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

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Abstract

The operation of residential buildings 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 rented properties to satisfy minimum energy efficiency standards. The analysis shows significant investments in low capital expenditure retrofits. We estimate a 1-1.5% rent increase for the average property around the regulatory approval, which is not sufficient to compensate most landlords for the capital expenditures required to comply with the regulations. Moreover, the environmental gains were smaller than the energy efficiency ones, limited by the use of more polluting energy sources. Regulations targeting carbon emissions directly may be more effective in tackling the climate challenge.

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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 (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 understanding of the effectiveness of regulatory interventions assumes special relevance in light of the low household participation in subsidized programs (Fowlie, Greenstone, and Wolfram (2015), Fowlie, Greenstone, and Wolfram (2018)).

The MEES regulations introduce minimum standards that privately rented residential properties must satisfy. They are enforced by local authorities, who have the power to issue compliance and penalty notices to landlords. 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)).

Our analysis is particularly important as it sheds light on whether a single regulation can effectively target multiple objectives. The policy we study targets energy efficiency, a cost-based measure that considers the quantities of energy used and their price. At the same time,

[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)) and more recent work on the perception of individual's attitudes towards climate policies (Dechezleprêtre, Fabre, Kruse, Planterose, Chico, and Stantcheva (2022)).

many homes use energy from multiple sources (e.g., electricity, gas, etc.), which differ in their price and carbon emissions. A key takeaway of our analysis is that combining the price and quantities of the different energy sources in a single metric while making it easier to compare heterogeneous properties along the cost dimension ultimately has unintended consequences from an emissions perspective.

The primary analysis relies on the near-universe of Energy Performance Certificates (EPCs) for residential properties in England and Wales. Since October 2008, properties that are sold or rented out are legally required to have a valid certificate,[3] which tackles the important issue of energy efficiency measurement (see, for example Bardhan, Jaffee, Kroll, and Wallace (2014)), and it also provides a measure of the environmental impact of the home (the carbon emissions from its operation). The data covers roughly 14 million unique residential properties, a much larger and comprehensive sample than most which have been used in the existing literature.

We evaluate the effects of the regulations by comparing retrofit 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 on both the extensive and the intensive margins. On the intensive margin, we rely on a large sample of investments undertaken by landlords. The characterization of the retrofits shows that they tend to be similar to those carried out by homeowners and concentrated on investments that require lower capital expenditures (capex) and generate higher internal rates of return (IRR), such as low-energy lighting and main heating controls. 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 drive such retrofits. An important contribution of our paper is to document the large-scale evidence on the types of retrofits undertaken by both homeowners and landlords.

To assess the impact of the regulations and retrofits on the income received by landlords, we merge the EPC data with the rental listings from Rightmove, which has previously been used by Giglio, Maggiori, and Stroebel (2015). The empirical specification compares rental prices for properties below and above the regulatory threshold (i.e. the minimum efficiency standard that rental properties need to satisfy) before and after the approval of the regulations, controlling for time and property fixed effects. We estimate a positive 1% impact on rental income. While this effect is statistically significant, its economic magnitude is small and sufficient to compensate

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

those landlords who make low capex retrofits to meet the regulatory threshold but not large capex ones.

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. 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 the carbon factor of the energy source. We show how regulatory interventions targeting energy cost-based measures favor investments in reducing the consumption of expensive energy, and not necessarily the most polluting one.

A key insight from our analysis is that the tension between policies on the consumption and production sides of energy markets may drive the divergence between energy efficiency and carbon emissions. In 2013, the UK introduced a carbon tax on electricity production, which led to a large reduction in coal-based electricity and an increase in the use of gas and renewables.[4] At the same time, it may have contributed to higher electricity prices, as added costs are passed on to consumers. Hence, properties that use electricity as their main fuel source become less energy efficient, driven by higher costs, and in fact, we observe significant household investments with these properties shifting heating systems from electricity to gas. As electricity production becomes greener over time, this may soon become undesirable from an emissions point of view. Thus, it is important to not only think about policies on the production side (Harstad, 2012), but also coordinate these policies with the consumption side of the market.

Related Literature. Our paper is most closely related to the literature on residential energy efficiency (Dubin and McFadden (1984); Hausman (1979); Dubin, Miedema, and Chandran (1986)).[5] The literature has found low participation in programs that subsidize investments, even though they have positive private returns and generate environmental benefits (Fowlie,

[4] In the absence of optimal taxation on carbon use or energy, other policies could yield the same adjustments in resource allocation that can be generated by the combination of a land tax, a housing tax, and a commuting tax (Borck and Brueckner (2018).

[5] In addition, there is a 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. See also the recent work of Gupta, Martinez, and Nieuwerburgh (2023) on the conversion of energy inefficient office buildings into energy efficient homes.

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)).

A second contribution of our study lies in quantifying the effect of energy efficiency investments driven by regulations on rental prices. Our findings show small rent increases that are insufficient to compensate for the capital expenditures incurred by most landlords to comply with the regulations. In perfect markets, property and rental prices adjust to fully reflect the value of the savings associated with retrofits. However, prior work argues for the role of frictions such as imperfect information and financial constraints (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 (Myers (2019)). Moreover, their expected shorter tenure may make it uneconomical to pay for the costs of acquiring property-specific information (or to incur attention costs).

Our paper is also related to a recent literature that studies the impact of climate risk on the value of real estate assets,[6] and the mortgages used to finance them.[7] Different from these studies, we document the effects of regulatory intervention and concomitant investments in energy efficient retrofits. Finally, there are also papers that study residential energy efficiency in England. For instance, Hilber, Palmer, and Pinchbeck (2019) study how historic preservation policies affect the ability of property owners to make energy efficiency improvements, with an impact on energy consumption. Fuerst, McAllister, Nanda, and Wyatt (2015) studies the relation between home prices and energy efficiency using hedonic price regressions and finds a positive correlation. 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

[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 Adelino and Robinson (2023) for an analysis of how credit availability leads to the purchase of larger houses which consume more energy. Giglio, Kelly, and Stroebel (2021) provides a literature review on climate finance.

our analysis on the regulatory intervention, its effects on energy efficiency and carbon emissions, and draw general implications for regulatory design.[8]

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

2 The certificates data and background analysis

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

2.1 EPCs

The Energy Performance of Buildings Directive (2002/91/EC) is an EU Directive which aims to tackle climate change by reducing the amount of carbon produced by buildings. An essential component of the legislation is the measurement of the efficiency of homes through EPCs. Measurement is one of the crucial bottlenecks discussed by Bardhan, Jaffee, Kroll, and Wallace (2014) for energy efficiency retrofits. In England and Wales, EPCs have been required by law since the 1st of October 2008 to sell or rent out a home.[9] The certificates are valid for ten years but may be updated before expiration.

EPCs for existing homes are generated using a Reduced data Standard Assessment Procedure (RdSAP). An accredited assessor visits the property to gather information on its characteristics (property type, size, insulation, heating system, etc.) and its energy sources. The information is collected in a datasheet following certain conventions.[10] The assessor must collect documentary evidence (photographs and invoices for works carried out). The information

[8] In addition, our paper also contributes to the literature that investigates the role of information provision in energy-efficiency investments (Allcott and Taubinsky (2015); Allcott and Sweeney (2017); Allcott and Knittel (2019); Houde (2018); Newell and Siikamäki (2014); Brounen and Kok (2011); Aydin, Brounen, and Kok (2020)).

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

[10] The information collected is fairly thorough. 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.

is then entered into government-approved software that generates the EPC. The cost of a certificate 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.[11] In addition, the data includes a description of the property element (e.g., type of windows, insulation thickness) that we use to characterize the retrofits carried out by households.

The EPCs provide a measure of the overall energy efficiency rating of the property on a numerical scale of 1 to 100 (SAP points) that reflects its energy running costs. Total energy cost is equal to the sum of the estimated energy used for each of the purposes (space heating, water heating, ventilation, and lighting minus energy saving/generation technologies) multiplied by the prevailing prices of the type(s) of fuel used in the property.[12] It is deflated by a fuel price index equal to the weighted average price of heating fuels so that the rating is not affected by the general rate of fuel price inflation, and the ratings of homes assessed when energy prices were different are comparable. Note that as the rating depends on the fuel mix at the property and hence individual home ratings are affected by relative changes in the price of particular heating fuels (e.g., electricity and gas) used in the home. Therefore, relative price changes may affect incentives to undertake investments that favor a particular fuel type. (Appendix A.1 provides more details.)

Table 1 shows how the SAP points ratings are grouped in bands and converted into a letter rating, from A (the most efficient, 92 plus points) to G (the least efficient, 1-20 points). In the analysis that follows, we exploit the thresholds.

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

[11] 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).

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

The EPCs data for England and Wales are publicly available from the Ministry of Housing, Communities, and Local Government (MHCLG) Open Data Communities website. The data include information that is not in the actual certificate but that is relevant for our analysis. For instance, on tenure type (owner-occupied, private rented, social rented), property age, the reason for the request of the certificate (e.g., marketed sale, private rented, etc.), and several additional property characteristics (e.g., energy sources used in the home).

2.2 Sample construction and summary statistics

We carry out some data cleaning. First, we remove entries corresponding to certificates issued prior to 22 September 2008, the starting date of RdSAP 2005 version 9.82. conventions (our sample includes data until September 2020). Given our focus on retrofits, we remove new build observations from the sample (but retain subsequent observations (if any) for the new build properties).[13] In addition, we remove duplicate observations from the sample and in the case of multiple entries with the same inspection date but a different lodgement date/time in the system we keep only the last entry, which is the valid certificate. (Appendix B.1 provides further details.)

The full sample of EPC data contains 17.7 million certificates for 14 million unique residential properties located in England and Wales. This compares with an estimated total number of dwellings in 2010 of 24.2 million.[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. Our primary sample includes multiple certificate properties that allow us to examine retrofit investments by owners, while we use the full sample of EPCs to characterize the energy efficiency of the housing stock in England and Wales.

For most multiple certificate properties, we have exactly two certificates, meaning one observation pair and one observation for changes. However, for properties with three certificates, we have two observation pairs and two observations for changes (and so on for properties with more than three certificates). The sample of multiple certificate properties has 6.8 million entries, corresponding to 3.1 million unique properties. The majority of properties in the multiple certificates sample (85%) have exactly two certificates. Appendix Table A1 reports the number

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

[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.

of properties for which we observe a given number of certificates. The multiple certificates sample allows us to characterize energy retrofits for the same property over time.

Naturally, the sample of properties for which we observe multiple EPCs is not random, as we observe subsequent certificates being issued following retrofits. Figure 1 plots the SAP points distributions for single certificate properties and the first certificate of multiple certificate properties. The latter has a much larger mass on the left tail. Therefore, we are more likely to observe a second certificate for initially lower-rated properties.[15] The distributions show bunching. For single certificate properties it occurs at 39 and 55, the lower bounds of the E and D ratings, respectively. For the first certificate of multiple certificate properties the bunching is at 38, the upper bound of the F rating. For the latter group, even small investments will bring the properties to the next letter grade rating of E.

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

The last two columns of Table 2 report the mean and standard deviation of the number of stars, with one for very poor and up to five stars for very good. For all the elements, single certificate properties have higher mean and lower dispersion than the first certificate of multiple certificate properties. The analysis of the subsequent certificate of multiple certificate properties allows us to study the elements for which we observe improvements and to characterize them. In Appendix C we construct an empirical regression model for energy efficiency rating as a function of property type and the star classification of its elements, which allows us to translate retrofits into energy efficiency rating point increases and measure the extent to which different investments help meet the regulatory requirements (in Section 4.3 we give more details on how we use these estimates).

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

2.3 The importance of the initial level for the investments

An important determinant of the decision to carry out a retrofit is the initial level of energy efficiency. In order to show this, we take the sample of multiple certificate properties and divide it into terciles based on their initial efficiency. More precisely, we calculate the SAP points cut-offs corresponding to the bottom and top one-third of the distribution of first certificates of multiple certificate properties shown in 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.1 of Table 3 reports the number of observations in each group, the average initial and change in points, and the percentage change. The number of observations refers to observation pairs.[16] There are large increases in energy efficiency for properties in the bottom group: an average increase of 13.5 points or 33.3% of the base value. On the other hand, there is a small decline of 3.4 points or 4.7% for properties in the top group. This is due to depreciation in the features of the home, not counteracted by retrofits. These results show the importance of the initial level of efficiency for the investments.

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

2.4 Housing stock prior to the approval of regulations

One of the main arguments for introducing the regulation is that investment inefficiencies in the private rental sector imply that the level of investments carried out by landlords is sub-optimal. Panel B of Table 3 compares owner-occupied and private rental properties using all the certificates issued before April 1, 2015. The first two rows report the mean and median energy efficiency points. Perhaps surprisingly, we find that rental properties are better on average (and at the median) than owner-occupied ones. The regulations target the left tail

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

of the distribution, and there may be more mass in this tail in the rental sector, even if, on average, properties in this sector are better. Figure 2a plots the whole distributions to show that this is not the case.

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

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

These results complement evidence in 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.[17]

3 The effects of the regulations

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

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

3.1 The regulatory framework

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

One reason to expect differential investment could be that imperfect information may be more prevalent in the rental than in the owner-occupied sector. Renters tend to have shorter home tenures and less incentive to pay the costs of acquiring home-specific information. In equilibrium, imperfectly informed renters may not be willing to pay higher rents for more energy efficient homes, and investments that, in the absence of imperfections, would be privately optimal are not undertaken.[18] 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.[19] 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.[20]

In England and Wales, in 2010, of the 24.2 million dwellings that formed the housing stock, 66% were owner-occupied, 17% privately rented, and 18% rented from social landlords (local authorities and housing associations). The corresponding 2020 percentages were 64%, 19% and 17%. In comparison, in our full sample of 17.7 million certificates, 56% are owner-occupied, 23% are privately rented, and 19% are rented from social landlords.[21] Therefore, our sample includes a smaller proportion of owner-occupied and a larger proportion of privately rented

[18] Imperfect information also arises in the case of inattentive households. Due to shorter expected home tenure, renters may be less willing to incur attention costs than owner-occupiers (Lu and Spaenjers, 2023).

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

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

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

properties than the overall stock.

3.2 Magnitude of the investments

As a first step, we plot the distributions of SAP points for owner-occupied and private rental properties for certificates issued in selected calendar years. We take the full sample of certificates (including single certificate properties) but restrict the analysis to certificates requested for the purpose of a marketed sale (for owner-occupied) or private rental (for privately rented properties). They constitute 78% and 87% of all the observations for each tenure type, respectively.[22]

Figure 3 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 disproportionate number of observations, first cluster just above 55 and then, in 2018, also above 39. It could be due to some homeowners investing in their assets just enough to bring them to the next letter rating or to client pressure (implicit or explicit) on appraisers to provide higher ratings. In either case, it shows increased importance of the energy efficiency letter rating for the purpose of selling a property. The bottom figures plot the distributions for private rental. Compared to owner-occupied properties, bunching at the 39 thresholds becomes very pronounced in 2018, and significantly more than in the owner-occupied sector.

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

Table 4 shows the number of observations, the proportion of observations with a given tenure type, average initial SAP points, and the absolute and percentage change in points between the

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

first and the second observations of the pair. The classification by tenure type is done using the second certificate of each observation pair. We divide the sample into observation pairs for which the second certificate was issued before/after April/15, the date when the parliament initially approved the regulations.

There are significant differences between each of the periods and between owner-occupied and private rental. After April 2015, there is a 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. On average, private rental properties are initially less efficient than owner-occupied ones, with a larger gap after April/15. This shows a change in the composition of private rental properties with second certificates requested after this date. Such a change in composition is not visible for other tenure types. The 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.[23]

3.2.1 Extensive margin

We investigate the number of second certificates in the context of regression analysis. A caveat is that we only observe when the inspection took place and the certificate issued, and not when the actual investments were undertaken. It is, therefore, possible that some of the investments were made before the regulations were introduced but that the certificate was only requested in response to the regulations. We think that this is unlikely for private rental properties: 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, we expect landlords who invest in energy efficiency measures to update their certificate.

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

[23] 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.

$$\mathbb{1}_{it}^{Subsequent} = \alpha + \gamma_1 \mathbb{1}_{it}^{Points<39} + \gamma_2 \mathbb{1}_{it}^{RentalPrivate} + \gamma_3 \mathbb{1}_{it}^{Points<39} \times \mathbb{1}_{it}^{RentalPrivate} + \epsilon_{it} \quad (1)$$

where $\mathbb{1}_{it}^{Points<39}$ is an indicator variable for properties with a rating below 39 (the minimum cut-off for the E band) and $\mathbb{1}_{it}^{RentalPrivate}$ is an indicator for private rental properties.

The regression in column (1) of Table 5 shows the unconditional mean of the left hand side dummy variable: for 0.21 of the certificates there is a subsequent property certificate. In column (2) we include among the explanatory variables the dummy for low energy efficiency. The large estimated coefficient of 0.194 confirms that subsequent certificates are much more likely to be requested for initially lower rated properties. In columns (3) and (4) we focus on the role of tenure type. The results show that we are much more likely to observe a subsequent certificate for rental properties than for owner-occupied ones, and especially so for those initially below the 39 points threshold. The fifth column shows that this is also the case in the sample of properties in the bottom tercile of initial energy efficiency. In the last column we further restrict the sample to certificates issued prior to Apr/15, and estimate the likelihood that there is a subsequent certificate (including in the post approval period). We are less likely to have a subsequent certificate for private rental, unless they have a rating below 39, in which case the likelihood is higher.

3.2.2 Intensive margin

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

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

We then calculate 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''). Figure 4a shows the results and corresponding confidence intervals distinguishing between owner-occupied properties and private rental properties. The vertical lines mark the approval date (April 2015), the issuance of guidance (October 2017), and the enforcement (April 2018) of the MEES regulations.

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

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

3.3 Nature of retrofit investments

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

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

The private rental differences in the pre versus post 2015 periods are economically more significant for lighting (13% versus 38%), mainheat controls (21% versus 27%) and pitched roof insulation thickness of at least 270 mm (5% versus 10%). 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, focused on similar retrofits. The analysis of financial returns of the retrofits helps to explain why.

3.3.1 Financial returns

EPCs contain recommendations on how best to improve energy efficiency rating, the indicative capex required to implement them and their projected monetary savings. We use them to measure the financial returns on the investments undertaken. It is important to note that although the recommendations depend on the specific characteristics of the home (e.g. solid walls or cavity walls), the monetary savings are estimates based on a typical property occupancy and not on actual energy consumption.[24]

This matters since Fowlie, Greenstone, and Wolfram (2018) and Christensen, Francisco, Myers, and Souza (2020) have found a wedge between projected and actual savings from energy retrofits, meaning the actual investment returns are lower than those predicted by engineering models. Fowlie, Greenstone, and Wolfram (2018) use data on actual energy consumption, discount rates equal to 3%, 6% and 10% and investment lifespans of 10, 16, and 20 years to calculate present values of savings equal to between 31% and 76% of the average upfront investment costs. If our engineering model suffers from the same bias, the estimates that we provide in this section are an upper bound for the returns that can be achieved through such retrofit investments. However, the savings estimates that we use are an order of magnitude similar to those documented in Kattenberg, Eichholtz, and Kok (2023) for Netherlands, who measure actual energy savings achieved.

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

[24] 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.

Wolfram (2018).[25]

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

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

In order to address the shortcoming that the capital expenditure figures included in the certificates are indicative and do not depend on property type, we obtain property-specific figures for a sub-sample of the retrofits from Palmer, Livingstone, and Adams (2017). We use their medium and high cost estimates and calculate monetary savings in our data by retrofit and property type. Appendix D shows that 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 7. This is because of higher capex estimates.[26]

[25] 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 Graff 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. In addition, Kotchen (2017), Jacobsen and Kotchen (2013), and Novan, Smith, and Zhou (2022) investigate the impact of building codes on residential energy consumption.

[26] 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.

3.4 Moves in tenure in response to regulations

The regulations apply to private rentals and not to owner-occupied properties, 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 this case, we might see a significant number of lower rated properties transacted around the date when the regulations were introduced. In Appendix F.2, we investigate this hypothesis using the full sample of certificates merged with Land Registry data on property transactions. We do not find evidence in support of the hypothesis. One potential reason is that the financial cost of meeting the regulatory requirements is not significant, a hypothesis that we investigate next.[27]

4 Impact on rents

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

4.1 Rents

To assess the impact of the regulations on rents we use a rental listing dataset provided by `rightmove.co.uk`, which has previously been used among others by Giglio, Maggiori, and Stroebel (2015). Our original dataset contains roughly 11.2 million rental listings corresponding to 4.1 million unique properties from 2006 to 2023. We retain those only from 2008 to 2020 to match our certificates sample and merge the two using the unique property reference numbers (UPRNs) that are included in both.[28] More precisely, we merge each rental listing in the Rightmove data with the EPC that is valid at the time of the listing, i.e. the EPC for the specific property that was most recently issued prior to the listing. Therefore, our data has, for many properties, *within* variation in both listing prices and energy performance. Our final

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

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

merged data has roughly 7.2 million listings for 2.8 million unique properties. (Appendix E provides details and Appendix Table A5 shows summary statistics for the merged data.)

4.2 Empirical specification

The dependent variable is the logarithm of the listing price of property i in listing l at time t, denoted by $Log(Price_{ilt})$. Our estimates for the rent effects rely on properties for which we observe more than one listing price and on moves in energy performance from a below 39 rating to an above 39 rating (for the same property). The primary equation that we estimate is:

$$Log(Price_{ilt}) = \quad \alpha + \gamma_1 \mathbb{1}_{it}^{Points \geq 39} + \gamma_2 \mathbb{1}_{it}^{Points \geq 39} \times \mathbb{1}_{it}^{Post-Approval} + \theta_i + \theta_t + \epsilon_{ilt}$$

where $\mathbb{1}_{it}^{Points \geq 39}$ is an indicator variable for listings for properties with a rating of 39 or above at the time of the listing. The other indicator variable takes the value of one for listings in the post approval period. The base case is rental listings in the pre-approval period for properties with energy efficiency of 39 or below. The θ_i, θ_t are property and time fixed effects, and ϵ_{ilt} is the residual.

The coefficient of interest is γ_2 which measures additional rents for properties with a rating 39 or above in the post-approval periods relative to the rents for the *same* property in the pre-approval period when it had a rating of below 39, controlling for the general increase in rents over time (Table 8, columns 3 and 6). Additionally, for comparison, we also present two additional specifications: (i) without the inclusion of property fixed effects (columns 1 and 4), and (ii) we control for property characteristics by including dummies for construction age, property type, built form, and floor area (columns 2 and 5).

Table 8 reports the estimates. In the first three columns, the sample consists of all properties, and in the last three columns, the properties that were initially in the bottom tercile of the energy efficiency distribution.

In columns 1 and 4, controlling only for the time series evolution in rents, we estimate a 4.6% (5%) average increase in rents for all (bottom tercile) properties above 39 in the post-approval period relative to pre-approval period. Notably, this effect is attenuated when we control for property characteristics in column 2 (column 5), with the average increase being 4.5% (3%).

Lastly, in columns 3 and 6, we identify the effects from properties that in the pre-approval period had a below 39 rating which increased to above 39 in the latter periods, controlling for the overall increase in rents over the years (through the year fixed effects). The estimated coefficients are positive and statistically significant with values of 1.4% (1%) for the sample of all (bottom tercile) properties. Overall, the regulation had a positive and roughly 1%-1.5% effect on rents.

4.3 Capex required and investment returns

The regulations have forced owners of low rated properties to make investments. We can combine the estimated rent effects with capex data to calculate the returns on these investments.

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 the main heat, if the first certificate says "Room heaters, electric" and the subsequent certificate "Boiler and radiators, mains gas," this means that there was a change in heating to a gas condensing boiler. Associated with this change, there is an increase in the (median) number of stars of that element from 1 in the first certificate to 4 in the subsequent certificate.[29] Finally, we use the estimated coefficients of the engineering model (Appendix C) to translate the increase in star ratings into SAP points. We do so using the estimated coefficients of the RdSaP period from 8 December 2014 to 18 November 2017, from just prior to approval to enforcement of the regulations, for the retrofits more commonly observed in the data, and focusing on flats due to their prevalence in the rental sector.

Table 9 shows the results. In the first row, we report the results for the retrofit described in the previous paragraph. The £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 (£979 per point) and installing double glazed windows (£1,155 per point). On the other hand, the installation of low energy lighting, improvements in main heat controls and roof insulation require much less capex and deliver more points per pound of investment. Therefore, retrofits that require more capex tend to yield larger changes in number of points, but smaller changes in points per pound of capex spent.

In our sample of certificates issued prior to the approval of the regulations the median

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

private rental property with an energy efficiency below 39 had a rating of 26 SAP points, thus requiring an additional 13 points to satisfy the minimum threshold. In Table 10 we evaluate the net present value of several retrofits. The first option is the change in heating to gas condensing boiler, a large capex item. The second option is the combination of several low capex retrofits (low energy lighting, mainheat controls) and the installation of double glazing. The third option involves only low capex retrofits, but the increase in points that is achieved is smaller. Panel A shows that these options yield 13.92, 13.28 and 9.78 points increases, respectively. In Panel B we report the capex needed for each of the options.

The final row of Table 10 calculates the net present value. The median monthly rent before the approval of the regulations for properties with an energy efficiency rating below 39 is £650. The previously estimated rent increase is 1.0% meaning an annual rent increase of £85.8. We assume that this value increases at the annual rate of inflation of 2%. In options 1 and 3, the lifespan of the investments is 10 years so the calculations use this horizon. In option 2, the lifespan of the investment in windows is 20 years, so we assume an additional investment in low energy lighting and mainheat controls at the end of the first 10 years and convert the net present value into 10 year payments to make the values comparable to options 1 and 3.

We consider three values for the discount rate when computing the net present values. For a discount rate of 3%, the net present value of the retrofits are £-4,275, £-2,468 and £287, respectively. Therefore, a combination of several low capex retrofits may be a lower cost path to comply with the regulations than a large investment, with marginally positive net present value. We say may be because the combination considered only achieves a 9.78 points increase which is not sufficient for the median property below the 39 points threshold. Note that the conclusions are not sensitive to the choice of discount rate.

The fact that the rent increases are not sufficiently large enough to compensate for the capital expenditures required for most retrofits may explain why landlords do not make these investments in the absence of the regulations.

5 From energy efficiency to carbon emissions

One of the main objectives of the regulations is a reduction in carbon emissions. 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 low carbon footprint energy source improve energy efficiency without having a large effect on carbon emissions. Similarly, shifts towards cheaper but more polluting energy sources reduce energy costs but may actually lead to larger carbon footprints. In this section, we study the effects of the regulation on carbon emissions. What makes this study particularly interesting compared to the energy usage of electrical appliances is that homes often rely on multiple energy sources that differ in their cost and environmental impact.

5.1 Environmental gains

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

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

Figure 4a 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 4b. There is a divergence between the relative gains in energy efficiency and in environmental impact. In order to investigate this further, we calculate the ratio of energy efficiency and environmental impact ratings for each observation. We then calculate the change in this ratio between the two property observations before averaging across all observations for second certificates issued in a given year/quarter. Figure 4c shows the results. The changes are larger for rental private than owner-occupied, with a gap that widens significantly post-approval.

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

$$\Delta Y_{it} = \alpha + \gamma_1 \mathbb{1}_{it}^{RentalPrivate} + \gamma_2 \mathbb{1}_{it}^{ApprovalToEnforcement} + \gamma_3 \mathbb{1}_{it}^{PostEnforcement} + \gamma_4 \mathbb{1}_{it}^{RentalPrivate} \mathbb{1}_{it}^{ApprovalToEnforcement} + \gamma_5 \mathbb{1}_{it}^{RentalPrivate} \mathbb{1}_{it}^{PostEnforcement} + \theta_1 + \theta_2 + \epsilon_{t,i} \quad (3)$$

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

The estimated coefficients shown in the first column of Table 11 imply that during the period from approval to enforcement, the energy efficiency of rental private properties increased by 2.416 points (=0.378+2.038) more than that of owner-occupied ones. The comparable number for the change in environmental impact is -0.278 points (column (2), equal to the sum of the coefficients on rental private and the interaction term between rental private and approval to enforcement). The corresponding difference for the ratio of energy efficiency to environmental impact (column (3)) is 0.053.

In columns (4) to (6), we add fixed effects for property construction age, type, built-form and floor area (ten decile dummies) and for the conventions in effect at the time that the certificates were issued. The estimated differences between rental private and owner-occupied from approval to enforcement are 1.709 (energy), 0.527 (environment), and 0.023 (ratio). These differences are smaller than when we do not include the fixed effects in the regressions so that the type of properties in the owner-occupied and rental sectors and convention changes are partly responsible for the divergence. However, it still is the case that the gains achieved in energy efficiency in the private rental sector (relative to owner-occupied housing) are not accompanied by similarly large gains in environmental impact.

Another way to control for the differences in characteristics of properties in the owner-occupied and private rental samples is through propensity score matching. More precisely, we adopt a multivariate-distance matching approach to identify properties in our owner-occupied group that best resemble private rental ones. Our approach matches each certificate of a private rental property to another certificate of an owner-occupied property exactly on property characteristics (built form, property type, construction age band) and timing (pre-approval,

approval to enforcement, and post-enforcement periods). Additionally, the properties are also matched based on the closest floor area. We then estimate regressions similar to those in Table 11, but on the private rental and owner-occupied matched samples. Appendix Table A6 shows that, as before, there is a divergence between energy efficiency and environmental impact.

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

5.2 Energy sources, fuel costs, and carbon factors

Table 12 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 initial proportion of private rental (owner-occupied) properties relying on electricity as the main energy source is equal to 35.3% (17.7%). 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 are significantly smaller, showing once again that the composition of properties matters, but it still is the case that rental homes are more likely to rely on electricity as the main source.

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. 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.[30]

Figure 5 plots the evolution over time of domestic gas and electricity prices. The solid lines plot the electricity and gas unit prices (pence/kWh) used in the RdSAP calculations which are updated every semester.[31] The dashed lines plot the quarterly evolution of the fuel components of consumer price indices. The figure shows an increase in the price of electricity

[30] The last three rows of each panel of Table 12 show the prevalence of investments in renewable energy sources. There are larger changes for owner-occupied than private rental, but the magnitudes are small. 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.

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

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. In line with these price incentives, Table 12 shows that indeed there has been a shift both in the rental private and owner-occupied sectors away from electricity and towards natural gas (shown in the Δ columns) which is beneficial from a cost point of view but not necessarily from an environmental perspective.

5.3 Policy implications

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 Table 12 shows, 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 to 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.

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 rental sector) and to reduce carbon emissions. Our main data source are the 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 rental sector, mostly on the retrofits requiring lower capital expenditure and generating higher projected internal rates of return, such as low energy lighting, heating controls, and roof insulation. Additionally, we find significant investments in windows, even though they are not attractive from a purely financial energy efficiency point of view. This shows that other considerations, such as home comfort (e.g. noise reduction) are important. Further, we estimate an 1% rent increase around the regulatory approval. While this effect is statistically significant, its economic magnitude is small and sufficient only to compensate those landlords who make low capex retrofits to meet the regulatory threshold but not large capex ones.

Importantly, our analysis showed the regulations and investments undertaken led to a divergence in energy efficiency and environmental impact gains in the rental properties compared to owner-occupied ones. 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.

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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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.

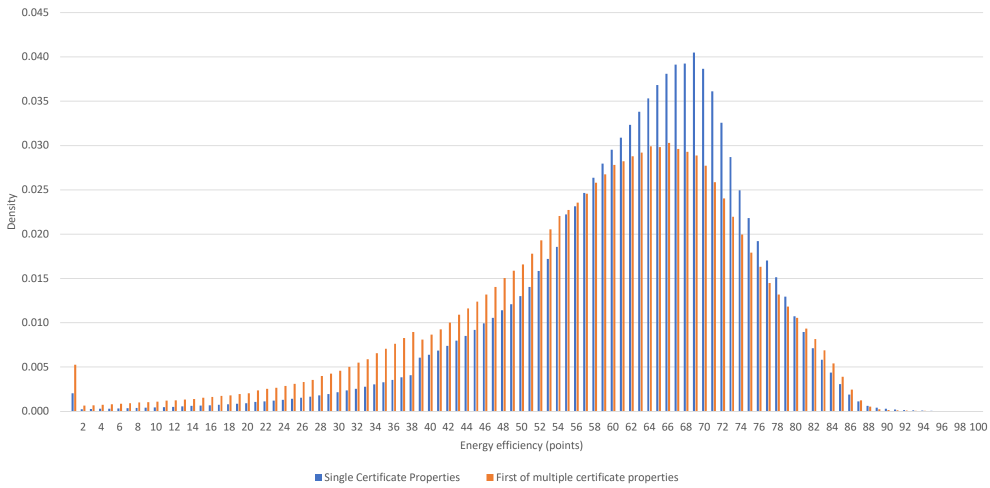
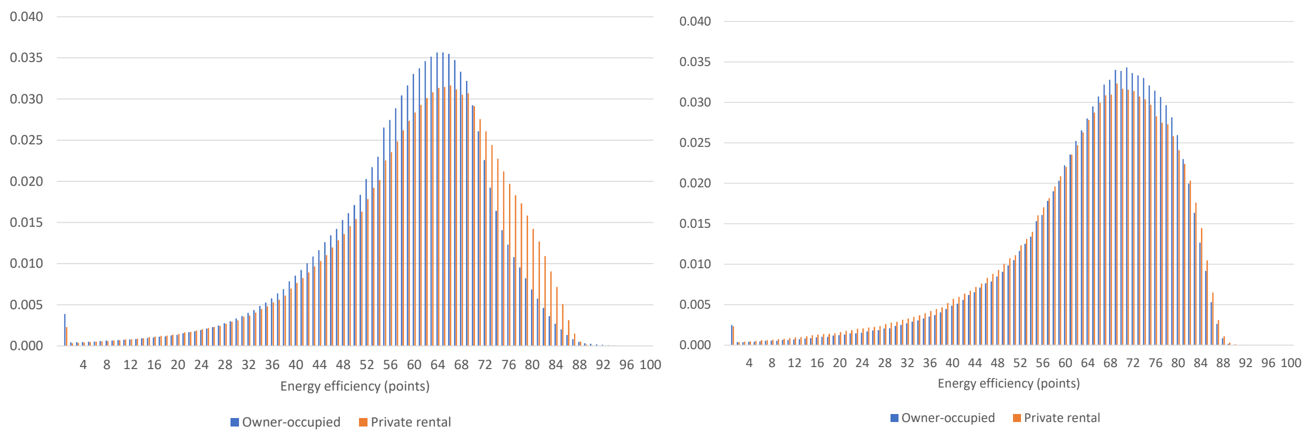


Figure 2: Energy efficiency distributions by tenure.

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.

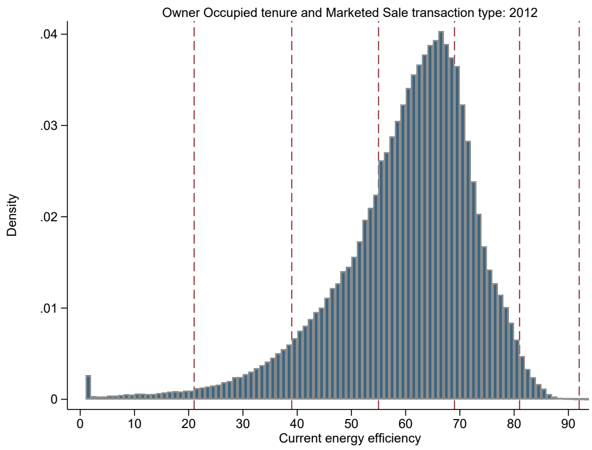


(a) All properties

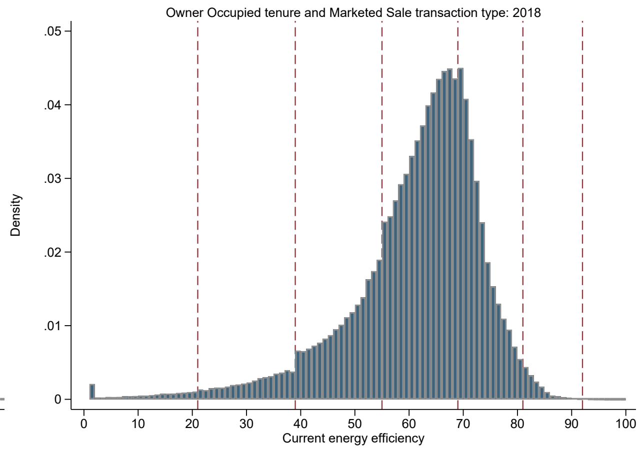
(b) Flats and maisonettes

Figure 3: Distributions of energy efficiency for selected calendar years.

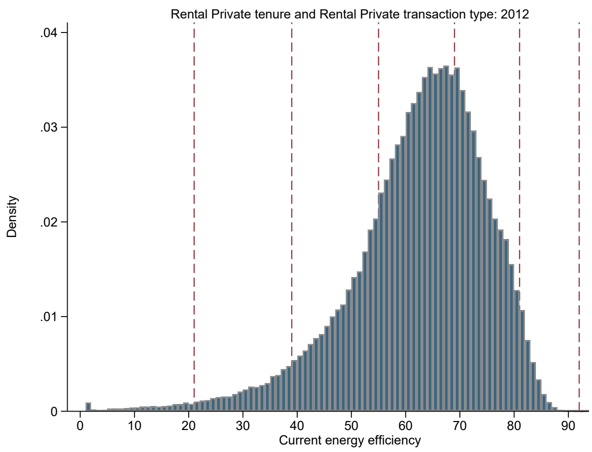
The sample includes both first certificates and subsequent certificates for the properties. In Panels (a) and (b) the sample is restricted to certificates for owner-occupied properties requested for the purpose of a marketed sale. In Panels (c) and (d) the sample is restricted to certificates for private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



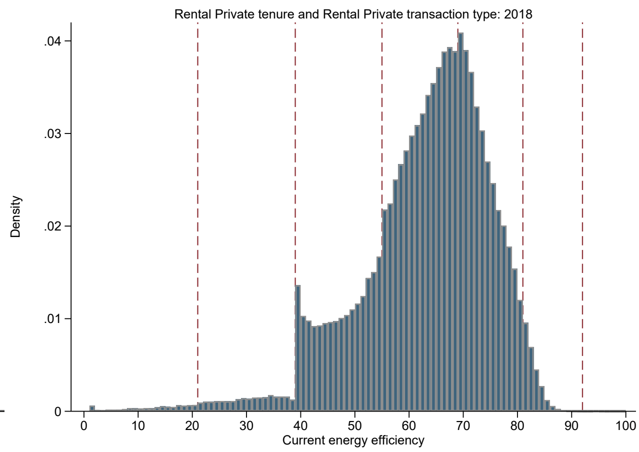
(a) Owner-occupied, Year 2012



(b) Owner-occupied, Year 2018



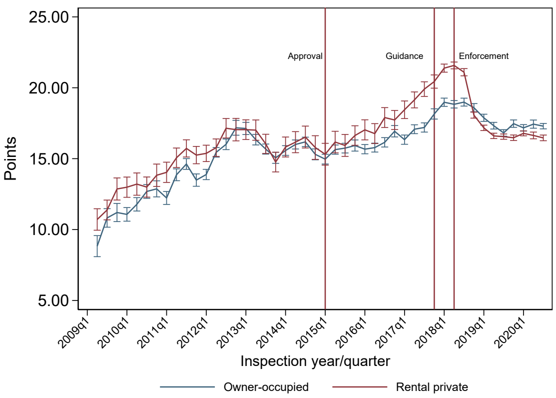
(c) Rental private, Year 2012



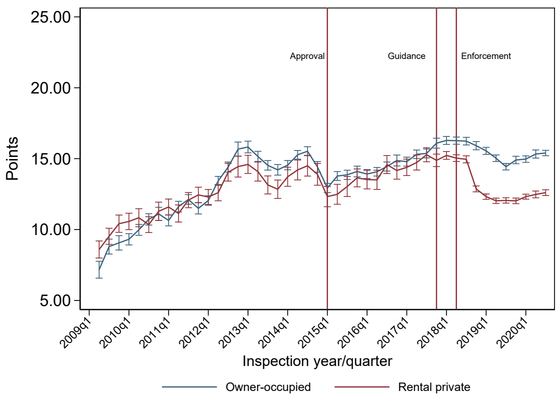
(d) Rental private, Year 2018

Figure 4: Changes in energy efficiency and environmental impact ratings (points) over time

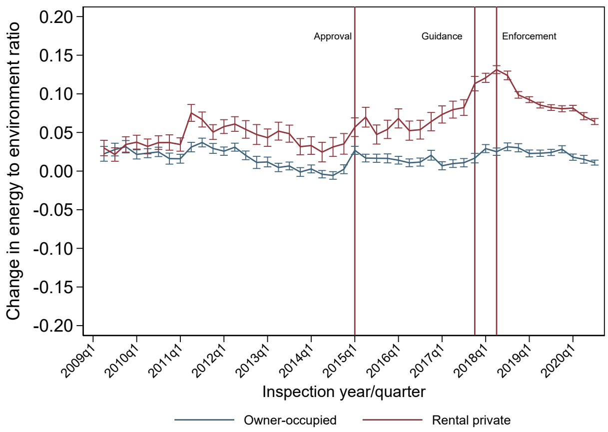
The sample is restricted to multiple certificate properties in the bottom tercile of initial energy efficiency. For each pair of certificates for the same property, we calculate the difference in energy efficiency rating (points) between the first and the second certificate (within property changes, second minus first certificate). Figure 4a 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 4b 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 4c 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 5: Energy prices

This figure 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.

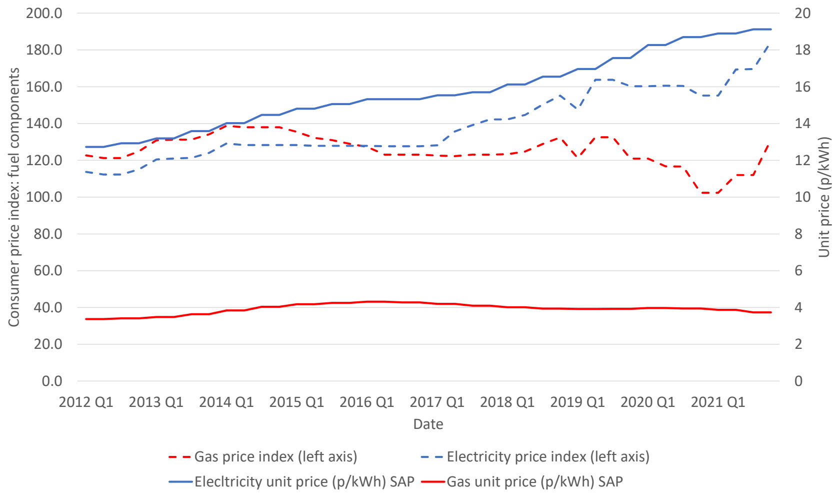


Table 1: Energy efficiency rating

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: 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 3: Initial characteristics

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

Panel A: Heterogeneity as a function of the initial level of efficiency

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

Panel B: Initial characteristics by tenure

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

Table 4: Heterogeneity as a function of tenure and time period

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

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

Table 5: Probability and timing of subsequent certificate

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

	(1)	(2)	(3)	(4)	(5)	(6)
Constant	0.210***	0.197***	0.174***	0.177***	0.242***	0.636***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\mathbb{1}_{Points<39}$		0.194***	0.200***	0.168***	0.102***	0.133***
		(0.000)	(0.000)	(0.000)	(0.001)	(0.001)
$\mathbb{1}_{PrivateRental}$			0.063***	0.055***	0.041***	-0.064***
			(0.000)	(0.000)	(0.001)	(0.001)
$\mathbb{1}_{Points<39}$ x $\mathbb{1}_{PrivateRental}$				0.125***	0.138***	0.128***
				(0.001)	(0.001)	(0.002)
Sample	Full	Full	Owner-O./ Priv. rental	Owner-O./ Priv. rental	Owner-O./ Priv. rental Bot. tercile	Owner-O./ Priv. rental Bot. tercile Pre Apr/15
Observations	17,701,555	17,701,555	13,968,431	13,968,431	3,686,438	1,296,017
R^2	0.000	0.013	0.021	0.023	0.028	0.033

Table 6: Initial characteristics and retrofits by tenure and time period

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

		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 7: Financial returns on retrofits

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

	Capex (£)	Savings (£)	PV sav/Capex			IRR (%)	Lifespan (years)
Discount rate values			3%	2%	1%		
Install low energy lighting	38	30	7.3	7.7	8.2	80.7	10
Upgrade heating controls	400	58	1.3	1.4	1.5	9.1	10
Install hot water cylinder thermostat	300	61	1.9	2.0	2.1	17.3	10
Increase loft insulation to 270mm	225	83	9.4	10.8	12.7	38.9	30
Change heating to gas condensing boiler	5,000	360	0.7	0.7	0.7	-4.0	10
Replace single with double glazing windows	4,851	56	0.2	0.2	0.3	-9.5	20
Cavity wall insulation	1,000	148	3.8	4.4	5.1	16.5	30
50 mm internal or external wall insulation	9,000	197	0.6	0.6	0.8	-0.7	30

Table 8: Impact on rents

The dependent variable is the logarithm of the listing price of property i in listing l at time t, denoted by $Log(Price_{ilt})$. Columns 1 through 3 include all certificates, while in columns 4 through 6, we restrict the sample to the properties initially in the bottom tercile. $\mathbb{1}_{Points \geq 39}$ is a dummy variable that takes the value of one for certificates with SAP points 39 or above and zero otherwise. $\mathbb{1}_{Post-Approval}$ takes the value of one for second certificates issued after March/15 and zero otherwise. Property characteristics fixed effects are dummies for construction age, property type, built form, and floor area. The model is estimated using ordinary least squares. Standard errors are corrected for heteroscedasticity and autocorrelation. Standard errors are reported in parentheses.*,**, and *** indicate significance at 10%, 5%, and 1% respectively.

Dependent variable	Log(price)					
	All certificates			Bottom tercile		
	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{Points \geq 39}$	0.025***	0.055***	-0.007***	0.036***	0.033***	-0.006
	(0.003)	(0.003)	(0.002)	(0.005)	(0.004)	(0.006)
$\mathbb{1}_{Post-Approval} \times \mathbb{1}_{Points \geq 39}$	0.046***	0.045***	0.014***	0.050***	0.030***	0.010***
	(0.004)	(0.003)	(0.002)	(0.005)	(0.005)	(0.003)
Fixed effects:						
Year	Yes	Yes	Yes	Yes	Yes	Yes
Property characteristics	No	Yes	No	No	Yes	No
Property	No	No	Yes	No	No	Yes
R^2	0.06	0.26	0.91	0.05	0.27	0.90
Observations	5,960,456	5,960,456	5,960,456	323,691	323,691	323,691

Table 9: Indicative capex required for complying with the regulation: Flats in bottom tercile

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

Property element	Initial element description (stars)	Subsequent element description (stars)	ΔSAP points	Capex incurred (£)	Capex/ ΔSAP
Mainheat	Room heaters, electric (1)	Boiler and radiators, mains gas (4)	13.92	5000	359.20
Mainheat controls	Programmer, no room thermostat (1)	Programmer, room thermostat and TRVs (4)	7.41	400	53.98
Windows	Single glazed (1)	Fully double glazed (3)	4.20	4851	1,155.00
Roof	Pitched 100mm, loft insulation (3)	Pitched 270mm, loft insulation (4)	1.42	225	158.45
	Pitched no insulation (1)	Pitched 270mm, loft insulation (4)	8.64	225	26.04
Lighting	Low energy lighting (<=20% of fixed outlets) (1)	Low energy lighting (>=80% of fixed outlets) (5)	2.37	38	16.03
Walls	Cavity wall (no insulation) (2)	Cavity, insulated (4)	7.18	1000	139.28
	Solid brick (no insulation) (1)	Solid brick, insulated (4)	9.19	9000	979.33

Table 10: Increase in rents vs. additional capital expenditures

This table compares the rent increase to the capital expenditures landlords must make to satisfy the regulations. Panel A quantifies the increase in SAP points achieved through different retrofits, while panel B presents the commensurate capital expenditures in pounds. Panel C computes the net present value from making the investments against the increase in rent as captured by the coefficient from estimates in column 6 of Table 8. In the calculations we assume that rents grow at the annual rate of 2% and we consider three values for the discount rate. In options 1 and 3 the horizon is 10 years, corresponding to the lifespan of the retrofits. In option 2, the lifespan of the investment in windows is 20 years, so that we assume an additional investment in low energy lighting and mainheat controls at the end of 10 years, and convert the net present value into two ten year payments to make the values comparable to options 1 and 3.

	Option 1	Option 2	Option 3
	Panel A: Increase in points achieved through capex		
Mainheat	13.92	-	-
Low energy lighting	-	2.37	2.37
Mainheat controls	-	7.41	7.41
Windows	-	4.20	-
Total points	13.92	13.98	9.78
	Panel B: Capex required		
Mainheat	£5,000	-	-
Low energy lighting	-	£38	£38
Mainheat controls	-	£400	£400
Windows	-	£4,851	-
Total capex	£5,000	£5,289	£438
	Panel C: Net Present Value		
Discount rate of 3%	-£4,275.0	-£2,467.5	£287.0
Discount rate of 2%	-£4,235.3	-£2,305.9	£326.7
Discount rate of 1%	-£4,192.4	-£2,138.0	£369.6

Table 11: Energy efficiency versus environmental impact rating gains

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

Dependent variable	Δ Energy	Δ Environ.	Δ Energy/Env.	Δ Energy	Δ Environ.	Δ Energy/Env.
	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{RentalPrivate}$	0.378***	-0.738***	0.028***	0.528***	0.285***	0.004***
	(0.077)	(0.073)	(0.001)	(0.077)	(0.072)	(0.001)
$\mathbb{1}_{ApprovalToEnforcement}$	2.099***	1.741***	-0.001	1.298***	1.220***	-0.006**
	(0.063)	(0.060)	(0.001)	(0.151)	(0.142)	(0.003)
$\mathbb{1}_{PostEnforcement}$	3.152***	2.350***	0.006***	0.836***	1.422***	-0.021***
	(0.058)	(0.055)	(0.001)	(0.185)	(0.174)	(0.003)
$\mathbb{1}_{RentalPrivate} \times \mathbb{1}_{ApprovalToEnforcement}$	2.038***	0.460***	0.043***	1.180***	0.247**	0.027***
	(0.119)	(0.113)	(0.002)	(0.119)	(0.112)	(0.002)
$\mathbb{1}_{RentalPrivate} \times \mathbb{1}_{PostEnforcement}$	-0.531***	-1.890***	0.039***	-0.102	-1.096***	0.028***
	(0.095)	(0.090)	(0.002)	(0.094)	(0.089)	(0.002)
Constant	14.555***	13.015***	0.016***	15.698***	12.935***	0.044***
	(0.040)	(0.038)	(0.001)	(0.116)	(0.110)	(0.002)
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 12: 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

For Online Publication

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

A Energy performance certificates

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.[32] 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:

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

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

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.

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

A.2 The relation between environmental 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, 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. 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. The conventions that apply during our sample period are:

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

B Certificates data

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

B.1 Sample construction

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 Summary statistics

In the main paper we use primarily two samples, the full sample and the sample of multiple certificate properties. Table A2 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.

In the data, the reason for the request of the certificate is registered in a separate variable named transaction type. Table A3 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 A3 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.

C 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. 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:

$$\text{Energy efficiency points}_{it} = \alpha + \sum_{j} \sum_{l=1}^{5} \beta_{jl} D_{ijlt} + \gamma X_{it} + \epsilon_{it} \tag{7}$$

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).[33] During the sample period, there are seven versions of the conventions that apply.[34] 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 A5 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: 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 A5 shows the R^2 for each of the seven regressions; its value is fairly stable over time at around 0.8.

Figure A6 plots the estimated coefficients for construction age band, built form, and property type.[35] 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.[36] Flats and maisonettes have fewer external walls and are on average more energy efficient than houses.

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:

$$\Delta\text{Energy efficiency}_{i,t',t''} = \text{Energy efficiency rating}_{i,t''} - \text{Energy efficiency rating}_{i,t'}. \quad (8)$$

[33]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.

[34]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.

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

[36]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.

And using equation (7):

$$\Delta\text{Energy efficiency}_{i,t',t''} = (\alpha_{t''} - \alpha_{t'}) + \sum_j \sum_{l=1}^{5} (\beta_{j,l,t''} D_{i,j,l,t''} - \beta_{j,l,t'} D_{i,j,l,t'}) + (\gamma_{t''} X_{i,t''} - \gamma_{t'} X_{i,t'}). \quad (9)$$

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:

$$\Delta\text{Energy efficiency}_{i,t',t''} = \sum_j \sum_{l=1}^{5} \beta_{j,l} (D_{i,j,l,t''} - D_{i,j,l,t'}) \quad (10)$$

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 A5; (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.

D Heterogeneity in capex, savings and IRRs

The certificates include retrofit recommendations along with estimated capex and savings for each recommendation. A drawback is that the capex figures are for a standardized property and do not vary with property type or size. Naturally, this is not realistic (e.g., the larger a house, the more expensive insulating walls is). To address this drawback, 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 A4. In the second column we show the average monetary (annual) savings by property type and size obtained from our data.

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 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. In the calculations we assume that the savings grow at the annual rate of 2%.

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, external wall insulation and replacing single with double glazing windows tend to have low and mostly negative IRRs. These are retrofits that require large upfront capex. 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 7. 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 most property types except terraced houses that have positive low single digits returns. The cost of a boiler does not vary by much with property type, but the number of bathrooms is a very important factor (Palmer, Livingstone, and Adams (2017)). Larger houses tend to have more bathrooms which increases the cost of the retrofit.

E Rental listings data

We merge rental listings with our EPC dataset using UPRNs (unique property reference numbers). The UPRN is the unique identifier for every addressable location in United Kingdom. For each rental listing in the rightmove dataset we associate it with its EPC rating that is valid at the time of the listing. We can easily distinguish what is a new rental listing or an old rental listing with a revised price (since such entries are properly flagged on the dataset). If there is a listing with one or more price revisions we keep the latter price.

Figure A7 illustrates the matching process for one property in our sample. Property with UPRN 57910 was listed for rental in rightmove 11 times between 2012 and 2022 (i.e. it was listed once every year). This property had 3 certificates issued in Dec/09, Mar/18 and Dec/19, with energy efficiency scores of 37, 49 and 55 respectively. All rental listings between Dec/09 and Feb/18 will have an associated EPC rating of 37. The rental listings between Mar/18 and Dec/19 have an associated EPC rating of 49. All listings on or after Jan/20 have an EPC rating of 55.

F Property transactions data

The property transactions data is from the Land Registry Price Paid dataset. It covers all residential property transactions in England and Wales since 2005.

F.1 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.

F.2 Moves in tenure in response to the regulations

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.

F.2.1 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 A7 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 A7 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 $\geq$ 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 A7; for properties with an initial score $\geq$ 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 A8 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).

F.2.2 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 regulations were 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 A8 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.

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

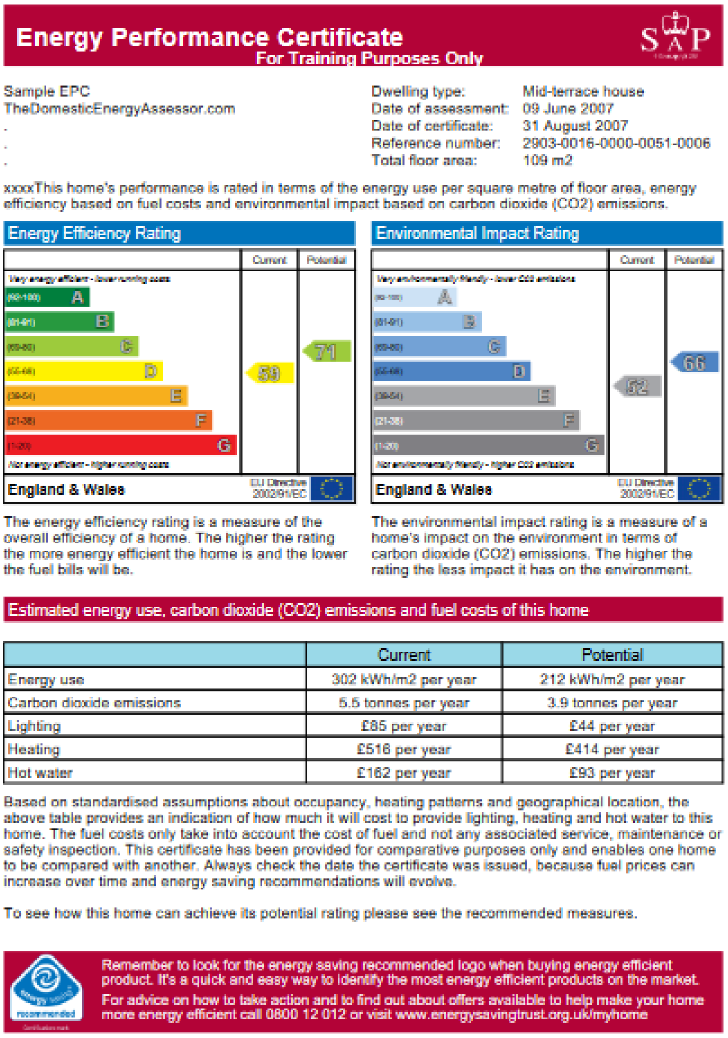
This figure shows a screenshot of the "The Government's Standard Assessment Procedure for Energy Rating of Dwellings" regulation, SAP 2012 version 9.92 (October 2013). It displays the individual components of energy consumption and their CO_2 emissions that drive environmental impact rating.

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

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.

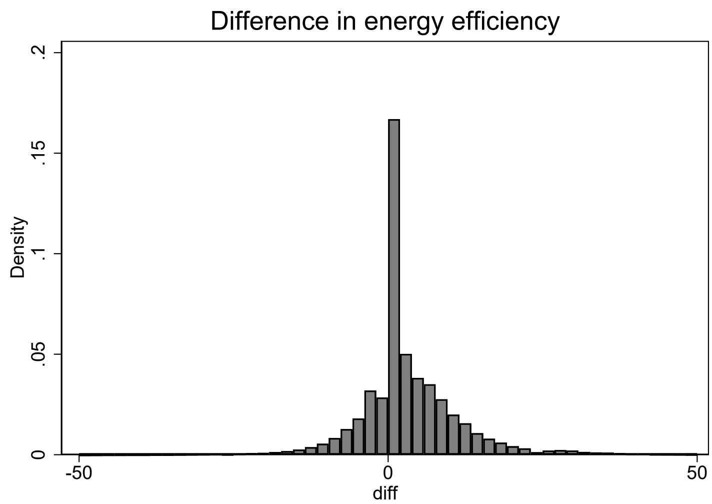


Figure A5: Empirical model for energy efficiency: estimated coefficients and model fit.

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.

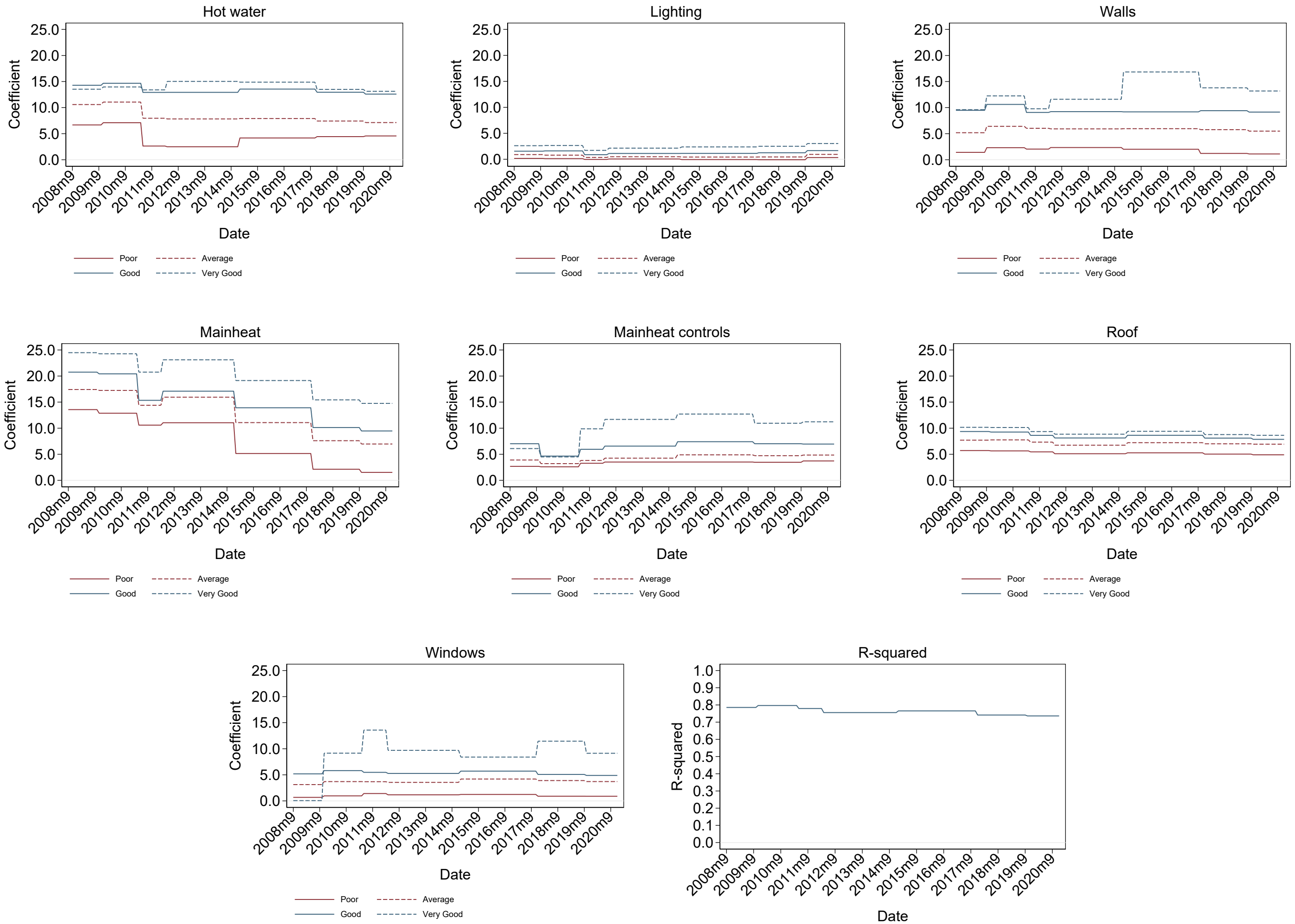
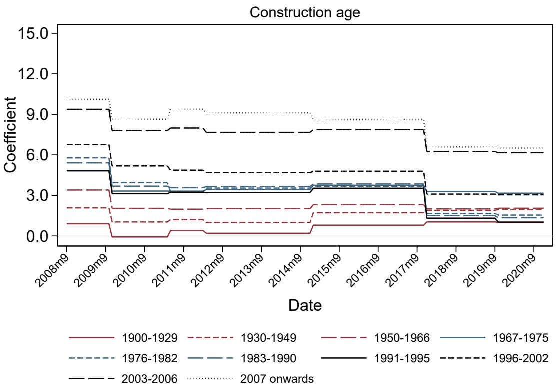
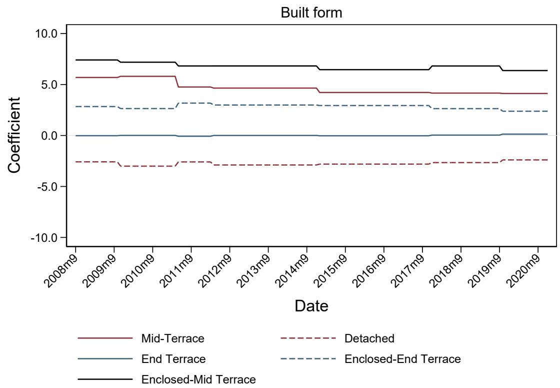


Figure A6: Estimated effects of construction age, built form and property type

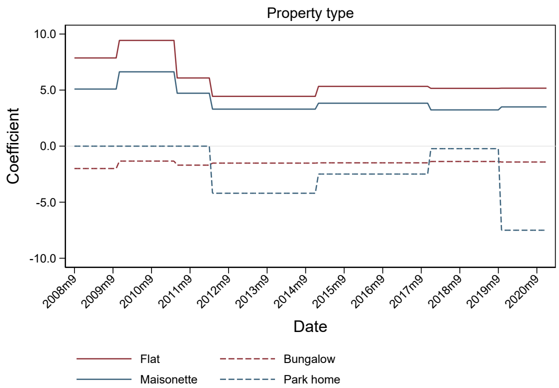
The figure plots the estimated coefficients for construction age band, built form and property type for the different RdSAP periods. The omitted categories are: construction years before 1900, semi-detached, and house, respectively.



(a) Construction age



(b) Built form



(c) Property Type

Figure A7: Merge of rental listings and certificates

This figure illustrates the merge process of the Rightmove listings and certificates data for one specific property in our sample.

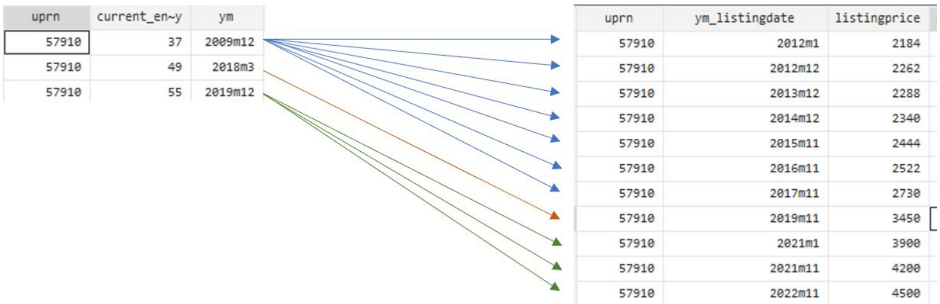


Figure A8: Fraction of transacted properties with energy below 39 over the total number of transactions

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.

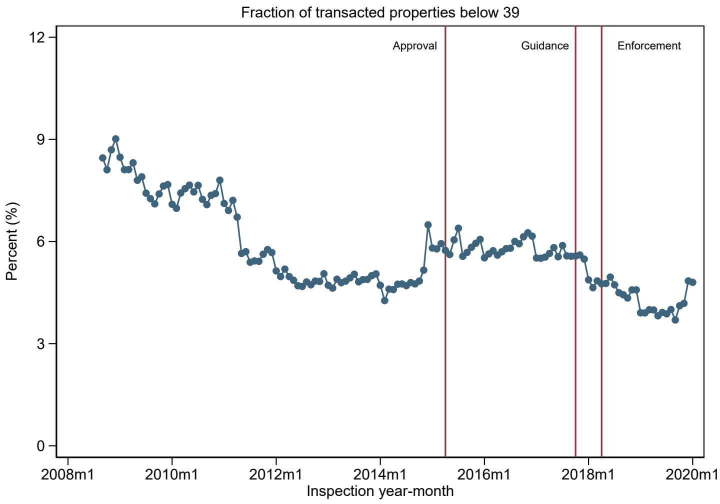


Table A1: Number of certificates per property

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 A2: 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

Table A3: 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

Table A4: Capex, savings and internal rates of return by property type and size

The table shows capital expenditures, initial annual monetary savings, and internal rates of return for various types of retrofits, by property type and size. The capex estimates shown are the medium value from Palmer, Livingstone, and Adams (2017). The savings estimates are the average values from the energy performance certificates for the corresponding property type and size. The capex and savings figures are in pounds. The savings are assumed to grow at an annual rate of 2% for the calculations of the IRRs, which are calculated using the investment lifespans reported in Table 7. 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
	External wall insulation				Cavity wall insulation			
Small flat (<54m^2)	5300	115	-0.7%	-1.5%	380	88	25.0%	15.6%
Large flat (>54m^2)	6700	158	-0.2%	-0.2%	430	117	29.2%	20.2%
Small mid−terrace house (<76m^2)	6800	119	-1.9%	-2.8%	460	73	17.6%	12.4%
Large mid−terrace house (>76m^2)	7500	180	-0.2%	-0.2%	505	118	25.3%	19.5%
Small semi−det. or end−of−terr. (<80m^2)	7800	223	0.9%	0.0%	529	140	28.5%	23.2%
Large semi−det. or end terr. (>80m^2)	8400	283	1.9%	0.8%	660	180	29.2%	28.1%
Small detached house (<117m^2)	10200	333	1.7%	0.7%	680	227	35.4%	30.4%
Large detached house (>117m^2)	11500	456	3.0%	-0.5%	950	299	33.4%	26.9%
Bungalow (around 117m^2)	9800	176	-1.8%	-2.4%	650	128	21.6%	18.9%
	Replace single with double glazing windows				Change heating to gas condensing boiler			
Small flat (<54m^2)	2400	43	-6.6%	-8.1%	2700	230	-1.2%	-6.7%
Large flat (>54m^2)	3600	49	-8.4%	-9.4%	3300	305	0.2%	-3.9%
Small mid−terrace house (<76m^2)	3900	48	-9.2%	-10.7%	3400	434	6.4%	1.0%
Large mid−terrace house (>76m^2)	5000	63	-9.0%	-9.6%	3800	538	8.6%	3.0%
Small semi−det. or end−of−terr. (<80m^2)	5500	47	-11.4%	-12.9%	3800	453	5.0%	-1.8%
Large semi−det. or end terr. (>80m^2)	6400	64	-10.4%	-11.7%	4200	523	5.9%	-0.8%
Small detached house (<117m^2)	5900	57	-10.6%	-11.6%	4400	467	2.7%	-4.0%
Large detached house (>117m^2)	8300	118	-8.2%	-9.4%	5800	423	-3.8%	-8.7%
Bungalow (around 117m^2)	6600	48	-12.4%	-13.5%	4600	382	-1.6%	-8.2%
	Increase loft insulation to 270 mm (joists)							
Small flat (<54m^2)	-	-	-	-				
Large flat (>54m^2)	-	-	-	-				
Small mid−terrace house (<76m^2)	350	58	18.5%	11.0%				
Large mid−terrace house (>76m^2)	420	86	22.4%	15.0%				
Small semi−det. or end−of−ter. (<80m^2)	360	55	17.0%	10.1%				
Large semi−det. or end terr. (>80m^2)	470	88	20.5%	15.1%				
Small detached house (<117m^2)	510	66	14.5%	9.8%				
Large detached house (>117m^2)	600	129	23.4%	15.1%				
Bungalow (around 117m^2)	620	94	16.8%	11.7%				

Table A5: Rental listings and certificates merged dataset: summary statistics

This table shows summary statistics for properties on the Rightmove/EPC merged dataset for the full sample of properties and for those in the bottom tercile of initial energy efficiency.

	Full sample	Bottom tercile
Panel A: Listing prices and energy efficiency		
Listing price (£, monthly, mean)	992.35	986.52
Listing price (£, monthly, median)	795.00	750.00
Energy efficiency points (mean)	62.51	43.03
Energy efficiency points (median)	64.00	46.00
Panel B: Property type (%)		
House	56.48	66.89
Flat	36.05	23.64
Other	7.47	9.47
Panel C: Number of stars (mean)		
Main heat	3.59	3.20
Main heat controls	3.06	2.67
Windows	3.07	2.67
Roof	3.07	2.36
Lighting	3.20	2.97
Walls	2.65	1.72
Hot water	3.49	2.86

Table A6: 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. $\mathbb{1}_{RentalPrivate}$ is a dummy variable that takes the value of one for private rental properties, and zero for owner-occupied. $\mathbb{1}_{ApprovalToEnforcement}$ is a dummy variable that takes the value of one for second certificates between April/15 and April/18, and zero otherwise. $\mathbb{1}_{PostEnforcement}$ takes the value of one for second certificates after April/18, and zero otherwise. The sample includes multiple certificate properties in the bottom third of initial energy efficiency with tenure equal to owner-occupied (and certificate requested for marketed sale) or private rental (and certificates requested for the purpose of a private rental). Tenure and transaction type are measured using the second certificate of each observation pair. Property characteristics fixed effects are dummies for construction age, property type, built form and floor area. RdSAP fixed effects are dummies for the conventions in effect at the times of the first and second certificates of each observation pair. Standard errors are reported in parentheses.*,**, and *** indicate significance at 10%, 5%, and 1% respectively.

Dependent variable	Δ Energy	Δ Environ.	Δ Energy/Env.	Δ Energy	Δ Environ.	Δ Energy/Env.
	(1)	(2)	(3)	(4)	(5)	(6)
$\mathbb{1}_{RentalPrivate}$	0.841***	0.627***	0.003**	0.836***	0.624***	0.003**
	(0.091)	(0.087)	(0.001)	(0.089)	(0.085)	(0.001)
$\mathbb{1}_{ApprovalToEnforcement}$	1.691***	1.149***	0.012***			
	(0.098)	(0.094)	(0.001)			
$\mathbb{1}_{PostEnforcement}$	2.915***	1.828***	0.022***			
	(0.073)	(0.070)	(0.001)			
$\mathbb{1}_{RentalPrivate} \times \mathbb{1}_{ApprovalToEnforcement}$	2.446***	1.052***	0.025***	2.447***	1.051***	0.025***
	(0.139)	(0.133)	(0.002)	(0.136)	(0.130)	(0.002)
$\mathbb{1}_{ApprovalToEnforcement} \times \mathbb{1}_{PostEnforcement}$	-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

Table A7: 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 A8: 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