The value of energy efficiency in residential buildings – A matter of heterogeneity?!

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24 March 2021

Abstract

Increasing energy efficiency is the key to fully decarbonizing the building sector. It requires high investments in insulation and heating technology. Unfortunately, investors do not necessarily benefit from future savings themselves, as buildings frequently change owners and occupants - incentives are split - a general problem for efficiency investments. Real estate markets that function optimally should pass the savings to the investor as an efficiency premium and thus overcome the problems of the split. Energy efficiency ratings make the savings transparent and support the pass-through. But how efficiently does this really work? Empirical analyzes of the premiums for energy-efficient residential buildings do not provide direct conclusions. They only show that surcharges for comparable, efficient buildings exceed discounts for below-average buildings by two to twenty times - unexpected if homeowners value savings homogenously. We discuss possible reasons like discount rate heterogeneity and show in a hedonic model that this enables discounts to shift demand to supply peaks - causing the observed nonlinear premium. If heterogeneity is accounted for the pass-through of the investment can be narrowed to an interval of 73% to 100% a motivating high value to converting the building sector into climate neutrality.

Keywords: Energy efficiency; residential buildings; market price premium; Hedonic equilibrium; Heterogeneity of the willingness to pay; Heterogeneity of buildings.

JEL Codes: Q41, D41

1. Introduction

In recent years, an increasing number of countries have committed themselves not just to reducing greenhouse gas emissions, but rather to completely avoid them from 2050 (EU) or 2060 (China). This tightening of the climate targets has far-reaching consequences, since all sectors have to drive their emissions towards zero. Especially in the building sector, which accounts for 36% of CO_2 emissions in the EU (19% worldwide; IPCC 2014), decarbonisation is a challenge. In the residential building sector, this is due to the fact that living space and thus the building-related energy consumption are continuously increasing. Furthermore, due to their long lifespan, 70-80% of the buildings that should be climate-neutral by 2050 have already been built and equipped with non-climate-neutral technologies.

Unlike in industry or the mobility sector, where factories or vehicles are gradually replaced by climate-neutral technologies, the vast majority of the building stock will have to be converted to climate-neutral buildings over the next 30 years. According to current estimates, this can be achieved by increasing the energy efficiency (insulation) to a degree that buildings can be heated with renewable electricity (heat pumps) (Kavvadis et al., 2019; Zhang et al., 2017).

Even if the technical problems had already been resolved and despite this considerable period of time left, the EU Commission believes that the EU climate targets in the building sector (2020, ...) cannot be achieved on time as long as only 1% of the building stock is renovated each year. The EU Commission is therefore planning to double the refurbishment rates by 2030. This goal can be attained by subsidizing the renovations, by increasing the opportunity costs of non-renovation (e.g. through CO_2 taxes or efficiency certificates), through building regulations and standards, and by increasing market transparency (Lucon et al., 2014).

The latter approach has become a cornerstone of energy policy over the past 20 years. As early as 2002, the EU introduced binding energy efficiency ratings for buildings with the Energy Performance of Buildings Directive. In the USA the "Energy Star Certified Home" scheme was established in 1998 (others: Lee et. Al., 2018). The ratings aimed to reduce uncertainties about the energy consumption of buildings on the market, promoting investments in energy efficiency in order to reduce dependence on fossil fuels and also to meet the greenhouse gas reduction targets, which were lower at that time. The tightening of the climate targets has now encouraged new interest in increasing energy efficiency in the building sector and in the policy instruments that stimulate it. However, the effectiveness of the ratings is still considered insufficiently proven (IPCC report 2014).

Since it is difficult to provide direct evidence of the effectiveness of the investments, international evaluation studies between 2010 and 2016 (overview in Zancanella et al., 2018) aimed to measure whether energy efficiency ratings were reflected in the building price. This is a prerequisite for the profitability of investments: one would expect that rational homeowners offset the reduction in the building's operating costs through energy efficiency investments for the same housing quality against the building price. For homes that are otherwise comparable, the premium for an above-average energy-efficient building should then be just as high as the price discount for a building that is equally below-average.

In fact, evaluation studies show positive rewards for energy-efficient buildings. However, the discounts on comparable inefficient buildings are two to twenty times lower than the expected energy cost penalty. This result can be found in several studies of different countries. The unexpected asymmetry of the premium makes it difficult to interpret the effectiveness of the ratings and raises fundamental questions about incentives for energy efficiency investments.

In this study we explicitly present the asymmetry of the premiums and discuss possible explanations, such as econometric errors and demand heterogeneity with regard to income, discount rate and environmentally friendly attitudes of the owners. We examine the suitability of these approaches to explain the premium asymmetry measured and examine their implications.

Then we point out that buildings differ in ways beyond the objective criteria such as size, age, etc. - and therefore not all purchase options are equally desirable for market participants. If this unsystematic heterogeneity of the buildings and individual traits like the willingness to pay for efficiency is taken into account, it becomes apparent that the purchase decision is systematically influenced: depending on market supply arbitrage will be incomplete, and prices will no longer equilibrate across efficiency classes. We show analytically that this can also cause the observed non-linearity of the premiums.

In this analysis, we step beyond the evaluation studies of energy efficiency ratings in the building sector, by asking questions that clarify the impact of ratings on purchasing decisions. Thereby the effectiveness of a central policy option in the process of complete decarbonization is analyzed and we hope to contribute to the political discussion.

First of all - in section 2 - the hedonic theory is presented with individual traits and building heterogeneity and a closed form solution of the premium function is derived. Special cases are obtained as limiting solutions, especially the “intuitive” homogenous solution. This solution is confronted in section 3 with international statistical analyses of the premiums for energy efficiency. The non-linearity of the premiums in terms of efficiency is seen as “non-intuitive”, respectively as puzzle. Possible explanations are stated in section 4 and 5. Section 4 describes in detail how the heterogeneity of willingness to pay for efficiency impacts on the premiums and which explanation is reasonable - especially the heterogeneity of the discount rate. Subsequently, the model of building heterogeneity explained above is presented in Section 5, using a simplified model. Further reasons for premium nonlinearity are composed in section 6. The model from section 2 is then quantified in section 7 and its implications to estimate the passthrough of efficiency investments on building premiums are introduced. In section 8 the findings of the previous sections are summarized, and conclusions are drawn for the short and long-term and the development of efficiency in section 9.

2. The value of energy efficiency

Investment in a building’s efficiency reduces its operating costs. The questions we would like to address in this section are: “What does theory tell us about the value of the modified (more efficient) building on a market?”, “What happens to the prices of the buildings on the market if efficiency increases?” and “What are the conditions to invest with profits?”.

The answers to these questions can be derived from a hedonic model of product differentiation under perfect competition applied to the building sector (e.g., Tinbergen (1956), Rosen (1974), Ekeland et al. (2004)). The model includes demand, supply and a hypothesis of market functioning. Buildings are described by a large number of parameters (characteristics) z_i such as the living space, building age and location. Personal traits of the buyer, among others the willingness to pay for energy efficiency, are also considered. Under these circumstances, rational buyers are assumed to choose a building and market prices direct demand and supply until they are balanced.

If characteristics and traits do not influence each other - the distributions of the characteristics and traits are statistically independent - then each characteristic is priced separately. In other words, the total price of a building $P(z)$ is the sum of price components p_i that only depend on one single characteristic: $P(z) = \sum_i p_i(z_i)$. This notion justifies hedonic regressions.[1]

In the empirical literature, the energy efficiency of a building is generally interpreted as such an independent characteristic of the building[2], measured as the cost of a standardized (person-independent) energy consumption x with an efficiency rating. Independency is not implausible as e.g., aesthetic and location aspects of a building do not influence the evaluation of the efficiency.[3] In this sense, hedonic regressions are used to identify and measure the relationship between the price premium p_i and the efficiency x. Particularly, a comparable living space is considered that allows residents the same standard of living and only differs in terms of efficiency, respectively operating costs in net present value terms.

The buyers of the buildings have individual willingness to pay for the characteristics $U(x)$. While in the general deterministic Tinbergen model (Tinbergen, 1956) the consumers have an ideal idea of the characteristics such as the age of the building (bliss point), as mentioned energy efficiency is considered in terms of welfare-reducing energy costs only[4]. Against this background it is assumed that the potential buyer collects building offers in each efficiency class and selects exactly one building for purchase. The selected building maximizes welfare for a given income minus the price $P(x)$ to be paid for the building and minus its long-term operating costs βx. β is used as index to characterize individuals.

Buildings with annual energy bill x have further properties like the state of decoration or the size of individual rooms perceived subjectively by a buyer β. While x is observable, the idiosyncratic valuation of these features, $\varepsilon_{\beta x}$ is known to the potential buyer only. λ ($\lambda > 0$) weights the impact of the random component. The consumer values each option separately on a linear additive scale $U(x|P,\beta)$ based on prices $P(x)$ and energy costs x with uniform weighting parameters α (> 0) and the individual marginal willingness to pay β (> 0)

$$U(x|P,\beta) = -\alpha P(x) - \beta x \tag{1}$$

The buyer selects the building class x that maximizes his wellbeing. It is assumed that $P(x)$ is convex:

$$\max_{x \in X} U(x|P,\beta) + \lambda \varepsilon_{\beta x} \tag{2}$$

Since the unobserved properties of the building sometimes outweigh the observables, the consumer's decision seems random to an observer. An observer only knows the distribution of the total influence of the properties on the consumer's valuation $\varepsilon_{\beta x}$, which can be used to build expectations. The expected demand of individual β for a building with efficiency level x given the prices P is the distribution $d(x|P,\beta)$. Individual demand can then be aggregated across all buyers to market demand $D(x|P)$.

Building supply is considered independent of the price. This assumption is based on the observation that there are only 200,000 new residential buildings being built annually in the UK compared to 1.2 million property transactions and a building stock of 30 million (Table 1). Therefore, annual supply of

[1] In principle, the analysis is also possible analytically without independence, but the results are unnecessarily untransparent.
[2] Although efficiency of a building comes from a bundle of technologies (including heating and insulation technologies), we interpret it as an individual characteristic of the building - measured as the costs of a standardized annual energy consumption (energy efficiency rating).
[3] However, ventilation technologies in highly efficient buildings create additional comfort of living, so building quality and efficiency become correlated - these characteristics would no longer be priced independently. Nevertheless, we follow the customs and discuss energy efficiency as independent.
[4] Here we leave the standard quadratic utility Tinbergen (1956) model but still derive a quadratic closed form solution.

new buildings is small, and the refurbishment rates are very low (1%). In that regard the supply of buildings in each efficiency class is modelled as fixed – in the short run.

Under perfect competition a pricing function P emerges that attributes a price to each efficiency class $x \in X$ of a building, such that all supplied buildings will be demanded[5].

$$D(x|P) = S(x) \tag{3}$$

Technically, it is assumed that the supply of buildings in each efficiency class equals the probability density $f_N(x|\mu_b, \sigma_b)$ of a normal distribution. Similarly, the share of the buyer's marginal willingness to pay β is the density $f_N(\beta|\mu_\beta, \sigma_\beta)$ - again - of a normal distribution.

A bit more intuition about market functioning can be provided in figure 1. Starting from the distribution of individual traits (figure 1.a; red curve) two individuals characterized by their willingness to pay β' and β'' are selected. At the optimal efficiency level x' and x'' the willingness to pay equals the slope of the pricing function P (figure 1.b; blue curve touches green curves; $\varepsilon = 0$). The lower the absolute slope of the linear utility function the higher the willingness to pay for efficiency and the higher the preferred efficiency level. However, the decision is blurred by unobservables (figure 1 c) distributed according to the red curve. So, demand for x^* may stem from either β' or β'' buyers with the unobservables shown. Market demand for x^* (figure 1 d) is thus the probability that a buyer selects x^* weighted with his population share. If market demand does not equal supply everywhere P folds to stretch demand until it equals supply.

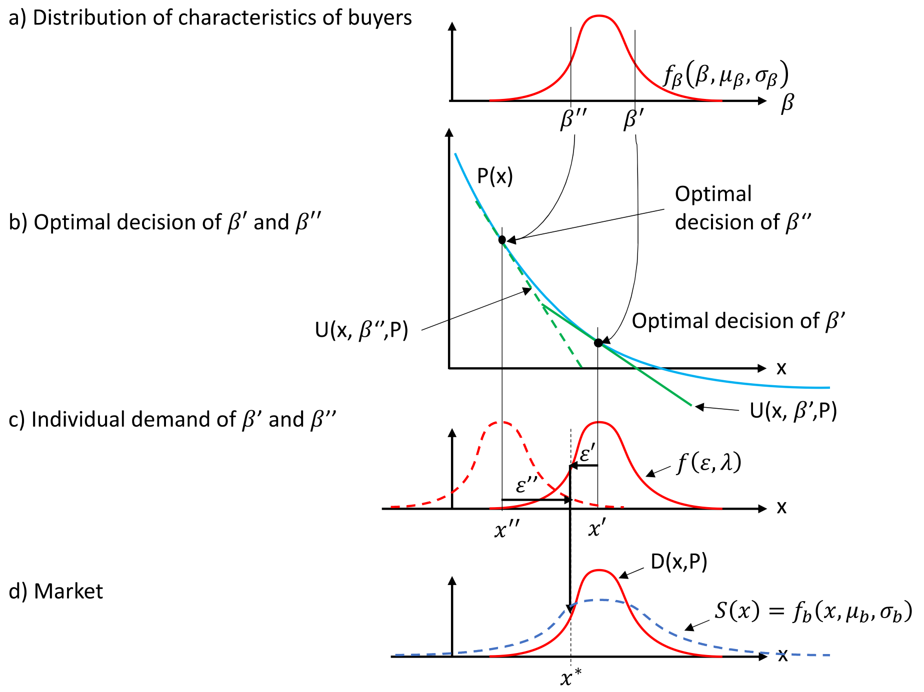

Figure 1: Illustrating the deviation of demand. Two buyers differ by their marginal willingness to pay for annual energy costs β' and and β''. Both blurred decisions may result in the demand for an efficiency level x*. The resulting market Demand D does not equal supply S, so not an equilibrium yet. An equilibrium would have a lower slope of P to stretch demand more.

[5] In general, there would be a "not-buying" option, that depends on opportunity costs of not buying a new building, that introduces macroeconomic conditions. As we are only interested in the structure of demand with respect to efficiency, only the sub-decision of efficiency is analysed. This study does not examine the absolute building price on property markets, which balances demand and supply, but only the relative prices of different efficiency classes. Therefore, it is assumed that every consumer finds a building and we can focus on market shares - respectively the distribution - of the efficiency classes of buildings across efficiency classes.

We specify the distribution of unobservables as in the multinomial logit model (Train, 2009), despite its undesirable properties like the independence of irrelevant alternatives, because it allows a closed form solution of (3) with respect to the pricing function P (details in Appendix I):

$$P^*(x) = -\frac{\mu_\beta}{\alpha}(x-\mu_b) + \frac{\sigma_\beta^2}{\alpha\left(-\lambda+\sqrt{\lambda^2+4\sigma_b^2\sigma_\beta^2}\right)}(x-\mu_b)^2 \tag{4}$$

While nonlinearities of the pricing function are a well-known property of hedonic models, generally little is said about the "mechanics" of the allocation. We will provide this intuition in three special cases: No stochastics in decision making (Section 3), no heterogeneity (section 4) and both (section 5). These special cases reveal insights into the effect of heterogeneous self-selection of buyers into markets of different efficiency and the interaction with constant supply. The hedonic functions in the special cases are the limits with respect to λ and σ_β or both (Appendix I):

No stochastics
$$P^{det}(x) = -\frac{\mu_\beta}{\alpha}(x-\mu_b) + \frac{\sigma_\beta}{2\alpha\sigma_b}(x-\mu_b)^2 \tag{4a}$$

No heterogeneity in the WTP
$$P^{rep}(x) = -\frac{\mu_\beta}{\alpha}(x-\mu_b) + \frac{\lambda}{2\alpha\sigma_b^2}(x-\mu_b)^2 \tag{4b}$$

Deterministic homogeneity
$$P^{dr}(x) = -\frac{\mu_\beta}{\alpha}(x-\mu_b) \tag{4c}$$

The case (4c) is best known, and we will refer to it as the "intuitive" solution. It reveals that the value of every building is the same, independent of the efficiency level. What happens on these markets is that a rational buyer asks for the building that has the highest value. If there was a building with higher value, all consumers would bid for this building. Then, the sellers of not demanded buildings would lower the prices in order to avoid the costs of vacancy. This incentive only vanishes if the value of the building remains unchanged by investing in efficiency. Therefore, on the market the premium corresponds to the energy savings (pricing by arbitrage). This is anticipated in the investment phase and investments are therefore profitable as long as the difference in operating costs exceeds construction costs. That means:

1. The price passes the savings that will "arise" for the buyer only in future through to the seller of the building in the present.
2. The price "hoovers" the savings completely.
3. Cost differences should result in the same price differences. Therefore, the relationship between premiums and the operating costs is linear.
4. The premium is an important indicator of the return on investment.

In a sense featureless consumers and buildings force premiums into a simple linear structure. The next section shows whether the world appears as simple as that i.e., whether empirical studies support this view.

3. Empirics – The energy efficiency puzzle

Energy efficiency ratings determine a resident-independent energy consumption reference point for buildings. The ratings thus provide an objective comparison of energy consumption and costs of buildings (details in Appendix I). Based on this definition, Fuerst et al. (2015) estimate energy label-specific premiums in the UK real estate markets (Table 1 and Figure 2). They take into account a large number of building characteristics such as age, building type and energy efficiency class etc. and determine their impact on the building price based on market transaction data. The authors found that buildings of efficiency class B, which accounted for 2% of the building stock in 2015 - but 82% of the new buildings – have a 5% higher price than buildings of class D (43% of the stock and only 4 % of new buildings). The price of a class F building (5% of the existing, 0% of the new buildings) was 0.9% lower.

UK Energy efficiency rating				**Data 2019**		**Fuerst et al. (2015)**	
Band	Score	Interval middle	Average costs£	New built homes England	Stock England, Wales	Stock	Estimated premiums
A	92-100	96	95	1%	0%	0%	5.0%
B	81-91	86	345	82%	3%	2%	
C	69-80	74.5	635	11%	36%	24%	1.8%
D	55-68	61.5	730	4%	43%	45%	0%
E	39-54	46.5	1315	1%	15%	23%	-0.7%
F	21-38	29.5	1825	0%	3%	5%	-0.9%
G	1-20	10	2650	0%	1%	1%	-6.8%
	Total number of dwellings			200.000	30 Mio	333.000	
	Annual property transactions (>£40k)			1.200.000			

Table 1: Energy efficiency ratings in new and existing houses; Ministry of Housing, Communities & Local Government, HM Revenue & Customs

If these premiums are compared to operating costs - determined by the rating (Appendix 2) - then the premiums (Figure 1; blue dots) decrease as expected as annual energy costs rise, but unexpectedly at a decreasing rate. This means that the discount for inefficient buildings is smaller than the premium for the more efficient ones. Thus, the intuitive linear relationship between cost savings and the efficiency premium is not confirmed.

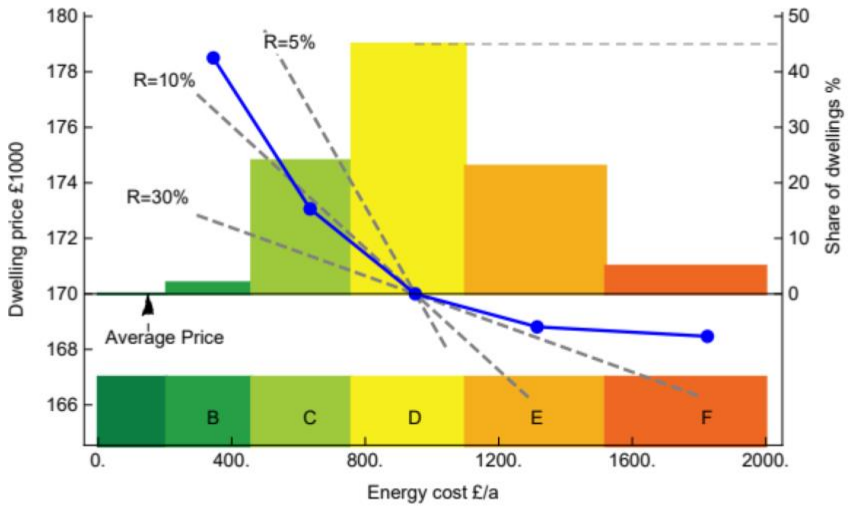

Figure 2: Housing price and energy costs; Blue dots mark the price premium of energy efficiency bands measured by hedonic regression of Fuerst et al. 2015. Dashed black lines: arbitrage solution with 5%, 10% and 30% interest rate.

Capital markets compete with the implicit transfer of future energy savings to the present. The opportunities for transferring future savings into current premiums are shown in Figure 2, compared to buildings in efficiency class D at discount rates of 5%, 10% and 30% (as dashed lines). The premium for a class C building corresponds exactly to the present value of the energy cost savings that are subject to interest on the capital market at a rate of 10%. The premium for a class B building compared to a C building matches an interest rate of 5%. The additional costs of the inefficient building classes E and F are, however, greatly underestimated as a present value. The reduction measured for an E building can only be justified as rational at a discount rate of 30%. The discounting of an F building would have to be even higher.

This non-linearity of the premiums is explicitly addressed in further publications: Fuerst et al. (2015) review an Australian analysis “they find evidence of a nonlinear effect—the marginal addition to the price effect declines as rating increases.” This probably encouraged them “To capture the effects of EPC rating on these variables, …” via “a set of binary variables…” in their hedonic analysis – a praxis applied in almost all hedonic analyses. Later Fuerst et al. (2016) find that "a statistically significant price premium only exists for the highest (ABC) energy ratings and no impact is found for below average ratings." Recently, Evangelista et al. (2020) suggest that “… the market reaction to good energy performance is of a higher magnitude than to low performance standards.”

In addition to these explicit quotations of the non-linearity, premiums from studies in further European countries are shown in figure 3[6]. All time series display the non-linearity. The premiums for above-average efficient buildings exceed those for below-average by 2-50 times. This non-linear pattern is described as the “energy efficiency premium puzzle”. Several reasons might explain it.

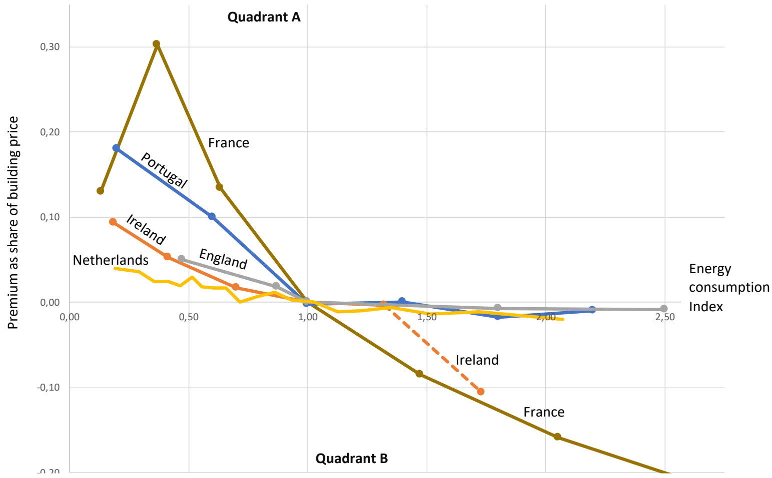

Figure 3: International price premiums of energy efficiency.

4. Explanation I - discount rates differing

Diversity of building buyers and their preferences is a good reason for the non-linear premium. We will now examine the mechanism by which willingness to pay impacts on premiums more closely and discuss reasons for the heterogeneity of the willingness to pay.

4.1. How does it work?

In an example, it is easy to see how different willingness to pay works in a market with differently efficient buildings. Assume building A with energy costs x_A and a less efficient building B with energy costs $x_B(> x_A)$ should be sold to two potential buyers with willingness to pay $\beta_1 = 1$ and $\beta_2 = 1 + \sigma_\beta$. Their utility equals (1) with $\alpha = 1$ and p_B normalized to 0, such that for buyer 1 $U_1(x_A|p_A, 1) = -p_A - x_A$ and $U_1(x_B|p_A, 1) = -x_B$, while for buyer 2 $U_2\left(x_A|p_A, 1 + \sigma_\beta\right) = -p_A - \left(1 + \sigma_\beta\right)x_A$. Buyer 1 will prefer the efficient building A if $U_1(x_A|p_A, 1) > U_1(x_B|p_A, 1)$ thus if $x_B - x_A > p_A$ and 2 will prefer it if $\left(1 + \sigma_\beta\right)(x_B - x_A) > p_A$.

If $\sigma_\beta = 0$ both individuals have the same willingness to pay for energy costs. So, both will be willing to buy A if its price is below $x_B - x_A$. If it equals $x_B - x_A$ they will be indifferent between A and B. And they will not be willing to buy A for a price above $x_B - x_A$. The individual demand curves for building

[6] Since no cost basis was chosen in these publications, the premiums were compared to an energy consumption index as a proportion of the building price. The British data were converted using the method from Appendix 2. (Linear relationship between energy consumption and rating).

A are plotted in figure 4 as solid and dotted lines and aggregated in figure 5. With one of each building supplied prices will adjust such that each is sold which is only possible if the price equals $x_B - x_A$.

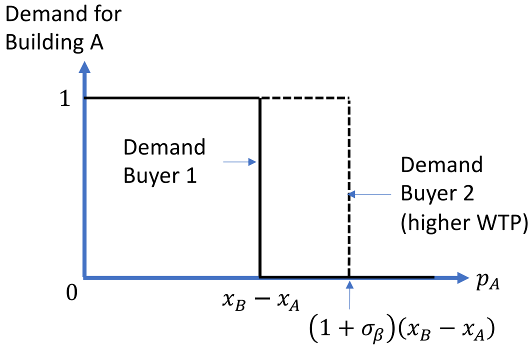

Figure 4: individual demand for building A

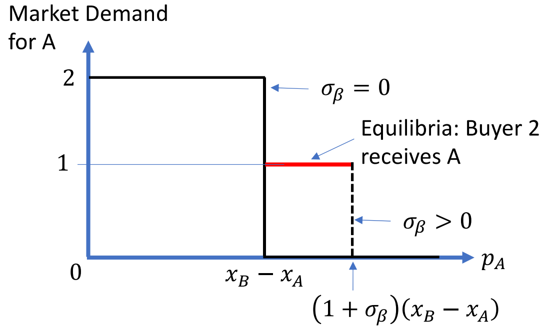

Figure 5: Market demand for building A

Things change if the willingness to pay of person B increases to $1 + \sigma_\beta > 1$. Now buyer 2 is willing to acquire A up to $p_A \leq (1 + \sigma_\beta)(x_A - x_B)$. Individual demand shifts to the right in figure A (dashed graph) and aggregate demand gets an additional step. Prices will adjust until each building is sold with a price in the range of $x_A - x_B \leq p_A \leq (1 + \sigma_\beta)(x_A - x_B)$. The more efficient building A is in every case sold to the buyer (2) with higher willingness to pay, with at least one buyer strongly preferring their option.

The varying willingness to pay spreads demand and prices can control demand smoothly, such that the buyer with higher willingness to pay receives the more efficient building. So, the market sorts demand according to the willingness to pay and the buildings according to efficiency and assigns the buyer with the highest willingness to pay the most efficient building and so on. This feature of market functioning is called sorting (equilibrium). There is no longer complete arbitrage with indifference of the buyers between the markets.

Given a normally distributed willingness to pay with expected value μ_β and standard deviation σ_β sorting leads to the market pricing function (4a). This price function is a non-linear parabolic in energy expenditures x opening upwards, with a minimum at $\sigma_b\, \mu_\beta / \sigma_\beta + \mu_b > \mu_b$.This represents the asymmetry of the shape of the premium. Heterogeneity of the willingness (σ_β) 'bends' the linear relationship into a parabola. Without heterogeneity ($\sigma_\beta = 0$), the price function becomes linear (4c). Sorting no longer takes place and the intuitive solution appears to be a limiting case. If the distribution of buildings σ_b becomes sufficiently equal ($\sigma_b \to \infty$), the price again converges to a linear efficiency premium.

It is now transparent, how willingness to pay affects price premiums: buyers sort themselves to buildings with respect to efficiency. Prices fold downwards around the average efficiency levels to draw demand to high supply. This symmetric scarcity premium around the average efficiency level is overlaid with the linear efficiency premium (figure 6). If these premiums are offset against energy costs to derive the market price, then in highly efficient buildings the scarcity premium and the energy savings have "the same direction" compared to the average and increase the price, while in inefficient buildings they have "opposite directions" and therefore neutralize each other - the observed non-linearity. However, if heterogeneity was irrelevant, the net present value would dominate demand and the non-linearity would disappear.

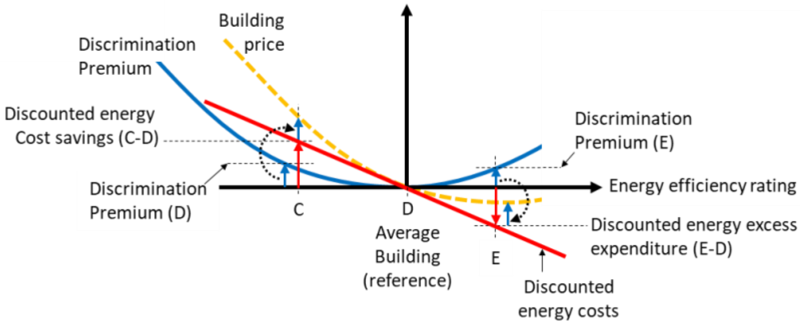

Figure 6: sketch of building price components: discounted energy savings and discrimination premium. Note that the vertical scale of the discrimination premium may have been exaggerated for clarity.

4.2. Sources of heterogeneity

One of the most obvious reasons for heterogeneity in the willingness to pay is income. In fact, Næss-Schmidt et al. (2016) find in a Danish choice experiment a 40% increase in the willingness to pay for efficiency in the top income quartile. Yet, the evidence is mixed.

In particular, data from Great Britain (BRE Housing et al.: Energy Use in Homes, 2009) show a diffuse picture in one of the few publications that relates occupants' characteristics and the efficiency of the buildings they live in (Table 2). In this analysis, buildings were classified according to the net income of occupants. Aside from the highest and lowest efficiency bands income and efficiency are fairly independent (though the hypothesis of complete independence is rejected by a $\mathcal{X}^2$ test), in the sense that measured and independent shares deviated by less than 10% (Table 2). Only the lowest income quintile is relatively more likely to live in especially inefficient (or efficient) buildings. In contrast, wealthy occupants are less likely to inhabit extremely efficient buildings. Unfortunately, income data related to the owners who decide on purchase and investment are not available, except that 63% of the buildings in Great Britain (Department for Communities and Local Government, 2015) are owner-occupied and income data for these are therefore owner related.

A better understanding of the reasons for these effects can be obtained from the author's comments on the impact of income on the efficiency class of the buildings (page 13), given that over 70% of particularly wealthy households live in detached houses. "Although high income households will be able to afford a vast range of available efficiency measures, the size of the dwellings they occupy may restrict their ability to achieve a high SAP rating. In contrast, households with low incomes will benefit from the energy efficiency properties of the smaller dwellings that they tend to live in such as purpose-built flats and terraced dwellings, leading to higher SAP ratings."[7] The numbers also reflected that some low-income households live in newer, more energy-efficient social housing. The low correlation between efficiency and income classes is taken as an indication that income does not dominate the premiums.

SAP-Rating		Occupancy by income quintiles					Total Buildings	
Points	Band	Q1 lowest	Q2	Q3	Q4	Q5 Highest	Absolute	Share
<30	F-G	531	444	374	275	256	1880	9%
30-50	E-F	1319	1459	1542	1459	1597	7376	36%
50-70	C-E	1713	1845	1851	2032	1957	9398	46%
>70	A-C	539	355	335	337	292	1858	9%
Total		4102	4103	4102	4103	4102	20512	100%

[7] A hint that the assumption of independency of the building characteristics is heroic.

SAP-Rating		Deviation of measured from statistically independent shares				
Points	Band	Q1 lowest	Q2	Q3	Q4	Q5 highest
<30	F-G	144%	120%	101%	74%	69%
30-50	E-F	89%	99%	104%	99%	108%
50-70	C-E	91%	98%	98%	108%	104%
>70	A-C	146%	96%	91%	91%	79%

Table 2: Building Research Establishment, 2005. The lower panel gives the share of the population in each cell relative to the share expected if income and living in buildings of a given SAP was independent. In the top right cell, for example, we would expect 1.8% = 9% x 20% of the population to be people in Q1 living in homes rated below 30, when in fact, it was 1.44 times 1.8%.

The non-linearity of the premium can also be justified by preferences for efficiency itself. Fuerst et al. (2016) state that "Some buyers may derive higher utility from living in greener dwellings ... because of their intrinsic environmental values and preferences ...". This connection was confirmed by Ramos et al. (2016) in a choice experiment. Direct evidence of these attitudes would require data of the homeowners. However, households would have to completely subordinate themselves to the “efficiency dictate” and other effects of building heterogeneity would be dominated. What happens if that is not the case, will be analyzed in detail in the following section.

A well-documented source of heterogeneity that impacts on efficiency investment is the discount rate. This heterogeneity is analyzed by Fischbacher et al. (2021) and previously by Newell and Siikamäki (2015) in discrete choice experiments. Unfortunately, there are no combined analyses of building owner’s traits and building characteristics. We will therefore assume that purchase of a building follows the same principles as buying appliances in Newell and Siikamäki.

Analyzing purchase decisions for hot water systems, the authors measure a distribution of discount rates with a median of 11%, a mean of 19% and a standard deviation of 22%. If we would apply this discount heterogeneity in the sorting equilibrium then low-discounting purchasers would buy the more efficient buildings and vice versa. [8] Although there is no simple correlation between income and the discount rate when purchasing hot water devices, this could be the case when buying a building, which is a multiple of the purchase price. We consider the discount rate as dominating source of individual heterogeneity and will apply these parameters for the empirical investigation in section 7.

5. Explanation II: Heterogeneity of buildings

Alongside individual heterogeneity, the heterogeneity of dwellings themselves can cause nonlinear efficiency premiums. Although hedonic regressions have removed the impact of observable characteristics, buildings still differ in unobservable ways which sometimes outweigh observable characteristics and therefore not all options are equally desirable. What efficiency premia can be expected under these circumstances?

As the valuation of unobserved characteristics is only known to the buyer, his decision seems random to an observer. It is generally assumed that an observer knows the distribution of the total influence of the characteristics on the buyer’s valuation ε, which can be used to build expectations. How do the unobserved properties affect demand? This can be illustrated with the following simple partial equilibrium example.

Assume there is an efficient building A and an inefficient building B with operating costs $x_A = 0 < x_B = 1$. The buildings objectively differ only in their operating costs and building A in non-observable

[8] The authors identify the level of education and creditworthiness as the most significant influencing factors on the level of the discount rate. The latter factor indicates liquidity constraints.

details $\varepsilon \in \{-1,0,+1\}$ each occurs with probability 1/3 and a scaling factor λ – like the variance. The price of building B is normalized to 0. Furthermore, motivation is described by (1) with $\alpha = \beta = 1$ and rational decision making by (2). The buyer can observe ε, the econometrician cannot. He can therefore only determine a demand distribution or the expected demand and the expected equilibrium price. The decision tree is shown in Figure 7.

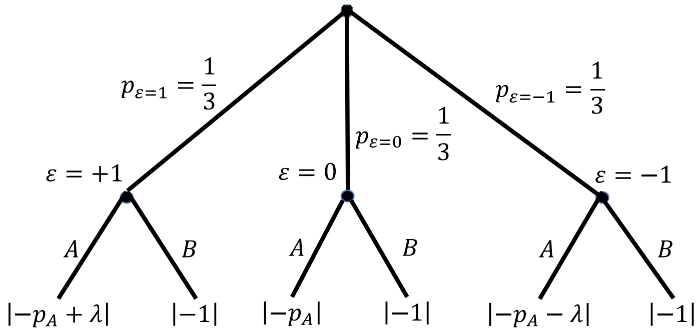

Figure 7: decision tree for the purchase decision of the efficient building A and the less efficient building B depending on random impact epsilon

In the case without uncertainty ($\lambda = 0$), the class A building will be bought with certainty if the price is lower than 1 (reservation price). If the price exceeds the reservation price, building B will definitely be purchased. If the market price corresponds to the reservation price, then the buyer is indifferent between the buildings. The probability of the demand for good A is shown in Figure 8 as a step function (solid curve). For a given supply S_A, the equilibrium price 1 arises and the market clears.

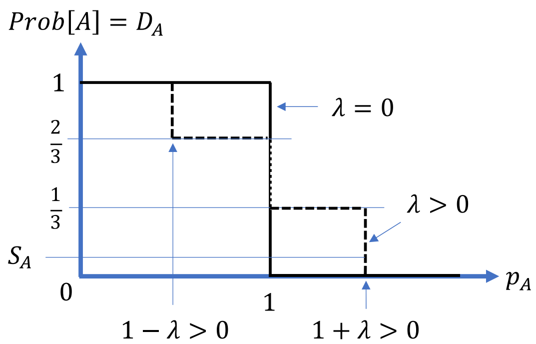

Figure 8: distribution of demand for building A depending on its price

As buildings differ a little, a positive premium may arise, so that even if the price is above the reservation price – interpreted as net costs – there is still a willingness to pay. In Figure 8, for example, at $\lambda > 0$, there is a 1/3 probability that building A will be bought, even though the price is up to λ greater than the net cost of building B (equal to 1). The reason is that there is a characteristic in A that the buyer appreciates. Conversely, there may be a negative premium, so that the willingness to pay declines below the reservation price. The subjective heterogeneity of the buildings reduces the size of the expected demand steps.[9]

A large number of these decisions can be aggregated to give the market demand for type-A buildings, D_A. This market demand decreases in the price, as (based on a plausible assumption about the

[9] In the deterministic context, willingness to pay is the (reservation) price, below which (discrete) demand jumps from 0 to 100%. In the discrete choice context, on the other hand, the (marginal) willingness to pay is the amount for which one is willing to exchange money for an infinitesimal additional feature. It is therefore a substitution rate that is constant for all levels of demand in linear random utility models (RUM). Both concepts are only related to one another by name. However, they have nothing in common.

distribution) it becomes increasingly difficult to find building-buyer pairs in which non-observable properties of the building are sufficiently outstanding to raise the willingness to pay above the reservation price.

In equilibrium prices clear the market, such that market demand D_A equals constant market supply S_A. We call the difference between the reservation price and the market price based on the idea of finding buildings that are increasingly less outstanding: scarcity premium. This model generalizes the reservation price conception of demand and again reduces arbitrage between markets A and B.

If supply S_A on the market is less than 1/3 of the overall market, then only buyers who have an above-average appreciation of these buildings will be satisfied on this market. This appreciation corresponds to the price, which exceeds 1. In this example the impact of supply on the price formation becomes apparent.

In the more general case (4b) with multinomial logit specification of the disturbance but without trait heterogeneity the market pricing function becomes as nonlinear (parabolic) in energy costs as in the case with personal traits in section 4. λ, the variance (scaling) of the disturbance ε_x, affects the pricing function in a very similar way as the standard deviation (heterogeneity) of the personal traits σ_β.

Some buyers privately value details of a building so much that their willingness to pay increases beyond its NPV, then customers self-select into the markets of the efficiency classes according to their highest willingness to pay. If they encounter a low supply there (small market), the average willingness to pay will be higher than on large markets and the small markets "discriminate" by imposing a price premium. Scarcity would result in premiums for very high and low efficiency classes (as they are typically on the tails of a distribution; figure 8). Again, offsetting of the parabolic premium for scarce building types and the linear premium for efficiency occur resulting in the nonlinear pricing function. If disturbances disappears and $\lambda \to 0$ the pricing function becomes linear and arbitrage pricing applies. Therefore, the same reasoning of overlaying scarcity premium as in section 4.3 is effective.

6. Explanation III: Econometrics and Information

We have shown in Section 2 that a hedonic price function can be non-linear in energy costs despite linear utility with heterogeneity. Such a non-linear function has been estimated in the literature as a mixed linear and - in terms of efficiency - non-linear hedonic function as a reduced form.

6.1. Econometric problems?

Could an incorrect estimate of a linear hedonic price function have caused the non-linearity? An estimation error in the sense of an inconsistent estimation can arise due to the unobserved quality of the buildings (Fuerst et al., 2015). E.g., assume efficiency of buildings is measured as x and the unobserved quality of the building may be Q. The hedonic pricing function would then be ($\beta_x, \beta_Q, \delta_1 > 0$)

$$p = \ldots + \beta_x x + \beta_Q \delta_1(Q) + \varepsilon_p \tag{5}$$

Now the two characteristics x and Q are assumed not to be independent anymore but correlated ($\delta_2 > 0$)

$$Q = \delta_2(x) + \varepsilon_{Qn} \tag{6}$$

The marginal effect β_x of x on the price is not identifiable anymore and by plugging Q into p we estimate the marginal effect of x on p as

$$\frac{\partial p}{\partial x} = \beta_x + \beta_Q \frac{d\delta_1}{dQ}\frac{d\delta_2}{dx} \tag{7}$$

The divergence of β_x is called inconsistency of the estimator and the whole problem endogeneity. The price premium $\partial p/\partial x$ would be over-estimated, but not necessarily non-linearly. To serve as a source for nonlinearity of p at least δ_1 or δ_2 need to be nonlinear. This cannot be ruled out, as the quality was assumed to be unobservable. Intuitively, this means that if higher efficiency goes hand in hand with higher building quality, the willingness to pay for a building ($\partial p/\partial x$) not only increases by β_x but also by the unobservable, and hence not separately priced, influence on the building quality.

The endogeneity problem (Train, 2009; section 13) can be solved by the BLP (Berry, Levinsohn, and Pakes) approach, the control function approach (Heckmann) and a full maximum likelihood estimation. BLP could also identify the nonlinearity with respect to unobserved building quality without endogeneity bias. Berry derives an instrument from share data of the products that would cover average utility of the efficiency classes and serves as instrument in further estimation stages.

As far as I know, this approach has not yet been attempted in empirical practice, although the endogeneity problem is recognized and regularly discussed in connection with the measurement of premiums. Among others Olaussen et al. (2017) find that hedonic regressions consistently measure significant premiums. They then evaluate a data set of real estate transactions in Oslo, which allows to compare transaction prices of the same buildings before and after the introduction of a binding Energy Performance Rating in 2010. They show that significant premiums can be estimated even before the introduction of the ratings, which differ only slightly from those after the introduction. They conclude that either the efficiency must have been taken into account in the pricing on the markets even without a rating, i.e., there was no uncertainty in the market, or that unmeasured aesthetics is correlated with the efficiency and the premium estimate is thus biased. Hedonic regression analyzes are therefore systematically distorted.

In empirical practice, on the one hand, it is argued that building quality is not correlated with efficiency. Fuerst et al. (2015) object, that "the EPC rating is not a proxy for the overall condition or the visual appeal of a property as it is possible to obtain a high EPC rating for a property with poor non-energy related maintenance, decoration and visual appeal (and vice versa)." The authors therefore consider it justified to assume a low correlation between the rating and the non-measured quality variable, so that the estimate remains unbiased. Naess-Schmidt et al. (2016) counter this by saying that investments in efficiency might very well result in amenities in buildings that are not directly related to energy - e.g., increased indoor air quality. This additional quality could increase the willingness to pay beyond pure cost savings and thus explain the premiums for efficient buildings.

On the other hand, researchers have tried to exclude quality changes by excluding "suspicious" data and thus to obtain estimates that are not influenced by the quality. Fuerst et al. (2015) address the case that an unobserved quality variable is correlated with the rating. They test robustness with truncated datasets, that exclude "observations that had a relatively high level of unexplained variation in the full sample model."

The idea is that renovated buildings have a higher unexplained price variation in the estimate, and they eliminate "dwellings that have been 'flipped' in under two years.", which indicates a low quality of the dwellings. The estimate results remain “broadly stable”. The authors regard these results as “reassuring”.

More convincing is the approach of expanding the scope of the data used in such a way that few quality aspects of the building are not taken into account. The integration of additional information succeeds in a later analysis for the Finnish real estate market (Fuerst et al., 2016). However, taking quality into account did not significantly change the results.

While not all concerns about the quality of hedonic regression have been resolved, convincing evidence against the nonlinearity has not yet been established. Therefore, we consider it premature to discard a whole series of high-quality publications with stable results from hedonic regressions as systematically flawed.

6.2. Information problems

The decision to invest in efficiency is influenced by uncertainties about the long-term development of energy prices. This also includes uncertainties about the future taxation of fossil fuels. Such uncertainties can justify an option value of waiting with the building renovation. This would occur as an additional value (Næss-Schmidt et al., 2016) for inefficient buildings only and would explain an “overestimation” of energy-inefficient buildings.

A lack of information about the costs and benefits of building refurbishment and its promotion could also cause the nonlinear premiums. However, there would have to be a systematic misjudgment by owners depending on the efficiency of the building. In view of the heterogeneity of the real estate markets, such a simple relationship between energy efficiency and energetic illiteracy or bounded rationality is again difficult to imagine. Similar doubts apply with the hypothesis that residents of inefficient buildings have a lower comfort level or save on heating. In these cases, the standardized efficiency rating would not reflect the preferences of the residents and would therefore overestimate the savings potential and thus the willingness to pay.

7. Implications of the Model: Estimation

The reduced form of the hedonic premium function (4) is a quadratic function $P(x) = \pi_1(x - x_D) + \pi_2(x - x_D)^2$ of the energy costs with parameters π_1 and π_2. This equation can be estimated with OLS methods based on the original datasets of the hedonic analyses. With these parameters conditions (8) and (9) allow identification:

$$\pi_1 = -\frac{\mu_\beta}{\alpha} \tag{8}$$

$$\pi_2 = \frac{\sigma_\beta^2}{\alpha\left(-\lambda + \sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}\right)} \tag{9}$$

Which deep model parameters would we like to identify? From the data of the building stock the standard deviation of the energy efficiency rating (the energy costs) $\sigma_b = 0.33$ are known. Building on Section 5 it is assumed that discount heterogeneity ($\mu_\beta = 11, \sigma_\beta = 5$)[10] is the only source of individuality.

[10] To approximate the original skewed frequency data with a normal distribution we use the inverse of the median of the discounting rates as mean of the distribution of discounting factors and chose the standard deviation as half of the mean. This implies that 95% of the population discount between 0% and 20% with an average of 10%.

However, we distrust the ability of buyers to fully anticipate the benefits of the investment decision and would therefore like to estimate μ_β and compare it with estimates cited in section 5. Deviations would then indicate an incomplete passthrough $\tau = \mu_\beta/\mu_{\beta L}$ (<100%) of investments on the efficiency premium. Unfortunately, it is not possible to identify λ, μ_β and α from π_1 and π_2 alone. At least α can be eliminated from (8) and (9) and thus the passthrough can be determined as a function of λ:

$$\tau(\lambda) = -\frac{\pi_1}{\pi_2}\frac{\sigma_\beta^2}{\mu_\beta\left(-\lambda + \sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}\right)} \tag{10}$$

Although we do not have original data available, the estimated premium constants (Table 1, Fuerst) can be interpolated using the same quadratic price function. The result is $\pi_1 = -8.55$ and $\pi_2 = 8.11$. So, $\lambda = 1.08$ and $\alpha = 1.28$ can be identified from π_1 and π_2 from (8) and (9). A passthrough interval can be calculated based on (10) assuming $\tau \leq 1$:

$$\tau \in [\tau(0), \tau(1.06)] = \left[-\frac{\pi_1}{\pi_2}\frac{\sigma_c}{2\sigma_b\mu_c}, 1\right] = [0.73, 1.00]$$

The lower bound of the passthrough is thus 73%. The analysis shows that an estimate of the passthrough is only possible with the comprehensive model including individual willingness to pay.

8. Summary

Although the conclusions from the model itself are intuitive, the complete presentation of the effect is not simple. Therefore, we summarize: With arbitrary supply of buildings in all efficiency classes and without heterogeneity of buyers, the price premiums for efficiency correspond to energy cost savings and the premium function is linear in energy costs and the (net) values of the buildings are all equal. If there was a difference in value, then value-maximizing buyers and sellers would ignore unfavorable bids or ask for the entire supply. Prices would then adjust until the value of the buildings of all efficiency classes was equal.

If the idea that buyers would be willing to switch between buildings for the smallest price difference was given up, competitive markets would behave differently. Guess that the number of buildings in each efficiency class is initially the same. Now assume the supply of medium-efficient buildings was increased. Then the premium curve can modulate demand by diversifying the purchase decisions through heterogeneity of the buildings and the willingness to pay: namely buyers with the highest willingness to pay would ask for the most efficient buildings and vice versa. Object heterogeneity increases the willingness to pay for certain buildings, so that the energy costs of the building are no longer the only factors that determine the purchase. This also fans out demand.

Fanned demand offers the premiums “points of attack” to shift demand to the respective neighboring classes - until supply and demand in all classes are balanced. In other words, the premium curve deforms non-linearly and “pulls” demand into high-supply regions. In our example, the price premium for buildings with medium efficiency falls because their supply is high, and it increases for buildings with high and low efficiency because their supply is low.

This effect of concentrated supply is overlaid by the linear efficiency premium. As a result, in the case of efficient buildings, the premium from cost savings and scarcity adds to the net premium; in the case of inefficient buildings, the cost surcharge and scarcity premium balance out and are therefore reduced. This results in an asymmetric non-linearity of the net premiums for efficiency. Heterogeneity in demand or buildings and concentrated supply together cause a non-linear premium curve - exactly as empirically observed.

9. Conclusion

Investing in energy efficiency brings energy cost benefits for building owners. As long as the owner lives in the building himself, this connection is obvious. If the building is rented out, the investment enables the tenant to reduce operating costs. Rationally acting landlords anticipate this, and they price the savings into the rent. Even if the building is sold, a price premium enables the seller to participate in future savings. In both cases, prices have to 'pass-through' the anticipated monetary savings of the investment to the investor without loss in order not to distort investment incentives.

Empirical analyzes of efficiency premiums show that this lossless pass-through is not easily detectable. Rather, different perceptions of future savings and the scarcity of efficient buildings can cloud the transmission: the premium for energy-efficient buildings exceeds the discount for inefficient buildings by many times. This paper models the effect of buyer and building heterogeneity on the premium pass-through, showing that between 73% and 100% of the expected savings are passed through to building prices.

This may not be relevant for building owners who invest in efficiency and never move. However, for most property owners, especially commercial landlords, the prospective pay back in the case of a sale is important, and this is reduced by at most a quarter. This is an encouraging result though the prospect that the premium falls as the share of really efficient buildings rises may prove a hurdle on the way to increasing energy efficiency in the building sector and thus to climate neutrality in 2050. Some reasons for an incomplete passthrough are discussed in the context of the energy efficiency gap (Allcott and Greenstone, 2012).

It would be important to improve the estimation strategy to foster the results and estimate the pass through directly. Empirical analyzes that take into account both building characteristics and buyer characteristics would be of crucial importance. These could be analyzed with statistical methods e.g., Berry (1994). The latter makes it possible to estimate premiums undistorted despite an unobserved nonlinear building quality.

Stated preference methods, on the other hand, would not be sufficient, as buying a home is the biggest investment decision a household makes. This and the richness of detail of the decision are hard to simulate experimentally.

Rising fossil fuel prices might increase the savings potential and could therefore push the pass-through. Should this not be the case, there would still be building regulations and efficiency standards that would deprive building owners of the freedom of choice and force them to invest - with considerable efficiency losses in implementation and political-economic implications. It is therefore reassuring that the efficiency premium puzzle can in fact be explained by supply, demand and heterogeneity.

Acknowledgments

This work is part of The Active Building Centre research program, supported by the Engineering and Physical Sciences Research Council, Grant EP/S016627/1.

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Appendix I: Hedonic Prices

While demand equals (constant) supply

$$D(x,P)=\int_{-\infty}^{+\infty} f_N(\beta|\mu_\beta,\sigma_\beta)\frac{e^{U(x|P,\beta)}}{\int_{-\infty}^{+\infty} e^{U(y|P,\beta)}dy}d\beta = f_N(x|\mu_b,\sigma_b)=S(x) \tag{A1}$$

Start with the solution given the parameter a:

$$P(x)=-\frac{\mu_\beta}{\alpha}x+\frac{\sigma_\beta^2}{2\alpha a\sigma_b^2}(\mu_b-x)^2 \tag{A2}$$

Plugging into utility

$$U(x|P)=\frac{1}{\lambda}\left((\beta-\mu_\beta)x-\frac{\sigma_\beta^2}{2a\sigma_b^2}(\mu_b-x)^2\right) \tag{A3}$$

So aggregate demand for x becomes

$$D(x|P)=\int_{-\infty}^{+\infty} f_N(\beta|\mu_\beta,\sigma_\beta)\frac{e^{U(x|P,\beta)}}{\int_{-\infty}^{+\infty} e^{U(y|P,\beta)}dy}d\beta \tag{A4}$$

With this utility the demand normalizing integral (denominator of A4) becomes with $\mathrm{Erf}(z)=\frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$

$$\int_{-\infty}^{+\infty} e^{U(y|P,\beta)}dy = -\frac{\sigma_b}{\sigma_\beta}\sqrt{\frac{\pi\lambda a}{2}}\, e^{\frac{2\mu_b\sigma_\beta^2(\beta-\mu_\beta)+a\sigma_b^2(\beta-\mu_\beta)^2}{2\lambda\sigma_\beta^2}}\left[\mathrm{Erf}\left(\frac{\sigma_\beta^2(\mu_b-y)+a\sigma_b^2(\beta-\mu_\beta)}{\sigma_\beta\sigma_b\sqrt{2\lambda a}}\right)\right]_{-\infty}^{+\infty}$$

$$=\frac{\sigma_b}{\sigma_\beta}\sqrt{2\pi\lambda a}\; e^{\frac{2\mu\sigma_\beta^2(\beta-\mu_\beta)+a\sigma_b^2(\beta-\mu_\beta)^2}{2\lambda\sigma_\beta^2}} \tag{A5}$$

So, we can combine the three components of (A4) and integrate over β

$$\int_{-\infty}^{+\infty} f_N(\beta|\mu_\beta,\sigma_\beta)\frac{e^{U(x|P,\beta)}}{\int_{-\infty}^{+\infty} e^{U(y|P,\beta)}dy}d\beta \tag{A7}$$

$$=\frac{1}{2\pi\sigma_b\sqrt{a\lambda}}\int_{-\infty}^{+\infty} e^{-\frac{1}{2\lambda}\left(-2(x-\mu_b)(\beta-\mu_\beta)+\frac{(\lambda+a\sigma_b^2)(\beta-\mu_\beta)^2}{\sigma_\beta^2}+\frac{(x-\mu_b)^2\sigma_\beta^2}{a\sigma_b^2}\right)}d\beta$$

$$=\frac{e^{-\frac{(x-\mu_b)^2\sigma_\beta^2}{2a\sigma_b^2(\lambda+a\sigma_b^2)}}}{2\sqrt{2\pi}\sigma_b\frac{\sqrt{a}}{\sigma_\beta}\sqrt{\lambda+a\sigma_b^2}}\left[\mathrm{Erf}\left(\frac{(\lambda+a\sigma_b^2)(\beta-\mu_\beta)-(x-\mu_b)\sigma_\beta^2}{\sigma_\beta\sqrt{2\lambda(\lambda+a\sigma_b^2)}}\right)\right]_{-\infty}^{+\infty}$$

$$=\frac{e^{-\frac{(x-\mu_b)^2}{2\sigma_b^2\frac{a}{\sigma_\beta^2}(\lambda+a\sigma_b^2)}}}{\sqrt{2\pi}\sigma_b\frac{\sqrt{a}}{\sigma_\beta}\sqrt{\lambda+a\sigma_b^2}}$$

a can now be chosen to fulfill $\frac{\sqrt{a}}{\sigma_\beta}\sqrt{\lambda + a\sigma_b^2} = 1$. In that case, $D(x|P) = S(x) = f(x|\mu_b, \sigma_b)$. Solving for a:

$$a^* = \frac{-\lambda + \sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}}{2\sigma_b^2} \tag{A8}$$

Equilibrium hedonic pricing function finally becomes (with an unknown constant)

$$P(x) = -\frac{\mu_\beta}{\alpha}(x + const.) + \frac{\sigma_\beta^2}{\alpha\left(-\lambda + \sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}\right)}(\mu_b - x)^2$$

The constant can be determined by the normalizing condition $P(x_0) = 0$

$$P(x) = -\frac{\mu_\beta}{\alpha}(x - x_0) + \frac{\sigma_\beta^2}{\alpha\left(-\lambda + \sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}\right)}((\mu_b - x)^2 - (\mu_b - x_0)^2) \tag{A9}$$

With $x_0 = \mu_b$ we get

$$P(x) = -\frac{\mu_\beta}{\alpha}(x - \mu_b) + \frac{\sigma_\beta^2}{\alpha\left(-\lambda + \sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}\right)}(\mu_b - x)^2 \tag{A10}$$

Switching off building heterogeneity:

$$P^{det}(x) = \lim_{\lambda\to 0}P(x) = -\frac{\mu_\beta}{\alpha}(x - \mu_b) + \frac{\sigma_\beta}{2\alpha\sigma_b}(\mu_b - x)^2 \tag{A10a}$$

Switching off individual heterogeneity applying de L'Hospital:

$$P^{rep}(x) = \lim_{\sigma_\beta\to 0}P(x) = -\frac{\mu_\beta}{\alpha}(x - \mu_b) + \lim_{\sigma_\beta\to 0}\frac{2\sigma_\beta(\mu_b - x)^2}{\alpha\frac{4\sigma_b^2\sigma_\beta}{\sqrt{\lambda^2 + 4\sigma_b^2\sigma_\beta^2}}}$$

$$= -\frac{\mu_\beta}{\alpha}(x - \mu_b) + \frac{\lambda}{2\alpha\sigma_b^2}(\mu_b - x)^2 \tag{A10b}$$

And switching off heterogeneity and stochasticity

$$P^{dep}(x) = \lim_{\lambda\to 0}\lim_{s\to 0}P(x) = -\frac{\mu_\beta}{\alpha}(x - \mu_b) \tag{A10c}$$

Appendix II: Energy efficiency rating in the UK

The UK Standard Assessment Procedure (SAP) is an asset-based (in contrast to operational) mandatory scheme. Its Energy Efficiency Rating (EER) is based on the normalised annual energy costs, in contrast to the ratings in most other countries. The rating is determined, using standard energy cost factors, from the calculated annual regulated energy demands. These are the energy demands that are controlled by the Building Regulations and which therefore exclude the energy used by plug-in appliances, which was 26% of all UK domestic demand in 2016.

Data needed for SAP calculations are obtained from a home energy survey undertaken by a qualified assessor. A reduced data SAP is invariably calculated as this has less onerous survey data requirements. The national Energy Performance of Buildings Register currently holds over 18 million records, each of which includes the dwellings' total usable floor area and the heating fuels used. The SAP has evolved over the last decade the essential features, however, have been the same.

In particular, a one-point increase in the EER rating is equivalent to a reduction of energy standardized consumption in the building[11]. The exact linkage is described by the rating formula (Lomas et al., 2019) with x total annual energy cost (£) and the floor area A (m^2):

$$\mathrm{ECF}(x) = \quad 0.42\frac{x}{45 + A} \tag{1}$$

$$\mathrm{EER}(x) = \quad \begin{cases} 117 - 121\log_{10} ECF\,(x) & ECF(x) \geq 3.5 \\ 100 - 13.95 ECF(x) & ECF(x) > 3.5 \end{cases} \tag{2}$$

The UK approach to the EER is rough compared to other more data intensive and potentially more accurate schemes. However, it has the valuable advantage that there is a one-to-one relationship to normalized energy costs. Based on (1) and (2) normalized energy costs of an average size dwelling with A =100m^2 depending on its energy efficiency rating have been determined (table 1).

The average EER rating of the UK building stock (Mio. 30 dwellings) is D (43%). Therefore, it has average energy costs of £730. There are practically no class A and few class G buildings. We therefore excluded these classes from our analysis. The 200,000 new build homes every year are constructed according to regulation, so that 80% fulfill a class B rating.

[11] Ratings can be quite accurate. This is shown in a comparison of ratings and energy consumption in the Netherlands by Entrop, et al. (2010).