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Investments that make our homes greener: The role of regulation[☆]

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A B S T R A C T

Operation of residential buildings is responsible for roughly 22% of global energy consumption and 17% of CO_2 emissions. We study the investments triggered by a regulatory intervention requiring rented properties to satisfy minimum energy efficiency standards. The analysis shows significant investments in low capital expenditure retrofits. Using an instrumented difference-in-differences methodology, we show that the investments do not have an economically significant impact on rents, so that landlords are not compensated for them.

1. Introduction

Operation of residential buildings (our homes) account for roughly 22% of global energy consumption and 17% of CO_2 emissions (Programme, 2020; International Energy Agency, 2023). Investments that improve the energy efficiency and environmental performance of homes can therefore make a very significant contribution to addressing climate change.[1] Understanding the determinants of these investments — and, in particular, their financial returns — is thus essential. Moreover, the belief that private investment levels are suboptimal has prompted governments worldwide to introduce regulations aimed at closing this gap (Hausman and Joskow, 1982; Allcott and Greenstone, 2024), while businesses and investors increasingly view regulation as a leading source of climate risk (Stroebel and Wurgler, 2021).

In this paper, we analyze one such regulation, the Minimum Energy Efficiency Standard (MEES) Regulations, approved by the United Kingdom Parliament in March 2015, which require privately rented

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[1] Our main focus is on improvements to the stock of existing properties rather than on new construction. Including building construction and non-residential operations raises real estate's shares to 35% of global energy consumption and 38% of CO_2 emissions.

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dwellings to meet minimum energy-efficiency thresholds.[2] We analyze the magnitude and nature of the investments triggered by the regulations, including required capital expenditures, their financial returns, and rent effects. In doing so, we contribute to the growing climate-finance literature (Hong et al., 2020; Giglio et al., 2021a) and shed light on the regulatory risks faced by real estate investors, an asset class particularly exposed to climate risk (Bernstein et al., 2019; Baldauf et al., 2020).

Our primary analysis uses the near-universe of Energy Performance Certificates (EPCs) for residential properties in England and Wales. Since October 2008, properties that are sold or rented out have been legally required to hold a valid certificate,[3] which addresses the important issue of measuring energy efficiency (see, for example, Bardhan et al., 2014). The dataset covers roughly 14 million unique dwellings, providing a large and comprehensive sample of properties. Further, EPCs recommend improvements to a property's energy efficiency rating, the indicative capital expenditures needed to implement them, and their projected monetary savings, which we use to analyze financial returns.

We evaluate the effects of the regulations by comparing retrofit investments in the private rental sector before and after approval to that in the owner-occupied sector. The analysis shows that the regulations triggered significant investments in the rental sector along both the extensive and intensive margins. On the intensive margin, we use a large sample of investments undertaken by investors (landlords). The characterization of the retrofits shows that they tend to be similar to those carried out by owner-occupiers and concentrated on investments that require lower capital expenditures (capex), such as low-energy lighting and main heating controls. We obtain estimates of the lifespan and energy savings of the investments and show that these low-capex investments also deliver the highest internal rates of return (IRR). Thus, our first main contribution is to provide large-sample evidence on the types and financial returns of retrofits undertaken by both homeowners and investors—evidence that informs barriers and policy solutions to climate change (see, Lanteri and Rampini, 2025, Känzig and Williamson, 2024, among others).

In England and Wales, utilities are typically not included in rents but, rather, are paid directly by tenants. Therefore, property investors do not benefit directly from the energy-bill savings generated by retrofits and instead compare the cost of investments with the additional rent they expect to receive. To assess the impact of the regulations and retrofits on the income received by these investors, we merge the EPC data with property-level rental listings from Rightmove, a dataset previously used by Giglio et al. (2015). We estimate a difference-in-differences (DiD) model comparing rents for properties below versus above the minimum energy-efficiency standard before and after the approval of the regulations, controlling for property and time fixed effects. We find a statistically significant increase in rents of 0.9%—approximately £70.2 annually. However this estimate, sufficient to compensate investors only for the low-capex retrofits (e.g., low-energy lighting and mainheat controls), does not account for selection.

To separate regulation-induced rent changes from selection by landlords who choose to invest in their properties, we use an instrumented DiD (IVDiD) design (De Chaisemartin and d'Haultfoeuille, 2018; Hudson et al., 2017). The key idea is to compare properties where the regulation binds to those for which it does not, based on their pre-regulation status. Specifically, we use the pre-regulation status as an instrument for the energy performance of the property, allowing us to estimate the local average treatment effect for properties whose status was affected by the regulation (i.e., compliers). In the first stage, we confirm that pre-regulation status strongly predicts post-regulation energy-efficiency scores: properties required to comply record a 6.6-point increase—about a 25% increase relative to the median pre-regulation score among below-threshold homes. In the second stage, we find no economically meaningful effect on rents, implying that landlords are not compensated even for the low-capex upgrades undertaken to meet the regulatory requirement. These conclusions hold even when comparing rent increases with the energy cost savings from such investments.

Accordingly, the DiD estimate of a 0.9% rent increase should be interpreted as an upper bound, whereas the IVDiD estimates that account for selection show no rent effect. We conclude that landlords cannot pass on reductions in energy costs arising from energy efficiency investments to tenants via higher rents, explaining why, absent regulation, they choose not to invest, and why, when mandated, they focus on low-capex investments. This is the second main contribution of our paper.

The third main contribution is to examine the regulations' effects on carbon emissions. Although emissions reduction was not the policy's stated objective, assessing this dimension is important given housing's sizable carbon footprint and the centrality of emissions cuts to climate targets. Our analysis shows that the energy-efficiency gains in the rental sector relative to the owner-occupied sector were not matched by commensurate improvements in carbon footprint. Two mechanisms explain this divergence. First, energy efficiency is a cost-based metric — a function of energy use and unit prices of fuel —, whereas a home's carbon footprint depends on energy use and the carbon intensity of the fuels consumed. Therefore, regulations targeting energy cost-based measures favor investments that reduce the consumption of expensive energy but not necessarily the most polluting one.

During our sample, electricity became relatively more expensive than gas; as a result, switching from electricity to gas delivered larger energy efficiency gains, and we indeed observe many more properties moving from electricity to gas than the reverse. This fuel switching occurred precisely as electricity generation was rapidly decarbonizing — owing to the phase-out of coal — a trend that Arkolakis and Walsh (2023) predicts will continue. A second source of divergence is measurement: the carbon factors used in measuring the environmental performance are not frequently updated.

A key takeaway from our analysis is that combining the prices and quantities of different energy sources into a single cost-based metric, while making it easier to compare heterogeneous properties along the cost dimension, can create incentives misaligned with decarbonization goals, favoring cheaper rather than cleaner fuels. In doing so, our analysis sheds light on the nature of regulatory risks that property investors face.

Related literature. Our paper is related to a recent literature that studies the impact of climate risk on the value of real estate assets (see Ortega and Taspinar, 2018; Murfin and Spiegel, 2020; Giglio et al., 2021b; Keys and Mulder, 2020; Bakkensen and Barrage, 2022, in addition to those previously cited) and the mortgages used to finance them (Issler et al., 2024; Gete et al., 2024; Bakkensen et al., 2025).[4] Different from these studies, we analyze the impact of regulatory risks that real estate investors face.

A second contribution of our study lies in quantifying the rental price (cash-flow) effects of the investments. Our findings show economically small and insignificant effects on rents, suggesting that investors are not compensated for the capital expenditures incurred to comply

[2] By focusing on the private rental sector, the regulations presume more pervasive investment inefficiencies in this sector, leading to suboptimal levels of private investment (a private energy-efficiency gap, as defined by Gerarden et al. (2017)). See also Allcott and Greenstone (2012).

[3] There are some exceptions, such as listed properties, but they represent a very small proportion of the housing stock.

[4] See also, Berkouwer and Dean (2022), Adelino and Robinson (2023), Bellon et al. (2024) on the role of credit constraints affecting household investment decisions.

with the regulations. In perfect markets, property and rental prices adjust to fully reflect the value of the financial savings associated with retrofits. However, prior work argues for the role of frictions such as imperfect information and financial constraints (Gerarden et al., 2017; Gillingham and Palmer, 2013; Berkouwer and Dean, 2022). Imperfectly informed or inattentive tenants may not be willing to pay more for energy-efficient homes (Myers, 2019). Moreover, their expected shorter tenure may make it uneconomical to pay for the costs of acquiring property-specific information (or to incur attention costs), explaining the economically small estimated effects on property cash-flows.

Our paper is related to the literature on residential energy efficiency that has largely focused on specific investments (Dubin and McFadden, 1984; Hausman, 1979; Dubin et al., 1986), with more recent work on conversion of energy inefficient office buildings into energy efficient homes (see, Gupta et al., 2023).[5] We contribute to this literature by showing evidence on a wide range of retrofits, in a large sample of residential properties, and relating them to both the capital investments that they require and the internal rates of return that can be achieved.

Our work is also related to papers that study residential energy efficiency in England. For instance, Hilber et al. (2019) study how historic preservation policies affect the ability of property owners to make energy efficiency improvements. Fuerst et al. (2015) studies the relation between home prices and energy efficiency using hedonic price regressions. As the authors acknowledge, the main difficulty is that energy efficiency may be correlated with unobserved property characteristics that also affect its price. We focus our analysis on the regulatory intervention, which we use as instrument in a difference-in-differences empirical design to estimate the cash-flow effects.

The paper is structured as follows. Section 2 describes the data sources, the most relevant institutional details, and presents some background data analysis. Section 3 characterizes the housing stock prior to the regulations' approval, and studies its effects on investment intensity and nature. Section 4 investigates the impact on rents. Section 5 compares energy efficiency and environmental gains. The final section concludes.

2. The certificates data and background analysis

Our main data source are the EPCs. But for parts of the analysis we also merge them with rental listing prices from Rightmove and residential property transactions from the Land Registry.

2.1. EPCs

The Energy Performance of Buildings Directive (2002/91/EC) is an EU Directive which aimed to promote the improvement of the energy performance of buildings. An essential component of the legislation is the measurement of the efficiency of homes through EPCs. Measurement is one of the crucial bottlenecks discussed by Bardhan et al. (2014) for energy efficiency retrofits. In England and Wales, EPCs have been required by law since the 1st of October 2008 to sell or rent out a home.[6] The certificates are valid for ten years but may be updated before expiration.

EPCs for existing homes are generated using a Reduced data Standard Assessment Procedure (RdSAP). An accredited assessor visits the property to gather information on its characteristics (property type, size, insulation, heating system, etc.) and its energy sources. The information is collected in a datasheet following certain conventions.[7] The assessor must collect documentary evidence that include photographs and invoices for works carried out. The information is then entered into government-approved software that generates the EPC. The cost of a certificate ranges from £60–120. The EPCs are valid for ten years but can be updated anytime before expiration.

Table 1
Energy efficiency rating.
The table shows the SAP points and corresponding letter rating classification ordered from most to least efficient.

Efficiency	SAP points	Rating
Most efficient	92 plus	A
	81–91	B
	69–80	C
	55–68	D
	39–54	E
	21–38	F
Least efficient	1–20	G

The certificate includes a star rating that ranges from one (very poor) to five (very good) of the energy performance of the elements of the home, namely walls, roof, floor, windows, main heating, main heating controls, secondary heating, hot water, and lighting.[8] In addition, the data includes a description of the property element (e.g., type of windows, insulation thickness) that we use to characterize the retrofits carried out by households.

The EPCs provide a measure of the overall energy efficiency rating of the property on a numerical scale of 1 to 100 (SAP points) that reflects its energy running costs. Total energy cost is equal to the sum of the estimated energy used for each of the purposes (space heating, water heating, ventilation, and lighting minus energy saving/generation technologies) multiplied by the prevailing prices of the type(s) of fuel used in the property.[9] It is deflated by a fuel price index equal to the weighted average price of heating fuels so that the rating is not affected by the general rate of fuel price inflation, and the ratings of homes assessed when energy prices were different are comparable. Note that because an individual home's rating depends on its fuel mix, it is affected by relative changes in the prices of specific heating fuels (e.g., electricity or gas) used in the property. Therefore, relative price changes may affect incentives to undertake investments that favor a particular fuel type. Appendix A.1 provides more details.

Table 1 shows how the SAP points ratings are grouped in bands and converted into a letter rating, from A (the most efficient, 92 plus points) to G (the least efficient, 1–20 points). In the analysis that follows, we exploit the regulatory threshold that targets properties in the private rental sector, as discussed below.

The EPCs also measure the environmental performance of the home using an environmental impact rating (EI) on a scale of 1 to 100. It is based on the carbon emissions of the home, which in turn depend on the estimated energy usage and the carbon footprint of the specific type(s) of fuel(s) used in the property. (Appendix A.2 provides details. The appendix also includes an example of a certificate.)

The EPCs data for England and Wales are publicly available from the Ministry of Housing, Communities, and Local Government (MHCLG) Open Data Communities website. The data include information that is not in the actual certificate but that is relevant for our analysis. For instance, on tenure type (owner-occupied, private rented,

[5] In addition, there is a literature that studies the energy performance of commercial buildings (e.g., Eichholtz et al., 2010, Jaffee et al., 2019) for which data has traditionally been more readily available.

[6] There are a few exceptions, such as listed homes and residential properties that will be used for less than four months of the year.

[7] The information collected is fairly thorough. An example of an assessor sheet is available here.

[8] A star rating is not produced for secondary heating and floor, nor when it is not relevant (e.g., for the roof when there is another dwelling above).

[9] The estimated energy consumption uses standardized assumptions for occupancy and location and is scaled by floor area. The normalization by location (climate) and floor area was done so that higher standards would not be required for properties in colder areas and smaller properties. While it is preferable to have actual energy consumption, our data has the advantage of allowing us to measure the retrofits carried out for a large sample of properties and quantify the effects on rental prices, a novel contribution of our paper.

social rented), property age, the reason for the request of the certificate (e.g., marketed sale, private rented, etc.), and several additional property characteristics (e.g., energy sources used in the home).

2.2. Sample construction and summary statistics

We carry out some data cleaning. First, we remove entries corresponding to certificates issued prior to 22 September 2008, the starting date of RdSAP 2005 version 9.82 conventions, and use data until September 2020. Given our focus on retrofits, we remove observations for newly built properties from the sample but retain any subsequent observations for those properties.[10] In addition, we remove duplicate observations and in the case of multiple entries with the same inspection date but a different lodgement date/time in the system we keep only the last entry, which is the valid certificate. (Appendix B.1 provides further details.)

The full sample of EPC data contains 17.7 million certificates for 14 million unique residential properties located in England and Wales. This compares with an estimated total number of dwellings in 2010 of 24.2 million.[11] Existing homes that have not been sold or rented out since October 2008 are not required to have an EPC, so that they may not appear in the data. Our primary sample includes multiple-certificate properties, which allow us to examine retrofit investments by owners, while we use the full EPC sample to characterize the energy efficiency of the housing stock in England and Wales.

For most multiple certificate properties, we have exactly two certificates, meaning one observation pair and one observation for changes. However, for properties with three certificates, we have two observation pairs and two observations for changes (and so on for properties with more than three certificates). The sample of multiple certificate properties has 6.8 million entries, corresponding to 3.1 million unique properties. The majority of properties in the multiple certificates sample (85%) have exactly two certificates. Appendix Table A1 reports the number of properties for which we observe a given number of certificates. The multiple certificates sample allows us to characterize energy retrofits for the same property over time. In our sample of properties with two or more certificates the time interval between the two is on average 4.38 years while the median is 3.38 years.

Naturally, the sample of properties for which we observe multiple EPCs is not random, as we observe subsequent certificates being issued following retrofits. Fig. 1 plots the SAP points distributions for single certificate properties and the first certificate of multiple certificate properties. The latter has a much larger mass on the left tail. Therefore, we are more likely to observe a second certificate for initially lower-rated properties.[12] The distributions show bunching. For single certificate properties, it occurs at 39 and 55, the lower bounds of the E and D ratings, respectively. For the first certificate of multiple certificate properties, the bunching is at 38, the upper bound of the F rating. For the latter group, even small investments will bring the properties to the next letter grade rating of E.

The first five columns of Table 2 show the star rating distributions of the different elements of the home, classified from very poor to very good. More precisely, they show the percentage of properties with a given star rating in each sample (single certificate properties in Panel A and first certificate of multiple certificate properties in Panel B). There are significant differences across the elements. For all of them except lighting, the percentage of very good classifications is less than ten percent. For walls, a much larger fraction of the observations are for the very poor and poor classifications.

[10] New builds are assessed using a more complete SAP than that used for old properties

[11] The estimates are available for England and Wales.

[12] Appendix Table A2 shows the distributions of construction age, property type, and built form for the single and multiple certificate samples. The latter includes a larger proportion of older properties and flats.

The last two columns of Table 2 report the mean and standard deviation of the number of stars, with one for very poor and up to five stars for very good. For all the elements, single certificate properties have a higher mean and lower dispersion than the first certificate of multiple certificate properties. The analysis of the subsequent certificate of multiple certificate properties allows us to study the elements for which we observe improvements and to characterize them.

In Appendix C, we construct an empirical regression model for energy efficiency rating as a function of property type and the star classification of its elements. Using the model, we show that changes in the characteristics of properties (such as improvements) are much more important than changes in the assessment procedure. Importantly, it allows us to translate retrofits into energy efficiency rating point increases and measure the extent to which different investments help meet the regulatory requirements (in Section 4.4 we give more details on how we use these estimates).

2.3. The importance of the initial level for the investments

An important determinant of the decision to carry out a retrofit is the initial level of energy efficiency. In order to show this, we take the sample of multiple certificate properties and divide it into terciles based on their initial efficiency. More precisely, we calculate the SAP points cut-offs corresponding to the bottom and top one-third of the distribution of first certificates of multiple certificate properties shown in Fig. 1. Their values are 54 and 66, respectively. We then assign each observation pair to one of three groups based on these cut-offs and the starting value for the efficiency rating of the observation pair.

Panel A.1 of Table 3 reports the number of observations in each group, the average initial and change in points, and the percentage change. The number of observations refers to observation pairs.[13] There are large increases in energy efficiency for properties in the bottom group: an average increase of 13.5 points or 33.3% of the base value. On the other hand, there is a small decline of 3.4 points or 4.7% for properties in the top group. This is due to depreciation in the features of the home, not counteracted by retrofits. These results show the importance of the initial level of efficiency for the investments.

In Panel A.2 the tercile cut-offs are calculated using the full sample of certificates that includes single certificate properties. They are equal to 58 and 68, respectively. In this case, there are more (fewer) observations in the bottom (top) group, but the conclusions are similar. We use the groups defined in Panel A.1 in the analysis that follows.

2.4. Housing stock prior to the approval of regulations

One of the main arguments for introducing the regulation is that investment inefficiencies in the private rental sector imply that the level of investments carried out by landlords is sub-optimal. Panel B of Table 3 compares owner-occupied and private rental properties using all the certificates issued before April 1, 2015. The first two rows report the mean and median energy efficiency points. Perhaps surprisingly, we find that rental properties are better on average (and at the median) than owner-occupied ones. The regulations target the left tail of the distribution, and there may be more mass in this tail in the rental sector, even if, on average, properties in this sector are better. Fig. 2(a) plots the whole distributions to show that this is not the case.

[13] There is not an equal number of observations in each group since we use the first property certificate to define the cut-offs and then assign all observation pairs to groups using these cut-offs. The larger number of observations for the bottom group means that those properties for which we observe more than two certificates are more likely to have low starting efficiency in the second and subsequent certificates. The results are not sensitive to an alternative definition of cut-offs based on the first certificate of all observation pairs (instead of the first property certificate).

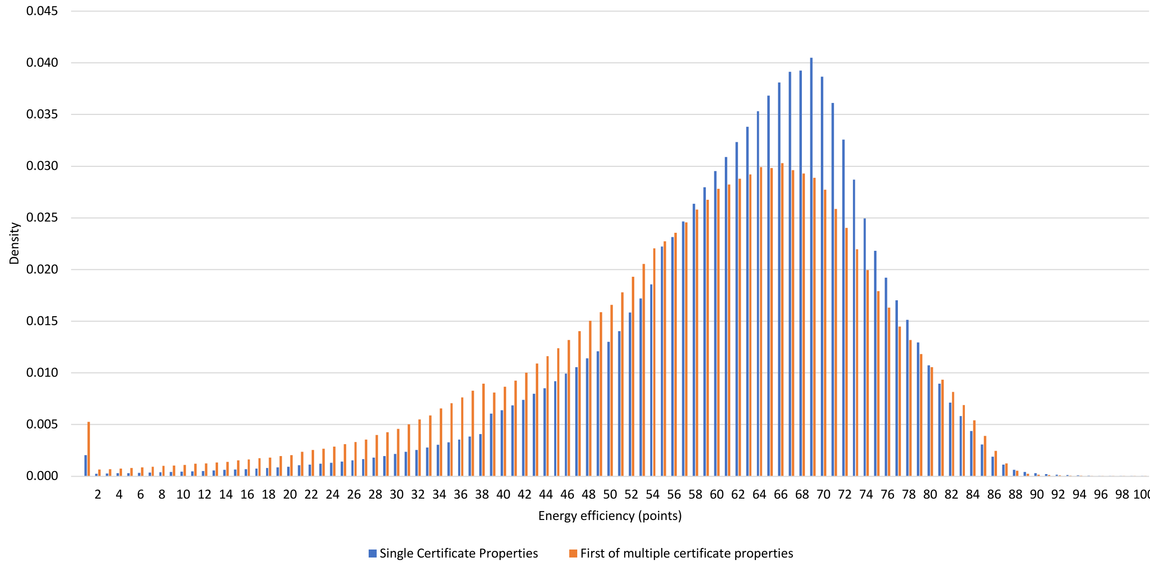


Fig. 1. Distributions of energy efficiency: The figure plots the SAP points distributions for single certificate properties and for the first certificate of multiple certificate properties. The data are from 2008 to 2020.

Table 2
Classification for the different elements of the home: The first five columns show the distributions of the classification of the different property elements. The table reports the percentage of observations with each classification. The last two columns report the mean and standard deviation of star ratings, where very poor is given a value of one, poor a value of two, and so on until a value of five for very good. Panel A reports the distributions for the sample of single certificate properties. In Panel B the data are for the first certificate of multiple certificate properties.

Property element	Percentage of observations with classification (%)					Number of stars	
	Very poor	Poor	Average	Good	Very good	Mean	Stdev
Panel A: Single certificate properties							
Main heat	4.0	3.8	11.7	75.6	4.9	3.74	0.78
Main heat controls	6.5	11.1	34.0	47.6	0.8	3.25	0.90
Windows	7.3	5.2	57.1	30.0	0.4	3.11	0.81
Roof	17.2	6.4	21.8	45.9	8.7	3.22	1.23
Lighting	17.5	12.0	17.7	19.5	33.3	3.39	1.48
Hot water	6.4	7.6	16.6	63.4	6.0	3.55	0.95
Walls	26.8	16.9	7.9	47.1	1.4	2.79	1.31
Panel B: First certificate of multiple certificate properties							
Main heat	6.1	7.9	16.0	61.2	8.8	3.59	0.97
Main heat controls	10.4	23.9	36.7	28.6	0.3	2.84	0.96
Windows	11.8	7.3	54.1	26.7	0.1	2.96	0.90
Roof	21.6	9.0	24.5	38.7	6.3	2.99	1.26
Lighting	23.6	14.5	18.5	18.6	24.8	3.07	1.50
Hot water	10.2	10.7	19.7	50.6	8.9	3.37	1.11
Walls	32.4	21.1	5.0	41.1	0.4	2.56	1.32

The bottom part of Panel B of Table 3 shows that there is an important composition effect. The proportion of flats and maisonettes in the private rental sector (46% of the observations) is much larger than in the owner-occupied sector (15%). Flats have fewer external walls than detached houses, which as the engineering model of Appendix C shows, contributes to better energy efficiency—for instance, the estimated coefficients on flats imply that their rating is roughly five points higher than houses, holding other variables fixed.

Fig. 2(b) compares owner-occupied and rental properties within flats. There is more mass in the left tail in the rental sector. The percentage of flats and maisonettes with a rating below 39 (54, the cut-off for the bottom tercile) is 7.3% (21.6%) in the rental sector compared to 5.9% (19%) in the owner-occupied sector. A similar picture emerges when we compare within detached and semi-detached houses. The percentage with a rating below 39 (54) is 10.8% (37.9%) in the rental sector compared to 9.3% (34.3%) in the owner-occupied one. Therefore, within property type and prior to the approval of the regulations, the rental sector featured a larger proportion of lower-rated properties. These results illustrate the importance of property heterogeneity and of controlling for property type, which we address in our estimations by including property fixed effects.

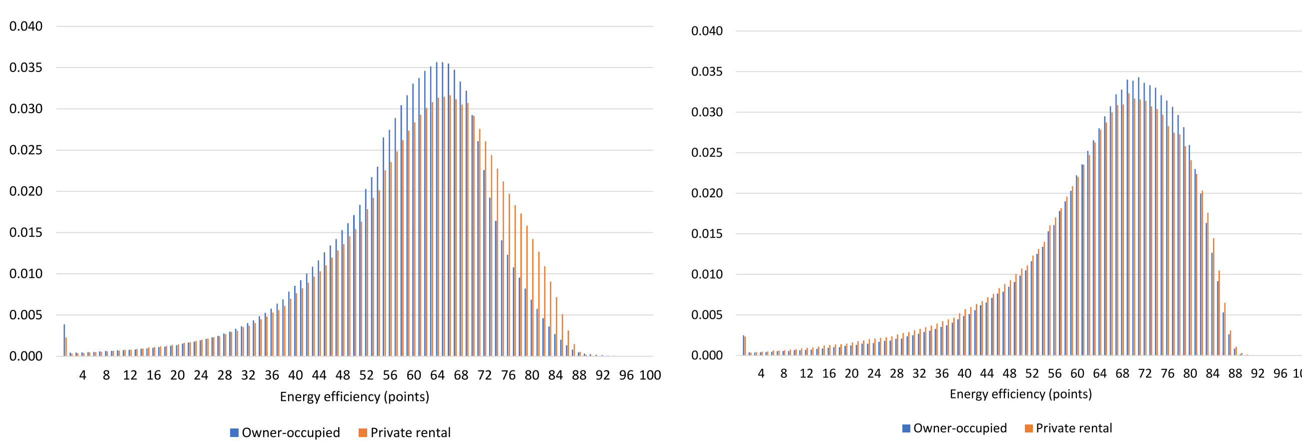
These results complement findings in Davis (2010) and Gillingham et al. (2012), who show that renters are less likely to own energy efficient appliances and are more likely to live in properties with worse wall insulation. It may be due to investment inefficiencies and provides a *potential* rationale for regulatory intervention. We say potential since less efficient rental properties is not conclusive evidence of sub-optimal investments. Tenants may have different preferences and value energy efficiency features differently than owner-occupiers.[14]

[14] Best et al. (2021) finds that renting households use around 9% more electricity than non-renters after controlling for location, socioeconomic, and appliance-quantity.

Table 3
Initial characteristics: In Panel A the sample is that of multiple certificate properties. For those properties with n certificates, there are $n-1$ observation pairs ($n-1$ observations for changes). We divide these pairs of observations into groups depending on the initial level of energy efficiency (i.e. the one in the first observation of the pair). In Panel A.1 the group cut-offs are the terciles of the distribution of energy score of the first certificate of multiple certificate properties. In Panel A.2 the group cut-offs are the terciles of the overall distribution of energy efficiency, including single certificate properties. The table reports the number of observations in each group, the average initial and change in SAP points, and the percentage change in points between the two certificates of each pair. The number of observations are for pairs. In Panel B the sample includes all certificates issued pre April/15 with tenure equal to owner-occupied or private rental. The table reports the mean and median of the overall energy efficiency points, and the percentage of observations of different property types, built form, roof and walls type, by tenure.

Panel A: Heterogeneity as a function of the initial level of efficiency				
Group	Number obs.	Initial points	Δ Points	Perc. change
Panel A.1: Cut-offs defined using first certificate of multiple certificate properties				
1. Lowest efficiency	1,276,916	40.62	13.54	33.3%
2.	1,234,062	60.79	1.35	2.2%
3. Highest efficiency	1,198,818	73.37	−3.42	−4.7%
Panel A.2: Cut-offs defined using the full sample				
1. Lowest efficiency	1,642,758	44.17	11.25	25.5%
2.	1,088,619	63.57	0.14	0.2%
3. Highest efficiency	978,414	74.69	−3.86	−5.2%

Panel B: Initial characteristics by tenure			
Element	Variable	Owner-occupied	Private rental
Energy efficiency	Points (mean)	58.5	60.5
	Points (median)	61	63
Property type	House, Bungalow, Park home (%)	84.9	54.5
	Flat, Maisonette (%)	15.1	45.5
Built form	Detached, Semi-detached (%)	61.9	40.3
	Other built-forms (%)	37.2	56.8
Roof type	Pitched roof (%)	82.8	62.6
	Another dwelling above (%)	8.9	27.2
Walls type	Cavity walls (%)	65.7	49.9
	Solid brick walls (%)	22.7	35.0



(a) All properties (b) Flats and maisonettes

Fig. 2. Energy efficiency distributions by tenure: The sample includes all certificates issued prior to April/1/15 with tenure equal to owner-occupied or private rental. Panel (a) shows the energy efficiency points distributions for all property types. Panel (b) shows the distributions for flats and maisonettes.

3. The effects of the regulations

In this section we study the effects of the regulation on the magnitude and nature of the investments undertaken. In the next section, we focus on their effects on rents.

3.1. The regulatory framework

In perfect markets without frictions and information asymmetries, property and rental prices adjust to reflect the value of the savings associated with energy efficiency retrofits. Investments with a positive net present value are undertaken, whether the property is owner-occupied or rented. In reality, departures from perfect markets, such as information or financing frictions, may affect the investments undertaken.

One reason to expect differential investment could be that imperfect information may be more prevalent in the rental than in the owner-occupied sector. Renters tend to have shorter home tenures and less incentive to pay the costs of acquiring home-specific information. In equilibrium, imperfectly informed renters may not be willing to pay higher rents for more energy efficient homes, and investments that, in the absence of imperfections, would be privately optimal are not undertaken.[15] This gives rise to a landlord-tenant agency problem. A regulation that targets standards in the rental sector may help to address the under-investment.

The MEES regulations set a minimum level of energy efficiency — EPC band E, minimum SAP points equal to 39 — that privately rented residential properties must satisfy.[16] The Parliament initially approved the regulations on 26 March 2015 and amended them on 21 June 2016. The guidance document for landlords was published in October 2017. They finally came into force on 1 April 2018 and initially applied to new tenancies, i.e., tenancies that started after this date.[17]

In England and Wales, in 2010, of the 24.2 million dwellings that formed the housing stock, 66% were owner-occupied, 17% privately rented, and 18% rented from social landlords (local authorities and housing associations). The corresponding 2020 percentages were 64%, 19% and 17%. In comparison, in our full sample of 17.7 million certificates, 56% are owner-occupied, 23% are privately rented, and 19% are rented from social landlords.[18] Therefore, our sample includes a smaller proportion of owner-occupied and a larger proportion of privately rented properties than the overall stock.

3.2. Magnitude of the investments

As a first step, we plot the distributions of SAP points for owner-occupied and private rental properties for certificates issued in selected calendar years. We take the full sample of certificates (including single certificate properties) but restrict the analysis to certificates requested for the purpose of a marketed sale (for owner-occupied) or private rental (for privately rented properties). They constitute 78% and 87% of all the observations for each tenure type, respectively.[19]

Fig. 3 plots the distributions of SAP points for certificates issued in selected calendar years around the regulations—2012 and 2018. The top (bottom) plots are for owner-occupied (private rental). The dashed vertical lines correspond to the letter rating cut-offs. The top figures reveal a disproportionate number of observations, first cluster just above 55 and then, in 2018, also above 39. It could be due to some homeowners investing in their assets just enough to bring them to the next letter rating or to client pressure (implicit or explicit) on appraisers to provide higher ratings. In either case, it shows increased importance of the energy efficiency letter rating for the purpose of selling a property. The bottom figures plot the distributions for private rental properties. Compared to owner-occupied properties, bunching at the 39 thresholds becomes very pronounced in 2018, and significantly more than in the owner-occupied sector.

In order to analyze changes within a property, we then turn to the sample of multiple certificate properties in the bottom tercile. Recall that the rating cut-off for this tercile is equal to 54, which is higher than the minimum threshold specified in the regulation. This allows us to capture any potential investments undertaken by landlords in anticipation of potential future increases in the regulatory thresholds or changes in the calculations of the assessment procedure. But we will also use the 39 threshold in the analysis that follows.

Table 4
Heterogeneity as a function of tenure and time period: The sample is that of multiple certificate properties in the bottom one third of initial level of energy efficiency. The table reports the number of observations for each type of tenure, the proportion of observations of each tenure type, the average initial SAP points, the average percentage change in points between the first and second observations of the pair. The number of observations reported refers to pairs of observations. The sample is restricted to observations with certificates requested for the purpose of a marketed sale (for owner-occupied), private rental, or social rental. Tenure and transaction type are measured using the second observation of the pair. Panel A (Panel B) is for the sample of observations for which the second observation of the pair is pre (post) April/15.

Group	Number obs.	Fraction	Initial points	Δ Points	Change
Panel A: Before April 1, 2015					
Owner-occupied	157,411	0.65	39.9	14.5	36%
Rental private	59,430	0.24	39.2	14.8	38%
Rental social	27,099	0.11	44.1	15.6	35%
Panel B: After April 1, 2015					
Owner-occupied	241,083	0.47	40.1	17.3	43%
Rental private	228,962	0.45	37.4	17.9	48%
Rental social	37,552	0.07	44.2	16.8	38%

Table 4 shows the number of observations, the proportion of observations with a given tenure type, average initial SAP points, and the absolute and percentage change in points between the first and the second observations of the pair. The classification by tenure type is based on the second certificate of each observation pair. We divide the sample into observation pairs for which the second certificate was issued before/after April/15, the date when the parliament initially approved the regulations.

There are significant differences between each of the periods and between owner-occupied and private rental. After April 2015, there is a significant increase in the number of observations for rental private compared to owner-occupied: the proportion of rental private observations increases from 0.24 to 0.45. On average, private rental properties are initially less efficient than owner-occupied ones, with a larger gap after April/15. This shows a change in the composition of private rental properties with second certificates requested after this date. Such a change in composition is not visible for other tenure types. The point increases between the first and second property certificates are larger for certificates issued after April/15 for all sectors. However, the percentage increase is larger for private rental.[20]

3.2.1. Extensive margin

We next investigate changes in the probability and timing of subsequent certificate using regression analysis. A caveat is that we only observe when the inspection took place and the certificate was issued, and not when the actual investments were undertaken. It is possible that some of the investments were made before the regulations were introduced but that the certificate was only requested in response to the regulations. This may be less likely for rental than owner-occupied properties: the cost of a certificate is relatively small and a better rating may improve the desirability of the property from the point of view of

[15] Imperfect information also arises in the case of inattentive households. Due to shorter expected home tenure, renters may be less willing to incur attention costs than owner-occupiers (Lu and Spaenjers, 2025).

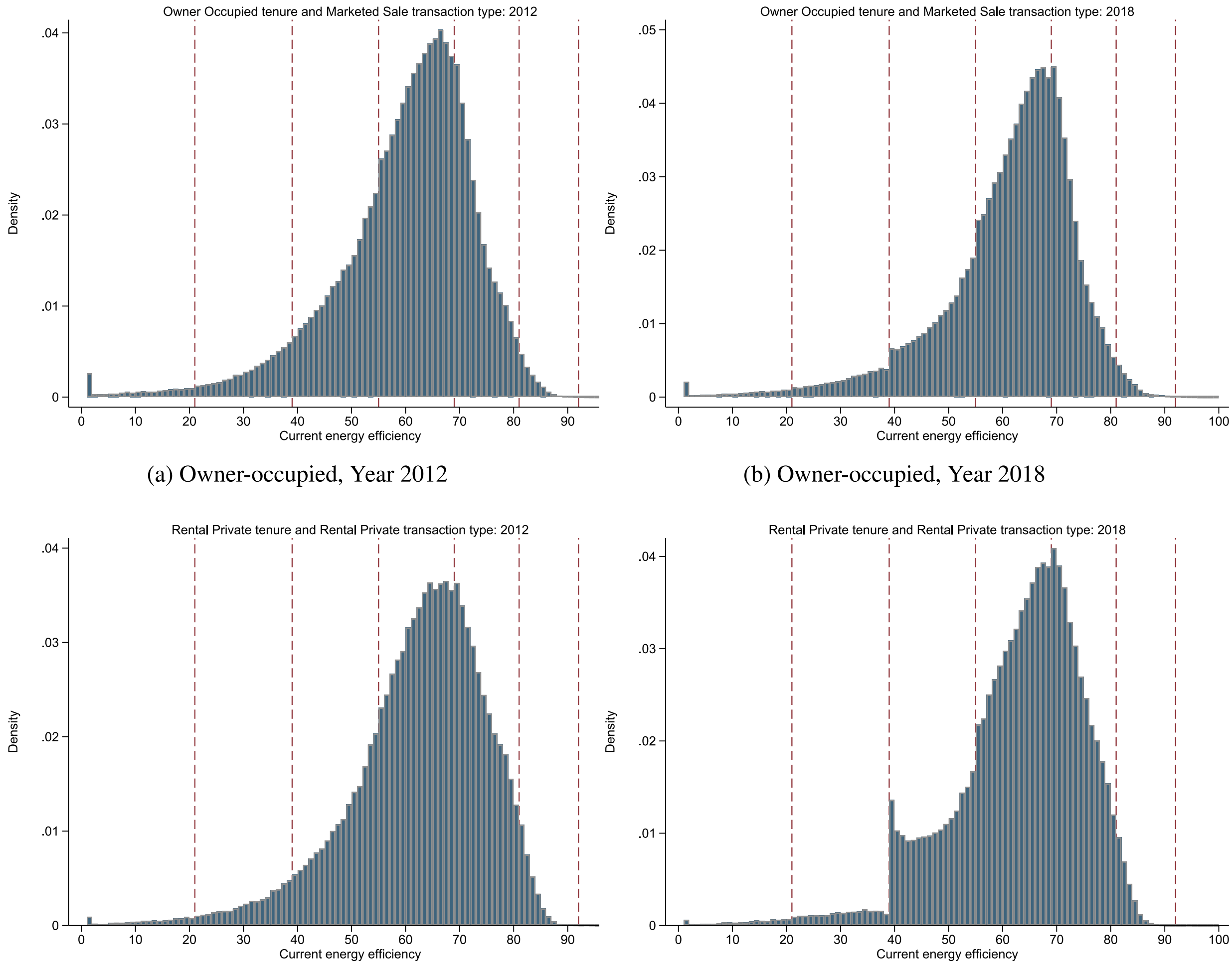
[16] Properties that are exempt from the legal requirement to have a certificate are also exempt from the MEES regulations. The regulations apply to properties let on assured, regulated, and domestic agricultural tenancies. Guidance is available here.

[17] Since 1 April 2020, the requirement was extended to existing tenancies. Landlords may apply for an exemption in case they spend £3500 on improvements, and these are not sufficient to bring the rating to E.

[18] Tenure type is missing for 2% of the sample.

[19] These restrictions exclude mainly certificates issued for the purpose of benefiting from subsidies to undertake energy improvements. The reason for the request for the certificate is registered in a separate variable named transaction type. Appendix Table A3 reports the number of certificates by tenure type and transaction type. Most certificates are requested for the purpose of a sale or a rental. However, a significant number of certificates are requested under the Energy Company Obligation (ECO) program, a scheme that subsidizes energy improvements by low-income homeowners or landlords who let their properties to low-income tenants.

[20] The higher initial levels of energy efficiency in the social rental sector are in part the result of the Home Energy Conservation Act 1995, which required local authorities to develop a plan for energy efficiency improvements in the sector.



(a) Owner-occupied, Year 2012

(b) Owner-occupied, Year 2018

(c) Rental private, Year 2012

(d) Rental private, Year 2018

Fig. 3. Distributions of energy efficiency for selected calendar years: The sample includes both first certificates and subsequent certificates for the properties. In Panels (a) and (b) the sample is restricted to certificates for owner-occupied properties requested for the purpose of a marketed sale. In Panels (c) and (d) the sample is restricted to certificates for private rental properties issued for the purpose of a private rental. The dashed vertical lines correspond to the letter rating cut-offs.

potential tenants. Therefore, unlike homeowners who do not plan to sell their property, landlords who invest in energy efficiency measures may have an incentive to update their certificate.[21]

We take the full sample of certificates that include single and multiple certificate properties. For each property i and year t certificate observation, we create a dummy variable ($\mathbb{1}_{it}^{\text{Subsequent}}$) that takes the value of one if there is a subsequent certificate for the same property and zero otherwise. Therefore, the dummy variable will take the value of zero for all single certificate properties and the last certificate of multiple certificate properties. The empirical specification that we estimate is:

$$\begin{aligned}\mathbb{1}_{it}^{\text{Subsequent}} &= \alpha + \gamma_1 \mathbb{1}_{it}^{\text{Points<39}} + \gamma_2 \mathbb{1}_{it}^{\text{Rental private}} \\ &\quad + \gamma_3 \mathbb{1}_{it}^{\text{Points<39}} \times \mathbb{1}_{it}^{\text{Rental private}} + \epsilon_{it},\end{aligned} \tag{1}$$

where $\mathbb{1}_{it}^{\text{Points<39}}$ is an indicator variable for properties with a rating below 39 (the minimum cut-off for the E band) and $\mathbb{1}_{it}^{\text{Rental private}}$ is an indicator for private rental properties. Standard errors are clustered at the property-level.

The regression in column (1) of Table 5 shows the unconditional mean of the left hand side dummy variable: for 0.21 of the certificates there is a subsequent property certificate. In column (2) we include among the explanatory variables the dummy for low energy efficiency. The large estimated coefficient of 0.194 confirms that subsequent certificates are much more likely to be requested for initially lower rated properties. In columns (3) and (4) we focus on the role of tenure type. The results show that we are much more likely to observe a subsequent certificate for rental properties than for owner-occupied ones, and especially so for those initially below the 39 points threshold. The fifth column shows that this is also the case in the sample of properties in the bottom tercile of initial energy efficiency. In the last column we further restrict the sample to certificates issued prior to April 2015, and estimate the likelihood that there is a subsequent certificate (including in the post approval period). We are less likely to have a subsequent certificate for private rental, unless they have a rating below 39, in which case the likelihood is higher.

3.2.2. *Intensive margin*

Next, we focus on the intensive margin and study the time series evolution of the *changes* in energy efficiency for the sample of multiple certificate properties in the bottom tercile. For each property i and pair of time t' and t'' certificates, we calculate the difference in points

[21] This means that unobserved retrofits, from a certificates data point of view, are more likely to exist in the stock of owner-occupied than rental properties. In section F.3, we merge the EPC data with property transactions data and show that this is not a major concern.

Table 5
Probability and timing of subsequent certificate: The dependent variable is a dummy variable that takes the value of one if for each certificate there is a subsequent certificate for the same property, and zero otherwise. In columns (1) and (2) the sample is the full sample of certificates (single and multiple certificate properties). In columns (3) and (4) we restrict the sample to owner-occupied and private rental properties. In column (5), we further restrict the sample to properties in the bottom tercile of initial energy efficiency while in column (6) additionally, we restrict the sample to properties for which the certificates were issued before the regulatory approval in April 2015. $\mathbb{1}_{\text{Points}<39}$ is a dummy variable that takes the value of one for certificates with SAP points below 39, and zero otherwise. $\mathbb{1}_{\text{Private Rental}}$ is a dummy variable that takes the value of one for private rental properties, and zero for owner-occupied. The model is estimated using ordinary least squares. Standard errors are corrected for heteroscedasticity and autocorrelation. Standard errors are clustered at the property-level and reported in parentheses.*,**, and *** indicate significance at 10%, 5%, and 1% respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
Constant	0.210***	0.197***	0.174***	0.177***	0.242***	0.636***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
$\mathbb{1}_{\text{Points}<39}$		0.194***	0.200***	0.168***	0.102***	0.133***
		(0.000)	(0.000)	(0.000)	(0.001)	(0.001)
$\mathbb{1}_{\text{Private Rental}}$			0.063***	0.055***	0.041***	−0.064***
			(0.000)	(0.000)	(0.001)	(0.001)
$\mathbb{1}_{\text{Points}<39}$ x $\mathbb{1}_{\text{Private Rental}}$				0.125***	0.138***	0.128***
				(0.001)	(0.001)	(0.002)
Sample	Full	Full	Owner-O./ Priv. rental	Owner-O./ Priv. rental	Owner-O./ Priv. rental Bot. tercile	Owner-O./ Priv. rental Bot. tercile Pre Apr/15
Observations	17,701,555	17,701,555	13,968,431	13,968,431	3,686,438	1,296,017
Adjusted-R^2	0.0001	0.0133	0.0213	0.0225	0.0278	0.0325

between the two certificates (within property changes):

$$\Delta\text{Energy efficiency}_{i,t',t''} = \text{Energy efficiency}_{i,t''} - \text{Energy efficiency}_{i,t'}, \quad (2)$$

We then estimate the following event-study specification:

$$\Delta\text{Energy efficiency}_{i,t',t''} = \sum_{k\in\{-21,-2\}} \beta_k D_k + \sum_{k\in\{0,21\}} \beta_k D_k + \theta_{t'} + \epsilon_{it'}, \quad (3)$$

where $\theta_{t'}$ are time (quarter) fixed-effects, and k=-1 is the omitted group, corresponding to one quarter before the approval (2015Q1). Fig. 4(a) shows the estimates (β_k) relative to 2015Q1 and the corresponding 95% confidence intervals distinguishing between owner-occupied properties and private rental properties. The vertical lines mark the approval date (April 2015), the issuance of guidance (October 2017), and the enforcement (April 2018) of the MEES regulations.

Fig. 4(a) shows similar changes for the two tenure types up to the date of the approval of the regulation, at which date the two series start to diverge, with significantly larger (both statistically and economically) improvements in the private rental sector. These larger improvements were made (mostly) in advance of the date of enforcement of the regulations. In the immediate period after enforcement, we still observe larger improvements for the rental private sector, since the regulations applied to new (and not existing) tenancies, but the two series converge shortly after. Once the investments needed to comply with the regulations have been made, the changes in energy efficiency in the two sectors become similar. We return to the other panels of this figure below, and we also show that the results hold in the context of regressions that control for property characteristics.

Overall, the analysis in this section shows that the MEES regulations triggered significant investments in the private rental sector, both on extensive and intensive margins.

3.3. Nature of retrofit investments

An important aspect of the EPC data is that it includes a description of the property elements. By comparing these descriptions between pairs of certificates for the same properties, we can characterize a large sample of retrofit investments made by homeowners and landlords. Table 6 shows the percentage of properties with given characteristics as recorded in the first certificate of the observation pair (Initial) and the percentage points difference in the incidence of the characteristic from the first to the second certificate (Δ). The table distinguishes between observation pairs with second certificates issued pre and post-April 2015. The split by tenure type and period is based on the second observation of each pair. In the table, the largest five changes are shown in bold.

In the rental private post April 2015 sample, the largest changes (Δ) are in lighting (an additional 38% of properties have low energy lighting in at least 80% of fixed outlets) and in mainheat controls (an additional 27% have improved controls). There also are large changes in the percentage of properties that derive hot water from the main system (23%, which is more efficient than electric immersion), which are fully double glazed (18%) and with roof insulation at least 200 mm thick (18%).

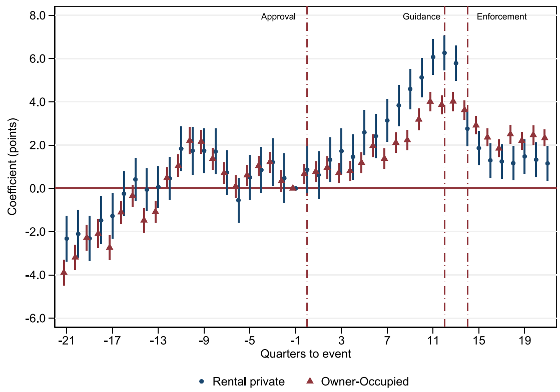
The private rental differences in the pre versus post 2015 periods are economically more significant for lighting (13% versus 38%), mainheat controls (21% versus 27%) and pitched roof insulation thickness of at least 270 mm (5% versus 10%). Notably, these also are the characteristics for which we observe larger differences in the owner-occupied sector in the pre versus post 2015 periods. They suggest that the regulations increased the probability of improvements in rental properties, focused on similar types of retrofits. The analysis of the financial returns to these retrofits helps explain why.

3.3.1. Financial returns

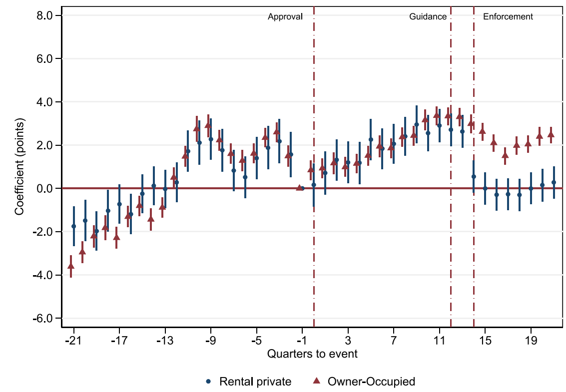
EPCs contain recommendations on how best to improve energy efficiency rating, the indicative capex required to implement them and their projected monetary savings. We use them to measure the financial returns on the investments undertaken. It is important to note that although the recommendations depend on the specific characteristics of the home (e.g. solid walls or cavity walls), the monetary savings are estimates based on a typical property occupancy and not on actual energy consumption.[22]

This matters since Fowlie et al. (2018) and Christensen et al. (2023) have found a wedge between projected and actual savings from energy retrofits, meaning the actual investment returns are lower than those predicted by engineering models. Fowlie et al. (2018) use data on actual energy consumption, discount rates equal to 3%, 6% and 10% and investment lifespans of 10, 16, and 20 years to calculate present

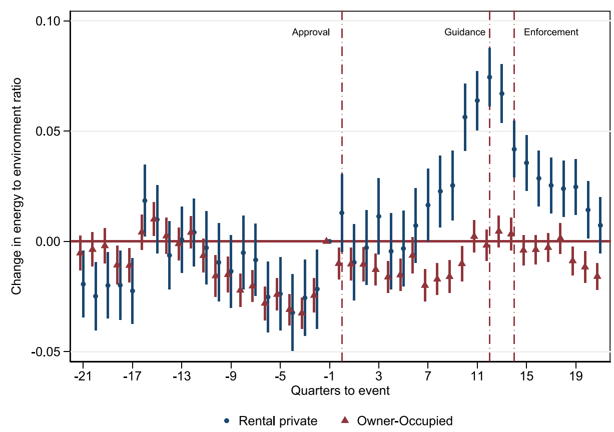
22 The dataset includes the annual savings from implementing all of the recommendations and not the savings associated with each recommendation. The savings per recommendation is available in the online certificates that we scrape.



(a) Changes in energy efficiency



(b) Changes in environmental impact



(c) Changes in energy efficiency/environmental impact

Fig. 4. Changes in energy efficiency and environmental impact ratings around approval: The figure plots the coefficient (β_k) relative to 2015Q1 and the 95% confidence intervals for changes in energy efficiency (panel A), changes in environmental impact (panel B), and changes in energy efficiency over environmental impact (panel C). For each pair of certificates for the same property, we calculate the difference in energy efficiency rating (points) between the first and the second certificate (within property changes, second minus first certificate) and estimate the following event-study specification: $\Delta y_{i,t',t''} = \sum_{k\in\{-21,-2\}} \beta_k D_k + \sum_{k\in\{0,21\}} \beta_k D_k + \theta_{t'} + \epsilon_{it'}$ The figure distinguishes between owner-occupied properties with certificates issued for the purpose of a marketed sale (red triangles) and private rental properties with certificates issued for the purpose of a rental (blue circles). Tenure is measured using the second certificate of each observation pair. The vertical dashed lines mark the approval date (Apr/15), the issuance of guidance (Oct/17) and the enforcement (April/18) of the MEES regulations. The sample is restricted to multiple certificate properties in the bottom tercile of initial energy efficiency.

Table 6

Initial characteristics and retrofits by tenure and time period: The sample is restricted to multiple certificate properties in the bottom tercile of initial energy efficiency. The table reports the percentage of properties with certain initial characteristics (using the first certificate of each pair) and the difference (Δ) in the percentage of properties with that characteristic between the initial and subsequent certificate of each observation pair. The table shows the results for owner-occupied properties with certificates issued for the purpose of a marketed sale and private rental properties with certificates issued for the purpose of a rental. Tenure and transaction type are measured using the second certificate of each observation pair. The table distinguishes between observation pairs with second certificates issued pre and post April/15. The values reported in the Initial and the Δ columns are percentages. The largest five changes are shown in bold.

Element	Description	Owner-occupied				Private rental			
		Pre Apr/15		Post Apr/15		Pre Apr/15		Post Apr/15	
		Initial	Δ	Initial	Δ	Initial	Δ	Initial	Δ
Mainheat	Boiler and radiators, mains gas	63	**13**	61	13	56	**14**	45	13
	Electric storage or room heaters, oil heating	25	−8	28	−9	33	−9	44	−8
Mainheat controls	Programmer, room thermostat and TRVs	19	**26**	21	**38**	13	**21**	13	**27**
Windows	Fully double glazed	56	**17**	60	**21**	52	**17**	56	**18**
Roof	Pitched, insulation ≥ 270 mm	3	6	4	12	2	5	3	10
	Pitched, insulation ≥ 200 mm	14	**17**	17	**20**	10	**14**	11	**18**
Lighting	Low energy lighting ≥80% of fixed outlets	8	8	11	**33**	11	13	16	**38**
Walls	Cavity, insulated	14	10	14	13	8	5	8	7
	Solid brick, insulated	1	1	1	2	1	2	1	2
Hot water	From main system	51	**26**	52	**30**	45	**24**	40	**23**
	From main system, no cylinder thermostat	21	−12	21	−11	16	−8	13	−4
	Electric immersion	22	−11	22	−12	31	−13	37	−12

Table 7

Financial returns on retrofits: The table reports the mean capital expenditure and annual savings for the main types of retrofits observed for each property element. The capital expenditures are from the recommendations file and are indicative. The savings of implementing a given type of investment are based on a typical energy consumption for the property. The savings are assumed to grow at the annual growth rate of inflation of 2%. The table reports the present value of savings (using three values of discount rate of 3%, 2%, and 1%) divided by capital expenditure, and the internal rate of return. The assumed lifespans are reported in the last column.

Discount rate values	Capex (£)	Savings (£)	PV sav/Capex			IRR (%)	Lifespan (years)
			3%	2%	1%		
Install low energy lighting	38	30	7.3	7.7	8.2	80.7	10
Upgrade heating controls	400	58	1.3	1.4	1.5	9.1	10
Install hot water cylinder thermostat	300	61	1.9	2.0	2.1	17.3	10
Increase loft insulation to 270mm	225	83	9.4	10.8	12.7	38.9	30
Change heating to gas condensing boiler	5,000	360	0.7	0.7	0.7	−4.0	10
Replace single with double glazing windows	4,900	56	0.2	0.2	0.2	−9.6	20
Cavity wall insulation	1,000	148	3.8	4.4	5.1	16.5	30
50 mm internal or external wall insulation	9,000	197	0.6	0.6	0.8	−0.7	30

values of savings equal to between 31% and 76% of the average upfront investment costs. If our engineering model suffers from the same bias, the estimates that we provide in this section are an upper bound for the returns that can be achieved through such retrofit investments. However, the savings estimates that we use are similar to those documented in Kattenberg et al. (2024) for the Netherlands, who measure actual energy savings achieved.

In Table 7, we use the mean capex and savings for each retrofit, lifespans between 10 and 30 years (depending on the retrofit), and three values of discount rate to calculate financial returns. In the calculations, we assume that the savings grow at an annual rate of 2% equal to inflation. Although our calculations rely on estimated savings, we still find that several of the retrofits — installing double glazing windows, insulation of solid walls, installing a gas condensing boiler — yield a present value of savings significantly lower than the required investment. These are some of the retrofits being funded by the Weatherization Assistance Program (WAP) studied by Fowlie et al. (2018).[23]

Table 7 shows that those retrofits that require smaller upfront investment generate positive IRRs. Among them are the installation of low-energy lighting, the upgrading of heating controls, and the installation of a hot water cylinder thermostat. As far as the envelope of the property is concerned, increasing roof insulation provides the largest IRR. These are the retrofits more commonly observed in the data (as shown in Table 6).

An exception is the installation of double glazed windows: it is a fairly unattractive investment from an energy efficiency point of view, but it is quite prevalent in the data. This suggests that home comfort (e.g., noise reduction) or aesthetics may be important factors behind these investment decisions. Finally, the financial attractiveness of wall insulation depends on the type of walls: insulating cavity walls is less costly and more frequently carried out than insulating solid brick walls.

The certificates include retrofit recommendations along with estimated capex and savings for each recommendation. A drawback is that the capex figures are for a standardized property and do not vary with property type or size. Naturally, this is not realistic (e.g., the larger a house, the more expensive insulating walls is). To address this drawback, in Appendix D we obtain property-specific capex values for a sub-sample of the retrofits from Palmer et al. (2017), and perform IRR calculations using them. Although there are differences in IRRs across property type, several of the main conclusions are similar to those above for all property types considered.[24]

3.4. Moves in tenure in response to regulations

The regulations apply to private rentals and not to owner-occupied properties, which might lead landlords of privately rented properties to sell them and the property being moved out of this sector (so as to evade the regulations). In this case, we might see a significant number of lower rated properties transacted around the date when the regulations were introduced. In Appendix F.2, we investigate this hypothesis using the full sample of certificates merged with Land Registry data on property transactions. We do not find evidence in support of the hypothesis. One potential reason is that the financial cost of meeting the regulatory requirements is not significant, a hypothesis that we investigate next.[25]

4. Impact of the regulations on rents

In this section, we study the effects of the regulation on rents and investigate the attractiveness of the investments from landlords' point of view. In England and Wales, utilities are typically not included in rents and are paid for separately by the tenants. Therefore, landlords compare the cost of the investments to the additional rents received.

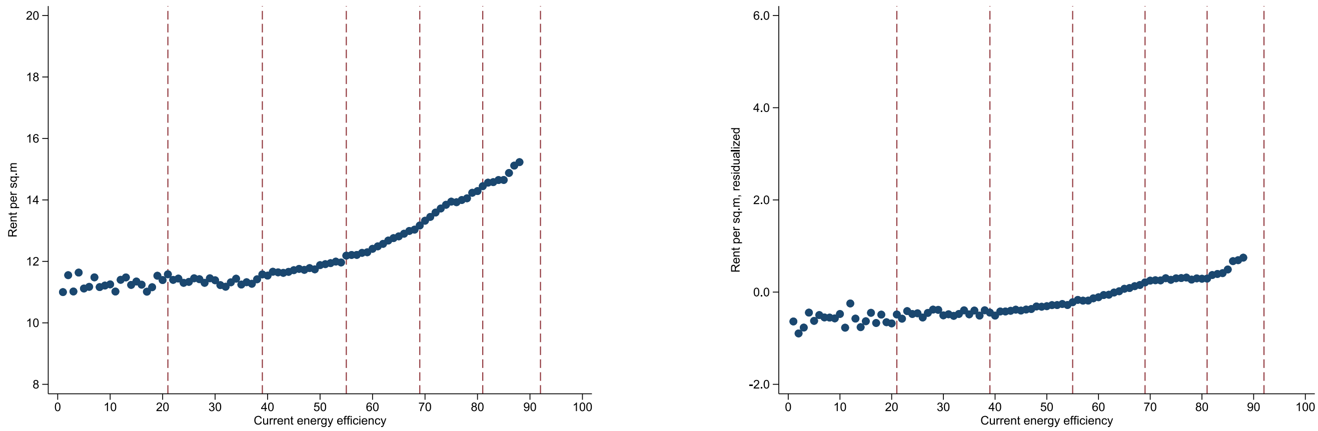
To assess the impact of the regulations on rents, we use rental listings from rightmove.co.uk, which has previously been used among others by Giglio et al. (2015). The original dataset contains roughly 11.2 million rental listings corresponding to 4.1 million unique properties from 2006 to 2023. We retain those only from 2008 to 2020 to match our certificates sample and merge the two using the unique property reference numbers (UPRNs) that are included in both.[26] More precisely, we merge each rental listing in the Rightmove data with the EPC that is valid at the time of the listing, i.e. the EPC for the specific property that was most recently issued prior to the listing.

[23] Christensen et al. (2023) study the wedge between projected and realized returns in energy efficiency programs. They find that a significant factor is a bias in engineering models, particularly in the overestimation of savings in wall insulation (see also Zivin and Novan (2016)). Levinson (2016) finds that the energy savings from changes to building codes are lower than those projected when the regulations were enhanced. In addition, Kotchen (2017), Jacobsen and Kotchen (2013), and Novan et al. (2022) investigate the impact of building codes on residential energy consumption.

[24] One retrofit where property type makes a difference is the changing of heating to gas condensing boiler. The cost of a boiler does not vary by much with property type, but the number of bathrooms is a very important factor (Palmer et al., 2017). Larger houses tend to have more bathrooms which increases the cost of the retrofit.

[25] Other potential explanations are that during the period of our analysis, the regulations only applied to new tenancies and not existing ones and that, in the period after their approval, enforcement was not consistent across local authorities who are responsible for doing so. Enforcement has been improving over time, especially with the changes introduced in April 2020, that require all private rental properties that require an EPC to comply with the regulations (including existing tenancies).

[26] The UPRN is the unique identifier for every addressable location in England and Wales.



(a) Average price per square meter

(b) Average residual price per square meter

Fig. 5. Rents as a function of energy efficiency: Panel A of the figure plots average rent per square meter as a function of SAP score. Panel B plots average residual rent per square as a function of SAP score after controlling for property characteristics (number of habitable rooms, property type, built form), listing quarter and local authority.

Further, following Guren (2018), we retain rental listings that are at least 90 days apart, ensuring that only listings with meaningful changes over time are retained for analysis. Therefore, our data has, for many properties, *within* variation in both listing prices and energy performance. Our final merged data has roughly 6.2 million listings for 2.6 million unique properties. Appendix E provides details and Appendix Table A5 shows summary statistics for the merged data.

We begin by examining the relationship between rents per square meter and energy efficiency. Fig. 5 shows the average rent per square meter as a function of energy efficiency for all properties in our sample. Panel A shows raw averages while Panel B shows averages after controlling for property characteristics (number of rooms, property type, built form), location (local authority) and listing date (quarter).

In the raw data, rents increase with the energy efficiency of the underlying property, particularly above the 39 points threshold. Naturally, one cannot attribute this rent increase solely to energy efficiency. Better rated properties are different along dimensions other than energy efficiency, which might explain the increase. This is confirmed in Panel B, where we control for observable property characteristics and time, showing a much flatter relationship. The key observation is that there are no visible discontinuities or increases in rents near the 39 points regulatory threshold.[27] This suggests that landlords may not be able to pass through the costs of energy efficiency improvements into rents, a hypothesis we test more rigorously in the following subsection.

4.1. Difference-in-differences

We begin by estimating changes in rents around the regulation. The dependent variable is the logarithm of the listing price of property i in listing l at time t, denoted by $Log(Rents_{ilt})$. Our estimates for the rent effects rely on properties for which we observe more than one listing price and on changes in energy performance. Following our analysis in Section 3.2.2, since most of the improvements were made in advance of the date of enforcement, we focus on changes in rent around the post-approval period. During this period, we still observe rental listings below and above the threshold of 39 points, allowing us to estimate the differential impact of the investments on rents.[28] In particular, we estimate the following DiD specification:

$$\text{Log}(\text{Rents}_{ilt}) = \alpha + \gamma_1 \mathbb{1}_{ilt}^{\text{Points}<39} + \gamma_2 \mathbb{1}_{ilt}^{\text{Points}<39} \times \mathbb{1}_{ilt}^{\text{Post-approval}} + \theta_i + \kappa_t + \epsilon_{ilt}, \tag{4}$$

where $\mathbb{1}_{ilt}^{\text{Points}<39}$ is an indicator variable for listings for properties with a rating less than 39 at the time of the listing. The other indicator variable takes the value of one for listings in the post-approval period. The base case is rental listings in the pre-approval period for properties with energy efficiency of 39 or below. The θ_i, κ_t are property and time (year-month) fixed effects, respectively, and ϵ_{ilt} is the residual. Standard errors are clustered at the property-level.

The coefficient of interest is γ_2 which compares rents for properties below versus above the minimum energy efficiency standard around the approval of the regulations, controlling for time and property fixed effects.

Panel A of Table 8 reports the estimates for the full sample of rental properties. In column (1), we find that properties below 39 in the post-approval period relative to pre-approval period and relative to those above 39, have on average 0.9% lower rents. In other words, those for which investments bring them from below to above the threshold, the increase in rents is equal to 0.9%. Note that this is after we control for the temporal increase in rents through the inclusion of year-month fixed effects. Compared to a median annual rent of £7800 for properties below 39 in the pre-approval period, the estimate suggests an annual rent increase of £70.2. However, these estimates do not control for selection.

4.2. Instrumented difference-in-differences

Next, to isolate the changes in rents driven by regulation from selection among landlords who choose to invest in their properties, we combine difference-in-difference strategy with an instrumental variables approach.[29] The key idea behind this estimation strategy is to compare properties where the regulation binds and those for which it does not based on their pre-period status. Specifically, we instrument

[27] In contrast, there is a large literature documenting price discontinuities at rating band thresholds, suggesting that buyers and seller pay attention to such bands in the context UK and Europe (Lu and Spaenjers, 2025; Sejas-Portillo et al., 2025).

[28] Note also that there are a few instances where we observe listings for properties below 39 after the enforcement period. This likely can be attributed to variation in enforcement across local areas.

[29] See, Agarwal et al. (2024), Sviatschi (2022), Abdulkadiroğlu et al. (2016), Duflo (2004), among others, following a similar approach.

Table 8
Impact of regulations on rents: The table presents the impact of regulations on rents. Panel A focuses on all certificates while Panel B focuses on the subsample of certificates in the bottom tercile in the period prior to the regulation. Across both panels, the dependent variable in columns (1) and (3) is the logarithm of the listing price, $Log(Rents_{ilt})$, while in column (2) it is the energy efficiency SAP points of property i in listing l at time t. Column (1) presents estimates from an OLS specification while columns (2) and (3) report estimates from an Instrumented Difference-in-Differences. Specifically, column (2) reports the first stage relationship between energy efficiency SAP points and the instrument, which is defined as the interaction between an indicator for whether the property in the pre-approval of the regulations period was below 39 points and the indicator for Post-Approval. $\mathbb{1}_{\text{Points}<39}$ is a dummy variable that takes the value of one for certificates with SAP points less than 39 and zero otherwise. $\mathbb{1}_{\text{Post-approval}}$ takes the value of one for second certificates issued after March/15 and zero otherwise. Standard errors are clustered at the property-level. Standard errors are corrected for heteroscedasticity and autocorrelation and reported in parentheses.*,**, and *** indicate significance at 10%, 5%, and 1% respectively.

Dependent variable	Panel A: All certificates		
	DiD	Instrumented DiD (IVDiD)	
	Log (rents) (1)	Energy Eff (2)	Log (rents) (3)
$\mathbb{1}_{\text{Points}<39}$	0.002 (0.003)		
$\mathbb{1}_{\text{Post-approval}} \times \mathbb{1}_{\text{Points}<39}$	−0.009*** (0.003)		
$\mathbb{1}_{\text{Post-approval}} \times \mathbb{1}_{\text{Pre- approval points}<39}$ (Instrument)		6.594*** (0.066)	
$\widehat{\text{Energy Efficiency}}$			−0.001*** (0.000)
Fixed effects:			
Year-month	Yes	Yes	Yes
Property	Yes	Yes	Yes
Kleibergen–Paap Wald F statistic		15,265.1	
Adjusted-R^2	0.87	0.95	–
Observations	2,943,983	2,943,983	2,943,983
Dependent variable	Panel B: Bottom tercile certificates		
	DiD	Instrumented DiD (IVDiD)	
	Log (rents) (1)	Energy Eff (2)	Log (rents) (3)
$\mathbb{1}_{\text{Points}<39}$	−0.004 (0.004)		
$\mathbb{1}_{\text{Post-approval}} \times \mathbb{1}_{\text{Points}<39}$	0.005 (0.004)		
$\mathbb{1}_{\text{Post-approval}} \times \mathbb{1}_{\text{Pre- approval points}<39}$ (Instrument)		5.470*** (0.065)	
$\widehat{\text{Energy Efficiency}}$			−0.00044 (0.0003)
Fixed effects:			
Year-month	Yes	Yes	Yes
Property	Yes	Yes	Yes
Kleibergen–Paap Wald F statistic		7050.2	
Adjusted-R^2	0.86	0.81	–
Observations	698,962	698,962	698,962

the energy performance of the property by their pre-regulation status of whether the property was below 39.

Note that this methodology allows us to estimate the local average treatment effect (LATE) for properties whose status was affected by the regulation (i.e., compliers). By contrast, the DiD specification would allow us to recover the *average treatment effect* for: (i) landlords who chose to invest in their homes in responding to the regulation ("compliers"); and (ii) landlords with properties having an energy efficiency score of 39 or above at the time of the regulation. This would confound the conclusions we could draw from the estimation about the impact of regulation on rents for those who make investments to comply.

We estimate the following IVDiD specifications:

$$\text{Energy Efficiency}_{ilt} = \alpha + \gamma_1 \mathbb{1}_{il}^{\text{Pre-approval points}<39} \times \mathbb{1}_{ilt}^{\text{Post-approval}} + \theta_i + \theta_t + \epsilon_{ilt}, \quad (5)$$

$$\text{Log}(\text{Rents}_{ilt}) = \alpha + \gamma_2 \widehat{\text{Energy Efficiency}}_{ilt} + \theta_i + \theta_t + \epsilon_{ilt}, \quad (6)$$

where Energy Efficiency is in SAP points, $\mathbb{1}^{\text{Post-approval}}$ is an indicator variable takes the value of one for listings in the post-approval period, and $\mathbb{1}^{\text{Pre-approval points}<39}$ is an indicator variable that takes the value of one if the last energy performance certificate before the regulation indicated that the property was below 39 points. Standard errors are clustered at the property-level.

Columns (2) and (3) in Panel A of Table 8 report the results. In column (2), we present the results from the first stage (Eq. (5)), where we estimate the relationship between the pre-regulation status and energy efficiency score, conditional on property and time fixed effects. The estimates imply a 6.6 SAP point increase for those properties who are required to comply with the regulation. This increase is statistically significant, with a large F-statistic, implying that our estimation is not subject to a weak instrument problem (Stock and Yogo, 2002; Olea and Pflueger, 2013; Andrews et al., 2019). Moreover, the economic magnitude of this increase is large, with the estimates implying a

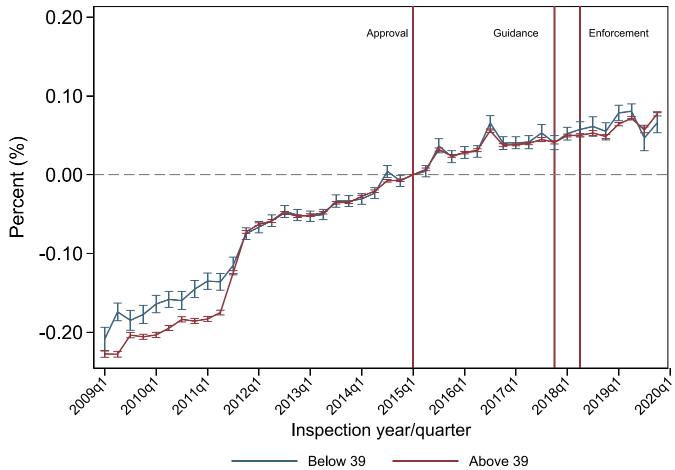


Fig. 6. Changes in rents around the regulation: The figure presents the evolution of rents around the regulation and compares properties where the regulation binds (Below 39) and those for whom it does not (Above 39), based on their pre-approval of the regulations status. Specifically, we estimate the following equation separately for the two groups: $\text{Log}(\text{Rents}_{ilt}) = \sum_{k\in\{-24,-1\}} \beta_k D_k + \sum_{k\in\{1,19\}} \beta_k D_k + \theta_i + \epsilon_{ilt}$ where i is property, l is listing, and t is year-month. The figure plots the estimated coefficients (β_k) normalized to the first quarter of fiscal year 2015, which marks the approval date, and their corresponding 95% confidence intervals. The vertical lines mark the approval date (April/15), the issuance of guidance (October/17) and the enforcement (April/18) of the MEES regulations. The model is estimated using ordinary least squares and controls for time-invariant property characteristics (property fixed effects). Standard errors are corrected for heteroscedasticity and autocorrelation, and are clustered at the property-level.

25% increase relative to pre-regulation energy efficiency scores for the median property below 39.[30]

Column (3) reports two-stage least squares estimates from Eq. (6), where we instrument the energy efficiency of the property with its pre-regulation status. The estimates suggest that landlords who chose to invest in their homes in responding to the regulation experienced 0.1% *lower* rent growth around the regulation, conditional on property and time fixed effects. Thus, the baseline DiD estimates a 0.9% increase in rents for properties above the 39 points threshold in the post period, while the estimate for the instrumented DiD is negative and equal to −0.1%. Compared to a median annual rent of £7800 for properties below 39 in the pre-approval period, the IVDiD estimate suggests an annual rent *decrease* of £7.44 or a monthly decrease of only £0.62, so economically zero.

Identification assumptions. De Chaisemartin and d'Haultfoeuille (2018) and Hudson et al. (2017) provide a detailed discussion of the identification conditions needed for the consistency of the IVDiD estimators. The main identifying assumptions are threefold. First, in the absence of regulation, rents evolve in parallel. To examine the validity of this assumption, in Fig. 6, we present evidence that rents indeed evolve in parallel in the period before the regulation, for properties where the regulation binds and those for whom it does not, based on their pre-approval status.

The second identifying assumption is that the instrument for energy performance, namely $\mathbb{1}^{\text{Pre-approval points}<39}$, must only affect rents through its effect on regulation on energy efficiency points, conditional on property and time fixed effects. While the exclusion restriction cannot be tested directly, we conduct additional analyses to rule out concerns that may invalidate the exclusion restriction. We first note that the empirical specification already includes property fixed effects that control for time-invariant property differences across the groups while year-month fixed effects controls for granular fluctuations in national economic conditions of landlords and tenants. Additionally, evidence in Appendix F.2 shows that private landlords of lower-rated properties did not sell them, to a significant extent in the aggregate, to avoid having to make the investments required to comply with the regulations. This is also consistent with evidence documented in Section 3.3 and the subsequent section, that landlords could combine several low capital expenditure retrofits to comply with the regulation.[31] Together, these results support the validity of the exclusion restriction.

Lastly, as discussed in Section 3, the necessary assumptions surrounding monotonocity, whereby regulation leads properties with an energy efficiency score below 39 in the pre-period to (weakly) improve their energy performance, is quite plausible in our setting. Therefore, our estimates could be interpreted as LATE.

4.3. Comparison of the DiD and instrumented DiD estimates

The uninstrumented and instrumented analyses yield different estimates for rent changes, and it is important to understand the source of this difference. The DiD estimates the effect of being subject to the regulation (intention-to-treat) while the IVDiD estimates the effect of actual energy efficiency change (treatment-on-the-treated). The key advantage of the instrumented approach is that it deals with selection that may arise in the properties that are treated, as properties below and above the 39 threshold are likely to be different along several dimensions. In the DiD estimation we control for these differences using property fixed effects, but it is possible that the rents of properties below and above the 39 threshold evolve differently over time, in response to economic shocks other than the regulatory intervention, but correlated with the timing of the intervention. The IV strategy attempts to solve this by using regulation as an exogenous shock to energy efficiency—allowing us to isolate the causal effect of improvements, not selection.

In this section we present results that show the importance of selection. In a first step, we take the same full sample of rental properties and re-estimate the DiD specification with additional explanatory variables that capture pre-regulation property characteristics, such as age, type and size interacted with the post-regulation approval dummy.[32] Most of these property characteristics are time-invariant and their level effect on rents is captured by the property fixed-effects included in the regressions. But by interacting property characteristics with the post-regulation approval dummy, we allow for the possibility that rents of properties with such characteristics evolve differently in the post-period. This essentially allows us to control for observable differences in property characteristics with varying treatment intensity—landlord investments are endogenous and could potentially differ along observable dimensions of property characteristics such as age, type and size.

The results are shown in column (2) of Appendix Table A9 , in Panel A for the DiD and in Panel B for the IVDiD. To facilitate the comparison column (1) of the same table shows the previous results, without the controls for pre-period characteristics interacted with the post-approval dummy. Panel A of column (2) shows an estimated post-approval

[30] In Section 3, we provide evidence that we are more likely to observe a certificate after the regulation for private rental properties, compared to owner-occupied properties, that have a rating below 39 in the pre-period.

[31] Moreover, consistent with the investments documented in that section, we find that the properties that complied with the regulation in the sample saw larger improvements (increase in mean star ratings) in the elements that require lower capex: Lighting (0.42), Mainheat control (0.18), Hot water (0.08), Windows (0.07), Walls (0.07), and Mainheat (0.06).

[32] The property characteristics that we consider are construction age bands, property type and built form, number of rooms, and floor area. We use dummies for the former (with the categories shown in Appendix Table A2) and decile dummies for the floor area.

increase in rents for properties above the 39 points threshold of 0.6%, which is one third lower than the estimated value in the baseline specification in column (1). The decrease in the estimated magnitude of the rent effects, which becomes closer to the IV estimates, suggests that indeed selection may be at work. In addition, the IV estimates remain unchanged when we add the additional controls (Panel B of Appendix Table A9).[33] This exercise tries to control for selection in the DiD estimates using observable property characteristics. But there could also be selection on unobservables that it does not tackle, but that is addressed by the IVDiD.

We perform a second exercise that further highlights the importance of selection. The estimates in Panel A of Table 8 are for the full sample of rental properties, including those with high energy efficiency scores both before and after the approval of the regulations. Properties with high energy efficiency scores throughout are likely to be different, including along some unobservable dimensions. Thus, we obtain estimates for a restricted sample of rental properties initially in the bottom tercile of the energy efficiency distribution.[34] This essentially reduces the size of the control group making the properties included more similar to the group of treated properties.

Panel B of Table 8 shows the estimates. Focusing first on the DiD results and the estimated coefficient on the interaction term between the indicator for post-approval and points below 39, we now obtain an estimate that is not statistically different from zero (Column (1)). As far as the instrumented DiD results are concerned, shown in column (3) of the same table, we still estimate a negative coefficient but much smaller in absolute value and not statistically different from zero. Therefore, when we restrict the sample to include properties in the control group that are more comparable to those in the treated group, we find that there is not a statistically (or economically) significant effect on rents, either using the DiD or the IVDiD approach. The fact that we now obtain more similar results for both approaches, suggests that the previous differences were due to selection.

Therefore, the estimated 0.9% increase in rents (full sample, DiD estimate, Column (1) of Panel A) is an upper bound in the estimates, and approaches that deal with selection — IVDiD and restricting the sample to properties initially in the bottom tercile of the energy efficiency distribution — yield no effect on rents. The latter are therefore a more plausible estimate, and the general conclusion is that landlords cannot pass on reductions in energy costs arising from energy efficiency investments to tenants in the form of higher rents.

4.4. Capex required, savings, and investment returns

Section 3 showed that the regulations led owners of low-rated properties to make investments. We can combine the estimated rent effects with capex data to calculate the returns on the investments that landlords of low rated properties achieved.

We proceed in the following steps. For each of the property elements, we use the description in the first and second certificates of the observation pair to identify the investment that has been made. For example, for main heat, if the first certificate says "Room heaters, electric" and the subsequent certificate "Boiler and radiators, mains gas", this means that there was a change in heating to a gas condensing boiler. Associated with this change, there is an increase in the (median) number of stars of that element from 1 in the first certificate to 4 in the subsequent certificate.[35] Finally, we use the estimated coefficients of the engineering model (Appendix C) to translate the increase in star ratings into SAP points. We do so using the estimated coefficients of the RdSAP period from 8 December 2014 to 18 November 2017, from just prior to approval to enforcement of the regulations, for the retrofits more commonly observed in the data, and focusing on flats due to their prevalence in the rental sector.

Table 9 shows the results. In the first row, we report the results for the retrofit described in the previous paragraph. The £5000 required yields a 13.92 SAP points increase, or £359 per point. The table includes data for several other retrofits. The retrofits that require more £s per point are the insulation of solid brick walls (£979 per point) and installing double glazed windows (£1155 per point). On the other hand, the installation of low energy lighting, improvements in main heat controls and roof insulation require much less capex and deliver more points per pound of investment. Therefore, retrofits that require more capex tend to yield larger changes in number of points, but smaller changes in points per pound of capex spent.

In our sample of certificates issued prior to the approval of the regulations the median private rental property with an energy efficiency below 39 had a rating of 26 SAP points, thus requiring an additional 13 points to satisfy the minimum threshold. In Table 10 we evaluate the net present value of several retrofits. The first option is the change in heating to gas condensing boiler, a large capex item. The second option is the combination of several low capex retrofits (low energy lighting, mainheat controls) and the installation of double glazed windows. The first two columns of Panel A show that these two options yield 13.92 and 13.98 points increases, respectively. The first stage of the IVDiD regressions estimates a 6.594 points increase (column (2) of Table 8). Therefore, in the last column of Panel A we consider a third option that involves only two most common and low capex retrofits and yields a 9.78 points increase. In Panel B we report the capex needed for each of the options.

We use our estimates to calculate the rent changes. We perform calculations for the DiD estimates that do not account for selection and for the Instrumented DiD estimates. For the former the estimated rent increase is 0.9%, corresponding to an annual rent increase of £70.2.[36] For the IVDiD estimates, we use a rent change of zero since the negative estimate is economically zero.

Panel C shows that even for the DiD estimates that do not account for selection and generate larger rent increases, the energy cost savings are always larger than the rent changes. The differences are particularly large for option 1, and smallest for option 3 that requires the lowest capex. Naturally, since for the IVDiD estimates there is no economically significant rent effect, the differences relative to the energy cost savings are larger than for the DiD estimates.

Panel D of Table 10 calculates the net present value of the rent changes minus the capex required. We assume that rents increase at the annual rate of inflation of 2%. In options 1 and 3, the lifespan of the investments is 10 years so the calculations use this horizon. In option 2, the lifespan of the investment in windows is 20 years, so we assume an additional investment in low energy lighting and mainheat controls at the end of the first 10 years and convert the net present value into 10 year payments to make the values comparable to options 1 and 3.

[33] There is a small decrease in the number of observations from column (1) to (2) due to missing property characteristics information for some of the data entries.

[34] This is the same sample that we use for other parts of the analysis. Recall that the energy efficiency cut-off for this sub-sample is 54 points.

[35] We report the median values since there is some heterogeneity in the data, e.g. not all flats with a main heat description of "Boiler and radiators, mains gas" have 4 stars for the main heat element. This is in part due to the fact that different boilers have different degrees of efficiency and that may affect the star rating received (the efficiency of the boiler is recorded by the assessor, but we do not have the information in our data).

[36] We have also considered obtaining rent change estimates for sub-samples of properties for which we observe certain types of investments. However, we have refrained from doing that since that would lead to further selection concerns, that the IVDiD tries to address.

Table 9
Indicative capex required for complying with the regulation: Flats in bottom tercile: This table shows the capex required and the points increase achieved for several retrofits. The first column reports the element (main heat, main heat controls, etc.). The second (third) column shows the initial (final) element description (and the associated number of stars in parenthesis). The fourth column shows the increases energy efficiency SAP points while the fifth column shows the capital expenditure (from Table 7). The improvement is calculated using the empirical model of Appendix C, using the fifth RdSAP period (from 8 December 2014 to 18 November 2017). The last column shows the ratio of capex incurred to changes in SAP points.

Property element	Initial element description (stars)	Subsequent element description (stars)	ΔSAP points	Capex incurred (£)	Capex/ ΔSAP
Mainheat	Room heaters, electric (1)	Boiler and radiators, mains gas (4)	13.92	5000	359.20
Mainheat controls	Programmer, no room thermostat (1)	Programmer, room thermostat and TRVs (4)	7.41	400	53.98
Windows	Single glazed (1)	Fully double glazed (3)	4.20	4900	1166.66
Roof	Pitched 100mm, loft insulation (3)	Pitched 270mm, loft insulation (4)	1.42	225	158.45
	Pitched no insulation (1)	Pitched 270mm, loft insulation (4)	8.64	225	26.04
Lighting	Low energy lighting (<=20% of fixed outlets) (1)	Low energy lighting (>=80% of fixed outlets) (5)	2.37	38	16.03
Walls	Cavity wall (no insulation) (2)	Cavity, insulated (4)	7.18	1000	139.28
	Solid brick (no insulation) (1)	Solid brick, insulated (4)	9.19	9000	979.33

Table 10
Increase in rents, energy savings and capital expenditures: This table compares the rent increase to the energy cost savings and capital expenditures landlords must make to satisfy the regulations. Panel A quantifies the increase in SAP points achieved through different retrofits, while panel B presents the commensurate capital expenditures in pounds. Panel C compares the annual energy cost savings and rent increase for each of the alternatives. For rent increase, we rely on the sample of all certificates. Panel D computes the net present value from making the investments against the increase in rent. In the calculations we assume that rents grow at the annual rate of 2% and we consider two values for the discount rate. In options 1 and 3 the horizon is 10 years, corresponding to the lifespan of the retrofits. In option 2, the lifespan of the investment in windows is 20 years, so that we assume an additional investment in low energy lighting and mainheat controls at the end of 10 years, and convert the net present value into two ten year payments to make the values comparable to options 1 and 3.

Retrofit (lifespan)	Option 1	Option 2	Option 3
	Panel A: Increase in points achieved through capex		
Mainheat (10-years)	13.92	–	–
Low energy lighting (10-years)	–	2.37	2.37
Mainheat controls (10-years)	–	7.41	7.41
Windows (20-years)	–	4.20	–
Total points	13.92	13.98	9.78
	Panel B: Capex required		
Mainheat (10-years)	£5,000	–	–
Low energy lighting (10-years)	–	£38	£38
Mainheat controls (10-years)	–	£400	£400
Windows (20-years)	–	£4851	–
Total capex	£5,000	£5,289	£438
	Panel C: Energy cost savings and rent change (annual)		
Energy cost savings	£360	£144	£88
Rent change (DiD)	£70.2	£70.2	£70.2
Rent change (IVDiD)	£0	£0	£0
	Panel D: Present value of rent change minus capex (10-years horizon equivalent)		
DiD			
Discount rate of 3%	−£4,347	−£2,547	£215
Discount rate of 2%	−£4,312	−£2,390	£250
IVDiD			
Discount rate of 3%	−£5,000	−£3,260	−£438
Discount rate of 2%	−£5,000	−£3,146	−£438

We consider two values for the discount rate when computing the net present values. For a discount rate of 3% and reduced form rent increase estimates, the net present value of the retrofits are £-4347, £-2547 and £215, respectively. When we consider the Instrumented DiD rent increase estimates, that control for selection and are a more plausible estimate, the net present values are negative for all options and equal to £-5000, £-3260 and £-438, respectively.

The lack of an economic effect on rents implies that landlords are not compensated for their investments, and explain why landlords do not make these investments in the absence of regulation, and why, when faced with regulation, they focus on low-capex improvements.

5. From energy efficiency to carbon emissions

The objective of the regulations was to improve the energy efficiency of private rental properties. Given the centrality of emissions reductions to climate targets, this section evaluates their effects on carbon emissions. This analysis is particularly important since there is not a one-to-one mapping between energy efficiency and carbon emissions. Reductions in the use of an expensive but low carbon footprint energy source improve energy efficiency with limited impact on carbon emissions. Shifts towards cheaper but more polluting energy sources reduce energy costs but may actually lead to larger carbon footprints.

We measure environmental gains from the EPC data, and relate them to the energy sources and the investments undertaken.

5.1. Limited environmental gains

The certificates measure the environmental impact (EI) rating of the dwelling (on a scale of 1 to 100, the higher the rating the lower the environmental impact). It is a measure of the carbon emissions of the property. It depends on the quantities of the different types of energy consumed and how polluting they are (their emission factors in $KgCO_2$/kWh; Appendix A.2 provides additional details).

We previously characterized the energy efficiency gains and the retrofits. We now take the same sample and quantify the environmental gains. More precisely, we first calculate the changes in environmental score between the first and second certificates (second minus first) of each property pair (within property changes) and then average across all observations with second certificates issued in a given year/quarter. This is similar to what we have previously done for the energy rating. Fig. 4(b) plots the changes in environmental impact around approval.

Fig. 4(a) shows large improvements in energy efficiency for private rental properties relative to owner-occupied from the date of approval until the date of enforcement of the regulations. However, the same pattern is not visible in Fig. 4(b). There is a divergence between the relative gains in energy efficiency and in environmental impact. In order to investigate this further, we calculate the ratio of energy efficiency and environmental impact ratings for each observation. We then calculate the change in this ratio between the two property observations before averaging across all observations for second certificates issued in a given year/quarter. Fig. 4(c) plots the evolution around approval of this ratio. The changes are larger for rental private than owner-occupied, with a gap that widens significantly post-approval. This shows that the large improvements in energy efficiency for private rental properties were not accompanied by similarly large environmental gains (relative to owner-occupied properties).

We quantify the effects in regressions. The dependent variable (ΔY_{it}) is the within property i time t change in energy points (or environmental impact rating) compared to the previous certificate for the same property. The independent variables are indicators for private rental (zero for owner-occupied, the sample is restricted to these two tenure types) and for whether the observation corresponds to the period pre-approval of the regulations, approval to enforcement or post enforcement:

$$\begin{aligned} \Delta Y_{it} = \alpha + \gamma_1 \mathbb{1}_{it}^{\text{Rental private}} + \gamma_2 \mathbb{1}_{it}^{\text{Approval to enforcement}} \\ + \gamma_3 \mathbb{1}_{it}^{\text{Post enforcement}} + \gamma_4 \mathbb{1}_{it}^{\text{Rental private}} \mathbb{1}_{it}^{\text{Approval to enforcement}} \\ + \gamma_5 \mathbb{1}_{it}^{\text{Rental private}} \mathbb{1}_{it}^{\text{Post enforcement}} + \theta_1 + \theta_2 + \epsilon_{t,i} \end{aligned} \quad (7)$$

where θ_1 denotes property characteristics fixed effects and θ_2 denotes RDSAP convention dates fixed effects. The dependent variable are within property changes and since for most properties we only have one observation for changes, we do not include property fixed effects in the regression. However, we allow the changes to depend on property characteristics by including dummies (θ_1). Standard errors are clustered at the property-level.

The estimated coefficients shown in the first column of Table 11 imply that during the period from approval to enforcement, the energy efficiency of rental private properties increased by 2.416 points (=0.378+2.038) more than that of owner-occupied ones. The comparable number for the change in environmental impact is −0.278 points (column (2), equal to the sum of the coefficients on rental private and the interaction term between rental private and approval to enforcement). The corresponding difference for the ratio of energy efficiency to environmental impact (column (3)) is 0.071.

In columns (4) to (6), we add fixed effects for property construction age, type, built-form and floor area (ten decile dummies) and for the conventions in effect at the time that the certificates were issued. The estimated differences between rental private and owner-occupied from approval to enforcement are 1.708 (energy), 0.532 (environment), and 0.031 (ratio). These differences are smaller than when we do not include the fixed effects in the regressions so that the type of properties in the owner-occupied and rental sectors and convention changes are partly responsible for the divergence. However, it still is the case that the gains achieved in energy efficiency in the private rental sector (relative to owner-occupied housing) are not accompanied by similarly large gains in environmental impact.

Another way to control for the differences in characteristics of properties in the owner-occupied and private rental samples is through propensity score matching. More precisely, we adopt a multivariate-distance matching approach to identify properties in our owner-occupied group that best resemble private rental ones. Our approach matches each certificate of a private rental property to another certificate of an owner-occupied property exactly on property characteristics (built form, property type, construction age band) and timing (pre-approval, approval to enforcement, and post-enforcement periods). Additionally, the properties are also matched based on the closest floor area. We then estimate regressions similar to those in Table 11, but on the private rental and owner-occupied matched samples. Appendix Table A6 shows that, as before, there is a divergence between energy efficiency and environmental impact. The next section examines the reasons for the divergence.

5.2. Reasons for the divergence

Properties differ in their main energy source (natural gas, electricity, oil, etc.), and these sources entail different trade-offs between cost (energy efficiency) and CO_2 emissions (environmental impact). In this section, we show that the composition of energy sources, their price dynamics, and the measurement of carbon factors matter for explaining the divergence.

5.2.1. Energy sources

In our sample, private rental properties are more likely than owner-occupied homes to rely on electricity as their primary energy source (35.3% vs. 17.7%). Conversely, natural gas is less prevalent among private rentals (52.6%) than among owner-occupied properties (67.6%).[37]

The RdSAP conventions specify fuel prices used in energy-efficiency measurements. Fig. 7(a) plots the evolution of electricity and gas prices over time. The solid lines plot the unit prices (pence/kWh) used in the RdSAP calculations, which are updated every semester.[38] The dashed lines plot the quarterly evolution of the fuel components of consumer price indices. The figure shows that prices specified in the RdSAP conventions follow the market evolution.

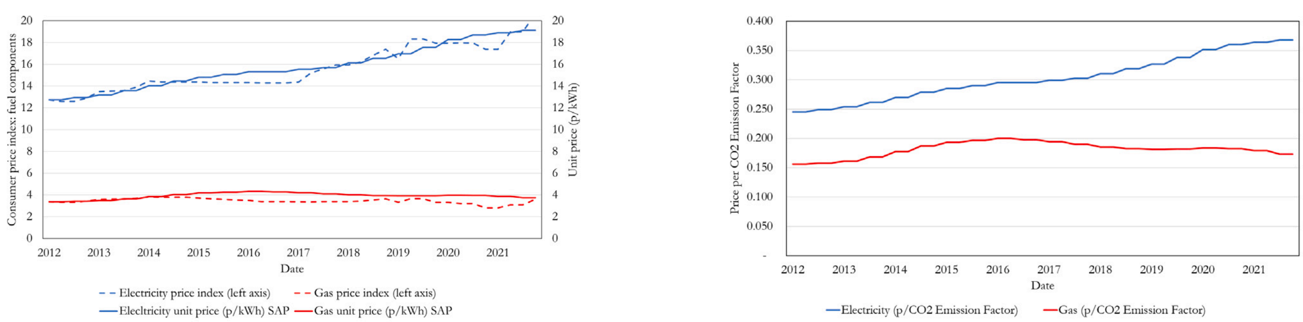
Fig. 7(a) shows that, over the sample period, electricity prices rose relative to gas prices. Abrell et al. (2022) and Grubb and Drummond (2018) analyze the source of the increase and attribute it (at least partially) to the introduction in the UK, in 1 April 2013, of a Carbon Price Floor (CPF) that supports the European Union Emissions Trading System (EU ETS) allowance prices. When ETS prices are below the CPF, an additional tax equal to the difference between the two is levied on producers using fossil fuels to generate electricity. The same production side policy is behind the marked shift in the energy sources used to generate electricity in the UK over this period. Fig. 8 shows, starting in 2013, a large reduction in the use of coal for electricity production, replaced by gas and renewables. This large reduction is consistent with the prediction of the model of Arkolakis and Walsh (2023) that policy interventions significantly accelerate renewable uptake in electricity production.

[37] These proportions are measured using the first certificate of each observation pair. The remaining properties use heating oil and other energy sources. We focus the discussion on electricity and natural gas which are the most prevalent.

[38] For electricity, we use the prices for the standard tariff but the patterns are similar for the other tariffs.

Table 11
Energy efficiency versus environmental impact rating gains: The dependent variables are the changes in energy efficiency, in environmental impact, and in the ratio of energy efficiency to environmental impact between pairs of certificate observations for the same property. $\mathbb{1}_{Rental\,Private}$ is a dummy variable that takes the value of one for private rental properties, and zero for owner-occupied. $\mathbb{1}_{ApprovalToEnforcement}$ is a dummy variable that takes the value of one for second certificates between April/15 and April/18, and zero otherwise. $\mathbb{1}_{PostEnforcement}$ takes the value of one for second certificates after April/18, and zero otherwise. The sample includes multiple certificate properties in the bottom third of initial energy efficiency with tenure equal to owner-occupied (and certificate requested for marketed sale) or private rental (and certificates requested for the purpose of a private rental). Tenure and transaction type are measured using the second certificate of each observation pair. Property characteristics fixed effects are dummies for construction age, property type, built form and floor area. RdSAP fixed effects are dummies for the conventions in effect at the times of the first and second certificates of each observation pair. Standard errors are clustered at the property-level and corrected for heteroscedasticity and autocorrelation. They are reported in parentheses.*,**, and *** indicate significance at 10%, 5%, and 1% respectively.

Dependent variable	Δ Energy	Δ Environ.	Δ Energy/Env.	Δ Energy	Δ Environ.	Δ Energy/Env.
	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{Rental\ Private}$	0.378***	−0.738***	0.028***	0.528***	0.285***	0.004***
	(0.077)	(0.073)	(0.001)	(0.077)	(0.072)	(0.001)
$\mathbb{1}_{Approval\ to\ enforcement}$	2.099***	1.741***	−0.001	1.298***	1.220***	−0.006**
	(0.063)	(0.060)	(0.001)	(0.151)	(0.142)	(0.003)
$\mathbb{1}_{Post\ enforcement}$	3.152***	2.350***	0.006***	0.836***	1.422***	−0.021***
	(0.058)	(0.055)	(0.001)	(0.185)	(0.174)	(0.003)
$\mathbb{1}_{Rental\ Private} \times \mathbb{1}_{Approval\ to\ enforcement}$	2.038***	0.460***	0.043***	1.180***	0.247**	0.027***
	(0.119)	(0.113)	(0.002)	(0.119)	(0.112)	(0.002)
$\mathbb{1}_{RentalPrivate} \times \mathbb{1}_{PostEnforcement}$	−0.531***	−1.890***	0.039***	−0.102	−1.096***	0.028***
	(0.095)	(0.090)	(0.002)	(0.094)	(0.089)	(0.002)
Constant	14.555***	13.015***	0.016***	15.698***	12.935***	0.044***
	(0.040)	(0.038)	(0.001)	(0.116)	(0.110)	(0.002)
Fixed effects:						
Property characteristics	No	No	No	Yes	Yes	Yes
RdSAP convention period	No	No	No	Yes	Yes	Yes
Adjusted-R^2	0.01	0.01	0.02	0.06	0.07	0.06
Observations	671,492	671,492	671,485	671,274	671,274	671,267



(a) Electricity and gas prices

(b) Electricity and gas prices per unit of CO_2

Fig. 7. Energy prices: Panel A plots the evolution over time of domestic gas and electricity prices. The dashed lines (left y-axis) plot the quarterly evolution of the fuel components of consumer price indices obtained from https://www.gov.uk/government/statistical-data-sets/monthly-domestic-energy-price-stastics. We set the starting point for the consumer price indices to be the same as the starting prices of electricity and gas in the RdSAP calculations for ease of comparison. The solid lines plot the evolution over time of unit prices (pence/kWh) of electricity and gas used in the RdSAP calculations (right y-axis). The prices used in the RdSAP calculations are updated every semester. For electricity, we use the prices for the standard tariff. Panel B plots the evolution of over time of unit prices of electricity and gas used in the RdSAP calculations (pence per KWh) divided by the corresponding emission factors of the energy source (Kg CO_2 per kWh) specified in the RdSAP conventions.

The RdSAP conventions also specify fuel-specific emission factors, and Fig. 7(b) plots the ratio of prices to these emission factors. The figure shows that electricity is more expensive per unit of emissions than gas, and that the gap widens over the sample period, mirroring their relative price dynamics. Therefore, reductions in electricity usage tend to have relatively larger cost than emission benefits when compared to gas. This, together with a larger reliance on electricity in the private rental sector and the high incidence of low-energy lighting retrofits, help to explain the previously documented divergence between energy efficiency and environmental impact.

Table 12 shows the importance of fuel source more formally in the context of regression analysis that control for property characteristics and RdSAP convention periods. The dependent variable is the within property changes in the ratio of energy efficiency to environmental impact that we previously analyzed. For ease of comparison column (1) reports the estimates from column (6) of Table 11. In column (2) we add main fuel fixed effects to the set of explanatory variables. The estimated increase in the ratio of energy efficiency to environmental performance for rental private relative to owner-occupied from approval to enforcement declines from 0.031 (column 1, adding the estimated coefficients in the first and fourth rows) to 0.021 (column 2) and the adjusted-R^2 of the regression almost doubles. This shows that fuel source is indeed important for explaining the differences.

In the remaining columns of Table 12 we report estimates with the sample restricted to properties that use gas (column 3) and electricity (column 4) as main fuel. These regressions show that properties that use electricity as main fuel drive most of the divergence. The estimated increase in the ratio of energy efficiency to environmental performance for rental private relative to owner-occupied from approval to enforcement is only 0.014 (=0.004+0.010) among those that use gas compared to 0.078 (=0.006+0.072) among those that use electricity as main energy source.

Table 12
Importance of main fuel source in explaining the divergence: This table reports the results examining the role of main fuel in explaining the divergence between energy efficiency and environmental impact. Across the columns, the dependent variable is the ratio of energy efficiency to environmental impact between pairs of certificate observations for the same property. For ease of comparison, column 1 reports estimates from column 6 of Table 11. The second column adds dummies for different types of main fuel used by the property as reported in the first certificate of an observation pair. Subsequently, the third (fourth) columns splits the sample by properties using gas (electricity) as main fuel, reported in the first certificate of an observation pair. $\mathbb{1}_{\text{Rental Private}}$ is a dummy variable that takes the value of one for private rental properties, and zero for owner-occupied. $\mathbb{1}_{\text{Approval to enforcement}}$ is a dummy variable that takes the value of one for second certificates between April/15 and April/18, and zero otherwise. $\mathbb{1}_{\text{Post enforcement}}$ takes the value of one for second certificates after April/18, and zero otherwise. The sample includes multiple certificate properties in the bottom third of initial energy efficiency with tenure equal to owner-occupied (and certificate requested for marketed sale) or private rental (and certificates requested for the purpose of a private rental). Tenure and transaction type are measured using the second certificate of each observation pair. Property characteristics fixed effects are dummies for construction age, property type, built form and floor area. RdSAP fixed effects are interactions of dummies for the conventions for assessment in effect at the times of the first and second certificates for each observation pair. Standard errors are clustered at the property-level and corrected for heteroscedasticity and autocorrelation. They are reported in parentheses.*,**, and *** indicate significance at 10%, 5%, and 1% respectively.

Dependent variable	Δ Energy/Environment			
Sample	All properties		Main fuel: gas	Main fuel: electricity
	(1)	(2)	(3)	(4)
$\mathbb{1}_{\text{Rental Private}}$	0.004***	0.005***	0.004***	0.006*
	(0.001)	(0.001)	(0.001)	(0.004)
$\mathbb{1}_{\text{Approval to enforcement}}$	−0.006**	−0.004*	−0.003**	−0.023**
	(0.003)	(0.002)	(0.001)	(0.009)
$\mathbb{1}_{\text{Post enforcement}}$	−0.021***	−0.019***	−0.010***	−0.033***
	(0.003)	(0.003)	(0.002)	(0.010)
$\mathbb{1}_{\text{Rental Private}} \times \mathbb{1}_{\text{Approval to enforcement}}$	0.027***	0.016***	0.010***	0.072***
	(0.002)	(0.002)	(0.001)	(0.006)
$\mathbb{1}_{\text{Rental Private}} \times \mathbb{1}_{\text{Post enforcement}}$	0.028***	0.022***	0.009***	0.069***
	(0.002)	(0.002)	(0.001)	(0.005)
Constant	0.044***	0.004**	−0.001	0.125***
	(0.002)	(0.002)	(0.001)	(0.007)
Fixed effects:				
Property characteristics	Yes	Yes	Yes	Yes
RdSAP convention period	Yes	Yes	Yes	Yes
Main fuel	No	Yes	–	–
Adjusted-R^2	0.06	0.11	0.07	0.14
Observations	671,267	671,267	411,722	168,515

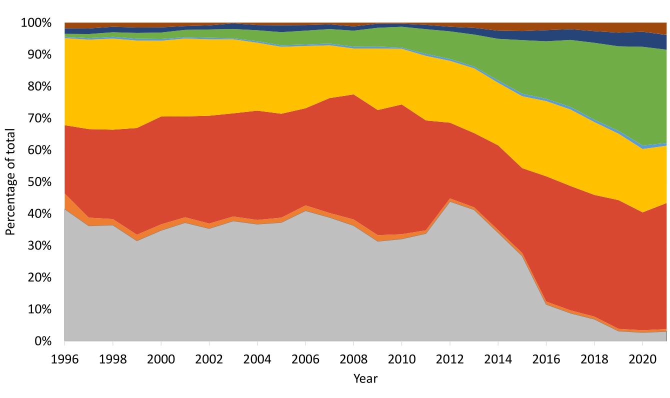


Fig. 8. Fuel sources used in electricity production: The figure plots the fuel sources used in the generation of UK electricity over time, as a percentage of the total. The data are from the National Statistics publication Digest of UK Energy Statistics (DUKES) produced by the Department for Business, Energy and Industrial Strategy.

We assess the role of energy source by calculating within-property changes in annual energy costs between pairs of certificates as a function of the property's primary fuel.[39] Column (1) of Table 13 reports the average change in energy costs (£/year) between the first and second certificates in each pair, classified by the main fuel recorded on each certificate. The largest (smallest) energy cost reductions are for properties that switch from electricity (gas) to gas (electricity). These reductions are the result of changes in energy sources, their prices and the energy efficiency investments undertaken in between the dates of certificates. Consistent with energy costs driving investment decisions, the last column shows that a much larger number of properties shift from electricity to gas than the reverse (45,399 versus 3400 properties, respectively).

5.2.2. Measurement

Column (2) of Table 13 reports average changes in annual emissions (tons CO_2/year) between the first and second certificates in each pair, based on the assessment-procedure carbon factors and classified by the property's main fuel on each certificate. However, unlike for energy prices, these emission factors were not regularly updated during our analysis period. Appendix Figure A9 compares the time-series evolution of the RdSAP emission factors with the government's greenhouse-gas conversion factors. For example, RdSAP 2012 version 9.92 (applicable from 2014 onward) specifies emission factors of 0.216 $kgCO_2$/kWh for natural gas, 0.519 for electricity, and 0.298 for heating oil, and these same values were used in EPC calculations through the end of our sample. They reflect the carbon footprint of the energy sources in the

[39] As for other parts of the analysis, the sample is restricted to multiple-certificate properties in the bottom tercile of initial energy efficiency that are either owner-occupied (with the certificate requested for a marketed sale) or privately rented (with the certificate requested for a private rental).

Table 13

Energy sources, energy costs and CO_2 emissions: The table shows the average change in energy costs (£/year) and emissions (Ton CO_2/year) between the first and second certificates of each observation pair, as a function of the type of main fuel at the time of each of the certificates. For instance, electricity to gas refers to properties that used electricity as the main fuel source in the first certificate and gas in the second certificate. The sample is restricted to multiple certificate properties in the bottom tercile of initial energy efficiency that are owner-occupied (and the certificate is requested for a marketed sale) or rented privately (and the certificate requested for a private rental). The third column shows the changes in CO_2 when emissions are calculated using the Government conversion factors for company reporting of greenhouse gas emissions instead of those specified in the conventions. The last column shows the number of properties.

Main fuel initial to final	(1) ΔEnergy cost (£/year)	(2) ΔEmissions (Ton CO_2/year)	(3) ΔEmissions upd. (Ton CO_2/year)	(4) Number of properties
Gas to gas	−141.99	−1.89	−2.23	404,135
Electricity to electricity	−124.52	−0.86	−2.54	113,879
Oil to oil	−144.06	−2.14	−2.37	19,268
Electricity to gas	−351.89	−4.04	−4.02	45,399
Gas to electricity	−15.27	−0.41	−1.98	3400

UK in 2014, but fail to take into account the subsequent large decline in electricity emissions that has happened as a result of the change in fuel sources used in its production.

Because the fuel-specific emission factors have not been updated, the assessment procedure fails to capture improvements in the environmental impact of properties that rely primarily on electricity. Column (3) seeks to quantify this measurement issue by recalculating changes in CO_2 emissions using updated carbon factors for the year in which each certificate was issued, rather than the fixed factors specified in the RdSAP conventions. These are our calculations but which come with the caveat that for the properties that use more than one fuel type, the EPC data does not allow us to split the energy consumed by fuel type. Therefore, in the calculations we use the emissions of the main fuel for the total amount.

Comparing columns (2) and (3), the largest differences arise for electricity to electricity (−0.86 versus an updated value of −2.54) and gas to electricity (−0.41 versus −1.98). Thus, properties using electricity have become much "greener" in a way that is not captured by the measures included in the certificates. However, higher electricity prices may also be the reason why a larger number of property owners switch from electricity to gas than vice-versa (column (4)). While this shift reduces current costs, it is not necessarily aligned with decarbonization objectives and climate targets.

5.3. Policy implications

A key insight from our analysis is that combining different fuel prices and quantities into a single cost-based metric — while it simplifies comparisons across heterogeneous properties and can spur energy-efficiency upgrades — does not necessarily deliver commensurate emissions reductions. Households will focus their investments on energy cost reduction, meaning a reduction in the use of more expensive fuels, which are not always the dirtiest. If certificates are to be used to tackle the climate challenge, they should report information that accurately reflects emissions, and regulation should target carbon directly rather than efficiency (cost) metrics. This is particularly important in light of the reductions in carbon emissions of electricity that we have witnessed over the past few years. If they continue going forward, electricity will become a greener source of energy than the most common alternative of natural gas, and its use should be favored in regulatory interventions.

Another important lesson concerns the link between the production and consumption side of energy. Interventions in electricity generation to make it greener may during a transition phase make electricity more expensive as producers pass on the added costs to customers. This may lead households and investors to make investments to switch to less expensive energy sources (from electricity to gas), a switch which in the not-so-distant future may become detrimental to carbon emissions. Furthermore, this shift may also not be beneficial from a future cost point of view. The model of Arkolakis and Walsh (2023) predicts that as more renewable-capital is installed for electricity production, investment prices will fall due to global spillovers from learning by doing, leading to falls in electricity prices. A regulatory intervention on the consumer side that targets emissions directly would align the objectives on the consumption and production sides of the market, in order to achieve climate targets.

6. Conclusion

We have studied the effects of a regulatory intervention that required private rental properties to meet a minimum energy efficiency standard. Our main data source is the energy performance certificates needed to sell or rent out a home in England and Wales since October 2008. The analysis shows that the regulations increased investment intensity in energy efficiency within the rental sector, primarily in retrofits with lower capital expenditure and higher projected internal rates of return, such as low-energy lighting and heating controls.

Using a DiD empirical design, we estimate a rent increase of 0.9% — an upper bound on the effect of the regulations — as it does not account for selection. In an instrumented DiD design, which uses the pre-regulatory threshold as an instrument, the estimated rent effects are economically small — both relative to renters' energy-bill savings and capital expenditures incurred by landlords. Overall, we conclude that landlords are unable to pass energy-cost savings from efficiency upgrades on to tenants through higher rents, explaining why they do not make the investments in the absence of the regulations, and why, when faced with regulations, they focus on low-capex improvements.

Our analysis shows that the regulations, and the investments they induced, generated a divergence between energy-efficiency and environmental-impact improvements in rental versus owner-occupied properties. While rental properties experienced larger energy-efficiency gains, these were not matched by commensurate reductions in environmental impact. Energy efficiency is a cost-based measure that depends on both the quantity of energy consumed and its unit price. By contrast, carbon footprint depends on the quantity of energy consumed and the carbon intensity of the fuel source. Therefore, regulatory interventions that target cost-based metrics favor reductions in the consumption of the most expensive energy sources but not necessarily the most polluting ones.

CRediT authorship contribution statement

Nuno Clara: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **João F. Cocco:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **S. Lakshmi Naaraayanan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Varun Sharma:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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