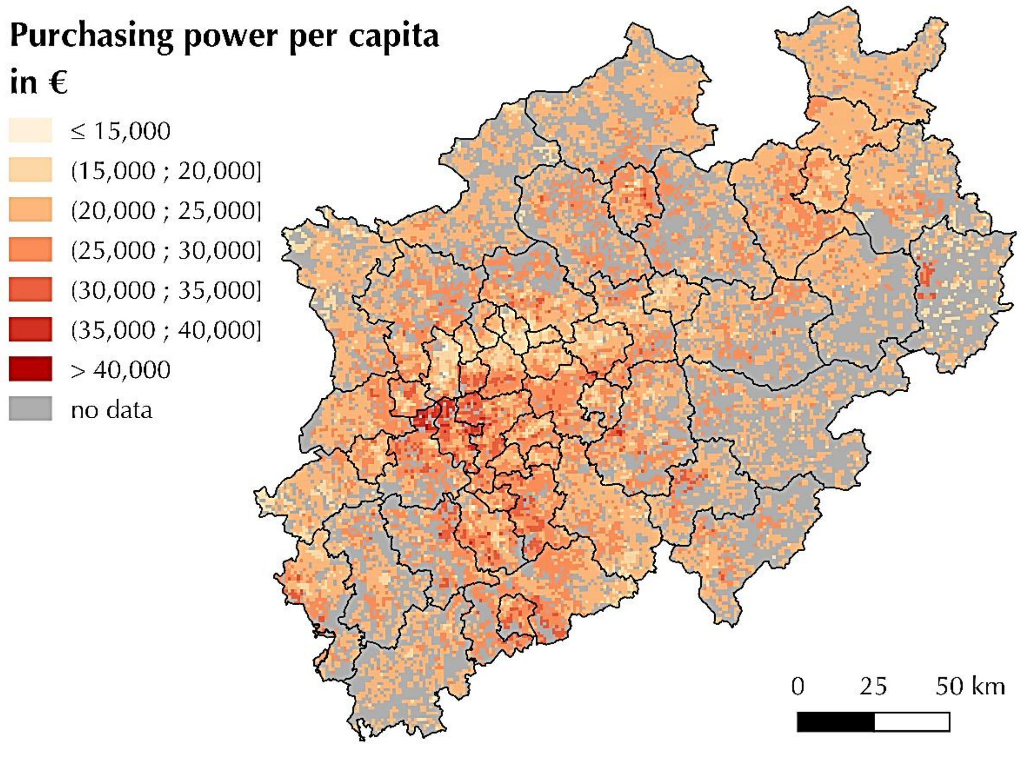


Figure A 2 Purchasing power per capita on grid level (2018)
Authors' calculation and illustration based on RWI-GEO-GRID. Map Data: @GeoBasis-de/BKG 2019

Table A 1 Summary of factor variables

Variable		absolute	%
TYPE			
	Flat	482,372	57.14
	Attic flat	104,762	12.41
	Raised ground floor	10,283	1.22
	Maisonette	313	0.04
	Penthouse	21,417	2.54
	Souterrain	1,450	0.17
	Flat with terrace	5,570	0.66
	Other	5,879	0.69
	Unknown	212,183	25.13
FACILITIES			
	Normal	259,152	30.70
	Simple	7,580	0.90
	Sophisticated	131,114	15.53
	Deluxe	3,648	0.43
	Unknown	442,735	52.44
CONDITION			
	Well kept	292,225	34.61
	1st Occupancy after reconstruction	33,969	4.02
	Like new	26,701	3.16
	Reconstructed	23,779	2.82
	Modernized	59,048	6.99
	Renovated	83,278	9.86
	Needs renovation	6,266	0.74
	By arrangement	6,923	0.82
	Unknown	312,040	36.96
FLOORS_BUILDING			
	Up to 3	337,271	39.95
	4 to 6	160,292	18.99
	7 to 10	21,200	2.51
	More than 10	3,572	0.42
	Unknown	321,984	38.13
ROOMS			
	1	60,486	7.16
	2	334,169	39.58
	3	304,686	36.09
	4	138,199	16.37
	5 or more	6,689	0.79
MODERNIZED after 2000			
	Yes	182,913	21.67
	No	661,316	78.33
BALCONY			
	Yes	512,282	60.68
	No	260,008	30.80
	Unknown	71,939	8.52
GARDEN			
	Yes	121,877	14.44
	No	626,999	74.27
	Unknown	95,353	11.29

Table A 1 (continued)

Variable		absolute	%
KITCHEN			
	Yes	114,202	13.53
	No	634,741	75.19
	Unknown	95,286	11.29
CONSTRUCTED			
	Between 1900 and 1910	34,634	4.10
	Between 1911 and 1920	17,596	2.08
	Between 1921 and 1930	28,048	3.32
	Between 1931 and 1940	24,847	2.94
	Between 1941 and 1950	26,120	3.09
	Between 1951 and 1960	217,461	25.76
	Between 1961 and 1970	192,338	22.78
	Between 1971 and 1980	121,822	14.43
	Between 1981 and 1990	61,893	7.33
	Between 1991 and 2000	97,909	11.60
	Between 2001 and 2010	21,561	2.55
LIVING SPACE			
	(20;30]	12,837	1.52
	(30;40]	45,634	5.41
	(40;50]	97,074	11.50
	(50;60]	168,033	19.90
	(60;70]	183,503	21.74
	(70;80]	158,073	18.72
	(80;90]	85,005	10.07
	(90;100]	43,718	5.18
	(100;110]	22,897	2.71
	(110;120]	13,686	1.62
	(120;130]	7,569	0.90
	(130;140]	4,166	0.49
	(140;150]	2,028	0.24
	(150;160]	6	0.0007

Author's illustration and calculation based on RWI-GEO-RED.

Table A 2 Summary statistics across regional types according to INKAR

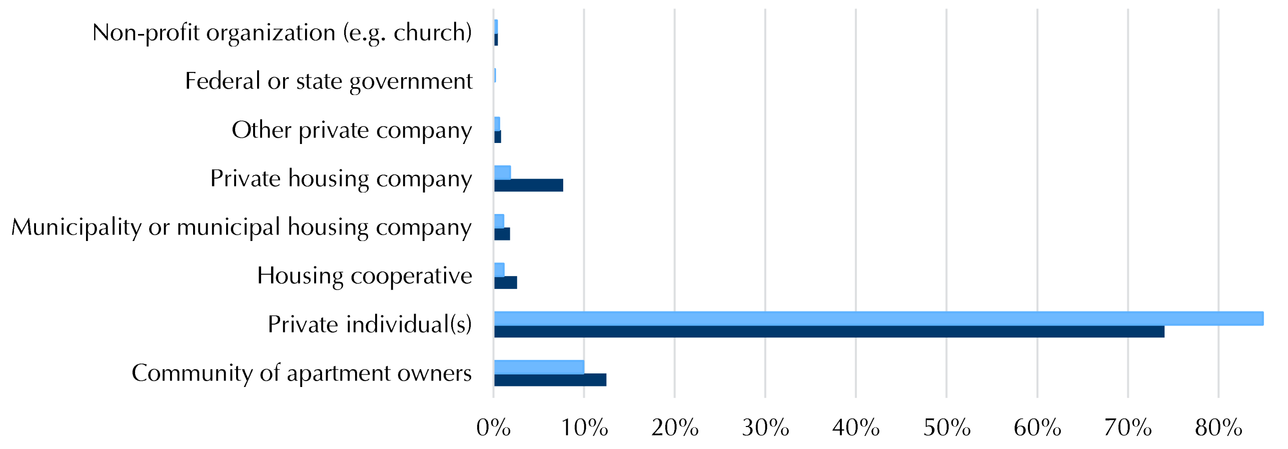
Variable	No. of obs.	Mean	St. Dev.	Min	Max	Median
DTYPE - Large cities						
Net rent	544,567	7.13	2.09	3.85	19.00	6.55
Energy consumption	544,567	142	47	43	320	137
Living space	544,567	66	20	23	152	64
Age	544,567	60	22	10	120	59
Duration of advertisement	544,567	25	32	1	365	14
Population density	544,567	5,641	3,638	19	20,165	4,685
Unemployment rate	544,567	11.13	4.69	0.00	26.29	11.29
Share of households with foreign household head	544,567	16.50	7.71	0.00	77.09	15.97
Purchasing power per capita	544,567	21,370.92	4,132.30	10,416.77	42,990.06	20,435.29
DTYPE – Urban area						
Net rent	296,070	6.54	1.45	3.85	15.88	6.30
Energy consumption	296,070	137	48	43	320	130
Living space	296,070	71	20	24	152	69
Age	296,070	50	21	10	120	50
Duration of advertisement	296,070	27	33	1	365	16
Population density	296,070	3,302	2,243	16	15,008	2,971
Unemployment rate	296,070	8.01	3.76	0.00	26.29	7.73
Share of households with foreign household head	296,070	11.25	5.83	0.00	64.80	10.58
Purchasing power per capita	296,070	22,094.06	3,546.13	12,373.85	45,564.72	21,613.04
DTYPE – Densely populated rural areas						
Net rent	3,592	5.01	0.65	3.86	8.61	5.00
Energy consumption	3,592	136	47	51	311	124
Living space	3,592	72	19	25	150	70
Age	3,592	54	19	12	120	55
Duration of advertisement	3,592	31	36	1	305	19
Population density	3,592	1,840	1,138	35	4,611	1,573
Unemployment rate	3,592	6.12	3.12	0.29	18.05	5.09
Share of households with foreign household head	3,592	9.31	6.22	0.00	48.06	7.74
Purchasing power per capita	3,592	21,103.63	2,703.16	14,992.49	33,278.28	20,772.30

Author's illustration and calculation based on RWI-GEO-RED, RWI-GEO-GRID and INKAR.

Table A 3 Energy multiplier for benchmark model and regional subsamples

Mean energy price for heating (P_e) in €/kWh	Annual net rent increase in € per €1 decrease in annual energy costs				
	Benchmark	District type subsamples		Regional subsamples	
		Large city	Urban area	Ruhr region	Other regions
0.05	0.23	0.29	0.19	0.24	0.40
0.06	0.19	0.24	0.16	0.20	0.34
0.07	0.16	0.21	0.14	0.17	0.29
0.08	0.14	0.18	0.12	0.15	0.25
0.09	0.13	0.16	0.11	0.13	0.22
0.10	0.12	0.15	0.09	0.12	0.20
0.15	0.08	0.10	0.06	0.08	0.13

Author's illustration and calculation based on RWI-GEO-RED, RWI-GEO-GRID and INKAR.



	Community of apartment owners	Private individual(s)	Housing cooperative	Municipality or municipal housing company	Private housing company	Other private company	Federal or state government	Non-profit organization (e.g. church)
Other	9.92%	84.90%	1.12%	1.08%	1.81%	0.62%	0.16%	0.37%
Ruhr region	12.45%	74.04%	2.61%	1.81%	7.69%	0.84%	0.08%	0.47%

Figure A 3 Type of ownership of residential buildings in NRW
Authors' calculation and illustration based on Statistische Ämter des Bundes und der Länder 2022 [83].

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