SEREN DEMIRBAS (9033) & ALINA CHRISTIN SPRAUL (9119)
SUPERVISOR: PETER MOLNAR

The Impact of Population Density, Electricity Prices, and Temperature on People's Behaviour towards Energy Efficiency Investments: Insights from Scotland's EPC Registry

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Abstract

Climate change affects us all, so it is crucial to prioritise efforts to mitigate its impact. Improving building energy efficiency is a cost-effective solution to reduce CO_2 emissions, which has significant influence on climate change. Our study examines how external factors, specifically population density, temperature, and energy prices, influence people's behaviour towards investing in energy efficiency. By using multiple linear regression, we analyse these variables against the Energy Performance Certificate (EPC) rating of dwellings in Scotland to understand people's decision-making. Our results show that higher population density is positively associated with energy performance rating, indicating greater energy efficiency in densely populated areas. Additionally, low temperature also positively influences energy performance rating, most likely driven by people's desire for comfort, cost savings from energy efficiency upgrades, and improved heat retention through house insulation. Regarding energy prices, we observed a mixed relationship depending on the type of energy fuel. Overall, our research demonstrates that external factors have an impact on energy performance rating, i.e., on people's decisions towards energy efficiency.

1. Introduction and Literature Review

The United Nations have declared climate change as the "defining issue of our time" due to its global impact on food and water security, public health risks, infrastructure, buildings, and energy security (European Commission, n.d.; United Nations, n.d.). Urgent action is necessary to reduce greenhouse gas emissions (GHG) and mitigate climate change, as highlighted by the Intergovernmental Panel on Climate Change (IPCC) and other institutions (Howarth & Frankhauser, 2021; IPPC, 2014; UNFCCC, n.d.). The building sector plays a crucial role in reducing global GHGs since it accounts for one-third of energy-related emissions worldwide (Nejat et al., 2015). Furthermore, the sector's energy demand is increasing, making it imperative to address the issue (IEA, 2022). To mitigate CO_2 emissions, which have the most significant impact on climate change (Hansen et al., 2007), improving the energy efficiency of buildings is an inexpensive and effective solution (Amecke, 2012). The European Union's (EU) most known strategy for enhancing energy efficiency is Energy Performance Certificates (EPCs), which were first introduced in the *Energy Performance of Buildings Directive 2002* (Directive 2002/91) and later refined by the *Energy Performance of Buildings Directive 2010* (Directive 2010/31) and the *Energy Efficiency Directive 2012* (Directive 2012/27).

EPCs are a rating system (A – G) that offers information about a building's energy efficiency and cost-effective methods to improve energy performance (Directive 2002/91). Their goal is to reduce information asymmetry and promote market transformation by providing reliable and transparent information to potential buyers or tenants (Amecke, 2012; Cajias et al., 2019). EPCs are valid for ten years and must be renewed if the property is built, rented, or sold to a new owner. This ensures that the information about the building's energy efficiency remains up-to-date and relevant to potential buyers or tenants (Scottish Government, n.d.-b).

However, the impact of EPCs in reducing information asymmetry and raising energy efficiency is a topic of ongoing debate in the literature. For instance, Amecke (2012) stated that while the information provided by the EPC is understood, it is not trusted. Additionally, the financial implications to reach better energy efficiency are not well demonstrated and require improvement. Christensen et al. (2014) argue that the greatest barriers for energy retrofits are not lack of knowledge and awareness but rather the usability of EPC recommendations. Nonetheless, despite these criticisms, it can be generally said that EPCs were partially successful in reducing information asymmetry, and the quality of information provided has improved over time (Cajias et al., 2019).

The most extensive research field regarding EPCs is the relationship between EPCs and house prices, yet there is no clear consensus in the literature. Some studies suggest that EPCs can increase the value of a property (Cajias et al., 2019; Davis et al., 2015; De Ayala et al., 2016; Fuerst et al., 2013, 2015, 2016, 2020; Taruttis & Weber, 2022), while others state that EPCs have little to no effects on house prices. Instead, other factors such as location, size, and condition of the property seem to have greater influence on a property's value (Aydin et al., 2020; Barreca et al., 2021; Bisello et al., 2020; Marmolejo-Duarte & Chen, 2022; McCord et al., 2020; Murphy, 2014; Olaussen et al., 2017, 2019, 2021; Wilhelmsson, 2019, 2023).

Since there is comprehensive research on the relationship between EPC ratings and house prices, our study aims to explore the impact of external factors on EPC ratings and infer their potential effect on people's behaviour regarding energy efficiency. Specifically, we investigate the relationship between EPC ratings and population density, energy prices, and temperature. Thus, our research question is: "Do population density, energy prices, and temperature influence people's behaviour to invest in energy efficiency?"

To the best of our knowledge, the literature about these topics is still heavily limited. Therefore, we attempt to have a closer look at them.

To gain a deeper understanding of the relationship between population density and energy efficiency, we will look at the relationship between urbanisation and energy intensity, which is the amount of energy needed per unit of output or activity (Office of Energy Efficiency and Renewable Energy, n.d.). As populations increase, so does residential energy consumption. The US and EU, however, show a declining trend in energy consumption despite population growth (González-Torres et al., 2022). This phenomenon could be explained by energy efficiency and its relationship with urbanisation. Research suggests that urbanisation can enhance energy efficiency through agglomeration economies (Sadorsky, 2013; Yan, 2015), changes in consumer behaviour due to increased income (Zhang & Lin, 2012), and the government's need for better infrastructure (Poumanyvong & Kaneko, 2010). In addition, a monocentric city design significantly decreases energy intensity and, therefore, enhances energy efficiency (He et al., 2023). Generally, it seems agreed that population density induces energy efficiency (Antonietti & Fontini, 2019; Feng et al., 2023; Jain & Goswami, 2021; Morikawa, 2012; Sarpong et al., 2022; Su, 2023). Therefore, we can expect a positive relationship between population density and EPC ratings.

In contrast, the impact of energy prices on energy efficiency shows mixed findings. Gorus & Karagol (2022) found that energy prices affect energy efficiency differently across countries. Negative effects in energy efficiency were observed among Finland, Greece, and South Korea, while Austria, Italy, and Mexico experienced positive effects. This result is further supported by Antonietti & Fontini (2019), who employed panel cointegration tests and dynamic panel data models to reach the same conclusion. Additionally, while Jain & Goswami (2021) found that higher energy prices induce energy efficiency, the research of Song & Zheng (2012) showed no significant impact of energy prices on energy efficiency. Noteworthy, Gorus & Karagol (2022) found that capital income has a greater influence on energy efficiency than energy prices.

Lastly, we take a closer look at temperature. While there is currently a lack of literature explicitly addressing temperature and energy efficiency, we can explore the connection between temperature and energy consumption. Guo et al. (2022) found that during the warmer months with longer daylight hours (March to October), people tend to spend less time at home and use their appliances less frequently. Conversely, in the colder months with shorter daylight hours (November to February), there is an inclination to use appliances more often, particularly for secondary electric heating and water heating purposes. Also, 5°C seem to be a critical threshold for energy consumption. When temperatures drop below 5°C, there is a rapid increase in electricity demand, while being 5°C and above, a slight negative impact on electricity demand is observed (Guo et al., 2022). This is also supported by other studies that indicate temperature plays an important role in energy consumption (D'Amico et al., 2019; Shi et al., 2018; Verbai et al., 2014). Interestingly, higher population density has a direct influence on temperature, causing it to raise in urban areas. Consequently, this raise in temperature reduces the necessity for heating in those regions but may raise the need for cooling (Alola et al., 2019; Okeil, 2010). Hence, temperature seems to play a crucial role in energy consumption and, subsequently, energy efficiency.

The remainder of this paper is organised as follows. Section 2 provides information about the regulations for EPCs in Scotland and various governmental incentive schemes. Section 3 presents our data, while Section 4 shows the methodology of our paper. Section 5 discusses our findings, Section 6 presents the limitations of our study, and Section 7 concludes our paper.

2. Background

2.1 Scotland and EPC

Scotland first introduced EPCs in 2008 with the *Energy Performance of Buildings (Scotland) Regulations 2008*. The primary objective of implementing this regulation was to enhance energy efficiency, alleviate fuel poverty – the inability to afford sufficient heating for one's home, and mitigate the emission of GHGs. Amendments to this regulation were made in 2012, 2013, 2015, 2016 and 2017. The *Energy Performance of Buildings (Scotland) Regulations* are the Scottish version of the formerly mentioned *Energy Performance of Buildings Directives* from the EU.

In contrast to England and Wales, there appears to be no specific regulation in Scotland as of now that prohibits the rental of dwellings with an EPC rating of E or lower. However, the Scottish government is working on introducing legislation that requires all private rented sector properties to reach a minimum standard equivalent to EPC grading C by 2025, with a backstop in 2028. A similar requirement applies to owner-occupied dwellings, albeit with a deadline of 2033. In the case of social housing, the target is to achieve a minimum EPC rating of B by 2032. (Scottish Government, n.d.-a). Currently, these regulations are primarily referenced within Scotland's *Heat in Buildings Strategy*, a visionary plan aimed at attaining Scotland's climate change objectives, maximising economic potential, facilitating a fair transition, and addressing fuel poverty. Furthermore, Scotland aims to have no new homes connected to the gas grid by 2025. Instead, the government strives for new homes to be heated using low-carbon sources and achieve exceptionally high levels of energy efficiency (Scottish Government, 2021).

2.2 Government incentives

Our dataset includes information on the utilisation of four government incentives, which we describe in the following. Firstly, the Green Deal, operational from 2012 to 2015, aimed to support households in financing energy-efficient home improvements through loans (Scottish Government, n.d.-c). However, due to low take-up rates, with only 1,815 signed plans, high-interest rates (7-10% APR), and a lack of cost-effectiveness, the Green Deal was ultimately discontinued (Thorpe, 2016).

The Feed-in Tariffs (FiT) scheme is designed to promote the adoption of small-scale renewable and low-carbon electricity generation technologies, for example, solar panels. Under this scheme, FIT licensees (certified electricity suppliers) are obligated to provide fixed tariff payments for electricity produced and fed into the National Grid. These payments run for 10 to 25 years based on factors such as technology type, capacity, commissioning date of the installation, and previous accreditation under the Renewables Obligation scheme (Ofgem, n.d.-c).

Thirdly, the Domestic Renewable Heat Incentive (RHI) is a government financial incentive to encourage the adoption of renewable heat sources, aiding in carbon emissions reduction and achieving the UK's renewable energy targets. It is accessible to all households, regardless of their connection to the gas grid, provided they have installed a renewable heating system and meet the eligibility requirements. Participants receive regular payments over seven years, corresponding to the estimated amount of renewable heat their systems generate (Ofgem, n.d.-a).

Lastly, the Energy Company Obligation (ECO) is a government scheme targeting energy efficiency, fuel poverty reduction, and carbon emission reduction. Eligibility for ECO is based on the need for energy efficiency upgrades, assessed through retrofit evaluations. It is open to homeowners and tenants with landlord permission, but to be eligible, participants need to receive at least one specified government benefit, such as child benefits or income support (Ofgem, n.d.-b). As of 2023, only the ECO incentive remains in operation, while the other incentives have been discontinued. It is worth mentioning that achieving a higher letter grade, despite the availability of government incentives, can be challenging. The Scottish EPC dataset offers insights into potential improvements and the corresponding EPC grading that can be attained through these enhancements. However, in many instances, the grading remained the same letter grade despite the improvements.

3. Data

This paper utilises multiple source data from the Scottish EPC data, the Scottish population estimate data, the UK consumer fuel prices data, and the E-OBS temperature data. The data is freely attainable on the internet.

Official Dataset name	Description	Type	Timespan	Source
Domestic Energy Performance Certificates - Dataset	Environmental data from every current Domestic EPC assessment	CSV	2012-2022	Scottish Government
Mid-Year Population Estimates for Scotland, mid-2021: Time series data	Estimates for Scotland's population for the complete calendar year	Excel	1981-2021	National Records of Scotland
Consumer prices index UK: fuel components in the UK	Price indices for a range of fuels purchased by UK domestic consumers	Excel	1990-2022	Department of Energy Security and Net Zero
E-OBS Temperature and Precipitation Datasets	Daily gridded land-only observational dataset over Europe	NC-file	2011-2022	EU-FP6 project UERRA and Copernicus Climate Change Service

***Table 1**: Overview of Datasets*

Our primary dataset is the Scottish EPC data from which we extracted the unique property number, date of certificate (in years), the current energy efficiency rating, tenure, property type, transaction type, local authority, and main heat description (describes fuel component and system used). This dataset is structured quarterly, and we combined it into ten years. Also, to be able to work with date of certificate, tenure, property type and transaction type, those variables were transformed into dummy variables.

There are some inconsistencies in the written information in this dataset. Some information was in uppercase, while others were recorded in lowercase throughout the same column. This inconsistency is also seen in the description columns, where some data was more detailed spelt out than others. In order to utilise the information, we brought it to the same format.

For our data analysis, we used the statistical software R-studio (R Core Team, 2023). To gain our complete dataset, we combined the population data, the fuel consumer prices and the temperature with the extracted variables of the EPC dataset by using the *inner-join* function.

The population data were merged year by year based on the council areas (formerly named local authority). Since the data is only available until 2021, we first calculated the average growth of each council area's population over the whole nine years and multiplied this growth rate by the population of 2021 to get the estimates for 2022. To achieve inhabitants per square kilometre, we divided the given population by its corresponding council area size in square kilometres and named the variable population density.

Next, we incorporated the annual fuel consumer prices based on the main heat description, which we changed to show the main fuel component used. The consumer prices shown represent a period of four years. Specifically, they indicate the fuel price at the time the property's certificate assessment was conducted, and up to three years before that date. Additionally, the prices are presented using dummy variables, which show the price if the corresponding fuel is used and zero otherwise.

The temperature data were combined based on the council areas. We decided on the most populated city in each council area and used it for the whole council area. To gain the Heating Degree Day (HDD) values, we utilised the *climate4R.indices* package and applied the *hdd.th* function. Since each city needed to be calculated alone, the *apply* command in the *hdd.th* function needed to be exchanged with the *sapply* command to gain results. To obtain yearly values for each city, we divided the provided data, which spanned 11 years and six months, into individual years. Then the 365 values for each year were summed up to determine the final yearly HDD value for each city.

Yearly HDDs are calculated in the following way:

$$HDD = \sum_{i=1}^{365} (T_{base} - T_i)^+ \tag{1}$$

where, for each day

$$T_i = \frac{T_{i,max} + T_{i,min}}{2} \tag{2}$$

and,

$$X^+ = MAX(X, 0) \tag{3}$$

In short, HDDs are the results of subtracting the base temperature from the average daily temperature, summed up over a given period. Negative results in the subtraction will be replaced by zero. The average daily temperature is calculated by summing up each day's maximum and minimum temperatures and dividing it by two.

At the time of the writing of this paper, the E-OBS data was only available until June 2022, and we, therefore, substituted the year 2022 with 2021 since we assumed there would not be a significant difference between the two years. The council area of Shetland Islands has no data available in the dataset; however, it is very near the Orkney Islands, so we assumed they are similar and substituted them. Throughout our whole process, we cleaned our dataset further by excluding missing data points.

In the end, our dataset contains 57 variables (including dummy variables) and 1 433 961 observations (dwellings) and ranges from the year 2012 to the year 2022. Please note that the number of observations in the original EPC dataset is larger, but not all could be utilised for this paper.

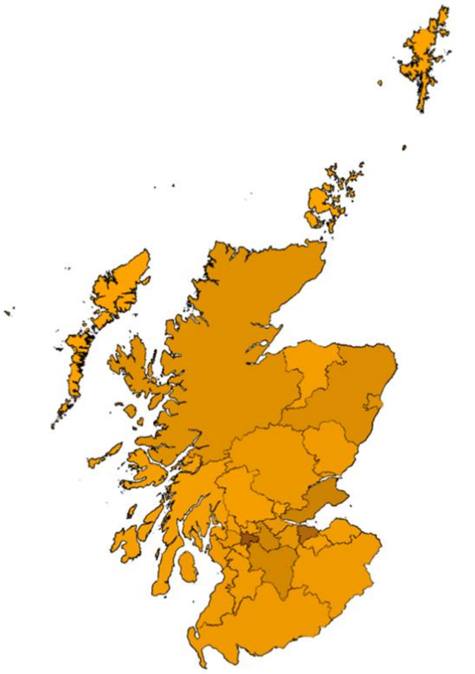
In our regression analysis, we used the following variables:

Main Variable	**Type**	**Description**
Current Energy Efficiency Rating	Numerical	Rating from 1-100
Tenure	Numerical	Owner-occupied (Base) Rental private Rental social Unknown
Property Type	Numerical	House (Base) Bungalow Flat Maisonette
Transaction Type	Numerical	Market sale (Base) Non-market sale New Dwelling Rental Green deal assessment Following green deal FiT application ECO assessment RHI application None of the above
Heating Nominal (Current) and Real price (respectively)	Numerical	Current to three years of assessment: Gas Electricity Liquid fuels Solid fuels
Population density	Numerical	Inhabitants/km² per council area
HDD	Numerical	Heating Degree Days per council area

Table 2: *Overview of the Variables*

3.1 Observations, inhabitants, property-, and transaction types

Figure 1 visualises the number of inhabitants in Scotland, while *Figure 2* displays the number of dwellings observed in the dataset. Both figures are quite similar, and we can assume that our dataset represents Scotland accordingly. It is also noteworthy that the size of the areas differs from the number of inhabitants, as seen in the big council area on top of the map, which presents the highlands, most of which are uninhabited. Most people and observations are in Glasgow.



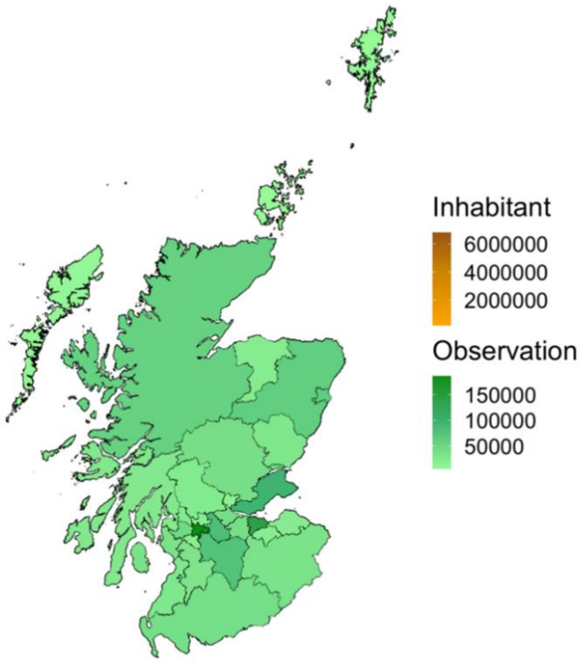


***Figure 1**: Map of Scotland's Inhabitants*

***Figure 2**: Map of Observations recorded in Dataset*

Figure 3 presents the common property types recorded in the dataset. According to the visualisation, houses and flats are our dataset's most frequently recorded dwellings.

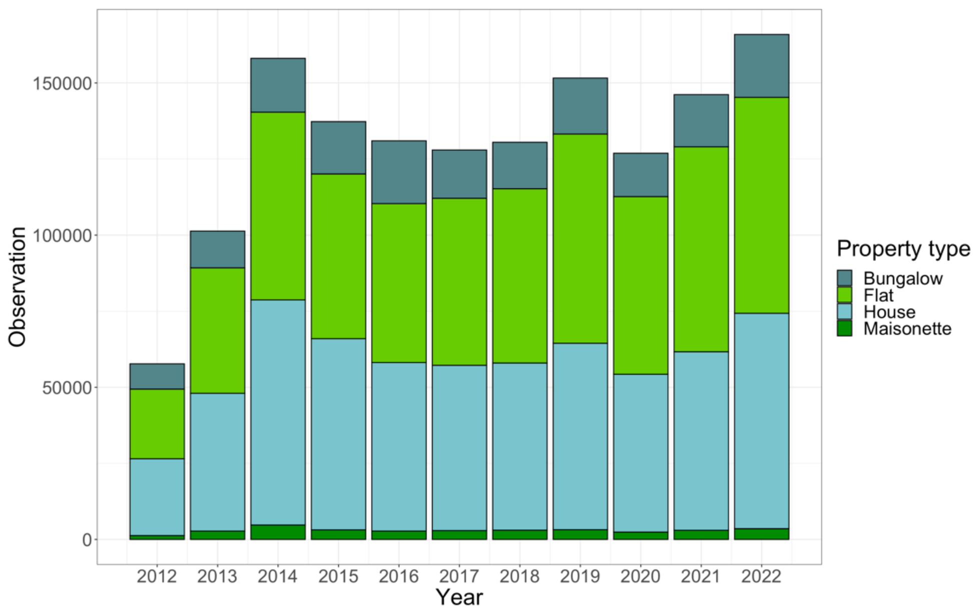


***Figure 3**: Overview Property type*

Knowledge about the property type is essential since the heating situation will likely differ due to the property's design, affecting the energy grading. Flats, for example, have the advantage of shared walls with other flats, which reduces the overall heating used by each residence.

Therefore, less money and fewer resources for heating might be required. The same can account for a maisonette. A maisonette is a self-contained two-story apartment with its own entrance and stairway; it is located within a larger building (Cambridge Dictionary, n.d.-b).

A house, in most cases, will need more resources and has higher bills for heating than the previous two property types. The same will be for a bungalow since this property type represents a detached one-story house (Cambridge Dictionary, n.d.-a).

Figure 4 shows the distribution of transaction types recorded in the dataset. The visualisation shows that most EPC certificates were obtained due to a market sale or a new tenant.

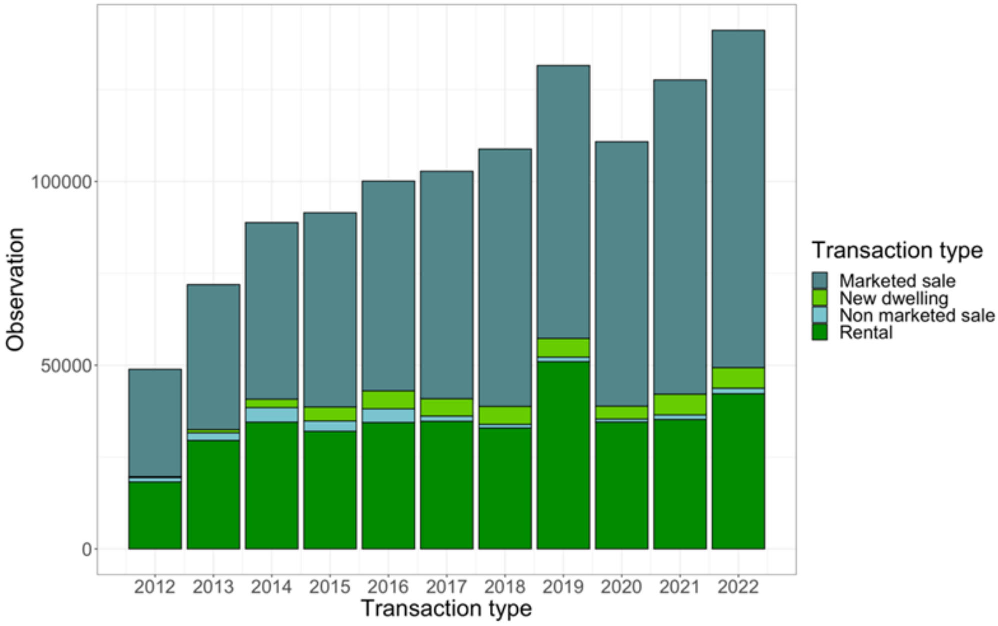


***Figure 4**: Overview Transaction type*

Knowledge about the transaction type can help identify whether people are motivated to improve their dwellings' EPC rating when selling or renting out their property. We assume that a market sale might lead to energy efficiency improvements in order to gain a higher sales price. Although, new dwellings are not extensively represented in our dataset, we presume they achieve high ratings due to people investing in building according to today's energy efficiency standards.

3.2 Overview of EPCs

Figure 5 presents a comprehensive picture of the distribution of all grades from 2012 to 2022. Between 2015 and 2016, the graph shifts from a primarily D-grading to a primarily C-grading. A factor causing this could be precautionary action since England and Wales issued the legislation: *Energy Efficiency (Private Rented Property) (England and Wales) Regulations*

2015 that makes an F and G rating unlawful to rent. However, changed construction standards and a greater awareness of energy efficiency might have also played a role in the recorded shift in EPC grading.

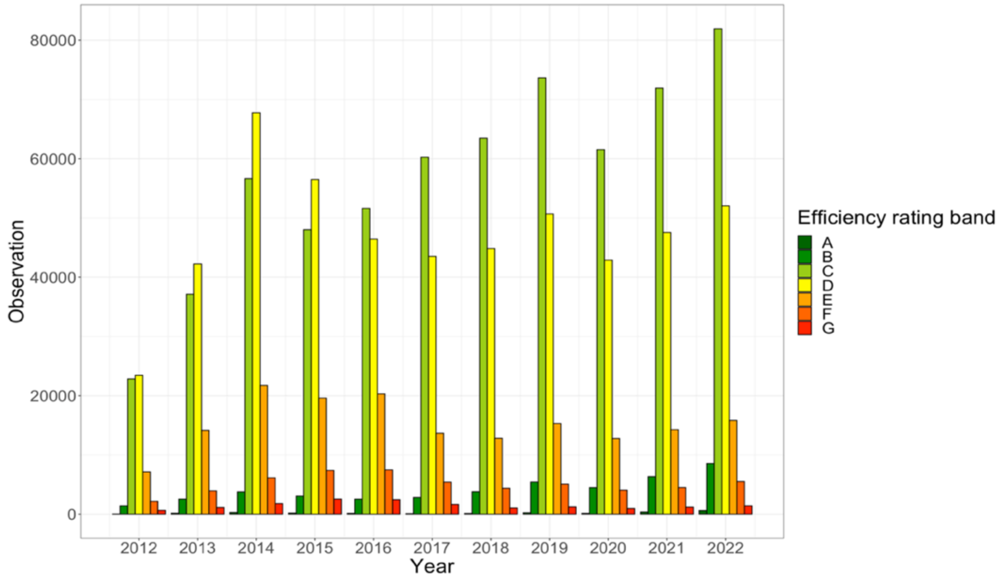


Figure 5*: Overview Energy Performance Rating*

The construction age of the property types can give a better insight into EPC grading. *Figure 6* presents three visualisations that show the grades of the construction band before 1919,1984-1991 and 2008 onwards.

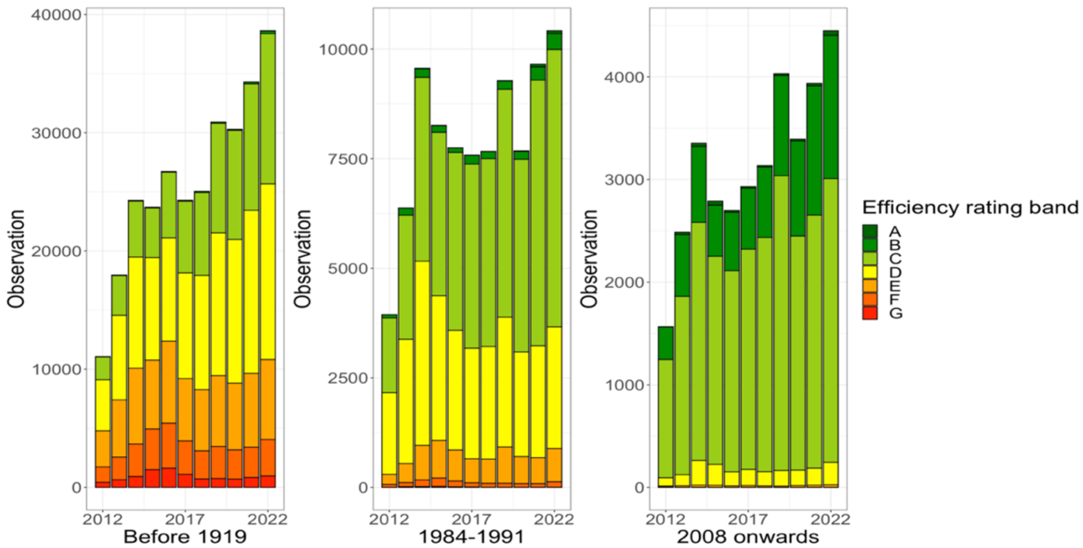


Figure 6*: Energy Performance Rating for three various construction age bands*

While the accommodations before 1919 present each grade of the scale, mainly a D, the accommodations from 2008 onward consist mainly of the grades B and C. This result could be attributed to improved construction standards related to energy efficiency and the use of different building materials and techniques.

3.3 Heating used and fuel prices

To know how energy prices affect the EPC grading, we must first understand the heating types employed. *Figure 7* displays the primary heating type used by households in our dataset. Based on the presented graph, gas is the primary heating fuel, followed by electricity. One possible explanation for the widespread use of gas is its easy accessibility due to the United Kingdom's ownership of natural gas fields in the North Sea.

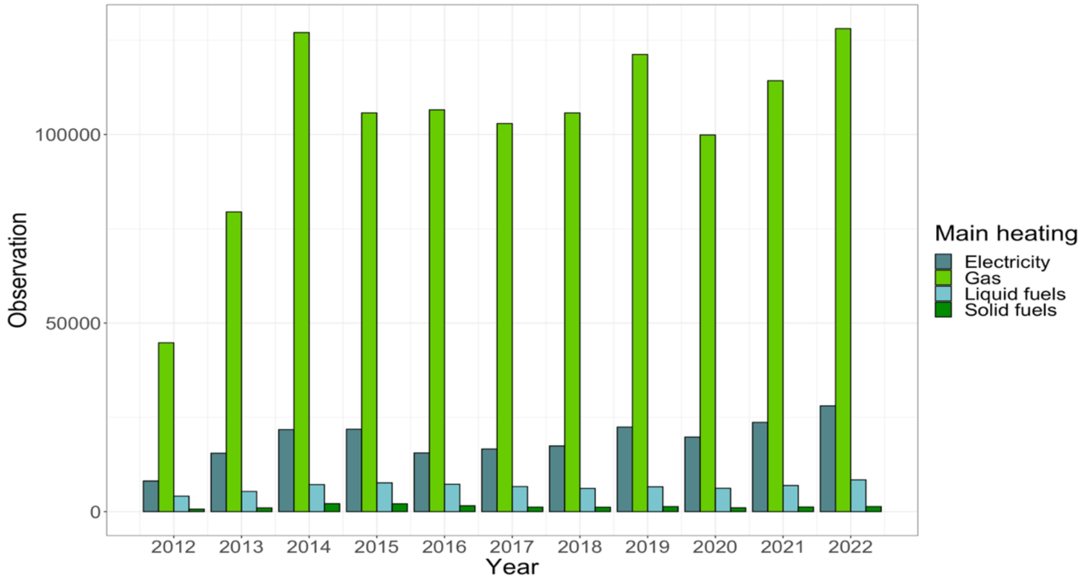


***Figure** 7: Overview Heating Used*

In our findings section, we will investigate further to see whether energy prices motivate consumers to invest in energy efficiency and, therefore, in a better EPC grading.

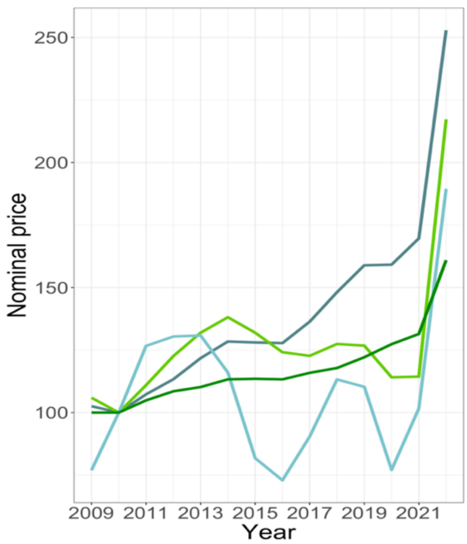


***Figure 9**: Overview Nominal Price Indices for UK's fuel components*

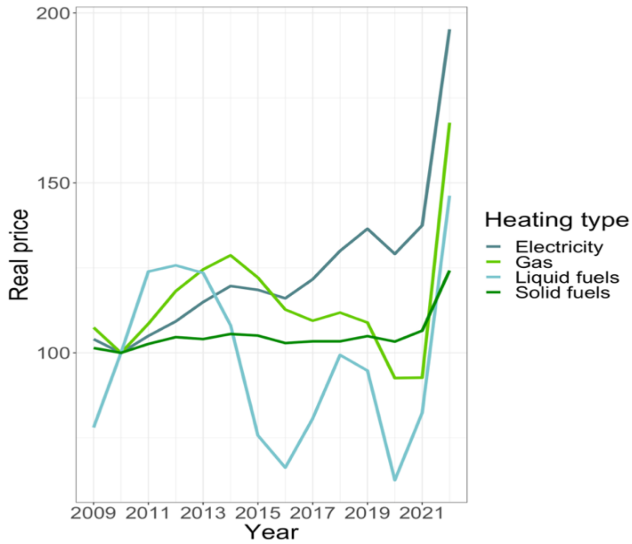


***Figure 8**: Overview Real Price Indices for UK's fuel components*

Figure 8 and *Figure 9* present the annual price indices for electricity, gas, liquid fuels, and solid fuels purchased by domestic consumers in the UK. *Figure 8* shows the nominal price, whereas

Figure 9 displays the real price. The real price is deflated using the GDP (market price) deflator and is rebased on 2010 prices. Both prices include VAT, which accounts for the present fuels at 5%. Further information, for example, the derivation of the energy prices can be found in the Excel sheet of the utilised dataset from the Department of Energy Security and Net Zero itself.

3.4 HDD

Finally, our last focus point are HDDs. HDDs are meteorological indices that represent integrated temperature variations from a base temperature over time and are used to determine weather-related energy requirements in buildings. In short, a Heating Degree Day is the outdoor temperature above a threshold for which a building would not need heating (Mistry, 2018). Since the EPC grading is based on how much energy per m² is used and lost in a building, HDDs are an imperative variable to include in our analysis.

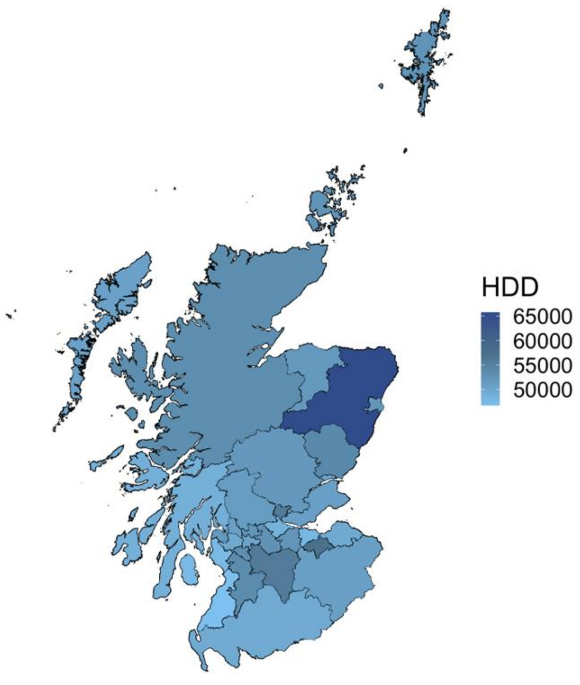


***Figure 10**: HDD Map of Scotland 2012-2021*

Figure 10 shows the HDD values of each council area from 2012-2021. It is to note that the annual HDD values range approximately from 2000 to 3700.

Aberdeenshire, in dark blue, has the most days that require heating, whereas South Ayrshire has the least. One of our focus points is whether outside temperature affects people's behaviour in order to improve their EPC rating. *Figure 11* shows the mentioned council areas, and we can see that Aberdeenshire, the colder area, generally has a better rating than South Ayrshire, the warmer area.

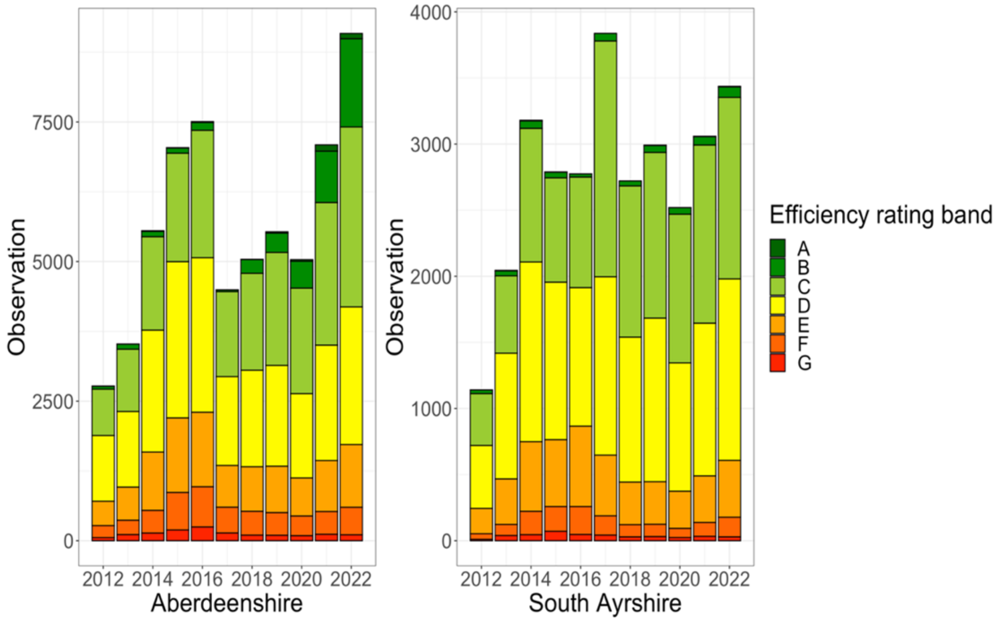


Figure 11*: Comparison EPC rating of Aberdeenshire and South Ayrshire*

We assume the increased need for heating during colder temperatures motivates people to attain energy-efficient dwellings as a means of saving money. However, we will look closer into the relationship between HDDs and EPC rating in our findings.

Further, if this assumption holds, it will be relevant in future research. According to Eurostat, the HDD values for the EU decreased by 19% between 1979 and 2022 (Eurostat, n.d.), meaning less heating was required over the years. This could influence consumers' behaviour towards energy efficiency. However, Cooling Degree Days (CDD), the days when the use of air conditioning is required, are rising. Therefore, future research concerning CDD values influence instead of HDD values influence might need to be done.

4. Methodology

Our analysis is based on multiple linear regression. Multiple linear regression is a commonly applied research tool used to test and examine simultaneous linear associations among several variables with one continuous outcome (Hoyt et al., 2006). Since the main objective of this research is to determine the impact of several factors on people's choices through the Energy Efficiency Rating, multiple linear regression is the best fit for this endeavour. The adoption of this approach is further underlined by our utilised data being cross-sectional, as seen in the primarily one-time occurring unique property numbers from 2012 to 2022.

Therefore, the following regression specification will be used in estimation:

$$EPC_i = \beta_0 + \sum_j \beta_j h_{i,j} + \varepsilon_i + \sum_{k=1}^{10} \gamma_k \quad (4)$$

where EPC_i represents the independent variable, which denotes the Energy Efficiency Rating for all individual dwellings i. β_0 is the intercept, whereas β_j is the corresponding regression coefficient for the indexing variables j of $h_{i,j}$. $h_{i,j}$ denotes all variables for both the individual dwellings and indexing variables, which means that $h_{i,j}$ includes tenure, property type, transaction type, heating nominal price, population density and HDD. For a detailed description of these variables, please refer to *Table 2*. Please note that all variables, except population density and HDD, are dummy variables. Also, population density, measured as inhabitants per km², was divided by 1000. ε_i is the error term for all individual dwellings and γ_k presents yearly dummy variables over the span of 10 years. We included γ_k to capture any time-related effects that are otherwise unobserved in our estimation and thus could lead to bias in the regression results.

We primarily conducted our analysis using nominal energy prices, but to ensure the robustness of our findings, we also tested the impact of using real prices (refer to Appendix A) and observed that our results remained largely unaffected. Reported standard errors are robust standard errors.

5. Findings and Discussion

*For each type, we estimated three regressions based on nominal energy prices: (1) energy prices in the year of assessment, (2) energy prices in one year prior to assessment, (3) energy prices in two year prior of assessment, (4) energy prices in three year prior of assessment.

Regression Results

	Dependent variable: Energy efficiency rating			
	Fuel price			
	(Current year)	(1yr prior)	(2yr prior)	(3yr prior)
Property bungalow	-2.712^{***}	-2.593^{***}	-2.570^{***}	-2.545^{***}
	(0.030)	(0.030)	(0.030)	(0.030)
Property flat	4.251^{***}	4.334^{***}	4.303^{***}	4.258^{***}
	(0.021)	(0.021)	(0.021)	(0.021)
Property maisonette	0.980^{***}	1.047^{***}	1.029^{***}	0.993^{***}
	(0.062)	(0.062)	(0.062)	(0.062)
Tenure private rented	-0.252^{***}	-0.193^{***}	-0.185^{***}	-0.187^{***}
	(0.042)	(0.041)	(0.041)	(0.041)
Tenure social rented	6.291^{***}	6.292^{***}	6.252^{***}	6.205^{***}
	(0.035)	(0.035)	(0.034)	(0.034)
Tenure unknown	5.367^{***}	5.379^{***}	5.443^{***}	5.378^{***}
	(0.116)	(0.116)	(0.115)	(0.115)
Transaction assessment green deal	-2.804^{***}	-2.744^{***}	-2.745^{***}	-2.772^{***}
	(0.065)	(0.064)	(0.064)	(0.064)
Transaction FiT application	8.612^{***}	8.653^{***}	8.588^{***}	8.601^{***}
	(0.089)	(0.089)	(0.089)	(0.089)
Transaction new dwelling	2.132^{***}	2.107^{***}	2.113^{***}	2.134^{***}
	(0.282)	(0.281)	(0.281)	(0.280)
Transaction non marketed sale	-3.141^{***}	-3.191^{***}	-3.148^{***}	-3.073^{***}
	(0.078)	(0.078)	(0.078)	(0.078)
Transaction none of the above	-2.236^{***}	-2.268^{***}	-2.250^{***}	-2.223^{***}
	(0.031)	(0.031)	(0.031)	(0.031)
Transaction rental	-0.051	-0.099^{***}	-0.084^{**}	-0.058
	(0.039)	(0.038)	(0.038)	(0.038)
Transaction following green deal	12.700^{***}	12.479^{***}	12.613^{***}	12.786^{***}
	(0.196)	(0.195)	(0.195)	(0.195)
Transaction ECO assessment	-3.945^{***}	-3.980^{***}	-3.946^{***}	-3.903^{***}
	(0.046)	(0.046)	(0.046)	(0.046)
Transaction RHI application	-1.795^{***}	-1.805^{***}	-1.792^{***}	-1.744^{***}
	(0.073)	(0.072)	(0.072)	(0.072)
Population density	0.138^{***}	0.130^{***}	0.127^{***}	0.125^{***}
	(0.004)	(0.004)	(0.004)	(0.004)
HDD	0.376^{***}	0.349^{***}	0.361^{***}	0.368^{***}
	(0.009)	(0.009)	(0.009)	(0.009)
Electricity price	0.023^{***}	0.024^{***}	0.034^{***}	0.030^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
Liquid fuels price	0.029^{***}	0.032^{***}	0.038^{***}	0.027^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
Solid fuels price	-0.050^{***}	-0.048^{***}	-0.041^{***}	-0.050^{***}
	(0.001)	(0.001)	(0.001)	(0.002)
Gas price	0.107^{***}	0.122^{***}	0.131^{***}	0.126^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
Constant	33.766^{***}	42.113^{***}	40.790^{***}	39.983^{***}
	(0.345)	(0.284)	(0.288)	(0.306)
Observations	1,433,961	1,433,961	1,433,961	1,433,961
R2	0.294	0.302	0.303	0.304
Adjusted R^2	0.294	0.302	0.303	0.304
Note:				*p<0.1; **p<0.05; ***p<0.01

Table 3: *Regression results for EPC rating as independent variable and the variables presented in Table 2 as dependent variables. The regression includes yearly dummy variables; however, they show no effect.*

5.1 Overview property, tenure, and transaction type

Table 3 shows that flats and maisonettes are more energy-efficient than houses, confirming our expectations from section 3.1. Furthermore, flats emerge as the most energy-efficient among all the property types in our dataset. This outcome can be attributed to the shared walls between flats, which result in reduced energy usage for heating. The reduced number of exposed walls also contributes to enhanced heat retention, thereby reducing energy consumption.

Interestingly, social rented tenure has received the highest ratings among all available tenure types. This can be attributed primarily to the implementation of the *Energy Efficiency Standard for Social Housing (EESSH)* in 2014. The EESSH made it mandatory for social dwellings to use gas or electricity for heating to achieve minimum gradings of D and C by 2020 and a minimum grading band of B or maximum energy efficiency feasible by 2032 (Scottish Government, 2019). In Scotland, social housing is owned and managed by public authorities, such as councils and housing associations; consequently, social housing is likely to have more financial resources available for enhancing energy efficiency compared to owner-occupied or privately rented dwellings.

On the other hand, private rented tenure exhibits the lowest energy efficiency among all tenure types. Several factors contribute to this situation. Those include most prominently the lack of financial incentives – principle-agent problem, but also low rental yields, low equity levels, lack of information as well as misinformation around energy-efficient improvements, the prioritisation of cosmetic improvements on the property, lack of long-term tenants, and low trust in government initiatives (Ambrose, 2015; Fuerst et al., 2016; Hope & Booth, 2014; Lang et al., 2021; Mccarthy et al., 2016; Nair et al., 2010). Better EPC-gradings are, however, expected in the future due to the need to have a C-grading by 2025 in order to rent (Scottish Government, n.d.-a).

If we leave government incentives aside, we can see that new houses are the most energy-efficient transaction type, followed by marketed sale and rental. New dwellings most likely achieve high ratings due to advanced technology and energy-efficient construction, while marketed sale properties prioritise higher returns on investment. Studies indicate that higher EPC grades are associated with price premiums (Cajias et al., 2019; Fuerst et al., 2013, 2015, 2016, 2020; Taruttis & Weber, 2022); however, literature is divided on this aspect (Aydin et al., 2020; Marmolejo-Duarte & Chen, 2022; Murphy, 2014; Olaussen et al., 2017, 2019, 2021).

The energy efficiency in transaction type rental is most likely achieved through governmental regulations.

Looking at the government incentives, following green deal has the highest energy efficiency ratings out of all transaction types. It is to note, however, that this incentive did run only from 2012-2015. As mentioned, the green deal made it possible to pay for energy efficiency improvements through savings on the energy bill. The incentive was sparsely used by the British property owners and altogether abolished in 2015 due to inadequate results and unaffordability, therefore, this high influence on EPC grading is surprising. The FiT application shows the second-best results in energy efficiency out of all transaction types. Property owners receive fixed tariff payments for their energy produced by small-scale renewable and low-carbon electricity generation technologies. The payments make it possible to pay back instalment costs. And even though this incentive scheme is not directly related to the energy efficiency of a dwelling, it is likely that people who care about renewable energy and are willing to produce their own also care about energy efficiency.

5.2 Population density and HDD

Our findings show that more densely populated areas have higher EPC gradings (higher energy efficiency). This relationship is supported by reduced energy use in buildings and transportation, as well as fewer GHG emissions in densely populated areas. While earlier studies on energy consumption showed small positive to insignificant results, recent research generally supports the notion that population density promotes energy efficiency (Liddle, 2014). Liddle's (2014) assessment aligns with the results of our literature analysis, which indicates a general consensus among studies that population density promotes energy efficiency due to agglomeration economies, consumer behaviour and governmental action. It is likely that new technologies and urbanisation strategies will further enhance energy efficiency in densely populated areas. For instance, the Residential Solar Block is an example of utilising solar exposure on buildings to improve energy efficiency, reduce urban heat islands, enhance airflow, promote green roofs, and decrease energy use in transportation (Okeil, 2010). However, there are some studies with opposite conclusion. Sheng et al. (2017) argue that urbanisation, which is associated with high population density, can lead to inadequate energy efficiency due to insufficient infrastructure that cannot accommodate the fast-growing population in urban areas and a lack of energy-efficient consumer behaviour.

Table 3 shows a positive relationship between HDD and EPC grading, which supports our expectations from *section 3.4*. Generally, colder areas tend to encourage people to invest more in house insulation and energy efficiency, likely driven by the need for a comfortable living climate, to minimise costs and raise heat rendition. Our premise is backed up by Fuerst et al. (2016), who found that in Finland, energy costs raised people's willingness to pay for higher EPC ratings as well as by Wilhelmsson (2019), whose results showed that EPCs hold greater value in the northern and colder areas of Sweden than in the warmer ones. Additional support for our explanation is also lent by Guo et al. (2022), who state temperatures below 5°C represent a critical threshold leading to a substantial increase in energy demand. It is to note that the size of the heating effect does not only rely on temperature level but also on income level - this is because households in wealthier countries tend to exhibit a more robust response to temperature fluctuations (Petrick et al., 2010). This notation may also apply to densely populated areas, as they tend to be wealthier than rural regions.

5.3 Energy Prices

Our findings in *Table 3* show that gas prices have the greatest influence on people's investment decisions towards energy-efficient improvements out of all energy fuels. This effect is particularly pronounced for gas price within a two-year timeframe leading up to the assessment. One possible explanation for this correlation is the extensive utilisation of gas as an energy source. Interestingly, the prices of liquid fuel exert a more substantial influence than electricity prices, despite electricity being the second most utilised energy source in Scotland. A possible reason for this finding is that people do not necessarily associate their electricity bill with heating costs, as electricity is utilised for a wide range of other purposes as well.

*For each type, we estimated three regressions based on nominal energy prices: (1) energy prices in the year of assessment, (2) energy prices in one year prior to assessment, (3) energy prices in two year prior of assessment, (4) energy prices in three year prior of assessment.

Regression Results

	Dependent variable: Energy efficiency rating			
	Fuel price			
	(Current year)	(1yr prior)	(2yr prior)	(3yr prior)
Electricity * New dwellings	0.001	0.003	0.002	-0.001
	(0.007)	(0.007)	(0.007)	(0.008)
Electricity * All existing dwellings	-0.034^{***}	-0.038^{***}	-0.039^{***}	-0.042^{***}
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Liquid fuels * New dwellings	-0.013	-0.009	-0.010	-0.011
	(0.011)	(0.011)	(0.011)	(0.013)
Liquid fuels * All existing dwellings	-0.083^{***}	-0.093^{***}	-0.093^{***}	-0.095^{***}
	(0.0005)	(0.001)	(0.001)	(0.001)
Solid fuels * New dwellings	-0.055	-0.052	-0.053	-0.052
	(0.047)	(0.048)	(0.049)	(0.049)
Solid fuels * All existing dwellings	-0.152^{***}	-0.159^{***}	-0.163^{***}	-0.167^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
Gas * New dwellings	0.049^{***}	0.055^{***}	0.058^{***}	0.061^{***}
	(0.003)	(0.003)	(0.003)	(0.003)
Gas * All existing dwellings	0.038^{***}	0.045^{***}	0.046^{***}	0.046^{***}
	(0.0002)	(0.0003)	(0.0003)	(0.0003)
Constant	62.628^{***}	64.279^{***}	64.036^{***}	63.843^{***}
	(0.056)	(0.040)	(0.040)	(0.043)
Observations	1,433,961	1,433,961	1,433,961	1,433,961
R2	0.161	0.168	0.169	0.171
Adjusted R^2	0.161	0.168	0.169	0.171
Note:				$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table 4*: Impact of energy prices on the EPC grading on new and existing dwellings*

To gain a deeper insight to our findings regarding energy prices, we examine the impact of energy prices on EPC grading for both new and existing dwellings, as presented in *Table 4*. The data shows a positive relationship between gas prices and EPC grading for both new and existing dwellings, which can be attributed to the prevalent use of gas as a heating fuel. Interestingly, in the case of new dwellings, positive relationships are observed only for gas and electricity prices, although the effect of electricity prices appears to be relatively minor. When analysing the impact of gas prices over time, we observe that the influence on EPC grading increases as we go further back in time. This is evident in the results for *gas prices*new dwellings* three years before the assessment. The increasing influence of gas prices could be attributed to factors such as dwellings being in the planning stage, people's prolonged exposure to high gas prices, and the availability of new technologies. However, similar to the previous regression, the impact of energy prices on EPC grading and, consequently, energy efficiency is not large. Most likely, consumers refrain from considering energy efficiency improvements due to the regularity of energy price fluctuations, leading them to anticipate a rebound in prices. Furthermore, the greatest impact of price fluctuations is typically observed in the short term, which could deter long-term investments. This is supported by Alberini et al. (2011), who found that survey respondents with uncertainty about future energy prices lean towards the status quo and prioritise investment costs over those anticipating price increases. In addition, alternatives to energy efficiency investments in countering price increases include reducing energy consumption, relying on savings, and practising reduced spending. Generally, income appears to have a greater influence on energy efficiency than energy prices, as evidenced by the findings in Gorus & Karagol (2022). This is further underlined by Damigos et al. (2021), who found that people who struggle to maintain a comfortable temperature at home are less inclined to invest in energy efficiency compared to those dealing with issues such as dampness or overdue bills. Moreover, the individuals who are most in need of energy efficiency improvements to mitigate the impact of high prices, namely those facing fuel poverty, are unable to afford them, and even current governmental intervention seems unable to rectify this completely (Charlier & Legendre, 2021; Damigos et al., 2021; Foster et al., 2000; Rosenow et al., 2013).

6. Limitations

Our study is based on cross-sectional data, which limits our ability to observe changes in individual houses over time. To enhance the impact of our research, it would have been beneficial to have a dataset spanning over more than ten years, enabling us to assess if houses underwent improvements and achieved higher EPC grading. This time frame arises from the fact that the EPC for a dwelling must be renewed every ten years. Additionally, due to the unavailability of household data and energy supplier information for Scotland, we could not account for the variations in energy suppliers and tariffs among households. As a result, we could only rely on the energy prices available for the entire UK, preventing us from conducting a more detailed analysis. Furthermore, people's behaviour and EPC grading are influenced by various factors, thus resulting in a need for a more comprehensive set of variables to provide a more accurate and nuanced understanding of the subject. The chosen variables should include external factors, for instance population density and temperature but also internal factors such as the year of construction, building materials, and other relevant factors. Also, to enhance further research, it is suggested to integrate both qualitative and quantitative methods, for example incorporating survey responses from households.

7. Conclusion

Energy efficiency plays a crucial role in mitigating climate change, which has prompted the EU to introduce EPCs. However, to fully leverage the potential of this regulation, it is essential to understand the factors that influence people's decisions to invest in energy efficiency. Our research paper examines the impact of external factors, specifically population density, temperature, and energy prices, on EPC grading. By analysing these factors, we aim to gain insights into consumer behaviour concerning energy efficiency improvements. We found that population density has a positive relationship with EPC gradings, suggesting that more densely populated areas lead to higher energy efficiency. In light of this, policymakers should consider extending more funding for infrastructure enhancements to rural areas to ensure equitable access to improved energy efficiency. Additionally, low temperature also shows a positive relationship with EPC grading, this is most likely due to people's preference for comfort, cost savings from energy-efficient improvements, and enhanced heat retention through house insulation. This behaviour could be most likely enhanced further by targeted location-based incentives that expand the adoption of temperature-adapting technologies for improved energy efficiency for a wider population. The impact of energy prices on our study did not align with our initial expectations. Also, the relationship between energy prices and EPC grading varied depending on the type of energy fuel, exhibiting both positive and negative associations. Nevertheless, it is generally observed that high energy prices contribute to an increase in fuel poverty, which subsequently hinders investments in energy efficiency. This observation is consistent with existing literature, which suggests that income plays a significant role in driving energy efficiency improvements, particularly in the face of elevated energy prices. Therefore, policymakers should create affordable incentives that surpass market conditions, prioritise consumer benefits, and explore prepayment options for energy efficiency improvements. This solution is based on our information that most people in Scotland cannot afford the required energy efficiency investments despite the incentives introduced by the Scottish government. The presented incentives in this paper typically require people to pay for investments upfront, certify their energy efficiency improvements, and then apply for reimbursement; however, acceptance is not guaranteed. This uncertainty discourages people from applying for these incentives. To achieve higher energy efficiency and promote behaviour aligned with energy-saving practices, it is important to implement tailored schemes. A "one size fits all" approach falls short in motivating people because energy efficiency involves multiple factors that a uniform approach cannot adequately address. Policies and incentives should carefully consider factors such as people's location, existing infrastructure, household characteristics, and income levels.

To obtain a more comprehensive understanding of people's behaviour regarding energy efficiency, future research should extend the analysis of EPC gradings beyond a 10-year timeframe. This longer-term perspective would allow for the observation of grading changes within the same dwellings.

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Appendix A – Regression with real energy prices

*For each type, we estimated three regressions based on real energy prices: (1) energy prices in the year of assessment, (2) energy prices in one year prior to assessment, (3) energy prices in two year prior of assessment, (4) energy prices in three year prior of assessment.

Regression Results

	Dependent variable: Energy efficiency rating			
	Fuel price			
	(Current year)	(1yr prior)	(2yr prior)	(3yr prior)
Property bungalow	-2.686***	-2.621***	-2.591***	-2.552***
	(0.030)	(0.030)	(0.030)	(0.030)
Property flat	4.290***	4.355***	4.326***	4.281***
	(0.021)	(0.021)	(0.021)	(0.021)
Property maisonette	1.009***	1.063***	1.045***	1.009***
	(0.062)	(0.062)	(0.062)	(0.062)
Tenure private rented	-0.239***	-0.209***	-0.200***	-0.194***
	(0.041)	(0.041)	(0.041)	(0.041)
Tenure social rented	6.308***	6.317***	6.277***	6.226***
	(0.035)	(0.035)	(0.035)	(0.034)
Tenure unknown	5.337***	5.357***	5.407***	5.333***
	(0.116)	(0.116)	(0.116)	(0.115)
Transaction assessment green deal	-2.788***	-2.745***	-2.740***	-2.763***
	(0.065)	(0.064)	(0.064)	(0.064)
Transaction FiT application	8.706***	8.724***	8.655***	8.664***
	(0.089)	(0.089)	(0.089)	(0.089)
Transaction new dwelling	2.108***	2.089***	2.096***	2.119***
	(0.282)	(0.281)	(0.281)	(0.281)
Transaction non marketed sale	-3.164***	-3.222***	-3.183***	-3.104***
	(0.078)	(0.078)	(0.078)	(0.078)
Transaction none of the above	-2.258***	-2.285***	-2.269***	-2.242***
	(0.031)	(0.031)	(0.031)	(0.031)
Transaction rental	-0.075*	-0.115***	-0.101***	-0.073*
	(0.039)	(0.038)	(0.038)	(0.038)
Transaction following green deal	12.594***	12.423***	12.532***	12.691***
	(0.196)	(0.195)	(0.195)	(0.195)
Transaction ECO assessment	-3.971***	-4.016***	-3.979***	-3.932***
	(0.046)	(0.046)	(0.046)	(0.046)
Transaction RHI application	-1.804***	-1.835***	-1.828***	-1.768***
	(0.073)	(0.072)	(0.072)	(0.072)
Population density	0.137***	0.132***	0.129***	0.126***
	(0.004)	(0.004)	(0.004)	(0.004)
HDD	0.363***	0.332***	0.346***	0.357***
	(0.009)	(0.009)	(0.009)	(0.009)
Electricity price	0.008***	0.011***	0.025***	0.022***
	(0.001)	(0.001)	(0.001)	(0.001)
Liquid fuels price	0.010***	0.017***	0.030***	0.019***
	(0.001)	(0.001)	(0.001)	(0.002)
Solid fuels price	-0.078***	-0.072***	-0.056***	-0.064***
	(0.002)	(0.001)	(0.002)	(0.002)
Gas price	0.105***	0.118***	0.132***	0.125***
	(0.001)	(0.001)	(0.001)	(0.001)
Constant	39.482***	45.487***	43.775***	42.412***
	(0.326)	(0.280)	(0.283)	(0.300)
Observations	1,433,961	1,433,961	1,433,961	1,433,961
R2	0.295	0.300	0.302	0.303
Adjusted R^2	0.295	0.300	0.302	0.303

Note: *p<0.1; **p<0.05; ***p<0.01

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