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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. In addition, we are able to take advantage of a unique trait in building design to compare rental and non-rental properties which were identical at the time of their construction. The findings from this sub-group mirror our finding for the sample as a whole.

1. Introduction

Buildings and building construction account for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO_2) emissions globally (GABC, 2019). The demand for energy from buildings and construction is also expected to grow - driven by increased demand for floor space, as well as improved access to energy in developing economies and growth in the adoption of energy using appliances.

Despite this increase in demand, final energy use from buildings may remain constant or even decline by mid-century if the cost-effective technologies and practices available today are implemented globally (Lucon et al., 2014). Historically, energy efficiency improvements have also ensured that energy use is lower today than what would otherwise have been the case. The International Energy Agency (IEA) estimate that globally, energy use in 2017 would have been 12% higher, had it not been for the energy efficiency improvements observed in buildings since the year 2000 (IEA, 2018). Although this is an encouraging trend, the authors also suggest that a lot of cost-effective energy efficiency improvements still remain on the table, a phenomenon commonly referred to as the "Energy Efficiency Gap" (Allcott and Greenstone, 2012; Jaffe and Stavins, 1994).

In this paper we focus on a principal-agent market failure which can explain this under-investment in the case of rental properties, known as the *landlord-tenant problem*. 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. Where energy bills are the responsibility of the tenant, we expect landlords to under-invest in energy efficiency measures, since any returns to such investment come in the form of reduced utility bills, which accrue to the tenant. Within the landlord-tenant problem literature, this is typically referred to as the *efficiency problem*.

The purpose of this paper is to test for the presence of the efficiency problem. To do this, we compare the energy efficiency of observably similar rental and non-rental properties using matching methods and a comprehensive database on the population of energy performance certificates issued in the Republic of Ireland. The Republic of Ireland is a region which legally requires landlords to display an energy rating when

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advertising a rental property,[1] and where the majority of rental contracts stipulate that tenants are responsible for energy bills.[2] We build on the existing literature by testing for the influence of the landlord-tenant problem on the efficiency of the property as a whole, rather than on specific energy using appliances. In addition, we exploit a unique trait in residential building design to attempt to identify observationally identical rental and non-rental properties and approximate a natural experiment. The findings illustrate evidence of the landlord-tenant problem even in the case of mandatory energy performance certificate disclosure, however the effect appears to be relatively small.

We also attempt to further extend the literature on the efficiency problem 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 to change also. For example, when location is a scarce property characteristic,[3] this may have an influence on the premium for energy efficiency, and hence landlords' decision to invest in energy efficiency improvements. 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). Significant variation in the landlord-tenant problem based on location makes the asymmetric information channel as the sole explanation/solution to the problem appear less likely.

The structure of this paper is as follows. Section 2 provides some background and related literature on the landlord-tenant problem. Section 3 outlines the data and methodology used in our empirical analysis. In Section 4, we present our results for the sample as a whole. We then explore the influence of location scarcity in Section 4.1. To test the robustness of our results we focus on semi-detached properties in Section 4.2. Finally, in Section 5 we draw some conclusions from the evidence presented in the analysis and provide some policy recommendations and suggestions for future research.

2. Background and related literature

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 et al., 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 directly and may or may not own the dwelling (typically referred to as the *usage problem*) and
2. When the occupant pays for energy use and does not own the dwelling, (referred to as the *efficiency problem*).[4]

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 et al., 2016). Renters may also be more likely to belong to lower income groups, and lower income groups tend to be less likely to adopt energy efficiency improvements in general (Schleich, 2019).

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 than 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 a 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.[5]

Much of the literature which focuses on the efficiency problem has focused on the asymmetric information channel as an explanation (Gillingham et al., 2012; Melvin, 2018; Myers, 2020). Consequently, governments have introduced energy performance labels on residential properties in order to correct for asymmetric information between landlords and prospective tenants (and also sellers and buyers). 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).[6] 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 capitalized in the purchase/rental price and may encourage investments in efficiency. However, mandatory labelling alone may be insufficient in correcting the efficiency problem and encouraging investment in improving energy efficiency, and this is the focus of this study.

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] Using US data Davis (2010) finds

[1] 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 (European Union (Energy Peformance of Buildings) Regulation 2012; SEAI 2013a).

[2] Data on the population of rental properties in the Republic of Ireland suggest that roughly 75% of renters are responsible for at least one type of energy-related utility bill (Petrov and Ryan, 2021).

[3] A vast literature, dating back to Ricardo (1817) and George (1884) exists which has established a link between location and rental premium.

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

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

[6] 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.

[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.

that across four end-uses (refrigerators, clothes washers, dishwashers and lighting), renters were 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 et al. (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 et al. (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 16% more likely to change their heating setting at night, while owner-occupied dwellings were 20% more likely to have attic insulation. This is similar to more recent findings by Nie et al. (2020) who find that homeowners are much more likely to have installed efficiency measures such as insulation, and are also more likely to adopt energy saving behaviours such as turning the heating down at night. In a similar vein, 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 prices.

If the principal agent problem was caused solely by asymmetric information, then effective energy performance labels should allow landlords to capitalize 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 (Brounen and Kok, 2011; Hyland et al., 2013; Stanley et al., 2016; Zheng et al., 2012). 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 et al. (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 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 et al. (2012), the aim of this paper is to test for differences in energy efficiency between 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 measure the energy performance of the dwelling as a whole. This data set 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 et al., 2016).

Secondly, if energy performance certificates are successful at correcting the information asymmetry problem, then information measures alone may not be sufficient in encouraging 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 facilitated by variation in the scarcity of other property characteristics, such as location. To our knowledge, no other study has explored the interaction of location scarcity and energy efficiency in a residential rental setting.

[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 °F at the temperature that water has its greatest density (approximately 39 °F). 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.

[10] Rental properties are likely to be let more frequently than residential properties are sold. As per RTB (2018b) 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).

[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.

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 (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). 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 capitalized in the purchase/rental price and encourage investments in efficiency.

The 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, 2011). It has been compulsory for landlords to present a BER if requested by a prospective tenant at the point of lease since 2009.[12] However, the lack of solicitor involvement when compared to a property sale agreement, and lack of awareness among prospective tenants has made enforcement challenging. The legislation was updated in 2013 and since then it has been compulsory to present a BER certificate for the sale or lease 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. It is important to note that this is a selected sample - i.e. we only have information about the efficiency of properties which have undergone a BER assessment.[13] 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. Fig. 1 gives the monthly average BER value of newly issued certificates for rental and non-rental properties over our period of study.

From Fig. 1 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,[14] with newly built dwellings being more likely to be owner occupied.[15] Another possible explanation for the improvement in efficiency of non-rental buildings over time maybe increased adoption of energy efficiency measures such as insulation or newer heating systems. 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, since the categorical version of the BER is created based on the underlying continuous rating.[16] In total, we have 585,578 observations in our data, 64,985 of which are identified as 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.[17] 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 based on county and city code divisions, and this is presented in online Appendix Table A2.

In terms of the distribution of the BER grades from Fig. 2 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 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 (Building Regulations (Part L Amendment) 2011; SVP 2015), and fewer new builds are for rental purposes. 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.

CEM can be used as a pre-processing technique for regression in order to reduce model dependence, bias and improve efficiency (Iacus et al., 2012). Using matching in this manner allows us to reduce the functional form dependence of the subsequent parametric regression

[12] Introduced as part of the European Communities (Energy Performance of Buildings) Amendment (2008).

[13] This means that the observed efficiency values for rental properties may not be representative for the population of rental properties, if poor-performing properties are less likely to undergo an assessment.

[14] These regulation changes are discussed further in the Results section of this paper, and also in App. Table A6.

[15] Of the 50,490 properties built on or after 2012 in our sample, only 1360 are rental properties (or roughly 2.7%).

[16] We use the continuous form of the BER in kWh/m2/yr since it contains information on within grade variation in efficiency. Please refer to Appendix Figure A1 for further detailed information on the BER.

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

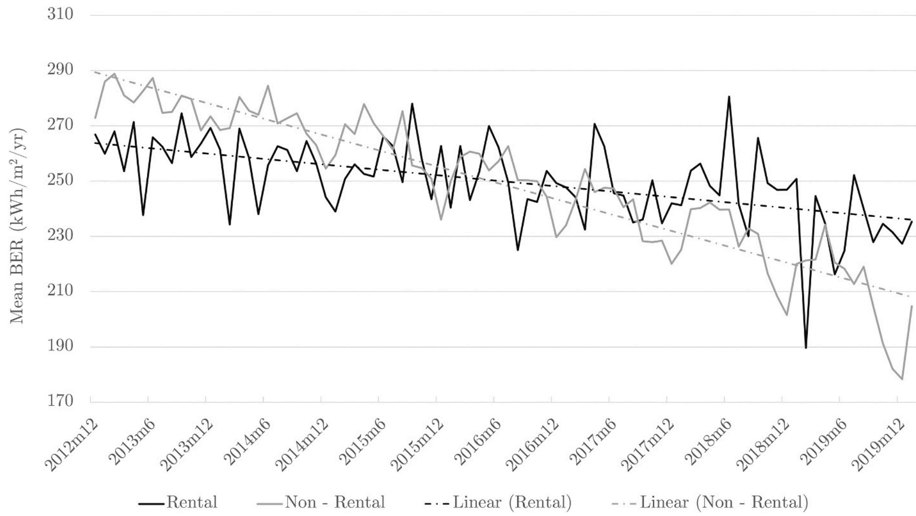

Fig. 1. Average Issued BER per Month – Rental vs Non-rental Properties.

Table 1
Summary statistics - full sample.

	Full Sample		Rental		Non-Rental		Non-Rental - Rental	
	Mean	St. Dev	Mean	St. Dev.	Mean	St. Dev.	Difference	t
	(1)	(2)	(3)	(4)	(5)	(6)	(5)–(3)	(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). House (general) and Apartment (general) capture property types which are not included in any of the other house and apartment types, and hence represent a very small proportion of the sample.

(Ho et al., 2007). In addition, domain specific knowledge can be built into the model through the choice of coarsening of continuous variables.

In general, 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, 2008), the ATT is defined as follows:

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

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.

$$D_i = \begin{cases} 1 & \text{if treated} \\ 0 & \text{if otherwise} \end{cases} \quad (2)$$

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:

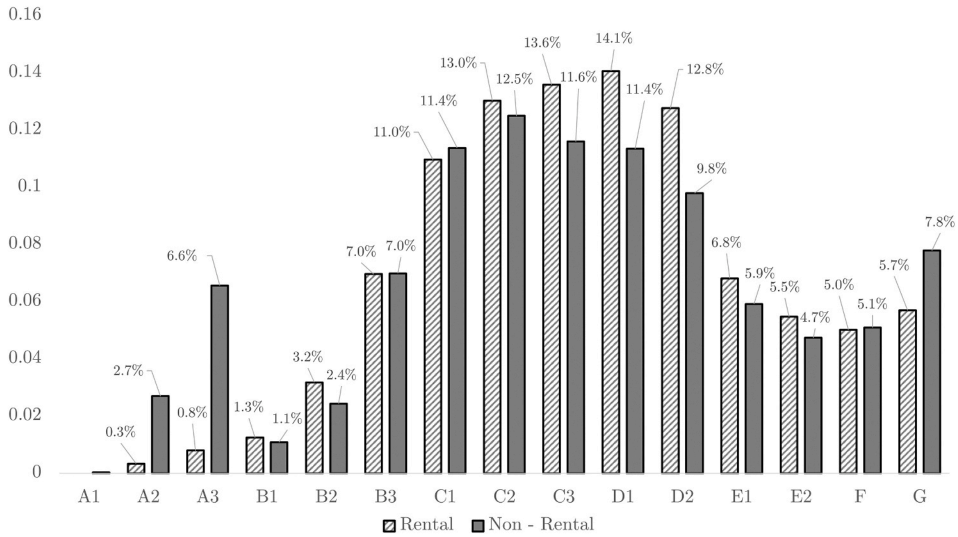

Fig. 2. Distribution of BER Grades – Rental vs Non-Rental Properties.

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

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 assumption asserts that, conditional on a set of observed covariates (X_i), treatment exposure is independent of potential outcomes (Abadie and Imbens, 2016).

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

This assumption is sometimes referred to in the literature as unconfoundedness, selection on observables and exogeneity (Imbens and Wooldridge, 2009). In our case it implies that given the observable characteristics we match on, treatment (D_i), or whether or not a property is rental, should be as good as randomly assigned, and that there are no omitted variables which can influence selection into treatment.[18] This is a strong assumption when the unit of study is an individual, since unobserved variables such as ability/skills/interest are likely to be important for selection into treatments such as training programmes. In our application however, the unit of observation is a dwelling, and the probability of treatment is the probability that a given property is, or becomes, rental. While we control for a range of physical characteristics in X_i which may influence the probability of selection into treatment, we also provide a robustness test in Section 4.2 by attempting to identify treated and non-treated properties in building estates which were identical at the time of their construction in order to approximate a natural experiment. However, we first begin by estimating the overall effect of renting on efficiency for the entire sample of rental properties at our disposal.

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 area 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

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	4241	6340	9384
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

[18] 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.

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 built under the same building regulations must legally adhere to the same standards in terms of efficiency.[19] 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).[20] 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 et al. (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 10 m^2 and 5 m^2 intervals respectively. From consultation with BER assessors it was determined that the 5 m^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 300 m^2 respectively.

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

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 et al. (2016) and Stuart (2010). It presents the standardised percentage difference in means between treated and control groups.[21] 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.

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 (Iacus et al., 2012):

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

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 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.[22] 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 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. The interpretation of the coefficient on a dummy variable in a semilogarithmic equation follows Kennedy (1981). All subsequent interpretations of coefficients on dummy variables in this paper are treated in the same manner.[23]

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 Fig. 1, 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.

[19] 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.

[20] For more information on these bands please refer to Appendix Table A5.

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

[22] 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).

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

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: values in columns labelled "t" represent t-statistics from t-tests for equality of means which assume unequal population variances. %SB is calculated as per Asensio and Delmas (2017).

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 make the matching more precise, the effect of renting on efficiency decreases. An explanation for the difference in the magnitude of the effect between OLSand the models using CEM weights is that under the OLS specification 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 specification.

While the effect of renting on efficiency appears to be relatively small (approx. 1%), given that efficiency is measured in $kWh/m^2/yr$ and given the size of the rental market the implications for total emissions are significant. A simple back of the envelope calculation suggests that this difference translates to roughly 21.5ktCO_2 excess emissions annually across all rental properties.[24] In the context of total CO_2 emissions from the residential sector, this number is quite small and represent just 0.4% of total annual residential sector CO_2 emissions in Ireland.[25] However, this effect may also be understated if there is selection into treatment, whereby landlords with worse performing properties are less likely to undertake a BER assessment to begin with.

The efficiency problem identified here may also have significant economic implications for future low-carbon technology adoption. If landlords are less likely to invest in energy saving measures this may undermine the effectiveness of future policies which aim to increase the uptake of energy efficiency-improving and low-carbon technologies. In addition, given that renters are likely to belong to lower income groups, such policies may have undesirable distributional or regressive impacts.

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 subsample, 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.

One potential explanation for this finding is that there may be an

[24] Please refer to Appendix Table A8 for further details on this calculation.

[25] Total residential sector CO_2 emissions amounted to 5742.5 ktCO_2 in 2017 (EPA, 2019).

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	*(reference)*	*(reference)*	*(reference)*	*(reference)*
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	*(reference)*	*(reference)*	*(reference)*	*(reference)*
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

Dependent variable: natural log of BER in $kWh/m^2/yr$. Standard errors in parentheses. Further details on location FE in Appendix Table A2.
***Statistically significant at $p < 0.01$.
**Statistically significant at $p < 0.05$.
*Statistically significant at $p < 0.1$.

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

	OLS	CEM1	CEM2	CEM3
Rental *(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
Rental *(cities sub-sample)*	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
Rental *(rural sub-sample)*	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

Dependent variable: natural log of BER in $kWh/m^2/yr$. Coefficient on main variable of interest reported for each regression. Standard errors in parentheses.
***Statistically significant at $p < 0.01$.
**Statistically significant at $p < 0.05$.

interplay between the principal-agent problem and rental property supply. 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%). To put these increases into context, the average rental price in the Dublin region for Q4 of 2020 was €1,951, compared to a national average of €1414 (DAFT, 2020).

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).[26] If location is a scarce characteristic, this will be reflected in its implicit price. Landlords in supply constrained locations may therefore be able to extract higher prices from less efficient properties than would otherwise be possible in less contested markets, thereby lessening the incentive 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 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).

RPZs 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, 2018a).[27] Within an area designated as a Rent Pressure Zone, rents are not permitted to rise more than 4% annually based on a prescribed formula.[28] In total, there are currently 53 Local Electoral Areas which are designated as Rent Pressure Zones. With respect to our data, 445,421 BERs were issued for properties that are located in a county which contains a designated RPZ.[29] 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.

When we only look at properties which are located in a RPZ, we find a significant and positive difference in efficiency between rental and non rental dwellings across all of our specifications. Under the OLS specification, 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

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

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

[28] 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).

[29] 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 RPZs typically reflect the most densely populated areas.

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

	OLS	CEM1	CEM2	CEM3
Rental *(RPZ sub-sample)*	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
Rental *(Non RPZ sub-sample)*	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

Dependent variable: natural log of BER in $kWh/m^2/yr$. Coefficient on main variable of interest reported for each regression. Standard errors in parentheses. ***Statistically significant at $p < 0.01$.

difference falls 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 OLS 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.[30] 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 RPZs 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).

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.[31] 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.[32]

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 (Fig. 3). Early architectural guides on the construction of such properties paid particular attention on making semi-detached properties appear identical, so as to create the illusion 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 (Fig. 4). 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. While there may be a plethora of reasons why a particular property within an estate becomes rental (e.g. change of ownership, inheritance etc.) these are unrelated to observable building characteristics, which are identical at the time of construction. If treatment assignment is random at the unit of observation, which in our case is a dwelling, then this approximates a natural experiment. We assume that subsequent changes to building performance are predicated on whether the occupants are owners or tenants.

Although due to the anonymised nature of our data we do not have

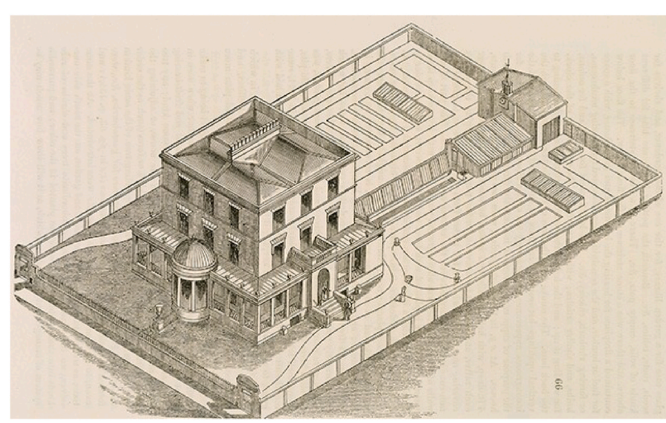

Fig. 3. Early example of a semi detached House
Source: Loudon (1838).

[30] 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.

[31] 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.

[32] 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).

Fig. 4. Example of a more modern semi detached Property
Source: Author.

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 online 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 A3.

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 Table 2. These, along with summary statistics on each of our matching procedures are presented in Table 8.

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 3.2. 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 Table 2, as we make the coarsening choice stricter, we lose more control units in comparison to

Table 7
Summary statistics - semi detached properties.

	Full Sample		Rental		Non-Rental		Non-Rental - Rental	
	Mean	St. Dev	Mean	St. Dev.	Mean	St. Dev.	Difference	t
	(1)	(2)	(3)	(4)	(5)	(6)	(5)–(3)	(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			

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	9628	4890
% 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	1258	3608	8346
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	3426	3855	3336

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	(*reference*)	(*reference*)	(*reference*)	(*reference*)
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

Dependent variable: natural log of BER in $kWh/m^2/yr$. Standard errors in parentheses. Further details on location FE in Appendix Table A2.
***Statistically significant at $p < 0.01$.
**Statistically significant at $p < 0.05$.
*Statistically significant at $p < 0.1$.

treated units. Under our strictest matching criteria we are left with 21,432 observations, 4890 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 specification. 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 manner as Section 4.1. The coefficient on the treatment variable (rental) is presented in Table 10 in each case.

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 4.1. 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 4.1 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 online 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. Conclusion and policy implications

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

Table 10
Parametric regression results: Semi-detached properties only.

	OLS	CEM1	CEM2	CEM3
Rental (*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
Rental (*urban sub-sample*)	0.154***	0.074***	0.082***	0.072***
	(0.006)	(0.005)	(0.005)	(0.008)
N	47,804	27,156	16,215	4811
Rental (*rural sub-sample*)	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
Rental (*RPZ sub-sample*)	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
Rental (*Non RPZ sub-sample*)	0.067***	0.021***	0.037***	0.033***
	(0.005)	(0.005)	(0.005)	(0.007)
N	35,033	23,773	15,100	4499

Dependent variable: natural log of BER in $kWh/m^2/yr$. Coefficient on main variable of interest reported for each regression. Standard errors in parentheses.
***Statistically significant at $p < 0.01$.
**Statistically significant at $p < 0.05$.

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 is 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 RPZs. 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 adoption 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 such as those described in Bird and Hernández (2012) or regulation may be necessary. This conclusion appears to be supported by the findings of Ástmarsson et al. (2013) who find that although there are many policy options available to tackle the landlord-tenant dilemma, no single option can correct for the problem in its entirety and ultimately a package solution is likely needed.

CRediT authorship contribution statement

Ivan Petrov: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Lisa Ryan:** Conceptualization, Supervision, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112458.

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