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Are tenants willing to pay for energy efficiency?

Evidence from a small-scale spatial analysis in Germany

Keywords: Energy efficiency, willingness-to-pay (WTP), hedonic regression, spatial regression, rental markets, split incentive

Highlights

- Tenants pay a price premium (WTP) for energy efficiency of 0.017% per kWh/sqm*a.
- WTP translates into a payback period of 48 years for a moderate EE-renovation (EPC G to C).
- WTP for other property features is higher than for energy efficiency (EE).
- The price premium differs between neighbourhoods.
- EE policies have to be embedded in social and urban development objectives.

Abstract

To address climate change, the decarbonisation of Germany's existing building stock urgently needs to be prioritised. However, the rate and depth of refurbishment has lagged behind official targets for years. This is a particular problem in the rental sector, where the costs and benefits of energy efficiency measures tend to be unevenly distributed between landlords and tenants (the so-called 'landlord-tenant dilemma'). Within the context of the current policy landscape, investments in energy efficiency consequently make most sense for landlords if the upfront costs can be refinanced via increased rental income or reduced vacant periods. This paper seeks to investigate the validity of this statement at city level by using a large dataset from one of Germany's main internet property platforms to examine how the willingness of tenants to pay for energy efficiency varies across residential locations in the city of Wuppertal.

The small-scale spatial analysis highlights the existence of a price premium for energy efficiency in the rental market for apartments; however, this premium is generally small (especially in comparison to other property enhancements, especially visible improvements) or even non-existent in some residential areas. Consequently, investing in energy efficiency is rarely an attractive option for landlords. Therefore, strong policy action, aligned with social and urban development policy objectives, is necessary to establish an effective incentive structure in the market and make investing in energy efficiency more attractive for both landlords and tenants.

1 Introduction

Decarbonising the building stock can make an important contribution to tackling climate change, meeting German and international climate goals (e.g. The Paris Agreement) and limiting global temperature rise, because the buildings sector accounts globally for 36% of final energy use and 39% of CO₂ emissions (Global Alliance for Buildings and Construction et al., 2019). Germany is aiming to achieve “virtually climate-neutral building stock by 2050” (BMUB, 2016; BMWi, 2010). In light of the country’s relatively old building stock – two-thirds of residential buildings were constructed before 1979 and, therefore, before the introduction of minimum energy efficiency standards – the decarbonisation of existing buildings needs to be a priority (Statistische Ämter des Bundes und der Länder, 2015).

Some progress has been made to date in this area: the German buildings sector has reduced its CO₂ emissions by 43% since 1990 (BMUB, 2016). However, this trend in reducing emissions has tailed off in recent years. The refurbishment rate has remained at the low level of 1% p.a. over the last decade, which is lower than both Germany’s official political target of 2% p.a. and the refurbishment rates deemed necessary by the scientific community (Cischinsky and Diefenbach, 2018; Diefenbach et al., 2010). Moreover, the volume of investments in energy efficiency in the building sector in Germany has decreased in both absolute and relative values over recent years (BBSR, 2016).

Although scientific research studies highlight the economic and macro-economic advantages and co-benefits of energy-related building refurbishment (Thema et al., 2017; März, 2018a; Ürge-Vorsatz et al., 2016), and national governments regulate, promote and advertise appropriate investments by setting political frameworks, reluctance to invest persists (Galvin, 2014). This reluctance – present in both the rate and depth of energy-efficient retrofits – varies among different property owner groups, with private landlords having one of the largest refurbishment backlogs (Cischinsky and Diefenbach, 2018).

One explanation for this is the split incentives present in rental markets, where – in contrast to owner-occupied properties – most of the unlocked co-benefits of energy-efficient retrofits ultimately benefit the tenant and not the landlord or investor. Due to this so-called ‘landlord-tenant dilemma’ or ‘investor-user dilemma’ (Ástmarsson et al., 2013; Bird and Hernández, 2012; Gillingham et al., 2012), energy-efficient retrofitting in rental properties tends to be most attractive to landlords when it also leads to long-term economic benefits in the form of increased rents, higher property prices or reduced vacant periods.

This raises the question whether and to what extent landlords can obtain a price premium for energy efficiency in rental markets; i.e. to what extent are tenants willing to pay a premium for energy efficiency? This is the starting point for our analysis, which has four concrete aims. Firstly, we seek to address this research gap and contribute to the scientific discussion on energy efficiency premiums in the rental market by conducting hedonic and spatial regression analyses on a large database of rental apartment listings in the city of Wuppertal, Germany. Secondly, we aim to understand the relative impact of energy efficiency criteria on rental prices compared to other apartment features and neighbourhood characteristics. Thirdly, we split

our analysis by the type of residential area to explore potential small-scale differences in the willingness to pay for energy efficiency. This analysis aims to improve our understanding of the reluctance to invest in energy efficiency and, therefore, finally forms the basis for policy recommendations to boost energy efficiency investments and retrofits in the residential rental market.

The paper is structured as follows. Section 2 provides a brief overview of the relevant scientific studies and literature assessing the evidence for energy efficiency premiums in the property sales and rental markets. Section 3 then describes the data used, methodology employed and model specifications. This is followed by a presentation of the main empirical results in Section 4. The paper closes with a discussion of the results, policy implications, study limitations and key conclusions (Sections 5 and 6).

2 Literature Review

Much of the literature to date points towards the existence of price premiums for energy efficiency in the residential sector (Fizaine et al., 2018; Hyland et al., 2013; Mudgal et al., 2013). Generally, these tend to be significantly larger in the property sales market than in the property rental market (Fuerst and Warren-Myers, 2018; Hyland et al., 2013; Kholodilin et al., 2017).¹ In the rental market, Fuerst and Warren-Myers (2018) identify price signals for other sustainability and energy efficiency-related characteristics, such as rental discounts for electric and gas heating, as well as rental premiums for other heating types, insulation, energy-efficient windows, solar PV systems, central heating, evaporative cooling and split-system air conditioning.

Such results contribute to the view that energy efficiency is often clearly rewarded in the market; for instance, a 2013 report for the European Commission concludes that “the effects of energy efficiency are clear and positive” (Mudgal et al., 2013, p. 155). However, more recent evidence does not unequivocally support this conclusion. Not all studies identify significant price premiums for energy efficiency in the rental market (Fuerst et al., 2016) or in the sales market (Olaussen et al., 2017). Survey findings suggest that other criteria – such as the location, available outdoor space, condition, the neighbourhood and size of the property – play a greater role in the decision-making process around home purchasing than energy efficiency (Amecke, 2012; Lainé, 2011; Murphy, 2014; Olaussen et al., 2017; Tigchelaar et al., 2011).

In a meta-analysis of published literature to date, Fizaine et al. (2018) correct for the presence of publication bias, leading them to adjust the value of the energy efficiency premium in the sales market down from an average of 8% to between 3.5% and 4.5%. Additionally, the authors find that while 92% of the reviewed studies identify a sales premium, there is a large variability in estimates, even within a single geographical context. Indeed, aside from geographical location and publication type, the inclusion of spatial and environmental characteristics also accounted to a large degree for the variability in results of the reviewed studies. Specifically, spatial aspects – such as the distance to the city centre or transportation links, presence of amenities in the vicinity or the exact location of the property – all impacted on the size of the energy efficiency premium obtained, leading the authors to suggest that “the use of models [...]

¹ Studies vary in their chosen approach, examined property types, data and methodology. Therefore, results are not always directly comparable. Typically, energy efficiency data is included either as a series of binary, categorical variables (representing different energy efficiency classes), as a continuous variable (i.e. final energy consumption values in kWh/sqm*a), or simply by the presence of a green certification label.

The latter has been found to increase sales prices by between 3.2% and 3.5% for apartments (Fesselmeier, 2018; Salvi et al., 2010) and between 4.9% and 9% for houses (Bruegge et al., 2016; Kok and Kahn, 2012; Salvi et al., 2010). Salvi et al. (2010) found a 4.9% premium on gross rent in the rental sector.

Comparisons of higher energy performance certificate (EPC) ratings to lower ratings generally identify higher price premiums in both sales and rental markets, although the rise in premiums is not always linear (Fuerst and Warren-Myers, 2018). Premiums for the highest rating categories commonly range from 5% to 14% in the sales market (Ayala et al., 2016; Bisello et al., 2020; Deng et al., 2012; Evangelista et al., 2020a; Fuerst et al., 2016; Fuerst and Warren-Myers, 2018; Hyland et al., 2013; Mudgal et al., 2013). Smaller premiums for properties with higher energy efficiency ratings are identified in the rental sector, ranging from 1.8% to 4.4% (Fuerst and Warren-Myers, 2018; Hyland et al., 2013; Mudgal et al., 2013).

Modelling energy efficiency as a continuous variable, Taruttis and Weber, 2020 found that for every decrease in energy consumption of 1 kWh/sqm*a, there was an associated increase in house price of 0.04% to 0.1%.

incorporating spatial data [...] is likely to be necessary for an efficient interpretation of the impact of intrinsic and extrinsic building characteristics on real-estate prices” (p. 1029).

While spatial or neighbourhood characteristics are sometimes controlled for in hedonic regression models, many conventional hedonic modelling approaches do not account for spatial dependence² – despite academic consensus that its omission can lead to biased and overestimated results (Bisello et al., 2020). This is particularly important, as hedonic regression analyses accounting for spatial dependence (see Bisello et al., 2020, for an overview) do not always replicate previous findings of sizable premiums for energy efficiency. Taltavull et al., 2017, for instance, performed a conventional hedonic analysis, as well as a spatial analysis, in the city of Bucharest and found the presence and size of the energy efficiency price premium to vary in different neighbourhoods, with significant premiums of 6.5% and 2.2% obtained in the north and west of the city respectively, whereas no significant premiums were identified elsewhere. In contrast to the 3.5% premium predicted in the traditional hedonic model, the spatial analysis shows a much more differentiated picture of the spatial variability of the energy efficiency premium. In a country-wide comparison of the German housing market, Cajias et al., 2019 found that although units that are more energy-efficient generate a premium and are also rented out faster, this effect varied across geographical locations and was not present in large metropolitan areas with more competitive rental markets.

Therefore, the literature on energy efficiency premiums (see Table 1 for an overview), while representing a large and growing field, remains inconclusive. While most studies do identify energy efficiency premiums, and larger premiums for sales than for rentals, study results have sometimes proven to be overestimated and also show significant variability based on the locations studied, the level of analysis, the methodological approach and other control variables included. Given this variability in results, small-scale spatial approaches and analyses are needed to adequately evaluate the existence of an energy efficiency price premium and provide concrete recommendations for local governments and administrations grappling with the challenge of how to encourage private landlords to invest in energy efficiency. There is a distinct lack of studies examining energy efficiency premiums in the rental market – a market which harbours large CO₂ reduction potential – and, consequently, this should be further investigated.

The present small-scale analysis – conducted within the context of the ‘Solar Decathlon Europe’, an international student architecture competition for sustainable housing and living in the German city of Wuppertal – examines the impact of the energy efficiency of property on rental prices in Wuppertal’s local market in order to assess whether and to what extent tenants are willing to pay a premium for energy efficiency. It addresses the existing research gap by enhancing the understanding on how WTP varies among residential areas of differing quality and spatial characteristics. To the authors’ knowledge, it represents the first such city-level spatial analysis in Germany.

² Spatial dependence describes “the propensity for nearby locations to influence each other and to possess similar attributes” (Goodchild, 1992, p. 33; Anselin, 1989).

Table 1: Overview of literature

Citation	Location	Transaction type	Property type	Method	Variable type (Energy Performance)	Main findings
Amecke, 2012	Germany	Sales	Houses	Online survey	N/A	<ul style="list-style-type: none"> > Energy efficiency (M = 4.61; Scale: 1-7) was a purchasing criterion of only minor importance. > Location, price, outdoor space and the condition of the property were the most important criteria in the purchasing decision.
Ayala et al., 2016	Spain	Sales (stated housing price)	Houses	Hedonic regression	Categorical	<ul style="list-style-type: none"> > Energy-efficient properties have a price premium of between 5.4% (ABCD) and 9.8% (ABC) compared to those with the same characteristics but lower energy efficiency.
Bisello et al., 2020	Italy	Sales	Houses	Hedonic and spatial regression	Categorical	<ul style="list-style-type: none"> > Price premiums of around 6.5%, 5.5% and 3% for A, B, and C labelled houses respectively (compared to G as the default category).
Bruegge et al., 2016	USA (Florida)	Sales	Single-family residential properties	Hedonic regression	Green certification (comparing labelled to non-labelled)	<ul style="list-style-type: none"> > Estimated premium for Energy Star homes of approximately 4.9%.
Cajias et al., 2019	Germany	Rentals	Range of residential property types	Hedonic regression	Categorical	<ul style="list-style-type: none"> > Overall German market: energy-efficient rental units are rented at a premium (on average 0.9% for A+, 1.4% for A, 0.1% for B and 0.2% for C (compared to reference category D)); energy-inefficient properties have longer marketing periods. > Effect not confirmed for the largest metropolitan housing markets.
Deng et al., 2012	Singapore	Sales	Private condominiums and apartments	Hedonic regression	Categorical	<ul style="list-style-type: none"> > 4% average price premium for certified properties. > Up to 14% price premium for highest Platinum rating.
Evangelista et al., 2020	Portugal	Sales	Apartments and houses	Hedonic regression	Categorical	<ul style="list-style-type: none"> > Sales premium for energy-efficient properties (A/B ratings) is more pronounced for apartments (13%) than for houses (5% to 6%).
Fesselmeier, 2018	Singapore	Sales	Privately developed apartments	Hedonic regression	Green certification (comparing labelled to non-labelled)	<ul style="list-style-type: none"> > Green certification increases prices by 3.2% on average.
Fuerst et al., 2016	United Kingdom (Wales)	Sales and rentals	Range of residential property types	Hedonic regression	Categorical	<ul style="list-style-type: none"> > For sales transactions: positive price premiums for properties in EPC bands A/B (12.8%) and C (3.5%) compared to properties in band D; significant discounts for properties in EPC bands E (−3.6%) and F (−6.5%). > For rental transactions: energy-efficient properties in bands A, B and C achieve price premiums that are comparable to the general market; low EPC-rated properties are not traded at a significant discount.
Fuerst and Warren-Myers, 2018	Australia (Australian Capital Territory (ACT))	Sales and rentals	Range of residential property types	Hedonic regression	Categorical	<ul style="list-style-type: none"> > Energy efficiency levels and other sustainability-related characteristics both influence sales and rental transactions. > For sales transactions: the price paid for energy efficiency rises as the star rating increases, except for the highest group (8+ stars). Second highest category (7 stars) provides a premium of 9.4%. > For rental transactions: properties with higher energy ratings attract small but statistically significant rental premiums (2.6% to 3.6%) but rise in premiums in the above-average EER categories is not linear.
Hyland et al., 2013	Ireland	Sales and rentals	Housing	Hedonic regression	Categorical & continuous	<ul style="list-style-type: none"> > For sales transactions: relative to D rated properties, A rated properties receive a sales price premium of 9.3%

						<ul style="list-style-type: none"> > For rental transactions: relative to D rated properties, A rated properties receive a rental price premium of 1.8% > When modelling energy efficiency as a continuous variable, for each rating decline along the EPC scale there is an associated price reduction of 1.3% for sales and 0.5% for rental prices.
Kholodilin et al., 2017	Germany	Sales and rentals	Apartments	Hedonic regression	Continuous	<ul style="list-style-type: none"> > If energy consumption decreases by 1 kWh/sqm*a, the price per square meter increases on average by 0.05% in the sales market and by 0.02% in the rental market. > In the rental segment, the value of future energy cost savings exceeds tenants' implicit willingness to pay by a factor of 2.5.
Kok & Kahn, 2012	USA (California)	Sales	Houses	Hedonic regression	Green certification (comparing labelled to non-labelled)	<ul style="list-style-type: none"> > Price premium of 9% ($\pm 4\%$) for homes with a green energy label.
Lainé, 2011	United Kingdom	Sales and rentals	Range of residential property types	Survey	N/A	<ul style="list-style-type: none"> > The EPC influenced decisions about buying or renting a home only for 18% of respondents. > Location remains the main decision factor after cost and size of homes, but 14% of prospective buyers and tenants do consider energy issues to be important.
Murphy, 2014	Netherlands	Sales	Range of residential property types	Online survey	N/A	<ul style="list-style-type: none"> > 10% (29 subjects) of the EPC sample group stated that the EPC influenced the property purchase. > Of these 29, only 6 used the EPC to negotiate the price of the property.
Olaussen et al., 2017	Norway	Sales	Range of residential property types	Hedonic regression	Categorical	<ul style="list-style-type: none"> > Houses with better energy certification sold for a higher price both before and after the introduction of EPC ratings → there is no effect of the energy label itself and no price premium associated with energy performance certificates.
Salvi et al., 2010	Switzerland	Sales	Single-family houses and apartments	Hedonic regression	Green certification (comparing labelled to non-labelled)	<ul style="list-style-type: none"> > Price premiums of 7% for single family homes and 3.5% for apartments.
Taltavull et al., 2017	Romania (Bucharest)	Sales	Apartments	Hedonic and spatial regression	Comparing refurbished to non-refurbished	<ul style="list-style-type: none"> > Overall model (OLS): price premiums of 3.5% for refurbished housing. > Spatial model: price premiums of 6.5% in the north and 2.2% in the west; no significant premium for refurbished housing in other parts of the city.
Taruttis & Weber, 2020	Germany	Sales	Single-family houses	Hedonic regression	Continuous	<ul style="list-style-type: none"> > If energy consumption decreases by 1 kWh/sqm*a, the price per square meter increases on average: <ul style="list-style-type: none"> > by 0.04% in large cities > by 0.06% in urban areas > by 0.09% in densely populated rural areas > by 0.10% in sparsely populated rural areas
Tigchelaar et al., 2011	Denmark, Finland, Germany, Netherlands, United Kingdom, Belgium, Bulgaria, Czech Republic, Latvia, Portugal	Sales	Houses	Interviews, Survey	N/A	<ul style="list-style-type: none"> > The EPC currently has little effect on people's decision-making when buying a home (but expected utility costs were mentioned as important by 60% of the survey respondents and type of heating system by 40%). > Other factors, such as property price, location and availability of outdoor space, play a much more influential role.

3 Data and methodology

3.1 Data

3.1.1 Data on hedonic apartment characteristics

Data from Germany's largest internet property platform *Immoscout24.de* (IS24) – including data on energy efficiency performance (final energy consumption/demand) provided in the energy performance certificate (EPC), the rental price and the hedonic apartment characteristics of a large number of listings – forms the basis for the present analysis. The data used was restricted to the city of Wuppertal. According to its own reports, the platform has a market share of about 63% (Göschl, 2018). In a survey of professional property marketers, 74.3% stated that their properties were advertised on IS24 (IVD, 2018)³.

Advertisements can be placed by private individuals as well as by commercial providers for the appropriate fee. Advertisers complete an online form giving details about a variety of the characteristics of their property. As IS24 does not check the validity of the information provided, we carried out a two-step outlier analysis. Firstly, we removed implausible values across all variables (e.g. negative energy efficiency performance). Secondly, we removed extreme values (more than three times the interquartile range below and above the first and third quartile respectively) for rental prices, living space and energy performance. Although the original dataset covered the period from January 2007 to December 2019, energy efficiency performance data was only recorded by IS24 from 2012 onwards; consequently, the current data subset used is restricted to the time period 2012-2019. Our final dataset consists of a total of 12,232 advertisements for rental apartments where information for all variables included in our model were available.

The use of the dataset presents some methodological challenges. The data is based exclusively on the information given by the providers; incorrect information or subjectively biased information cannot, therefore, be excluded. Listed rental prices are also to some extent negotiated, with the result that the prices quoted may overestimate the actual prices. However, international experience indicates that the use of listed prices is a good substitute for actual transaction prices (Shimizu et al., 2012).

There are a number of positive reasons for using the dataset. Due to IS24's high market share, the dataset has a substantial number of cases. Combined with address-based geo-referencing, small-scale spatial analyses can be carried out and the respective neighbourhood, street and other geographical aspects can be assigned to each advertisement. The long time period allows for observations about rental market

³ The platform is primarily an offer for private individual tenants because every apartment is offered individually. Larger apartment portfolios are generally not offered, which means that larger tenancies (e.g. by universities or companies) will most likely not take place via the portal. Likewise, it cannot be assessed whether certain tenant groups (e.g. social benefit holders, tenants in the high-priced segment) tend to search on other portals. Due to the high market share, however, reliable results for private individual tenants can be assumed.

development over time and, therefore, for assessments of the impact of wider, external market factors (e.g. external shocks like the 2008 financial crisis and Fukushima's influence on property prices in locations in proximity to nuclear power plants around the world) and internal, city-wide developments (e.g. urban development projects) on local housing markets (Bauer et al., 2017, 2015).

3.1.2 Data on neighbourhood characteristics

To model the advertisements' surrounding neighbourhoods, small-scale, building block level spatial data (dividing Wuppertal into more than 2,800 segments) was provided by the city of Wuppertal, which we linked to the georeferenced IS24 data using QGIS 3.10. This neighbourhood data includes socio-demographic and socio-economic data (e.g. unemployment rate, population density). We also added results from the 2017 German federal election (share of votes for the Green Party 'Bündnis90/Die Grünen') as a proxy for community environmentalism and environmental awareness in the neighbourhood (Kahn, 2007). Additionally, we included data on the settlement structure (share of traffic area, share of recreational area) based on ALKIS-data⁴.

The city of Wuppertal also provided information on the quality of different residential areas. There is considerable variation in residential quality across the city due to its specific history. In the 19th century, the city developed as one of the first industrial hotspots in Germany with a focus on the textile industry. However, globalisation and relocation of the textile industry led to structural changes in recent decades with typical socio-economic side-effects (high unemployment, population decline, vacant properties, etc.). Although this negative trend was reversed in recent years, the housing market overall can still be described as depressed and in low demand compared to many other large German cities. However, there is variation on the small-scale. Wuppertal had – and still has – highly-priced residential areas, especially in the former villa districts (e.g. Briller Viertel, Zoo Viertel). The city is also characterised by a valley axis in an east-west direction. The former workers' housing estates, which were built in the highly dense valley areas, are still simple residential areas, often inhabited by lower-income households. Meanwhile, the middle class lives mainly on the southern and northern hillsides. To reflect these differences, an indication of the quality of the residential area was also assigned to each listing (split into four levels: simple, average, good and exclusive; see Figure 2b) to allow for a small-scale and differentiated perspective on the tenants' WTP.

⁴ Official property register, which collates and integrates several data points of a property (address, usage, ownership, etc.) into a single dataset.

3.2 Methodology

3.2.1 Hedonic Regression

As shown in section 2, hedonic regression models are mainly used to determine willingness to pay for energy efficiency in housing markets. This makes it possible to assign a value to different characteristics of a property, even though it is not possible to observe the actual value of these characteristics.

We estimated a semi-log regression model with the listed price per square meter for apartment rents as the dependent variable. The log of the rental price can be expressed by the following equation (1):

$$\ln(\text{price}_i) = \alpha + \beta \text{EE}_i + \gamma \text{H}_i + \delta \text{N}_i + \mu \text{T}_i + \varepsilon_i \quad (1)$$

EE - Energy performance of the apartment based on EPC measured in kWh/sqm*a (Note: a higher value indicates lower energy efficiency, and vice versa)

H - Housing/apartment characteristics (e.g. floor, fitted kitchen, building age, living space, etc.)

N - Neighbourhood characteristics (e.g. population density, unemployment rate, etc.)

T - Dummy variable for year of advertisement

ε - Error term

3.2.2 Spatial Regression

One of the key assumptions of ordinary least squares (OLS) regressions is that the observations are independent of each other. However, this assumption is often violated, especially in the case of spatial data – or, as Tobler (1970) describes: “Everything is related to everything else, but near things are more related than distant things.” If spatial autocorrelation exists, estimates of the coefficients are inaccurate and the standard errors show spatial dependencies (i.e. meaningful information). Therefore, spatial regression models are more appropriate as they can accurately take into account the spatial dependence of variables. Spatial regression models have been widely applied to different research questions and areas, ranging from the environmental sector (Sannigrahi et al., 2020; Wu et al., 2020; Zou and Shi, 2020) to mobility studies (Sanni and Abrantes, 2010) and the field of economics (Calabrese et al., 2017; Woods and Gordon, 2011).

We assessed the degree of spatial dependence of the OLS model above (see section 3.2.1) using a Moran’s I value of the residuals of the regression (I_r). We then calculated the weights matrices of our dataset for different distances⁵, ultimately focusing on a 100m radius to assess the direct neighbourhood effects.

⁵ We used GeoDa 1.14 for the calculation. Examining distances of 100m, 250m and 500m yielded similar results; therefore, we only report the results of the 100m weights matrices.

Subsequently, Lagrange Multiplier (LM-lag, LM-Error) and Robust LM (robust LM-lag, robust LM-Error) were calculated to choose the appropriate spatial regression model specification. Based on the recommendation by Anselin and Rey (2014)⁶, we ran a spatial error model (SEM)⁷. SEM assumes that spatial dependence exists within the residuals. Therefore, the residuals are decomposed into a spatial component of the error term and a random component.

$$\ln(\text{price}_i) = \alpha + \beta EE_i + \gamma H_i + \delta N_i + \mu T_i + u_i \quad (2)$$

EE - Energy performance of the apartment based on EPC measured in kWh/sqm*a

H - Housing/apartment characteristics (e.g. floor, fitted kitchen, building age, living space, etc.)

N - Neighbourhood characteristics (e.g. population density, unemployment rate, etc.)

T - Dummy variable for year of advertisement

ϵ - Error term

with

$$u_i = \lambda w_i * u_j + \epsilon_i \quad (3)$$

where u_i and u_j are the error terms at locations i and j respectively, w_i is a vector that expresses the spatial relationship (weights matrix), and λ is the coefficient of spatial component errors.

Finally, in a second analysis, we subset the dataset with regard to the four residential areas described in section 3.1.2 and illustrated in Figure 2b to assess small-scale spatial differences between the tenants' WTP.

⁶ The authors propose a multi-stage decision process to decide whether an OLS, a spatial error or a spatial lag model should be performed. For this purpose, LM-lag and LM-Error diagnostics are first performed for the OLS regression. If the results are significant, a robust LM-lag and robust LM-Error are carried out in the second step. Following these steps for the model presented here suggests the use of an SEM as the recommended model.

⁷ The regression analysis was conducted using R version 4.0.1. For the spatial regression we used the “spdep” package.

4 Results

4.1 Descriptive statistics

Table 2 provides an overview of all variables included in the model. Appendix 1 also presents a correlation matrix of the key variables. The dependent variable (rental price) and main independent variable (energy performance) are now described in more detail.

With a median rent level of 5.84 Euro/sqm (IQR=1.32) during the period observed, the housing market in Wuppertal can be described as relatively low compared to other German cities – despite an increase in rental prices of almost 12% between 2012 and 2019 (see Figure 1). However, rent levels vary across the city, with lower rents observed along the highly dense valley axis, especially in the east of the city, as well as along the main transport routes. In contrast, rents are higher on the so-called southern and northern hillsides, which are less densely built up. Highly priced inner-city locations exist mainly in the former villa districts (Briller Viertel, Zoo Viertel). This spatial pattern also correlates with the social structure of the areas, as illustrated in Figure 2.

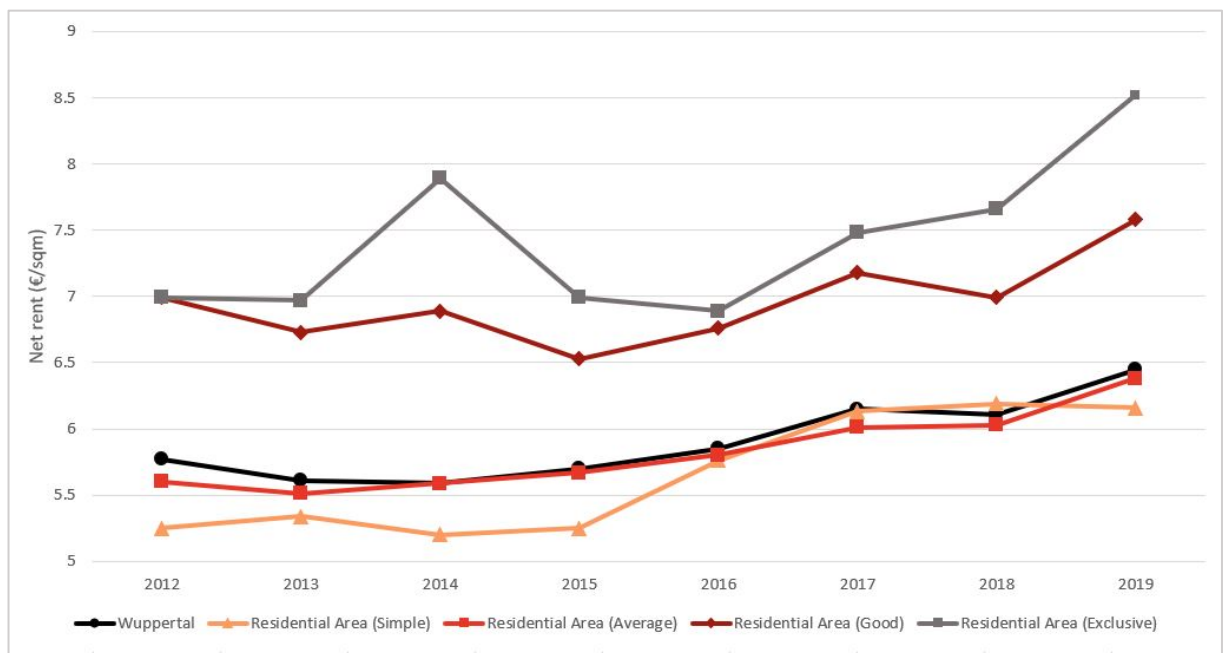


Figure 1: Median rent level development 2012-2019 in Wuppertal and in different residential locations

Table 2: Model variables and descriptive statistics

Statistic	Codification	Description	N	Mean	St. Dev.	Min	Max
Hedonic apartment characteristics							
Rent	€/sqm	Requested net rent per square metre (Dependent Variable)	12,232	6.05	1.10	3.07	12.97
EE_EPC	kWh/sqm*a	Final energy performance based on EPC	12,232	145.70	50.12	0	374
Living space	sqm	Living space of the apartment (Logarithmized)	12,232	4.18	0.34	2.77	5.12
BAge_1750_1850	(0/1)	Building constructed before 1851 (reference category)	12,232	0.00	0.02	0	1
BAge_1851_1918	(0/1)	Building constructed between 1851 and 1918	12,232	0.13	0.34	0	1
BAge_1919_1948	(0/1)	Building constructed between 1919 and 1948	12,232	0.07	0.26	0	1
BAge_1949_1978	(0/1)	Building constructed between 1949 and 1978	12,232	0.60	0.49	0	1
BAge_1979_2019	(0/1)	Building constructed after 1979	12,232	0.19	0.39	0	1
Quality		Indicates the quality of the facilities of the apartment					
Quality (Simple)	(0/1)	Simple quality	12,232	0.03	0.17	0	1
Quality (Normal)	(0/1)	Normal quality (reference category)	12,232	0.66	0.47	0	1
Quality (Upmarket)	(0/1)	Upmarket quality	12,232	0.30	0.46	0	1
Quality (Luxury)	(0/1)	Luxury quality	12,232	0.01	0.12	0	1
Kitchen	(0/1)	Fitted kitchen included in the rent	12,232	0.18	0.39	0	1
Balcony	(0/1)	Balcony belongs to the apartment	12,232	0.57	0.50	0	1
Basement	(0/1)	Basement belongs to the apartment	12,232	0.43	0.49	0	1
Elevator	(0/1)	Elevator available	12,232	0.19	0.40	0	1
Garden	(0/1)	Garden available and free to use	12,232	0.22	0.41	0	1
Guest toilet	(0/1)	Guest toilet belongs to the apartment	12,232	0.14	0.34	0	1
Accessibility	(0/1)	Apartment and/or building is disability friendly	12,232	0.01	0.12	0	1
Parking	(0/1)	Garage or parking space belongs to the apartment	12,232	0.12	0.33	0	1
EPC	(0/1)	Indicates whether the EPC is based on calculated energy demand (0) or measured energy consumption (1)	12,232	0.83	0.38	0	1
EPC_HotWater	(0/1)	Hot water included in the EPC	12,232	0.23	0.42	0	1
Central Heating	(0/1)	Apartment heated by central heating	12,232	0.62	0.49	0	1
Environmental Heating	(0/1)	Heating system completely or partly fuelled by environmentally friendly fuels (e.g. solar heating, pellet heating)	12,232	0.07	0.26	0	1
Runtime	Days	Number of days the advertisement was online	12,232	42.41	60.35	1	1,049
Neighbourhood characteristics							
Traffic area	%	Share of traffic area within the building block	12,232	22.09	9.76	1.62	80.54
Recreational area	%	Share of recreational area within the neighbourhood	12,232	47.59	20.05	3.05	90.08
Green voters	%	Share of Green (Bündnis 90/Die Grünen) voters in the voting district (2017 federal election)	12,232	8.34	2.88	1.43	19.18
Unemployment	%	Unemployment rate (2017) within the building block	12,232	7.81	4.83	0.00	53.03
Pop.Density	Pop/sqkm	Population density in inhabitants per square km	12,232	1,369	864.7	0.18	4,893
Time							
Year		Year the advertisement was online					
2012	(0/1)		12,232	0.06	0.23	0	1
2013	(0/1)		12,232	0.06	0.24	0	1
2014	(0/1)		12,232	0.19	0.39	0	1
2015	(0/1)		12,232	0.26	0.44	0	1
2016	(0/1)		12,232	0.16	0.37	0	1
2017	(0/1)		12,232	0.12	0.33	0	1
2018	(0/1)		12,232	0.08	0.28	0	1
2019	(0/1)		12,232	0.06	0.25	0	1

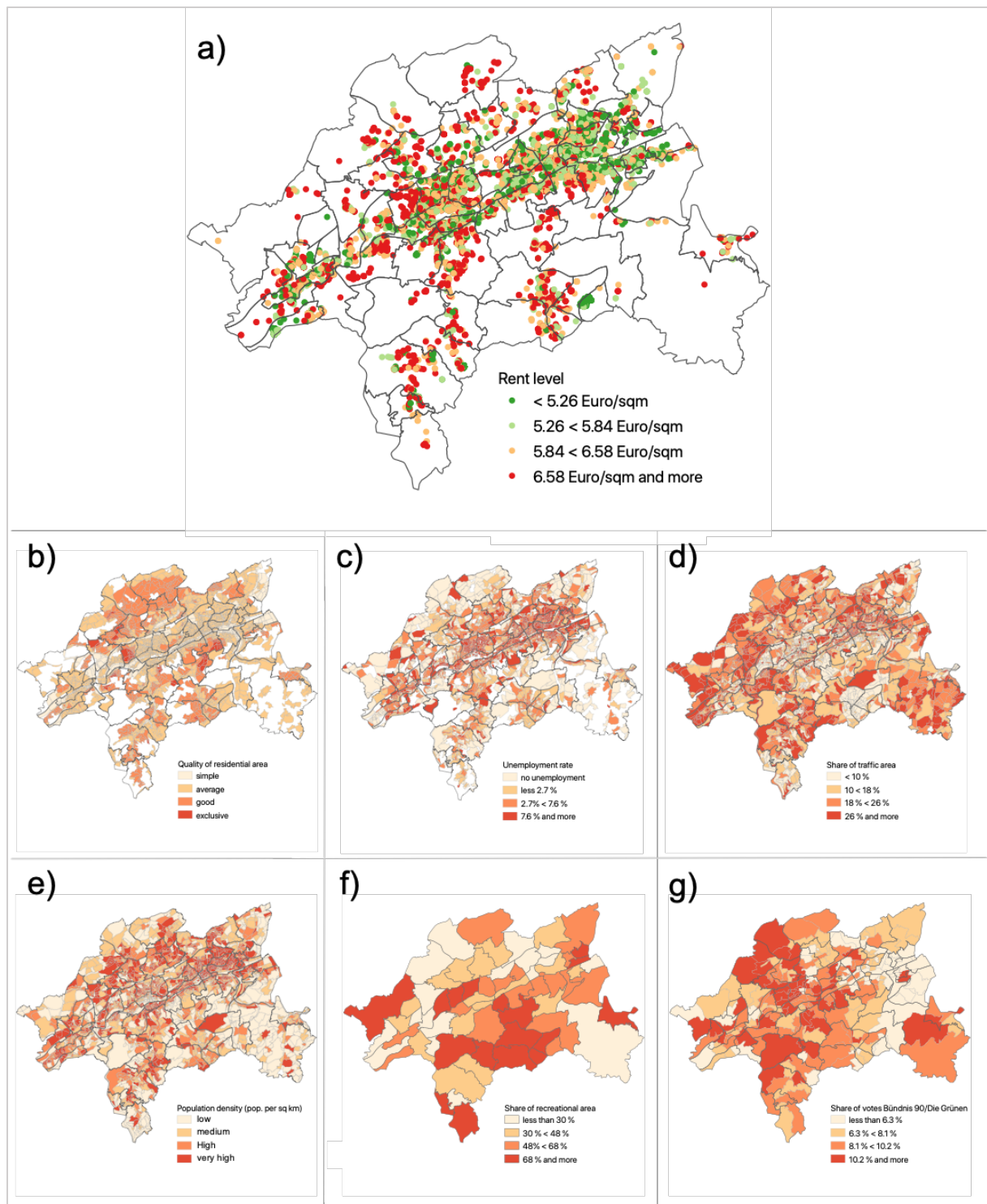


Figure 2: Spatial distribution of the dependent variable (rental price (a)) and spatially relevant independent variables (quality of residential area (b); unemployment rate (c); share of traffic area (d); population density (e); share of recreational area (f); share of Green Party votes (g))

According to the EPC, the average final energy performance of the rental apartments on offer was 143 kWh/sqm (Median=143, IQR=66.25). With a total range of 374 kWh/sqm, it is clear that the city has some highly energy-efficient buildings and some buildings with enormous energy efficiency potential. Only 2% of all listed apartments have an A+/A EPC rating, while almost 12% are labelled G/H and more than 80% are labelled C to F (see Figure 3). As the bivariate comparison between the rental price and the energy performance shown in Figure 3 further illustrates, a substantially higher monthly net rent price (compared to the median) can be obtained on the market for apartments with an energy efficiency label of A+ (1.71 Euro/sqm), A (2.67 Euro/sqm) or B (0.95 Euro/sqm) (6% of all cases). Most of these apartments are in properties built after 1978; i.e. after the introduction of the first Thermal Insulation Ordinance defining minimum energy efficiency standards for new buildings. For all other cases there seems to be no evidence of this price effect; although there is an energy efficiency price premium, the extremely energy-inefficient properties are not penalised by the market with a price discount.

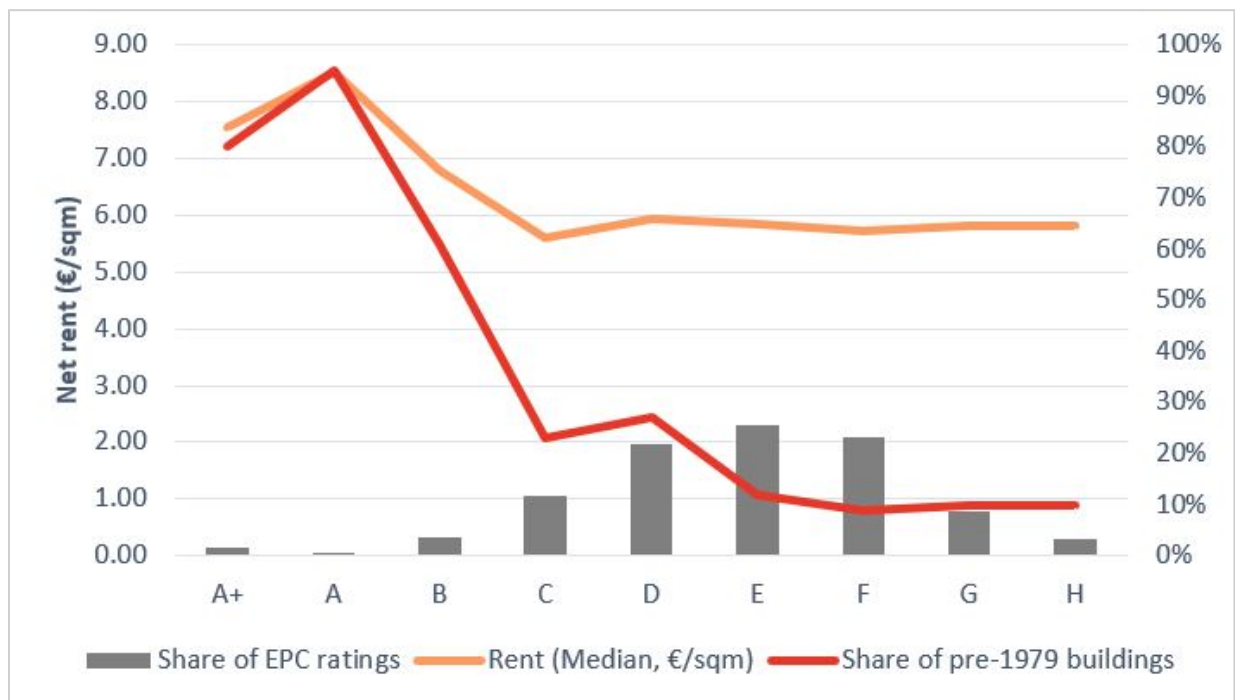


Figure 3: Median rent level depending on the EPC rating

4.2 Regression analysis

4.2.1 Wuppertal

Table 3 shows the results of the hedonic ordinary least squares (OLS) regression and the spatial error model (SEM) regression. Both models yielded similar results and allow for similar conclusions to be drawn. As the dependent variable shows spatial autocorrelation (Moran's $I = .493$, $z\text{-value} = 121.23$, $p < .001$) and the residuals of the OLS model indicate spatial dependency (Moran's $I_{\text{Residuals}} = 0.32$, $p < .001$),

the SEM model appears to be preferable. This is also supported by the lower Akaike information criterion (AIC) value and the overall higher fit of the model.

Table 3: Results of OLS and SEM regression

	OLS		SEM	
	<i>Coefficient</i>	<i>Standard Error</i>	<i>Coefficient</i>	<i>Standard Error</i>
(Intercept)	1.98468384 ***	0.097687	1.933182 ***	(0.049316)
Energy Performance	-0.00007408 ***	0.000022	-0.000166 ***	(0.000023)
Living space	-0.11591536 ***	0.003895	-0.112507 ***	(0.003268)
Building Age 1851_1918	0.01731401	0.089293	0.022636	(0.034930)
Building Age 1919_1948	0.02114847	0.089287	0.019827	(0.035064)
Building Age 1949_1978	0.03309164	0.089234	0.029718	(0.034889)
Building Age 1979_2019	0.07795310	0.089279	0.058154	(0.034996)
Quality (Simple)	-0.05679756 ***	0.005330	-0.044319 ***	(0.005705)
Quality (Upmarket)	0.10644928 ***	0.002540	0.087984 ***	(0.002271)
Quality (Exclusive)	0.21911791 ***	0.010028	0.181007 ***	(0.008268)
Kitchen	0.04612818 ***	0.002950	0.037307 ***	(0.002440)
Balcony	0.03606259 ***	0.002239	0.034536 ***	(0.002193)
Basement	-0.00539780 *	0.002715	-0.005419 *	(0.002376)
Elevator	-0.00997136 **	0.003318	-0.003752	(0.003467)
Garden	0.01451244 ***	0.002443	0.010769 ***	(0.002422)
Guest toilet	0.03791239 ***	0.003324	0.024863 ***	(0.003122)
Accessibility	0.03675994 **	0.012261	0.018873 *	(0.008038)
Parking	0.02606115 ***	0.003643	0.021141 ***	(0.003294)
EPC	-0.02100609 ***	0.002889	-0.011557 ***	(0.002757)
EPC_HotWater	-0.00401462	0.002555	-0.004509	(0.002423)
Central heating	0.00686402 **	0.002188	0.002508	(0.002183)
Environmental heating	0.04468381 ***	0.004775	0.022187 ***	(0.004924)
Runtime	0.00000073	0.000022	0.000042 **	(0.000015)
Traffic area	-0.00034552 **	0.000112	-0.000006 ***	(0.000002)
Recreational area	0.00008961	0.000052	0.000001	(0.000001)
Green voters	0.00550426 ***	0.000400	0.000058 ***	(0.000007)
Unemployment	-0.00469154 ***	0.000324	-0.000031 ***	(0.000003)
Population Density	-0.00000217	0.000001	-0.000000	(0.000002)
2013	-0.00611904	0.005569	-0.001974	(0.004762)
2014	0.00872710	0.004648	0.019020 ***	(0.004127)
2015	0.02333274 ***	0.004617	0.025383 ***	(0.004145)
2016	0.04145683 ***	0.005020	0.046629 ***	(0.004429)
2017	0.06966202 ***	0.005700	0.074256 ***	(0.005036)
2018	0.07355080 ***	0.005865	0.085047 ***	(0.005199)
2019	0.09908348 ***	0.006423	0.111744 ***	(0.005449)
Spatial error (λ)			0.665085 ***	(0.008927)
<i>N</i>	12232		12232	
<i>F</i> / Likelihood Ratio (LR)	283.00 ***		3263.20 ***	
Adjusted / Pseudo R^2	0.452		0.611268	
AIC	-19535		-22796.12	

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; Heteroscedasticity-consistent standard errors are shown for the OLS regression

As the SEM model appears preferable, the following explanations focus exclusively on its data. The SEM model was found to be significant ($LR=3263.20$, $p<.001$), with a Nagelkerke Pseudo R^2 of 0.61, indicating a reasonable goodness of fit. In line with the descriptive statistics and the findings of other studies (see section 2), the SEM model (as well as the OLS model) shows a statistically significant price premium for energy performance ($b_{Energy\ Performance}=-0.00017$, $p<.001$). This can be interpreted as follows: the willingness to pay increases by 0.017% for each improvement in energy efficiency of 1 kWh/sqm*a (i.e.

the energy performance value is reduced by 1 kWh/sqm*a). In terms of the EPC rating, this results in the following picture: apartments with an A or B rating receive a price premium of 3.15% and 2.76% respectively compared to those apartments with a G rating.

A comparison of the relative influence of other apartment features on rental prices shows that these lead to larger increases in prices. For example, rental prices increase by 3.7% if an apartment features a fitted kitchen. Translating the WTP for different apartment features into corresponding improvements in energy efficiency shows that landlords would have to improve the energy performance of their rented apartment by 223 kWh/sqm*a⁸ to achieve the same price premium on the market as for a fitted kitchen. According to our model, the rental price is most strongly influenced by the general equipment and quality of the apartment ($b_{Quality\ (Exclusive)} = 0.18101, p < .001$). Consequently, exclusive features in a property, such as a high-quality wooden floor, high-quality fittings, doors, lighting and electrical installations or smooth plastered walls, are likely to be rewarded with a rental premium, while their absence tends to be penalised with a rental discount. This is clearly indicated by the relative reduction in rental price for apartments of simple quality compared to those of normal quality ($b_{Quality\ (Simple)} = -0.044329, p < .001$) and highlights that while WTP for energy efficiency does exist, other features have a stronger effect on the rental price. Although we do not make a definitive economic comparison between the investment costs for increased energy efficiency performance and the other features, the figures point in a clear direction: although the WTP-equivalent energy efficiency improvement is mathematically possible for many features (e.g. kitchen, balcony), it makes no sense from a building physics point of view. An improvement of the energy performance by 223 kWh/sqm*a would turn 94% of the apartments in our dataset into energy-plus properties.

4.2.2 Residential areas

The analysis of WTP for energy efficiency split by residential locations (see Table 4) allows for a more differentiated understanding of the willingness to pay for energy efficiency across Wuppertal. While energy efficiency significantly affects rental prices in simple, average and good residential areas, it does not have a significant influence in exclusive areas. Furthermore, improvements in energy efficiency lead to higher rental prices in average and good areas but not in simple residential areas – suggesting that WTP increases with the prestige of the location. In simple residential areas, energy-efficient housing tends to be penalised with a discount ($b_{Energy\ Performance} = 0.00014, p < .05$).

Table 4: SEM-Model for each residential area

	Simple	Average	Good	Exclusive
Energy Performance	0.00014 *	-0.00019 ***	-0.00029 ***	-0.00026
	(0.00006)	(0.00003)	(0.00008)	(0.00023)
Apartment characteristics	✓	✓	✓	✓
Neighbourhood characteristics	✓	✓	✓	✓
Time	✓	✓	✓	✓
Lambda	0.58003 ***	0.67856 ***	0.56532 ***	0.33045 ***
	(0.02869)	(0.01068)	(0.02267)	(0.08422)
N	1545	9260	1260	155
(Pseudo) R2	0.61411	0.57407	0.68705	0.67343
AIC	-2954.57772	-18031.03925	-2243.33783	-255.43674

⁸ WTP increases by 3.8% for a fitted kitchen. 3.8% divided by 0.017% per kWh/sqm leads to an increase of 223 kWh/sqm, which equals the WTP for a fitted kitchen.

*** p < 0.001; ** p < 0.01; * p < 0.05.

4.2.3 Sensitivity Analysis

In order to examine the sensitivity of the impact of energy efficiency performance on rental prices, the different regression models were modified by omitting relevant variables. Following Evangelista et al. (2020), a total of six variables were identified and the models were re-estimated in seven different scenarios without these variables. The variables chosen were dwelling characteristics that correlate most with energy efficiency (BAge_1979-2019, Balcony, Elevator) and neighbourhood characteristics that are not commonly used in hedonic regression models (Traffic area, Recreational area, Green voters). For each of the first six scenarios, one variable is omitted respectively. In the seventh scenario, all six variables are omitted.

Overall, the sensitivity analysis revealed only minor changes compared to the benchmark model (Table 5). The largest change was observed for the exclusive residential area. However, since this model contains only 155 cases, it is not surprising that the coefficient is slightly more sensitive to the different omitted variable scenarios than in all other regression models. For the all-omitted scenario of the SEM model, the coefficient of the energy performance parameter increases to -0.00018 compared to -0.00017. In terms of the EPC rating, this result means that apartments with an A or B rating receive a price premium of 3.33% (3.15%) and 2.93% (2.76%) respectively compared to those flats with a G rating.

Table 5: Sensitivity analysis of energy performance parameter estimates

	Wuppertal		Simple	Residential areas		
	OLS	SEM		Average	Good	Exclusive
Energy Performance (Benchmark)	-0.00007*** (0.00002)	-0.00017 *** (0.00002)	0.00014 * (0.00006)	-0.00019 *** (0.00003)	-0.00029 *** (0.00008)	-0.00026 (0.00023)
Energy Performance parameter estimates, omitted variables scenarios						
Building Age 1979_2019	-0.00007*** (0.00002)	-0.00017*** (0.00002)	0.00017** (0.00006)	-0.0019*** (0.00003)	-0.00029*** (0.00008)	-0.00026 (0.00023)
Balcony	-0.00010*** (0.00002)	-0.00018*** (0.00002)	0.00013* (0.00006)	-0.0018*** (0.00003)	-0.00028*** (0.00008)	-0.00440 (0.00021)
Elevator	-0.00007*** (0.00002)	-0.00016 *** (0.00002)	0.00017** (0.00006)	-0.0019*** (0.00003)	-0.00029 *** (0.00008)	-0.00023 (0.00025)
Traffic area	-0.00008*** (0.00002)	-0.00017*** (0.00002)	0.00017** (0.00006)	-0.0017*** (0.00003)	-0.00027*** (0.00008)	-0.00025 (0.00023)
Recreational area	-0.00007*** (0.00002)	-0.00017*** (0.00002)	0.00017** (0.00006)	-0.0019*** (0.00003)	-0.00029*** (0.00008)	-0.00025 (0.00023)
Green voters	-0.00005** (0.00002)	-0.00016*** (0.00002)	0.00015* (0.00006)	-0.0020*** (0.00003)	-0.00028*** (0.00008)	-0.0030 (0.00023)
All omitted	-0.00008*** (0.00002)	-0.00018*** (0.00002)	0.00012* (0.00006)	-0.0018*** (0.00003)	-0.00027*** (0.00008)	-0.00030 (0.00024)

*** p < 0.001; ** p < 0.01; * p < 0.05.

5 Discussion and policy implications

Our model supports the results of other studies: tenants are willing to pay a premium for energy efficiency⁹. However, their WTP is low, both compared to other apartment features and in absolute terms. This means that investments in energy efficiency are barely economically viable for landlords under the conditions observed for the 2012-2019 housing market in Wuppertal. For example, a price premium of 3.15% for an energy efficiency improvement resulting in an upgrade of the EPC rating from G to A relates to an absolute increase of the median rent of 0.18 Euro/sqm per month. The Germany Energy Agency predicts that energy-related investment costs will amount to 230 Euro/sqm for such a renovation, resulting in a payback period of more than 100 years. A less ambitious renovation (upgrading from a G rating to a C rating) is expected to cost 80 Euro/sqm, which still implies a payback period of 48 years. Both calculations are rather rough, as the actual renovation costs depend very much on the building in question. Nevertheless, it is clear that the WTP in Wuppertal, which is in line with previous studies presented above (see Table 1), is currently not sufficient to refinance the energy-related renovation costs via the rental market within a reasonable time frame. In addition to increased rents, the easier re-letting of property and resultant reduced vacant periods are commonly perceived to be areas where landlords who invest in energy-efficiency retrofitting benefit. However, there is no evidence of easier re-letting (indicated by shorter runtimes of online listings for more energy-efficient listings) in our dataset ($R_s = -.01$; $p > .05$).

Moreover, there is the issue of opportunity costs for landlords, who must consider and choose from a number of possible investment options. This is particularly true in low-demand markets such as Wuppertal. The analysis illustrates that a balcony, a fitted kitchen, a guest toilet – in short, a variety of visible apartment features – are more appreciated by tenants. Although energy efficiency, like the other features, increases living comfort (e.g. fewer draughts, reduced risk of mould, etc.) and offers cost savings (in terms of heating), the market rewards other, more visible features with comparatively higher rents. From the landlords' perspective, therefore, it seems rational to allocate their limited financial budgets to those investments that will be more profitable in the long run. Although few landlords perform quantitative analyses like the one presented here, anecdotal evidence and general knowledge of “how the market works” is gained over time and is very likely to broadly reflect the findings from this quantitative analysis. Six conclusions can be drawn regarding the implications of these findings for the required increase in energy-related renovation rates and depth.

First, although numerous studies highlight the economic benefits and profitability of energy efficiency and its co-benefits (Thema et al., 2017; März, 2018a; Ürges-Vorsatz et al., 2016), there is still a considerable refurbishment backlog (Cischinsky and Diefenbach, 2018). Our analysis provides an important

⁹ For the interpretation of results, it should be pointed out that tenants in Wuppertal, as in the rest of Germany, pay their heating costs themselves in most cases, either through direct supply contracts with energy providers or by allowing landlords to pass on the heating costs completely. One exception is recipients of transfer payments. Their heating costs, if reasonable, are covered by state authorities, where what is considered reasonable is decided individually by each municipality. In Wuppertal, an actual heating energy consumption of 190-210 kWh/sqm is assumed. If the heating costs are higher, the transfer recipient must pay the additional costs themselves. If they are lower, there is no energy efficiency incentive for either the tenant or the landlord, as the actual costs are covered.

explanation for this backlog in rental housing markets, especially where demand is low. Our model shows that investments in energy efficiency are not appealing from a landlord's perspective while tenants' WTP remains so low. The risk of not being able to refinance the upfront investment costs on the market through a higher net base rent or easier re-letting and reduced vacant periods is high. In Germany, the legislator has reacted to this challenge by creating the "modernisation surcharge" ("Modernisierungsumlage"), a policy instrument under which the annual net base rent can be increased by 8% of energy-related investment costs. However, this instrument applies primarily to existing lettings, not to new lettings as examined in this study. Furthermore, studies have shown that landlords tend to adjust the rent only partially in ongoing tenancies (Henger and Voigtländer, 2011); our analysis additionally makes it clear that WTP in the case of new tenancies is low. The instrument has also attracted considerable criticism in recent years due to the risk of combining energy efficiency renovations with luxury renovations (involving other features shown here to increase the attractiveness of rented property) and the resulting risk of energy-related gentrification¹⁰. Other refinancing models are therefore needed. The German National Tenants' Association, for example, proposes a shared cost model for energy efficiency, where the investment costs are split equally between the federal state (through a system of grants, possibly repayment grants), the owner (equity capital) and the tenants (rising net rent) (Siebenkotten, 2018).

Against the backdrop of the required rapid decarbonisation of the existing building stock, it seems appropriate to start a debate about introducing an obligation to refurbish (at key windows of opportunity, such as at the point of sale, inheritance, etc.) or linking the permission to let to the energy efficiency of the property (Gaßner and Neusüß, 2011; März, 2018b; Pehnt et al., 2015). There are international precedents: in France, an obligation to refurbish has already been introduced, requiring all private residential buildings with a primary energy consumption of more than 330 kWh/sqm*a to be renovated by 2025. In addition, from 2030 onwards, residential buildings can only be sold if they have undergone energetic renovation (Légifrance, 2020). The US city of Boulder is taking an indirect approach to imposing an obligation to refurbish: residential property landlords must apply for letting licences and since 2019, as part of the 'SmartRegs-Ordinance', these licences have been linked to minimum energy standards (City of Boulder, 2018).

Another regulatory way forward could be a step-by-step renovation roadmap for the entire German residential building stock. In such a model, mandatory standards for energy efficiency and for the reduction of greenhouse gas emissions would be set out for the future, with the limits set based on the long-term goal of a climate-neutral building stock by 2050 (Pehnt et al., 2015, p. 54ff.).

¹⁰ It is difficult to differentiate between maintenance costs and energy-related additional costs, and this has led in some cases to considerable cost increases because maintenance costs have also been included. §559c of the German Civil Code (BGB) allows for a simplified procedure, in which a fixed amount of 70% of the investment costs can be assessed and apportioned as being energy-related.

While the different paths vary quite significantly, the intention remains the same: to create financial incentives and pressure for landlords to act, because the current landscape of financial incentives – grants, soft loans and the modernisation surcharge – is insufficient to galvanise most landlords.

Second, in addition to strengthening the investment incentives for private landlords, stronger incentives are needed for tenants to make energy efficiency a relevant rental criterion and to demand it on the market. Campaigns have long been used as a tool to highlight the co-benefits of energy efficiency and, by doing so, to foster intrinsic behaviour – but these campaigns have had limited success. The lack of accessible information on heating costs has been a contributory factor, as the heating costs currently listed in advertisements (based on the heating behaviour of previous tenants) or the EPC do not allow for an easy and realistic calculation of expected heating costs. Using campaigns instead to focus on and explain economic or even regulatory instruments may prove more beneficial and create greater acceptance for other policies, such as charging for CO₂ emissions. Germany will introduce a CO₂ tax on 1st January 2021 at a rate of 25 Euro/t (BMWi, 2020). However, this starting price is unlikely to lead to significant changes in the willingness to pay. For natural gas, the end customer price would increase by 0.6 cents per kWh (net), i.e. by 12%. Assuming an annual consumption of 10,000 kWh, the additional burden on the household would only amount to 73 Euro inc. VAT, which could probably be offset by changing to an alternative energy provider with lower tariffs. Consequently, a higher entry price or rapid increase in the CO₂ price would be necessary for this instrument to be effective. With a CO₂ price of 180 Euro/t, as demanded by the German Environmental Protection Agency ‘UBA’ (Matthey and Bünger, 2019) and the climate movement ‘Fridays for Future’ (Fridays for Future, 2019), the price increase would amount to 88%, or 529 Euro per year. This would create a significantly higher incentive for tenants to make energy efficiency a central rental criterion and for landlords to invest in energy efficiency to stay competitive in the market. However, such measures would need political support in order to reduce social inequalities and ensure affordable housing.

The third aspect refers to spatial or neighbourhood-specific framework conditions for energy efficiency. While we identified an energy efficiency premium at city-wide level, the small-scale analysis of four diverse residential areas provides a more differentiated picture. For the average and good residential locations a price premium does exist, and it increases according to the quality of the residential location. Tenants are not only willing to pay higher rents overall but are also prepared to pay above average prices for energy-efficient apartments. However, this effect is reversed in simple residential locations, where energy efficiency is actually penalised by the market in the form of reduced rents. We can only speculate about the causes at this point. An above-average number of social benefit holders live in these residential locations. Since the German social welfare system covers their heating costs, it is plausible that energy efficiency is not a relevant rental criterion for them because heating costs do not burden their household income. Likewise, these neighbourhoods tend to be increasingly inhabited by people with lower educational backgrounds who also tend to have lower awareness of environmental and cost-effectiveness issues. All in all, it appears that the investment conditions for landlords are particularly unfavourable in

locations where energy efficiency has the greatest potential to provide co-benefits (e.g. avoidance of energy poverty, health improvement due to avoidance of mould, reduction of tax expenditure for social benefit holders, etc.) On the one hand, the low rent level makes refinancing more difficult and, on the other hand, there is no WTP on the tenants' side – in fact, quite the opposite. A possible solution could be a spatial differentiation of the funding framework. As it does for urban development funding programmes (e.g. Stadtumbau West), the German development bank *KfW* could, for example, provide specific funding for neighbourhoods with high energy efficiency potential but low likelihood to tap into this potential.

A fourth aspect refers to the shift in the relative roles of energy efficiency and renewable energies in achieving climate-neutral building stock. The two complementary strategies are essential for the decarbonisation of the building stock and are promoted by the German government through grants and low-interest loans. However, the respective level of ambition with regards to each strategy may differ. Within the German government's 'Energy Efficiency Strategy for Buildings' framework, a target corridor has been calculated which contributes to the decarbonisation of the building stock. Accordingly, a decarbonisation strategy focusing on renewable energies needs to reduce final energy consumption by 36%, and 69% of buildings need to be supplied with renewable energies. If the focus is on energy-related building refurbishment, on the other hand, final energy consumption needs to be reduced by 54%, and 57% of buildings need to be supplied with renewable energies (BMW, 2015, p. 15). Our model suggests that in rental markets, a stronger focus on the expansion of renewable energies may be an easier way to achieve a climate-neutral building stock, provided the potential for heat supply from renewable energies exists. Tenants show a significantly higher WTP for renewable heating technologies, meaning investments may be more likely to be refinanced via the market, depending on the level of investment needed.

The fifth observation is that even in a low-demand residential market, such as in Wuppertal, rents have been on an upward trajectory in recent years. While the median net rent remained largely stable between 2006 and 2012, it subsequently rose by 12% in the period 2012-2019. This development illustrates that rent increases to refinance energy efficiency investments are possible. However, as shown in section 3.2.21, tenants currently have different rental preferences, making it difficult to pass on price increases for energy efficiency. The observed increase in rental prices can be explained partly by higher apartment quality (e.g. increase in the share of fitted kitchens), but it also reflects general price development on the German and international housing markets (Neubrand and Brack, 2020; OECD, 2020). Since 2014, the year dummy variables are statistically significant in all models, landlords have been receiving a price premium on their rented apartments independent of the apartment characteristics and explained by the time factor alone. This effect has also increased over the years. While the price premium was only 1.9% in 2014, by 2019 it was already 11.2%, all else being equal.

The sixth aspect refers to the importance of rent increases within the context of urban development policy. The price increase observed for the city as a whole is also visible in the different residential locations within the urban fabric. Rents are rising in all four residential locations considered; however, the

increase differs in intensity, with advertisements for exclusive residential locations showing the highest price increase (22%). However, the few rental properties in this category (n=155) are of no importance for urban development policy from an energy efficiency point of view. The second highest increase in rental prices is recorded in advertisements for simple residential areas (17%). This increase is even higher than the city-wide average. Taking into account the fact that real household income in Wuppertal has fallen by an average of 2.8% since 2000, it is clear that the rent burden ratio has risen in Wuppertal in recent years. Consequently, low-income households face the risk of gentrification, i.e. they are likely to find it increasingly difficult to rent affordable housing in Wuppertal. This difficulty is compounded by the policy of only adjusting the regulations for benefit recipients in response to rent increases to a limited extent and with delay. In 2019, for example, only 9.07% of all IS24 apartment rental listings in Wuppertal were below the level of the net rent (per sqm) set and financed by the municipality. Furthermore, our data shows that low-priced housing is mainly in undesirable residential locations (e.g. in areas with high volumes of traffic) and that low-income households are overrepresented in these areas. This points to the existence of segregation tendencies in urban development policy. Investments in energy efficiency and the associated cost allocations are in danger of furthering this social segregation and should, therefore, be considered against the backdrop of social and urban development policy objectives. In addition, as previously highlighted, investments in energy efficiency in 'simple' housing for low-income groups should receive special funding to limit the resulting increases in rent, since improved energy efficiency in such housing has higher social benefits than in other types of residential properties.

To conclude, the analysis underlines that the rental housing market alone has so far not provided sufficient investment incentives to achieve the political goal of a climate-neutral building stock by 2050. In fact, an adjusted political framework is needed to boost energy efficiency investment. It is beyond the scope of this paper to present a comprehensive policy design. Nevertheless, some indications for policy adjustments emerge from the analysis and the results. Regulatory measures, such as a renovation obligation should play a stronger role in the future than they have so far. In this way, the lack of market incentives shown in the analysis could be overcome and the energy refurbishment rate could be significantly increased. The introduction of individual renovation roadmaps is important in order to create planning and investment security for the owners. The analysis supports the current discussion around banning the installation of fossil heating systems, because the data show a greater willingness to pay for renewable heating systems. However, a stronger obligation for landlords will only increase renovation activities if the investments can be refinanced. Therefore, the funding rates should be increased and, in the current low-interest phases, funding should primarily be given in the form of a grant. A three-way division of the costs between landlords, tenants and the state seems reasonable for a fair share of renovation costs. The political adjustments should always take into account social hardship for tenants but also landlords. The challenge is to balance the vital environmental transformation with social and urban development policy objectives in order to avoid segregation and gentrification tendencies. Regulative and financial measures should also go hand in hand with a training offensive for and the digitalisation of the

construction sector (e.g. serial renovation) in order to take account of the increased demand as well as to lower investment costs and renovation time and thus enhance acceptance by both tenants and landlords.

6 Conclusion

Boosting the rate of energy-efficiency retrofitting is an important factor in achieving a climate-neutral building stock in Germany. Despite existing funding programmes, the investment volume in energy efficiency has for years been too low to achieve environmental goals. This applies particularly to the rental housing market and is exemplified in the so-called landlord-tenant dilemma, where the benefits and costs of energy efficiency measures are distributed unevenly among different groups of actors. Due to this dilemma, investments in energy efficiency are only attractive and cost-effective for landlords if the investment costs can be refinanced by increasing rental income. We have, therefore, analysed a large dataset of rental apartment advertisements from the German property platform IS24 for the city of Wuppertal to explore tenants' WTP for energy efficiency.

In line with previous research, our results show that a price premium for energy efficiency does exist. However, this premium is too low, meaning that – according to our model – investments in energy efficiency are not an attractive investment for landlords from an economic perspective. The risk of not being able to refinance the investment costs on the market through a higher net rent or reduced vacant periods is high. Moreover, investments in other apartment features (e.g. fitted kitchen, balcony, guest toilet), as well as in heating systems based on renewable energy sources, led to significantly better refinancing on the rental market in the period 2012 to 2019.

Therefore, new or changed framework conditions are necessary to make investments in energy efficiency more attractive for both landlords and tenants. The challenge is to balance the vital environmental transformation with social and urban development policy objectives in order to avoid segregation and gentrification tendencies and create sufficient acceptance for energy-related refurbishment measures.

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Appendix 1: Spearman rank correlation matrix

	(1) Rent	(2) EE_EPC	(3) Living_s pace	(4) Building Age 1851_19 18	(5) Building Age 1919_19 48	(6) Building Age 1949_19 78	(7) Building Age 1979_20 19	(8) Quality (Simple)	(9) Quality (Upmark et)	(10) Quality (Luxury)	(11) Kitchen	(12) Balcony	(13) Basemen t	(14) Elevator	(15) Garden	(16) Guest toilet	(17) Accessibi lity	(18) Room Number
(1)		-0.079***	-0.093***	-0.12***	-0.059***	-0.12***	0.29***	-0.15***	0.38***	0.13***	0.25***	0.15***	0.13***	-0.023*	0.053***	0.10***	0.10***	0.19***
(2)			-0.065***	0.062***	0.15***	0.091***	-0.27***	-0.078***	-0.11***	-0.08***	0.019*	-0.17***	-0.029**	-0.15***	0.065***	-0.076***	-0.016	-0.046***
(3)				0.091***	0.014	-0.091***	0.024**	-0.032***	0.20***	0.098***	-0.19***	0.29***	-0.002	0.08***	0.029**	0.43***	-0.027**	0.02*
(4)					-0.11***	-0.48***	-0.19***	-0.019*	0.037***	0.016	-0.006	-0.20***	-0.082***	-0.18***	0.077***	-0.045***	-0.035***	-0.12***
(5)						-0.35***	-0.14***	-0.016	-0.057***	0.048***	-0.036***	-0.14***	0.013	-0.14***	0.087***	-0.043***	-0.029**	-0.046***
(6)							-0.60***	0.075***	-0.12***	-0.12***	-0.074***	0.068***	0.063***	0.066***	-0.045***	-0.063***	-0.052***	-0.03**
(7)								-0.067***	0.16***	0.11***	0.12***	0.18***	-0.015	0.16***	-0.069***	0.15***	0.11***	0.17***
(8)									-0.11***	-0.021*	-0.058***	0.073***	0.0015	0.068***	-0.057***	-0.051***	-0.021	0.0036
(9)										-0.08***	0.098***	0.12***	-0.03***	-0.076***	0.051***	0.17***	0.049***	0.018*
(10)											0.031***	0.027**	-0.017	-0.004	0.022*	0.061***	-0.009	-0.015
(11)												-0.023*	0.0055	-0.041***	0.0069	-0.003	0.054***	0.067***
(12)													0.059***	0.25***	-0.06***	0.20***	0.033***	0.11***
(13)														0.065***	0.0061	-0.019*	0.089***	0.31***
(14)															-0.15***	0.15***	0.16***	0.13***
(15)																0.0019	0.0004	-0.046***
(16)																	0.0003	0.042***
(17)																		0.14***
(18)																		

	(19) EPC	(20) EPC_Hot Water	(21) Central heating	(22) Environ mental heating	(23) Runtime	(24) Traffic area	(25) Recreatio nal area	(26) Green voters	(27) Unemplo yment	(28) Population Density	(29) 2013	(30) 2014	(31) 2015	(32) 2016	(33) 2017	(34) 2018	(35) 2019
(1)	-0.025**	0.049***	0.11***	0.095***	-0.033***	-0.11***	0.021*	0.19***	-0.37***	-0.15***	-0.053***	-0.11***	-0.08***	0.016	0.10***	0.088***	0.13***
(2)	0.023*	0.095***	-0.022*	-0.081***	0.021*	0.028**	-0.025**	0.072***	-0.022*	-0.002	-0.03**	-0.046***	0.055***	0.025**	0.017	-0.002	-0.041***
(3)	-0.081***	-0.064***	0.059***	0.036***	0.095***	-0.10***	0.015	-0.028**	-0.076***	-0.11***	0.0092	0.006	0.039***	0.018	-0.019*	-0.043***	-0.05***
(4)	0.031***	-0.033***	-0.13***	-0.057***	0.0073	0.056***	-0.029**	0.085***	0.085***	0.13***	0.011	0.028**	0.026**	0.0037	-0.05***	-0.021*	-0.046***
(5)	-0.026**	0.032***	-0.066***	-0.036***	-0.011	0.025**	0.013	0.064***	-0.04***	-0.043***	-0.003	-0.022*	0.032***	-0.004	0.0085	-0.007	-0.004
(6)	0.07***	-0.057***	-0.004	-0.036***	0.004	0.021*	0.017	-0.18***	0.14***	0.034***	-0.014	-0.02*	-0.022*	0.011	0.033***	0.025**	0.035***
(7)	-0.095***	0.078***	0.16***	0.12***	-0.005	-0.091***	-0.005	0.11***	-0.22***	-0.12***	0.0083	0.014	-0.015	-0.014	-0.004	-0.009	-0.001
(8)	0.056***	-0.065***	-0.031***	-0.035***	-0.048***	0.046***	-0.032***	-0.058***	0.13***	-0.036***	-0.034***	0.022*	-0.008	0.002	0.041***	-0.003	-0.017
(9)	-0.07***	0.025**	0.061***	0.065***	0.022*	-0.11***	0.041***	0.031***	-0.24***	-0.12***	0.03***	-0.01	-0.003	0.0057	-0.011	-0.032***	-0.013
(10)	-0.10***	-0.027**	0.0019	0.0057	0.011	-0.007	0.0042	0.039***	-0.062***	-0.046***	0.024**	0.0015	0.012	-0.01	-0.011	-0.013	-0.019*
(11)	0.045***	0.058***	0.024**	0.0021	-0.05***	-0.013	-0.032***	0.086***	-0.085***	-0.006	0.0007	-0.018*	-0.03**	0.019*	0.0043	0.023*	0.029**
(12)	-0.033***	-0.019*	0.18***	-0.002	-0.044***	-0.17***	0.016	-0.063***	-0.087***	-0.13***	-0.009	0.0096	-0.033***	0.017	0.022*	-0.001	-0.017
(13)	0.18***	0.014	0.0048	-0.027**	-0.064***	-0.025**	-0.037***	-0.022*	-0.024**	0.016	-0.22***	-0.41***	-0.044***	0.14***	0.34***	0.24***	0.21***
(14)	0.0098	-0.031***	0.22***	0.30***	0.076***	-0.056***	-0.005	-0.11***	0.14***	-0.047***	-0.018*	-0.003	-0.07***	0.027**	0.065***	0.027**	0.0093
(15)	-0.0006	0.07***	-0.041***	-0.082***	-0.035***	-0.05***	0.039***	0.055***	-0.14***	-0.06***	0.047***	-0.023*	-0.02*	0.0062	0.0042	-0.011	-0.015
(16)	-0.058***	0.024**	0.13***	0.088***	0.028**	-0.16***	0.052***	0.014	-0.12***	-0.11***	0.037***	0.022*	-0.005	0.0091	-0.029**	-0.048***	-0.033***
(17)	0.053***	0.089***	0.044***	0.12***	0.024**	-0.041***	0.0063	-0.005	-0.045***	-0.068***	-0.031***	-0.054***	-0.07***	-0.013	0.076***	0.071***	0.10***
(18)	0.17***	0.046***	0.10***	-0.01	-0.029**	-0.038***	-0.043***	0.019*	-0.04***	-0.055***	-0.092***	-0.16***	-0.21***	0.023*	0.30***	0.17***	0.17***
(19)		0.25***	0.0068	-0.058***	-0.006	0.01	-0.038***	-0.03**	0.045***	0.022*	-0.025**	-0.12***	-0.14***	-0.0003	0.17***	0.14***	0.12***
(20)			-0.057***	0.0052	0.021*	0.013	-0.031***	0.013	-0.084***	-0.042***	0.085***	-0.019*	-0.11***	-0.046***	0.026**	0.044***	0.043***
(21)				0.032***	0.063***	-0.14***	-0.007	-0.035***	-0.034***	-0.12***	0.053***	-0.025**	-0.066***	0.016	0.046***	0.009	-0.024**
(22)					0.078***	0.073***	-0.017	0.01	-0.018	-0.034***	0.032***	-0.001	-0.009	-0.028**	-0.019*	-0.005	0.021*
(23)						-0.012	-0.034***	-0.095***	0.021*	-0.004	0.049***	0.021*	-0.037***	0.053***	-0.038***	-0.031***	-0.061***
(24)							-0.043***	0.035***	0.28***	0.41***	-0.035***	0.041***	0.039***	-0.029**	-0.015	-0.007	0.0052
(25)								0.13***	0.048***	0.15***	0.023*	0.032***	0.029**	-0.044***	-0.025**	-0.009	-0.015
(26)									-0.24***	0.0013	-0.003	-0.001	0.011	-0.007	-0.018	0.0016	0.011
(27)										0.44***	-0.032***	0.04***	0.0033	0.0058	-0.012	0.0045	0.0088
(28)											-0.022*	0.0028	0.009	-0.016	-0.002	0.034***	0.019*
(29)												-0.12***	-0.16***	-0.11***	-0.096***	-0.078***	-0.068***
(30)													-0.29***	-0.21***	-0.18***	-0.14***	-0.13***
(31)														-0.26***	-0.22***	-0.18***	-0.16***
(32)															-0.16***	-0.13***	-0.11***
(33)																-0.11***	-0.098***
(34)																	-0.079***
(35)																	

*** p < 0.001; ** p < 0.01; * p < 0.05.

