Investments that Make our Homes Greener: The Role of Regulation*

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November 28, 2022

Abstract

The operation of residential buildings (our homes) is responsible for roughly 22% of the global energy consumption and 17% of the CO_2 emissions. We study the effects of a regulatory intervention aiming to reduce carbon emissions by requiring privately rented properties to satisfy minimum energy efficiency standards. The regulation triggered significant investments in the rental sector. However, the environmental gains were smaller, limited by the use of more polluting energy sources. Regulatory interventions that target carbon emissions directly may be more effective in tackling the climate challenge.

Keywords: Real Estate, Household Finance, Energy Efficiency, Climate Change.

JEL Classification: R1, G5, Q4, Q5.

*We would like to thank Marcin Kacperczyk, Thomas Fischer, Baridhi Malakar, Hana Nguyen, Stef Schildermans, Nancy Wallace, and seminar participants at Cambridge Judge Business School, Conference on Financial Economics and Accounting, FMA Annual Meeting, London Business School, HEC-HKUST Sustainable Finance Seminar, KWC/SNEE Conference on Sustainable Finance, NBER Summer Institute, OCC Symposium on Climate Risk in Finance and Banking, UNC Real Estate Research symposium and 11^{th} European Meeting of the Urban Economics Association for comments and suggestions. We would also like to thank David Jones for numerous conversations and materials that have helped us understand the assessment procedure.

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1 Introduction

The operation of residential buildings (our homes) is responsible for roughly 22% of the global energy consumption and 17% of the CO_2 emissions (Programme (2020)). Investments that improve the energy efficiency and environmental performance of homes can make a very significant contribution to the climate challenge.[1] This and the belief that investment levels are below the optimal have motivated government interventions around the world, in the form of subsidies (Fowlie, Greenstone, and Wolfram (2018), Hahn and Metcalfe (2021)) and regulations (Hausman and Joskow (1982), Allcott and Greenstone (2017)).[2] In this paper we analyze one such intervention, the Minimum Energy Efficiency Standard (MEES) Regulations, first approved by the United Kingdom Parliament in March 2015, and draw general implications for their design.

The MEES regulations aim to improve the energy performance of the worst-performing buildings by introducing minimum standards, meaning a minimum level of energy efficiency that privately rented residential properties must satisfy. By targeting the private rental sector exclusively, the regulations presume that investment inefficiencies in this sector are more pervasive and yield sub-optimal levels of private investment (a private energy-efficiency gap as defined by Gerarden, Newell, and Stavins (2017)). Another of the regulations' aims is to reduce carbon emissions, which are socially excessive in the presence of energy use externalities (a social energy-efficiency gap). A Pigouvian tax would internalize such externalities, but this approach was not followed, possibly because it lacked political support. As a result, the MEES regulations have multiple confounding objectives and take a second-best approach to addressing externalities. This is not uncommon (Allcott and Greenstone (2012)), making it particularly important to evaluate their effects.

Our main data source are Energy Performance Certificates (EPCs) for residential properties in England and Wales. Since October 2008, properties that are sold or rented out are legally required to have a valid EPC.[3] An accredited assessor carries out a physical inspection of the property and inputs the results into government-approved software that generates the certificate. It measures the energy efficiency of the different elements of the home (such as walls, main

[1] Our main focus is on improvements to the stock of existing properties, as opposed to the construction sector and the features of new build homes. When the building construction industry and the operation of non-residential buildings are also considered, the proportions of global energy consumption and CO_2 emissions of the real estate sector increase to 35% and 38%, respectively.

[2] See also papers on appliance rebate programs (Houde and Aldy (2014), Davis, Fuchs, and Gertler (2014))

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

heating, etc.,) and its overall efficiency. The calculations are based on an engineering model built into the software. The energy efficiency is a cost-based measure: it depends on the type(s) of energy consumed (electricity, gas, etc.) during the operation of the property, their quantities, and prices. The certificates tackle the important issue of energy efficiency measurement (see, for example Bardhan, Jaffee, Kroll, and Wallace (2014)). They also provide a measure of the environmental impact of homes (the carbon emissions from the operation of the property).

The data covers roughly 14 million unique properties. It includes properties for which we observe only one certificate and those for which we observe multiple certificates. Naturally, the sample of multiple certificate properties is not random; those owners who invest in their properties are more likely to request a new certificate. Our analysis exploits the timing of and the reason for issuing a new certificate. We also merge the certificates with information on property sales, providing further evidence on the nature of selection.

We first evaluate the investment inefficiencies rationale for the regulation to apply to the private rental sector. In perfect markets, property and rental prices reflect the value of the savings associated with energy efficiency retrofits. Hence, positive net present value investments will be undertaken regardless of tenure. In reality, there are departures from perfect markets such as imperfect information and financing frictions (Gerarden, Newell, and Stavins (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. Moreover, their expected shorter tenure may make it uneconomical to pay for the costs of acquiring property-specific information (or to incur attention costs). In this case, we expect rental properties to be less efficient than owner-occupied ones.

We characterize the housing stock prior to the regulations' approval. Perhaps surprisingly, we find that private rental properties are more energy efficient than owner-occupied ones, both on average and in the left tail of the distribution. However, further analysis shows that this is due to a composition effect. The rental sector has a much larger proportion of flats and a smaller proportion of detached and semi-detached houses than the owner-occupied sector. Flats have fewer external walls, which enhances their energy efficiency. We find that conditional on property type, properties in the private rental sector tend to be less energy efficient than owner-occupied ones. For instance, 21.6% of the flats in the private rental sector is in the bottom one-third of the overall distribution of energy efficiency, compared to 19% of the flats in the owner-occupied sector.

In order to evaluate the effects of the regulations, we compare the investments in the private rental sector before and after their approval to those in the owner-occupied sector. The regulations triggered significant investments in the private rental sector. Furthermore, there is a shift in the composition of private rental properties in which investments are made towards initially lower-rated properties and in retrofits that lead to larger percentage increases in energy efficiency.

The characterization of the retrofits shows that they tend to concentrate on those elements that require lower capital expenditures and generate higher projected internal rates of return (IRR), such as low energy lighting, main heating controls, and roof insulation. An exception is the double glazing of windows; it is quite prevalent in the data even though it is unattractive from a financial point of view. Home comfort (e.g., noise reduction) or aesthetics may be the driver of such retrofits. On the other hand, the insulation of walls, particularly solid brick walls, is rare. An important contribution of our paper is the large-scale evidence on the types of retrofits that both homeowners and landlords undertake.

A second main argument for the regulations is the reduction in carbon emissions. Our analysis shows that the improvements in the energy efficiency of rental properties relative to owner-occupied ones were not accompanied by similarly large improvements in environmental impact. After March 2015, there is a divergence between the energy efficiency and environmental impact gains for private rental properties. Energy efficiency is a cost-based measure; it depends on the quantity and types of energy consumed and their unit price. On the other hand, the carbon footprint of homes depends on the quantity and types of energy consumed and how polluting the energy source is (as measured by their carbon factor). Regulatory interventions targeting energy cost-based measures favor investments in reducing the consumption of expensive energy, and not necessarily the most polluting one, thus driving the divergence between energy efficiency and carbon emissions. Governments around the world, including the United States, use energy efficiency as a critical policy tool to achieve reductions in CO_2 emissions.[4] As these countries expand energy efficiency policies to decarbonize the housing stock, our results point to a more nuanced view of energy efficiency's role as a credible climate mitigation tool.

Our analysis also reveals a tension between policies on the consumption and production sides of energy markets. In 2013 the UK introduced a carbon tax on the production of electricity. This led to a large reduction in coal-based electricity and an increase in the use of gas and renewables. At the same time, it may have contributed to higher electricity prices, as added costs are passed

[4]For example, the U.S. Energy Information Administration assumes that energy efficiency will account for a 42 percent reduction in CO_2 as part of its crucial mitigation plans (EIA (2015))

on to consumers. Properties that use electricity as the main fuel source become less energy efficient, and in fact, we observe significant household investments in shifting heating systems from electricity to gas. As electricity becomes greener, this may soon become undesirable from an emissions point of view. Coordinated policies on the production and consumption sides of the market that target emissions directly may be more effective at addressing the climate challenge. The main lesson is that regulations are likely to be more effective at addressing the climate challenge if they target carbon emissions directly.

Our paper is most closely related to the nascent literature on residential energy efficiency.[5] The literature has found low participation in programs that subsidize investments, even though they have positive private returns and generate environmental benefits (Fowlie, Greenstone, and Wolfram (2015), Fowlie, Greenstone, and Wolfram (2018)). The results are consistent with the high non-monetary costs of program participation. In addition, Allcott and Greenstone (2017) find that ex-ante projections overestimate energy savings and that the programs attract households whose participation in the programs generates low social value. This evidence makes it more important to understand other forms of intervention, such as the role of regulations in spurring investments in energy efficiency. This is particularly the case in light of the evidence that mandatory energy efficiency disclosure requirements encourage energy-saving investments (Myers, Puller, and West (2022)).

There is a recent growing literature that studies the impact of climate risk on the value of real estate assets,[6] and the mortgages used to finance them.[7] Our paper differs from these by focusing on the energy efficiency investments and the effects of the regulatory intervention. Some papers use the same data we do to address different questions. For instance, Fuerst, McAllister, Nanda, and Wyatt (2015) studies the relation between home prices and energy efficiency using hedonic price regressions and finds a positive correlation between the two. 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, its effects on both energy efficiency and carbon emissions, and draw

[5]There is a larger literature that studies the energy performance of commercial buildings (e.g., Eichholtz, Kok, and Quigley (2010), Jaffee, Stanton, and Wallace (2019)) for which data has traditionally been more readily available.

[6]It includes Bernstein, Gustafson, and Lewis (2019), Ortega and Taspinar (2018), Baldauf, Garlappi, and Yannelis (2020), Murfin and Spiegel (2020), Giglio, Maggiori, Krishna, Stroebel, and Weber (2021), among others.

[7]E.g. Issler, Stanton, Vergara, and Wallace (2020), Gete and Tsouderou (2021)). See also Giglio, Kelly, and Stroebel (2021) for a review of the literature on climate finance.

general implications for regulatory design.

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 compares energy efficiency and environmental gains. Section 5 merges the certificates with property transactions data to provide further evidence on selection. The final section concludes.

2 The data

Our main data source are the EPCs. But for parts of the analysis we also merge them with Land Registry data that includes information on residential property transactions in England and Wales.

2.1 EPCs

The Energy Performance of Buildings Directive (2002/91/EC) is an EU Directive on the energy performance of buildings. It aims to tackle climate change by reducing the amount of carbon produced by buildings. An essential component of the legislation addresses the measurement of the efficiency of homes through EPCs. Measurement is one of the crucial bottlenecks discussed by Bardhan, Jaffee, Kroll, and Wallace (2014) for energy efficiency retrofits. The legislation was implemented on a phased basis across the UK. In England and Wales, EPCs have been required by law since the 1st of October 2008 to sell or rent out a home.[8] EPCs are valid for 10 years, but they may be updated before they expire.

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 guidelines or conventions, and it is fairly thorough.[9] The assessor must collect documentary evidence (photographs and invoices for works carried out). The information is imputed into a government-approved software that

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

[9]An example of an assessor sheet is available at https://quidos.co.uk/wp-content/uploads/2016/05/RdSAP_9.92_Data_Collection_Sheet.pdf.pdf.

generates the EPC. Its cost ranges from £60-120.

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.[10] In addition to these, the data includes a brief description of the property element (e.g. type of windows, insulation thickness) that we exploit in the analysis. EPCs provide a measure of the overall energy efficiency rating of the property on a numerical scale of 1 to 100 (SAP points).

The SAP rating is a measure of the energy running costs of the property based on the estimated energy consumption needed for space heating, water heating, ventilation and lighting (minus energy saving/generation technologies). The estimated energy consumption uses standardized assumptions for occupancy and location and it is scaled by floor area.[11] Total energy cost is equal to the sum of the energy used for each of the purposes multiplied by the prevailing prices of the type(s) of fuel used. 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. However, individual home ratings are affected by relative changes in the price of particular heating fuels (e.g. electricity and gas). Appendix A.1 provides more details on the calculations and on the relation between energy costs and rating. It makes it clear that the energy efficiency rating is an energy cost measure.

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 thresholds.

[Insert Table 1 here]

In addition to measuring the energy efficiency of the property, EPCs include recommendations on how to improve it. They depend on the characteristics of the property and they are automatically generated by the software. The assessor can override the software recommendations but must provide a valid reason for doing so. For each recommendation, there is the indicative capital expenditure (capex) required to implement it, and the typical annual monetary savings likely to be achieved. EPCs include several recommendations that often differ

[10] 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).

[11] The normalization by location (climate) and floor area was done so that higher standards would not be required of properties located in colder areas and of smaller properties.

in the levels of capex required (e.g., the installation of low-energy lighting versus wall insulation). The recommendations, capex and savings figures depend on the property characteristics; a more significant investment is needed to insulate solid walls (they are hard to treat) than cavity walls.

EPCs measure the environmental performance of the home in a scale of 1 to 100. It depends on the estimated energy usage and the carbon footprint of the type of fuel(s) used in the property. Appendix A.2 provides details on the calculations and on the relation between environmental impact (EI) rating and CO_2 emissions. Similarly to the energy efficiency rating, the environmental index is based on standardized assumptions for occupancy and location and it is normalized by floor area. The appendix also includes an example of a certificate.

Over the years, there have been amendments and additions to the RdSAP conventions used to perform the calculations. Some of them reflect new knowledge on the efficiency of a given element, such as the efficiency of a given boiler type. Other amendments provide more precise guidance on the assessment data inputs.[12] In the analysis we take into account these convention changes. (Appendix A.3 provides information on the conventions that apply.)

The EPCs data for England and Wales are publicly available from the Ministry of Housing, Communities, and Local Government (MHCLG) Open Data Communities website. There are two data files, one for the property characteristics and another for the recommendations. The two can be easily merged using a unique identifier. The data include information that is not in the actual certificate, but that is relevant for our analysis. For instance, on tenure (owner-occupied, private rented, 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).

For the recommendations, the certificates include information not in the dataset. The actual certificates include the annual savings that may be achieved by implementing each recommendation, but the dataset only includes a measure of the overall savings that can be achieved from implementing all the recommendations, i.e., not broken down by recommendation. In order to obtain savings by recommendation, we scrape data from the EPCs that are available online.[13]

[12]For instance, whether a property has wall insulation is difficult to ascertain from a visual inspection. The assessor often has to decide based on the type of wall, the age of the property and knowledge of the building practices at the time of construction. However, the assessor may also make a determination based on documentary evidence of wall insulation installation by the owner. Some convention changes reflect updated guidance on the assumptions and documentary evidence required.

[13]For each property, only the latest certificate is available online. Therefore, we only have savings by recom-

2.2 Sample construction and summary statistics

Our sample starts on 22 September 2008, the starting date of RdSAP 2005 version 9.82, and it includes data until September 2020. New builds are assessed using a more complete Standard Assessment Procedure (SAP). Given the different procedure used for their assessment, and our focus on retrofits, we remove new build observations from the sample (but retain subsequent observations (if any) for the new build properties).

We carry out some data cleaning. There are some entries for a given property with the same inspection date but a different lodgement date/time in the system. There are several possible reasons for this. The first is that the assessor has introduced the data in the system twice, and in fact, we find that some of the entries are identical except for the lodgement date. In other cases, the entries are not exactly the same; the assessor may have made a mistake during the first entry and decided to enter the data in the system again. In these cases, we keep only the information from the last entry, which is the valid certificate. (Appendix B.1 provides further details on the sample construction.)

For the analysis, we use two main samples. The first is the full sample of EPC data for existing homes that contains 17.7 million certificates for 14 unique residential properties located in England and Wales. This compares with an estimated total number of dwellings in 2010 of 24.2 million.[14] 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. This full sample of EPC data provides a more comprehensive picture of the energy performance of the housing stock.

The second sample includes properties for which there are multiple observations, i.e., for which there are at least two EPC entries. A main advantage is that it allows us to measure energy retrofits within property. The sample of multiple certificates has 6.8 million entries, counting the first observation for each property, corresponding to 3.1 million unique properties. Table 2 reports the number of properties for which we observe a given number of certificates. The vast majority of properties with multiple certificates have two certificates.

[Insert Table 2 here]

Naturally, the sample of properties for which we observe multiple EPCs is not random. In order to start analyzing selection, Figure 1 plots the SAP points distributions for single

mendation for a sub-sample of the observations. We provide additional details below.

[14]The estimates for England are available at https://www.gov.uk/government/statistical-data-sets/live-tables-on-dwelling-stock-including-vacants and for Wales at https://statswales.gov.wales/Catalogue/Housing/Dwelling-Stock-Estimates/dwellingstockestimates-by-year-tenure.

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.[15]

[Insert Figure 1 here]

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. Therefore, we are more (less) likely to observe a second certificate for properties just below (above) this threshold.

The first five columns of Table 3 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). Reflecting their higher efficiency, single certificate properties tend to have less mass in low classifications (very poor and poor), and more mass in the right tail of the distributions (good and very good).

[Insert Table 3 here]

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. The last two columns 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 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.

2.3 The engineering model for energy efficiency rating

The engineering model that calculates energy efficiency for a property as a function of its characteristics is deterministic. (An approved computer software is used by the assessor.) However, our data does not include all the information required to replicate the calculations.

[15] Appendix Table A1 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.

Therefore, we construct an empirical regression model for energy efficiency rating as a function of the classification of its elements. It allows us to translate retrofits into energy efficiency rating point increases and measure the extent that they help meet regulatory requirements.

We let i denote property, j the element (j = main heat, walls, etc), l the star rating associated with that element ($l = 1, ..., 5$), and t time. The equation that we estimate is:

$$\text{Energy efficiency points}_{it} = \alpha + \sum_{j} \sum_{l=1}^{5} \beta_{jl} D_{ijlt} + \gamma X_{it} + \epsilon_{it} \tag{1}$$

where D_{ijlt} is a dummy variable that takes the value of one if property i element j has star rating l at time t, and zero otherwise, X_{it} is a vector of other property characteristics that affect its energy efficiency score, and ϵ_{it} is the residual. The vector X_{it} includes dummy variables for construction age band, built form (semi-detached, mid-terrace, etc.), and property type (house, flat, etc).[16] During the sample period, there are seven versions of the conventions that apply.[17] We use the full sample of EPCs to estimate the model for each of these periods, denoted t_1 through t_7, and obtain seven sets of estimated regression coefficients $(\alpha, \beta_{jl}, \gamma)$.

Figure 2 plots the estimated coefficients on the dummy variables for each of the elements as a function of time. The base category is very poor, so that the lines represent the additional points of a move from this base case. As expected, the estimated coefficients are increasing in the star rating, and there are only a few exceptions (for movements from good to very good). The coefficients for the very good category are sometimes imprecisely estimated due to the relatively small number of observations. The estimated coefficients seem to be fairly stable across periods for the remaining star ratings, except for main heating, whose estimated coefficients decline over time.

The figure uses the same y-axis scale for the plots of the different elements, making it easier to compare their importance. We have also calculated the points increase per one additional star rating by averaging across the estimated dummy coefficients for each element and RdSAP convention period and then averaging across all periods. The most important elements are:

[16]Recall that the calculations do not depend on the characteristics of the household occupying the dwelling nor on its geographical location (except for dwellings with a fixed air conditioning systems rating). The data includes other variables that affect the energy efficiency rating (such as the proportion of glazed area). However, their additional contribution to the overall R^2 is less than one percent, so that we keep the model parsimonious and do not include them among the explanatory variables.

[17]Beginning with RdSAP 2005 version 9.82 (from 22 September 2008 to 17 October 2009) until RdSAP 2009 version 9.94 (from 22 September 2019). Appendix A.3 provides the dates of all revisions.

main heating (with 5.1 points per additional star), hot water (3.5), and walls (3.1). The least important is lighting with 0.6 points per additional star. The remaining elements are: windows (2.2), roof (2.3), and main heat controls (2.4). The last panel of Figure 2 shows the R^2 for each of the seven regressions; its value is fairly stable over time at around 0.8.

[Insert Figure 2 here]

Figure 3 plots the estimated coefficients for construction age band, built form, and property type.[18] The omitted age category is prior to 1900. Older properties are significantly less efficient: the average difference between the most recent and oldest is roughly 9 points. There is also a considerable variation with built form. (The omitted category is semi-detached.) Within houses, detached properties are the least efficient, and enclosed mid-terrace the most efficient. The former have external walls on all sides, while the latter only have one external wall.[19] Flats and maisonettes have fewer external walls and are on average more energy efficient than houses.

[Insert Figure 3 here]

For multiple certificate properties we are able to measure energy efficiency retrofits and their impact on the rating. Let t' and t'' denote the two times at which a certificate is issued for a given property. The change in energy efficiency rating:

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

And using equation (1):

$$\Delta\text{Energy efficiency}_{i,t',t''} = (\alpha_{t''} - \alpha_{t'}) + \sum_{j} \sum_{l=1}^{5} (\beta_{j,l,t''} D_{i,j,l,t''} - \beta_{j,l,t'} D_{i,j,l,t'}) + (\gamma_{t''} X_{i,t''} - \gamma_{t'} X_{i,t'}). \quad (3)$$

When the two observations are in the same convention period the estimated regression coefficients are the same so that we drop the time subscript, and since X_{it} includes only time invariant property characteristics, the equation simplifies to:

[18] These controls are important for the overall model fit. When we exclude them from the regressions the R^2 drops to roughly 0.7.

[19] Enclosed refers to "back-to-back" terraces. Detached properties have four external walls, end-terraces have three external walls, enclosed end-terraces have two adjacent external walls, mid-terraces have two external walls on opposite sides, and enclosed mid-terraces have an external wall on one side only. The number of external walls is an important determinant of energy efficiency.

$$\Delta\text{Energy efficiency}_{i,t',t''} = \sum_j \sum_{l=1}^{5} \beta_{j,l}(D_{i,j,l,t''} - D_{i,j,l,t'}) \quad (4)$$

This equation makes clear the channels for changes in efficiency score: (i) the importance of the property elements, as measured by $\beta_{j,l}$ and shown in Figure 2; (ii) changes in the star rating l of a given property element j as measured by $(D_{i,j,l,t''} - D_{i,j,l,t'})$.

More generally, for two observations for a given property but with different applicable conventions, there are changes in efficiency score that arise from differences in the: (i) estimated regression coefficients; (ii) the star rating of the property elements; and (iii) covariance between the two. We have performed a model variance decomposition to evaluate their relative importance: (i) 8.9% is explained by changes in the estimated coefficients (loadings); (ii) 111.1% by changes in the property elements (characteristics); and (iii) -20% is explained by a negative covariance between loadings and characteristics. Therefore, changes in the characteristics of properties (such as improvements) are much more important than changes in the assessment procedure. In most of the analysis that follows, we focus on the former.

2.4 The importance of the initial level for the investments

We use the sample of multiple certificate properties to characterize the retrofits. For most properties in this sample, 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). We calculate the SAP points cut-offs that correspond to the bottom and top one-third of the distribution of first certificates of multiple certificate properties shown in Figure 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 of Table 4 reports the number of observations in each group, the average initial and change in points, and the percentage change. The number of observations reported refers to observation pairs.[20] There are large increases in energy efficiency for properties in the bottom

[20]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

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.

[Insert Table 4 here]

In Panel B 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 in the analysis that follows.

3 Housing tenure and the regulations

In this section, we focus on housing tenure and the effects of the MEES regulations. 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).[21] 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.[22] Therefore, our sample includes a smaller proportion of owner-occupied and a larger proportion of privately rented properties than the overall stock. This is addressed in the analysis that follows.

3.1 The regulatory framework

In perfect markets, property and rental prices 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 out. In reality, there may be departures from perfect markets, such as investment inefficiencies or financing frictions, that affect the investments undertaken. Among these one potential candidate is imperfect information: households may not be perfectly informed of the financial savings that can be achieved.

sensitive to an alternative definition of cut-offs based on the first certificate of all observation pairs (instead of the first property certificate).

[21]The corresponding 2020 proportions were 0.64, 0.19 and 0.17.

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

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 are not 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.[23] 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 Minimum Energy Efficiency Standard (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.[24] 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.[25]

3.2 The housing stock prior to the approval of the regulations

One of the main arguments for introducing the regulations is that investment inefficiencies in the private rental sector imply that the level of investments carried out by landlords is below the optimal one. In this case, one might expect rental properties to be less energy efficient than owner-occupied ones. We compare the quality of the housing stock in the two sectors prior to the approval of the regulations.

Table 5 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 it is possible that there is more mass in this tail in the rental sector, even if, on average,

[23]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.

[24]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 an assured, regulated, and domestic agricultural tenancies. Guidance is available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882957/Domestic_Private_Rented_Property_Minimum_Standard_-_Landlord_Guidance_2020.pdf.

[25]Since 1 April 2020, the requirement was extended to existing tenancies. Landlords may be able to apply for an exemption, in case they spend £3,500 on improvements and these are not sufficient to bring the rating to E.

properties in this sector are better. Figure 4a plots the whole distributions to show that this is not the case. Properties in the private rental sector are more efficient.

[Insert Table 5 and Figure 4 here]

The second panel of Table 5 shows the average number of stars and the proportion of observations with very poor and poor classifications for several property elements. Except for lighting, rental properties are on average worse and have more mass in the left tail. The bottom panel of the table sheds light on the composition effect that explains why rental properties tend to have higher overall ratings in spite of worse elements. 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 section 2.3 has shown, 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).

To address the composition effect, Figure 4b compares owner-occupied and rental properties within flats. Although the differences do not appear very large, 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 once. Therefore, within property type and prior to the approval of the regulations, the rental sector featured a larger proportion of lower-rated properties.

This evidence is consistent with that of Davis (2010) and Gillingham, Harding, and Rapson (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 it 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.

3.3 The effects of the regulation

We now provide evidence on the effects of the regulation. In 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. These restrictions exclude mainly certificates issued for the purpose of benefiting from subsidies to undertake energy improvements.[26]

Figure 5 plots the distributions of SAP points for certificates issued in selected calendar years (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 bunching of observations, first 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. It is also possible that the MEES regulations, and the discussions around them, raised public awareness about the importance of energy ratings, even if the regulations do not apply to the owner-occupied sector. In either case, it suggests increased importance of the energy efficiency letter rating for the purpose of selling a property. The bottom figures plot the distributions for private rental. Compared to owner-occupied properties, bunching at the 39 thresholds becomes very pronounced in 2018.

[Insert Figure 5 here]

In order to analyze within a property, we first turn to the previous 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 as a precaution for future increases in the regulatory thresholds or changes in the calculations of the assessment procedure. However, we will also use the 39 threshold in the analysis.

Table 6 shows the number of observations, the proportion of observations with a given tenure, 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 is done using the second certificate of each observation pair. Our sample of certificate pairs in the bottom third

[26] In the data, the reason for the request of the certificate is registered in a separate variable named transaction type. Appendix Table A2 reports the number of certificates by tenure and transaction type for the full sample of certificates. 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.

includes 53% of owner-occupied properties, 38% in the private rental sector, and 9% in the social rental sector. Therefore, in terms of the number of observations, and compared to the full sample that also includes single certificate properties, there is a larger proportion of private rentals, which are less energy efficient but have larger increases than owner-occupied ones.

[Insert Table 6 here]

In the bottom part of the table, we divide the sample into observation pairs for which the second certificate was issued before/after April/15.[27] There are significant differences between each of the periods and between owner-occupied and private rental. After April 2015, there is a very large 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.[28]

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 the other tenure types. The points 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.[29]

3.4 Number and timing of certificates

We investigate the number and timing of second certificates in the context of regression analysis.[30] We take the full sample of certificates that include single and multiple certificate prop-

[27]This was the date when the parliament initially approved the regulations. The conclusions that we emphasize are not sensitive to using an alternative cut-off date, such as the date of amendments.

[28]Appendix Figure A5 plots the number of certificates issued over time, summed over each quarter. It distinguishes between first certificates (including single certificate properties) and subsequent certificates. As expected, there is a steady decline in the number of first certificates and an increase in subsequent certificates.

[29]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.

[30]A caveat is that we only observe when the property inspection took place and the certificate issued, and not when the actual investments were undertaken. It is possible that some of the investments were made long before the regulations were introduced but that the certificate was only requested in response to the regulation. We think that this is not very likely: the cost of a certificate is relatively small and a better rating improves the desirability of the property from the point of view of potential tenants. Therefore, one would expect that landlords who invest in energy efficiency measures do not take long before updating the certificate.

erties. For each certificate observation, we create a dummy variable 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 regression in column (1) of Table 7 shows the unconditional mean of this dummy variable: for 0.21 of the certificates there is a subsequent property certificate. In column (2) we include among the explanatory variables a dummy that takes the value of one if the SAP points in the initial certificate are less than 39 and zero otherwise. This is the minimum cut-off for the E band. 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. Private rental is a dummy variable that takes the value of one for private rental and zero for owner occupied (and the sample is restricted to these tenure types). Tenure is measured using the initial certificate since the sample includes single certificate properties. The results show that we are much more likely to observe a subsequent certificate for rental properties, and particularly so for those initially below the 39 points threshold.

The estimated coefficients in column (4) indicate that we observe a subsequent certificate for 0.525 of the private rental properties with a rating below 39 (the sum of all the coefficients in the column). There are several reasons why this may happen, including some properties being moved from private rental to sectors not covered by the regulations, some properties being exempt, and a lack of enforcement. We address these below.

[Insert Table 7 here]

Columns (5) to (7) provide evidence on the timing of certificates. We restrict the sample to certificates with a date prior to April 2015 for which we observe a subsequent one and construct a dependent dummy variable that takes the value of one if the subsequent certificate is post April 2015 and zero otherwise. Therefore, these regressions tell us the likelihood that subsequent certificates are issued in the post-regulation period. Since the sample includes subsequent certificates for all observations, we now measure tenure using these. Column (5) shows that there is a higher probability of a post April 2015 certificate for lower rated properties that are privately rented. However, the interaction effect is relatively small.

Certificates are required by law since the 1st of October 2008 and are valid for ten years. This means that some of the certificates issued in the first couple of years of the sample expire in the last two years.[31] In order to distinguish them from those certificates that may have been issued in response to the regulations, in columns (6) (and (7)) we restrict the sample to observations for which the new certificate was issued when there were still at least 2 years (5 years) left of validity in the previous one. The estimated coefficients on the interaction term are now significantly larger. There is a very significant increase in the issuance of certificates for lower-rated properties in the private rental sector (compared to owner-occupied) after April 2015.

3.5 Magnitude and nature of the investments

We study the time series evolution of the changes in energy efficiency for multiple certificate properties in the bottom tercile. For each pair of certificates, we calculate the difference in points between the first and second certificates (within property changes). Figure 6a plots the average change in energy efficiency for second certificates issued in each year/quarter (i.e. $\Delta\text{Energy efficiency}_{i,t',t''}$ averaged across all properties i with a second certificate issued in year/quarter t''). The figure distinguishes between 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 is measured using the second certificate of each observation pair. The vertical lines mark the approval date (April 2015), the issuance of guidance (October 2017), and the enforcement (April 2018) of the MEES regulations.

[Insert Figure 6 here]

Figure 6a 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, but since the regulations applied to new (and not existing) tenancies, we still observe large investments after April 2018. (We return to the other panels of this figure below.)

The data includes a description of the property elements that we use to characterize the retrofits. Table 8 shows the percentage of properties with given characteristics as recorded in the first certificate of the observation pair (Initial), and the percentage points difference

[31] Appendix Table A3 shows, for the sample of multiple certificates, the age of the previous certificate when a new one is issued. There are significant increases in mean and median age in 2018 and 2019.

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 and period is done using the second observation of each pair.

[Insert Table 8 here]

Comparing the initial values for private rental for the pre and post April 2015 periods, we see that the largest differences are in main heat. The post April 2015 sample has a much larger proportion of properties that derive heating from electricity or oil (44% for the post April 2015 compared to 33% for the pre April 2015 sample), which are less energy efficient fuel sources (more costly) than natural gas. This reflects the change in composition of private rental properties in the post April 2015 sample, with a larger proportion of initially lower rated properties.

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% of properties 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 200mm thick (18%). However, these also are features for which there are large improvements in the pre April 2015 sample (before the regulations were approved). In the table, the largest five changes are shown in bold.

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%). These also are the characteristics for which we observe larger differences in the owner-occupied sector in the pre versus post 2015 periods, so that the regulations increased the probability of improvements in rental properties, but do not seem to have significantly impacted the nature of the investments undertaken. The analysis of financial returns of the retrofits helps to explain why.

EPCs contain recommendations on how best to improve energy efficiency rating, the indicative capex required to implement them and their projected monetary savings. The recommendations depend on the specific characteristics of the home (e.g. solid walls or cavity walls). However, the capex and savings figures are indicative. The capex does not depend on property type (we address this shortcoming below). The monetary savings of the retrofits are estimates based on a typical property occupancy and not on actual energy consumption.[32]

Fowlie, Greenstone, and Wolfram (2018) and Christensen, Francisco, Myers, and Souza (2020) have found a wedge between projected and actual savings from energy retrofits, so that the actual investment returns are lower than those predicted by engineering models. They 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 values of savings equal to between 31% and 76% of the average upfront investment costs (Fowlie, Greenstone, and Wolfram, 2018).

In Table 9 we perform similar calculations. We use the mean capex and savings for each retrofit, a discount rate of 3%, and lifespans between 10 and 30 years (depending on the retrofit). Although our calculations rely on estimated energy consumption, 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 WAP program studied by Fowlie, Greenstone, and Wolfram (2018).[33]

[Insert Table 9 here]

Table 9 shows that some of the retrofits, particularly those that require smaller upfront investment, generate significant IRRs. Among them is 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 8).

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

[32] 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.

[33] Christensen, Francisco, Myers, and Souza (2020) 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 our data, the savings that can be achieved from wall insulation, and the attractiveness of the investment from a financial point of view, depends on the type of wall. Insulating solid brick walls is unattractive.

of walls: insulating cavity walls is less costly and more frequently carried out than insulating solid brick walls.

In Appendix D.1 we use the engineering model of section 2.3 and the previous table to obtain estimates of the capex and points increase for different retrofits. We focus on flats given their prevalence in the private rental sector. We find that the retrofits that require more capex tend to yield larger changes in number of points, but smaller changes in points per pound of capex spent. Therefore, a combination of several low capex retrofits is a lower cost path to comply with the regulations than a large investment (and in line with the evidence that we provided).

In order to address the shortcoming that the capex figures included in the certificates are indicative and do not depend on property type, we have obtained figures for a sub-sample of the retrofits from Palmer, Livingstone, and Adams (2017), which differentiates by property type. We use their medium and high cost estimates and calculate monetary savings in our data by retrofit and property type. The values and corresponding IRRs are included in Appendix D.2. Although there are differences in IRRs across property type, several of the main conclusions are similar for all types considered: (i) internal and external wall insulation and replacing single with double glazing windows have negative IRRs; (ii) cavity wall insulation and loft insulation have positive IRRs, although the IRRs of the latter tend to be significantly smaller than the vale of 36.9% shown in Table 9. This is because of higher capex estimates.[34]

The regulations apply to private rentals and not to owner-occupied and rental social, which might lead owners of privately rented properties to sell them and the property being moved out of this sector (so as to evade the regulations). In Appendix E we investigate this hypothesis using the full sample of certificates merged with Land Registry data that includes all transactions of residential properties in England and Wales since 2005. We do not find evidence in support of this hypothesis. There are several potential reasons for this. First, landlords have at their disposal several low capex retrofits that may allow them to meet the regulations. Second, during the period of our analysis the regulations only applied to new tenancies and not existing ones. Third, in the period after the approval approval of the regulations their enforcement was not consistent across local authorities who are responsible for doing so.[35]

[34]One retrofit where property type makes a difference is the changing of heating to gas condensing boiler. The IRRs are negative for the high capex estimate for detached houses and bungalows and positive (albeit in the low single digits) for other property types.

[35]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

4 From energy efficiency to carbon emissions

A second objective of the regulations is a reduction in carbon emissions. When energy use generates externalities that are not internalized by the price system the levels of investment in energy efficiency are below the socially optimal. This market failure can be corrected through a Pigouvian tax that internalizes the social cost of carbon. However, the introduction of a Pigouvian tax is not always politically feasible. Other forms of intervention such as minimum standards (the MEES regulations) are often used as a second-best approach.

Since the regulations target energy efficiency (energy costs) and not carbon emissions directly, there is a divergence between what they target and their objective. Reductions in the use of an expensive but with a low carbon footprint energy source improves energy efficiency without an as large effect on carbon emissions. Shifts towards cheaper but more polluting sources reduce energy costs (and improve efficiency), but may actually lead to larger carbon footprints. In this section, we focus on the effects of the regulation on carbon emissions.

4.1 Environmental impact rating

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). Naturally, ceteris paribus, a retrofit that leads to a reduction in energy usage reduces the costs and carbon emissions of the dwelling, and leads to increases in energy efficiency and environmental impact ratings. In the sample of multiple certificate properties, the correlation between changes in energy efficiency and environmental impact ratings is 0.86. When we restrict the sample to properties in the bottom tercile of initial energy efficiency, the correlation drops to 0.81. Therefore, even though the correlation is positive and significant, it leaves open the important question of the extent to which the retrofits contribute to a reduction in carbon emissions.

The previous section characterized the energy efficiency gains and the retrofits in the sample of multiple certificates and bottom tercile of energy efficiency. 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

tenancies).

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. Figure 6b plots the evolution over time of the average changes.

Figure 6a 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 Figure 6b. There is a divergence between the relative gains in energy efficiency and in environmental impact. In order to investigate this further, we calculate for each observation the ratio of energy efficiency and environmental impact ratings. 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. Figure 6c shows the results. The changes are larger for rental private than owner-occupied, with a gap that widens significantly post-approval. This means that the ratio of energy efficiency to environmental impact increased between the first and second certificates more for rental than owner-occupied properties.

We quantify the effects in regressions of the changes in energy efficiency (and environmental impact) rating on dummies for rental private, period (approval to enforcement and post-enforcement), and interactions between the two. The sample is restricted to these two tenure types, excluding social rental properties (and those for which tenure is missing). The estimated coefficients shown in the first column of Table 10 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 0.053.

[Insert Table 10 here]

As previously shown, there are differences in the composition of the owner-occupied and private rental samples. In columns (4) to (6), we add fixed effects for property construction age, type, built-form and floor area (ten decile dummies). We also introduce dummies for the conventions in effect at the time that the first and second certificates of each observation pair were issued (that control for convention changes). The estimated differences between rental private and owner-occupied from approval to enforcement are 1.709 (energy), 0.527 (environment), and 0.023 (ratio). Therefore, the divergence as measured by the ratio is in part explained by the type of properties in the two sectors and by convention changes. 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. In other words, there is a divergence between the two.

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 the following property dimensions: 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. As before, all property characteristics are measured as of the first certificate of the observation pair. We then estimate regressions similar to those in Table 10, but on the private rental and owner-occupied matched samples. Appendix Table A8 shows that the estimates are similar.

The next section focuses on the energy sources to understand the reasons for the divergence.

4.2 Energy sources, fuel prices, and carbon factors

Panel A of Table 11 shows the main energy source for the first and second certificate of each observation pair for properties in the bottom tercile of initial energy efficiency. Private rental properties are much more likely to rely on electricity than owner-occupied ones. The initial proportion of private rental (owner-occupied) properties relying on electricity as the main energy source is equal to 35.3% (17.7%). The changes between certificates are similar, even though private rental starts from a much higher level. This may be due differences in the sample of properties in the owner-occupied and rental sectors. In Panel B we report similar data but for the sample of owner-occupied properties that are matched to private rental ones. The initial differences in energy sources are smaller, as now we are comparing similar properties, but it still is the case that rental ones are more likely to rely on electricity as the main source than owner-occupied.

[Insert Table 11 here]

Both energy costs and CO_2 emissions depend on energy usage, but the former also depend on fuel prices whereas the latter depend on the carbon footprint of the energy. The RdSAP conventions specify prices and emission factors for the different types of fuel. For instance, RdSAP 2012 version 9.92 specifies unit prices of 3.48, 13.19, and 5.44 pence per kWh for gas, electricity (standard tariff), and heating oil, respectively. The corresponding emissions are 0.216, 0.519, and 0.298 Kg CO_2 per kWh. The ratios of unit price to emissions are 18.1, 25.4 and 18.3 for gas, electricity and heating oil, respectively. Therefore, reductions in electricity usage tend to have relatively larger cost than emission benefits when compared to other energy sources, and in particular gas. This, together with a larger reliance on electricity in the private rental sector and the large incidence of low energy lighting retrofits, help to explain the previously documented divergence between energy efficiency and environmental impact.

The last three rows of Table 11 show the prevalence of investments in renewable energy sources. There are larger changes for owner-occupied than private rental, but the magnitudes are small. For instance, solar photovoltaic was initially present in 0.04% of owner-occupied properties, and even though the value increased to 0.14% in the second certificate of the observation pair, the absolute difference is only 0.10%. It should be noted that we are restricting the sample to properties initially in the bottom one-third of energy efficiency and to certificates requested fro the purpose of a marketed sale or private rental, thus excluding certificates requested to take advantage of subsidies and Feed-in-Tariff schemes. When these are not excluded, the values are larger but still quantitatively small.

The first two columns of Table 12 show the average changes 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. As before, 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 private rental. The largest (smallest) energy cost reductions are for properties that switch from electricity (gas) to gas (electricity). They reflect the larger cost of electricity compared to natural gas.

[Insert Table 12 here]

Figure 7a plots the evolution over time of domestic gas and electricity prices. The dashed lines plot the quarterly evolution of the fuel components of consumer price indices. The solid lines plot the electricity and gas unit prices (pence/kWh) used in the RdSAP calculations which are updated every semester. For electricity, we use the prices for the standard tariff but the patterns are similar for the other tariffs. The figure shows an increase in the price of electricity compared to natural gas over the sample period, so that a switch in main heating source from electricity to gas becomes increasingly beneficial from a cost and energy rating point of view.

[Insert Figure 7 here]

It is important to note, however, that while the fuel prices used for the calculations are updated twice a year, the emission factors have not been regularly updated. In particular, the emission factors specified in RdSAP 2012 version 9.92 of 0.216 $KgCO_2$/kWh for natural gas, 0.519 for electricity, and 0.298 for heating oil have been kept at these values until the end of the sample period. Their values reflect the carbon footprint of the energy consumed in the UK in 2014, the starting date for the conventions (0.184973 for mains gas, 0.4926 for electricity, and 0.28670 for heating oil,[36] taken from the Government conversion factors for company reporting of greenhouse gas emissions), but not at the end of the sample period. The largest differences are in electricity emissions.

How polluting electricity is as a source of energy depends on how electricity is produced in the first place. If electricity is produced using coal, its carbon emissions are large. On the other hand, if electricity is produced using renewable sources such as wind and sun, then its environmental impact will be significantly smaller and "indirect" only (from stages of the life cycle other than power generation). By 2020 the UK Kg CO_2 emissions per KWh of natural gas, electricity and heating oil were 0.20374, 0.23314, and 0.28484, respectively. Therefore, the electricity consumed in the UK became much "greener" by the end of the decade. Even though carbon emissions from electricity generation were still 14% larger than natural gas, their value more than halved compared to 2014.

This large change was in part the result of 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 the ETS prices are below the CPF an additional tax on the fossil fuels used to generate electricity is levied on producers (equal to difference between the ETS price and the CPF). Figure 7b plots the fuel sources used in the production of UK electricity over time, as a percentage of the total. There was, starting in 2013, a very large reduction in the use of coal, replaced by gas and renewables. Abrell, Kosch, and Rausch (2022) and Grubb

[36] These values do not include the transmission and distribution of electricity.

and Drummond (2018) analyze the effects of the CPF policy, and attribute (at least partially) the shift in fuel sources and rising electricity prices to the policy.

The fact the emission factors of the fuel sources have not been updated to reflect the changes in electricity production, means that the environmental impact of properties that use electricity as a main source of fuel has improved in a way that is not captured by the assessment procedure. The last column of Table 12 tries to quantify this. It shows the changes in CO_2 emissions calculated using the Government conversion factors for company reporting of greenhouse gas emissions in the year in which the certificates were issued (instead of the carbon factors specified in the conventions). A caveat is that the data does not allow us to split the energy consumed by fuel type, which is relevant for properties that use more than one type, so that when doing the calculations we use the emissions of the main fuel for the total amount. As expected, the largest differences are in electricity to electricity (-0.86 compared to an updated value of -2.54) and mains gas to electricity (-0.41 compared to an updated value of -1.98).

If certificates are used to tackle the climate challenge, it is important that the information contained in them accurately reflects emissions. Furthermore, it is important to do so using a forward-looking perspective. If the reductions in carbon emissions of electricity that we have witnessed over the past few years continue going forward, electricity will become a greener source of energy than the most common alternative of natural gas. However, as Tables 11 and 12 show, over the sample period there have been significant reductions in the proportion of properties that use electricity as the main fuel source, which have been converted to gas. This has improved their energy efficiency (due to the higher cost of electricity relative to natural gas), but may become undesirable from an emissions point of view. This again illustrates the pitfalls of using energy efficiency (cost) based metrics to tackle carbon emissions.

Another important lesson concerns the links between the production and consumption of energy. Interventions in electricity production to make it greener may, at least during a transition phase, make electricity more expensive as producers pass on the added costs to customers. This may lead households 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 for carbon emissions. From this perspective, the significant investments that households have made in the change of heating from electricity to gas seem undesirable. A regulatory intervention on the consumer side that targets emissions directly would align the objectives on the consumption and production sides of the market.

5 Unobserved retrofits

A valid certificate is required for a sale and new rental, but not by homeowners living in a property. Furthermore, certificates are valid for 10 years and property owners who make improvements do not need to update them even when selling or renting. This means that there are likely to be improvements among the single certificate properties for which we do not have a second certificate. With this said, we think that it is reasonable to assume that owners who make significant investments do request a new certificate prior to a sale or a new rental. The cost of the certificate is low and a better rating makes the property more attractive. If those who invest in property improvements are more likely to request a new certificate, the sample of multiple certificate properties includes a larger investment intensity than the population.

Most UK rental properties are offered on an Assured Shorthold Tenancy with a fixed term of between six months and three years. This means that new rentals are fairly frequent and that landlords who make investments and request a new certificate prior to a new rental are likely to appear in the data. On the other hand, homeowners who invest in their property but who do not plan to sell it may not request a new certificate. This means that unobserved retrofits are more likely to exist in the stock of owner-occupied than rental properties. We merge our certificates data with property transactions from the HM Land Registry Price Paid data to provide additional evidence on sample selection.

The transactions data includes all residential property sales in England and Wales since 1995. In addition to the transaction price, date, and address, it includes several property characteristics such as its type (detached, semi-detached, flat, etc.) and tenure (freehold, leasehold, etc.). The data are publicly available from the HM Land Registry Open Data repository. The same property may have multiple entries in the EPC and Price Paid data, corresponding to multiple certificates and transactions, respectively. It is also possible that a property appears in one but not the other dataset. A property not transacted during the sample period will not appear in the Price Paid data, but its owner may have requested an EPC. Listed properties that are sold appear in the transactions data, but they are exempt from the legal requirement to have a valid certificate. We merge each transaction in the price Paid data with the certificate that is valid at the time of the transaction. The merge is done using the property address. (Appendix B.2 provides details on the merge.)

Our working assumption is that property owners would have requested a new certificate prior to a sale if investments had been made. Figure 8a plots the distribution of the time elapsed between the certificate and the property transaction (each bar represents a quarter).

Roughly 60% of the valid certificates at the time of the transaction were issued in the four quarters prior to the transaction. This is consistent with the information on transaction types in the certificates data that shows a large number of certificates being requested for the specific purpose of a marketed sale.

[Insert Figure 8 here]

We now focus on the sample of properties for which we observe at least *two* sales. Under the assumption that property owners who undertake investments request a new certificate prior to a sale, this sample provides a more complete picture of the investment intensity. There is only one certificate for roughly 72% of the properties; these are properties for which significant investments are unlikely to have been carried out between the transactions. For the remainder 28% we observe two or more certificates. For this latter group, Figure 8b plots the histogram of the previous certificate's remaining validity when a new certificate is issued. A large majority of the certificates had several years to expiry, consistent with the hypothesis that certificates are requested in response to investments. The 72% figure for the proportion of properties for which investments are unlikely to have been undertaken is smaller but comparable to the proportion of single certificate properties (78%) in the full sample of certificates.

For the sample of at least two sales and two certificates, we measure the initial level of energy efficiency and the change between the two certificates. The average starting level of energy efficiency is 55.1. Recall that the upper threshold for multiple certificate properties in the bottom tercile is 54. Therefore, there is a significant overlap between this sample and those in the two bottom terciles of energy efficiency. The average change in energy efficiency score between the two certificates is 7.6, or 13.8%, consistent with the average improvements that we have shown in Table 4 for the bottom two groups.

6 Conclusion

We have used a large dataset to study the effects of a regulatory intervention that requires private rental properties to meet a minimum energy efficiency standard. The regulations aim to improve the energy efficiency of the worst-performing buildings (in the private rental sector) and to reduce carbon emissions. Our main data source are the energy performance certificates needed to sell or rent out a home in England and Wales since October 2008.

The analysis showed that the regulations led to higher investment intensity in energy efficiency in the private rental sector, mostly focused on the retrofits that require lower capital expenditure and that generate higher projected internal rates of return, such as low energy lighting, heating controls, and roof insulation. In addition, there were significant investments in windows, even though they are not an attractive investment from a purely financial energy efficiency point of view. This shows that other considerations such as home comfort (e.g. noise reduction) are important. Investments in wall insulation, and in particular solid brick wall insulation, were rare.

Importantly, our analysis showed the regulations and investments undertaken led to a divergence in energy efficiency and environmental impact gains in the private rental sector compared to owner-occupied. The large gains in energy efficiency in private rental relative to owner-occupied were not accompanied by similarly large environmental gains. Energy efficiency is a cost based measure; it depends on the quantity of energy consumed and on its unit price. On the other hand, the carbon footprint of homes depends on the quantity of energy consumed and how polluting the energy source is (as measured by its carbon factor). Regulatory interventions that target energy cost measures favor investments in the reduction of the consumption of expensive energy, and not necessarily the most polluting one.

Over the sample period there have been significant reductions in the number of properties that use electricity as the main fuel source, which have been converted to natural gas. This has improved their energy efficiency (due to the higher cost of electricity relative to natural gas), but may soon become undesirable from an emissions point of view. Even though by the end of our sample period electricity still was more polluting than natural gas, in the last few years there have been very significant reductions in its carbon footprint due to use of renewable sources such as wind and sun for its production. In other words, the electricity consumed in the UK became much "greener" by the end of the decade and this is not reflected in the certificates. Furthermore, the shit in the electricity production to greener sources was the result of a regulatory intervention, namely the introduction of a carbon tax (carbon price floor) in the production of UK electricity. This is likely to have contributed to the increase in price of electricity relative to natural gas that we observe in the sample period, incentivizing households to make the investments necessary to switch to gas both for cost reasons and to meet regulatory requirements.

Regulations worldwide incentivize efficient energy use, frequently relying on cost based measures. A reduction in carbon emissions may be more effectively achieved by changing the focus of the certificates and regulations to environmental impact metrics. At the same time, it is important that the certificates accurately reflect emissions and that the regulations take a forward-looking perspective. This includes regulatory interventions on the consumption side of energy markets aligned with those on the production side and that recognize transition effects. This might help guide the efficiency of the retrofits and speed up the transition towards cleaner energy-efficient technologies.

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I Figures

Figure 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.

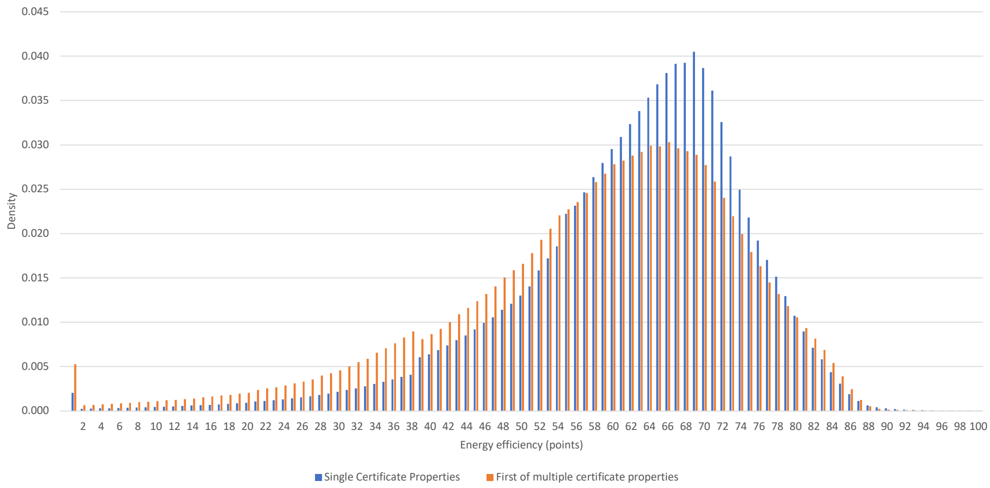


Figure 2: Empirical model for energy efficiency: estimated coefficients and model fit.

The figure plots the estimated coefficients for the dummy variables that take the value of one if the property element has a given star rating and zero otherwise. The base category is very poor (one star); the estimated coefficients measure the increase in points from this base case. The regressions are estimated separately for each of the seven RdSAP convention periods. The last panel plots the R-squared of the estimated models. The explanatory variables include property type (House, Flat, Bungalow, Maisonette and Park Home), built form (Semi-Detached. Mid-Terrace, Detached, End-Terrace, Enclosed Mid-Terrace) and construction age band dummies.

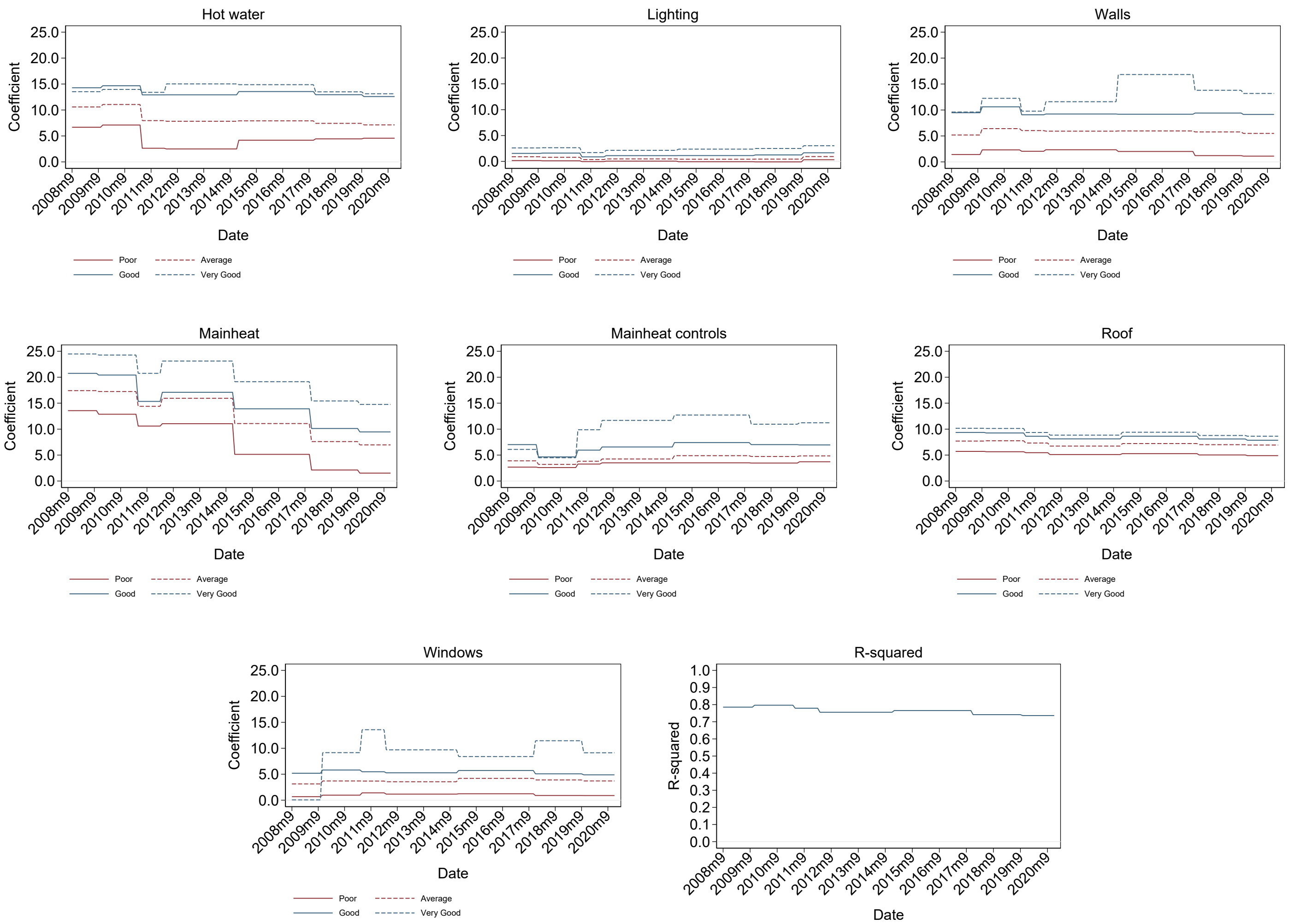
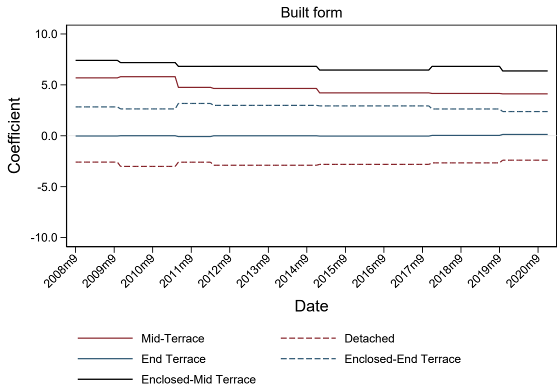


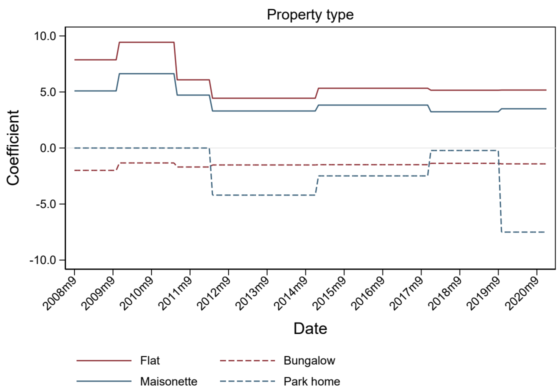
Figure 3: Estimated effects of construction age, built form and property type

The figure plots the estimated coefficients for construction age band, built form and property type for the different RdSAP periods. The omitted categories are: construction years before 1900, semi-detached, and house, respectively.

(a) Construction age



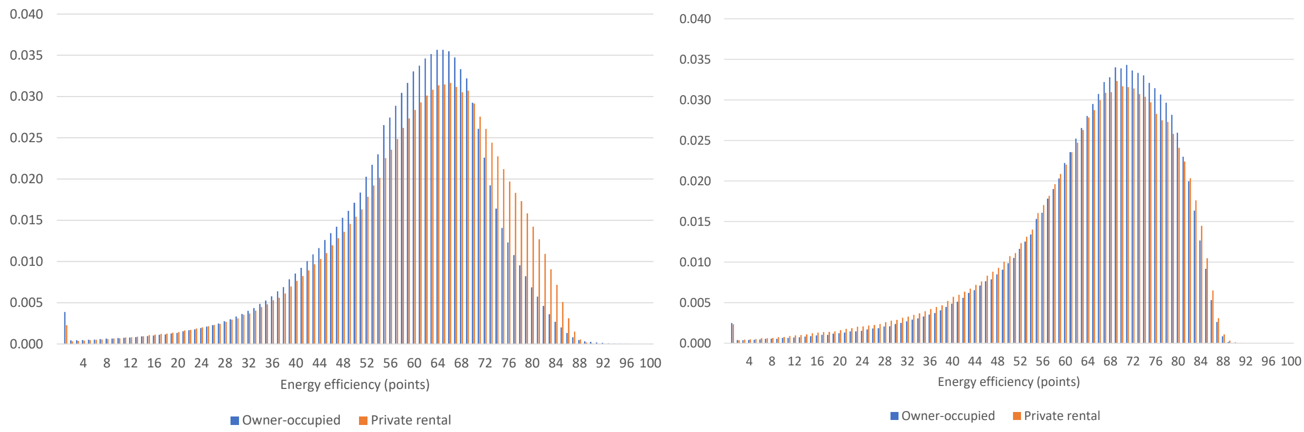
(b) Built form



(c) Property Type

Figure 4: Energy efficiency distributions by tenure.

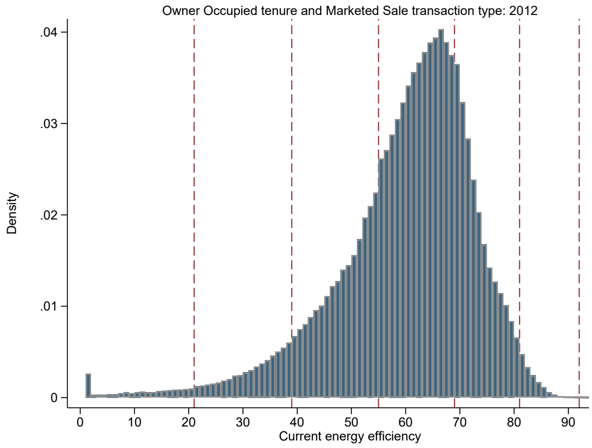
The sample includes all certificates issued prior to April/1/15 with tenure equal to owner-occupied or private rental. Panel (a) shows the energy efficiency points distributions for all property types. Panel (b) shows the distributions for flats and maisonettes.



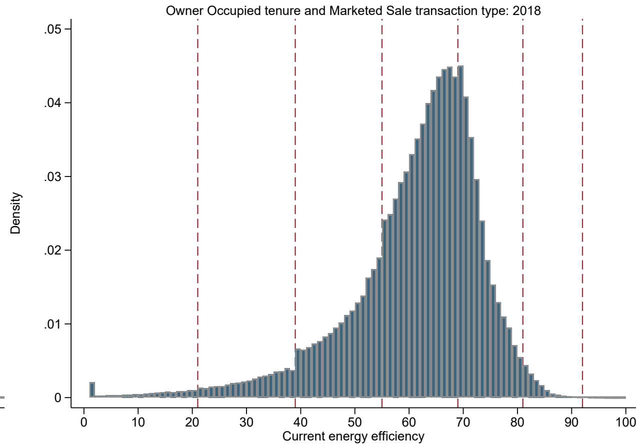
(a) All properties **(b)** Flats and maisonettes

Figure 5: Distributions of energy efficiency for selected calendar years.

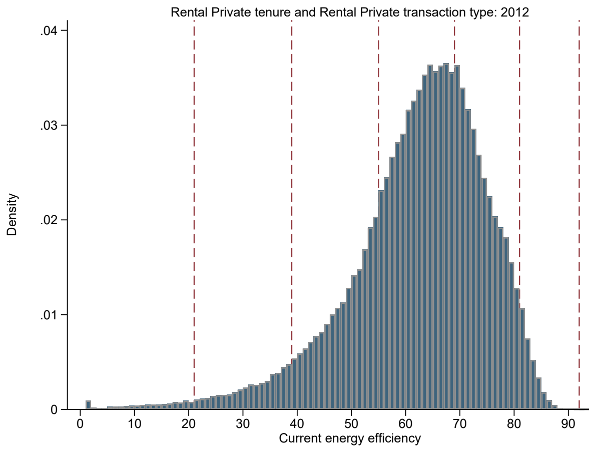
The sample includes both first certificates and subsequent certificates for the properties. In Panels (a) and (b) the sample is restricted to certificates for owner-occupied properties requested for the purpose of a marketed sale. In Panels (c) and (d) the sample is restricted to certificates for private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



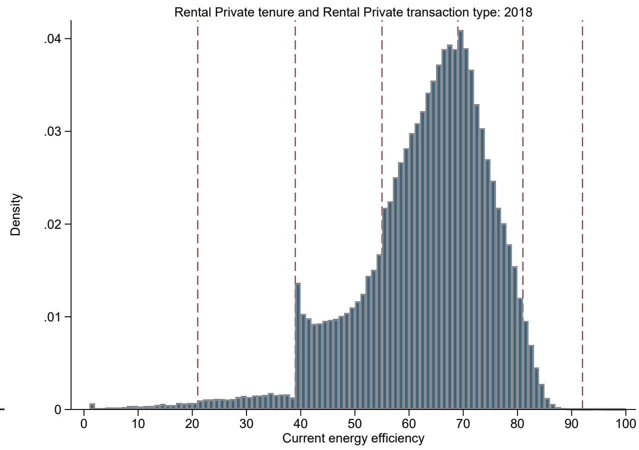
(a) Owner-occupied, Year 2012



(b) Owner-occupied, Year 2018



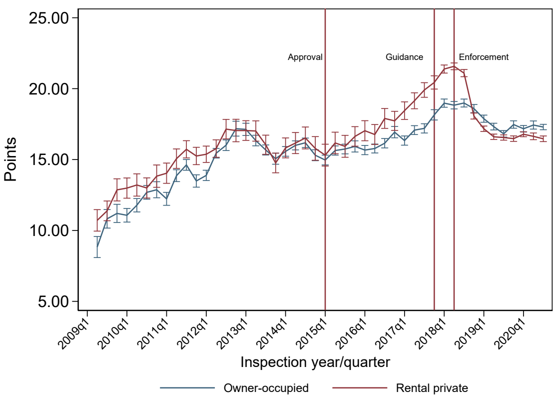
(c) Rental private, Year 2012



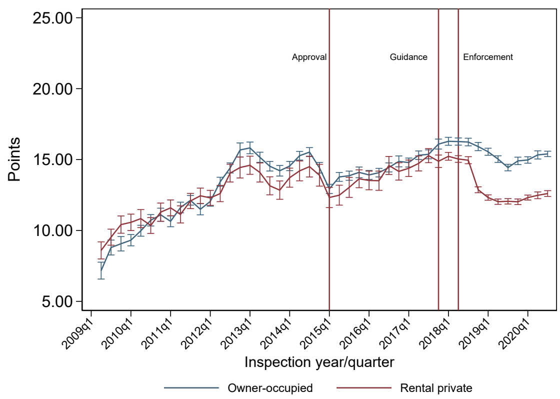
(d) Rental private, Year 2018

Figure 6: Changes in energy efficiency and environmental impact ratings (points) over time

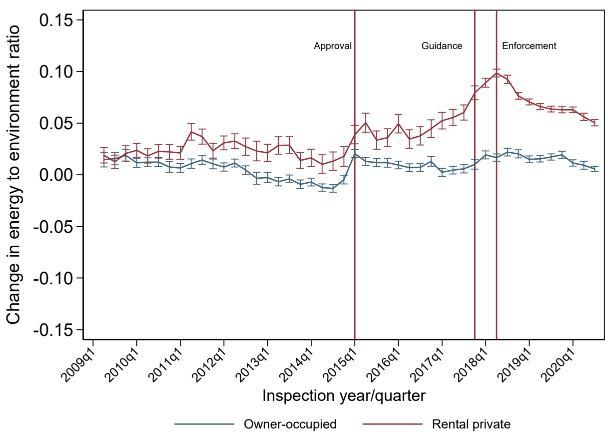
The sample is restricted to multiple certificate properties in the bottom tercile of initial energy efficiency. For each pair of certificates for the same property, we calculate the difference in energy efficiency rating (points) between the first and the second certificate (within property changes, second minus first certificate). Figure 6a plots the average change in energy efficiency for second certificates issued in each year/quarter. The figure distinguishes between 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 is measured using the second certificate of each observation pair. The vertical lines mark the approval date (Apr/15), the issuance of guidance (Oct/17) and the enforcement (April/18) of the MEES regulations. Figure 6b plots the difference in environmental impact score between the second and first certificates, averaged across all second certificates issued in each year/quarter. In Figure 6c we first calculate for each certificate the ratio between energy efficiency and environmental impact points. We then calculate the difference of this ratio between the two certificates for the property. The figure plots the average change for all second certificates issued in each year/quarter.



(a) Changes in energy efficiency



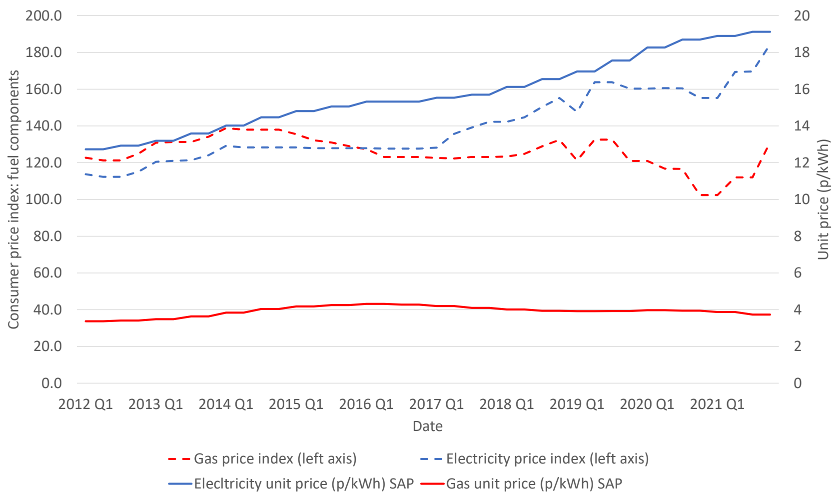
(b) Changes in environmental impact



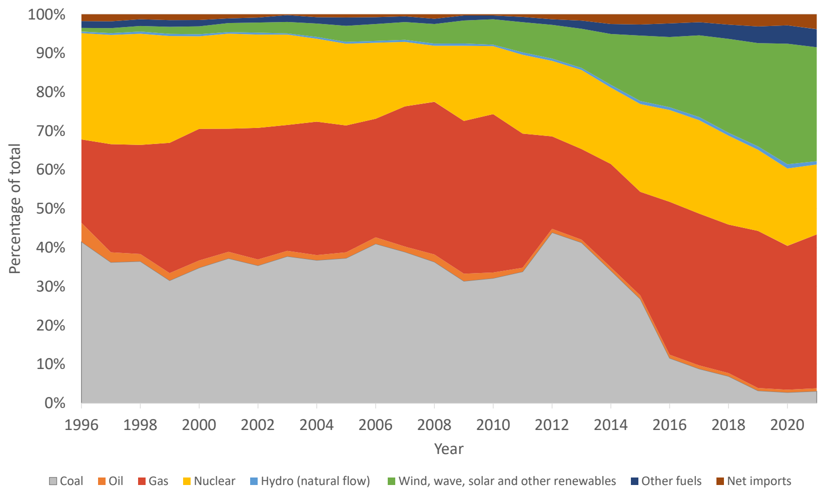
(c) Changes in energy efficiency/environmental impact

Figure 7: Energy prices and electricity production.

Panel (a) plots the evolution over time of domestic gas and electricity prices. The dashed lines 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. The solid lines plot the evolution over time of unit prices (pence/kWh) of electricity and gas used in the RdSAP calculations. The prices are updated every semester. For electricity, we use the prices for the standard tariff. Panel (b) 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.



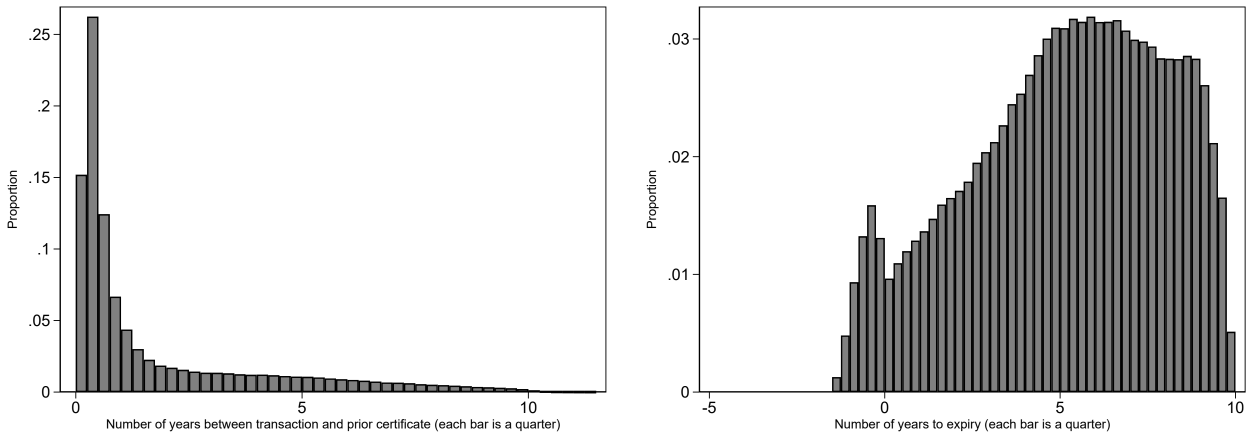
(a) Energy prices



(b) Fuel used in electricity production

Figure 8: Property transactions and certificates.

The data is the merged sample of property transactions from the Price Paid data and EPC certificates. We calculate, for each transaction, the number of years that have passed since the most recent certificate for the property has been issued. Panel (a) plots the distribution of the number of years that have passed. Panel (b) restricts the sample to those properties for which we observe at least two transactions and two certificates. It plots the histogram of the remaining validity in the previous certificate when a new certificate for the property is issued.



(a) Years between transaction and certificate

(b) Years of remaining certificate validity

II Tables

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

Table 2: Number of certificates per property

The table shows the number of properties for which there is a given number of certificates in the data.

Number of certificates	Number of properties
1	10,852,861
2	2,669,986
3	387,355
4	65,729
5	12,383
6	2,609
7	627
8	147
9	42
10	9
11	7
12 and above	2
Total	13,991,759

Table 3: 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.

	Percentage of observations with classification (%)					Number of stars	
Property element	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

Table 4: Heterogeneity as a function of the initial level

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 the group cut-offs are the terciles of the distribution of energy score of the first certificate of multiple certificate properties. In Panel B 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 of observations. The number of observations reported in the table are for pairs of observations.

Group	Number obs.	Initial points	Δ Points	Perc. change
Panel A: 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 B: 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%

Table 5: Initial characteristics of properties by tenure

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, the average number of stars and the percentage of observations with very poor and poor classification (one and two stars, respectively) for the different property elements, by tenure. The bottom part of the table reports the percentage of observations of different property types, built form, roof and walls type, by tenure.

Element	Variable	Owner-occupied	Private rental
Energy efficiency	Points (mean)	58.5	60.5
	Points (median)	61	63
Main heat	Number of stars (mean)	3.7	3.6
	Very poor or poor (%)	7.3	16.2
Main heat controls	Number of stars (mean)	3.1	2.8
	Very poor or poor (%)	21.6	34.5
Windows	Number of stars (mean)	3.1	3.0
	Very poor or poor (%)	14.6	21.8
Roof	Number of stars (mean)	3.1	2.9
	Very poor or poor (%)	26.5	32.9
Lighting	Number of stars (mean)	3.0	3.1
	Very poor or poor (%)	38.7	38.8
Walls	Number of stars (mean)	2.7	2.4
	Very poor or poor (%)	50.3	57.0
Hot water	Number of stars (mean)	3.5	3.4
	Very poor or poor	15.9	18.4
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

Table 6: 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 includes all observations. Panel B (Panel C) restricts the sample to 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: Sample period 2008 - 2020					
Owner-occupied	398,494	0.53	40.0	16.2	41%
Rental private	288,392	0.38	37.8	17.3	46%
Rental social	64,651	0.09	44.2	16.3	37%
Panel B: 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 C: 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 7: Probability and timing of subsequent certificate

In columns (1) to (4) 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 columns (5) to (7) the sample is multiple certificate properties and certificate observations with date pre April/15 for which there is a subsequent certificate. For each certificate observation we create a dummy variable that takes the value of one if the subsequent property certificate has date post April/15 and zero otherwise. This is the dependent variable in the regressions. In column (5) the sample includes multiple certificate properties with tenure equal to owner-occupied or private rental. Tenure is measured using the second certificate of each observation pair. In columns (6) (and (7)) we restrict the sample to certificates that had at least 2 years (5 years) of validity at the time of the new certificate. Points<39 is dummy variable that takes the value of one for certificates with SAP points below 39, and zero otherwise. 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.

	Probability of subsequent certificate				Timing of subsequent certificate		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Constant	0.210***	0.197***	0.174***	0.177***	0.470***	0.359***	0.261***
	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Points<39		0.194***	0.200***	0.168***	0.017***	0.041***	0.011***
		0.000	0.000	0.000	0.001	0.000	0.001
Private rental			0.063***	0.055***	0.211***	-0.030***	-0.049***
			0.000	0.000	0.001	0.000	0.001
Points<39 x Priv. rental				0.125***	0.026***	0.209***	0.140***
				0.001	0.002	0.001	0.001
Sample	Full	Full	Owner-o./ Priv. rental	Owner-o./ Priv. rental	Multiple certificates	Validity $\geq$2 years	Validity $\geq$5 years
Observations	17,701,555	17,701,555	13,968,431	13,968,431	2,573,394	1,823,498	1,456,972
R^2	0.000	0.013	0.021	0.023	0.044	0.011	0.005

Table 8: 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.

		Owner-occupied				Private rental			
		Pre Apr/15		Post Apr/15		Pre Apr/15		Post Apr/15	
Element	Description	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 $\geq$ 270 mm	3	6	4	12	2	5	3	10
	Pitched, insulation $\geq$ 200 mm	14	**22**	17	**20**	10	**14**	11	**18**
Lighting	Low energy lighting $\geq$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 9: Financial returns

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 table reports the present value of savings (using a discount rate of 3%) divided by capital expenditure and the internal rate of return. The assumed lifespans are reported in the last column.

Retrofit	Capex (£)	Savings (£)	PV sav/ Capex	IRR (%)	Lifespan (years)
Install low energy lighting	-38	30	6.7	78.7	10
Upgrade heating controls	-400	58	1.2	7.4	10
Install hot water cylinder thermostat	-300	61	1.7	15.5	10
Increase loft insulation to 270mm	-225	83	7.2	36.9	30
Change heating to gas condensing boiler	-5,000	360	0.6	-5.6	10
Replace single with double glazing windows	-4,851	56	0.2	-11.2	20
Cavity wall insulation	-1,000	148	2.9	14.5	30
50 mm internal or external wall insulation	-9,000	197	0.4	-2.5	30

Table 10: 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. Private rental is a dummy variable that takes the value of one for private rental properties, and zero for owner-occupied. 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. 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 dummies for the conventions in effect at the times of the first and second certificates of each observation pair. Standard errors 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)
Rental Private	0.378***	-0.738***	0.021***	0.528***	0.284***	0.002**
	(0.077)	(0.073)	(0.001)	(0.077)	(0.072)	(0.001)
Approval to enforcement	2.099***	1.741***	0.006***	1.298***	1.219***	-0.005***
	(0.063)	(0.060)	(0.001)	(0.151)	(0.142)	(0.002)
Post-enforcement	3.152***	2.350***	0.011***	0.835***	1.424***	-0.017***
	(0.058)	(0.055)	(0.001)	(0.185)	(0.174)	(0.002)
Rental Private × Approval to enforcement	2.038***	0.460***	0.032***	1.181***	0.243**	0.021***
	(0.119)	(0.113)	(0.002)	(0.119)	(0.112)	(0.002)
Rental Private × Post-enforcement	-0.531***	-1.890***	0.034***	-0.103	-1.101***	0.027***
	(0.095)	(0.090)	(0.001)	(0.094)	(0.089)	(0.001)
Constant	14.555***	13.015***	0.003***	15.699***	12.935***	0.030***
	(0.040)	(0.038)	(0.001)	(0.116)	(0.110)	(0.001)
Property Characteristics Fixed Effects	No	No	No	Yes	Yes	Yes
RdSAP Convention Fixed Effects	No	No	No	Yes	Yes	Yes
R-Squared	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

Table 11: Energy sources

The table shows the main energy source for the first and second certificate of each observation pair for properties in the bottom tercile of initial energy efficiency. The table distinguishes between owner-occupied properties (with certificates requested for the purpose of a marketed sale) and private rental properties (with certificates requested for the purpose of a private rental). Tenure is measured using the second observation of the pair. Panel A shows the results for the original sample and Panel B for the sample of owner-occupied properties that are matched to a rental property based on property type, built-form, construction age band, time period, and floor area.

	Owner-occupied			Private rental		
Main energy source	Initial (%)	Final (%)	Δ (%)	Initial (%)	Final (%)	Δ (%)
			Panel A: Original sample			
Natural gas	67.6	77.1	9.6	52.6	61.8	9.2
Electricity	17.7	11.0	-6.6	35.3	29.1	-6.2
Oil	7.9	8.0	0.1	5.7	6.2	0.5
Solar photovoltaic	0.06	0.27	0.21	0.03	0.13	0.10
Solar water heating	0.28	0.34	0.05	0.11	0.09	-0.02
Wind turbine	0.09	0.03	-0.06	0.10	0.02	-0.08
			Panel B: Matched sample			
Natural gas	59.2	68.5	9.3	52.6	61.8	9.1
Electricity	31.0	24.2	-6.7	35.4	29.2	-6.3
Oil	4.0	4.1	0.1	5.7	6.3	0.5
Solar photovoltaic	0.04	0.14	0.10	0.03	0.13	0.10
Solar water heating	0.13	0.18	0.05	0.11	0.09	-0.02
Wind turbine	0.07	0.03	-0.04	0.10	0.02	-0.08

Table 12: 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/final	Δ Energy cost (£/year)	Δ Emissions (Ton CO_2/year)	Δ Emissions updated (Ton CO_2/year)	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	3,400

Internet Appendix for

"Investments that Make our Homes Greener: The Role of Regulation"

A Energy performance certificates

In this appendix we explain the mapping between energy efficiency rating and energy costs and between environmental impact rating and CO_2 emissions. We include an example of a certificate and provide the dates of the conventions that apply.

A.1 The relation between energy efficiency rating and energy costs

The engineering model measures the quantity (kWh/year) of the different types of energy needed for space heating, water heating, ventilation and lighting minus energy saving/generation technologies. Total energy cost is equal to the sum of the energy used for each of these purposes multiplied by the fuel price (which depends on fuel type). Fuel prices are updated twice-yearly. Figure A1 shows the spreadsheet used for this calculation of total energy cost (£/year).

Total energy cost is converted into an energy cost factor (ECF) using the following formula:

$$\text{ECF} = \text{deflator} \times \text{total energy cost}/(\text{TFA} + 45) \tag{1}$$

where TFA denotes total floor area of the property (in m^2). Therefore, two adjustments are made in the calclutaion of ECF. The first is the division by floor area plus 45. The non-linear adjustment for floor area was introduced in SAP 2001 (before the beginning of our sample period) to ensure that houses that differ in size but are otherwise similar have similar ratings. Previously, larger homes had on average better ratings. There were several reasons for this: (i) geometry, for a general property shape the envelope area increases more slowly than the floor area; and (ii) occupancy, some energy uses (such as hot water) are closely related to occupancy but the assumed occupancy increases more slowly than floor area. The addition of 45 to the TFA in the denominator increases the ratings of smaller homes and decreases those of larger ones, and ensures that the ratings are independent of property size (Terry (2020)).

The second adjustment is the multiplication of total energy cost by a deflator. It varies with the weighted average price of heating fuels to ensure that the ratings of properties assessed at times when fuel prices are different are comparable.[37] However, individual SAP ratings are affected by relative changes in the price of particular heating fuels. The final step is the calculation of the SAP rating according to:

[37] See the footnote to Table 12 of https://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf.

$$\text{Energy Efficiency Rating} = 117 - 121 \times \log_{10}(\text{ECF}) \quad \text{if ECF} \leq 3.5 \tag{2}$$

$$\text{Energy Efficiency Rating} = 100 - 13.95 \times \text{ECF} \quad \text{if ECF} > 3.5 \tag{3}$$

The values are rounded to the nearest integer. The SAP rating scale is been set such that a value of 100 is achieved at a value of ECF equal to zero. The SAP rating will rise above 100 for a dwelling that is a net exporter of energy. If the result of the calculation is less than one, a value of one is attributed.

A.2 The relation between environmental impact rating and CO_2 emissions

The calculation of the environmental impact rating uses the energy needed for space heating, water heating, ventilation and lighting minus energy saving/generation technologies. Total CO_2 emissions (kg/year) are equal to the sum of the quantities of energy used for each of these purposes multiplied by the emission factors (which depend on fuel sources). The emission factors are specified in the conventions, but they have not not been regularly updated. For instance, the carbon factors specified in RdSAP 2012 version 9.92 were used until the end of our sample period. We return to this point in the main text. Figure A2 shows the spreadsheet used for calculating the total CO_2 emissions.

The CO_2 emissions are converted into an emission rate (denoted CF) using:

$$\text{CF} = (\text{CO}_2 \text{ emissions})/(\text{TFA} + 45). \tag{4}$$

Finally, the environmental impact (EI) rating is calculated from:

$$\text{EI rating} = 200 - 95 \times \log_{10}(\text{CF}) \quad \text{if CF} \geq 28.3 \tag{5}$$

$$\text{EI rating} = 100 - 1.34 \times \text{CF} \quad \text{if CF} < 28.3 \tag{6}$$

The EI rating scale has been set so that the rating 100 is achieved at zero net emissions. It can rise above 100 for a dwelling with negative emissions.

Figure A3 shows the first page of is an example of an energy certificate. The energy efficiency and the environmental impact ratings of the property are shown in the top left and right figures, respectively.

A.3 RdSAP convention dates

Over the years that have been several changes to the conventions that are used to measure energy efficiency. In the main body of the text we estimate an empirical model for energy efficiency to evaluate whether the changes in scores that we observe are primarily due to changes in the importance of the property elements (i.e. the factor loadings) or in the star rating of the elements. We found that most of the variability comes from the latter. We provide information on the conventions that apply during our sample period:

1. RdSAP 2005 version 9.82: from 22 September 2008 to 17 October 2009
2. RdSAP 2005 version 9.83: from 18 October 2009 to 16 April 2011
3. RdSAP 2009 version 9.90: from 17 April 2011 to 31 March 2012
4. RdSAP 2009 version 9.91: from 1 April 2012 to 7 December 2014
5. RdSAP 2012 version 9.92: from 8 December 2014 to 18 November 2017
6. RdSAP 2012 version 9.93: from 19 November 2017 to 21 September 2019
7. RdSAP 2012 version 9.94: from 22 September 2019

Figure A1: Energy efficiency rating calculation

This figure shows a screenshot of the "The Government's Standard Assessment Procedure for Energy Rating of Dwellings" regulation, SAP 2012 version 9.92 (October 2013). It displays the individual components of energy consumption and their commensurate cost that drive energy efficiency rating.

SAP 2012 version 9.92 (October 2013)

10a. Fuel costs – Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	(211)	×		× 0.01 =		(240)
Space heating - main system 2	(213)	×		× 0.01 =		(241)
Space heating - secondary	(215)	×		× 0.01 =		(242)
Water heating (electric off-peak tariff)						
High-rate fraction (Table 13, or Appendix F for electric CPSU)						(243)
Low-rate fraction	1.0 – (243) =					(244)
High-rate cost	(219) × (243)	×		× 0.01 =		(245)
Low-rate cost	(219) × (244)	×		× 0.01 =		(246)
Water heating cost (other fuel)	(219)	×		× 0.01 =		(247)
(for a DHW-only community scheme use (342a) or (342b) instead of (247)						
Space cooling	(221)	×		× 0.01 =		(248)
Pumps, fans and electric keep-hot	(231)	×		× 0.01 =		(249)
(if off-peak tariff, list each of (230a) to (230g) separately as applicable and apply fuel price according to Table 12a						
Energy for lighting	(232)	×		× 0.01 =		(250)
Additional standing charges (Table 12)						(251)
Energy saving/generation technologies	(233) to (235a) as applicable, repeat line (252) as needed					
<description>	one of (233) to (235a)	×		× 0.01 =		(252)
Appendix Q items:	repeat lines (253) and (254) as needed					
<description>, energy saved	one of (236a) etc	×		× 0.01 =		(253)
<description>, energy used	one of (237a) etc	×		× 0.01 =		(254)
Total energy cost				(240)...(242) + (245)...(254) =		(255)

11a. SAP rating – Individual heating systems including micro-CHP

Energy cost deflator (Table 12):		0.42	(256)
Energy cost factor (ECF)	[(255) × (256)] ÷ [(4) + 45.0] =		(257)
SAP rating (Section 13)			(258)

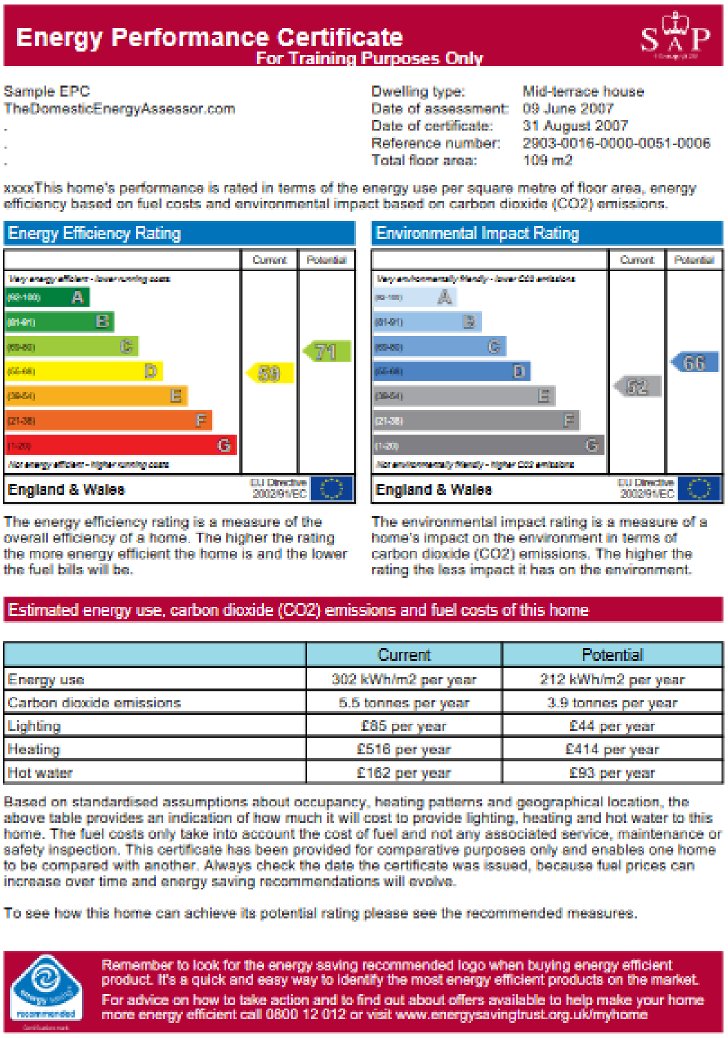
Figure A2: Environmental impact rating calculation

This figure shows a screenshot of the "The Government's Standard Assessment Procedure for Energy Rating of Dwellings" regulation, SAP 2012 version 9.92 (October 2013). It displays the individual components of energy consumption and their CO_2 emissions that drive environmental impact rating.

12a. CO_2 emissions – Individual heating systems including micro-CHP	Energy kWh/year		Emission factor kg CO_2/kWh		Emissions kg CO_2/year	
Space heating - main system 1	(211)	×		=		(261)
Space heating - main system 2	(213)	×		=		(262)
Space heating - secondary	(215)	×		=		(263)
Energy for water heating	(219)	×		=		(264)
(for a DHW-only community scheme use (361) to (373) instead of (264)						
Space and water heating	(261) + (262) + (263) + (264)			=		(265)
Space cooling	(221)	×		=		(266)
Electricity for pumps, fans and electric keep-hot	(231)	×		=		(267)
Electricity for lighting	(232)	×		=		(268)
Energy saving/generation technologies	(233) to (235a) as applicable, repeat line (269) as needed					
<description>	one of (233) to (235a)	×		=		(269)
Appendix Q items repeat lines (270) and (271) as needed						
<description>, energy saved *	one of (236a) etc	×		=		(270)
<description>, energy used *	one of (237a) etc	×		=		(271)
* where the item is concerned only with CO_2 emissions use the right-hand column only.						
Total CO_2, kg/year			sum of (265)…(271)	=		(272)
Dwelling CO_2 Emission Rate			(272) ÷ (4)	=		(273)
EI rating (section 14)						(274)

Figure A3: Example of a sample EPC certificate.

The figure shows the first page of a dummy example of an EPC certificate provided by Energy Key, an accredited Domestic Energy Assessor specialized in producing EPCs. The entire sample can be consulted at http://www.energykey.co.uk/epcsample.pdf



Energy Performance Certificate
For Training Purposes Only

Sample EPC
TheDomesticEnergyAssessor.com

Dwelling type:	Mid-terrace house
Date of assessment:	09 June 2007
Date of certificate:	31 August 2007
Reference number:	2903-0016-0000-0051-0006
Total floor area:	109 m2

xxxxThis home's performance is rated in terms of the energy use per square metre of floor area, energy efficiency based on fuel costs and environmental impact based on carbon dioxide (CO2) emissions.

The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills will be.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO2) emissions. The higher the rating the less impact it has on the environment.

Estimated energy use, carbon dioxide (CO2) emissions and fuel costs of this home

	Current	Potential
Energy use	302 kWh/m2 per year	212 kWh/m2 per year
Carbon dioxide emissions	5.5 tonnes per year	3.9 tonnes per year
Lighting	£85 per year	£44 per year
Heating	£516 per year	£414 per year
Hot water	£162 per year	£93 per year

Based on standardised assumptions about occupancy, heating patterns and geographical location, the above table provides an indication of how much it will cost to provide lighting, heating and hot water to this home. The fuel costs only take into account the cost of fuel and not any associated service, maintenance or safety inspection. This certificate has been provided for comparative purposes only and enables one home to be compared with another. Always check the date the certificate was issued, because fuel prices can increase over time and energy saving recommendations will evolve.

To see how this home can achieve its potential rating please see the recommended measures.

Remember to look for the energy saving recommended logo when buying energy efficient product. It's a quick and easy way to identify the most energy efficient products on the market. For advice on how to take action and to find out about offers available to help make your home more energy efficient call 0800 12 012 or visit www.energysavingtrust.org.uk/myhome

B Sample construction and summary statistics

We provide additional details on the sample construction and summary statistics.

B.1 Certificates data

Our initial sample has 20,125,562 certificate observations. We apply in sequence the following filters to the data:

1. Our focus is investments in the stock of existing properties as opposed to the features of newly built ones. We drop all new dwellings from the sample, which are assessed using SAP and not RdSAP. This means 2,138,522 observations deleted.

2. When for a given property, we observe multiple entries in the system on the same exact day (same lodgement date), we keep only those entries with the latest time stamp (latest lodgement time) (86,812 observations deleted). This is the certificate that is valid going forward.

3. For some properties, we observe multiple entries that are not lodged in the system on the same day, but that have the same inspection date. In this case, we keep only those entries with the latest lodgement date (183,923 observations deleted). Figure A4 plots the difference in energy efficiency between the certificate that we keep and the one that we delete. The mode of the distribution is zero, and most of the differences are small. However, there is more mass on positive values, implying that the certificates that we keep tend to have on average slightly larger scores

4. For some properties, we observe multiple entries with the same lodgement date and time. This is due to:

    (a) Duplicate entries: all the variables are the same. We keep only one of the entries (4,472 observations deleted).

    (b) Non-duplicate entries: we are not sure which certificate is valid, so that we drop all observations (5,041 observations deleted).

5. We drop all observations with inspection dates prior to the introduction of the first RdSAP version, i.e. prior to 22 September 2008 (4,186 observations deleted)

6. We drop all observations with energy efficiency scores above one hundred (1,051 observations deleted). It is possible for the energy efficiency score to be above one hundred in case of very efficient homes that sell energy back to the grid.

Our final sample has: Total Observations $= 20,125,562 - (2,138,522 + 86,812 + 183,923 + 4,472 + 5,041 + 4,186 + 1,051) =$ 17,701,555 observations.

B.2 Merge of certificates and Price Paid data

A property may have a certificate but not have been transacted in which case it will not appear in the Price Paid data. It is also possible for the property to have been transacted, but not have an entry in the EPC data. As explained in the main body of the paper, some properties are exempt from requirement to have a certificate and some property owners may request for the certificate not to be made public (and excluded from the data).

We merge the EPC and Price Paid data using the property address. We proceed in steps:

1. For each address in the Price Paid dataset we take its postcode and obtain all the addresses in the EPC dataset that have the same postcode. We remove all numbers and common words from the Price Paid and the corresponding EPC address (e.g. words such as "apartment" and "flat");

2. We make all addresses lower case and use the Levenshtein distance to compare them. The Price Paid addresses are split into two parts: primary and secondary address. The EPC data addresses are split in 3 parts: Address 1, Address 2 and Address 3. We consider several permutations of these variables when computing Levenshtein distances. If the distance is sufficiently close we consider the street names to to be a match;

3. We restrict our sample to EPC properties that were a match to the Price Paid dataset in terms of street name;

4. From this sub-sample we take all the numbers from each address and intersect them. If the intersection is perfect we consider two addresses to be a match.

B.3 Summary statistics

In the main paper we use primarily two samples, the full sample and the sample of multiple certificate properties. The advantage of the latter is that it allows us to measure the investments undertaken within property. But naturally there is sample selection. In order to provide some insights on its nature, Table A1 compares single certificate and multiple certificate properties along several dimensions. Multiple certificate properties tend to be older, which is consistent with older properties being less energy efficient, and with investments being more likely to be undertaken for such properties. There is a larger proportion of flats among multiple certificate properties, which may due to flats being more likely to be rented out, and investments undertaken as a result of the rental regulations.

Figure A4: Difference in energy efficiency score between certificates with the same inspection date but different lodgement date

The figure plots the difference in energy efficiency points between the certificate with the latest lodgement date and the earlier certificate. The sample are the certificates with same inspection date and different lodgement date.

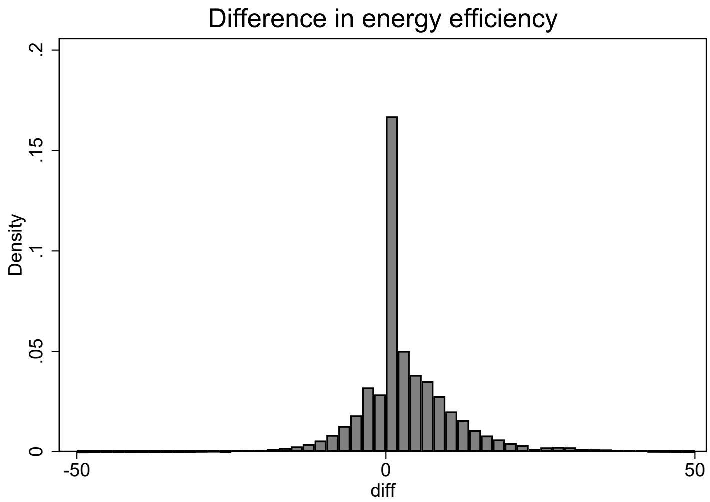


Table A1: Summary statistics

Panel A shows the distribution of construction age as a percentage of the total for the samples of single certificate properties and the first certificate of multiple certificate properties. Panels B and C show the distributions of property type and built form, respectively.

	Single certificate (%) (1)	Multiple certificate (%) (2)
Panel A: Construction age band		
Before 1900	11.01	12.93
1900-1929	14.08	16.96
1930-1949	13.67	13.00
1950-1966	17.40	16.80
1967-1975	12.16	11.70
1976-1982	6.28	6.02
1983-1990	7.15	6.53
1991-1995	3.90	3.58
1996-2002	5.33	4.58
2003-2006	4.39	4.17
2007 onwards	3.01	1.90
Others	1.63	1.83
Total	100.00	100.00
Panel B: Property type		
House	62.58	60.77
Flat	24.89	28.01
Bungalow	10.00	8.30
Maisonette	2.49	2.91
Park home	0.03	0.01
Total	100.00	100.00
Panel C: Built form		
Semi-Detached	31.54	29.21
Mid-Terrace	27.02	28.81
Detached	23.38	21.83
End-Terrace	13.61	14.26
Enclosed End-Terrace	1.61	2.07
Enclosed Mid-Terrace	1.27	1.78
Others	1.57	2.05
Total	100.00	100.00

C Additional details on sample selection

The sample of certificates that we observe is a selected sample. The main paper includes several results on the nature of sample selection. In this appendix we provide additional details.

In the data, the reason for the request of the certificate is registered in a separate variable named transaction type. Table A2 shows the number of certificates by tenure and transaction type for the full sample of certificates. Most certificates are requested for the purpose of a sale or a rental. However, there is a significant number requested for the Energy Company Obligation (ECO) program, a scheme that subsidizes energy improvements by low income homeowners or by landlords who let their properties to low income tenants. It covers work such as loft insulation and boiler replacement. The scheme is run and paid for by medium and large energy suppliers, who are obliged to meet certain energy efficiency improvement targets based on their domestic market energy share. Some certificates requested for the ECO program are also captured in the Other column: the program started in January 2013 and in the early period the answers for ECO program may not have been separately recorded. Finally, Feed-in-Tariff (FiT) refers to schemes whereby property owners receive a payment for energy that they sell to the grid.

Table A2 shows that the vast majority of certificates are requested by owner-occupiers for the purpose of a sale, by private landlords for the purpose of a private rental and by social landlords for the purpose of a rental. In some of the results in the main text we focus on these restricted groups. It makes the sample more homogeneous and excludes investments undertaken in response to subsidies.

Figure A5 plots the evolution over time of the number of observations for first certificates (including single certificate properties) and subsequent certificates. The figure distinguishes between owner-occupied properties with a certificate requested for a sale and private rental properties with a certificate requested for private rental. There is seasonality in the request of certificates for a sale. This is not surprising given that many owners request certificates shortly before a sale and there is seasonality in sales. Also as expected, the number of first certificates tends to decline over time and the number of subsequent certificates to increase. For private rental properties a large increase can be observed in the latter part of the sample period.

Certificates were introduced in 2008 and are valid for a period of 10 years. This means that those certificates that were issued in the early years of the sample are not longer valid by the end of the sample. This does not mean that a subsequent certificate will be requested: a valid certificate is only needed in the case of a sale or a new rental. Table A3 shows, for the sample of multiple certificate properties, the evolution over time of the age of the old certificate when the new one is issued. There is an increase in average age particularly pronounced in the last two years of the sample, with an average age reaching 8.83 years.

Figure A6 plots the average change in energy efficiency (points) as a function of the time elapsed between certificates for all private rental properties (panel a) and private rental properties in the bottom tercile of initial energy efficiency (panel b). The sample is that of multiple certificate properties with certificates requested for the purpose of a private rental (according to the second certificate of each observation pair). The buckets are defined in such as way that, for example, 5 years refers to subsequent certificates requested between 4 and 5 years since the date of the initial certificate. There are several interesting patterns, that again speak to the nature of the sample selection. There are larger changes for properties in the bottom tercile. There are significant drops in the average change in energy score from nine to ten years. Therefore, we see smaller improvements for certificates that are requested in the year prior to the expiry of the existing one, and after their expiry. This is again consistent with property owners who make investments in energy efficiency requesting a new certificate after the investments have been made even if the existing certificate is still valid.

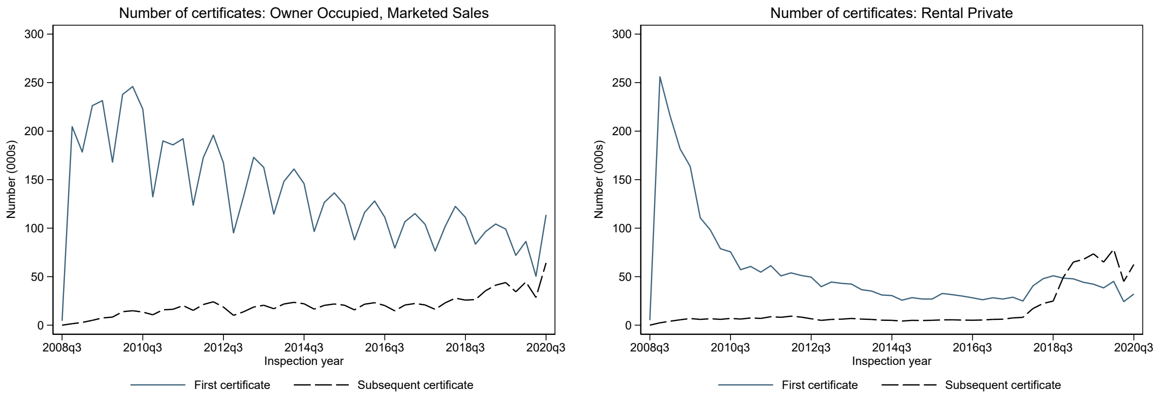
Table A2: Number of observations by tenure and transaction type

The table shows the number of certificate observations by housing tenure and transaction type, i.e. the reason for the request of the certificate. The sample includes all certificates issued from 2008 to 2020, including single certificate properties and multiple certificates for the same property. The ECO column refers to the Energy Company Obligation scheme.

	Transaction type					
Tenure	Sale	Rental private	Rental social	ECO	Feed-in-Tariff	Other
Owner-occupied	7,669,895	0	0	368,376	241,045	1,628,211
Rental private	96,736	3,551,307	0	112,166	5,534	295,161
Rental social	20,345	0	2,779,138	128,382	37,801	375,233
Missing tenure	180,112	0	0	5,507	2,963	203,643

Figure A5: Number of certificate observations over time

Number of observations for first certificates (including single certificate properties) and subsequent certificates. The figure distinguishes between owner-occupied properties with a certificate requested for a sale and privately rent properties with a certificate requested for private rental.



(a) Owner Occupied

(b) Rental Private

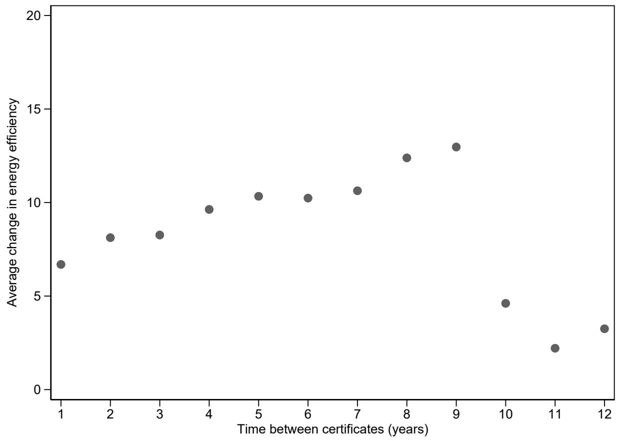
Table A3: Age (years) of the old certificate when new certificate is requested by year

The table shows several statistics for the age of the old certificate when a new one is requested, by calendar year. The sample is that of multiple certificate properties.

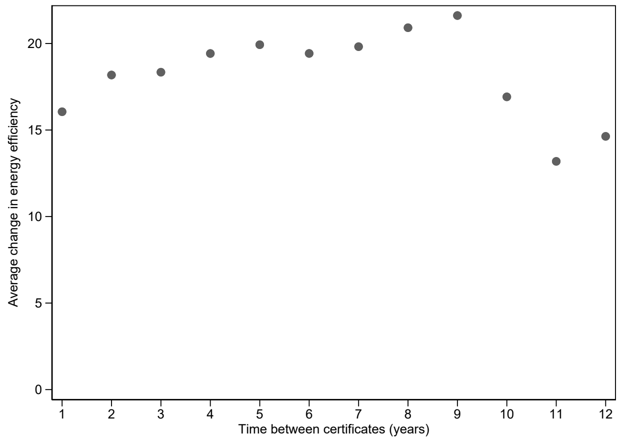
Inspection year	mean	median	p25	p75
2008	0.06	0.05	0.02	0.10
2009	0.44	0.40	0.18	0.66
2010	0.97	0.98	0.55	1.37
2011	1.54	1.59	0.88	2.21
2012	2.08	2.19	1.15	3.02
2013	2.12	2.04	0.44	3.61
2014	2.18	1.58	0.45	3.92
2015	2.62	1.91	0.72	4.61
2016	3.13	2.51	0.97	5.33
2017	4.11	3.68	1.75	6.63
2018	6.12	6.57	3.47	9.19
2019	8.12	9.98	6.06	10.25
2020	8.83	10.13	7.94	10.76

Figure A6: Energy efficiency improvement and time between certificates

This figure plots the average change in energy efficiency (points) as a function of the time elapsed between certificates for all private rental properties (panel a) and private rental properties in the bottom tercile of initial energy efficiency (panel b). The sample is that of multiple certificate properties with certificates requested for the purpose of a private rental (according to the second certificate of each observation pair). Time elapsed is in number of years. The buckets are defined in such as way that, for example, 5 years refers to subsequent certificates requested between 4 and 5 years since the date of the initial certificate.



(a) Rental private, all properties



(b) Rental private, bottom tercile properties

D Further evidence on capex, savings and IRRs

D.1 Capex required to meet the regulations

In our sample of certificates issued prior to April/2018 the median private rental flat with an energy efficiency below 39 had a rating of 32 SAP points, thus requiring an additional 7 points to satisfy the minimum threshold. We use the engineering model of section 2.3 to obtain estimates of the capex and points increase for different retrofits. We do so for some of the retrofits more commonly observed in the data in the sample of multiple certificate properties in the bottom tercile of energy efficiency. We focus on flats given their prevalence in the private rental sector.

We proceed in 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 gas condensing boiler. Associated with this change, there is a change in the (median) number of stars of that element from 1 in the first certificate to 4 in the subsequent certificate. 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 degree 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). Finally, we use the estimated coefficients of the empirical engineering model for energy efficiency to translate the change in star ratings into SAP points. We do 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.

Table A4 shows the results. In the first row we report the results for the retrofit described in the previous paragraph. The £5,000 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 (£980 per point) and installing double glazed windows (£1,150 per point). On the other hand, the installation of low energy lighting, improvements in main heat controls and roof insulation require much less capex, deliver smaller overall number of points changes, but a larger number of points per pound of investment.

D.2 Heterogeneity in capex, savings and IRRs

The certificates include retrofit recommendations along with estimated capex and savings for each recommendation. A significant drawback is that the capex figures is that they 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 should be). To address such a drawback, we obtain capex estimates from a UK government study (Palmer, Livingstone, and Adams (2017)). The authors interviewed organizations carrying out energy improvements for residential properties, surveyed them on upfront retrofit costs, and collected data from retailers on the cost of installing energy efficiency measures. They provide three estimates, low, medium and high, which vary with property type and size. The medium estimates are shown in the first column of each retrofit measure in Table A5. In the second column we show the average monetary (annual) savings by property type and size obtained from our data, averaged across all recommendations of the type for properties in that type and size category.

The capex and annual monetary savings figures have the expected patterns; detached houses and larger properties are more expensive to retrofit but also achiever larger annual savings than mid-terraced houses and smaller properties. In the third column of each retrofit, we report the IRR using the same investment lifespans for the measures as those reported in the main body of the paper. And in the fourth column we repeat the IRR calculation, but using the high capex cost estimate.

Although there are differences in IRRs across property type (and relative to the main body of the paper), several of the main conclusions are similar for all property types considered. First, internal and external wall insulation and replacing single with double glazing windows have negative IRRs. These are retrofits that require large upfront capex, reflected in the negative IRRs. Second, lower capex retrofits such as cavity wall insulation and loft insulation have positive IRRs. One difference relative to main body of the paper is that loft insulation has positive IRRs but the values tend to be significantly smaller than the vale of 36.9% shown in Table 9. This is because of higher capex estimates in Palmer, Livingstone, and Adams (2017) compared to the value in the certificates.

One retrofit where property type makes a difference is the changing of heating to gas condensing boiler. For the high capex estimates, whose values although not reported in the table are closer to the value from the certificates, the IRRs are negative for detached houses and bungalows and positive (albeit in the low single digits) for other property types. The cost of a boiler does not vary by much with property type, but the number of bathrooms is very important factor (Palmer, Livingstone, and Adams (2017)). Larger houses tend to have more bathrooms which increases the cost of the retrofit.

Table A4: Indicative capex required for complying with the regulation: Flats in bottom tercile

This table shows the capex required and points increase achieved for several retrofits. The first column reports the element (mainheat, mainheat controls, etc.). The second (third) column shows the initial (final) element description (and associate number of stars in parenthesis). The fourth column shows the median change in star ratings associated with the retrofit and the fifth column the energy efficiency SAP points increase. The improvement is calculated using the empirical model of section 2.3, using the fifth RdSaP period (from 8 December 2014 to 18 November 2017). The last column shows the indicative capital expenditure (from Table 9).

Property element	Initial element description (stars)	Subsequent element description (stars)	Change in star ratings (median)	Change in SAP points	Capex incurred (£)
Mainheat	Room heaters, electric (1)	Boiler and radiators, mains gas (4)	3.00	13.92	5000
Mainheat controls	Programmer, no room thermostat (1)	Programmer, room thermostat and TRVs (4)	3.00	7.41	400
Windows	Single glazed (1)	Fully double glazed (3)	2.00	4.20	4851
Roof	Pitched 100mm, loft insulation (3)	Pitched 270mm, loft insulation (4)	1.00	1.42	225
	Pitched no insulation (1)	Pitched 270mm, loft insulation (4)	3.00	8.64	225
Lighting	Low energy lighting (<=20% of fixed outlets) (1)	Low energy lighting (>=80% of fixed outlets) (5)	4.00	2.37	38
Walls	Cavity wall (no insulation) (2)	Cavity, insulated (4)	2.00	7.18	1000
	Solid brick (no insulation) (1)	Solid brick, insulated (4)	3.00	9.19	9000

Table A5: Capex, savings and internal rates of return by property type and size

The table shows capital expenditures, annual monetary savings, and internal rates of return for various types of retrofits, by property type and size. The capex estimates are the medium value from Palmer, Livingstone, and Adams (2017). The savings estimates are the average values from the EPC certificates for the corresponding property type and size. The capex and savings values are in pounds. The IRRs are calculated using the investment lifespans reported in Table 9. The last column reports the IRR for the high capex estimate in Palmer, Livingstone, and Adams (2017).

Property type and size	Capex	Savings	IRR	IRR high capex	Capex	Savings	IRR	IRR high capex
	Internal or external wall insulation				Cavity wall insulation			
Small flat (<54m^2)	5300	115	-2.6%	-3.3%	380	88	23.0%	13.6%
Large flat (>54m^2)	6700	158	-2.1%	-2.1%	430	117	27.2%	18.2%
Small mid−terrace house (<76m^2)	6800	119	-3.7%	-4.6%	460	73	15.6%	10.4%
Large mid−terrace house (>76m^2)	7500	180	-2.0%	-2.0%	505	118	23.3%	17.5%
Small semi−det. or end−of−terr. (<80m^2)	7800	223	-1.0%	-1.8%	529	140	26.5%	21.2%
Large semi−det. or end terr. (>80m^2)	8400	283	0.1%	-1.0%	660	180	27.2%	26.1%
Small detached house (<117m^2)	10200	333	-0.1%	-1.1%	680	227	33.4%	28.4%
Large detached house (>117m^2)	11500	456	1.2%	-2.3%	950	299	31.4%	24.9%
Bungalow (around 117m^2)	9800	176	-3.6%	-4.3%	650	128	19.7%	17.0%
	Replace single with double glazing windows				Change heating to gas condensing boiler			
Small flat (<54m^2)	2400	43	-8.3%	-9.8%	1700	230	6.0%	2.7%
Large flat (>54m^2)	3600	49	-10.1%	-11.0%	1800	305	10.9%	3.8%
Small mid−terrace house (<76m^2)	3900	48	-10.8%	-12.4%	2200	434	14.8%	7.4%
Large mid−terrace house (>76m^2)	5000	63	-10.6%	-11.2%	2400	538	18.2%	8.7%
Small semi−det. or end−of−terr. (<80m^2)	5500	47	-13.1%	-14.5%	2300	453	14.7%	2.3%
Large semi−det. or end terr. (>80m^2)	6400	64	-12.0%	-13.4%	2800	523	13.3%	0.8%
Small detached house (<117m^2)	5900	57	-12.2%	-13.3%	3200	467	7.5%	-4.3%
Large detached house (>117m^2)	8300	118	-9.8%	-11.0%	4300	423	-0.3%	-8.2%
Bungalow (around 117m^2)	6600	48	-14.0%	-15.1%	3200	382	3.4%	-7.5%
	Increase loft insulation to 270 mm (joists)							
Small flat (<54m^2)	-	-	-	-				
Large flat (>54m^2)	-	-	-	-				
Small mid−terrace house (<76m^2)	350	58	16.5%	9.0%				
Large mid−terrace house (>76m^2)	420	86	20.5%	13.0%				
Small semi−det. or end−of−ter. (<80m^2)	360	55	15.1%	8.2%				
Large semi−det. or end terr. (>80m^2)	470	88	18.5%	13.1%				
Small detached house (<117m^2)	510	66	12.6%	7.9%				
Large detached house (>117m^2)	600	129	21.4%	13.1%				
Bungalow (around 117m^2)	620	94	14.8%	9.8%				

E Moves in tenure as a result of the regulation

The minimum energy efficiency standard (MEES) regulations apply to private rentals and not to owner-occupied and social rentals. This might lead owners of privately rented properties to sell them, and the property being moved out of the private rental market. We provide evidence on whether this is the case using both the full sample of certificates and the merged sample of certificates and Land Registry data.

E.1 Certificates data

In a first step, we take the full sample of certificates and for each observation we measure tenure in that certificate and in the subsequent certificate for the same property (if available). The first panel of Table A6 shows, by tenure and energy efficiency score of the initial certificate, the number of observations in each tenure category in the subsequent certificate. The first column shows the number of observations for which there is no subsequent property certificate. The bottom panel shows the results as a fraction of the total for each row. For the majority of observations we do not observe a subsequent certificate. Certificates are required only in the case of a property sale or a new rental and valid for ten years. Property owners who do not invest in improving the energy efficiency of the property may not have an incentive to request a new certificate while the previous one is still valid.

For all tenure types, second certificates are more frequent for initially lower rated properties. For instance, for 0.34 of the owner-occupied properties with an initial score below 39 there is a subsequent certificate. The corresponding fraction for those with an initial score ≥ 39 is only 0.18. Property owners of lower rated properties are more likely to invest in their assets and to request a new certificate following such investments.

Table A6 shows that the absence of subsequent certificates is more common for owner-occupied properties than for rental ones (where tenure is measured using the initial certificate). The fractions for private rental (social rental) are 0.48 and 0.77 (0.59 and 0.78) for initial score below 39 and ≥ 39, respectively. There may be several reasons for this. First, a valid certificate is required for the sale or a new rental. If new rentals occur more frequently than sales, then subsequent certificates may be more frequently requested for rental properties than owner-occupied ones, in case the previous certificate is no longer valid or investments have been carried out. Second, the MEES regulations affect the likelihood of a subsequent certificate. This is visible in Table A6; for properties with an initial score ≥ 39, the proportions of subsequent certificates are 0.18 for owner-occupied, 0.23 for rental private, and 0.22 for rental social. For properties with an initial score < 39, the corresponding proportions are 0.34, 0.52, and 0.41, respectively.

Focusing now on initially privately rented properties with initial score <39, 0.14 of them (36,726 properties) move to the owner-occupied sector. This is not in itself evidence of the circumvention of the regulation. In fact, a much larger number of owner-occupied properties with initial score below 39 (65,282 properties) move from the owner-occupied to the private rental sector. The largest unknown is the group of 125,861 properties in the private rental sector with an initial score below 39 for which we do not observe a subsequent certificate. These properties may have been sold to owner-occupiers or social landlords (and a new certificate not requested) or they may still be privately rented to an existing tenant (the regulations only apply to new tenancies). Below we use Land Registry data to shed some light on this.

If in response to the regulation, private landlords of lower rated properties do not wish to undertake the investments required and decide to sell them, one might expect that to happen more for lower rated properties (for which larger investments are needed). Table A7 shows by initial tenure and for properties with an initial score below 39, the average initial score and the change in score. Naturally, for those properties for which there is no subsequent certificate we do not have the change in score.

Private rental properties with an initial score below 39 which remain in the private rental sector tend to have initial scores (27.0) that are on average similar to those which move to the owner-occupied sector (27.3), and to those for which we do not observe a subsequent certificate (26.3). Furthermore, the average change in score is similar for those properties which remain in the private rental sector and those which move to the owner-occupied sector (20.3 and 19.7, respectively). This shows that private landlords are not trying to dispose of low rated properties in order to avoid undertaking the investments required by the MEES regulations. A similar conclusion can be derived from the analysis of the properties that were initially owner-occupied: those that move to the private rental sector are similar to those that remain owner-occupied (25.7 and 26.3, respectively) and in fact the average change is score is larger (27.2 versus 23.5).

E.2 Merged certificates and price paid data

If private landlords sell their low energy rated properties in order to avoid undertaking the investments required, we might see a significant number of lower rated properties transacted around the date when the regulation was introduced. We use the merged sample of certificates and price paid data to measure the proportion of transactions of properties rated F and G (below 39), as a fraction of the total number of transactions. Figure A7 shows the results. The overall time trend is that of a decline in the proportion of lower rated properties that are transacted. This may also be a reflection of the investments made in energy efficiency, that reduce the proportion of low scoring properties in the housing stock. Focusing now on the potential effects of the regulation, there is a small increase of roughly one percentage point prior to approval, but there is a decline in the months prior to enforcement. Thus, it does not seem to be the case, at least to a significant extent, that private landlords of lower rated properties sold them to avoid having to make the investments required to comply with the regulations.

Table A6: Transition in tenure

We take the full sample of certificates and for each observation we measure tenure in that certificate and in the subsequent certificate for the same property (if available). The first panel shows, by tenure and energy score of the initial certificate, the number of observations in each tenure category in the subsequent certificate. The first column shows the number of observations for which there is no subsequent property certificate. The bottom panel shows the results as a fraction of the total for each row.

		Tenure in the subsequent certificate				
Initial tenure and score	No cert.	Owner-occ.	Rental priv.	Rental social	Other	Total
			Number of observations			
Owner-occupied <39	504,796	191,472	65,282	3,598	5,145	770,293
Owner-occupied ≥ 39	7,522,684	1,228,923	289,612	67,766	28,249	9,137,234
Rental private < 39	125,861	36,726	965,83	2,877	2,236	264,283
Rental private ≥ 39	2,918,741	281,953	542,848	36,349	16,730	3,796,621
Rental social < 39	29,151	2,218	3,516	14,459	257	49,601
Rental social ≥ 39	2,577,780	47,568	39,486	619,592	6,872	3,291,298
			Fraction of the total			
Owner-occupied < 39	0.66	0.25	0.08	0.00	0.01	1.00
Owner-occupied ≥ 39	0.82	0.13	0.03	0.01	0.00	1.00
Rental private <39	0.48	0.14	0.37	0.01	0.01	1.00
Rental private ≥ 39	0.77	0.07	0.14	0.01	0.00	1.00
Rental social <39	0.59	0.04	0.07	0.29	0.01	1.00
Rental social ≥ 39	0.78	0.01	0.01	0.19	0.00	1.00

Table A7: Initial energy efficiency (points) and change by transition in tenure

The table shows by initial tenure and for properties with an initial energy efficiency points below 39, the average initial points and the change in points between the first and subsequent certificate. Naturally, for those properties for which there is no subsequent certificate there is no change.

	Tenure in the subsequent certificate			
Initial tenure and score	No certificate	Owner-occupied	Rental private	Rental social
Owner-occupied < 39				
Initial points	27.20	26.25	25.72	26.30
Change in points	-	23.46	27.23	28.82
Rental private < 39				
Initial points	26.28	27.34	27.00	26.55
Change in points	-	19.67	20.26	23.43
Rental Social < 39				
Initial points	28.72	26.42	26.94	28.63
Change in points	-	24.23	22.24	26.37

Figure A7: Fraction of transacted properties with energy below 39 over the total number of transactions

The figure plots the evolution over time of the fraction of transactions of properties with energy efficiency score below 39 over the total number of transactions. The vertical lines show the dates of approval, issuance of guidance, and enforcement of the regulations. We use the merged sample of certificates and Land Registry data.

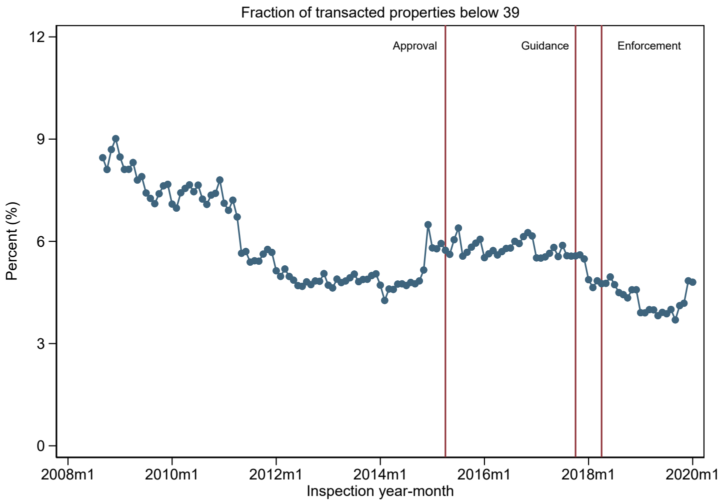


Table A8: Energy efficiency versus environmental impact rating gains using a matched sample

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. The sample includes private rental properties and owner-occupied properties matched exactly on the following property dimensions: 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. Private rental is a dummy variable that takes the value of one for private rental properties, and zero for owner-occupied. 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. 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 dummies for the conventions in effect at the times of the first and second certificates of each observation pair. Standard errors 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)
Rental private	0.841***	0.627***	0.003**	0.836***	0.624***	0.003**
	(0.091)	(0.087)	(0.001)	(0.089)	(0.085)	(0.001)
Approval to enforcement	1.691***	1.149***	0.012***			
	(0.098)	(0.094)	(0.001)			
Post-enforcement	2.915***	1.828***	0.022***			
	(0.073)	(0.070)	(0.001)			
Rental private × Approval to enforcement	2.446***	1.052***	0.025***	2.447***	1.051***	0.025***
	(0.139)	(0.133)	(0.002)	(0.136)	(0.130)	(0.002)
Rental private × Post-enforcement	-0.294***	-1.368***	0.022***	-0.291***	-1.364***	0.022***
	(0.104)	(0.100)	(0.001)	(0.102)	(0.097)	(0.001)
Constant	14.093***	11.651***	0.021***	16.241***	13.011***	0.038***
	(0.064)	(0.062)	(0.001)	(0.028)	(0.027)	(0.000)
Pair fixed effects	No	No	No	Yes	Yes	Yes
R-Squared	0.01	0.00	0.01	0.52	0.53	0.53
Observations	563,721	563,721	563,716	563,600	563,600	563,590