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The Landlord-Tenant Problem and Energy Efficiency in the Residential Rental Market

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Abstract

The aim of this paper is to test for the persistence of the landlord-tenant energy efficiency problem in the residential rental property market in the presence of information on property energy performance. To do this, we compare the efficiency of rental and non-rental properties using a combination of Coarsened Exact Matching (CEM) and parametric regression. We use a sample of 585,578 residential properties in the Republic of Ireland - a region that legally requires rental properties to display energy performance certificates when advertised. The findings suggest that the landlord-tenant problem is present in the Irish rental market but that it is not uniform across locations, indicating the influence of other factors. To explore this further, we exploit the regional variation in rental property prices. We find a larger difference between rental and non-rental properties' energy efficiency in markets with scarcity in rental property supply.

keywords energy efficiency, market failures, Energy Performance Certificate (EPC), Coarsened Exact Matching (CEM), residential properties, information asymmetry, split incentives

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1 Introduction

The objective of this paper is to examine the extent of the landlord-tenant problem in the residential rental property market. Utilising energy in a more efficient manner has the potential to both reduce energy consumption and save money, in addition to delivering a range of other benefits (Ryan and Campbell 2012).[1] While engineering studies highlight a range of energy efficient technologies that reduce both energy consumption as well as provide an attractive return on investment (Gerarden et al. 2015; Wada et al. 2012), the uptake of energy efficiency technologies remains below their economic potential. This is typically referred to as the "Energy Efficiency Gap" – a wedge between the cost-minimising level of energy efficiency and the level actually realised (Allcott and Greenstone 2012; Jaffe and Stavins 1994).

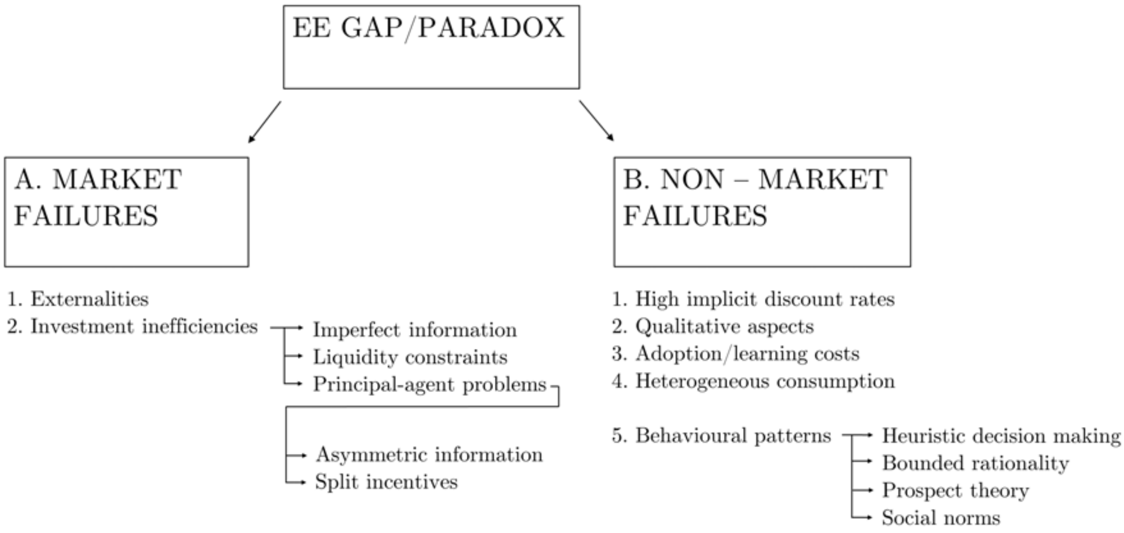
Market failures and other non-market failure barriers are responsible for this gap (Figure 1). Market failure explanations refer to situations where market conditions provide an inefficient outcome, resulting from flaws such as unpriced externalities, imperfect information or principal-agent problems. For example, energy prices may be too low as a result of un-priced environmental externalities, thereby discouraging investment in energy efficient technologies by lengthening payback periods. Typically, the presence of market failures gives justification for government intervention which can improve welfare (Baumol 1972). Allcott and Greenstone (2012) argue that government intervention in the form of subsidies or mandates for energy efficiency is only justified in cases where the market failure is not the result of unpriced environmental externalities, and cannot be fully addressed directly (for example by providing information to imperfectly informed consumers).[2] In this paper, we explore a potential market failure of this type.

Non-market failure explanations as per Jaffe and Stavins (1994) include high implicit discount rates, qualitative aspects of the technology, unpriced costs of adoption (such as learning costs) and the heterogeneity of energy consumers. Gillingham, Newell, and

[1] According to the World Energy Outlook by the International Energy Agency (IEA), global energy demand is projected to rise by 30% to 2040 – the equivalent of adding another China and India to today's global demand (IEA 2017).

[2] The authors argue that if energy use externalities are the only market failure, the social optimum will be obtained using Pigouvian taxes (or equivalent cap and trade programs) and no other forms of intervention. If however investment inefficiencies exist also, the first-best policy is to address the inefficiency directly – for example by providing information. If these direct interventions are not fully effective and investment inefficiencies remain, only then is there rationale for policies that subsidise or mandate energy efficiency.

Figure 1: Theoretical framework for the energy efficiency gap



Palmer (2009) later expand the non-market failure category to include concepts from behavioural economics such as bounded rationality, heuristic decision making and prospect theory.

In this study we focus on a principal-agent problem, known as the "Landlord-tenant problem" in the case of rental properties. The landlord-tenant problem is characterised as an agency problem which leads to an under-investment in energy efficiency by the landlord - or an over-consumption of energy by the tenant, depending on the contractual agreement as to which party pays the energy bills. This is a significant barrier to improving energy efficiency in rental properties; Murtishaw and Sathaye (2006) have estimated that 35% primary residential energy use in the US may be affected by landlord-tenant problems.

By definition, the landlord-tenant problem comprises both *split incentives* and *asymmetric information* issues (IEA 2007). Firstly, split incentives dictate that there must be a goal conflict between landlords and tenants in relation to energy efficiency or conservation. The idea of a goal conflict between parties engaged in a co-operative effort sits at the heart of agency theory (Eisenhardt 1989) and is termed split incentives in the energy efficiency literature (Gillingham, Harding, and Rapson 2012). Split incentives arise where the party responsible for investments in energy efficiency (or energy conservation) does not necessarily obtain any (or all) of the returns from such activities. In the building owner-occupant relationship, split incentives occur in mainly two ways: 1) where the occupant does not pay for energy use and may or may not own the dwelling, and 2) when the occupant pays for energy use and does not own the dwelling.[3] In the first case, this can lead to an over-consumption of energy as the occupant faces zero marginal cost with energy use (Levinson and Niemann 2004), while the second case may lead to an under-investment in efficiency by landlords since the returns to such investments accrue to tenants in the form of reduced utility bills. Tenants will likely not engage in high-cost energy efficiency improvements which would be lost when moving to another dwelling (Ramos, Labandeira, and Löschel 2016).

The second condition for the landlord-tenant problem (which also facilitates the first) is that there is asymmetric information between the two parties (IEA 2007). Asymmetric information refers to situations where one party in the transaction holds more information than the other party. Typically, the agent holds more information that the principal, allowing the agent to act in a manner which is inconsistent with the interest of the principal. In the landlord-tenant relationship, the landlord will generally have more information about the energy efficiency of the property than a prospective tenant. If the tenant cannot observe the efficiency of the property prior to entering into the rental contract, then an adverse selection problem occurs whereby in a manner similar to Akerlof (1970)'s "Market for Lemons" the market may become flooded with less efficient rental properties.[4]

Much of the literature on the landlord-tenant problem has focused on the asymmetric information channel as an explanation. Consequently, governments have introduced energy performance labels on residential properties in order to correct for the asymmetric information between landlords and prospective tenants (and also sellers and buyers). This should allow landlords with more efficient properties to communicate this to prospective tenants, and obtain a return on energy efficiency investments through higher rental prices. Yet energy efficiency labels alone may not necessarily completely solve the principal-agent issue, if the landlord-tenant problem persists even in the absence of information asymmetries. The purpose of this study will therefore be to test for (and quantify the magnitude of) the landlord-tenant problem in the case of mandatory energy performance disclosure. We do this by comparing the efficiency of observably similar rental and non-rental prop-

[3]Since we are focusing on the rental property market, and the majority of rental contracts in the Republic of Ireland stipulate that the tenant is responsible for energy-related utility bills, we are mainly concerned with the latter case.

[4]Assuming less efficient properties are less costly for the landlord.

erties in the Republic of Ireland - a region which legally requires landlords to display an energy rating when advertising a rental property.[5] We use a comprehensive database on the population of energy performance certificates issued in the Republic of Ireland to match observably similar rental and non-rental properties. In addition, we exploit a unique trait in residential building design to attempt to identify observationally identical rental properties and approximate a natural experiment. The findings suggest evidence of the landlord-tenant problem even in the case of mandatory energy performance certificate, however the effect appears to be relatively small.

We also attempt to further extend the theory by considering the effect of outside market forces and building attributes other than energy efficiency. As other non-energy characteristics of a property vary, we would expect the implicit price of energy performance for a dwelling in the rental market to change also.[6] For example, when location is a scarce characteristic, this may have an influence on the premium for energy efficiency, and hence landlords' decision to invest in energy efficiency improvements. To test the idea of heterogeneity in split incentives in the rental market, we exploit the variation in location characteristics in the Irish rental property market based on the introduction of rent-controlled or "Rent Pressure Zones" (RPZ). The findings suggest that the landlord-tenant problem is larger in locations with scarce rental property supply, which casts doubt on whether correcting for information asymmetries alone can correct the underlying principal-agent problem.

The structure of this paper is as follows. In the next section we explore some of the related literature. In Section 3 we present the data and methodology used in our empirical analysis. In Section 4, we present our results. Finally, we draw some conclusions from the evidence presented in the analysis and provide some policy recommendations and suggestions for future research.

[5] Since 2009, in the Republic of Ireland it has been compulsory to display a BER certificate at the point of lease of a property (if requested by a tenant). This legislation was further extended in 2013, requiring all landlords to display a BER rating when advertising a rental property across all types of media (SEAI 2013b; S.I. No. 243 2012).

[6] A vast literature, dating back to Ricardo (1817) and George (1882) exists which has established a link between location and rental premium.

2 Background

The literature suggests that principal-agent problems may affect a large share of residential energy consumption. Murtishaw and Sathaye (2006) quantify the extent to which principal-agent problems affect the purchase of water-heaters, refrigerators, space-heating and lighting appliances. Their findings suggest that across these four end uses, principal agent problems may affect up to 35% of the on-site energy consumed in the residential sector as a whole. IEA (2007) carry out a similar case study for the Netherlands and show that up to 41% of the energy consumption for space heating in the residential sector might be affected by principal agent problems.[7] Davis (2010) found that across four end-uses (refrigerators, clothes washers, dishwashers and lighting), renters were found to be less likely to possess energy efficient appliances, translating into 9 trillion BTU's of excess energy consumption annually (equivalent to 165,000 tons of CO_2 emissions).[8]

Gillingham, Harding, and Rapson (2012) develop a game-theoretical model in order to explain the under-investment in energy efficiency by landlords. The authors argue that when a landlord offers a rental contract in which the tenant is responsible for paying energy bills, in the absence of energy efficiency labelling the landlord cannot credibly communicate that he/she has made an energy efficiency investment, as not investing and claiming the contrary would be a profitable deviation in the first stage of the game. Therefore, landlords choose not to invest in the first place when they offer a contract where tenants are responsible for energy bills, if they cannot credibly communicate the energy efficiency of their property. On the other hand, if the landlord offers a contract where energy bills are included in the rental price then he/she will invest in energy efficiency as they can recover the returns to such investment through the rental price.[9] Gillingham, Harding, and Rapson (2012) provide empirical evidence of the landlord-tenant problem based tenant bill-paying arrangements. The authors find that tenants who pay for energy use were

[7]This result is partly due to the fact that almost 47% of the housing stock in the Netherlands at the time of the study was rental, and may therefore not be generalisable to rental markets elsewhere.

[8]BTU (or British Thermal Unit) is a measure of the heat content of fuels or energy sources. It is the quantity of heat required to raise the temperature of one pound of liquid water by 1 degree Fahrenheit at the temperature that water has its greatest density (approximately 39 degrees Fahrenheit). Source: EIA (2020).

[9]There may then be a reverse split incentive whereby the tenant uses more energy than optimal as they are not paying for energy use. Maruejols and Young (2011) find that tenants who do not pay directly for energy use themselves are more likely to opt for increased thermal comfort, and are less sensitive as to whether or not somebody is at home and the severity of the climate when deciding on temperature settings.

16% more likely to change their heating setting at night, while owner-occupied dwellings were 20% more likely to have attic insulation. Charlier (2015) also finds evidence for the split-incentives problem in the rental sector using data from France: tenants have higher energy bills due to inefficient buildings, and tax credits do not encourage the uptake of energy efficient upgrades in the rental sector. In Ireland, using a logistic regression Scott (1997) finds that private rental houses were less likely to have attic insulation and hot water cylinder insulation in comparison to owner-occupied properties. Melvin (2018) finds substantial under-investment in energy efficiency as a result of the split incentives problem using US data. Common to the preceding literature, the author attributes this effect to asymmetric information between landlords and tenants about the efficiency of the property. More recently, Myers (2020) finds that energy cost information asymmetries exist between landlords and tenants by exploiting energy cost variation in heating fuel prices. The author concludes that when tenants lack information, landlords under-invest in energy efficiency because they cannot capitalize those investments in higher rental price.

If the principal agent problem was caused solely by asymmetric information, then effective energy performance labels should allow landlords to capitalise on energy efficiency investments through higher rental income. This could then encourage investment in efficiency measures by landlords and ensure that rental properties have equivalent energy performance to owner-occupied properties. In the property sales market, researchers have found that properties with better energy ratings command consistently higher sales prices (Stanley, Lyons, and Lyons 2016; Hyland, Lyons, and Lyons 2013; Zheng et al. 2012; Brounen and Kok 2011). Energy efficiency labels could have an even greater potential for improving welfare in the rental property market, as they may be observed/advertised more often than in the sales market.[10]

There is far less analysis of the price effect of building energy labels in the residential rental market. For Ireland, using advertisement data from 2008 to 2012, Hyland, Lyons, and Lyons (2013) found that in comparison to D rated properties, A rated rental properties receive a premium of 1.8%. Sales properties on the other hand received a premium of 9% for the same improvement in efficiency. These findings from the Irish property market are matched internationally with Bio Intelligence Service, Lyons, and IEEP (2013) and Cajias

[10] Rental properties are likely to be let more frequently than residential properties are sold. As per RTB (2018a) the majority of tenancy agreements in Ireland last between 10 and 12 months. By comparison, the average mortgage term in Ireland is 27 years (Central Bank of Ireland 2018).

and Piazolo (2013) finding lower premium associated with energy efficiency in the rental sector compared with property sales. This might suggest that landlords are not able to fully internalise the energy savings associated with a more efficient property in the rental price, which could explain why other authors consistently observe a difference in efficiency between rental and non rental properties. Contrary to this however, using German data Weber and Wolff (2018) find that although energy efficiency retrofits in the rental sector reduced energy consumption, more than half of tenants faced increased overall costs due to subsequently higher rental prices.

In a manner similar to Scott (1997) and Gillingham, Harding, and Rapson (2012), the aim of this paper is to test for the landlord-tenant problem by comparing the energy efficiency of rental and non-rental properties. However, unlike previous studies which focus on specific energy saving appliances, we are able to take advantage of comprehensive engineering data which measures the energy performance of the dwelling as a whole. This data covers the population of energy performance certificates issued in the Republic of Ireland. We focus on the Republic of Ireland since it is a setting where landlords are legally required to display an energy rating when advertising a property for rent. Therefore, if we observe a difference in efficiency between rental and non-rental properties, we posit that this may be attributable to one of two things.

Firstly, energy performance labels may not be fully correcting for the information asymmetry between landlords and tenants. This may therefore discourage investments in efficiency improvements, since landlords are unable to convey the efficiency of their property to prospective tenants. One reason for this could be that tenants do not internalise/understand the energy efficiency information conveyed by the ratings. Although we recognise that BER ratings may not fully correct for the information asymmetry within letter grades,[11] recent empirical evidence from the Republic of Ireland suggests that prospective tenants may actually overvalue the energy savings associated with better rated properties (Carroll, Aravena, and Denny 2016).

Secondly, if energy performance certificates are successful at correcting the information asymmetry problem, then information measures alone may not be sufficient in encouraging

[11] For example, within letter grades, the tenant must assume that the efficiency of the property is in the lower bound of a grade rating range. Empirical evidence from Collins and Curtis (2018) shows bunching at the threshold levels of the BER letter grades following retrofit.

energy efficiency improvements by landlords. This would suggest that the underlying split incentives problem (or goal conflict) may remain even in the absence of information asymmetries. Furthermore, this goal conflict may be exasperated by variation in the scarcity of other property characteristics, such as location. When location characteristics are scarce this may crowd-out investments in efficiency, since tenants may be willing to substitute lower levels of energy efficiency for more desirable location options. To test this idea, we compare the magnitude of the landlord-tenant problem in different locations with varying scarcity in rental property supply, as identified by city boundaries and Rental Pressure Zones (RPZ). In addition, if there is significant variation in the landlord-tenant problem based on location, this makes the asymmetric information channel as an explanation/solution to the problem less likely. To our knowledge, no other study has explored the interaction of location scarcity and energy efficiency in a residential rental setting. This paper contributes to filling a gap in the literature in understanding the extent of split incentives and their interaction with scarcity in rental property supply.

3 Data and Methods

3.1 Data

We use data on the energy performance of rental and non-rental properties from the Building Energy Ratings (BER) database which is made available publicly by the Sustainable Energy Authority of Ireland (SEAI) in anonymised form. The BER database contains a detailed technical breakdown of the population of BER certificates issued since the introduction of the scheme in 2009. At an EU level, Article 7 the 2002 directive on the energy performance of buildings (Council directive 2002/91/EC 2002) set out the need for member states to adopt energy performance certificates which are to be displayed at the point of sale or lease of a property. The aim is to display an objective measure of the energy performance to prospective buyers/tenants not otherwise available even upon physical inspection of the property (e.g. insulation levels).[12] This then allows buyers/-tenants to make a more informed purchasing/renting decision, which in turn allows for the efficiency of the property to be capitalised in the purchase/rental price and encourage investments in efficiency.

In the Republic of Ireland, the Building Energy Rating (BER) certificate is an objective estimate of energy use for space and water heating, ventilation and lighting based on standard occupancy of a residential property. It is an engineering calculation based on the characteristics of major components of a property including wall, roof and floor dimensions, window and door sizes and orientation, as well as construction type and insulation, ventilation and airtightness features, the system for heat supply (including renewable sources), heat distribution and controls and the type of lighting (SEAI 2011b). Since 2013 it is compulsory to present a BER certificate for the sale or rent of a property in all advertising media, including: newspapers, magazines, brochures, leaflets, advertising notices, vehicle advertising, radio, television, internet (including apps and social media) and direct mail (SEAI 2013a).

The database includes highly detailed information on physical attributes such as type of dwelling, age, size of the building, whether it is a rental property, as well as the value of the BER for each certificate issued. The data period of this analysis covers all BER's issued between December 2012 and February 2020. Although this excludes all BER certificates issued from 2009 to 2012, the issue of whether the BER is for a rental property has only been recorded from 2012 onwards. Figure 2 gives the monthly average BER value of newly issued certificates for rental and non-rental properties over our period of study.

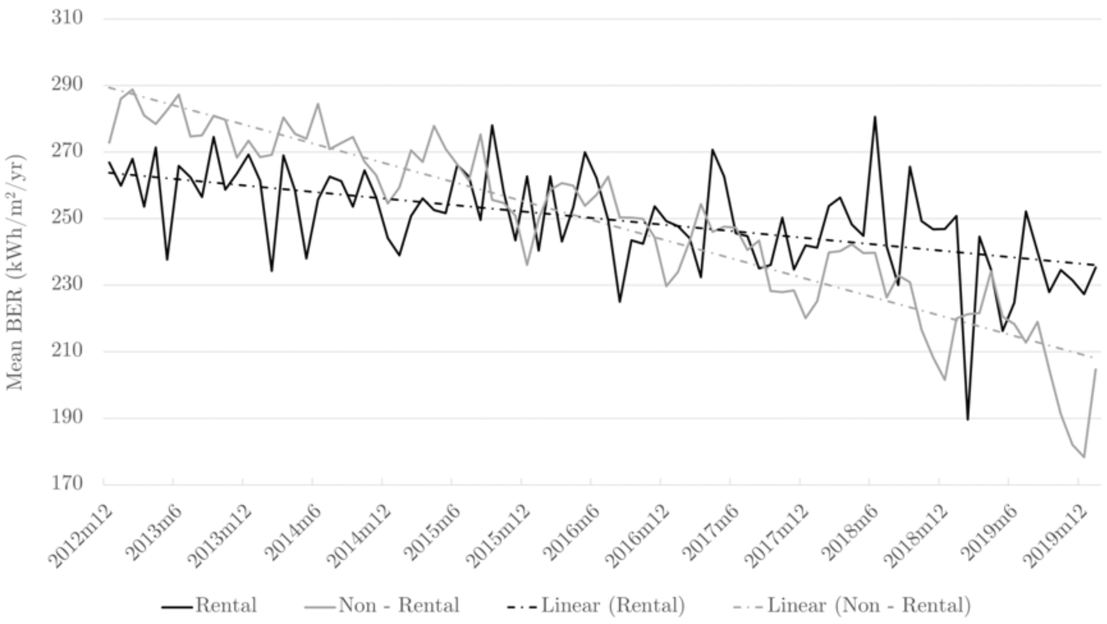
From Figure 2 we see a clear downward trend in average BER values for non-rental properties over time. This may be the result of building regulation changes that have come into effect during this time period which have affected the minimum efficiency standards for newly-built dwellings.[13] Although there is also a downward trend in BER values for rental properties, this is not as clear or as steep. This suggests that while both rental and non-rental buildings have improved over time, rental properties appear to have lagged behind in terms of their energy efficiency (measured in $kWh/m^2/yr$). For the following analysis, the BER in its continuous form (as opposed to the letter grade) will be our dependent variable.[14] In total, we have 585,578 observations in our data, 64,985 of which

[12]Common to the rest of the literature in this area, the energy performance rating on the BER (Building Energy Rating) certificate is used as a proxy for energy efficiency. We do not consider any differences between the theoretical engineering and the real in-use estimates of energy consumption, although we recognise these may occur.

[13]This is discussed further in the Results section of this paper, and also in App. Table A6.

[14]Please refer to appendix Figure A1 for further detailed information on the BER.

Figure 2: Average Issued BER per Month – Rental vs Non-rental Properties



are rental properties. Table 1 presents the summary statistics for all of the variables used in our analysis, presented for the sample as a whole and also by tenure status.

From the summary statistics in Table 1 we can see that a simple comparison of means would indicate that rental properties are on average slightly less efficient than their owner-occupied counterparts and this difference is statistically significant at the 1% level, although this difference is insufficient in realising a difference in a BER letter grade. However, we can also see that rental properties are significantly different from non-rental properties in terms of their observable characteristics. Rental properties on average are smaller, more likely to be apartments, more likely to be located in urban centres and are newer.[15] A simple comparison of means is therefore insufficient in determining the effect of renting on a given property's level of efficiency. In addition to the above, we have more detailed information on the location of properties in our sample, and this is presented in appendix Table A2.

In terms of the distribution of the BER grades from Figure 3 we see that rental and non-rental properties follow a similar pattern, with some notable exceptions. In particular, we see a comparatively much larger share of non-rental A3 rated properties. This difference is

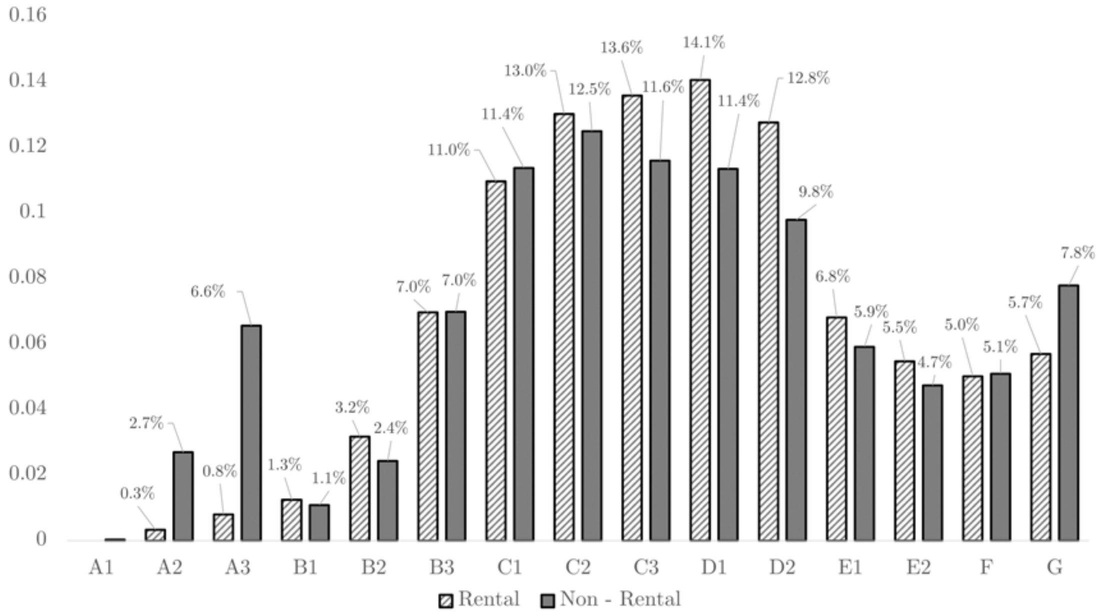
[15] For a more detailed definition of the variables used in this analysis please refer to Appendix Table A1

Table 1: Summary Statistics - Full Sample

	Full Sample		Rental		Non-Rental		Non-Rental - Rental	
	Mean (1)	St. Dev (2)	Mean (3)	St. Dev. (4)	Mean (5)	St. Dev. (6)	Difference (5) - (3)	t (8)
BER ($kWh/m^2/yr$)	248.63	180.06	253.16	120.20	248.07	186.18	-5.09***	(-9.47)
Year of construction	1981.84	34.35	1984.23	35.07	1981.54	34.25	-2.69***	(-18.48)
Ground floor area (m^2)	114.53	59.15	91.25	46.23	117.44	59.94	26.19***	(131.31)
Type of dwelling								
Detached house	0.31	0.46	0.15	0.36	0.33	0.47	0.18***	(116.33)
Semi-detached house	0.28	0.45	0.20	0.40	0.29	0.46	0.09***	(53.52)
End-of-terrace house	0.07	0.26	0.05	0.23	0.08	0.27	0.02***	(24.38)
Mid-terrace house	0.14	0.35	0.12	0.33	0.14	0.35	0.02***	(15.15)
House (general)	0.00	0.05	0.00	0.04	0.00	0.05	0.00	(1.41)
Maisonette	0.01	0.11	0.02	0.15	0.01	0.10	-0.01***	(-20.71)
Basement dwelling	0.00	0.02	0.00	0.04	0.00	0.02	-0.00***	(-6.41)
Ground-floor apartment	0.05	0.23	0.12	0.32	0.05	0.21	-0.07***	(-54.56)
Mid-floor apartment	0.07	0.25	0.19	0.39	0.05	0.22	-0.14***	(-88.61)
Top-floor apartment	0.06	0.23	0.14	0.34	0.05	0.21	-0.09***	(-66.55)
Apartment (general)	0.00	0.02	0.00	0.04	0.00	0.02	-0.00***	(-6.06)
Number of storeys								
1	0.32	0.46	0.48	0.50	0.30	0.46	-0.19***	(-90.35)
2	0.61	0.49	0.47	0.50	0.63	0.48	0.16***	(79.39)
3	0.07	0.25	0.05	0.21	0.07	0.26	0.02***	(24.00)
4	0.00	0.04	0.00	0.04	0.00	0.04	-0.00	(-0.32)
5	0.00	0.01	0.00	0.01	0.00	0.01	-0.00	(-1.13)
6	0.00	0.01	0.00	0.00	0.00	0.01	0.00***	(3.87)
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(1.41)
Urban	0.30	0.46	0.42	0.49	0.29	0.45	-0.13***	(-66.07)
Rural	0.70	0.46	0.58	0.49	0.71	0.45	0.13***	(66.07)
RPZ	0.76	0.43	0.80	0.40	0.76	0.43	-0.05***	(-29.67)
N	585,578		64,985		520,593			

Note: t-tests for equality of means assume unequal population variances. This was determined using standard F-tests for population variance homogeneity, as well as the normality assumption robust tests presented in Brown and Forsythe (1974)

Figure 3: Distribution of BER Grades – Rental vs Non-Rental Properties



explained by the fact that since the introduction of new building regulations in December 2011, all new builds were effectively required to be A3 standard or better (S.I. No. 259 2011; SVP 2015), and fewer new builds are for rental purposes.[16] We also observe a comparatively higher share of rental properties which are C3, D1 and D2 rated, however when looking at the least efficient BER category, we observe a comparatively higher share of non-rental properties which are G rated. This may be explained by uninhabited or derelict homes which are sold as renovation projects.

3.2 Methods

Due to the non-experimental nature of our data it is difficult to identify a causal effect of renting on efficiency. In an ideal experiment, we would randomly assign rental status to otherwise identical residential properties and then estimate the average treatment effect of renting on efficiency, after a certain duration of time. Since this not feasible, in order to attempt to identify a causal effect of renting on a property's energy efficiency level, we use a quasi-experimental design to approximate this experiment using a combination of Coarsened Exact Matching (CEM) and parametric regression.

[16] Of the 50,490 properties built on or after 2012 in our sample, only 1,360 are rental properties (or roughly 2.7%).

As shown by Iacus, King, and Porro (2012) CEM can be used as a pre-processing technique for regression in order to reduce model dependence, bias and improve efficiency. The idea behind matching is that for each treated unit, we look for a control unit with approximately the same characteristics. The matched units can then be used to recreate the missing counterfactual of the outcome for the treated units, had they not received treatment, which allows us to estimate the Average Treatment Effect of the Treated (ATT).

Using the notation in Angrist and Pischke (2008) of the Rubin framework for causal inference (Holland 1986; Rubin 1974; Rubin 2008), the ATT is defined as follows:

$$ATT = E[Y_{1i} - Y_{0i}|D_i = 1] = E[Y_{1i}|D_i = 1] - E[Y_{0i}|D_i = 1] \tag{1}$$

In the above D_i represents treatment status of unit (or property) i. In our case treatment is whether or not the property is a rental property.

$$Di = \begin{cases} 1 & \text{if treated} \\ 0 & \text{if otherwise} \end{cases} \tag{2}$$

The outcome of interest in our case is the observed BER rating, denoted by Y_i. The potential outcomes for individual i are therefore defined as:

$$Potentialoutcome = \begin{cases} Y_{1i} & if \quad D_i = 1 \\ Y_{0i} & if \quad D_i = 0 \end{cases} \tag{3}$$

Naturally, we can never observe $E[Y_{0i}|D_i = 1]$ i.e. the expected outcome for the treated units, had they not been treated. Using matching methods however, we can approximate $E[Y_{0i}|D_i = 1]$ using $E[Y_{0i}|D_i = 0]$ which we can observe, matching on a set of observable characteristics.

We can only do this however if we are willing to make the Conditional Independence Assumption (CIA). The CIA asserts that conditional on observed characteristics X_i selection bias[17] disappears.

$$\{Y_{0i}, Y_{1i}\} \perp D_i | X_i \tag{4}$$

If the matching covariates X_i are all either binary or categorical variables, it is easy to construct strata within which we can fit all our observations. Treated and control units within the same strata would then be considered a matched pair. However, in our list of explanatory variables we also have continuous variables, namely: ground-floor and year of construction. Using CEM, we transform continuous variables into discrete interval data and then apply exact matching on these intervals. An additional advantage of this method is that we can use domain specific information about threshold values of variables to identify relevant matches.

The matching procedure produces weights which we can apply to an additional parametric regression. Matched treated units are given a weight of 1 while matched control units are given a weight equal to $\frac{m_c}{m_t} \cdot \frac{m_t^s}{m_c^s}$, where m_c is the total number of control units, m_t is the total number of treated units, m_t^s is the number of treated units within stratum s and m_c^s is the number of matched control units within the same stratum s (Alberini and Towe 2015). Unmatched treated and control units receive a weight of zero.

In our analysis, we apply three versions of the CEM procedure. As per Blackwell et al. (2009), the choice of coarsening in relation to the continuous variables is at the discretion of the researcher. Using information obtained in consultation with BER assessors we construct three coarsening choices. Table 2 provides a summary of the three types of matching used.

In our first coarsening choice (CEM1), we coarsen the *ground-floor area* variable into 20 square-meter intervals up to a size of 300 square meters. This gives us 15 cutoff points, within which we consider a dwelling to be of approximately the same size. In the case of newer buildings, for the *year of construction* variable we coarsen the data based on national-level building regulations. This allows us to account for the fact that buildings

[17] Selection bias is denoted as $E[Y_{0i}|D_i = 1] - E[Y_{0i}|D_i = 0]$ i.e. the difference between the expected outcome for the treated units, had they not received treatment and the expected outcome of the non-treated units. Essentially it is the difference in the outcome for treated and control units, had the treated units not received treatment. In our case this may occur if rental properties would have been more/less efficient than their non-rental counterparts, had they not been rental.

Table 2: Matching Summary

	No matching	CEM1	CEM2	CEM3
Coarsened variables and bin sizes				
Ground-floor area (m^2)		20	10	5
Property type		exact	exact	exact
Number of storeys		exact	exact	exact
Location (Table A2)		exact	exact	exact
Year of construction (*years*)		regulation	regulation	regulation
Matched - Treated	64,985	60,744	58,645	55,601
% Treated retained	100%	93.47%	90.24%	85.56%
Matched - Control	520,593	371,795	325,485	269,917
% Control retained	100%	71.42%	62.52%	51.85%
Unmatched - Treated	0	4,241	6,340	9,384
Unmatched - Control	0	148,798	195,108	250,676
Number of strata	N/A	49,763	72,832	105,338
Number of matched strata	N/A	13,988	17,830	21,688

built under the same building regulations must legally adhere to the same standards in terms of efficiency.[18] For older buildings (pre 2005), we use building age bands as detailed in the Dwelling Energy Assessment Procedure (DEAP), which is the guidance document on carrying out BER assessments (SEAI 2019). CEM allows us to incorporate this information into our model in order to improve the quality of our matches. Dwellings built prior to 1900 are placed in the same category. Similarly, all dwellings greater than 300 square meters in size are also grouped together. As per Iacus, King, and Porro (2012) we apply exact matching on all categorical control variables used in the analysis. Please refer to Appendix A2 for further details and justification of our coarsening choices.

For our second (CEM2) and third (CEM3) coarsening choices we band the size variable into 10m^2 and 5m^2 intervals respectively. From consultation with BER assessors it was determined that the 5m^2 interval may be within the error bounds of the assessment procedure (particularly for very large properties). The goal of matching is to identify substantively similar properties, and hence we do not want to make the matching excessively strict to the point where we discard relevant matches. As with CEM1, the upper cut-offs for the age and size variables are 150 years and 300m^2 respectively.

From Table 2 we can see that as we make the coarsening more stringent, the number

[18]For a list of all recent building regulation changes and their relevance to the energy efficiency please refer to Appendix Table A6. National-level building regulations predating the 1970s are scarce, however the DEAP document provides guidance on distinct historical building age-bands for older dwellings.

of matched treated and control units decreases. As expected, we can also see that with stricter matching, the number of strata increases. It is important to note however that even when applying our most stringent matching criteria (CEM3) we still retain over 85% of treated units. The proportion of control units retained by comparison however is much smaller (52%). This illustrates that the matching procedure places more emphasis on retaining treated units, and discarding irrelevant controls – thereby reducing model dependence of the subsequent parametric regression (Ho et al. 2007).

Table 3: Overall Balancing of Covariates: Pre and Post Matching

	Unmatched		Matched(CEM1)		Matched(CEM2)		Matched(CEM3)	
Variable	t	%SB	t	%SB	t	%SB	t	%SB
Year of construction	18.48	7.76	-0.23	-0.10	-0.25	-0.11	-0.21	-0.10
Ground floor area (sq m)	-131.31	-48.93	-0.46	-0.20	-0.20	-0.09	-0.24	-0.11
Type of dwelling								
Detached house	-116.33	-43.05	0.00	0.00	0.00	0.00	0.00	0.00
Semi-detached house	-53.52	-21.17	0.00	0.00	0.00	0.00	0.00	0.00
End-of-terrace house	-24.38	-9.46	0.00	0.00	0.00	0.00	0.00	0.00
Mid-terrace house	-15.15	-6.14	0.00	0.00	0.00	0.00	0.00	0.00
House (general)	-1.41	-0.57	0.00	0.00	0.00	0.00	0.00	0.00
Maisonette	20.71	9.80	0.00	0.00	0.00	0.00	0.00	0.00
Basement dwelling	6.41	3.21	0.00	0.00	0.00	0.00	0.00	0.00
Ground-floor apartment	54.56	26.01	0.00	0.00	0.00	0.00	0.00	0.00
Mid-floor apartment	88.61	43.76	0.00	0.00	0.00	0.00	0.00	0.00
Top-floor apartment	66.55	32.29	0.00	0.00	0.00	0.00	0.00	0.00
Apartment (general)	6.06	2.95	0.00	-0.00	0.00	0.00	0.00	0.00
Number of Storeys								
1	90.35	38.89	0.00	0.00	0.00	0.00	0.00	0.00
2	-79.39	-33.47	0.00	0.00	0.00	0.00	0.00	0.00
3	-24.00	-9.29	0.00	0.00	0.00	0.00	0.00	0.00
4	0.32	0.13	0.00	0.00	0.00	0.00	0.00	0.00
5	1.13	0.51	0.00	0.00	0.00	0.00	0.00	0.00
6	-3.87	-0.76	0.00	0.00	0.00	0.00	0.00	0.00
7	-1.41	-0.28	0.00	0.00	0.00	0.00	0.00	0.00

Note: t-tests for equality of means assume unequal population variances. %SB is calculated as per Asensio and Delmas (2017).

In addition to the overall matching summary presented in Table 2, we present covariate-specific balance checks, pre and post matching in Table 3. The second column in Table 3 represents t-statistics from t-tests of equality of means between treatment and control groups for each of the covariates pre-matching. Prior to matching, the t-tests indicate that there is a significant difference in means between treatment and control groups for almost all of the covariates. Following the matching procedure, we do not observe any significant difference in means between treatment and control groups in any of the covariates, and for any of the matching procedures applied.

The values in the '%SB' columns in Table 3 represent a measure of bias as used by Asensio and Delmas (2017), Jones, Rice, and Zantomio (2016) and Stuart (2010). It presents the standardised percentage difference in means between treated and control groups.[19] As per Stuart (2010), bias of greater than 25% should be a cause of concern. From the above, we can see that the matching reduces the bias in all of the covariates significantly, with a standardised percentage difference in means between treatment and control group of approximately 0% post matching for all of the covariates used in our analysis. We attribute the success of our matching procedure to the large number of observations available in our dataset, allowing us to find suitable controls for our treated units across all of the covariates.

As per Iacus, King, and Porro (2012) in addition to the CEM matching procedures, we also run a parametric regression including all of coarsened variables on the RHS so as to correct for any remaining imbalance as follows:

$$ln(BER)_i = \alpha_0 + \alpha_1 D_i + \alpha_2 X_i + \epsilon_i \tag{5}$$

In the above $ln(BER)_i$ is the natural log of the BER variable in its continuous form, D_i is the treatment status and X_i is the vector of observable characteristics. We then apply the CEM matching weights as discussed previously to the above regression using weighted least squares. The results of the of the unweighted model and applying our three CEM matching weights are presented in Table 4.

4 Results and Discussion

The first column of Table 4 gives the OLS estimates of our parametric regression, without applying the CEM weights.[20] Almost all of the coefficients are significant at the 1% level and are of the expected signs. Our main coefficient of interest (rental) indicates that

[19] As per Asensio and Delmas (2017) this measure is calculated as $\%SB = \frac{100(\bar{X_t} - \bar{X_c})}{\sqrt{\frac{S_t^2 + S_c^2}{2}}}$. Where $\bar{X_t}$ is the mean of the treated group, $\bar{X_c}$ is the mean of the control group, S_t^2 is the variance of the treated group and S_c^2 is the variance of the control group.

[20] All standard errors presented are heteroskedasticity robust. The discrepancy in the number of observations between Column 1 and the total number of observations in Table 1 comes from the transformation of our dependent variable into ln(BER), since negative BER values are dropped (14 observations in total).

Table 4: Parametric Regression Results: Full Sample

	OLS	CEM1	CEM2	CEM3
Rental	0.098***	0.012***	0.012***	0.011***
	(0.002)	(0.002)	(0.002)	(0.002)
Year of construction	-0.009***	-0.007***	-0.007***	-0.007***
	(0.000)	(0.000)	(0.000)	(0.000)
Ground floor area (m^2)	-0.003***	-0.003***	-0.003***	-0.003***
	(0.000)	(0.000)	(0.000)	(0.000)
Dwelling type				
Detached house	0	0	0	0
	(omitted)	(omitted)	(omitted)	(omitted)
Semi-detached house	-0.131***	-0.124***	-0.124***	-0.117***
	(0.003)	(0.005)	(0.006)	(0.006)
End of terrace house	-0.180***	-0.161***	-0.158***	-0.148***
	(0.004)	(0.007)	(0.008)	(0.008)
Mid-terrace house	-0.271***	-0.273***	-0.273***	-0.266***
	(0.004)	(0.007)	(0.007)	(0.008)
House (general)	-0.174***	-0.070*	-0.076**	-0.100*
	(0.011)	(0.029)	(0.029)	(0.041)
Maisonette	-0.173***	-0.239***	-0.251***	-0.250***
	(0.006)	(0.010)	(0.011)	(0.012)
Basement dwelling	-0.393***	-0.363***	-0.383***	-0.370***
	(0.032)	(0.053)	(0.051)	(0.059)
Ground-floor apartment	-0.180***	-0.220***	-0.224***	-0.218***
	(0.004)	(0.006)	(0.007)	(0.007)
Mid-floor apartment	-0.424***	-0.441***	-0.448***	-0.441***
	(0.004)	(0.007)	(0.007)	(0.007)
Top-floor apartment	-0.144***	-0.183***	-0.189***	-0.184***
	(0.004)	(0.006)	(0.007)	(0.007)
Apartment (general)	-0.456***	-0.090	-0.137	-0.496***
	(0.016)	(0.071)	(0.091)	(0.035)
Number of storeys				
1	0	0	0	0
	(omitted)	(omitted)	(omitted)	(omitted)
2	-0.105***	-0.084***	-0.088***	-0.093***
	(0.003)	(0.005)	(0.005)	(0.005)
3	-0.176***	-0.084***	-0.090***	-0.104***
	(0.005)	(0.009)	(0.010)	(0.011)
4	-0.017	0.096	0.141*	0.118
	(0.020)	(0.058)	(0.067)	(0.066)
5	0.177*	0.462**	0.450**	0.358*
	(0.077)	(0.144)	(0.157)	(0.167)
6	0.311***			
	(0.053)			
7	0.606***			
	(0.120)			
Location FE	yes	yes	yes	yes
N	585,564	432,534	384,126	325,515

***Statistically significant at $p < 0.01$
**Statistically significant at $p < 0.05$
*Statistically significant at $p < 0.1$

rental properties are associated with a higher BER, meaning that they are less efficient, holding all other characteristics constant. The size of the coefficient suggests that rental properties are on average 10.3% less efficient than their owner-occupied counterparts. This is the correctly interpreted coefficient on a dummy variable in a semilogarithmic equation as per Kennedy (1981). All subsequent interpretations of coefficients on dummy variables in this paper are treated in the same manner.[21]

Focusing on the control variables of the OLS specification, the coefficient on the year of construction variable is negative, suggesting that newer dwellings are more energy efficient. This is consistent with our prior expectations and with the pattern observed in Figure 2, where we see that efficiency has improved with time. Conversely, we would expect that older properties are less energy efficient. In terms of size, the coefficient on the ground-floor area variable indicates that for a 1 unit increase in size (m^2) the BER decreases by 0.3%, meaning that as size increases efficiency improves. When looking at property type, compared to detached houses (our omitted category) all other property types are more efficient. Of these, mid-floor apartments appear to be the most efficient category with an average improvement in energy performance of 34.6% relative to detached houses. This is expected from an engineering standpoint as mid-floor apartments have the least number of external walls when compared to any other house type. This vast difference in efficiency highlights the importance of controlling for property type in our matching estimation. When looking at the coefficients associated with number of storeys an interesting pattern emerges. Relative to single storey dwellings, two and three storey properties are more efficient. This can be explained by the fact that two and three storey dwellings may represent newer, multi-development properties. On the other hand, properties with five or more storeys are found to be considerably less efficient than single storey dwellings. This effect is likely attributable to larger luxury properties which may be older, and hence less airtight/insulated.

When we apply the matching weights from our three versions of the CEM procedure we see a decrease in the size of the effect of renting on efficiency. Using CEM1 weights decreases the size of the effect of renting on efficiency to 1.2%, and this remains constant when applying CEM2 wights. This suggests that as we exclude irrelevant controls and

[21] The interpretation of the dummy variables in our regression follows Kennedy (1981), whereby the following formula is used: $g^* = exp(\hat{c} - \frac{1}{2}\hat{V}(\hat{c})) - 1$, where $\hat{c}$ is the coefficient presented in table 4, $\hat{V}(\hat{c})$ is its associated variance and g^* is its corrected interpretation.

make the matching more precise, the effect of renting on efficiency decreases. An explanation for the difference in the magnitude of the effect between the OLS model and the models using CEM weights is that under OLS model we may be placing an undue weight on control observations (or non-rental properties) which may not have comparable treated units (rental properties), hence overestimating the size of the effect.

Finally, when applying the weights from our most stringent coarsening choice, the effect of renting on efficiency falls only slightly to 1.1%. The effect remains statistically significant at the 1% level, regardless of the matching weights used. The main difference between matching specifications is observed in the overall number of observations, where we see that as we increase matching stringency we lose an increasing number of observations. Despite this however, the size and significance of our coefficient of interest remains stable between matching specifications, even in our most stringent matching criteria. We focus only on the coefficient on the variable of interest, however we also include all remaining independent variables to control for any residual imbalance. In addition, we also carry out the analysis excluding additional control covariates. When we remove all additional covariates the coefficient on the variable of interest (rental) remains the same, however we report these for completeness. These all have the expected sign and significance as per the OLS model.

4.1 Location Scarcity and Energy Efficiency

Although the difference in efficiency between rental and non-rental properties on a national level appears to be quite small, if there is significant regional variation this may be indicative of issues other than information asymmetries. Initially, to explore this we split our sample into two sub-samples: cities vs the rest of Ireland. In the urban sub-sample, we include properties located in the major cities in Ireland (Dublin, Cork, Galway, Limerick and Waterford), with the remainder of properties grouped in the rural sub-sample. Table 5 presents our main coefficient of interest (rental) in each case. What we can see is that across all of our specifications, the effect of renting on efficiency is bigger in the cities sub-sample than when looking at the country as a whole. In contrast, when we look outside of major cities, we find that the effect is much smaller, and is only significant at the 5% level when using CEM weights. Depending on the matching specification, the difference in efficiency between rental and non rental properties is roughly 3 to 4 times larger in cities when compared to the rest of Ireland. This suggests that the results we obtained when looking at the sample as whole are primarily driven by differences in efficiency between rental and non-rental properties in cities, since cities make up 30% of the sample of properties included in the analysis.

Table 5: Effect of Renting on Efficiency: Cities vs Rest

	OLS	CEM1	CEM2	CEM3
Full sample	0.098***	0.012***	0.012***	0.011***
	(0.002)	(0.002)	(0.002)	(0.002)
N	585,564	432,534	384,126	325,515
Cities	0.108***	0.021***	0.021***	0.018***
	(0.003)	(0.003)	(0.003)	(0.003)
N	178,509	129,328	117,159	101,925
Rest	0.091***	0.005**	0.006**	0.007**
	(0.002)	(0.002)	(0.002)	(0.002)
N	407,055	303,206	266,967	223,590

***Statistically significant at $p < 0.01$
**Statistically significant at $p < 0.05$

One potential explanation for this finding is that there may be an interplay between the principal-agent problem and rental property market tightness. The Dublin region in particular has experienced rising rents due to an overall shortage of rental accommodation over the past 6 years. According to Lyons (2017), although rents have risen significantly on a national level since their lowest point post the 2009 recession (41% increase), increases in rental prices in the capital have been disproportionately higher (66%). It may be the case that prospective tenants in supply constrained rental markets place less emphasis on the efficiency of the property as an attribute, focusing on other observable characteristics such as location or size in a hedonic-type model (Rosen 1974).[22] This may therefore allow landlords in supply constrained locations to extract a higher price from less efficient properties than would otherwise be possible in less contested markets, thereby lessening the incentive for landlords to invest in energy efficiency improvements.

To explore the connection between the landlord-tenant problem and rental market condition further, we next exploit the division of the Irish rental market into rent controlled areas or Rent Pressure Zones (RPZ). To do this, we split the sample into properties which

[22] As per Rosen (1974) the revealed price of a good is a function of the implicit prices of its attributes. Analyses such as Hyland, Lyons, and Lyons (2013) and Brounen and Kok (2011) follow this approach.

are located in a county which has an RPZ vs those which are not, based on the latest RPZ divisions as set out in the *Planning and Development (Housing) and Residential Tenancies Act 2016* (2016).

RPZ's were introduced in order to regulate the rise of rents in certain locations within the Republic of Ireland where rents have been rising at disproportionate levels and where households have greatest difficulties in finding accommodation they can afford (RTB 2018b).[23] Within an area designated as a Rent Pressure Zone, rents are not permitted to rise more than 4% annually based on a prescribed formula.[24] In total, there are currently 53 Local Electoral Areas which are designated as Rent Pressure Zones. With respect to our data, 445,421 BER's were issued for properties that are located in a county which contains a designated RPZ.[25] Although this is a less precise split in comparison to using a simple urban-rural divide, it allows us to identify counties which have seen disproportionate increases in rent due to more desirable location characteristics (such as commuter counties). Table 6 presents the results when we split our sample into properties which are located in a RPZ vs properties which are not.

Table 6: Effect of Renting on Efficiency: RPZ vs Non-RPZ

	OLS	CEM1	CEM2	CEM3
RPZ	0.117***	0.016***	0.016***	0.015***
	(0.002)	(0.002)	(0.002)	(0.002)
N	445,421	331,136	297,419	256,004
Non RPZ	0.015***	-0.005	-0.006	-0.002
	(0.003)	(0.003)	(0.003)	(0.003)
N	140,143	101,398	86,707	69,511

***Statistically significant at $p < 0.01$

When we only look at properties which are located in a RPZ, we find a significant and

[23]The Rent Pressure Zones are administered geographically based on Local Electoral Area divisions. Two conditions determine whether an area is a RPZ (RTB 2018b):

i The annual rate of rent inflation in the area must have been 7% or more in four of the last six quarters.

ii The average rent in the area in the previous quarter must be above the average national rent in that quarter.

For a list of the current and historical Rent Pressure Zones in the Republic of Ireland, as well as their effective dates please refer to Appendix Table A3.

[24]This formula is as follows: $R^* = R(1 + 0.04\frac{t}{m})$, where R^* is the new rent amount, R is the current rent amount, t is the number of months between the date the current rent came in to effect and the date the new rent will come into effect and m is the rent review frequency (=12 or 24).

[25]Since we do not have specific property addresses (only the county in which the property is located), we split the data based on whether or not the county in which the property is located contains a RPZ. In the case of County Dublin, this includes the entire county, however for less populated counties (such as Louth of Meath) the RPZ's typically reflect the most densely populated areas.

positive difference in efficiency between rental and non rental dwellings across all of our specifications. Under the OLS model, we find that rental properties in Rent Pressure Zones are roughly 12.4% less efficient than their comparable non-rental counterparts. Applying CEM1 and CEM2 matching weights we see the size of that difference fall to roughly 1.6%, and then further to 1.5% using CEM3 weights. These results, although smaller, are similar to what we observed when looking at the cities sub-sample

Outside RPZs however, we no longer observe a significant effect. Although the OLS model suggests a modest difference of 1.5%, all of our CEM matching specifications indicate a negative and insignificant effect. This stark contrast in findings when comparing the efficiency of similar rental and non-rental properties in RPZs vs outside of the RPZs seems to suggest that there may be an interplay between rental market forces and the landlord-tenant problem. One possible demand-side explanation may be that from the tenants point of view, the energy efficiency of the property becomes a less important consideration compared to other features of the rental property (such as location) in a more contested rental market. This may therefore allow landlords to extract higher rents for less efficient properties than would otherwise be possible - thereby allowing location characteristics to crowd out investment in energy efficiency improvements. Conversely, in less contested rental markets landlords may be forced to compete on rental property attributes such as energy efficiency.

Another possible explanation for this difference may be that Rent Pressure Zones may contain properties which have been rental for a much longer duration of time, and hence be less likely to have undergone a renovation.[26] If this is the case, then this would provide further evidence for the landlord-tenant problem and raises the question whether or not sufficient incentives exist for landlords to undertake energy efficiency investments in the first instance.

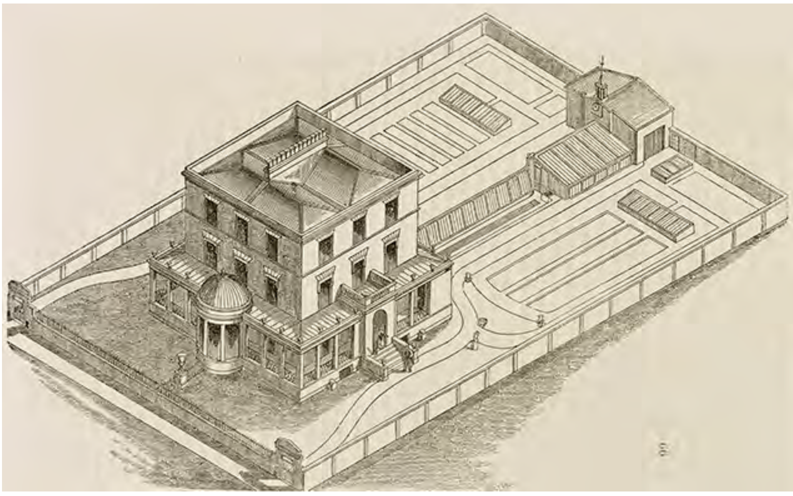
A supply-side explanation could be that RPZ's may be depressing investment in energy efficiency by landlords due to price caps on rent increases. This however does not seem likely in our case as an important condition of the RPZ legislation states that landlords are permitted to raise rents beyond the 4% limit if substantial refurbishment of the property are carried out (RTB 2017).

[26] In our analysis we control for the year of construction of the dwelling, however we are not aware of when the property became rental for the first time.

4.2 Semi Detached Properties - A Natural Experiment

The estimation of the treatment effect of renting on efficiency requires that conditional on the observable variables which we control for, treatment (or whether or not the property is rental) should be as good as randomly assigned. This means that there are no unobservable characteristics which may make a property more (or less) likely to become rental. Although so far in our analysis we have controlled for a wide variety of observable characteristics there may be other unobserved factors (such as building style or parking facilities for example) which may influence the selection into treatment.[27] In order to attempt to control for these unobservable characteristics, we further restrict our sample to look specifically at semi-detached properties, which is a relatively homogeneous segment.[28]

Figure 4: Early Example of a Semi Detached House



Source: Loudon (1838)

The origin of the semi detached property type dates back to 17th century England, where it was used by wealthy landowners to house labour in a relatively cheap manner, while at the same time making their estates appear as grand as possible (Wilkinson 2015). In fact, some of the earlier semi detached designs had their entrances tucked away on opposite sides of the property, so as to disguise the fact that the building was actually a double. Early architectural guides on the construction of such properties paid particular attention on making semidetached properties appear identical, so as to create the illusion

[27]This may be particularly true for detached or "One-off" houses. Apartments and terraced houses may also have such unobservable characteristics - e.g. the floor on which the apartment is situated or the distinction between end-of-terrace vs middle-terraced properties.

[28]Semi-detached properties in the Republic of Ireland (and UK) are defined as two similar properties which are joined together on only one side (Semi-detached 2020).

of one whole house (Loudon 1838).

The widespread adoption of the semi-detached house however did not come until the early 20th century, with a need to house an emerging new middle class. In the UK, between 1945 and 1964 semi detached-houses represented 40% of all new private dwellings (Wainwright 2015). The semi-detached property design enjoyed similar popularity in Ireland. The latest census indicates that there are currently 471,948 semi-detached dwellings in the Republic of Ireland, which represents roughly 28% of the entire housing stock (CSO 2016).

By the beginning of the 20th century, the idea of disguising the properties as one whole house was discarded in favour of economical designs which could be reproduced cheaply en masse. This design feature is the reason we focus specifically on semi-detached buildings in our analysis. Standardisation of design allowed for these properties to be produced cheaply at scale and typically these properties were built as part of housing estates/developments. This means that properties within an estate were virtually indistinguishable in terms of their physical characteristics at the time of their construction. Therefore, if we can identify rental and non-rental properties within the same estate, treatment (or whether or not a particular property becomes rental) is as good as randomly assigned. Accordingly, we focus our analysis solely on semi-detached properties.

Figure 5: Example of a More Modern Semi Detached Property

Source: Author

Although due to the anonymised nature of our data we do not have specific property addresses, we attempt to identify properties within the same estate by matching on an expanded set of detailed covariates. As part of the BER process, assessors are required to take detailed measurements of property characteristics, such as individual floor area, floor height, exposed wall area, window area and predominant roof area (presented in Table 7 and illustrated in Appendix Figure A6). These measurements are important in calculating the final $kWh/m^2/yr$ rating therefore they are carefully recorded by assessors on site and are subject to audit. We use these variables in combination with our matching procedure to identify relevant property matches. Further details such as individual distributions of each of the variables are presented in Appendix C.

Table 7: Summary Statistics - Semi Detached Properties

	Full Sample		Rental		Non-Rental		Non-Rental - Rental	
	Mean (1)	St. Dev (2)	Mean (3)	St. Dev. (4)	Mean (5)	St. Dev. (6)	Difference (5) - (3)	t (8)
BER ($kWh/m^2/yr$)	227.02	186.96	245.85	84.70	225.39	193.17	-20.45***	(-23.08)
Year of construction	1987.71	26.43	1987.68	25.90	1987.71	26.48	0.03	(0.11)
Ground floor area (m^2)	110.29	32.79	105.30	28.47	110.72	33.10	5.43***	(20.75)
Ground floor height (m)	2.49	0.21	2.48	0.11	2.49	0.22	0.02***	(13.47)
Exposed wall area (m^2)	95.83	26.34	92.83	23.66	96.09	26.55	3.26***	(15.06)
Window area (m^2)	19.40	9.99	17.94	8.78	19.52	10.08	1.58***	(19.63)
First floor area (m^2)	46.02	18.94	45.32	16.97	46.08	19.10	0.76***	(4.90)
First floor height (m)	2.44	0.83	2.47	0.79	2.44	0.84	-0.04***	(-4.88)
Predominant roof area (m^2)	51.60	16.20	50.33	15.56	51.71	16.25	1.38***	(9.74)
Number of storeys								
1	0.09	0.28	0.07	0.25	0.09	0.29	0.02***	(9.17)
2	0.83	0.38	0.87	0.34	0.82	0.38	-0.05***	(-14.71)
3	0.08	0.28	0.06	0.24	0.09	0.28	0.02***	(11.10)
4	0.00	0.03	0.00	0.03	0.00	0.03	-0.00	(-0.75)
5	0.00	0.00	0.00	0.00	0.00	0.01	0.00*	(2.00)
Urban	0.29	0.45	0.27	0.45	0.29	0.45	0.01***	(3.60)
Rural	0.71	0.45	0.73	0.45	0.71	0.45	-0.01***	(-3.60)
RPZ	0.79	0.41	0.74	0.44	0.79	0.40	0.05***	(13.73)
N	166,674		13,236		153,438			

In total, there are 166,674 semi-detached properties in our sample, 13,236 of which are rental. When looking at average values what we see again is that rental semi-detached properties are less efficient in terms of the BER when compared to non-rental properties. However, they are also different when compared to non-rental properties on observable characteristics such as size and height. In order to try to identify rental and non rental properties within the same estates we create strata of varying stringency as in Section 4.1. These, along with summary statistics on each of our matching procedures are presented in Table 8.

Table 8: Matching Summary - Semi Detached Properties

	No Matching	CEM1	CEM2	CEM3
Coarsened variables and bin sizes				
Ground floor area (m^2)		50	20	5
Ground floor height (m)		1	0.5	0.2
First floor area (m^2)		50	20	5
First floor height (m)		1	0.5	0.2
Wall area (m^2)		50	20	5
Predominant roof area (m^2)		50	20	5
Window area (m^2)		20	10	5
Year of construction ($years$)		regulation	regulation	regulation
Number of Storeys		exact	exact	exact
Location (Table A2)		exact	exact	exact
Matched - Treated	13,236	11,978	9,628	4,890
% Treated Retained	100%	90.50%	72.74%	36.94%
Matched - Control	153,438	93,439	57,566	16,542
% Control Retained	100%	60.90%	37.52%	10.78%
Unmatched - Treated	0	1,258	3,608	8,346
Unmatched - Control	0	59,999	95,872	136,896
Number of Strata	N/A	23,530	55,137	106,529
Number of Matched Strata	N/A	3,426	3,855	3,336

For our CEM1 and CEM2 matching criteria, we create comparatively larger bins for each of the coarsened variables when compared to the coarsening choice in Section 4.1. Since we are matching on an expanded set of covariates, even with large bin sizes the number of strata created increases dramatically. It therefore becomes more difficult to find strata in which we have both treated and control units, and overly strict coarsening may discard potential matches. For our final coarsening choice however (CEM3) we again apply the strictest criteria possible while keeping within the measurement error bound of the BER assessment procedure. Similarly to the analysis in Section 4.1, as we make the coarsening choice stricter, we lose more control units in comparison to treated units. Under our strictest matching criteria we are left with 21,432 observations, 4,890 of which are rental.

Table 9 presents the results when looking at the entire sample of semi-detached properties. We find a roughly 15% difference in efficiency between rental and non-rental semi detached properties under the OLS model. When we apply the CEM matching weights, we observe a remarkably robust effect size regardless of matching stringency. This suggests that among observationally similar semi-detached properties, rental properties are roughly 5-6% less efficient. We next split our sample based on city and RPZ divisions in the same

Table 9: Parametric Regression Results: Semi Detached Properties

	OLS	CEM1	CEM2	CEM3
Rental	0.144***	0.051***	0.059***	0.056***
	(0.003)	(0.002)	(0.003)	(0.004)
Year of construction (*years*)	-0.013***	-0.008***	-0.010***	-0.012***
	(0.000)	(0.000)	(0.000)	(0.000)
Ground floor area (m^2)	-0.005***	-0.005***	-0.005***	-0.003***
	(0.000)	(0.000)	(0.000)	(0.001)
Ground floor height (m)	-0.146***	0.058*	0.013	0.038
	(0.038)	(0.027)	(0.034)	(0.049)
Exposed wall area (m^2)	-0.000	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Window area (m^2)	0.003***	0.003***	0.003***	0.000
	(0.000)	(0.000)	(0.001)	(0.001)
First floor area (m^2)	-0.003***	-0.001***	-0.001	-0.003**
	(0.000)	(0.000)	(0.000)	(0.001)
First floor height (m)	-0.019***	-0.027**	-0.031*	0.020
	(0.005)	(0.010)	(0.014)	(0.029)
Predominant roof type area (m^2)	0.000**	0.000	0.001*	-0.000
	(0.000)	(0.000)	(0.000)	(0.001)
Number of storeys				
1	0	0	0	0
	(omitted)	(omitted)	(omitted)	(omitted)
2	0.094***	-0.016	-0.014	-0.148*
	(0.011)	(0.023)	(0.029)	(0.061)
3	0.071***	-0.032	-0.039	-0.299***
	(0.012)	(0.026)	(0.035)	(0.089)
4	0.183***	0.615***		
	(0.046)	(0.072)		
5	0.379			
	(0.368)			
Location FE	yes	yes	yes	yes
N	166,672	105,416	67,193	21,432

***Statistically significant at $p < 0.01$
**Statistically significant at $p < 0.05$
*Statistically significant at $p < 0.1$

manner as Section 4.1. The coefficient on the treatment variable (rental) is presented in Table 10 in each case.

Table 10: Parametric Regression Results: Semi-detached properties only

	OLS	CEM1	CEM2	CEM3
Full Sample	0.144***	0.051***	0.059***	0.056***
	(0.003)	(0.002)	(0.003)	(0.004)
N	166,672	105,416	67,193	21,432
Urban	0.154***	0.074***	0.082***	0.072***
	(0.006)	(0.005)	(0.005)	(0.008)
N	47,804	27,156	16,215	4,811
Rural	0.141***	0.043***	0.051***	0.051***
	(0.004)	(0.003)	(0.003)	(0.004)
N	118,868	78,260	50,978	16,621
RPZ	0.166***	0.061***	0.066***	0.064***
	(0.004)	(0.003)	(0.003)	(0.004)
N	131,639	81,643	52,093	16,933
Non RPZ	0.067***	0.021***	0.037***	0.033***
	(0.005)	(0.005)	(0.005)	(0.007)
N	35,033	23,773	15,100	4,499

***Statistically significant at $p < 0.01$

Once again we find a larger effect in cities vs outside cities across all of our matching specifications. This difference between urban and rural settings however does not appear as dramatic as that observed in Section 4.2. When we split the sample based on RPZ designation we see a larger disparity in findings. Within RPZs the difference in efficiency between rental and non-rental properties appears to be between 6 and 7%, while looking outside of RPZs this difference falls to roughly 2-4%. This result appears to confirm the finding in Section 4.1 of a possible link between the landlord-tenant problem an location specific rental market pressures. In contrast to the results in Section 4.2 however, we do observe a significant (albeit smaller) effect outside RPZs.

In addition to the CEM matching procedures used in the main body of this paper, as a robustness check we carry out a more traditional matching approach in Appendix A4. We use propensity score matching methods with and without replacement with varying numbers of nearest neighbours. The findings confirm the results observed in the main body of the article.

5 Conclusions

To answer whether there exists a principal-agent problem in the rental sector, we use a combination of matching (CEM) and regression estimation techniques to determine the effect of renting on energy efficiency. Our paper builds on existing analyses in the area in three ways. Firstly, using high quality engineering data on the population of energy performance audits in a small country, we are able to compare the overall efficiency of rental and non-rental properties. Much of the previous work in the area has had to rely on appliance specific data. Our findings suggest that in cases where information on the efficiency of the property is supplied, rental properties appear to be less efficient than their comparable non-rental counterparts, however the magnitude of this difference in efficiency is relatively small (roughly 1% for the sample as a whole). This difference implies that even in the case of mandatory disclosure and advertising of energy performance certificates the principal agent problem between landlords and tenants persists. Although it is possible that some of this remaining difference may still be explained by remaining information asymmetries, the stark difference in results when location is considered make the asymmetric information channel seem less plausible, and suggest that other factors are at work.

Secondly, we explore the effect of location-specific rental market pressure on the principal-agent problem by comparing the difference in efficiency between rental and non-rental properties in major Irish cities and the rest of Ireland. The results show that in cities, where there is a scarcity of rental properties, the difference in efficiency between rental and non-rental properties larger than for the remainder of the country. To explore this further, we split the sample based on Rent Pressure Zones (RPZ) and find that the difference in efficiency between rental and non-rental properties is larger in RPZs, while it is insignificant when looking at properties outside of RPZ's. This heterogeneity in the magnitude of the landlord-tenant problem when considering location-specific scarcity, coupled with mandatory disclosure of EPC's across all regions suggests that split incentives may play a role even in the absence of information asymmetries.

Finally, we use a unique building design feature and CEM to attempt to identify properties which are observably identical at the time of their construction. We focus specifically on semi-detached properties as a natural experiment, and again find a significant difference in efficiency between rental and non-rental properties which is larger in magnitude than our previous results.

The policy implications from this analysis are that although information asymmetries are an important component of the landlord-tenant problem, correcting for information asymmetries alone may not be sufficient in encouraging the adaption of energy efficiency measures by landlords, and ensuring that rental and non-rental properties have equivalent levels of energy performance. This appears to be particularly true in markets with scarce rental property supply, where prospective tenants may trade-off energy efficiency characteristics for location characteristics. This is also likely facilitated by remaining goal-conflicts or *split incentives*, particularly in cases where tenants are responsible for energy bills. Future work is needed to explore the interplay between location characteristics and the split-incentives problem in more detail, with more detailed data on utility bill paying arrangements and duration of rental status. Additional measures to encourage landlords to invest in energy efficiency improvements, either through financial incentives or regulation may be necessary.

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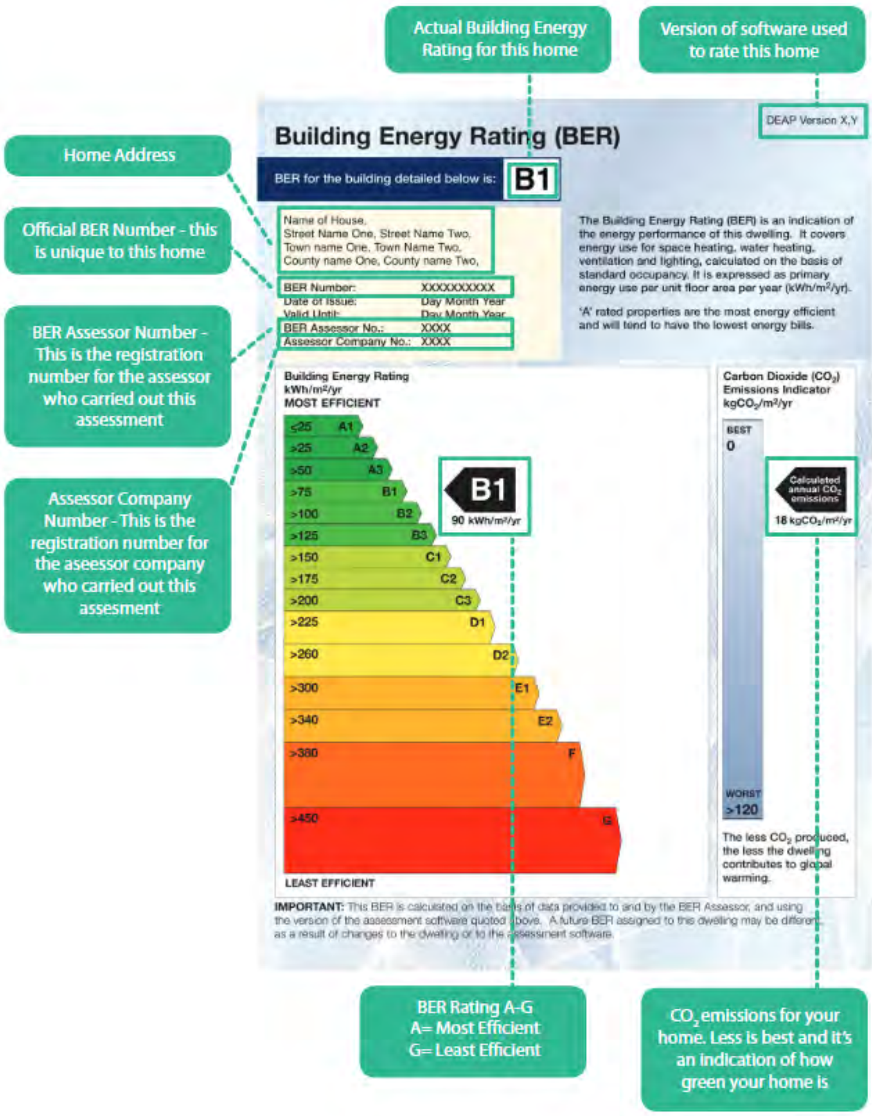
Appendices

A1 Supplementary Material

Figure A1: Building Energy Rating Certificate Example



Source: SEAI (2013a)

Table A1: Detailed Definition of Variables

Variable	Definition
BER ($kWh/m^2/year$)	The estimated efficiency of the property based on characteristics such insulation, airtightness etc. Measured in $kWh/m^2/yr$.
Ground-floor area (m^2)	The area of the ground floor of the dwelling. Measured in m^2.
Year of construction	The year the dwelling was originally constructed. This does not take into account of the construction of extensions to the dwelling at a subsequent date, however they are considered when estimating the BER.
Detached house	=1 if the dwelling is an detached house, =0 otherwise. A detached house is another term for a standalone dwelling, which is not attached to any other dwelling. Number of cases: 181,322.
Semi-detached house	=1 if the dwelling is a joined to another dwelling on one side only, =0 otherwise. Number of cases: 166,674.
End-of-terrace house	=1 if the dwelling is a an end of terrace house, =0 otherwise. Number of cases: 43,562.
Mid-terrace house	=1 if the dwelling is a mid-terrace house, =0 otherwise. Number of cases: 82,889.
House (general)	=1 if the dwelling is an unspecified type of house. Note, in total we observe only 1,261 such cases.
Maisonette	=1 if the dwelling is a maisonette, =0 otherwise. A maisonette is usually defined as a flat which has a separate outside door to other flats in the same building (Collins 2020). Number of cases: 6,678.
Basement dwelling	=1 if the dwelling is a basement dwelling, =0 otherwise. Number of cases: 254.
Ground-floor apartment	=1 if the dwelling is a ground-floor apartment, =0 otherwise. Number of cases: 31,563.
Mid-floor apartment	=1 if the dwelling is a mid-floor apartment, =0 otherwise. Number of cases: 38,308.
Top-floor apartment	=1 if the dwelling is a top-floor apartment, =0 otherwise. Number of cases: 32,707.
Apartment (general)	=1 if the dwelling is an unspecified type of apartment, =0 otherwise. Note, we only observe 360 such cases in total.
Number of storeys	The number of storeys in the dwelling. Discrete variable. Min = 1, Max = 7, Mean = 1.75, St. Dev. = 0.5763.
Urban	=1 if the dwelling is located in a city. Includes all dwellings which are based in any of the five major cities in the Republic of Ireland: Cork, Dublin (all city codes), Galway, Limerick and Waterford. For more details on our location breakdown please refer to Appendix Table A2.
Rural	Includes all dwellings which are not located in any of the major cities. =1 if rural, =0 otherwise.
RPZ	=1 if the dwelling is located in an RPZ, =0 otherwise. For more details on RPZ designation please refer to Appendix Table A3.
Ground-floor height (m)	Height of the ground floor in metres. Average height between the ceiling surface of the ground floor and the floor below.
Exposed wall area (m^2)	The total area of exposed and semi-exposed walls in the dwelling. Any wall separating the dwelling from another heated dwelling, e.g. the party wall in a semi-detached house, is assumed to have no heat loss so it is not included here.
Window area (m^2)	The total area of all windows in the dwelling. This is the area of the whole opening: glazing and frame.
First-floor area (m^2)	First floor area in square metres.
First-floor height (m)	Height of the first floor in metres. Average height between the ceiling surface of the first floor and the ceiling surface of the floor below.
Predominant roof area (m^2)	Area of the largest (most predominant) roof type in a dwelling

Source: SEAI (2011a)

Table A2: Location Variable Breakdown

	Total	Rental	Non Rental
CoCarlow	7,421	1,150	6,271
CoCavan	8,785	422	8,363
CoClare	13,269	1,519	11,750
CoCork	49,208	3,262	45,946
CoDonegal	16,915	2,012	14,903
CoDublin	46,413	5,139	41,274
CoGalway	20,156	1,875	18,281
CoKerry	17,582	2,056	15,526
CoKildare	27,741	2,846	24,895
CoKilkenny	8,611	817	7,794
CoLaois	8,526	768	7,758
CoLeitrim	4,924	336	4,588
CoLimerick	12,039	864	11,175
CoLongford	4,948	263	4,685
CoLouth	18,780	1,228	17,552
CoMayo	16,095	1,538	14,557
CoMeath	24,387	1,547	22,840
CoMonaghan	4,938	451	4,487
CoOffaly	7,501	870	6,631
CoRoscommon	7,324	456	6,868
CoSligo	8,519	927	7,592
CoTipperary	17,571	1,203	16,368
CoWaterford	8,261	708	7,553
CoWestmeath	10,959	1,494	9,465
CoWexford	18,690	1,865	16,825
CoWicklow	17,505	1,778	15,727
Dublin1	4,471	1,474	2,997
Dublin2	2,858	963	1,895
Dublin3	5,238	932	4,306
Dublin4	6,627	1,947	4,680
Dublin5	5,452	461	4,991
Dublin6	5,687	1,338	4,349
Dublin6W	3,572	523	3,049
Dublin7	7,495	1,423	6,072
Dublin8	8,176	2,100	6,076
Dublin9	7,317	1,036	6,281
Dublin10	2,419	111	2,308
Dublin11	6,603	836	5,767
Dublin12	6,996	717	6,279
Dublin13	5,277	617	4,660
Dublin14	6,562	660	5,902
Dublin15	14,551	1,676	12,875
Dublin16	6,199	516	5,683
Dublin17	2,050	416	1,634
Dublin18	7,150	1,261	5,889
Dublin19	3	0	3
Dublin20	1,613	401	1,212
Dublin21	6	1	5
Dublin22	4,708	460	4,248
Dublin23	2	1	1
Dublin24	10,522	1,447	9,075
GalwayCity	10,473	1,951	8,522
LimerickCity	11,871	1,954	9,917
WaterfordCity	7,065	731	6,334
CorkCity	17,547	1,638	15,909
Observations	585578	64985	520593

Table A3: Rent Pressure Zones (RPZ) Timeline

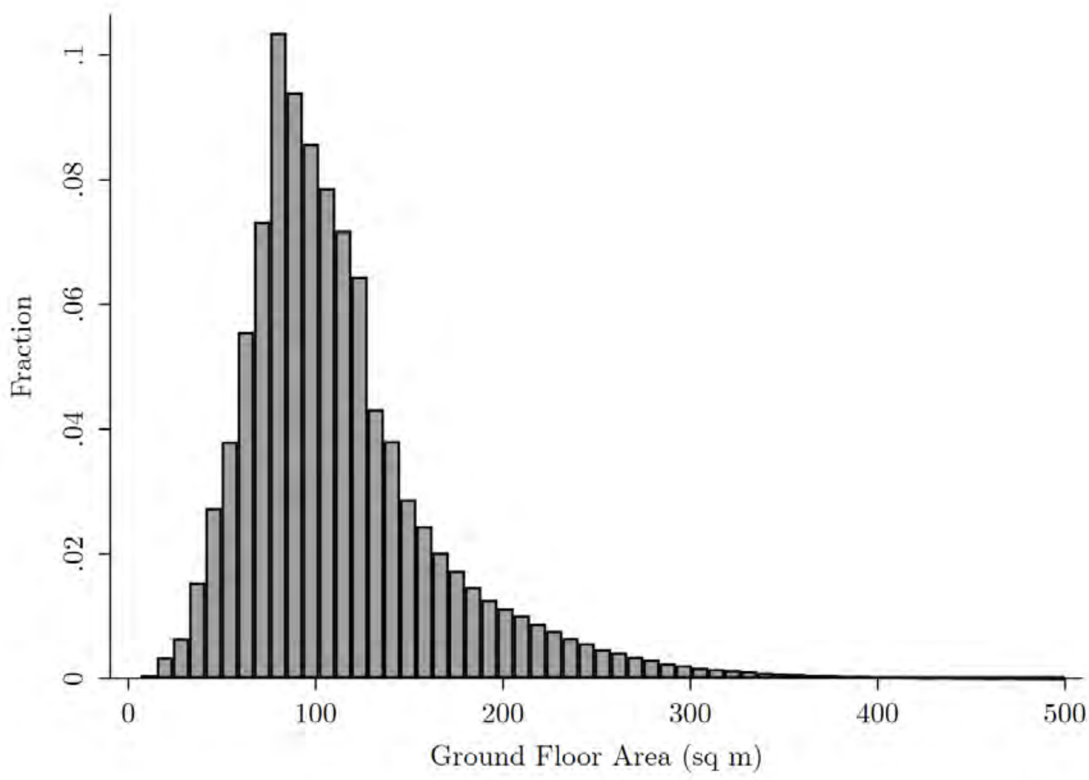
Effective From	Local Authority	Location Variable Affected
24th December 2016	Dublin City Council Dun Laoghaire/Rathdown County Council Fingal County Council South Dublin County Council Cork City Council	All Dublin City Codes Co. Dublin Cork City
27th January 2017	Ballincollig – Carrigaline, Co. Cork Galway City Council Galway City East Galway City West Celbridge-Leixlip, Co. Kildare Naas, Co. Kildare Newbridge, Co. Kildare Ashbourne, Co. Meath Laytown-Bettystown, Co. Meath Ratoath, Co. Meath Bray, Co. Wicklow Wicklow, Co. Wicklow	Co. Cork Galway City Co. Kildare Co. Meath Co. Wicklow
30th March 2017	Cobh, Co. Cork Maynooth, Co. Kildare	
20th September 2017	Drogheda, Co. Louth Greystones, Co Wicklow	Co. Louth
28th March 2019	Limerick City East Navan, Co. Meath	Limerick City
2nd July 2019	Ardee, Co. Louth Arklow, Co. Wicklow Athenry – Oranmore, Co. Galway Athlone, Co. Westmeath Dundalk – Carlingford, Co. Louth Dundalk South, Co. Louth Fermoy, Co. Cork Gorey, Co. Wexford Gort – Kinvara, Co. Galway Graiguecullen – Portarlington, Co. Laois Kells, Co. Meath Kilkenny City Limerick City North Limerick City West Midleton, Co. Cork Portlaoise, Co. Laois Trim, Co. Meath Waterford City East Waterford City South	Co. Galway Co. Westmeath Co. Wexford Co. Laois Co. Kilkenny Waterford City
26th September 2019	Carlow Town Macroom, Co. Cork	Co. Carlow
18th December 2019	Baltinglass, Co. Wicklow Cobh (to include Watergrasshill), Co. Cork Piltown, Co. Kilkenny Sligo-Strandhill, Co. Sligo	Co. Sligo
22nd April 2020	Athy, Co. Kildare Killarney, Co. Kerry Mallow, Co. Cork Mullingar, Co. Offaly Tullamore, Co. Westmeath	Co. Kerry Co. Offaly

A2 Justification of Coarsening Choices

A2.1 Choice of Coarsening: Ground-floor area variable:

Although in our analysis we have already accounted for dwelling type (i.e. apartment, semi-detached, detached and terraced housing etc), it may be the case that a significant variation in size exists within each of these dwelling types. For example, in the absence of the floor-area variable, we may be placing two detached houses of vastly different size in the same category. The histogram below displays the overall distribution of dwelling ground-floor area in our sample.

Figure A2: Distribution of Ground-floor Area Variable



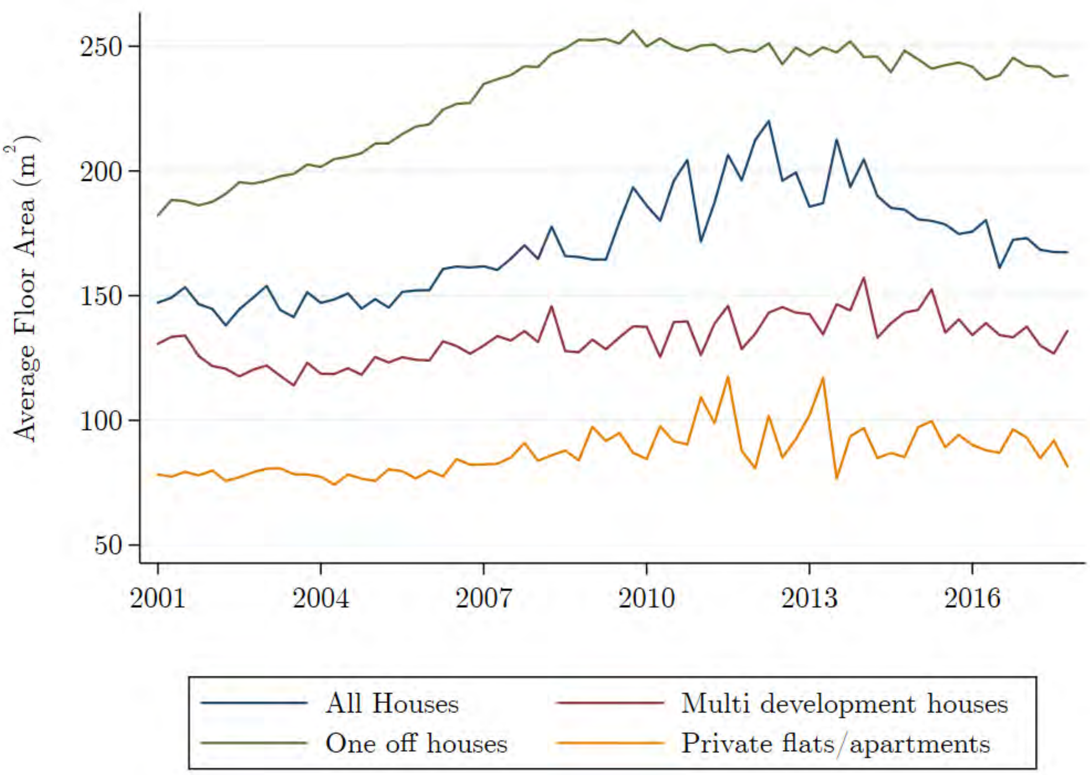
The above appears to be positively skewed with mean of 110.5^2 (as shown previously) and a mode of just under 100m^2. We can also see that the right-tail of the distribution appears to approach 0 in terms of density after 300m^2. We therefore group all properties which are greater than 300m^2 in the same category. In total we have 8,079 such properties.

Using a separate national dataset on planning permissions for residential dwellings

Table A4: CSO Data - Classification of Dwelling Size (m^2)

	2012Q1	2013Q1	2014Q1	2015Q1	2016Q1	2017Q1
Houses	212.4	185.7	204.6	180.6	185.7	173.1
Multi Development Houses	134.7	142.6	157.3	144.3	134.2	137.6
One-off houses	247.8	246.2	245.7	244.8	241.8	242.1
Private flats/apartments	80.8	102.1	96.9	97.2	90.1	93.1

Figure A3: CSO Data - Change in Dwelling Sizes



in the Republic of Ireland from the Central Statistics Office (CSO 2020) we can gain some further insights into the appropriate coarsening choice for the ground-floor area variable. As per the above we can see that the average floor area for all new houses (solid dark-blue line) increased steadily up to 2011-12 and has subsequently declined.[29] When looking at the division between one off and multi development houses, we can also see that one-off houses tend to be considerably larger (almost twice in size) in comparison to multi-development houses which in turn are about twice as large as private flats/apartments, on average. Over the period of our study (2012-2017) we can see that of the three categories of dwelling type[30], private flats/apartments have fluctuated the most in terms of floor area, ranging from 80.8^2 to 102.1^2. Multi-development houses also exhibit a similar degree of fluctuation ranging from a minimum of 134.2m^2 to 157.3m^2. In comparison, new one-off houses have remained relatively constant in terms of size since 2012, however as is visible from the graph had experienced a significant growth in size up to 2009.

Within any given year, properties of the same category appear to fluctuate in size by roughly 20m^2. For this reason, for our first coarsening choice (CEM1) we have decided to use 20m^2 intervals when coarsening the ground-floor area variable. We then make the interval stricter in our second and third coarsening choices to test if this has an impact on the size and significance of our results. Our strictest coarsening choice ($5m^2$) was determined through consultation with professional assessors and is in line with the allowable error rate on assessment audit.

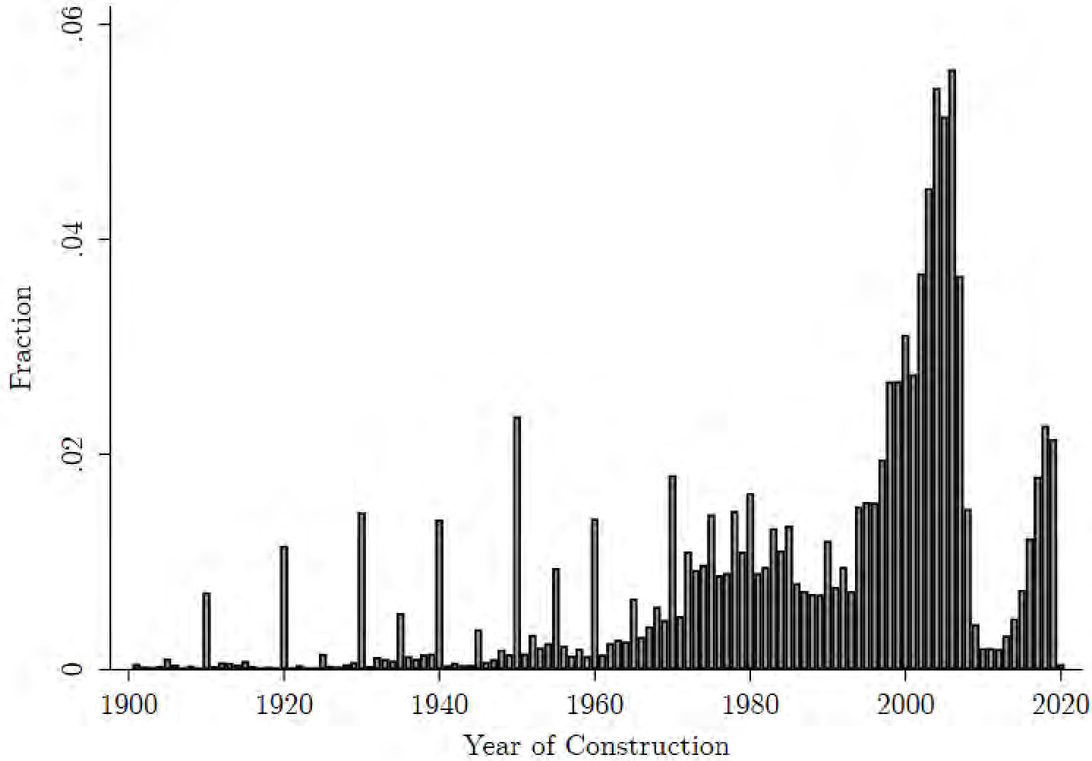
[29] Since we are also matching based on the age of the property, this change in size over time should be controlled for.

[30] Note: "Houses" includes both multi-development and one-off houses.

A2.2 Choice of Coarsening: Year of Construction

The below histogram gives the distribution of the year of construction variable in our sample:

Figure A4: Distribution of Year of Construction



For our coarsening choice we employ cut-offs which coincide with the age band definitions under the Dwelling Energy Assessment Procedure (DEAP) Manual, which is the guidance document followed by BER assessors (SEAI 2019). These are presented in Table A5, and highlight building eras for properties constructed up to 2005. After 2005, we coarsen the year of construction variable based on the introduction of new building regulations which impact energy efficiency directly (presented in A6), since we expect properties built under the same building standards to be similar in terms of energy performance. We have taken the legislation effective date as our coarsening choice cut off. If the effective date is in the second half of a calendar year, we use the following year as the cut off date. This is to allow for the fact that there may be a time lag in construction, as properties which are already partially completed will not be subject to the new regulations on the effective date.

Table A5: Era of Building Definition as per DEAP

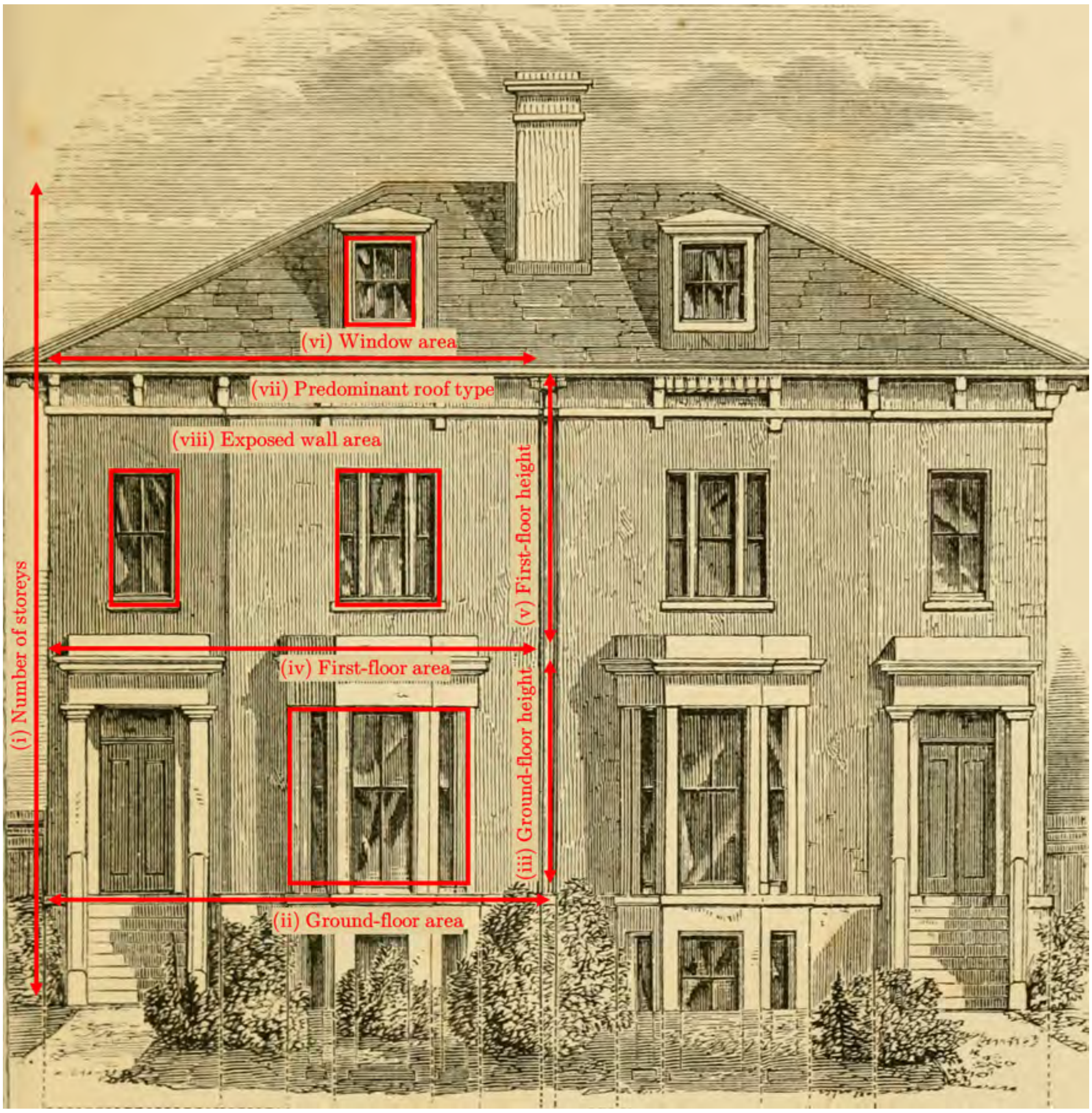
Age Band	Years of Construction
A	before 1990
B	1900 - 1929
C	1930 - 1949
D	1950 - 1966
E	1967 - 1977
F	1978 - 1982
G	1983 - 1993
H	1994 - 1999
I	2000 - 2004
J	2005 onwards (without BER certificate already)

Table A6: Building Regulation Changes

Reference	Amendment Focus	Effective Date	Relevant to Efficiency	Cut-off
S.I. No. 292 (2019)	Conservation of fuel and energy	1st November 2019	YES	2020
S.I. No. 57 (2017)	Fire safety	1st July 2017	NO	
S.I. No. 133 (2014)	Heat-producing appliances	1st September 2014	YES	2015
S.I. No. 180 (2014)	Stairways, ladders, ramps and guards	1st January 2015	NO	
S.I. No. 606 (2014)	Sound	1st July 2015	NO	
S.I. No. 224 (2013)	Materials and workmanship	1st July 2013	YES	2014
S.I. No. 138 (2012)	Harmonising design codes for buildings across EU	1st July 2013	NO	
S.I. No. 259 (2011)	Energy conservation and CO2 emissions	1st December 2011	YES	2012
S.I. No. 513 (2010)	Access and use	1st January 2012	NO	
S.I. No. 561 (2010)	Drainage and waste-water disposal	1st June 2011	NO	
S.I. No. 556 (2009)	Ventilation	1st October 2010	YES	2011
S.I. No. 229 (2008)	Conservation of fuel and energy - non domestic buildings	10th July 2008	NO	
S.I. No. 335 (2008)	Hygiene	1st November 2008	NO	
S.I. No. 259 (2008)	Conservation of fuel and energy	10th July 2008	YES	2009
S.I. No. 854 (2007)	Minimum efficiency standards of new oil and gas boilers	1st July 2008	YES	2009
S.I. No. 115 (2006)	Fire safety	1st June 2006	NO	
S.I. No. 666 (2006)	Compliance with EU energy performance directive	1st Jan 2007	YES	2007
S.I. No. 873 (2005)	Conservation of fuel and energy	1st July 2006	YES	2007

A3 Semi Detached Matching Variables Detail

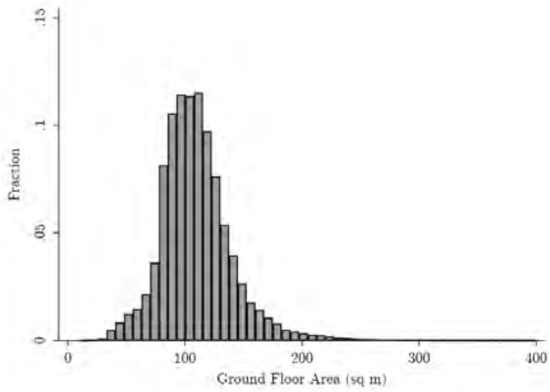
Figure A5: Illustration of Variables used in Matching



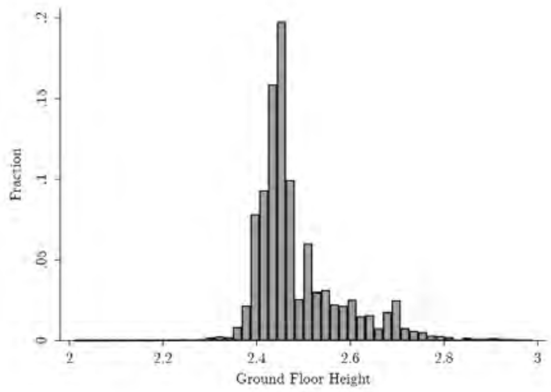
Source: Brooks (1874) – Licence to Reuse and modify

Figure A6: Distribution Semi Detached Size Variables

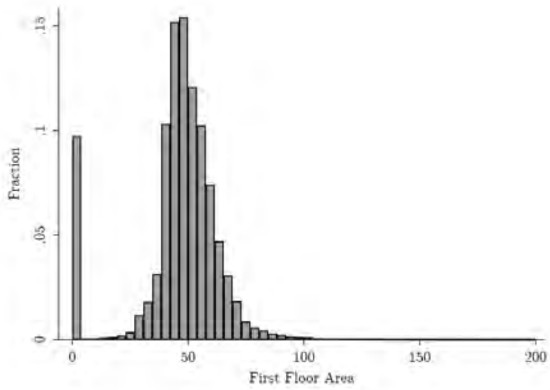
(a) Ground Floor Area



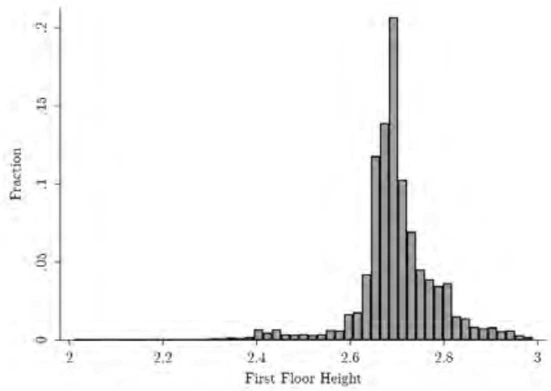
(b) Ground Floor Height



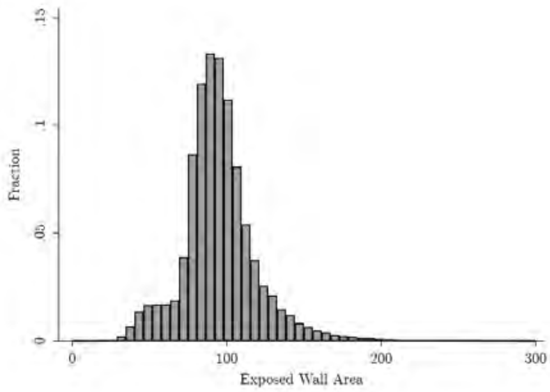
(c) First Floor Area



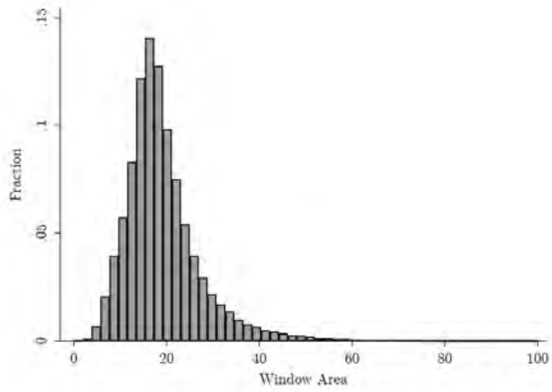
(d) First Floor Height



(e) Wall Area



(f) Window Height



A4 Matching Procedure Robustness

As a robustness check to the CEM matching procedure used in the main body of this paper we apply two additional, and more traditional matching approaches. We begin by estimating the Average Treatment effect on the Treated (ATT) using propensity score matching (Dehejia and Wahba 2002; Rosenbaum and Rubin 1983). Propensity score matching relies on estimating a propensity score, which is a conditional probability of treatment assignment given a vector of observed covariates (Rosenbaum and Rubin 1983). The matching algorithm is typically carried out in two steps. First, the propensity score is estimated via a logit or probit model with the treatment variable as the binary dependent variable and all matching covariates as independent variables. Predicted probabilities of treatment are then obtained and are used to match treated and control units, with various types of matching methods. In our application, we use nearest-neighbour matching, whereby the closest treated an control units based on the propensity score are matched. We present the results, both without and with replacement and varying numbers of nearest neighbours in Table A7. We also present the estimated average treatment effects graphically in Figure A7.

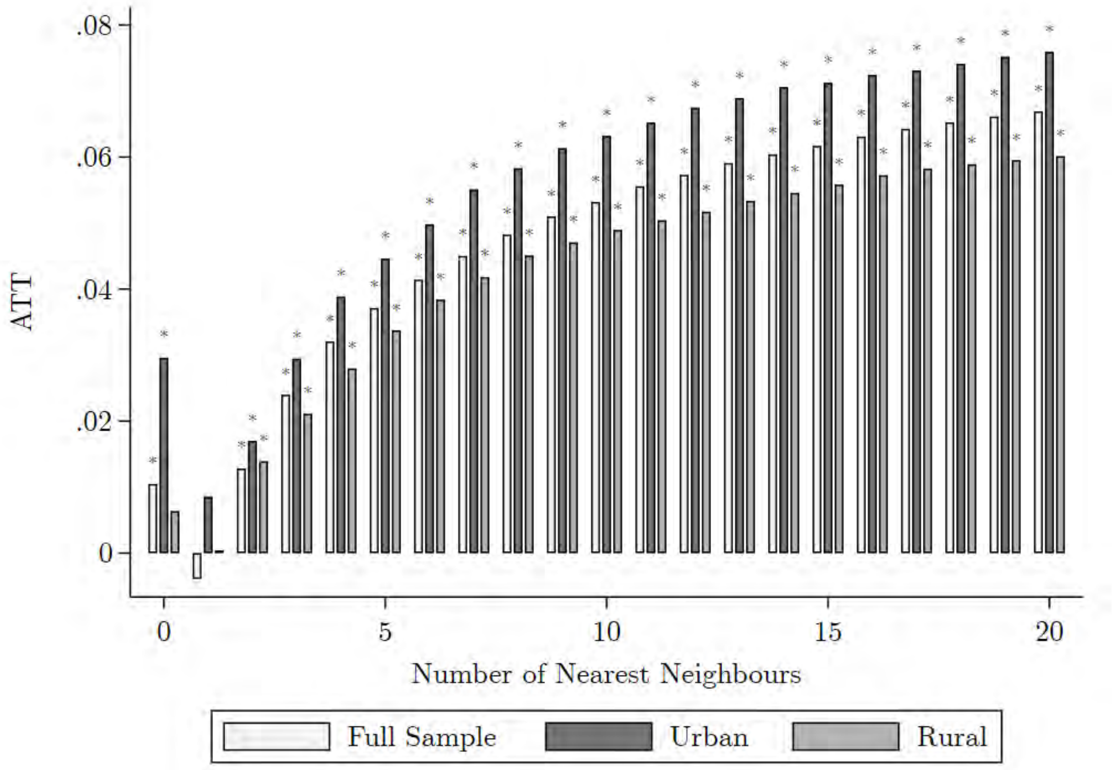
What we observe is very similar to the results presented in the main body of the article. There is a positive and significant effect of renting on efficiency when looking at the sample as whole - which ranges roughly between 1 and 7%. We also observe a significant difference in the effect of renting on efficiency when splitting the sample between urban and rural - whereby the difference in efficiency between rental and non-rental properties appears to be larger in magnitude in the cities. The average effect of renting on efficiency ranges roughly between 2 and 8% in cities depending on number of nearest neighbours used, while outside of cities this difference ranges between 1 and 6%. We do not find significant results when using 1 nearest neighbour with replacement, however we observe very similar results to the CEM results when using matching without replacement. This is expected as the CEM procedure does not allow control observations to be used more than once within strata. With replacement in this context means that control (non-rental) units which are matched to treated (rental) units can be used more than once in the matching procedure.

Table A7: Propensity Score Matching

No. of Nearest Neighbours	Whole Sample ATT	Urban ATT	Rural ATT	RPZ ATT	Non RPZ ATT
Without Replacement					
1	0.010***	0.030***	0.006*	0.029***	-0.010*
	(0.003)	(0.004)	(0.003)	(0.003)	(0.006)
With Replacement					
1	-0.004	0.009	0.000	0.014***	-0.019***
	(0.004)	(0.006)	(0.004)	(0.004)	(0.007)
2	0.013***	0.017***	0.014***	0.029***	-0.012**
	(0.003)	(0.005)	(0.003)	(0.003)	(0.006)
3	0.024***	0.029***	0.021***	0.040***	-0.008
	(0.003)	(0.005)	(0.003)	(0.003)	(0.005)
4	0.032***	0.039***	0.028***	0.046***	-0.007
	(0.003)	(0.004)	(0.003)	(0.003)	(0.005)
5	0.037***	0.045***	0.034***	0.052***	-0.006
	(0.003)	(0.004)	(0.003)	(0.003)	(0.005)
6	0.041***	0.050***	0.038***	0.056***	-0.006
	(0.002)	(0.004)	(0.003)	(0.003)	(0.005)
7	0.045***	0.055***	0.042***	0.059***	-0.005
	(0.002)	(0.004)	(0.003)	(0.003)	(0.005)
8	0.048***	0.058***	0.045***	0.063***	-0.003
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
9	0.051***	0.061***	0.047***	0.065***	-0.003
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
10	0.053***	0.063***	0.049***	0.067***	-0.002
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
11	0.056***	0.065***	0.050***	0.069***	-0.001
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
12	0.057***	0.067***	0.052***	0.071***	0.000
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
13	0.059***	0.069***	0.053***	0.072***	0.001
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
14	0.060***	0.071***	0.055***	0.073***	0.001
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
15	0.062***	0.071***	0.056***	0.075***	0.002
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
16	0.063***	0.072***	0.057***	0.076***	0.002
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
17	0.064***	0.073***	0.058***	0.076***	0.002
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
18	0.065***	0.074***	0.059***	0.077***	0.003
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
19	0.066***	0.075***	0.060***	0.078***	0.002
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)
20	0.067***	0.076***	0.060***	0.079***	0.003
	(0.002)	(0.004)	(0.003)	(0.003)	(0.004)

***Statistically significant at $p < 0.01$
**Statistically significant at $p < 0.05$
*Statistically significant at $p < 0.1$

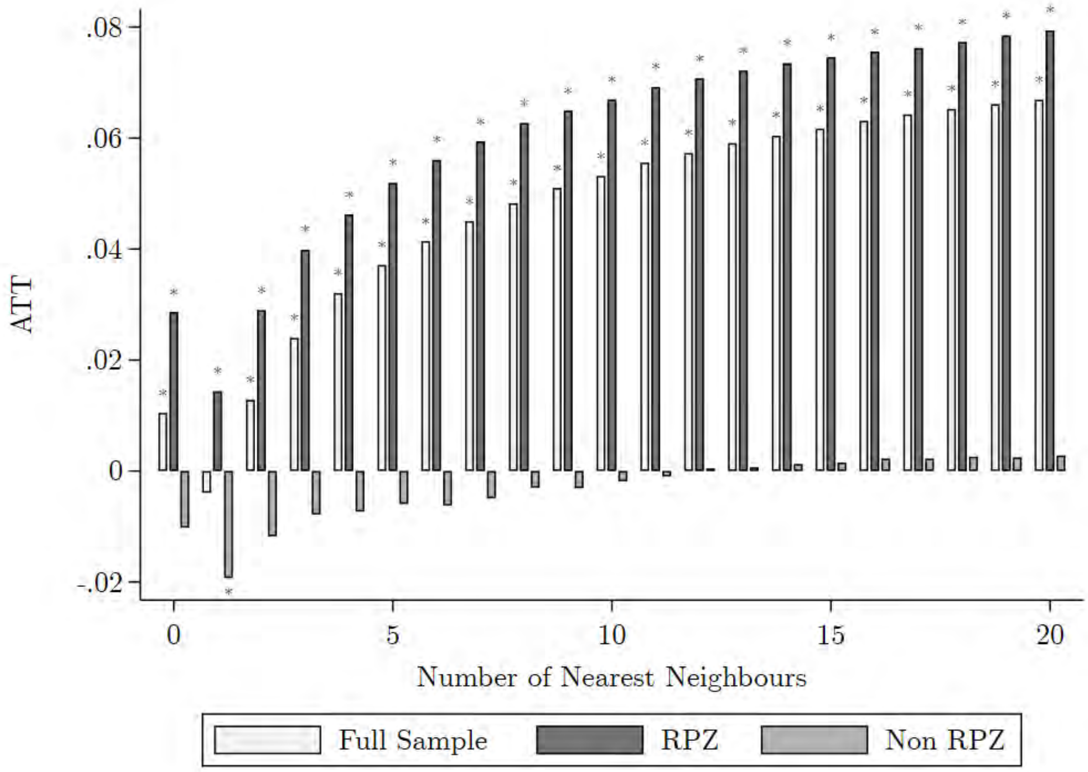
Figure A7: Propensity Score Matching Results: Cities vs Rest



*Statistically significant at $p < 0.01$

What we also see is that as we increase the number of nearest neighbours on to which we match our treated units, the size of the average treatment effect is increasing in magnitude (at a decreasing rate) and appears to be converging to the OLS estimates. In Figure A8 we present the propensity score estimates when splitting the sample based on RPZ divisions. What we find is a similar effect to the results in the main body of the paper, with estimates of the effect of renting on efficiency ranging from 3 to 8% in RPZ's. We also find a significant effect when using one nearest neighbour matching with replacement. Outside RPZ's however we find that the difference in efficiency between rental and non-rental properties appears to be negative - i.e. rental properties are more efficient. However, this striking effect appears to be small (less that 2%) and is only significant at the 1% level when using one nearest neighbour matching with replacement. When we increase the number of nearest neighbours, we no longer observe a significant effect.

Figure A8: Propensity Score Matching Results: RPZ vs Non-RPZ



*Statistically significant at $p < 0.01$

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