Modelling energy retrofit investments in the UK housing market: a microeconomic approach

Abstract

Purpose - Improving the energy efficiency of the existing residential building stock has been identified as a key policy aim in many countries. This study reviews the extant literature on investment decisions in domestic energy efficiency and presents a model that is both grounded in microeconomic theory and empirically tractable.

Design/methodology/approach – This study develops a modified and extended version of an existing microeconomic model to embed the retrofit investment decision in a residential property market context, taking into account tenants' willingness to pay and cost-reducing synergies. A simple empirical test of the link between energy efficiency measures and housing market dynamics is then conducted.

Findings - The empirical data analysis for England indicates that where house prices are low, energy efficiency measures tend to increase the value of a house more in relative terms compared to higher-priced regions. Secondly, where housing markets are tight, landlords and sellers will be successful even without investing in energy efficiency measures. Thirdly, where wages and incomes are low, the potential gains from energy savings make up a larger proportion of those incomes compared to more affluent regions. This, in turn, acts as a further incentive for an energy retrofit. Finally, the UK government has been operating a subsidy scheme which allows all households below a certain income threshold to have certain energy efficiency measures carried out for free. In regions, where a larger proportion of households are eligible for these subsidies, we also expect a larger uptake.

Originality/value - While the financial metrics of retrofit measures are by now well understood, most of the existing studies tend to view these investments in isolation, not as part of a larger bundle of considerations by landlords and owners of how energy retrofits might influence a property's rent, price and appreciation rate. In this paper, we argue that establishing this link is crucial for a better understanding of the retrofit investment decision.

Keywords: Energy retrofit investments, Microeconomic modelling, Rental market, Investment decision, Energy efficiency, energy efficiency gap

Paper Type: Research paper

1. Introduction

In most developed countries, buildings account for approximately 40% of total CO_2 emission from the use of fossil fuels (Ürge-Vorsatz et al 2007). Hence, improved energy efficiency of buildings, particularly in the residential sector, plays a key role in lowering domestic energy consumption and reducing greenhouse gas emissions. Despite a number of seminal studies, the economic drivers of domestic energy efficiency investments remain an under-researched area. In particular, there is a shortage of empirical research addressing the relationship between investments in energy efficiency in homes and the resulting change in energy bills and its implications for the profitability of energy retrofits. While both the technological and the financial aspects of energy retrofits are relatively well-understood, there are a very few studies that investigate the microeconomic decision rules of households opting for a retrofit or possibly choosing to forgo this option instead. These decision rules include, among others, the financial characteristics of an energy retrofit, any existing investment inefficiencies, the barriers influencing the financial outcomes and the asset pricing of energy efficiency in the residential property market. This microeconomic approach is useful for understanding observed outcomes in the presence of market inefficiencies such as the split incentive problem which has been identified as a major obstacle to energy retrofits in the non-owner-occupied property market. Split incentives arise when benefits and costs accrue asymmetrically to the parties to a transaction. For instance, if a tenant has a net lease contract, then the landlord has no priori incentive to invest in energy efficiency that would only benefit the tenant in terms of lower energy bills (Bird & Hernandez, 2012).

This paper seeks to demonstrate that energy efficiency investment decisions cannot be fully understood if they are viewed in isolation and outside of the real estate market context in which they take place. To this aim, we review the current literature and then present a

2

modified and extended model to embed the retrofit investment decision in a residential property market context, taking into account the split incentives problem, tenants' willingness to pay (WTP) and cost-reducing synergies. Finally, we present a simple empirical test of the link between energy efficiency measures and housing market dynamics.

2. Previous Empirical Research

Empirical studies by Berry et al, 2008; Brounen and Kok, 2011; Deng et al, 2012; Zheng et al, 2012; Cajias and Piazolo, 2013; Hyland et al, 2013; Kahn and Kok,2014 and Fuerst et al, 2015 provide the first valuable insights into the pricing of sustainable real estate. These studies test for the existence of 'green value', defined as the capitalisation of energy and resource saving features into property prices and rents. Assuming that energy efficiency investments are fully capitalised into house prices, the decision to undertake a retrofit reduces to a discounted cash flow model to evaluate the viability of such a measure. This approach estimates all future cash flow and discounts them to arrive at their present value, which is then used to evaluate the potential for investment. If the present value is higher than the current cost of the investment, the investment is considered to be good. Table 1 presents a summary of empirical studies of energy efficiency in residential dwellings. The consensus among these studies appears to be that energy efficiency investments are attractive for longer-term investors but there is no consensus on whether buyers and tenants are willing to pay for these capitalised energy savings in the short run. A problematic feature of some of these studies is that they do not establish a clear link between retrofit investments, subsequent cost savings and impact on prices and rents. Some of these studies also fail to take into account the opportunity cost of the capital investment defined as the expected rate of return forgone by not being able to invest the funds in alternative investment activities.

One of the first researchers to examine such an investment specifically from a residential landlord's perspective was Amstalden et al (2007). By applying retrofit measures to a model building scheduled for renovation, they report that expected energy prices affect the outcome of an investment analysis. Energy efficiency retrofits in residential housing are found to be an attractive investment in the presence of high energy prices. Conversely, given free-market conditions and particularly low energy prices, economic gains on energy efficiency retrofit measures are relatively small. Under rising energy prices, renovating a property without simultaneously investing in energy efficiency measures is a sub-optimal choice. Van Soest and Bulte (2001) shed some light on the reasons why households make these seemingly sub-optimal decisions. Their option value approach suggests that households are reluctant to invest in a retrofit even if it is profitable from a Net Present Value point of view when upfront investments of energy efficient technologies are fully or partially irreversible. Given the uncertainty of future technological developments, technologies that appear profitable from a net present value perspective, will not be adopted by the majority of households if the value of waiting, the opportunity cost and the rate of return of current alternative investments are high.

Tommerup and Svendsen (2006), on the other hand, report that if residential properties are upgraded in the process of general building refurbishment, a significant saving potential of 80% for energy used for space heating over a 45 year time horizon can be achieved. In a related study, Zavadskas et al (2008) find that in addition to energy savings potential, an energy retrofit improves the general condition of the building structure and extends the economic and physical lifetime of a building. Ultimately, this will increase the market value of the property more significantly than a 'non-green' renovation of a dwelling. Using retrofit scenarios for large-panel buildings in Vilnius, Lithuania; the authors suggest that cost-

effective energy-savings are highest for small and medium retrofit investment packages. Similarly, Morrissey and Home (2011) find significant cost savings from energy efficiency measures over 25 and 40 years' time horizons, particularly when energy prices are high. By applying a life cycle costing approach to a sample of Australian detached dwellings, the study determines the optimal level of energy efficiency for a given energy price level. Deep energy efficiency retrofits are found to be more cost-effective when energy prices are high, whereas a seven out of ten star thermal performance rating appears to be optimal when energy prices are low and the investor has a 25 year time horizon. For both low and high energy price scenarios, an eight star thermal performance rating is optimal for a 40 years' time horizon, though energy price levels appear to be less relevant for longer investment horizons. The Australian energy rating system ranges from 0 to 10 stars, 10 being the most energy efficient, and is based on the space heating and cooling demand of the dwelling.

Furthermore, a study by Jacobsen and Kotchen (2009) uses household data from Florida to show that the Florida's energy-code change in 2002 lead to a 4 % fall in electricity consumption and a 6 % fall in natural-gas consumption. They also report that, under the best-case scenario, the private payback period is 6.4 years for the average residence. The social payback period accounting for the avoided costs of air-pollution emissions, is estimated to be between 3.5 and 5.3 years. As mentioned above, standard discounted cash flow approaches are likely to overestimate the net present value of energy efficiency measures. Energy price elasticity and future annual energy price rises are understood to have a mutually offsetting effect on the net present value of an energy efficiency investment (Galvin and Sunikka-Blank, 2012). While the profitability of energy efficiency retrofits increases in line with energy prices, this effect will be dampened by the price elasticity of demand which in turn reduces the overall magnitude of the energy savings.

Galvin and Sunikka-Blank (2012) apply an alternative discounted cash-flow method incorporating energy price elasticity on to a housing estate retrofit project in Ludwigshafen, Germany. They conclude that the incorporation of prices elasticity into the analysis reduces the net present value of the energy efficiency measures by 14-24 % and extends the payback period by 5 years in some cases. Using an alternative calculation method in the form of probabilistic methodology based on Bayesian calibration of normative energy models, Heo et al (2012) also argue that energy retrofit financing options can be estimated accurately by explicitly calculating risks associated with each retrofit option.

Table 1: Overview of studies on residential energy efficiency investment decisions from several countries:

While the use of the discounted cash-flow model in most of these studies has contributed to the development of this research area, they have also been heavily criticised on theoretical grounds. As early as the 1990s, Metcalf and Hassett (1999) pointed out that discount rates used in conventional engineering studies lack crucial economic micro-foundations to yield plausible propositions and that such calculations are overestimating the returns to energy-saving investments. Hence, a microeconomic analysis of the behaviour of individual agents such as tenants or landlords that underpins an energy efficiency theory is required.

3. A Proposed Model of Residential Energy Retrofits

Investments in energy efficiency are typically measured in payback periods. A simple decision rule is that investments with shorter payback periods are favoured over longer periods. This is equivalent to an internal rate of return (IRR). For example, DeCanio (1998) describes this basic relationship for the payback period P_0 as:

$$P_0 = \frac{C_0}{S_0} = \frac{(1+r)}{r} - \frac{1}{r(1+r)^n} \quad (1)$$

Where C_0 is the initial cost of the efficiency investment, S_0 denotes the cost savings over the lifetime of the new equipment (n) and r is the IRR of the investment.

Payback periods can also be expressed as a linear function in a Taylor series:

$$\frac{C_0}{S_0} = f(1) + f'(1)(r-1) + \left(\frac{1}{2}\right) f'' \left(\frac{1}{2!}\right)(r-1)^2 + .. + \left(\frac{1}{n}\right) f^n \left(\frac{1}{n!}\right)(r-1)^n \quad (2)$$

What determines payback periods?

A key problem in any reliable calculation of payback periods is the uncertainty surrounding the true future cost savings as well as any investment inefficiencies at the market or at the individual level which may in turn lower investors' willingness to invest or WTP. Allcott and Greenstone (2012) propose a model in which Investor *i* will upgrade from the current standard e_0 to a more energy-efficient standard e_1 if:

$$\frac{pm_i\,(e_0 - e_1)}{(1+r)} > c \quad (3)$$

Where p is the private cost of energy, c represents the upfront cost of the retrofit and the intensity of using domestic heating and cooling systems is represented by m.

As in Equations (1) and (2), we expect that the discounted lifetime energy cost savings minus observed and unobserved capital costs determine the WTP of an investor. However, this simple formula fails to account for a number of crucial factors in the investment and pricing decision. Similar to Allcott and Greenstone's model (2012), we propose that a more complete representation of this decision might take the following form:

$$\frac{\gamma(\xi + p)m_i\,(e_0 - e_1)}{(1+r) - \psi} > c \qquad (4)$$

Where γ captures investment inefficiencies, ξ social cost of energy use and ψ investment opporunity costs.

The weighting parameter γ reflects a number of investment inefficiencies such as imperfect information, lack of attention or interest, excessive risk aversion or credit constraint. This weighting parameter is also a measure of the implied discount rate that an individual investor or a group of investors applies in excess of capital market risk-adjusted discount rates (*r*). If $\gamma<1$, an investor might not choose to upgrade even if net present value (NPV) of the investment is positive. Parameter ξ reflects the social cost or uninternalised externality of energy use that is added to the market price *p*. High values of this parameter entail low profitability and long payback periods. The externalities captured by γ and ξ can be influenced by imposing a pigovian tax, carbon trading scheme or a similar measure that aims to internalise externalities. At the social optimum, $\gamma=1$, i.e. there are no investment inefficiencies distorting prices and quantities and investors take the full social cost of energy ($\xi+p$) into account when making their energy efficiency investment decision. Next, investment opportunity costs are captured by ψ. The reasoning behind this parameter is that investments in energy efficiency are more likely to occur when expected returns for competing asset classes such as stocks and bonds are low (and vice versa).

Energy Efficiency Investments in the Rental Market

The retrofit investment decision in rental properties becomes even more intricate in properties for which the costs and benefit accrue to different parties as is typically the case in the rental market. Lease structures are crucial for alignment or misalignment of incentives. Assuming that the rent paid by the tenant is net of utilities and payable according to their individual energy usage, there is no *a priori* incentive for the landlord to bear the upfront capital investment of energy efficiency measures regardless of the payback period or IRR of the investment. However, a landlord may still be able to recoup her retrofitting expenses through higher rent payments, provided that tenants exhibit a higher WTP for inhabiting a more energy-efficient property and benefitting from lower energy bills (for a discussion of tenants' WTP see for example Fuerst & McAllister 2011). On the cost side of the formula, cost reductions are to be expected when energy retrofits are carried out as part of a general modernisation or refurbishment of a property. To reflect these synergies and the WTP in the rental market, we modify the formula as follows:

$$\frac{\mu[\gamma(\xi + p)m_i\,(e_0 - e_1)]}{(1+r) - \psi} > c - \delta \qquad (5)$$

where μ measures tenants' WTP and δ cost $-$ reducing synergies.

Parameter δ reflects how the cost effectiveness of energy retrofits is enhanced when the property undergoes a general modernisation, for example when contracts are bundled and other cost savings arising from a simultaneous upgrade of the general quality of a dwelling as well as its HVAC systems, wall and loft insulation, lighting systems etc. A further condition for δ to take on a significant value is that the property or rental unit is vacant at the time of refurbishment which can be difficult to achieve in practice. On the other hand, Fuerst and

Wegener (2015b) assume a negative relationship between vacancy rates and the energy efficiency upgrading of the existing stock based on the rationale that vacancy rates are a proxy for the rentability of upgrading. In the context of the rental market, μ reflects the degree to which energy efficiency and cost savings are capitalised into prices and rents. If $\mu=1$, the monthly rent increment tenants are willing to pay is exactly equal to the monthly cost savings that are due to higher energy efficiency. If $\mu<1$, landlords will only be able to defray some of the capital cost to tenants. It is debatable whether $\mu>1$ may also occur empirically, i.e. whether tenants are willing to pay more than the monthly rate required for the amortisation of costs. This would be the case if additional benefits accrue to tenants above and beyond mere cost savings. Examples of these additional benefits include enhanced indoor comfort and wellbeing as well as utility gains from being 'seen to be green'. In this case, we may observe $\mu>1$ in the form of a rental premium that exceeds the 'total occupancy cost' neutrality of energy efficiency investments. Increasingly, the inefficiencies arising from the split incentive problem are addressed by the establishment of green leases that aim to share costs and benefits between landlord and tenant and define benchmarks and targets for environmental performance at the building level.

Aggregation of individual investment decisions

How can these microeconomic decision rules be incorporated into a model that takes into account thousands or even millions of individual investment decisions? The specifics of building characteristics such as current insulation, heating systems and household consumption and preference parameters are not directly observable in most studies due to the aggregate nature of most datasets. A possible heuristic is to apply average values to each spatial zone and/or property type, such as detached, semi-detached and terraced properties and make assumptions about the distribution of investor preferences for each zone and/or

property type but this method is not accurate and potentially subject to ecological fallacy. A further challenge is the spatial variability of some of the parameters and variables. The WTP parameter μ is likely to vary across households and neighborhoods together with average income and lifestyles. Similarly, the intensity of energy usage m_i is a function of household income. By contrast, we use the simplifying assumption that the parameters γ (investment inefficiencies), ξ (uninternalised externalities), ψ (opportunity cost of retrofit investing) and δ (cost synergies) vary over time but not across space, at least not within a metropolitan area.

4. Discussion

The consensus on the energy efficiency gap in the empirical literature is that investors apply excessively high discount rates to energy efficiency retrofit decisions and that this leads to investment inefficiency (Giraudet and Houde 2013, Train 1985). Previous studies such as Alcott and Greenstone (2012) capture this energy investment inefficiency with a single parameter ranging from full efficiency to zero efficiency. However, an important issue arises regarding the use of a single parameter to account for all inefficiencies associated with energy efficiency retrofits. In accordance with Gillingham et al (2009), we argue that the energy investment inefficiency depends on both the economic efficiency of the market conditions individual face as well as the behavior of the individual decision makers. Various forms of market inefficiencies have been recognised in the literature, including imperfect information, environmental externalities or credit constraints. Giraudet and Houde (2013) calibrate a model of imperfect information to measure the magnitude of the energy investment inefficiency largely caused by moral hazard on the part of the suppliers or homeowners. Suppliers may take hidden actions, specifically when the purchase of an energy efficiency retrofit involves significant installation work such as insulation, double glazing, solar panels or HVAC system. Equally, homeowner may increase their energy consumption upon

installing energy efficiency retrofits. Giraudet and Houde (2013) estimate the marginal investment inefficiency due to moral hazard to be £281per thousand cubic metre consumption of natural gas for heating. This amount is interpreted as the extra unit of energy that is consumed but could have been saved by an optimal investment, a possible proxy for parameter γ in our model. Equally, market conditions individual face may well be inefficient in the presence of environmental externalities. Giraudet and Houde (2013) estimate the marginal investment inefficiency due to environmental externality to be £40 per thousand cubic metre consumption of natural gas for heating, significantly lower than the estimate for the energy investment inefficiency caused by imperfect information. This estimation could be used to estimate the social cost or uninternalised externality of energy use (parameter ξ in our rental model) since this implies even without the investment inefficiency caused by the split incentive or moral hazard problem, environmental externality of energy use exists.

It is also important to capture decision making behaviour of individuals in order to identify possible "behavioural inefficiencies" causing departure from investment optimality in energy efficiency retrofits. Notably, our proposed rental model dismantles the energy investment inefficiency further by introducing a new parameter into the analysis in the form of tenants' WTP for energy efficiency measure (μ). This additional investment inefficiency parameter (μ) is crucial for understanding the investment decision of investors. Several studies find evidence of a strong WTP for eco-labelled properties (see for example Yau Y, 2012 and Fuerst and McAllister, 2011). However, a recent study by Jonsson (2014) quantifying the magnitude of the WTP sheds initial light on the characteristics of the real estate rental markets and estimates WTP to be 5% of total rent for tenants in green buildings. This finding supports the inclusion of the WTP parameter as an additional source of energy investment inefficiency in the rental market analysis presented in this study.

Furthermore, in this study, cost-reducing synergies capturing enhanced cost effectiveness of energy retrofits when the property undergoes a general periodic modernization is accounted for. Kats (2003) suggests that energy efficient buildings save investors money by reducing operation and maintenance costs and estimates these cost-reducing synergies (parameter δ in our model) to be about £61 per square metre . Lastly, parameter ψ is introduced into the analysis in order to control for the opportunity costs of investment. Investments in energy efficiency are likely to be more appealing when expected returns for alternative asset classes such as stocks and bonds are low. For instance, a study by the Rhodium Group (2013) estimates that investing in energy efficiency retrofitting of buildings would yield an internal rate of return (IRR) four times higher than average corporate bond yields and more than double the returns of high-performing venture capitals` yield. The investment opportunity costs (ψ in our model) is estimated to be 6.8 % IRR on equity and 12.4 % IRR for high performing venture capital investments relative to investments in energy efficiency retrofit yielding an estimated internal rate of return of 28.6%.

5. Empirical analysis

In the absence of detailed information on most of the micro-economic decision parameters necessary to estimate the full model specified, we use aggregate information at the local authority level in England to investigate the basic drivers of energy efficiency measures. To understand the dynamics of upgrades better, the analysis is limited to the two most widespread measures, cavity wall and loft insulation. As Crawford (2012) points out, adding loft insulation is generally considered an inexpensive and cost-effective way to upgrade while adding cavity wall insulation is more expensive but still exhibits a favourable payback profile compared to a range of other possible energy efficiency upgrades.

Table 2 presents average regional house prices in our sample. House price levels exhibit marked persistent differences, with dwellings in the North East of England being priced at almost one-third of the average prices of dwellings in London.

Table 2: Regional house prices

Turning to the adoption rate of energy efficiency investment in the form of cavity wall and loft insulations per 10,000 dwellings, the north-south divide in property prices appears to be reversed. Figure 1 illustrates that the rate of energy efficiency measures is highest in northern local authorities and relatively low in the South East and London. A similar pattern is also found when breaking down the energy efficiency measures into loft insulation and cavity wall insulation (see the Appendix for details).

.FIGURE 1: UPTAKE OF ENERGY EFFICIENCY MEASURES (BUILDING INSULATION) AT LOCAL AUTHORITY LEVEL IN ENGLAND.

We have argued in the theoretical model section above that energy efficiency upgrades tend to occur when a property is temporarily vacant as this presents an opportunity to carry out these measures without undue disruption to the occupiers of a building. Following this argument, we would expect that higher vacancy rates, both at the building and the market level, are tied to higher levels of energy retrofitting. A high vacancy rate may also indicate a weak property market which may necessitate additional measures for properties to be successfully rented or sold in the marketplace. The map in Figure 2 shows indeed that local authorities in the South of England have lower vacancy rates relative to local authorities in the North. This seems to confirm the prediction that local housing markets with higher vacancy rates also experience higher take-up of energy efficiency measures.

.Figure 2: residential vacancy rates in England.

To further analyse the link between the energy retrofit decision and property market dynamics, we conduct a simple regression analysis of the English housing market. The rate of investment in energy efficiency in the form of the level of cavity wall and loft insulations per 10,000 dwellings is regressed on the local average vacancy rate as well as local average earnings and median local house prices.

Table 3 shows the results of four separate estimations. Models 1 and 4 present the impact of vacancy rate defined as the percentage of rental homes that are vacant on the rate of investment in energy efficiency. Next, model 2 captures the effect of local earnings, a proxy for local and regional wealth levels, on the rate of investment in energy efficiency. Model 3, on the other hand, estimates the impact of local house prices on the rate of investment in energy efficiency. In Table 3, the rate of investment in energy efficiency appears to be positively linked to vacancy rates with a 1% increase in vacancies entailing a 0.5% higher investment rate into energy efficiency. Yet, Model 4 shows that vacancy rates are rendered insignificant by the inclusion of local earning levels in the regression model, possibly reflecting the fact that regions with the highest per capita earnings such as London and the South East of England also exhibit some of the lowest vacancy rates and vice versa .More importantly, the rate of investment in energy efficiency is found to be negatively linked to the level of local earnings and negatively related to house price levels. A 1% increase in local earnings is predicted to reduce energy efficiency measures by 1.3%. Similarly, a percentage increase in local house prices is found to reduce the rate of energy efficiency measures by 0.7%

Table 3: Energy efficiency measures and housing market dynamics

These regression estimates indicate the following relationships with regard to energy efficiency measures. Firstly, where house prices are low, measures such as adding loft and cavity wall insulation may increase the value of a house more in relative terms compared to higher-priced regions. Secondly, where housing markets, both owner-occupied and privately rented, are tight, vacancy rates will be extremely low and landlords and sellers will be successful even without investing in energy efficiency measures due to the general shortage in the marketplace. In the context of the theoretical model set out in Equation 5, tenants' WTP for energy efficiency measure (μ) may be varying considerably across the UK. In regions where market conditions are worse, landlords and sellers have a larger incentive to invest at least a modest amount into energy efficiency improvements to increase the attractiveness of the asset compared to competing offers. Thirdly, where wages and incomes are low, the potential gains from energy savings make up a larger proportion of those incomes compared to more affluent regions. This, in turn, acts as a further incentive for an energy retrofit. Finally, the UK government has been operating a subsidy scheme which allows all households below a certain income threshold to have certain energy efficiency measures such as loft and cavity wall insulation carried out for free. In regions, where a larger proportion of households are eligible for these subsidies, we also expect a larger uptake. For instance, recent case studies in Australia report that feed-in tariffs and rebates are effective incentive schemes for increasing the uptake of solar photovoltaic panels and water heater technologies (Higgins & Foliente, 2013). The uptake rate is also found to vary with socio-demographics of consumers in different location and consumer behaviour in the presence of incentives (Higgins et al, 2014a and Higgins et al, 2014b).

6. Conclusion

The aim of this paper is to review the extant literature on investment decisions in domestic energy efficiency and present a model that is both grounded in microeconomic theory and empirically tractable. In particular, we develop an extension to an existing microeconomic model that takes into account a number of crucial behavioural and property market features such as the split incentives problem and the ability for landlords to recoup investments in energy efficiency via higher rental rates. At the dwelling unit level, the proposed model treats each energy efficiency measure as a separate decision, for example, the decision to upgrade loft insulation is treated independently of the decision to install a more energy-efficient boiler. In practice, however, these individual measures are more likely to be undertaken (simultaneously or spread out over a longer period) as part of a larger bundle of energy efficiency upgrades. For instance, better thermal insulation may lead to lower energy consumption, i.e. a lower value for the energy intensity of a dwelling (m_i *in the theoretical model*) and in turn a longer payback period if a new heating system is also installed. Future work may address the interaction and 'packaging' of these individual retrofit measures to capture the reality of energy retrofits better.
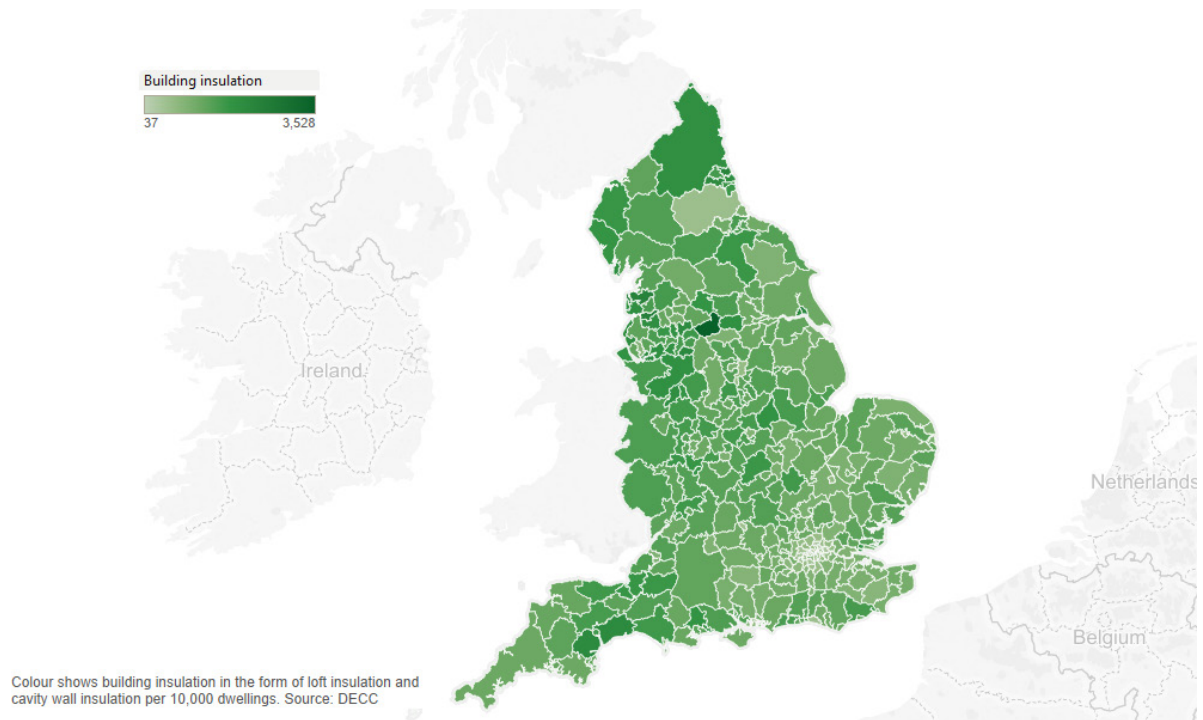
Using the proposed model, it should be possible to estimate the specified model empirically to understand better how the observed unequal patterns in energy retrofit investment decisions arise. While all the mechanisms and parameters in the model presented here were identified in the existing literature, we are not aware of any attempt to link them together in a comprehensive empirical model. A major challenge towards implementing this model empirically is the lack of specific individual household and property level data. Yet, a number of private and government initiatives in various countries seek to fill this data gap. One promising recent dataset is the UK National Energy Efficiency Data (NEED) framework by

17

the Department of Energy and Climate Change which combines household energy consumption data with records of energy efficiency measures as well as dwellings and households obtained from a variety of sources. Further efforts are underway in Australia where researchers are developing a comprehensive bottom-up model that incorporates detailed data on the building stock in New South Wales (Foliente and Sao, 2012). To estimate the proposed model empirically, it will also be necessary to recover the financial and behavioural parameters, many of which are not readily available. This problem could possibly be resolved by conducting choice experimental studies utilising survey data, for example in order to evaluate tenants` WTP for energy saving measures. Likewise, quasi-experimental techniques on billing data can be used to estimate the impact of cost-reducing synergies. Given heterogeneity of tenants and thus their WTP, both stated and revealed preference approaches can be used in future work to incorporate risk preferences as well as variations in the level of retrofits.

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Building insulation

37   3,528

Colour shows building insulation in the form of loft insulation and
cavity wall insulation per 10,000 dwellings. Source: DECC

.FIGURE 1: UPTAKE OF ENERGY EFFICIENCY MEASURES (BUILDING INSULATION) AT LOCAL AUTHORITY LEVEL IN ENGLAND.
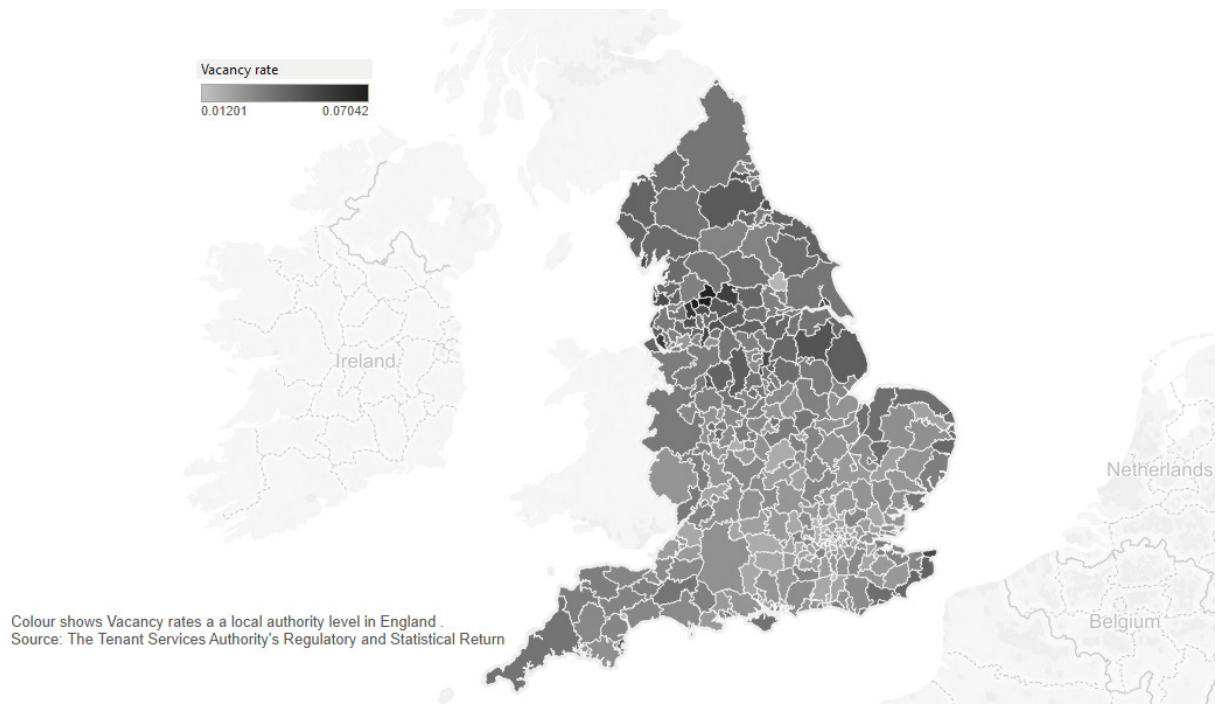
.Figure 2: residential vacancy rates in England.

Table 1: Overview of studies on residential energy efficiency investment decisions from several countries:

Citation	Country	Approach	Findings
Amstalden R.W et el (2007)	Switzerland	Discounted cash flow method.	Given future energy prices, efficiency investments are reported to be close to profitability even without government intervention.
Galvin R & Sunikka-Blank M (2012)	Germany	Ex-ante engineering analysis of energy costs.	The incorporation of energy prices elasticity into the analysis are found to reduce the net present value of the energy efficiency measures by 14-24 % and to extend the payback time by 5 years in some cases.
Jacobsen and Kotchen (2009)	USA	Payback calculation.	Average private payback periods of 6.4 years are found.
Morrissey J (2011)	Australia	Discounted cash-flow method.	Significant cost savings from energy efficiency measures, particularly given higher energy prices are reported.
Soest V & Bulte (2001)	Netherlands	Stochastic investment model.	It is suggests that it may "pay" to postpone investments in energy saving and wait for future technologies.
Tommerup H & Svendsen S (2006)	Denmark	Discounted cash flow method.	80% savings potential of energy used for space heating are found when buildings are retrofitted.
Y. Heo et al (2012)	UK	Probabilistic methodology.	The study suggests probabilistic outputs can be used to estimate risks of under-performance associated with retrofit interventions.
Yau, Y. (2012)	Hong Kong	A survey approach to assess willingness to pay for eco-labels.	The study finds that less than half of 231 respondents are willing to pay more for a new eco-labelled apartment than for its non-labelled counterpart. The number of "willing" Respondents' household income and environmental attitude is positively associated with willingness to pay but very few respondents are willing to pay for the highest level of eco-certification.
Zavadskas et al (2008)	Lithuania	Multiple criteria assessment.	Green retrofit is found to improve the general condition of the building structure and to extend the economic and physical lifetime of a building.

Table 2: Regional house prices

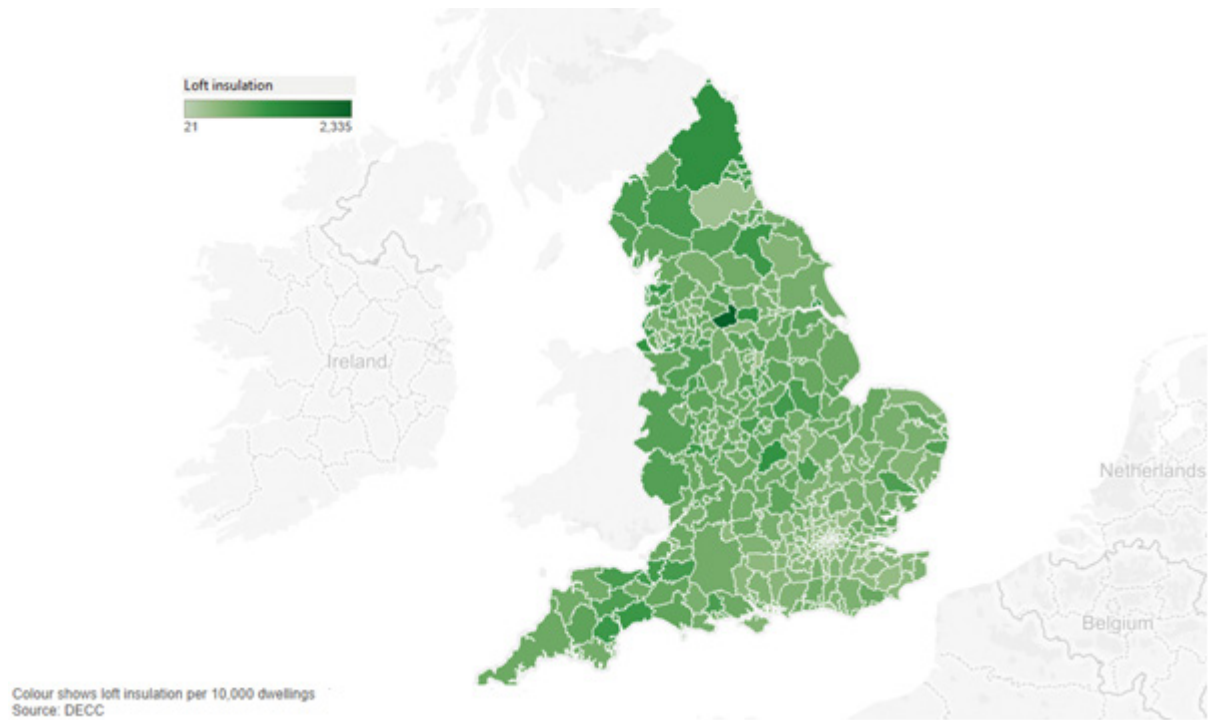| Region	House prices (£)
North East	117,313
North West	126,716
Yorkshire & the Humber	140,069
East Midlands	140,776
West Midlands	151,610
South West	194,739
East of England	196,361
South East	232,294
London	321,924
England average	180,200

Source: DECC

Table 3: Energy efficiency measures and housing market dynamics

	Model 1 ln_building insulation	Model 2 ln_building insulation	Model 3 ln_building insulation	Model 4 ln_building insulation
Log of Vacancy rate	0.47*** (6.08)			0.09 (0.82)
Log of local earnings		-1.346*** (-9.41)		-1.254*** (-4.66)
Log of local house price			-0.720*** (-11.92)	
Constant	8.70*** (31.94)	15.12*** (17.60)	15.73*** (21.55)	14.89*** (11.08)
N	325	325	325	325
R^2	0.088	0.215	0.305	0.216
adj. R^2	0.087	0.213	0.303	0.211

*t-statistics are indicated in brackets. Significance at the 0.10, 0.05, and 0.01 levels are marked *, **, and *** respectively.*

Appendix

.APPENDIX 1: LOFT INSULATION AT A LOCAL AUTHORITY LEVEL IN ENGLAND.

Colour shows cavity wall insulation per 10,000 per dwellings   Source: DECC
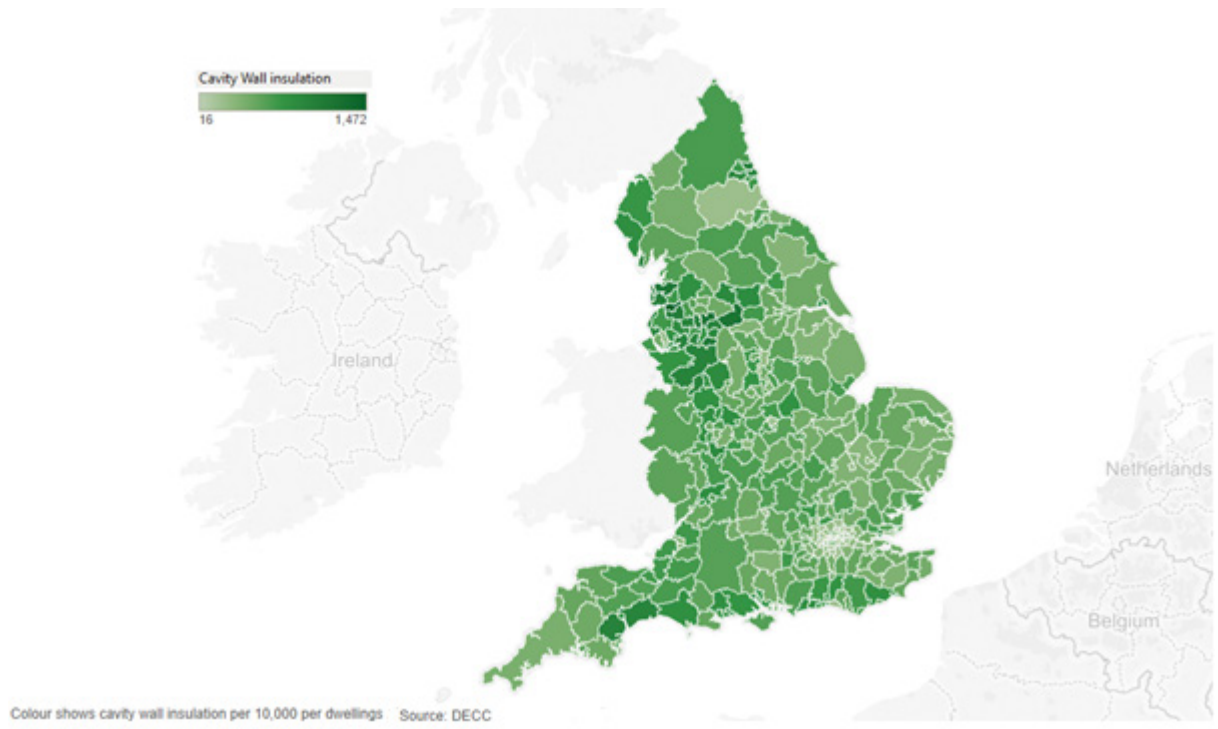
.APPENDIX 2: CAVITY WALL INSULATION AT A LOCAL AUTHORITY LEVEL IN ENGLAND.