Investments that Make our Homes Greener: The Role of Regulation

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Motivation

- The operation of residential buildings (our homes) is responsible for roughly 22% of the global energy consumption and 17% of the CO_2 emissions.
- Investments to improve energy efficiency and environmental performance can make a significant contribution to the climate challenge.
- However, such investment levels have been low and has led to government interventions (subsidies and regulations).

Motivation

- Energy efficiency regulations
  - → Improve energy performance of the worst-performing buildings
    - Targeted private rental sectors: Presumes that investment inefficiencies are more pervasive and yield sub-optimal levels of private investment (private energy-efficiency gap)
  - → Reduce carbon emissions, which in presence of energy use externalities are socially excessive (social energy-efficiency gap)
  - → A Pigouvian tax would internalize such externalities, but was not followed, presumably because it lacked political support
- As a result, energy efficiency regulations have multiple confounding objectives, and take a second-best approach to address externalities

This Paper

- Regulatory context: Domestic Minimum Energy Efficiency Standard (MEES)
  - → Minimum energy efficiency threshold that new private rentals must satisfy
  - → Assumes that investment inefficiencies in private rental sector are more pervasive
  - → Approved March 2015, Implemented April 2018
- What we do:
  - → Energy Performance Certificates (EPC) for residential properties in England and Wales
  - → Focus on the existing properties, instead of the construction sector (new builds)
    1. Evaluate the investment efficiencies rationale for regulation to apply to the private rental sector
    2. Examine whether regulations trigger investments in the rental private sector
    3. Investigate the drivers of investments in energy and environmental efficiency
    4. Examine whether investments are capitalized into rents and compensate for the additional capex
    5. Characterize the role of regulations in reducing carbon emissions.

Preview of results

- Energy efficiency of the housing stock
  - → Private rental properties are more energy efficient (on average and in the left tail).
  - → Rental sector has larger proportion of flats (fewer external walls).
  - → 21.6% (19%) of the private rental (owner-occupied) flats are in the bottom one-third of the overall energy efficiency distribution.
- Role of regulation in affecting investments in energy efficiency
  - → In lower-rated properties and in retrofits that lead to larger efficiency gains.
  - → Concentrate on elements that require lower capital expenditures and have higher IRR.
  - → Investments lead to economically small increases in rents which are not large enough to compensate for the additional investment.
- Examine concomitant change in environmental performance
  - → Large improvements in energy efficiency in the rental sector were not accompanied by similarly large improvements in environmental performance.
  - → Energy efficiency is a cost measure whereas environmental performance depends on carbon factors of the fuel source.

Related Literature

- Large literature on energy efficiency in commercial properties (e.g. Eichholtz, Kok, and Quigley 2010, Jaffee, Stanton, and Wallace 2019).
- Nascent literature that aims to understand residential energy efficiency programs:
  - → Low participation in programs that subsidize investments, even though they have positive private returns (Fowlie, Greenstone, and Wolfram 2015, Fowlie, Greenstone, and Wolfram 2018).
  - → Ex-ante projections on energy savings (Allcott and Greenstone 2017, Christensen et al. 2020, Berkouwer and Dean 2022).
- Impact of climate risk on:
  - → The value of real estate assets (Bernstein, Gustafson, and Lewis 2019, Ortega and Taspinar 2018, Murfin and Spiegel 2020, Giglio et al. 2021)
  - → The mortgages used (Issler et al. 2020, Gete and Tsouderou 2021).
- Papers that use the same data:
  - → Fuerst et al. 2015 studies the relation between home prices and energy efficiency using hedonic price regressions

INSTITUTIONAL BACKGROUND AND DATA

Energy performance certificates

- The Energy Performance of Buildings Directive (2002/91/EC) is an EU Directive on the energy performance of buildings
  - → Tackle climate change by reducing the amount of carbon produced by buildings
  - → Measurement of the efficiency of homes through EPCs.
- In England and Wales, a valid certificate is required to sell or rent out a property since 2008; valid for 10 years and costs about £60-£120
- An accredited assessor carries out a physical inspection of the property (assessor sheet) and inputs findings into a government-approved software
- Certificates provide:
  - → a measure of overall energy efficiency of the property (1-100)
  - → the quality of the elements (such as walls, main heating), star ratings (from 1 to 5)
  - → recommendations on how to improve energy efficiency (indicative capex and savings)
  - → measures of the environmental impact of the property (the carbon emissions from the operation of the property).

Energy efficiency rating: SAP points and letter rating

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

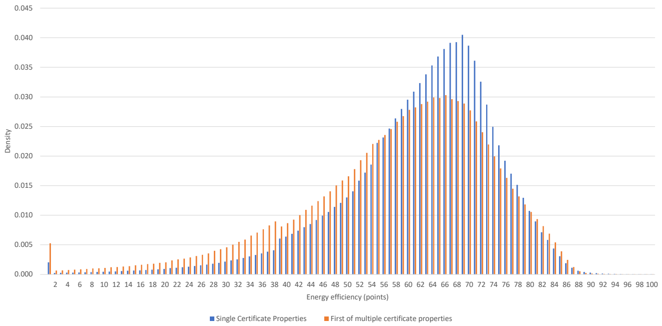
Sample construction: number of certificates per property

Summary: Full sample and multiple certificates

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

Distributions of energy efficiency

Second certificates are observed for initially lower-rated properties



Summary statistics

Empirical model for energy efficiency

- Over the years there have been seven amendments and additions to the RdSAP conventions (and software) used to perform the calculations
- Are the changes in energy score for the same property due changes in the procedure or in the underlying characteristics of the property?
- We construct an empirical regression model for energy efficiency score as a function of the star rating of its elements Empirical model
- **Summary of results:**
  - → Estimated coefficients stable across periods, except for main heating Estimates
  - → Estimated coefficients are increasing in star rating with few exceptions
  - → Importance of elements, SAP points increase per one additional star rating
    - Main heating (5.1), hot water (3.5), walls (3.1), Main heat controls (2.4), roof(2.3), windows (2.2), and lighting (0.6)
  - → Considerable variation in coefficients by built form, flats versus houses
  - → Changes in property characteristics more important than changes in assessment procedures Decomposition

Characterising retrofits using multiple certificate properties

Importance of the initial level of efficiency for investments

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

REGULATORY INTERVENTION AND INVESTMENTS

Minimum Energy Efficiency Standard (MEES)

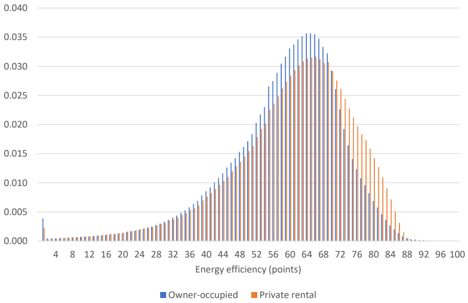
- The Minimum Energy Efficiency Standard (MEES) introduced minimum standards for energy efficiency aiming to:
  - → improve energy performance of the worst-performing buildings
  - → reduce carbon emissions, which in presence of energy use externalities are socially excessive (social energy efficiency gap)
- Minimum level of energy efficiency (SAP points equal to 39) that privately rented residential properties must satisfy
- Approved by the Parliament on 26 March 2015 and enforced on the 1 April 2018
- Sample composition
  - → In England and Wales, in 2010, of the 24.2 million dwellings that formed the housing stock: 66% owner-occupied, 17% private rental, and 18% social rental
  - → In our full sample of 17.7 million certificates: 56% owner-occupied, 23% private rental, and 19% social rental Unobserved investments

The role of housing tenure

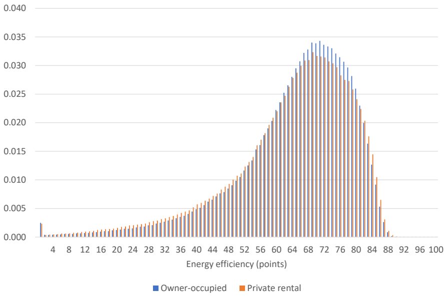
- Does tenure affect the magnitude and nature of the investments undertaken?
  - → In perfect markets:
    - Property and rental prices reflect the value of savings associated with energy efficiency retrofits
    - Investments with positive NPV are undertaken, irrespective of tenure (owner-occupied or rented out)
  - → In reality:
    - Information asymmetries and financing frictions affect the investments undertaken
    - Certain property owners (or tenants) may value the energy efficiency features of homes beyond their financial benefits
- Thus, one of the main arguments for introducing the MEES is that investment inefficiencies in the private rental sector imply that the level of investments carried out by landlords is sub-optimal.

Energy efficiency distributions by tenure

All certificates issued before April 1, 2015



(a) All properties

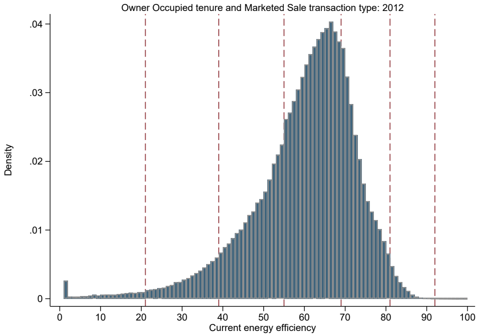


(b) Flats and maisonettes

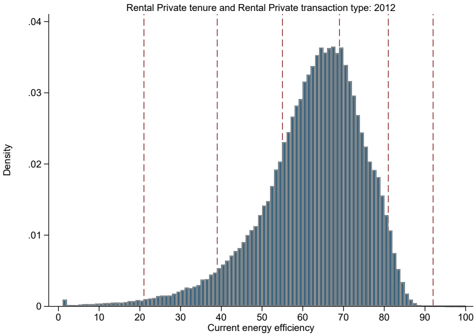
Description details

Regulatory Intervention and Investments

Distributions of energy efficiency score for selected calendar years



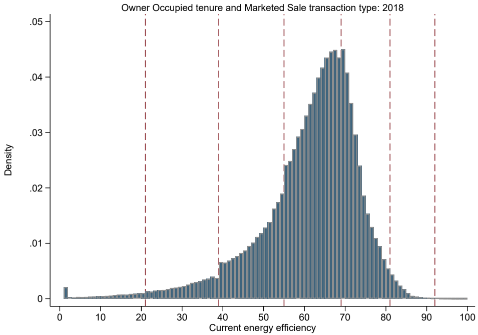
(a) Owner-occupied, 2012



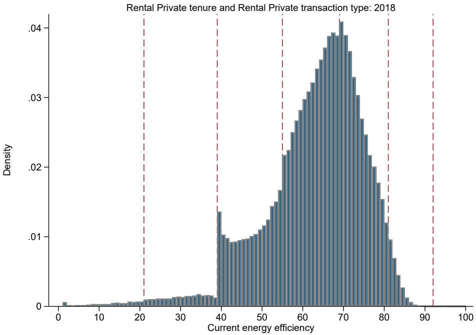
(b) Rental Private, 2012

Heterogeneity Timing

Distributions of energy efficiency score for selected calendar years



(a) Owner-occupied, 2018

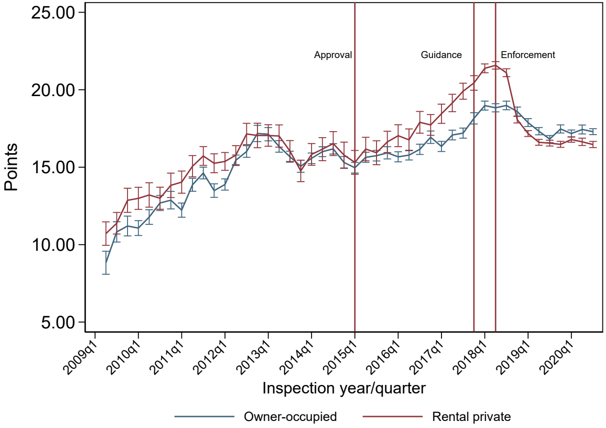


(b) Rental Private, 2018

Heterogeneity Timing

Change in energy efficiency score over time

Two series diverge with significantly larger improvements in the private rental sector



DiD: Matched sample DiD: ratings

Initial characteristics and retrofits by tenure and time period

Proportion of properties (multiple certificates in bottom tercile) for each characteristic

		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

Similar investments in rental private and owner-occupied sectors. Why?

(Indicative) Capital expenditures and savings

Concentrate on elements that require lower capex and generate significant IRRs

	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

Type/Size Transactions Compliance cost

Capital expenditures

Quick summary

- Regulatory intervention led to significant improvements in the private rental sector.
- However, we find similar investments among owner-occupied and renters.
- Concentrate on elements requiring lower capex and that generate significant IRRs.
- Do landlords who make energy efficient investments capitalize them into higher rents?

Impact on rents

Economically small increase in rents

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

Merge

Increase in rents vs. capital expenditures

Increase in rents not large enough to compensate additional capital expenditures

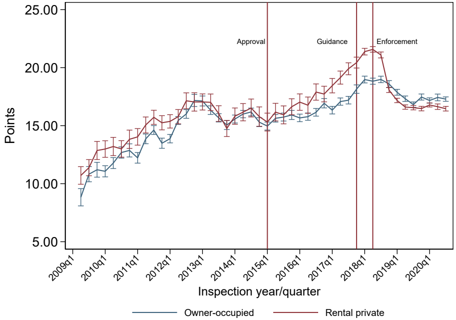
	Option 1	Option 2	Option 3
	Panel A: Increase in points achieved through capex		
Mainheat	13.92	-	-
Low energy lighting	-	2.37	2.37
Mainheat controls	-	7.41	7.41
Windows	-	4.20	-
Total points	13.92	13.98	9.78
	Panel B: Capex required		
Mainheat	£5,000	-	-
Low energy lighting	-	£38	£38
Mainheat controls	-	£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

ENERGY EFFICIENCY $\longrightarrow$ CARBON EMISSIONS

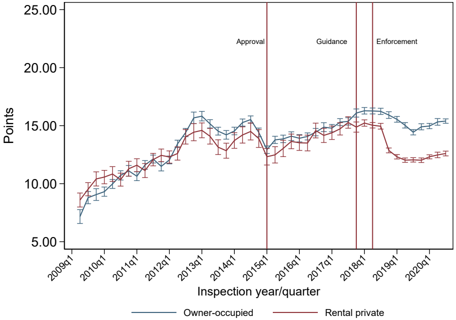
From energy efficiency to carbon emissions

- The carbon emissions of homes depend on the quantity of energy consumed and how polluting the type of fuel used
- The focus of the certificates and of the regulatory framework is on energy efficiency and not on carbon emissions
- To what extent does the focus on energy consumption lead to smaller improvements in carbon emissions than what might be otherwise achievable?
- Environmental impact rating:
  - → Measures the property's impact on the environment in terms of carbon dioxide (CO_2) emissions
  - → Scale of 1 to 100, the higher the rating the lower the CO_2 emissions
  - → Improving energy efficiency is positive for the environment

Change in energy efficiency and environmental impact over time



Energy efficiency



Environmental impact

DiD: ratings

DiD: cost vs emission

Energy sources and CO_2 emissions

- Improvements in energy efficiency (lower energy costs)
  - → Reductions in the use of an expensive but low carbon footprint energy source
    - Improves energy efficiency without a large effect on carbon emissions
  - → Shift towards cheaper but more polluting energy sources
    - Reduces energy costs (and improves energy efficiency) but may lead to larger carbon footprints
- How polluting an energy source depends on how it is produced
  - → If electricity is produced using coal, its carbon emissions are large
  - → If electricity is produced using renewable sources such as wind and sun, then its environmental impact will be significantly smaller and “indirect” only

What explains the divergence?

Energy costs, fuel sources, and CO_2 emissions

- Shifts in main fuel energy source from electricity to gas

Energy sources	Initial (%)	Final (%)	Δ (%)	Initial (%)	Final (%)	Δ (%)
	Owner-occupied			Private rental		
Mains 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

- Rating inputs and their reliance on energy sources
  - → Energy efficiency: price of fuel × energy usage `Fuel prices`
  - → Carbon emissions: carbon footprint × energy usage `Fuel sources`

Energy sources	Mains gas	Electricity	Heating oil
Price (pence per kWh)	3.48	13.19	5.44
CO_2 (Kg CO_2 per kWh)	0.216	0.519	0.298
Price per unit CO_2	18.1	**25.4**	18.3

- Backward-looking carbon factors of the fuel source `Carbon factors`

Conclusion

Conclusion

- Characterize and understand the drivers of residential property investments in energy efficiency.
- Financial considerations play an important role in the investments undertaken.
- Relates intensity and nature of investments undertaken to asset ownership
  - → Regulations are effective in triggering investment
  - → Investments are capitalized as higher rents but are economically small to compensate for the additional capital expenditures.
  - → At the same time, if certificates are used to tackle the climate challenge, it is important that the information contained in them accurately reflects emissions.
  - → Moreover, it is important to do so using a forward-looking perspective.
- The focus of the legislation and certificates on energy efficiency as opposed to environmental impact may have limited impact on reductions in carbon emissions.

Star rating for the different elements of the home

Property element	Percentage of observations with classification (%) Very poor	Poor	Average	Good	Very good	Number of stars 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

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Empirical model for energy efficiency score

Full sample:

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

i denotes property, j the element ($j =$ main heat, walls, etc), l the star rating associated with that element ($l = 1, ..., 7$), and t time

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

Sample of multiple certificate properties:

$$\Delta\text{Energy efficiency}_{i,t',t''} = \text{Energy efficiency}_{i,t''} - \text{Energy efficiency}_{i,t'}. \tag{2}$$

$t^{'}$ and $t^{''}$ denote the two times at which a certificate is issued for a given property

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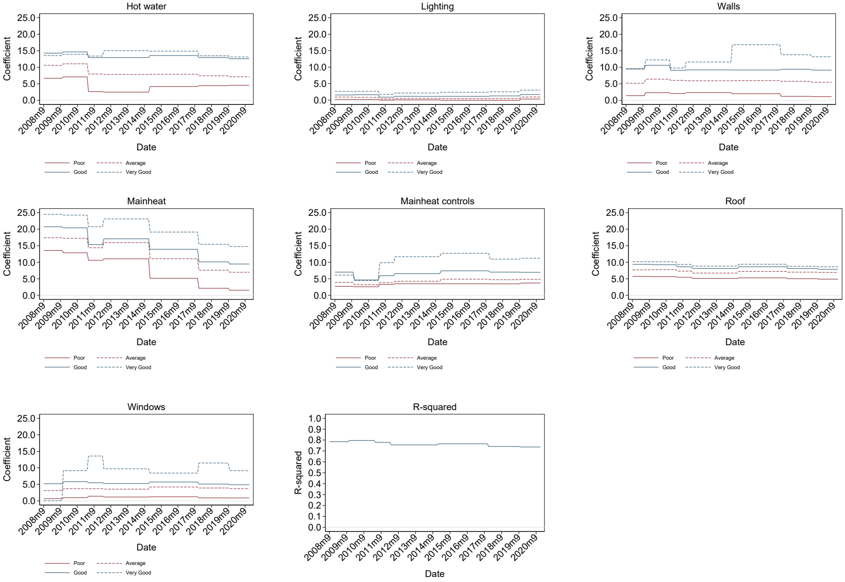
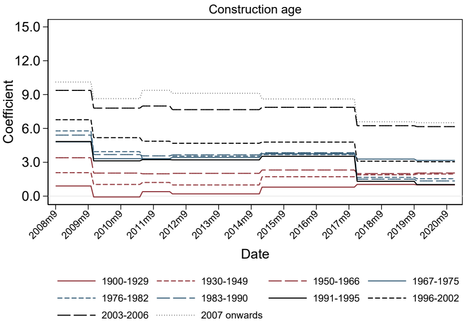
Empirical model for energy efficiency

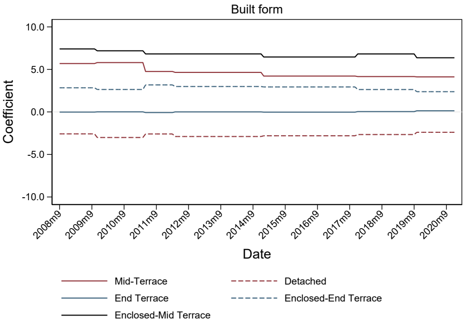


Empirical model for energy efficiency

Estimated coefficients of the control variables



Property age



Built form

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Empirical model for energy efficiency

Variance decomposition: factor loadings versus characteristics

	Total variance	Variance ΔLoadings	Variance ΔCharacteristics	Covariance ΔLoadings, ΔCharacteristics
Variance	113.36	10.07	125.91	-22.62
Fraction	100.0%	8.9%	111.1%	-20.0%

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Initial characteristics of properties by tenure

Element	Variable	Owner-occupied	Private rental
Energy efficiency	Points (mean)	58.5	60.5
	Points (median)	61	63
Main heat	Number of stars (mean)	3.7	3.6
	Very poor or poor (%)	7.3	16.2
Main heat controls	Number of stars (mean)	3.1	2.8
	Very poor or poor (%)	21.6	34.5
Windows	Number of stars (mean)	3.1	3.0
	Very poor or poor (%)	14.6	21.8
Roof	Number of stars (mean)	3.1	2.9
	Very poor or poor (%)	26.5	32.9
Lighting	Number of stars (mean)	3.0	3.1
	Very poor or poor (%)	38.7	38.8
Walls	Number of stars (mean)	2.7	2.4
	Very poor or poor (%)	50.3	57.0
Hot water	Number of stars (mean)	3.5	3.4
	Very poor or poor	15.9	18.4
Property type	House, Bungalow, Park home (%)	84.9	54.5
	Flat, Maisonette (%)	15.1	45.5
Built form	Detached, Semi-detached (%)	61.9	40.3
	Other built-forms (%)	37.2	56.8
Roof type	Pitched roof (%)	82.8	62.6
	Another dwelling above (%)	8.9	27.2
Walls type	Cavity walls (%)	65.7	49.9
	Solid brick walls (%)	22.7	35.0

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Windows	Number of stars (mean)	3.1	3.0
	Very poor or poor (%)	14.6	**21.8**
Roof	Number of stars (mean)	3.1	2.9
	Very poor or poor (%)	26.5	**32.9**
Lighting	Number of stars (mean)	3.0	3.1
	Very poor or poor (%)	38.7	38.8
Walls	Number of stars (mean)	2.7	2.4
	Very poor or poor (%)	50.3	**57.0**
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Windows	Number of stars (mean)	3.1	3.0
	Very poor or poor (%)	14.6	21.8
Roof	Number of stars (mean)	3.1	2.9
	Very poor or poor (%)	26.5	32.9
Lighting	Number of stars (mean)	3.0	3.1
	Very poor or poor (%)	38.7	38.8
Walls	Number of stars (mean)	2.7	2.4
	Very poor or poor (%)	50.3	57.0
Hot water	Number of stars (mean)	3.5	3.4
	Very poor or poor	15.9	18.4
Property type	House, Bungalow, Park home (%)	**84.9**	54.5
	Flat, Maisonette (%)	15.1	**45.5**
Built form	Detached, Semi-detached (%)	61.9	40.3
	Other built-forms (%)	37.2	56.8
Roof type	Pitched roof (%)	82.8	62.6
	Another dwelling above (%)	8.9	27.2
Walls type	Cavity walls (%)	**65.7**	49.9
	Solid brick walls (%)	22.7	**35.0**

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Heterogeneity as a function of tenure and time period

Larger improvements after the regulation for rental private properties

Group	Number obs.	Fraction	Initial points	Δ Points	Change
Panel A: Sample period 2008 - 2020					
Owner-occupied	398,494	0.53	40.0	16.2	41%
Rental private	288,392	0.38	37.8	17.3	46%
Rental social	64,651	0.09	44.2	16.3	37%
Panel B: Before April 1, 2015					
Owner-occupied	157,411	0.65	39.9	14.5	36%
Rental private	59,430	0.24	39.2	14.8	38%
Rental social	27,099	0.11	44.1	15.6	35%
Panel C: After April 1, 2015					
Owner-occupied	241,083	0.47	40.1	17.3	43%
Rental private	228,962	0.45	37.4	17.9	48%
Rental social	37,552	0.07	44.2	16.8	38%

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Probability and timing of subsequent certificate

Greater probability of requesting a second certificate, if the property is below the threshold and is on the private rental market)

	(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

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Merging EPC and Rightmove

- Consider a property with 3 issued certificates (2009, 2018 and 2019)
- The same property was on the rental market 11 times
- We associate each rental listing with the previous issued certificate
- We identify properties on both the EPC and the Rightmove dataset by their UPRN (unique property reference number)

uprn	current_en~y	ym
57910	37	2009m12
57910	49	2018m3
57910	55	2019m12

uprn	ym_listingdate	listingprice
57910	2012m1	2184
57910	2012m12	2262
57910	2013m12	2288
57910	2014m12	2340
57910	2015m11	2444
57910	2016m11	2522
57910	2017m11	2730
57910	2019m11	3450
57910	2021m1	3900
57910	2021m11	4200
57910	2022m11	4500

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Energy efficiency versus environmental impact gains

Difference-in-Differences

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

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Energy efficiency versus environmental impact gains

Difference-in-Differences, Matched sample

Dependent variable	Δ Energy	Δ Environ.	Δ Energy/Env.	Δ Energy	Δ Environ.	Δ Energy/Env.
	(1)	(2)	(3)	(4)	(5)	(6)
Rental private	0.722***	0.592***	0.002	0.703***	0.563***	0.002
	(0.093)	(0.089)	(0.001)	(0.088)	(0.080)	(0.001)
Approval to enforcement	1.647***	0.873***	0.014***			
	(0.100)	(0.096)	(0.001)			
Post-enforcement	3.071***	1.723***	0.025***			
	(0.075)	(0.072)	(0.001)			
Rental Priv. × Approval to enforcement	2.490***	1.328***	0.024***	2.504***	1.307***	0.024***
	(0.142)	(0.136)	(0.002)	(0.135)	(0.122)	(0.002)
Rental Priv. × Post-enforcement	-0.450***	-1.263***	0.020***	-0.439***	-1.265***	0.020***
	(0.106)	(0.101)	(0.001)	(0.101)	(0.091)	(0.001)
Constant	14.212***	11.686***	0.022***	16.455***	12.937***	0.041***
	(0.066)	(0.063)	(0.001)	(0.028)	(0.025)	(0.000)
Pair fixed effects	No	No	No	Yes	Yes	Yes
R-Squared	0.01	0.00	0.01	0.55	0.60	0.57
Observations	562,404	562,404	562,395	560,966	560,966	560,948

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Transition to tenure

	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

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

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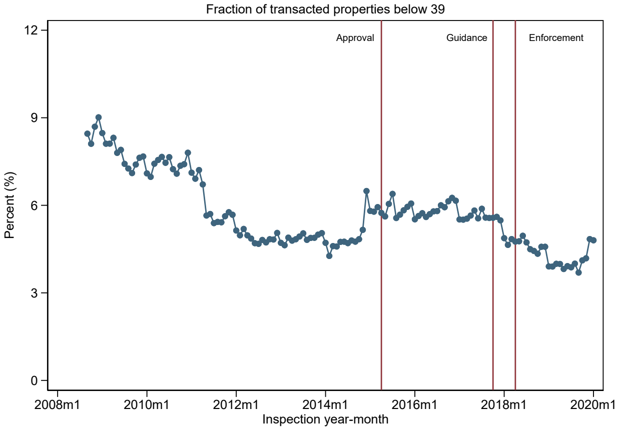
Fraction of transacted properties below 39



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Energy costs versus CO_2 emissions

Difference-in-Differences

Dependent variable	Δ En. Cost	Δ CO_2	Δ (En. Cost/CO_2)	Δ En. Cost	Δ CO_2	Δ (En. Cost/CO_2)
	(1)	(2)	(3)	(4)	(5)	(6)
Rental Private	1.322	193.185***	-2935.909***	-8.889***	-88.944***	-608.579***
	(0.926)	(11.310)	(94.112)	(0.929)	(11.197)	(93.504)
Approval to enforcement	-15.421***	-270.227***	831.850***	-8.069***	-105.244***	138.799
	(0.762)	(9.307)	(77.437)	(1.825)	(21.994)	(183.654)
Post-enforcement	-26.054***	-371.864***	349.799***	-3.511	-96.527***	1047.916***
	(0.702)	(8.578)	(71.379)	(2.237)	(26.956)	(225.093)
Rental Private × Approval to enforcement	-23.476***	-202.045***	-785.938***	-18.701***	-157.974***	-619.753***
	(1.432)	(17.481)	(145.457)	(1.437)	(17.316)	(144.597)
Rental Private × Post-enforcement	5.776***	129.268***	-941.712***	-3.642***	20.985	-1032.763***
	(1.146)	(13.995)	(116.452)	(1.139)	(13.724)	(114.597)
Constant	-148.435***	-1822.069***	1670.193***	-154.139***	-1842.662***	524.523***
	(0.481)	(5.870)	(48.845)	(1.410)	(16.994)	(141.908)
Property Characteristics Fixed Effects	No	No	No	Yes	Yes	Yes
RdSAP Convention Fixed Effects	No	No	No	Yes	Yes	Yes
R-Squared	0.00	0.01	0.01	0.04	0.07	0.07
Observations	671,491	671,492	671,462	671,273	671,274	671,244

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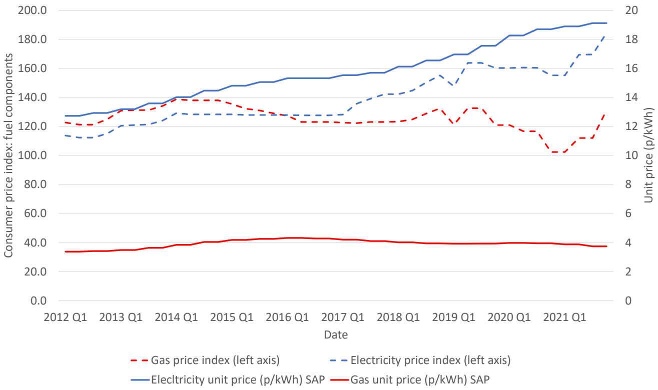
Fuel prices



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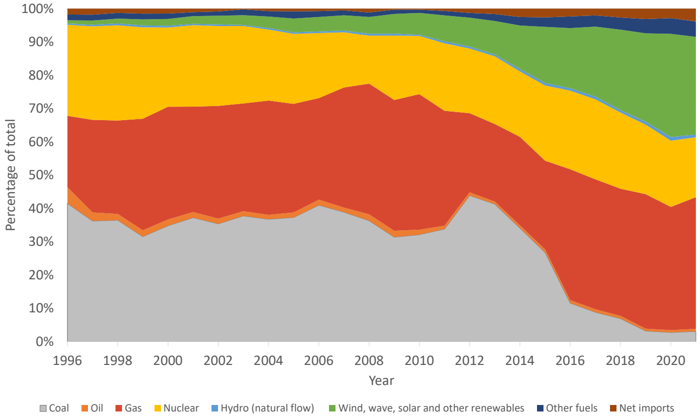
Fuel sources



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Information on carbon footprint

Carbon factors

- Certificates do not use updated information on carbon footprint
  - → In 2014 (2020), the Kg CO_2e emissions per KWh of electricity were 0.519 (0.23314)
  - → For natural gas they were 0.216 (0.20374), and heating oil 0.298 (0.28484)
  - → Electricity became "greener" by the end of the decade, but the CO_2 emissions from electricity generation were larger by 14% than those from natural gas by 2020

Main fuel initial/final	Δ Energy cost (£/year)	Δ Emissions (kg CO_2/year)	Δ Emissions updated (kg CO_2/year)	Number of properties
Mains gas to mains gas	-141.99	-1.89	-2.23	404,135
Electricity to electricity	-124.52	-0.86	-2.54	113,879
Oil to oil	-144.06	-2.14	-2.37	19,268
Electricity to mains gas	-351.89	-4.04	-4.02	45,399
Mains gas to electricity	-15.27	-0.41	-1.98	3,400

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Unobserved investments by owner-occupiers

- The properties for which and the times when certificates are issued are not random
- If those who invest in property improvements are more likely to request a new certificate, then the sample of multiple certificate properties includes a larger investment intensity than the full sample
- Homeowners who invest in their property but who do not plan to sell it may not request a new certificate
- Investments in energy efficiency that we do not observe more likely to be in the sample of owner occupiers than private rental.
- Merge EPC data with Land Registry data (residential property transactions in England and Wales)
- When do individuals request a certificate?

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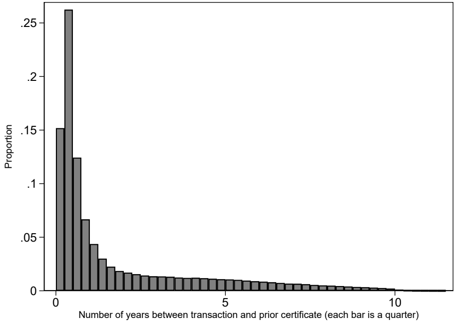
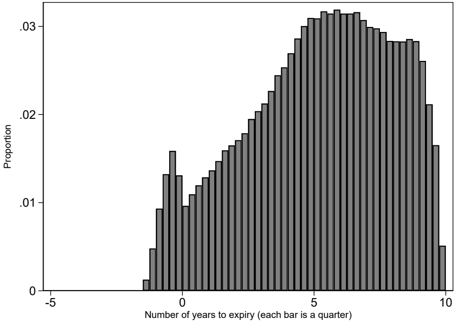
Property transactions and certificates



Years between transaction and certificate



Years of remaining certificate validity

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Unobserved investments by owner-occupiers

- Individuals request certificates prior to a transaction
- Sample for which we observe at least two transactions
  - → Assumption: those property owners who undertake investments request a new certificate prior to a sale.
  - → For this sample, for roughly 72% of the properties we only observe one certificate. For the remainder 28% we observe two or more certificates
  - → For those for which we observe two certificates, the average initial level of energy efficiency is 55.1 and the average change in energy efficiency score between the two certificates is 7.6, or 13.8%
  - → Main point: provide a number (of 72%) for the proportion of properties for which investments are unlikely to have been undertaken
  - → Fraction of properties with only one certificate in the full sample 78%

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Most common transitions

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

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