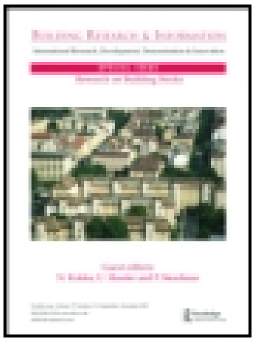

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How prebound effects compromise the market premium for energy efficiency in German house sales

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ABSTRACT
Recent studies indicate that houses with higher energy efficiency usually have higher market prices, a 'market premium for energy efficiency'. But in Germany the usefulness of this premium is confounded by the 'prebound effect': the gap between officially certificated energy ratings and actual energy consumption. Attempts have been made to close this gap from two complementary directions: downwards, by obtaining more accurate and less pessimistic technical estimates of idealised energy performance; and upwards, by estimating how much energy occupants realistically need for health and comfort. This study investigates prebound effects alongside an analysis of house prices in Germany, using a large database of house sale advertisements from 2007 to 2021, focusing on pre-1980 homes that were re-sold in 2019–2021. It uses ordinary least-squared multivariate regression to estimate market premiums for energy efficiency and sets these alongside estimates of prebound (and rebound) effects. It finds that prebound effects can lead purchasers to overestimate future energy savings and therefore pay more for properties than their actual worth. It also offers simple models to help purchasers interpret energy ratings more critically and estimate likely energy savings more realistically. Finally, it suggests how policymakers could modify energy ratings to reflect likely energy consumption more accurately.

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KEYWORDS
Prebound effect; rebound effect; energy-efficiency renovation; German real estate market; market premiums for energy efficiency

Introduction

This paper explores how prebound and rebound effects compromise market premiums for energy efficiency among older (pre-1980) houses in Germany, and what can be done to make market signals more reliably interpretable. To achieve Germany's climate goals, older residential buildings need to be retrofitted to very high energy standards (Saffari & Beagon, 2022). Homeowners need to feel that the costs of retrofitting will increase the value of their property accordingly, while purchasers need to feel they are getting value for money, with respect to energy efficiency (Cajias & Piazolo, 2013).

Recent studies have shown that, in general and on average, the market value of a home increases when it is retrofitted to a higher standard of heating energy efficiency (Taruttis & Weber, 2022). This should have a positive effect on the transition toward a low-carbon residential building stock, as it recompenses some or all of the costs of retrofitting. However, in the real world there are severe constraints on how well a real estate market can reflect the actual value of energy efficiency. Giraudet (2020) points out that, with respect to energy efficiency, there are both 'symmetric-information problems' and 'information asymmetries' in real estate markets. Symmetric information problems occur when all the actors in the market – vendors, purchasers, landlords/landladies, tenants, lenders, real estate agents, etc. – have the same information about a property but the information is wrong or incomplete. Information asymmetries occur when different actors have different information, or some have more or better information than others.

A typical 'asymmetric' information problem is whether the energy efficiency of a home is accurately reflected in its selling price. A vendor might add the cost of a recent energy efficiency retrofit to the asking price, but a potential purchaser would have great difficulty figuring out which features of the property can be related to what portions of its price, since a bare asking price does not specify this. Also, while the vendor knows precisely how much the energy efficiency retrofit cost when it was done, a potential purchaser does not know how much a retrofit

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of that kind would cost in, say, five- or ten-years' time in an alternative property that is much cheaper, especially since there are now steep increases in construction costs (Destatis, 2022).

An obvious 'symmetric' information problem is the uncertainty in energy prices over the next 25 years. The domestic gas price in Germany hovered close to 0.06 €/kWh from 2007 to 2021 but increased sharply in 2022 and was over 0.20 €/kWh at the time of writing, and very unstable. All the actors are in roughly the same position of not knowing what future energy prices will do (Zakeri & Paulavets, 2022). Potential house purchasers have to make estimates of their future expenses, based on whatever information is available at the time of purchase.

An information problem which can be either symmetric or asymmetric, and which has long bedevilled markets for energy efficiency, is the prebound effect. The prebound effect is the phenomenon that, in homes with low energy efficiency (high theoretical energy consumption), the amount of heating energy actually consumed is typically substantially lower than the home's theoretical energy consumption, which is reflected in its energy certificate. Sunikka-Blank and Galvin (2012) identified this phenomenon ten years ago in large datasets of actual and theoretical heating consumption in homes throughout western Europe. For Germany, Sunikka-Blank and Galvin found that for older, energy-inefficient homes, prebound effects of 30–35% were typical: on average the occupants consumed 30–35% less heating energy than would theoretically be consumed, based on the property's energy rating. Sunikka-Blank and Galvin also found the opposite phenomenon in homes with high energy efficiency. Occupants of such homes typically consumed more energy than the energy ratings suggested: a typical 'rebound effect'.

A large number of studies have referred to the prebound effect over the past 10 years. It is typically included in reviews of papers on occupant behaviour (e.g. Harputlugil & de Wilde, 2021; Zhang et al., 2018), technical estimation of buildings' energy efficiency (e.g. Hong et al., 2018; Manfren et al., 2021), and combinations of these (e.g. Pombo et al., 2016).

The prebound effect and rebound effect are a problem for the real estate market because they give a false signal as to how much heating energy a potential purchaser will consume. They tend to exaggerate the energy demand in older, energy-inefficient homes, and understate it in highly energy-efficient homes (Galvin, 2014). They thereby add another layer of uncertainty to the reliability of market premiums for energy efficiency. If a sales market appears to reflect, say, a premium of 300 € for each reduced kWh of energy consumption per m^2 of floor area per year (€/(kWh/m^2/y)), this does not relate to likely actual energy consumption in the dwellings that are on the market, but to a technical specification in each of these dwellings, which may or may not be an accurate reflection of how the buildings perform. When the occupants of a house change, the house's energy performance is important in assessing its value, but actual energy use will always depend on household energy practices.

There have recently been a number of studies of market premiums for energy efficiency in homes for sale and/or rent in Germany (Cajias et al., 2019; März et al., 2022; Taruttis & Weber, 2022) and several other countries (Chegut et al., 2016; Fuerst & Shimizu, 2015; Jensen et al., 2015; Marmolejo-Duarte & Chen, 2019). So far, no such studies take the prebound and rebound effects into account systematically. This study offers a first attempt to do so.

The study estimates prebound and rebound effects, and sales market premiums for energy efficiency, in detached and semi-detached houses that were built before 1980 and offered for re-sale in Germany in 2019–2021. It then brings these two sets of factors together to see how they might be interacting, and to offer suggestions for interpreting market signals with regard to energy efficiency more realistically.

Although the study mostly uses a rigorous, quantitative methodology, some of its findings need to be interpreted more qualitatively than quantitatively. This is because the low inflation and relative stability of energy prices and construction costs in 2019–2021 are now past. The lessons learned from the empirical work of this study can therefore indicate the dynamics and general trends influencing the (German) real estate market, but for some features it will not reflect the actual values the market is now dealing with.

Review of attempts to nullify the prebound effect

How prebound effects spoil estimates of energy savings

Amoruso et al. (2018) report on building refurbishments in Norway that had received government subsidies totalling 2.2 billion NOK (approx. 220 million €). Engineering calculations estimated that the energy savings would be 3.3 TWh/y, but actual savings were only 0.67 TWh/y. Amaruso and colleagues found that in Norway, as also in Germany, energy savings due to energy efficiency refurbishments were in most cases lower than estimations had predicted: a classic prebound effect. Heide et al. (2022) found that the prebound effect skews estimates of heating consumption in Norway by 60% and that 'the prebound effect should be taken into account to make a realistic analysis of the cost performance of energy retrofit'. Similar findings have been reported for Porto, Portugal and Barcelona, Spain, (Desvallées, 2022), and for Hungary (Gróf et al., 2022), Poland (Karpinska and Smeich, 2020) and Germany (Weber & Wolff, 2018). Geraldi and Ghisi (2020) see the prebound effect as one of a cluster of basic issues that need to be taken into account in estimating the performance of both individual buildings and building stocks. Guerra-Santin et al. (2016) argue that 'Uncertainties related to the actual energy consumption of buildings increase the risks for the investments in low carbon technologies'.

Literature on the prebound effect tends to see its significance in three main directions. (1) It indicates that households in dwellings with low energy efficiency deliberately under-consume heating energy to save money. (2) It indicates that methods currently used to estimate the thermal qualities of older building features (walls, roofs, basements, etc.) are inaccurate, based on questionable assumptions, because older buildings are often 'much better than their reputation' (Borse-Express, 2021). (3) It is a factor that should be incorporated in the technical calculation of theoretical energy consumption. I look at each of these in turn.

Under-consuming and energy practices

It is well known that household heating-related practices have a substantial effect on energy consumption (Gram-Hanssen, 2014; Steemers & Yun, 2010; Strengers et al., 2022). These practices, therefore, affect the potential energy savings from energy-efficiency retrofitting. For example, Berger and Höltl (2019) found that among low-income social housing tenants in Krems, Austria, prebound and rebound effects combined to prevent these tenants making any significant energy savings after energy-efficiency renovation. Their pre-renovation heating energy consumption had been much lower than the theoretical level required for full thermal comfort (prebound effect) and their post-renovation consumption was above the new theoretical level (rebound effect). Berger and Höltl note that 'no significant reduction in consumption can be expected after renovation' (p. 347) and that therefore only minimal refurbishment could be funded by savings generated by the monthly fee that residents were paying for building maintenance. A study with similar findings in the UK is offered by Tel et al. (2016). Here the emphasis is on occupants' inability to pay the high costs of heating an energy-inefficient home, leading to prebound effects, and the extra comfort-taking when heating becomes cheaper, leading to rebound effects. More generally, a range of household practices can influence actual energy consumption. This may include wider practices of saving money, lower demands for comfort or convenience, and better skills at coping with an energy-efficient house, such as using and heating fewer rooms in winter, dressing more warmly and carefully matching heating times to heating needs. There is also strong evidence for gender effects within energy-related practices, and these may need to be better accounted for in estimates of theoretical energy demand (Strengers et al., 2022).

Faulty technical measurements

Many studies argue that the difference between theoretical and actual energy consumption is largely due to technical factors, namely inaccuracies in estimating the thermal characteristics of older buildings (see reviews in Cozza et al., 2021). An example is Ahern et al.'s (2016) study of 463,582 old dwellings representing 32% of the Irish dwelling stock. Ahern and colleagues find large prebound effects, partly due to household energy behaviour but partly due to systematic underestimates of the energy performance of older building materials, i.e. overestimates of these materials' U-values. A standard practice in calculating theoretical energy performance is to assume a building has the U-values thought to be typical of its year of build, rather than specifically investigating the building materials themselves. Ahern et al. (2016) and other authors develop methods for better estimating these U-values, thereby bringing theoretical consumption closer to actual consumption (Ahern & Norton, 2020; Marshal et al., 2017; Rauschan et al., 2022). Similar findings are reported by Aksoezen et al. (2015) for Basel, Switzerland, Michelsen and Müller-Michelsen (2010) for Germany, Dineen et al. (2015) for Ireland, Francis et al. (2014) for England and Giuliani et al. (2016) for Italy. The latter developed a method to model the actual energy characteristics of high-mass historic buildings in Italy, thereby reducing the prebound effect from an average of 64% to 3.5%. Cozza et al. (2021) argue that methods such as these should be employed to create new energy certificates that more accurately reflect building performance. Giraudet et al. (2018) found further factors that contribute to inaccurate energy ratings – for example, energy-efficiency renovations done on a Friday are often done badly and do not increase efficiency as much as is estimated.

Incorporating user behaviour in theoretical calculations

Some studies attempt to bring more realistic user behaviour into calculations of theoretical energy consumption. They argue that a dwelling's objective, theoretical energy rating should not be based on the assumption that all rooms are heated to a comfortable level all year round, but on an average day-to-day, hour-to-hour occupant heating behaviour pattern. For example, Sun (2014) and Sun et al. (2014) use probabilistic models of occupant behaviour alongside the physical characteristics of buildings. A similar approach is seen in IEA Annex 66, which integrates simulated behaviour into the engineering modelling of a building's thermal quality (Yan et al., 2017). Other types of models of occupant heating behaviour include Random Walk and Markov Chain models (Hong et al., 2018).

Post-retrofit occupancy behaviour, which is often associated with rebound effects (the opposite of prebound), has also been modelled to more closely approximate what actually happens in practice. Examples are given in Van Dronkelaar et al. (2016), Menezes et al. (2012) and Choi et al. (2012). Using an approach of this kind, Cuerda et al. (2020) eliminate the influence of the prebound effect on predicted energy savings in an estate in Madrid, Spain. The savings turn out to be four times as high as they would be with standard methods. Guerra-Santin et al. (2016) develop a comparable method for owner-occupier apartments in Spain and social rented dwellings in the Netherlands.

Combining behavioural and technical issues

Moezzi and Janda (2014) make a strong case for developing energy ratings that combine both technical and social/behavioural drivers of energy consumption, including prebound effects. Adan and Fuerst (2016) show how this can work in practice, and van der Bent et al. (2021) offer an example from social housing in the Netherlands. Malik et al. (2018) explore how such an approach needs to be adapted on the micro-level – i.e. house by house or district by district – for differing conditions in developing countries.

Combining the two approaches is also useful for understanding post-retrofit energy consumption, where prebound effects (under-consumption) are often replaced by rebound effects (over-consumption). Calì et al. (2016) give the example of three large apartment buildings in Germany. Immediately after a retrofit in 2011, occupants were found to be over-consuming by 117%. After helping occupants improve their heating practices while also adjusting the heating equipment, this reduced to 107% in 2012 and 41% in 2013. Using large datasets, van den Brom et al. (2019) investigated the influence, on consumption, of building characteristics and occupant behaviour on energy consumption in Dutch and Danish homes. The method involved dividing houses in to 'stayers', where the dwelling had same occupants before and after a change in building characteristics, and 'movers', where the occupants changed rather than the building characteristics. An important finding was that about half the influence came from a change in occupancy and half from a change in building characteristics, but behavioural influence on energy consumption was itself influenced by the characteristics of the building. Van den Brom and colleagues concluded that building simulations would not be able to predict actual heating consumption correctly and accurately if occupant consumption patterns were not considered. There is, then, a strong case for combining behavioural and technical issues in devising energy certificates, but it is not straightforward.

What this means for the market

In a study in the UK, Geske (2022) argues that real estate markets under-price the value of energy efficiency because the stated energy consumption rating on energy certificates is too high, thereby over-estimating the energy savings of energy efficiency upgrades. Geske proposes a quadratic function to estimate more realistic energy ratings, by eliminating the portions of the prebound effect believed to be due to inaccurate engineering estimates and typical household behaviour. The new values provide a better fit to the study's regression model than the official energy ratings. Geske argues that the new values can better inform potential house buyers of the likely energy savings they will get if they purchase one property rather than another. In the analysis of results, below, I use a comparable but much-simplified approach for the German house sales market.

These approaches are useful if the aim is to predict what the actual consumption is likely to be for the average occupant if a country-wide system of energy ratings is envisaged. A potential purchaser or tenant would then have a better idea of approximately how much heating energy they are likely to consume to keep the dwelling warm enough for health and comfort. However, it could still mask the problem that low-income occupants of older, unrenovated dwellings may be living in unhealthily cold indoor environments due to over-frugal heating practices (Brunner et al., 2012) – or conversely, that the average occupant of a highly energy-efficient dwelling might be consuming far more than is needed for thermal comfort.

More generally, whatever system a country employs to give a dwelling an objective energy rating must be consistent across that country's entire real estate market so that potential purchasers or tenants know how an advertised dwelling compares with other dwellings. It is even better if the official energy rating gives a fair estimate of the actual energy demand that is required to keep the indoor temperature healthy and comfortable for an average or typical household. In Germany the official, objective, theoretical '*Bedarf*' energy rating enables only relative comparisons to be made, as it seldom reflects the amount of energy the dwelling is likely to consume, due to the issues discussed above.

With these issues in mind, we turn to a case study of prebound and rebound effects and sales market premiums for energy efficiency among detached and semi-detached houses in Germany, asking how the prebound and rebound effects might be influencing market premiums, and what could be done to mitigate this.

Method and data

The data

The study used a large database of advertisements for houses for sale, from Germany's largest real estate portal Immoscout24,[1] made available by RWI – *Leibniz-Institut für Wirtschaftsforschung* (Boelmann & Schaffner, 2022). These covered 1.9 million advertisements placed between January 2007 and December 2021. Property owners who use the Immoscout24 portal can give information on some 50 variables, including asking price, heating energy rating, floor area, postcode, year of build, ground area, number of bathrooms, presence of a guest toilet, presence of a parking place, and number of balconies, rooms and bedrooms, etc. The heating energy rating can be the theoretical, officially calculated heating energy consumption (*Bedarf*), or the actual average heating energy consumed over the past three years (*Verbrauch*), both expressed in kWh/m^2/y.

All advertisements which were repeated within the same 6-month period were dropped so as to avoid bias, and corrections were made for a systematic error in the year of build for a portion of the properties that were built in 2021. Immoscout24 also keeps a database of advertisements for houses for rent, which will be analysed in a later study.

Prebound and rebound effects in properties advertised for sale

A problem in estimating prebound and rebound effects is that each house advertised has either a *Bedarf* or *Verbrauch* energy rating but none has both. It is therefore not possible to calculate prebounds or rebounds for specific houses. Instead, using the database of houses for sale, the average energy ratings (both *Bedarf* and *Verbrauch*) were calculated for each year of build, from 1800 to 2021. These were plotted alongside each other in Figure 1 to show how they differed in relation to each other. Following Sunikka-Blank and Galvin (2012), the average prebound effect for each year's cohort of buildings is given by:

$$\text{Prebound} = \frac{\text{Bedarf} - \text{Verbrauch}}{\text{Bedarf}} \quad (1)$$

When the result of Equation (1) is negative, the result is regarded as a rebound effect.

A weakness of this approach is that it assumes there is no systematic difference between houses which have a *Bedarf* certificate or a *Verbrauch* certificate, but that these are randomly assigned according to what was available to the vendor at the time. However, as the results show, the values of prebound effects by year of build and by *Bedarf* are entirely in line with those

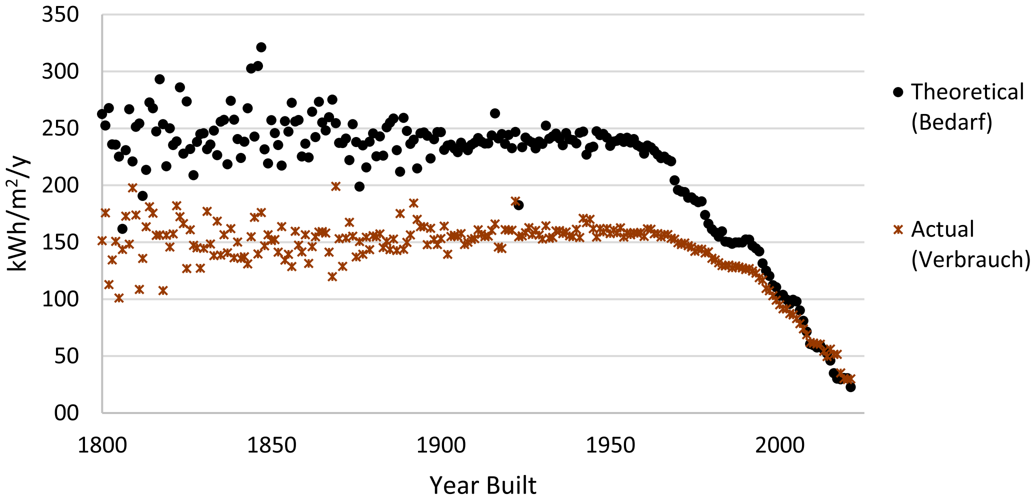

Figure 1. Theoretical and actual consumption (Bedarf & Verbrauch), averaged by year, for houses for sale in Germany 2007–2021.

observed for Germany by Sunikka-Blank and Galvin (2012) and other subsequent researchers.

It must be borne in mind that all prebound and rebound effects calculated by Equation (1) are averages, as are all the other results from the investigation. There is substantial heterogeneity between specific houses, some but not all of which is captured by the variables in the database.

Market premiums for energy efficiency

The sales market premium for energy efficiency was estimated using ordinary least squares multivariate regression analyses of the Immoscout24 data. The dependent variable was the asking price. In Germany, it is rare to negotiate over house prices, so it is assumed that the asking price is the market price. The independent variable of interest for the regressions was the *Bedarf* energy rating, i.e. the objectively calculated theoretical energy consumption, in kWh/m^2/y. A second set of regressions used *Verbrauch*, i.e. the actual, measured consumption. The *Bedarf* model was expected to give the most plausible results, with the best model fit, because the market actors know it reflects the thermal quality of the houses, rather than being contorted by the heating habits of the current or previous occupants.

A set of control variables was included in the regression analyses, as shown in Table 1. An initial, much larger set of potential control variables was selected, and stepwise regression was performed to eliminate variables that had no discernible impact on either the dependent variable or the fit of the model (high p-values and/or very low absolute t-statistics and/or no influence on adjusted R-Squared value), or that showed multicollinearity with other variables (variance inflation factor score > 3.5). For example, the number of bedrooms was strongly correlated with the floor area, so the number of bedrooms could not be included in the definitive regression analyses. As another example, the ground area showed no statistically significant correlation with the sales price, so including it would not have contributed to the findings.

Using the surviving control variables given in Table 1, regression analyses were performed for all houses for sale in all Germany, then for all houses in Germany built prior to 1980, then for these by federal state. The cut-off date, 1980, was chosen because building regulations first mandated energy efficiency standards in 1979.

The distributions of the variables Price, Energy Rating and Floor aera were right-skewed, so an additional multivariate analysis was performed for each of the above regressions using the logarithms of these three variables along with the actual values of the other variables (a log-linear model). The resulting regression coefficients were translated back into non-log values for easy comparison. In almost all cases the log-linear regressions gave higher adjusted R-Squared values and lower p-values than the non-log regressions, i.e. a better model fit. A further variance inflation factor test was performed for each regression, to check that there was no substantial multicollinearity. In all cases there was no significant multicollinearity using the variables listed in Table 1 (average variance inflation factor around 1.8).

The model for the linear regressions is given by:

$$P = \beta_E.E + \sum_{n=1}^{N} (\beta_n.n) \; + er + c \qquad (2)$$

where P is the sales premium, $ß_E$ is the coefficient of ‘Energy rating’, E is the energy rating, $ß_n$ are the regression coefficients of a matrix of N control variables, er is the error term, and c is a constant.

Table 1. Variables used in regression analyses of houses for sale.

	Variable	Units or data type	Comments
Dependent variable	Price	euros	
Independent variable of interest	Energy rating	kWh/m^2/y	*Bedarf* in first set of regressions; *Verbrauch* in second set
Control variables	Floor area	m^2	
	Number of bathrooms	integer	
	Month of advertisement	integer	Numbered from January 2007 as Month 1, but starting with Month 145, January 2019
	Year of build	date	Houses built before 1800 were excluded due to small numbers and extreme heterogeneity
	Price of car park	euros	
	Land area	m^2	
	Big city	Dummy	
	Medium city	Dummy	City with > 400,000 inhabitants
	Listed building	Dummy	City with 200,000–400,000 inhabitants
	Guest toilet	Dummy	

The log-linear models have the form:

$$\log(P) = \beta'_E . \log(E) + \beta'_F . \log(F) \sum_{t=1}^{T} (\beta'_m . m) + er + c \quad (3)$$

where $ß'_E$ is the coefficient of the log of the Energy rating, $ß'_F$ is the coefficient of the log of the Floor area F, and $ß'_m$ are the regression coefficients of a matrix of T other control variables.

For the log-linear models, the regression coefficients can be regarded as elasticities, e.g. the energy-rating elasticity of sales price. To translate $ß'_E$ into linear form, then, for example for sales premium, we use:

$$P = -\frac{S_a}{I_a} \cdot \beta'_E \quad (4)$$

where S_a is the average sales price, I_a is the average energy rating, and $ß'_E$ is the coefficient of log (E).

To translate the regression coefficients of the non-log variables that are in the log-linear model (e.g. Year of Build), into linear-linear form, we use:

$$Y = e^{(\beta'_Y + \log(S))} - S \quad (5)$$

where Y is the Year of build and S is the average sales Price.

The regression coefficient of the Energy rating indicates its correlation with the Sales price. For example, in the linear model, a regression coefficient of −300 means that each reduction in energy rating of 1 kWh/m^2/y is associated with an increase in sales price of 300 €. This therefore represents a sales premium of 300 € for each kWh/m^2/y of reduced energy rating.

A further set of regressions was performed for each of a set of bands of energy rating. This is because the cost of energy efficiency retrofitting increases sharply with the efficiency standard that is achieved, and it was interesting to see whether this increase is linear or otherwise.

Results

Prebound and rebound

Figure 1 plots theoretical and actual consumption (*Bedarf* and *Verbrauch*), averaged by year, for houses for sale in Germany 2007–2021. There is a clear difference between the two sets of values. For houses built before 1950, the average theoretical consumption (*Bedarf*) is around 250 kWh/m^2/y and the average actual consumption (*Verbrauch*) around 150 kWh/m^2/y. The gap closes as houses become more modern, and the two plots cross at about year-of build 2008, with both ratings at about 70 kWh/m^2/y. For the most recently built houses, which have very low energy ratings (i.e. the most energy-efficient), actual consumption is higher than theoretical consumption. The prebound effect is replaced by the rebound effect.

Figure 2 uses the same data to plot the prebound effect (Equation (1)) against year of build. It tends to be around 40% for houses built before 1900, then reduces gradually to around 37% for 1950, then to zero by about 2010, and for houses built since then there is a notable *rebound* effect in most years, peaking at 71% for houses built in 2017. There appear to be two main reasons for this crossover from prebound to rebound effects. First, household heating behaviour tends to be more liberal in highly energy-efficient

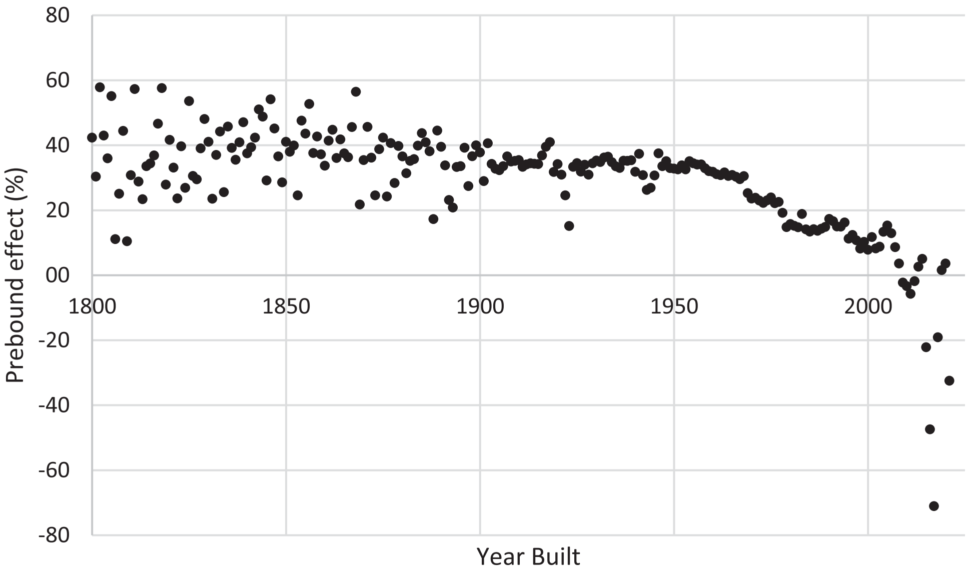

Figure 2. Prebound effect (Bedarf - Verbrauch/Bedarf), averaged by year of build, for houses for sale in Germany 2007–2021.

homes, as it is inexpensive to over-heat these. Second, technical difficulties often arise in highly energy-efficient homes, where users find it difficult to operate controls correctly. A clear example is given by Calì et al. (2016).

Figure 3 plots the actual energy consumption against the theoretical energy consumption for these year-by-year averaged values. A very good fit (R-squared = 0.9305) is given by the quadratic function displayed in the graph. This compares well with the datasets explored by Sunikka-Blank and Galvin (2012) and subsequent analyses.

Sales premiums for energy efficiency: basic averages

Table 2 gives the descriptive statistics for houses for sale in 2019–2021 using theoretical energy rating (*Bedarf*), for all years of build in all Germany, and for years-of-build prior to 1980, for all Germany and selected federal states. The mean energy rating for all houses in all Germany in this database is 142.1 kWh/m^2/y, but is much higher, at 219.7 kWh/m^2/y, for houses built prior to 1980. For one of the wealthiest states, Baden-Württemberg, the average energy rating of pre-1980 houses is close to that of the country-wide average, and for Saxony, one of the least wealthy, it is higher, at 238.6 kWh/m^2/y. Surprisingly, the figure for North-Rhine-Westphalia, Germany's most populous state, which is undergoing a slow transition from heavy industry to high-tech, is well below the country-wide average, at 174.2 kWh/m^2/y. This may be because North-Rhine-Westphalia was a vast battlefield in 1944–1945 and a very large proportion of its pre-1945 houses were destroyed or badly damaged and later replaced with 1950–1980 builds or refurbishments, which are somewhat more energy-efficient than those of pre-1950 houses, as shown in Figure 1.

Table 3 gives the results for log-linear regressions of the independent variables against (the log of) Sales price for all years of build in all Germany; and for pre-1980 houses for all Germany, for North-Rhine-Westphalia and for Saxony. Non-log transformations of the regression coefficients are also shown. The transformed coefficients of (the log of) Energy rating are the negatives of the sales price premiums for energy efficiency. For example, for all Germany, on average, the price is 164 € lower for each extra kWh/m^2/y that is theoretically required to heat all rooms of a house to 19 C all year round. Expressed another way, the vendor demands an extra 164 € for each reduction in heating demand of 1 kWh/m^2/y. This would mean, for example, that a house with an energy rating of 100 kWh/m^2/y (the legal maximum for comprehensive renovations) would be 16,400 € more expensive than an equivalent house with a rating of 200 kWh/m^2/y. If only houses built before 1980 are considered, the premium is 426 € per reduced kWh/m^2/y. It is higher in North-Rhine-Westphalia, at 685 €, and lower in Saxony, at 338 €.

It is important to consider the *t*-statistics and the regression coefficients of the control variables. The absolute values of the *t*-statistics give an approximate indication of the relative influence of each variable on the (log of the) sales price. For the second regression, for example (all Germany, pre-1980 houses), with *t*-statistics displayed graphically in Figure 4, the largest is for

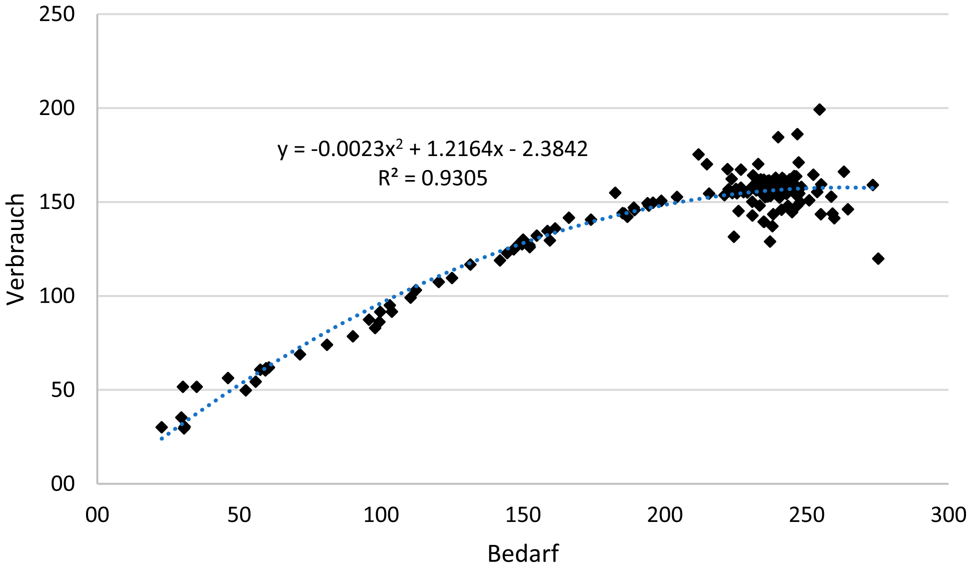

Figure 3. Average Bedarf and Verbrauch, houses built in 1860–2021.

Table 2. Descriptive statistics for houses for sale in 2019–2021 with theoretical energy rating (Bedarf), all years of build in all Germany, and year of build prior to 1980 for all Germany and selected federal states.

	All Germany		All Germany pre-1980		North-Rhine-Westphalia pre-1980		Baden-Württemberg pre-1980		Saxony pre-1980	
Variable	**Mean**	*Std dev*	**Mean**	*Std dev*	**Mean**	*Std dev*	**Mean**	*Std dev*	**Mean**	*Std dev*
Price (€)	**470,802**	*419,416*	**424,799**	*385,412*	**441,097**	*475,396*	**544,567**	*373,844*	**228,761**	*260,324*
Energy rating (kWh/m^2/y)	**142.1**	*109.6*	**219.7**	*86.4*	**174.3**	*43.1*	**217.4**	*88.4*	**238.6**	*98.1*
Floor area (m^2)	**167.5**	*77.2*	**174.2**	*85.2*	**184.6**	*100.6*	**183.0**	*82.2*	**181.8**	*114.0*
Number of bathrooms	**1.80**	*1.07*	**2.03**	*1.15*	**2.24**	*1.41*	**2.09**	*1.10*	**2.14**	*1.69*
Month of advertisement	**160.3**	*10.7*	**161.6**	*10.6*	**160.7**	*10.6*	**162.0**	*10.4*	**161.6**	*10.3*
Year of build	**1976**	*45*	**1943**	*37*	**1947**	*33*	**1946**	*40*	**1912**	*39*
Price of car park (€)	**450**	*3223*	**204**	*2129*	**182**	*1762*	**331**	*2790*	**22**	*871*
Land area (m^2)	**755**	*597*	**781**	*653*	**731**	*623*	**644**	*530*	**963**	*820*
Big city	**0.0766**	*0.2659*	**0.0917**	*0.2886*	**0.1211**	*0.3262*	**0.0359**	*0.1860*	**0.0848**	*0.2787*
Medium city	**0.0398**	*0.1956*	**0.0459**	*0.2092*	**0.1162**	*0.3205*	**0.0263**	*0.1600*	**0.0329**	*0.1784*
Listed building	**0.0037**	*0.0605*	**0.0057**	*0.0753*	**0.0044**	*0.0662*	**0.0055**	*0.0742*	**0.0148**	*0.1209*
Guest toilet	**0.6441**	*0.4788*	**0.4835**	*0.4997*	**0.5275**	*0.4992*	**0.5544**	*0.4970*	**0.3300**	*0.4703*

Floor area, indicating that sellers and buyers put a higher premium on floor area than any other factor. Also, the (transformed) regression coefficient indicates that each extra m^2 of floor area brings a premium of 1609 €. Being in a Big city (population > 400,000) has the next largest t-statistic and brings a premium of 390,000 €. The absolute value of the *t*-statistic for Energy rating is only 57.55, slightly larger than that for a Guest toilet, at 56.02. These relationships are comparable for North-Rhine-Westphalia, Saxony and other states, suggesting that the market rewards floor area most, and rewards energy efficiency about as much as an extra toilet (which is, nevertheless, still an important marketing factor). This should be taken into consideration because it indicates that, although a house's energy rating is important to prospective buyers, it is not as important as, or not much more important than, certain other factors. For example, it suggests that a potential vendor could increase the market value of their house by installing a guest toilet, at the cost of a few thousand euros, rather than add the same market value by undertaking a complex, expensive energy efficiency upgrade.

A summary of the key regression results and descriptive statistics for all federal states is given in Table 4. The market premiums for energy efficiency range from 104 € per reduced kWh/m^2/y for Berlin, to 539 € per reduced kWh/m^2/y for Bavaria. All are statistically significant with $p < 0.000$ except for Berlin, with $p = 0.117$. Note that Berlin, Hamburg and Bremen are city-states. There is not enough information in the database to investigate why the market premium varies from state to state.

However, Figure 5 plots the average energy ratings for each state against the average sale price per m^2 of floor area, again for houses built pre-1980 which were offered for sale in 2019–2021. There is a moderately strong negative correlation between these. In states where house prices are higher, average energy ratings are lower, i.e. energy-efficiency is higher, than average. This is almost certainly because these states have higher income per capita, so the proportion of houses retrofitted for energy efficiency is higher. However, the difference is not large: the standard deviation is only 12.0 kWh/m^2/y compared to an average of 221.4 kWh/m^2/y.

Influence of the prebound effect

As discussed above, due to prebound and rebound effects, the officially sanctioned *Bedarf* energy rating overstates the energy demand of non-retrofitted, energy-inefficient dwellings and tends to understate the energy demand of highly efficient, retrofitted or

Table 3. Regression results for log-linear model, regressions against log (Sales price), for all Germany with all years of build; and all Germany, North-Rhine-Westphalia and Saxony with pre-1980 years of build.

		All Germany, all years of build		All Germany, pre-1980 years of build		North-Rhine-Westphalia, pre-1980 years of build		Saxony, pre-1980 years of build	
Regressed against log of sales price (€)		log-linear regression	**Coef. Trans-formed to non-log**	log-linear regression	**Coef. Trans-formed to non-log**	log-linear regression	**Coef. Trans-formed to non-log**	log-linear regression	**Coef. Trans-formed to non-log**
Energy rating (kWh/m²/y) **(log of)**	**Coef**	**−0.0496**	**−164**	**−0.2205**	**−426**	**−0.2705**	**−685**	**−0.3523**	**−338**
	t-stat	−31.01		−57.55		−28.89		−14.23	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Floor area (m²) **(log of)**	**Coef**	**0.9482**	**2666**	**0.6598**	**1609**	0.6237	**1491**	0.4282	**539**
	t-stat	248.36		114.74		65.69		12.23	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Number of bathrooms	**Coef**	**0.00379**	**1788**	**0.03416**	**14763**	0.00525	**2207**	0.06930	**16,416**
	t-stat	2.6		16.82		1.63		6.87	
	p-value	*0.009*		*0.000*		*0.103*		*0.000*	
Month of advertisement	**Coef**	**0.00981**	**4641**	**0.01098**	**4688**	0.01048	**4418**	0.01185	**2728**
	t-stat	86.67		67.98		41.2		11.09	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Year of build	**Coef**	**0.00385**	**1815**	**0.00399**	**1699**	0.00343	**1440**	0.00350	**801**
	t-stat	100.8		85.31		40.48		12.03	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Price of car park (€)	**Coef**	**0.00002**	**8**	**0.00002**	**8**	0.00000	**1**	0.00000	**1**
	t-stat	42.97		23.34		1.59		0.2	
	p-value	*0.000*		*0.000*		*0.111*		*0.841*	
Land area (m²)	**Coef**	**−0.00002**	**−12**	**0.00002**	**10**	0.00011	**47**	0.00016	**36**
	t-stat	−11.67		8.37		22.93		11.36	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Big city	**Coef**	**0.6242**	**408,043**	**0.6515**	**390,124**	0.4779	**256,854**	1.0442	**421,184**
	t-stat	136.19		108.65		55.56		26.03	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Medium city	**Coef**	**0.3407**	**191,090**	**0.3921**	**203,964**	0.2889	**140,383**	0.4416	**127,007**
	t-stat	55.2		47.67		33.37		7.11	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Listed building	**Coef**	**0.0898**	**44,216**	**0.1089**	**48,853**	0.1471	**66,447**	0.3188	**85,897**
	t-stat	4.49		4.76		3.49		3.46	
	p-value	*0.000*		*0.000*		*0.000*		*0.001*	
Guest toilet	**Coef**	**0.1246**	**62,472**	**0.19885**	**93,460**	0.1326	**59,432**	0.2975	**79,263**
	t-stat	44.86		56.0200		23.44		12.39	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Constant	**Coef**	**−1.0441**	**−305,080**	**0.7217**	**449,406**	2.3738	**4,082,068**	2.6003	**2,852,187**
	t-stat	−12.18		6.94		12.48		3.99	
	p-value	*0.000*		*0.000*		*0.000*		*0.000*	
Observations		244,256		126,269		26,943		3100	
Adj. R-squared		0.4018		0.3573		0.459		0.4977	
F stat		*0.000*		*0.000*		*0.000*		*0.000*	

Note: Non-log transformations of regression coefficients are also shown.

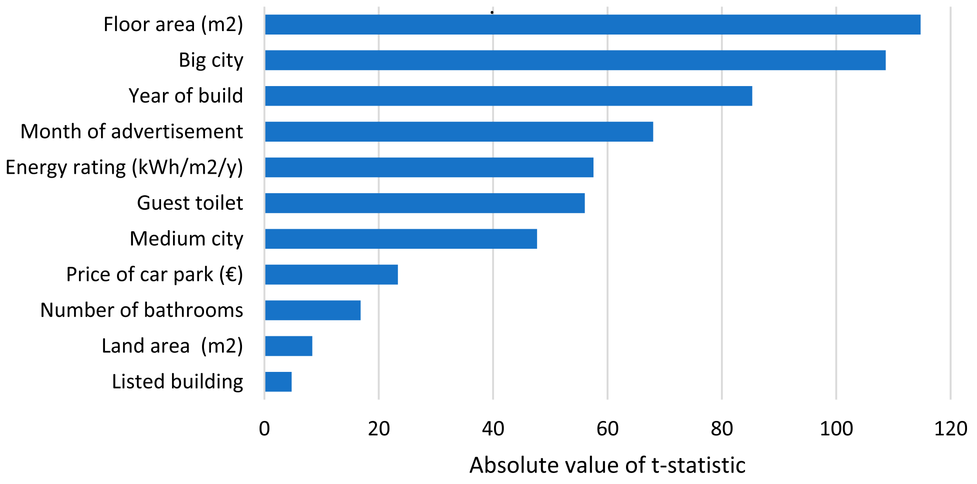

Figure 4. Absolute values of t-statistics for variables in regression against sales price, for houses built before 1980, all Germany.

new dwellings. Therefore, the figure of 426 € per reduced kWh/m^2/y for pre-1980 houses in Germany (Table 3) really indicates that the premium is 426 € for a reduction in *actual* energy demand of something *less* than 1 kWh/m^2/y. This would make the premium for each actual reduction of 1 kWh/m^2/y somewhat *higher* than 426 €.

A tempting solution might be to run the regressions using the *Verbrauch* certificate values of actual, measured consumption, but this would not be based on an objective indication of the thermal properties of the building: it would be compromised by the specific heating practices of the current or previous occupants. Such regressions were run as part of this study, but the results were inconsistent and somewhat nonsensical (information available on request).

A more promising approach is to make an estimate of what the objective, theoretical energy rating would be if there were no prebound effect, as suggested by Geske (2022). To do this robustly, a reliable figure would need to be calculated for each individual dwelling-user combination, but the Immoscout24 database does not give the information needed for this, such as building materials and socioeconomic characteristic of occupants. Instead, I offer a rule-of-thumb model which assumes that the correct average theoretical energy demand for each year's building cohort is half-way between the average *Bedarf* and *Verbrauch* values for that cohort. This approach assumes that part of this gap is due to technical over-estimates of U-values in old buildings, and part is due to user behaviour – somewhat in line with the findings of van den Brom et al. (2019). This is not intended as an accurate estimate of the objective performance of the buildings, but as an illustration of how the parameter values can change when prebound and rebound effects are taken into account in a reasonably credible way.

The modified energy ratings are plotted against the official *Bedarf* energy ratings in Figure 6. The figure gives three alternative modelling equations: quadratic, power, and linear. The quadratic has the best fit, with correlation coefficient R-squared = 0.9914, but this modelling equation would be cumbersome for a prospective house purchaser to use. The least complex is the linear model, which still has a high correlation coefficient of 0.9836. Rounding the numbers in this linear model gives:

$$B_m = 0.75B + 20 \tag{6}$$

Table 4. Average sales premium per reduced kWh/m^2/y of theoretical energy demand (Bedarf), average Bedarf, and average price per m2 of floor area, by federal state, houses built pre-1980 for sale in 2019–2021.

State	Premium (€ per reduced kWh/m^2/y)	Average *Bedarf* rating (kWh/m^2/y)	Price per floor area (€/m^2)
Schleswig-Holstein	396 €	213	2514 €
Hamburg	349 €	208	5533 €
Lower Saxony	319 €	218	1717 €
Bremen	191 €	204	2412 €
North-Rhine-Westphalia	387 €	216	2400 €
Hesse	512 €	219	2976 €
Rhineland-Palatine	363 €	235	1731 €
Baden Württemberg	428 €	217	2976 €
Bavaria	539 €	214	3212 €
Saarland	214 €	233	1262 €
Berlin	104 €	206	5126 €
Brandenburg	240 €	237	2513 €
Mecklenberg-Western Pommerania	466 €	215	1430 €
Saxony	323 €	239	1258 €
Saxony-Anhalt	284 €	237	993 €
Thuringia	371 €	233	1038 €
All Germany	**426 €**	**220**	**2439 €**

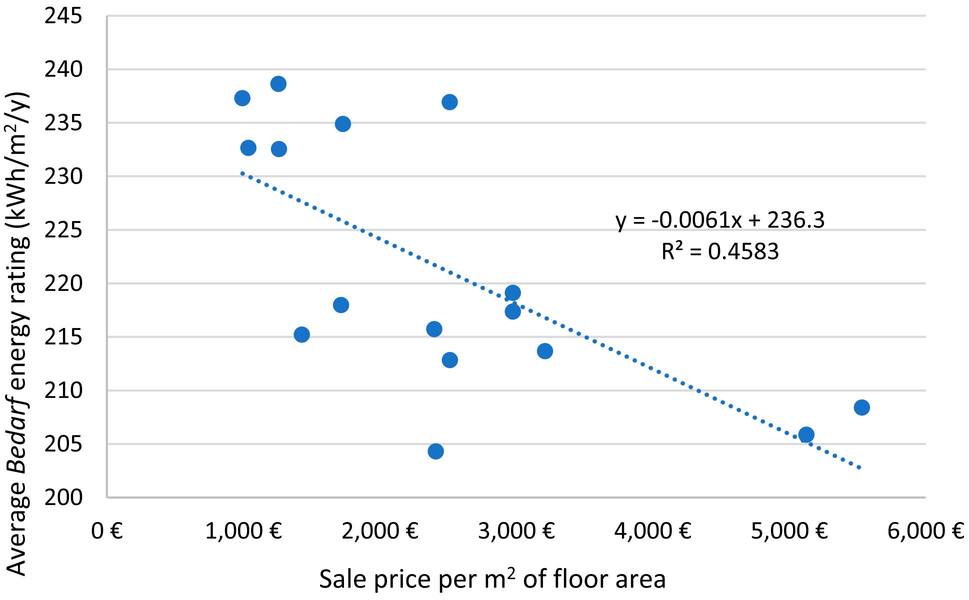

Figure 5. Average energy rating (Bedarf) plotted against sale price per m^2 of floor area, by federal state, houses built pre-1980 for sale in 2019–2021.

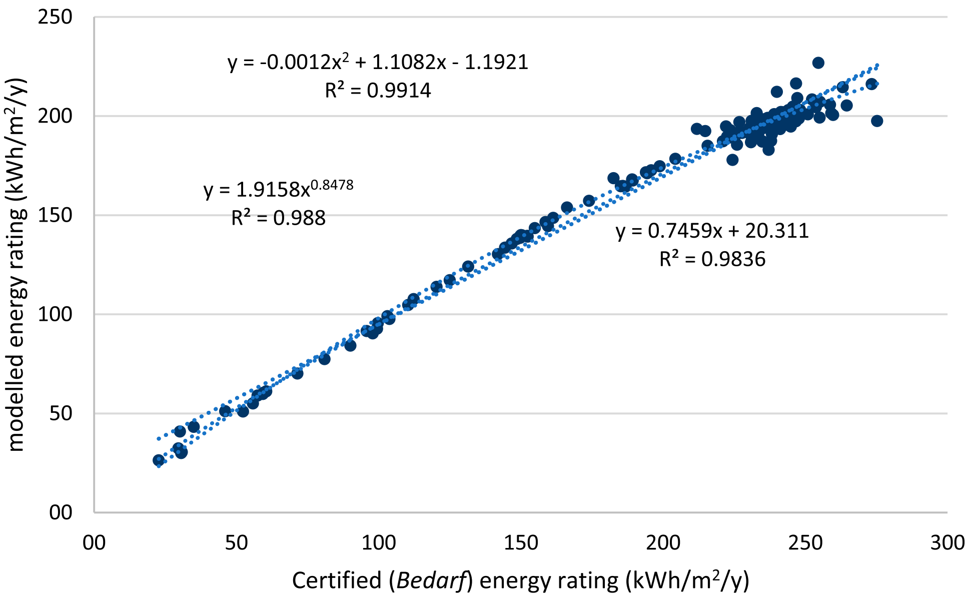

Figure 6. Modelled energy rating against certified energy rating, using halved average gap between Bedarf and Verbrauch, houses for sale, Germany, 2007–2021.

where *Bm* is the modified energy rating and *B* is the *Bedarf*, i.e. the official energy rating.

This equation can easily be used by prospective purchasers. They simply multiply the *Bedarf* energy rating by 0.75 and add 20. For example, they may wish to compare two houses, one unrenovated, with *Bedarf* 220 kWh/m^2/y, and one renovated, with *Bedarf* 50 kWh/m^2/y but in all other respects identical. Applying Equation (6) shows that a more realistic energy rating for the first house is 185 kWh/m^2/y, and for the second is 57.5 kWh/m^2/y. This means that, if they choose the second house rather than the first, this will not save them 170 kWh/m^2/y, but only 127.5 kWh/m^2/y (assuming they are an average, typical household in terms of heating practices). Even though the calculation of the modified rating used above was tentative and approximate, it does give a potential purchaser a good idea of the dimensions of the shortfall in energy savings.

Regarding energy costs, suppose the floor area is 174 m^2 (the average for pre-1980 houses, see Table 2) and the energy price 0.20 €/kWh (about the average at the time of writing). Choosing the second house rather than the first will not save the purchaser 5916 €/y but only 4437 €/y (again assuming they are an average, typical household in terms of heating practices). Using the *Bedarf* would have led to an overestimate of energy savings of some 33%.

The equation can also deal with rebound effects. It shows that a highly energy-efficient house with *Bedarf* 30 kWh/m^2/y is more credibly likely to have an energy demand of 42.5 kWh/m^2/y. A passive house, with *Bedarf* 15 kWh/m^2/y, would have a real-life demand of around 31.25 kWh/m^2/y. This is in line with analyses of the actual performance of passive houses (Blight & Coley, 2013; Molin et al., 2011; Ridley et al., 2013).

A differential of the inverse of Equation (6) can be used to estimate a more realistic value of the sales premium for each reduced kWh/m^2/y of energy demand. This is given by:

$$P_m = \frac{P \cdot \partial R}{0.75} \qquad (7)$$

where P_m is the modified sales premium, P is the sales premium calculated by the regression analysis above, and ∂R is the reduction in energy demand, here 1 kWh/m^2/y. The sales premium of 426 € per reduced kWh/m^2/y is thereby modified to 568 € per reduced kWh/m^2/y. This would imply that, for houses built before 1980, the Germany-wide average sales premium for energy efficiency was 568 €/(kWh/m^2/y) in 2019–2021, rather than the 426 €/(kWh/m^2/y) calculated from the *Bedarf* certificates in the regression analysis. People were paying a lot more for reduced energy consumption than the market led them to believe.

Finally, it should be noted that the costs of energy-efficient renovation increase sharply as energy efficiency becomes higher. This is illustrated in Figure 7, which plots sales price per unit floor area against theoretical energy demand, both *Bedarf* and the modified rating. Note that each data point here is the average of a band of energy ratings. The profile is almost identical for the two ratings, though of course this is because a *Bedarf* of, say 250 kWh/m^2/y is not the same as a modified rating of 250 kWh/m^2/y. For both these the average price is 2200 €/m^2, but a modified rating of 250 kWh/m^2/y represents a *Bedarf* of 333 kWh/m^2/y. Hence, the market (wrongly) indicates that a purchaser who pays an average premium of 2200 €/m^2 can purchase a house with energy rating 250 kWh/m^2/y, when it is more likely that they would only get a house with an energy rating of 333 kWh/m^2/y for this price.

Discussion and conclusions

The problem explored in this paper is rooted in what can broadly be termed a market failure. If a property owner has retrofitted a house before selling it, the costs of the retrofit are known and may be reflected in the asking price of the house, but the energy rating might not give an accurate indication of what the level of energy consumption is likely to be. This will be even less transparent if a property owner has not

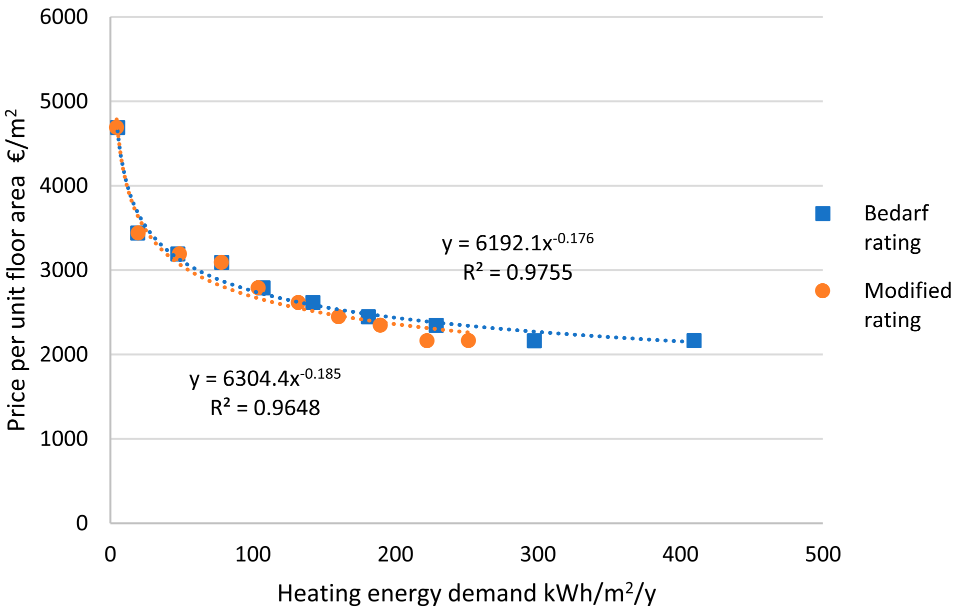

Figure 7. Price per unit floor area, plotted against energy demand (kWh/m^2/y), houses for sale in Germany 2019–2021.

undertaken refurbishments but is selling a house that simply has a *Bedarf* or *Verbrauch* energy rating. If it has a *Bedarf* rating, neither the owner nor potential purchasers know what the energy rating really indicates in terms of heating energy costs or savings. For a potential purchaser, comparing two houses according to their *Bedarf* energy ratings will give an over-optimistic view of the energy savings that are likely to be achieved by buying the property with the lower (better) energy rating. On the other hand, if the property has a *Verbrauch* rating, this will only indicate what the present owner has consumed over the past three years. Comparing houses according to their *Verbrauch* rating is unlikely to give any reliable information at all.

Policymakers need to see clearly that Germany is locked into this problem because of the way its *Bedarf* energy ratings are estimated. The work of Sun (2014), Menezes et al. (2012), Choi et al. (2012), Geske (2022) and others in developing more realistic energy ratings is very important in this regard, and it should be possible for Germany to make a transition, over time, toward a standardized approach of this kind. A vendor would then have the option of getting a modified energy rating (no doubt at some cost) to use in their advertisement: a '*Modifizierte*' rather than *Bedarf* or *Verbrauch* certificate. Vendors would have an incentive to do this if they wanted the likely actual energy demand to be transparent to potential purchasers – but a disincentive, of course, if they want to hide it. Policymakers should therefore rethink the current policy of simply allowing a *Bedarf* or *Verbrauch* certificate, and move towards mandating a certification that reflects the amount of energy an average household would realistically consume to meet its energy needs.

The study also has implications for potential house purchasers. Purchasers can use Equation (6) as a rule of thumb to estimate what the energy consumption would be for an average household who want their energy needs to be adequately met: multiply the *Bedarf* energy rating by 0.75 and add 20. This could especially benefit low-income households. Although Germany has a relatively low rate of home ownership and it is becoming harder for young people to afford to buy a house or apartment (Dustmann et al., 2022), there are still many low-income homeowners, and many have to sell and repurchase due to changes in household size or job location (Bayrakdar et al., 2018). The rule-of-thumb method developed above could be useful to such households in considering a purchase. A formula as simple as Equation (6) could help them avoid over-optimistic comparisons in potential energy consumption to be saved by choosing one house over another. Of course, this is not to claim that they can make accurate predictions of their future energy consumption, since they may not know where their consumption levels rate in relation to an average or typical household nor their future needs. However, it will bring them much closer to making a realistic assessment.

The study also has implications for further research. Most obviously, the *Bedarf-Verbrauch* dilemma also affects the rental market. This is extremely important for Germany since almost half its households are tenants, including by far the majority of low-income households. As noted above, a subsequent study will consider this issue, using an Immoscout24 database of houses for rent.

A further possibility for future research is to find real estate data sources that enable *Bedarf, Verbrauch* and modified energy ratings to be estimated on a house-by-house basis. This would enable more direct and reliable estimates of what purchasers are actually paying for energy efficiency in the houses they buy.

Another consideration for future research is that the stable market conditions of the past decade suddenly changed in 2022. The market premiums for energy efficiency explored in this paper were established in a market in which the cost of energy had hovered around 0.06 €/kWh and interest rates around 2% for almost a decade, and the costs of energy-efficiency retrofitting had not accelerated to the high, unstable levels they are today. Therefore, studies will almost certainly produce different results for the premiums if data from 2022 or later is used. This implies that the rental premiums as given in the regression result values cannot be relied upon for current sales and purchases. However, the general structure of the regression results is still likely to hold: floor area has the greatest impact on sales price, followed by whether or not the house is in a city of population > 400,000, followed by the year of build. Energy efficiency is likely to continue to be well down the list of purchasers' priorities, but probably significantly higher than the presence of a guest toilet, as it is now more expensive to retrofit and the energy cost savings are higher. These issues will become clearer as data for the real estate market for the complete year of 2022 becomes available.

Note

1. https://www.immobilienscout24.de/?seaid=g_brand&gclid=CjwKCAjw0dKXBhBPEiwA2bmObWTDqchZz9ptBcxQQztYYkRuZLvaw2jfNd6887btYE4EdTrelwp7DBoCW6MQAvD_BwE.

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