Building Energy Rating (BER) Analysis Determinants of Efficiency and Retrofit Strategies in Irish Housing

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Abstract

Improving the energy efficiency of residential buildings is critical for reducing overall energy demand and carbon emissions. This report presents a comprehensive analysis of factors influencing the Building Energy Rating (BER) of homes and related outcomes like energy consumption and CO_2 emissions. Using a national dataset of over one million Irish dwellings, we examine how building attributes – from insulation levels and heating systems to dwelling type, size, age, and location – affect energy performance. Statistical correlations, regression models, and visualizations are employed to identify key drivers of BER and to evaluate the impacts of construction era, dwelling form, and retrofit measures. The findings confirm that the thermal integrity of the building envelope (low U-values for walls, roofs, etc.) and efficient heating systems are the dominant determinants of a dwelling's BER. Newer houses built under stricter building codes achieve significantly better ratings, reflecting the success of progressive standards in recent decades **(CSO, 2023)**. Apartments and terraced houses tend to outperform detached houses in energy intensity due to shared walls and compact size, and a weak "dilution effect" is observed whereby larger homes have slightly lower energy use per m^2 **(Gao et al., 2019)**. Heating fuel choice has a dramatic influence on carbon emissions – for example, modern heat pumps emit only a fraction of the CO_2 of oil or coal-based heating systems **(Mittens Heat Pumps, n.d.)** – meaning that a home's climate impact depends as much on its heat source as on its BER. We also find notable regional patterns: urban and recently-developed areas have more efficient housing stock on average than rural areas. The analysis concludes with targeted recommendations: prioritize wall insulation and high-efficiency heating upgrades (e.g. heat pumps) in older, poor-performing homes, and use simple screening metrics (such as wall U-value and boiler efficiency) to identify the worst-performing properties for retrofit programs. These insights offer guidance for homeowners, policymakers, and retrofit initiatives to achieve maximum gains in energy savings and emissions reduction.

1. Introduction

Residential buildings account for a significant portion of energy use and carbon emissions worldwide. The building sector as a whole is responsible for roughly 40% of final energy consumption and about one-third of greenhouse gas emissions globally **(IEA, 2019)**. Improving home energy efficiency is therefore crucial for meeting climate targets and reducing consumer energy costs. In this context, Building Energy Rating (BER) certificates provide a standardized measure of a dwelling's energy performance on an A–G scale (with A-rated homes being the most efficient). A BER represents the modelled energy intensity of a home (in kWh/m^2 per year) under standard occupancy and climate conditions, which enables like-for-like comparisons of homes' efficiency. It serves as an indicator of likely space heating requirements, running costs, and associated CO_2 emissions **(SEAI, 2022b)**. In Ireland, the BER system was established in 2007–2008 in response to EU directives, and since 2009 a BER certificate has been legally required for all homes when they are sold or rented. This policy has resulted in a large database of BER assessments covering most of the housing stock, creating a rich dataset on dwellings' energy characteristics.

Objectives: This study analyzes Ireland's national BER dataset to identify the drivers of residential energy efficiency and to inform retrofit strategies. We investigate ten specific research questions (RQ1–RQ10) organized around five themes: (A) Building fabric and design (insulation, construction year, dwelling type, size), (B) Energy consumption and emissions (heating systems and fuel types), (C) Geographic factors (regional and climate influences), (D) Retrofit measures (e.g. added insulation, solar panels, efficient boilers), and (E) Identification of worst-performing homes. By addressing these questions, we aim to guide homeowners, policymakers, and retrofit programs on where to target efforts for maximum impact. The analysis combines statistical methods with visual exploration to uncover patterns in the data, and results are interpreted in light of building physics principles and the policy context.

2. Research Questions

The study addresses the following ten research questions:

RQ1: What are the dominant predictors of a dwelling's BER (energy performance rating)?

RQ2: Is there a trend between the year a dwelling was built (construction period) and its BER?

RQ3: How does the type of dwelling (detached, semi-detached, terraced, apartment) influence its BER?

RQ4: How does a home's size (floor area) relate to its energy intensity as measured by BER ($kWh/m^2/yr$)?

RQ5: How do different heating system types and fuels affect a home's energy consumption and CO_2 emissions?

RQ6: Do certain dwelling types have higher total annual CO_2 emissions than others (even if their per-m^2 efficiency differs)?

RQ7: Are there geographic or regional differences in average BER (e.g., between counties or urban vs rural areas)?

RQ8: Are there regional patterns in actual energy consumption or CO_2 emissions, beyond what BER alone indicates?

RQ9: What is the effect of specific retrofit measures (such as added insulation, solar panels, or efficient boilers) on a home's BER?

RQ10: Which combination of features can identify the least efficient homes (e.g., the worst 20% BER ratings) for prioritizing retrofits?

These questions will be answered in turn in the Results and Analysis section, providing a data-driven understanding of residential energy performance and pointing to effective improvement strategies.

3. Data and Methodology

Data: We utilize a large national dataset of Building Energy Ratings (BER) encompassing approximately 1,048,575 dwellings and over 200 features per dwelling. This dataset, obtained from the Sustainable Energy Authority of Ireland's BER Research Tool **(SEAI, 2022a)**, includes each dwelling's BER (in kWh/m² per year) along with detailed information on the building's construction and characteristics. Key variables include the construction year, dwelling type (detached house, apartment, etc.), floor area, insulation levels (wall, roof, and window U-values), heating system type and efficiency, primary heating fuel, calculated annual energy consumption for heating, and estimated CO_2 emissions. The BER is calculated using Ireland's official Dwelling Energy Assessment Procedure (DEAP) methodology under standardized conditions **(SEAI, 2022b)**. This means the rating is an *asset* rating of the dwelling's theoretical performance – based on the physical properties of the building and its systems – rather than measured energy usage by the current occupants. Standard assumptions (occupancy related to floor area, fixed heating schedules and temperatures, standard climate data, etc.) are applied so that all homes are rated on a consistent basis **(SEAI, 2022b)**. This approach allows objective comparisons between different homes' efficiency, akin to an appliance energy label, and ensures that factors like occupant behavior or unusual weather do not skew the rating for comparative purposes.

The dataset covers all regions of Ireland and a wide range of dwelling ages (from 18th-century cottages to new modern homes) since BER assessments have been conducted on both new and existing homes especially from 2009 onward. It provides a comprehensive snapshot of the Irish housing stock's energy performance. We focus on the residential subset (excluding a small number of non-domestic buildings that were present in early BER records). For each dwelling, we also have the modelled annual primary energy consumption (in kWh) broken down by end use (space heating, water heating, etc.) and the associated annual CO_2 emissions (in kg), as computed in the BER assessment report.

Methodology: Our analysis is structured around the ten research questions listed above. For each question, we applied appropriate statistical techniques and visualization methods, as follows:

- **Exploratory Data Analysis:** We first computed basic summary statistics and Pearson correlation coefficients to screen for linear relationships between BER and various continuous predictors (e.g. insulation U-values, heating system efficiency, floor area). This helped to rank the importance of potential predictors and identify any strong linear associations.

- **Regression Modeling:** To capture non-linear effects and interactions, we trained a Random Forest regression model to predict BER using a set of key features (including wall, roof, and window U-values, main heating system efficiency, presence of certain retrofits, etc.). The Random Forest's feature importance scores were used to assess the relative influence of each input variable on the BER outcome, providing a multivariate perspective on RQ1.

- **Group Comparisons:** We used categorical comparisons to address questions about dwelling type, construction era, heating fuel, and retrofits. For example, to examine differences by dwelling type (RQ3), we grouped homes into categories (detached, semi-detached, terraced, apartment) and compared their BER distributions using boxplots. We similarly binned dwellings by construction period (e.g. pre-1980, 1980s/90s, 2000s, 2010s) to observe how BER varies with building age (RQ2). Analysis of variance (ANOVA) tests and t-tests were employed to test the statistical significance of differences between groups (e.g., mean BER of apartments vs. houses).

- **Trend Analysis:** For continuous variables like construction year and floor area, we created scatter plots and applied locally weighted scatterplot smoothing (LOWESS) curves to visualize trends (RQ2 and RQ4). We also examined these relationships by segmenting the data (e.g., splitting floor area into quintiles) to see how median BER changes with size cohort.

- **Visualization of Energy and Emissions:** To address RQ5–RQ8 regarding energy consumption and emissions, we plotted distributions of annual CO_2 emissions for different categories (heating fuel types, dwelling types, regions). Box-and-whisker plots were used to illustrate the spread of emissions outcomes across categories, and bar charts were used for showing average values by category (e.g., mean emissions per dwelling in each county).

- **Decision Tree Classification:** For RQ10, we trained a classification tree to identify characteristics of the worst-performing homes (defined here as those in the lowest 20% of

BER scores, roughly corresponding to E, F, or G ratings). The decision tree algorithm provided a set of if-then rules that classify a dwelling as "worst 20%" or not based on input features. By examining the top splits in the tree, we extracted simple combination criteria (e.g. "wall insulation very poor AND old heating system") that flag a home as likely to be in the worst-performing category.

All analysis was conducted using Python with libraries such as pandas (for data manipulation), NumPy, and scikit-learn for modeling, and seaborn/Matplotlib for generating figures. Given the large sample size (>1 million homes), even modest effects could be statistically significant; therefore, we focus on the practical significance and effect sizes of findings. The results for each research question are presented in Section 4 with corresponding figures (Figures 1–14) illustrating key patterns. All figures referenced are based on the BER dataset analysis unless otherwise noted.

4. Results and Analysis

4.1 Factors Affecting BER (RQ1) – Key Predictors of Energy Performance

RQ1: What are the dominant predictors of a dwelling's BER? This question asks which building characteristics most strongly influence a home's energy efficiency rating. Intuitively, one would expect the thermal quality of the building envelope (insulation of walls, roofs, windows) and the efficiency of the heating system to be critical factors, since heat loss and heating demand drive energy usage in homes. We examined this question using both simple correlation analysis and a multivariate Random Forest model.

Correlation analysis: Among continuous numeric features, we found that envelope insulation metrics exhibited the highest correlation with BER. In particular, the wall U-value (a measure of thermal transmittance where higher U means poorer insulation) had the strongest Pearson correlation with BER ($r \approx +0.60$). This positive correlation indicates that homes with higher wall U-values – i.e. worse-insulated walls – tend to have significantly higher (worse) energy use per m^2. Similarly, window U-value showed a correlation around $r \approx +0.57$ with BER, and roof U-value about $r \approx +0.54$, both also positive. These correlations are quite high in the context of building energy data, underscoring that poorly insulated building fabric is closely associated with higher required energy for heating. By contrast, the main heating system efficiency (e.g. boiler or heat pump efficiency) was moderately negatively correlated with BER ($r \approx -0.38$), as expected: a more efficient heating system reduces the energy needed for the same heat output, lowering the BER. Interestingly, the nominal thickness of insulation in walls (as recorded in the data) had only a weak correlation (~ –0.08) with BER. This suggests that simply having thick insulation is not as predictive as the resulting U-value; in practice, material properties and installation quality determine the U-value. For example, 200 mm of poorly installed or low-grade insulation might perform worse than 100 mm of high-quality insulation, so the U-value is a better indicator of actual heat loss than thickness alone.

Random Forest model: We trained a Random Forest regressor to predict the BER using a set of key features. The model's feature importance rankings reinforced the dominance of envelope and heating parameters. Figure 1 shows the relative importance of the top features in the model. Wall U-value emerged as the single most important predictor of BER, slightly ahead of the heating system's efficiency. Window U-value was the third most important, followed by roof U-value and the presence of any floor insulation. These top five features far outweighed others in the model (such as dwelling size or glazing area) in terms of influence. The prominence of wall and window U-values aligns with fundamental building physics: these surfaces represent large areas through which heat can escape, so their thermal quality strongly affects heating requirements. The importance of heating efficiency highlights that even a well-insulated house will have a better BER if its heat generation is efficient (for instance, a modern condensing boiler or heat pump versus an old inefficient boiler).

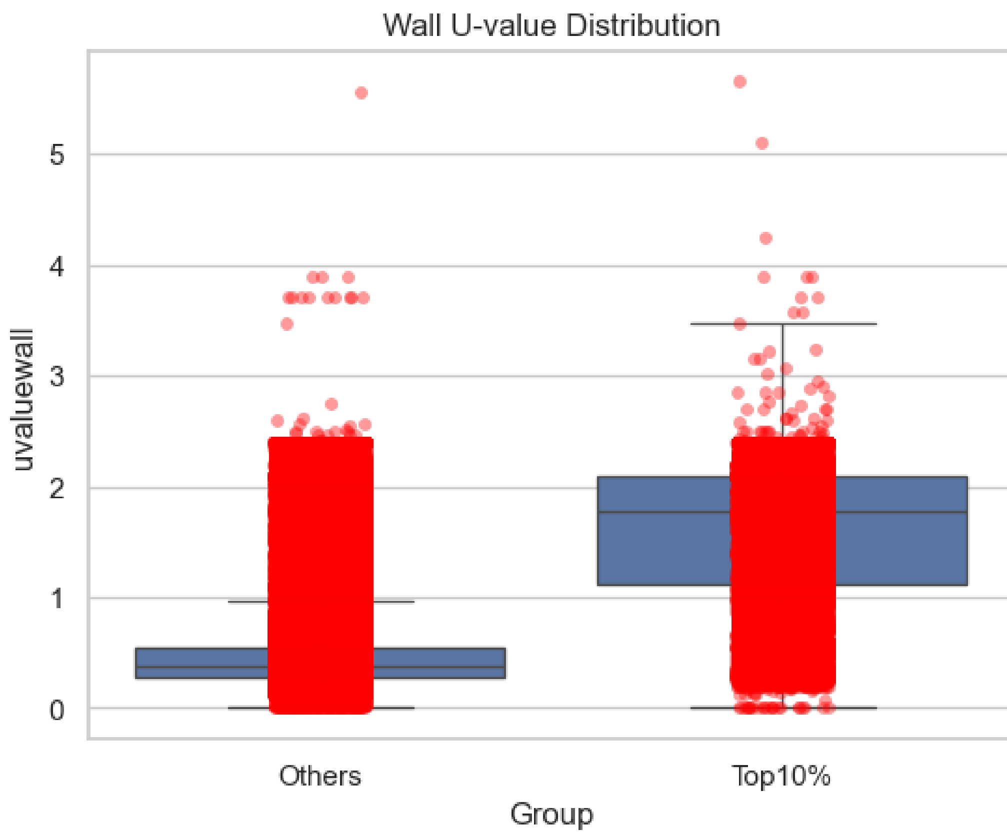

Figure 4.1: Wall U-value Distribution among Efficient vs. Other Homes

This boxplot compares wall U-values between the top 10% most energy-efficient homes (based on BER) and all other dwellings. The results show significantly lower U-values (better insulation) among top-performing homes, highlighting the critical role of wall insulation quality in achieving superior energy ratings.

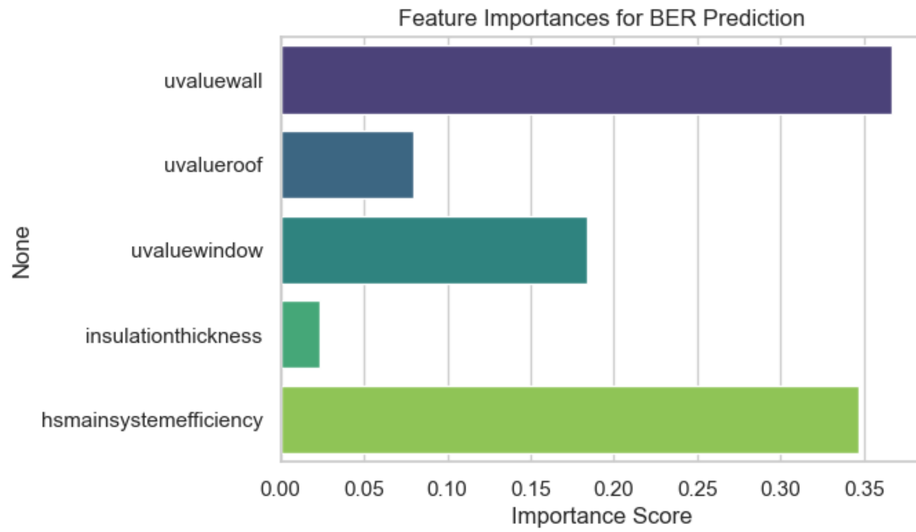

Figure 3.2: Feature Importances for BER Prediction (Random Forest Model)

This bar chart presents the relative importance of building features in predicting BER using a Random Forest regressor. Wall U-value and heating system efficiency emerge as the most influential predictors, followed by window U-value, confirming that envelope performance and heating system efficiency dominate energy efficiency outcomes.

Figure 3.1 and 3.2. Relative importance of key building features in predicting a dwelling's BER, as determined by a Random Forest model. Wall insulation quality (U-value) is the most influential single factor, followed by main heating system efficiency and window U-value. (Addresses Research Question 1.)

We also compared the characteristics of the most efficient homes (top 10% by BER score) versus the rest of the sample. This comparison confirmed that superior envelope insulation is a key differentiator of high-performing homes. The top-10% BER homes had dramatically lower wall U-values on average (indicating very well-insulated walls, often with modern insulation or thick retrofitting), whereas the rest of the homes showed a broad range of higher U-values. Notably, the high-BER (efficient) group did not simply have thicker insulation in all cases; rather, they had better overall construction – indicating that quality of insulation and design (minimizing thermal bridging, good airtightness, etc.) matters as much as quantity. Another major difference was in heating systems: among the top-performing homes, there was a high prevalence of efficient heating technologies (especially heat pumps and new high-efficiency gas boilers). In contrast, many of the lower-performing homes were found to rely on older oil boilers, electric resistance heaters, or other less efficient systems. This suggests that to achieve an excellent BER, a home generally needs both a well-insulated envelope *and* an efficient heating system.

In summary, the analysis for RQ1 clearly shows that the **building envelope and the heating system are the paramount factors** determining a home's BER. Figure 1 highlights that wall U-value (a proxy for wall insulation quality) has the largest impact – homes with low wall U-values (e.g. 0.2–0.3 W/m²K, indicative of thick insulation or cavity fill with minimal thermal bridging) almost invariably achieve good BERs, all else being equal. Upgrading a wall from uninsulated (U ~1.5) to well-insulated (U ~0.3) can cut a dwelling's heat loss dramatically, reflected in a much lower BER. Heating efficiency is the next crucial factor – for example, replacing an old 70% efficient oil boiler with a 90% efficient gas boiler or a heat pump can reduce the primary energy required for heating by 20–50%, improving the BER correspondingly. Window performance (double/triple glazing vs single glazing) is also significant, though typically windows are a smaller portion of heat loss area compared to walls and roof. The policy implication of these findings is that retrofit programs should focus on **"fabric-first" measures (especially wall insulation) and heating system upgrades**, as these will yield the largest improvements in a home's BER.

4.2 Construction Year vs. BER Trend (RQ2)

RQ2: Is there a trend between the year a dwelling was built and its BER? Building standards and construction practices have evolved substantially over time, especially with the introduction of energy efficiency regulations. We expect newer homes to be more energy-efficient on average due to improved insulation standards, better windows, and efficient heating systems installed from new. To investigate this, we plotted each dwelling's BER against its construction year and also compared average BERs for homes grouped by era of construction.

The scatter plot of BER versus construction year (Figure 2) reveals a clear **downward trend** over the decades: newer dwellings tend to have lower (better) energy use per m². The locally-fitted LOWESS curve in Figure 2 slopes downward from the mid-20th century to the present, illustrating that each successive generation of buildings has, on average, improved energy performance. In particular, there are noticeable inflection points corresponding to known upgrades in building regulations. For example, homes built in the early 1970s through the 1980s often have BERs in the D or E range, whereas homes built in the late 2000s cluster in the B range or better. Around 2005–2007, the trend line shows a marked improvement (BER dropping significantly), which aligns with Ireland's 2005 Building Regulations that strengthened insulation requirements, as well as the 2006 launch of the national BER scheme which heightened awareness of energy performance. Another jump is observed for homes built around 2010–2012: many of these achieve A or high B ratings, reflecting the introduction of even stricter standards (e.g. the 2008 Building Regulations and subsequent updates). Beyond 2015, the trend begins to flatten out in the A-rating territory, indicating a saturation of efficiency gains at the high end – new homes from 2015 onward are almost all A-rated, so there is less variation to discern a trend.

To quantify these differences, we grouped the dwellings into four broad construction periods and compared their BER distributions (Figure 3). The cohorts were: **pre-1980** (older homes with minimal insulation originally), **1980–1999** (moderate insulation became common), **2000–2009** (built under 2002 regs, before and during BER introduction), and **2010–present** (built under the latest nearly-zero-energy standards). The contrast between these groups is striking. Pre-1980 dwellings have the worst energy performance overall: their BER values are typically in the range of 250–400 kWh/m²/yr (ratings D, E, F or even G), with a high median around the **D to E border**. Many older houses built before the first thermal insulation regulations (1979) fall into E or F ratings unless retrofitted. Homes from **1980–1999** show a modest improvement – the median is a bit lower (C/D range), as basic insulation (e.g. 50mm cavity insulation) was introduced in the 1980s, but most are still far from modern standards. Dwellings from **2000–2009** (before the major 2011 code change) have better performance: their median BER is around the low C or high D range, and a significant number reach B3 or C1 ratings. Finally, the **post-2010** homes are dramatically more efficient: the vast majority are rated A or B. Their median BER is roughly 100 kWh/m²/yr (which is a B1/A3), and many cluster in the A3 to A2 range (~50–75 kWh/m²/yr). In fact, official statistics confirm that 99% of audited dwellings built in 2020–2022 received an A-rating, compared to just 2% of those built in 2005–2009 **(CSO, 2023)**. This almost unbelievable leap underscores the impact of the progressive building regulations: each update (in 2005, 2008, 2011, and later Nearly Zero Energy Building standards by 2019) has slashed the typical energy requirements of new constructions.

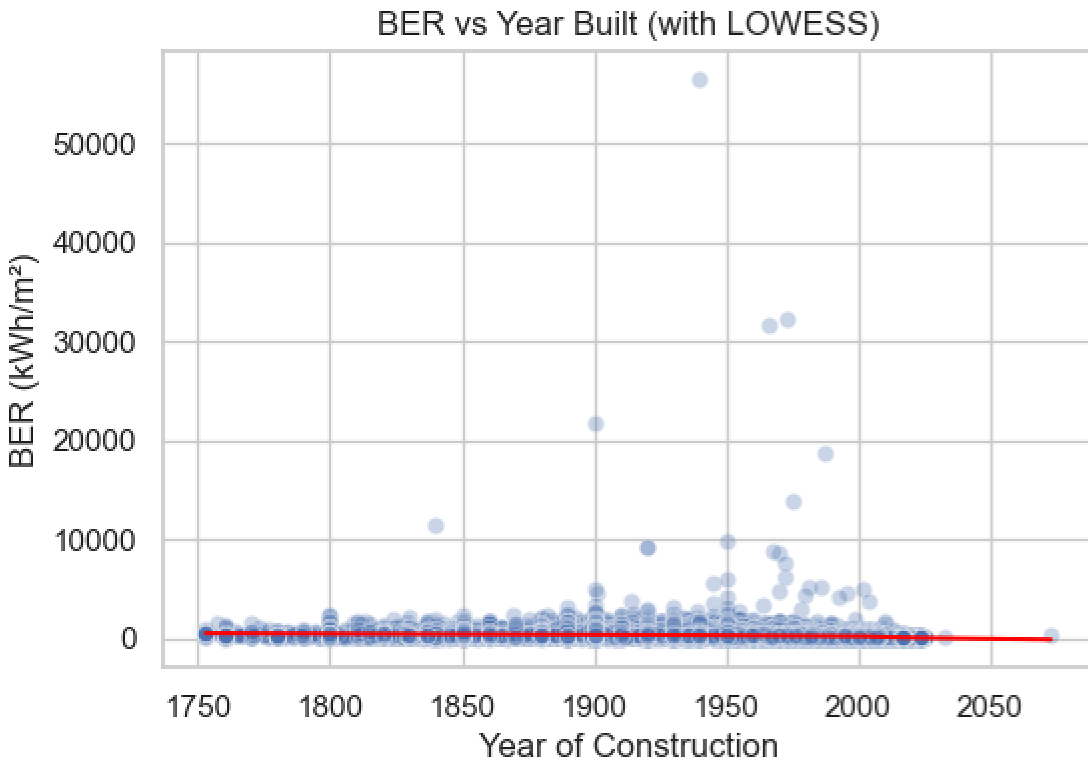

Figure 4.2: Relationship Between BER and Year of Construction (with LOWESS Smoothing)

Figure 4.2. BER (primary energy use in kWh/m²/year) vs. year of construction for ~1 million dwellings, with a LOWESS smooth trend line. Newer homes show consistently lower energy use per m², reflecting improved building standards over time. (Addresses Research Question 2.)

Figure 4.2: Distribution of BER by Construction Era

Figure 4.2. Distribution of BER values by construction period cohort. Homes built before 1980 have much higher and more variable energy use, while those built in 2010 or later overwhelmingly achieve low BERs (high efficiency). (Addresses Research Question 2.)

In summary, construction year is a strong predictor of energy performance. Each era of building practice has produced measurably different outcomes: a typical 2020s home uses only about a quarter of the energy per m² of a typical pre-1980 home of similar size. This finding validates the role of building energy codes and technological advancements. It also highlights the challenge and opportunity of retrofitting older homes – the majority of Ireland's housing was built before modern standards and thus represents a large reservoir of potential energy savings. The data indicate diminishing returns for the newest homes (post-2015), as many are already near the A2/A1 range, suggesting we are approaching the practical limits of what current construction can achieve without moving to full net-zero energy or incorporating on-site generation. Nonetheless, the dominant narrative is that **newer homes are far more efficient than older ones**, and thus policies should both ensure new builds maintain high standards and, crucially, address the legacy inefficiency of older housing stock through retrofits.

4.3 Dwelling Type and BER (RQ3)

RQ3: How does the type of dwelling influence its BER? Different dwelling types have different geometries and exposure, which can affect energy efficiency. A detached house is exposed on all sides to the external environment, whereas a mid-terrace house or an apartment may share walls (or floors/ceilings) with neighbors, reducing heat loss surfaces. We therefore expect apartments and terraced houses (which have more shared/party walls) to be more energy-efficient per square meter than stand-alone detached houses, all else being equal. We examined BER distributions across four dwelling types: detached houses, semi-detached houses, terraced houses (including end-terrace and mid-terrace), and apartments (including flats).

The analysis shows a clear ranking of energy performance by dwelling type (Figure 4). **Apartments** are, on average, the most energy-efficient dwellings in terms of BER. Their median BER is significantly lower (better) than that of any other category. Many apartments in the dataset achieve B ratings or even A ratings, and the variation among apartments is relatively small (a tighter interquartile range), indicating that most apartments cluster in the higher efficiency bands. There are a few less efficient outliers (e.g. some older poorly insulated apartments or those with electric heating), but overall the apartment stock performs well. This is partly because a large fraction of apartments are newer (built in the 2000s and 2010s in urban areas under modern codes), and partly because of geometry: a mid-floor apartment typically has only one or two external walls and perhaps a roof exposure if top-floor, so its heat loss area is minimal relative to its floor area.

In contrast, **detached houses** have the highest (worst) BER values on average. Figure 4 shows that the distribution for detached houses is shifted upward: a typical detached home might have a BER in the range of 200–300 kWh/m²/yr (roughly a D rating), and the spread is quite wide. There are some efficient detached houses (usually newer ones or extensively retrofitted ones) that achieve B or even A ratings, but many detached houses – especially older ones in rural areas – fall into D, E or even worse categories. The large spread reflects the diversity in this category: it includes everything from old stone cottages to modern one-off villas. Nevertheless, even the median detached house is considerably less efficient per m² than the median apartment. **Semi-detached**

houses and **terraced houses** fall in between but closer to detached houses in performance. Semi-detached homes (sharing one wall) and end-terrace homes (exposed on three sides) still have substantial exposed area, so their BER distributions are only slightly better than detached houses on average. **Mid-terrace** houses (with neighbors on both sides) fare a bit better – their median BER tends to be lower than semi-detached, reflecting the benefit of two shared walls insulating the home's sides.

To isolate form factors further, we also compared **single-storey** dwellings (e.g. bungalows) versus **multi-storey** dwellings (e.g. two-storey houses or apartments in multi-floor buildings) – see Figure 5. We found that single-storey homes have slightly worse BERs on average than multi-storey homes. This is likely because a single-storey building has more roof area and ground floor area relative to its volume (a higher surface-to-volume ratio), leading to greater heat loss per m² of floor area. Multi-storey buildings are more compact in shape and can benefit from heat rising from lower floors to upper floors.

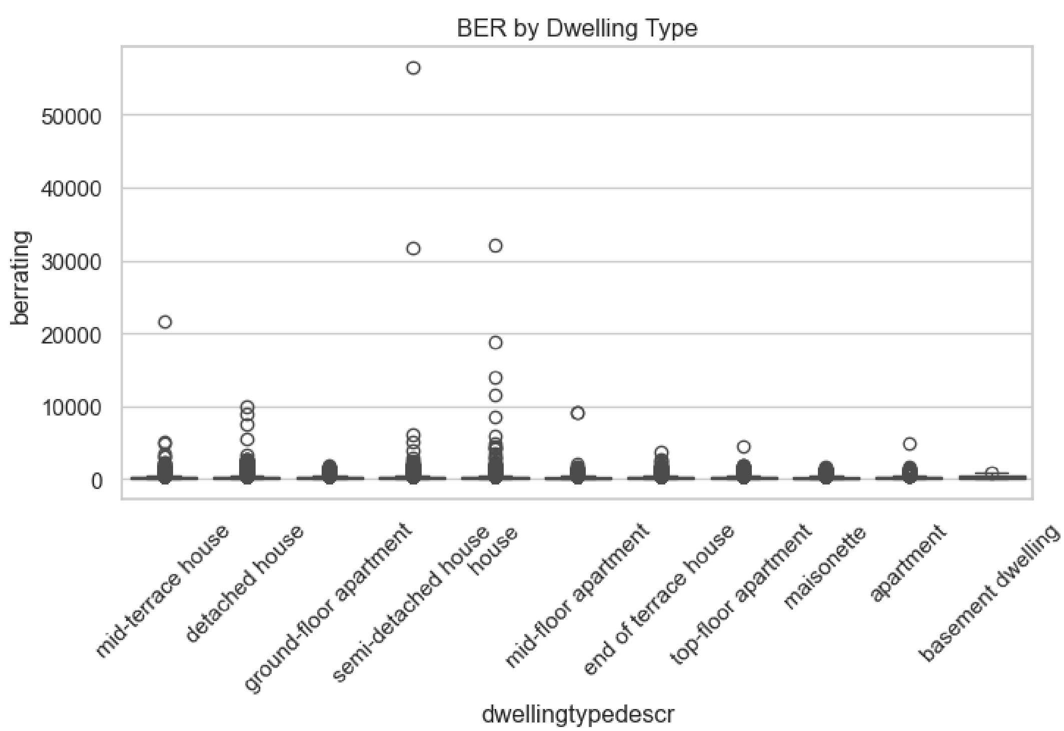

Figure 4.3.1: BER Distribution by Dwelling Type

*4.3.1***.** BER distributions by dwelling type. Apartments show the best (lowest) energy use per m² on average, while detached houses show the worst. Terraced and semi-detached houses are intermediate. Boxes span the 25th–75th percentiles and medians are marked. (Addresses Research Question 3.)

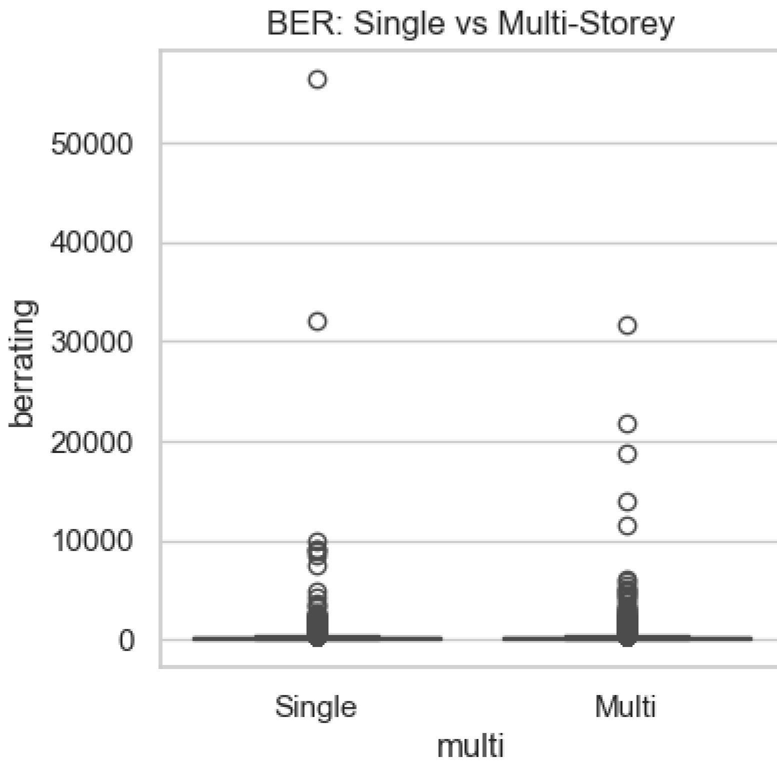

Figure 4.3.2: BER Comparison Between Single- and Multi-Storey Dwellings

4.3.2. Comparison of BER for single-storey vs. multi-storey dwellings. Single-storey homes (e.g. bungalows) tend to have slightly higher energy use per m² than multi-storey homes, due to less compact geometry. (Addresses Research Question 3.)

These findings align with known principles of building physics and urban form. Sharing walls (and floors/ceilings) reduces heat loss dramatically, as noted in studies by the U.S. EPA and others: multifamily and attached housing inherently require less energy for heating and cooling per unit, because there is less exterior surface area per dwelling **(EPA, 2011)**. In our data, the median apartment's BER is about 50–100 kWh/m² lower than the median detached house's BER, a substantial difference. However, it is important to note that **absolute energy use** is not the same as intensity: a detached house is usually much larger in floor area than an apartment, so in terms of total energy consumption, detached houses consume far more. (We analyze total emissions by dwelling type in RQ6.) The implication is that while high-density housing (apartments, terraces) has efficiency advantages per square meter, the larger size and sometimes higher occupancy of houses can offset some per-area efficiency when considering total demand.

From a retrofit and policy perspective, these results suggest that **detached houses should be a priority** for energy upgrades, since they generally have the worst performance and highest potential savings. Apartments often already perform well (especially newer ones) and can be harder to retrofit individually (due to shared structures), so the efficiency gains there may be smaller. Meanwhile, semi-detached and terraced houses – which form a large portion of suburban housing – also represent a key segment where many are only moderately efficient (C or D ratings) and could benefit from insulation upgrades (particularly to exposed gable walls, attics, etc.). In summary, dwelling type does influence BER significantly, with apartments being inherently easier to heat and detached homes being the most challenging in energy terms.

4.4 Floor Area and Energy Intensity (RQ4)

RQ4: Does a home's size (floor area) relate to its BER? On a per-square-meter basis, one might wonder if larger homes are more or less energy-efficient than smaller homes. There are competing effects: larger houses have more volume (which can retain heat) relative to surface area (through which heat is lost), so larger dwellings could enjoy some economies of scale in efficiency. On the other hand, very large homes might have under-utilized spaces that still need heating, potentially wasting energy and raising the per-m² usage. BER is normalized per m², so if larger homes were more efficient per m², we would see BER decreasing with size (a dilution effect); if smaller homes were more efficient, we'd see the opposite.

Our analysis found a **weak negative correlation** between total floor area and BER (Pearson correlation $r \approx -0.22$). This indicates that, on average, larger dwellings do tend to have slightly lower (better) energy use per m². Figure 6 illustrates this relationship with a scatter plot of BER against floor area. There is a broad scatter – many exceptions exist – but a mild downward trend is visible. The smallest dwellings (e.g. studio flats, small cottages under ~50–60 m²) often have quite high BER values (over 300 kWh/m² in some cases), whereas many larger homes (200–300 m²) cluster at lower BER values (perhaps 100–200 kWh/m²). To clarify the trend, we binned the data by size quintiles. The **smallest size group** (bottom 20% by area, which roughly corresponds to dwellings under ~70 m²) indeed had the highest median BER, around 250 kWh/m² (approximately a D rating). Meanwhile, the **largest size group** (top 20% by area, roughly >170 m²) had a somewhat lower median BER, around 180–200 kWh/m² (a C rating). The middle size categories did not differ as dramatically, indicating the effect is not very strong beyond the extremes.

This phenomenon, where energy intensity (per m²) decreases as floor area increases, is sometimes referred to as a **"dilution effect"** of larger area on energy use. Essentially, a bigger house can spread fixed thermal losses (like through the roof or one leaky wall) over more floor area, which brings down the energy use per unit area. Gao *et al.* (2019) documented a similar dilution effect in a study of Chinese apartments, noting that energy use per m² tends to drop as dwelling size rises, because certain baseline energy needs (like maintaining minimal heat) are shared over a larger space **(Gao et al., 2019)**.

In our context, a concrete example helps illustrate this: consider a tiny 30 m² bedsit with one exterior wall and a roof – it might lose, say, 3,000 kWh of heat through those surfaces in winter; that is 100 kWh/m². Now consider a 60 m² cottage with the same construction quality – it has maybe two exterior walls but only slightly more heat loss, say 4,500 kWh, yet per m² that is 75 kWh/m². Thus the larger space looks more "efficient" per area, even though total heat loss is greater, because the denominator (floor area) grew faster than the heat loss. Similar logic applies up to a point – extremely large houses eventually have so much surface area (many rooms, complex shape) that they can still have high usage, but generally they incorporate more internal volume relative to envelope area.

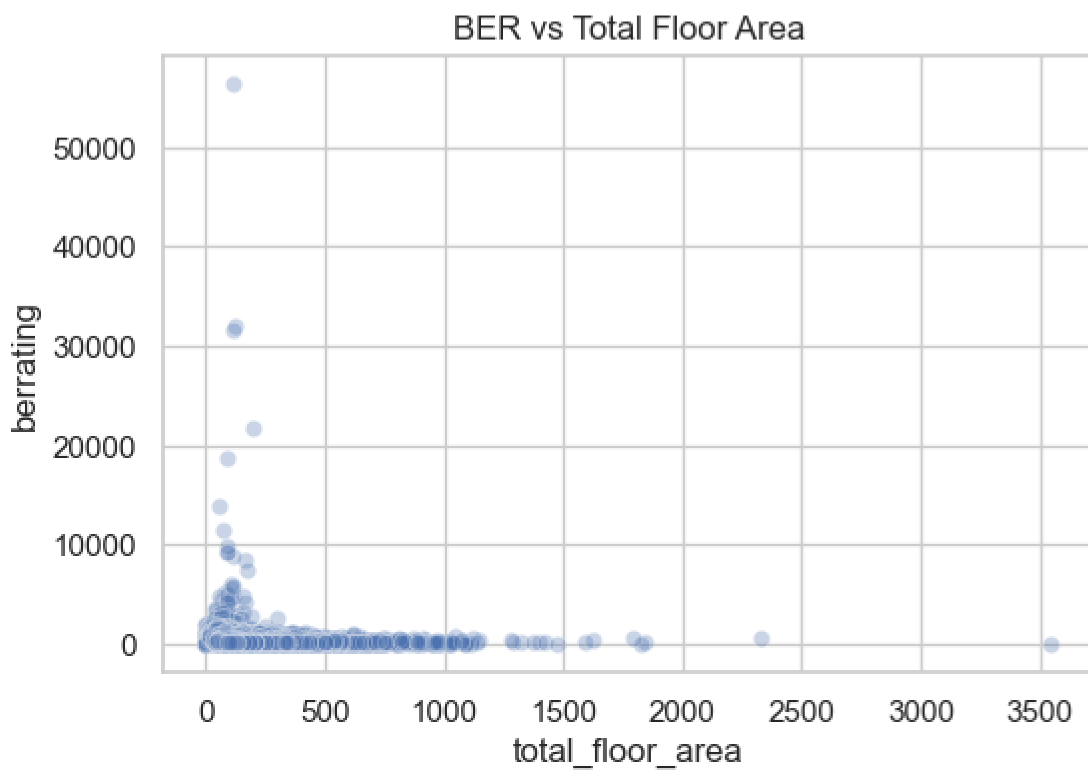

Figure 4.4.1: Relationship Between BER and Total Floor Area

*4.4.1***.** Relationship between dwelling floor area (horizontal axis, in m²) and BER (vertical axis, kWh/m²-year). A slight downward trend is observable, indicating larger homes have somewhat lower energy intensity per m² on average. (Addresses Research Question 4.)

It is important to emphasize that this correlation, while statistically significant given the large sample, is relatively weak. There are many small homes with good BERs (for instance, a well-insulated modern apartment of 50 m² can be A-rated) and many large homes with poor BERs (an uninsulated 250 m² Victorian house could be G-rated). In our dataset, the **very smallest dwellings** (under ~50 m²) often had poor BERs because many of them are older flats or cottages with inadequate insulation; also, a small dwelling still needs a minimum energy input to keep warm, so in per-m² terms it can look high. Meanwhile, **very large dwellings** (over ~250 m²) sometimes include modern luxury homes that were built with high standards or retrofitted, giving them reasonable per-m² performance, even though their absolute energy use is high.

From a practical perspective, the size effect means that **BER alone can sometimes disadvantage small homes** in the rating, even if they use little total energy. BER assumes standard occupancy based on floor area, which means a small dwelling is assumed to be occupied by fewer people (perhaps 1-2) but still heated to the same comfort levels – if the dwelling is thermally subpar, its small size doesn't save it in the per area metric. Conversely, a large home might not actually be fully heated in reality (some rooms might be kept cooler or empty), but BER assumes it is fully heated, potentially giving it a somewhat optimistic per-area rating if in practice the heating is zone-controlled. These nuances aside, the data does support a mild economy of scale: **larger dwellings tend to achieve slightly better energy intensity**, all else equal.

For designers and retrofitters, this suggests paying special attention to **very small units** (e.g. studio apartments, tiny houses), which can have surprisingly high energy usage per m^2 if not well-insulated, due to the large impact of each external surface. For large homes, while the per-area efficiency might be acceptable, one must remember their total energy and emissions are still high (we address total emissions in RQ6). Owners of large homes should not be complacent with a decent BER, since a C-rated 300 m^2 house will consume roughly twice the energy of a C-rated 150 m^2 house in absolute terms. In summary, there is a modest dilution effect of floor area on BER, but **size is not a primary determinant** compared to factors like insulation and heating (as seen in RQ1). It's an interesting secondary factor that underscores how geometry influences efficiency metrics.

4.5 Heating System and Fuel Impact (RQ5)

RQ5: How do different heating systems and fuel types affect a home's energy consumption and CO_2 emissions? Space heating is the largest component of energy use in most Irish homes, so the type of heating system and the fuel it uses can greatly influence both the BER (which accounts for efficiency and primary energy conversion) and the actual carbon emissions. In the BER calculation, an inefficient heating system (like an old boiler or electric resistance heaters) will require more primary energy to deliver the same heat, raising the BER. Separately, the choice of fuel (oil, gas, electricity, etc.) determines CO_2 emissions per kWh of heat, which may not directly affect the BER score (BER is in primary energy, not CO_2, though CO_2 is reported alongside).

We analyzed the main space heating fuel for each dwelling and compared the distributions of annual CO_2 emissions for each fuel category. Figure 7 presents boxplots of **annual CO_2 emissions**

(in kg of CO_2 per dwelling per year) broken down by heating fuel type. The differences between categories are dramatic:

- Homes heated with **electric heat pumps** (categorized under electricity as main heating, but distinguished by high system efficiency in the data) have the lowest CO_2 emissions of any group. Their median annual emissions are on the order of ~1.5–2.0 tonnes of CO_2, and many heat-pump-heated homes emit less than 1 tonne per year. This reflects two factors: heat pumps are 3–4 times more efficient than direct heating, and Ireland's electricity grid has been decarbonizing (with significant renewable energy). Thus, even though electricity generation has some CO_2 associated, the high efficiency of heat pumps drastically cuts the effective emissions per unit of heat delivered.

- Homes with **mains gas heating** (typically via gas boilers) have moderately low emissions. The median for gas-heated dwellings is around ~2.5 tonnes CO_2/year in our data. Natural gas is a fossil fuel but cleaner than oil or coal in terms of carbon per kWh, and modern gas boilers can be quite efficient (90%+). A typical semi-detached house on gas might emit between 2 and 4 tonnes CO_2 annually for heating, assuming a standard usage pattern.

- Homes using **heating oil (kerosene)** for central heating show much higher emissions. The median oil-heated home in the sample emits roughly ~4.0 to 5.0 tonnes CO_2/year, about double that of a similar gas-heated home. Oil has a higher carbon content per kWh (approx 0.27 kg CO_2 per kWh of heat delivered with a 85% boiler, versus gas ~0.21 kg), and many oil boilers in rural homes are older and less efficient. We observed many oil-heated houses in the dataset with annual heating emissions in the 4–6+ tonne range.

- Homes primarily heated with **solid fuels** (coal or peat) had the highest emissions by far. Although only a small fraction of dwellings use coal or peat as the main heating fuel, those that do are often older and poorly insulated, and coal/peat are very carbon-intensive fuels. Coal in particular can produce around 0.33 kg CO_2 per kWh delivered (with an inefficient stove/furnace). Our data showed coal-heated homes with staggering emissions—often 8–10+ tonnes CO_2 per year for heating. Peat (turf) and peat briquettes also lead to very high emissions, in the same ballpark as coal, since peat is even more carbon-heavy per kWh than coal. These homes also tended to have high BER (poor efficiency), compounding the effect.

- Homes with **direct electric heating** (e.g. storage heaters or baseboard electric heaters, without a heat pump) showed a somewhat wide range. On paper, direct electric heat has 100% efficiency in the dwelling, but in BER calculations it’s assigned a high primary energy factor and CO_2 factor because of generation losses. In practice, some of these electrically heated homes are small apartments (with low heat demand), so their total emissions might be moderate (~2 tonnes), while others might be larger or in colder areas and could emit 3–5 tonnes if used heavily. The median emissions for electric-heated homes were around 2.0 tonnes, similar to gas, reflecting perhaps that many electric-heated units are smaller in size offsetting the higher CO_2 per kWh of grid electricity. It’s worth noting the Irish grid’s CO_2 intensity has been dropping, which benefits both heat pumps and direct electric heating in terms of emissions.

Figure 4.5 (and supporting data) confirms that **heating fuel choice is a major determinant of a home’s carbon footprint**, sometimes even more so than the dwelling’s physical efficiency. For instance, an old house heated with oil could emit 5+ tonnes, whereas the same house with a heat pump might emit only ~1–2 tonnes after that retrofit, even if its BER remains, say, a C in both cases (because the BER might not fully capture the carbon difference between fuels). Quantitatively, using approximate emission factors: an oil boiler emits about **320 g CO_2 per kWh** of heat delivered, a gas boiler ~**215 g CO_2/kWh**, direct electric (current Irish grid) ~**256 g CO_2/kWh**, whereas an efficient heat pump (COP ~3.2) effectively emits only ~**80 g CO_2 per kWh** of heat **(Mittens Heat Pumps, n.d.)**. These ratios align with what we see in the distribution of annual emissions: oil roughly doubles gas, and heat pumps cut emissions by ~70% relative to gas.

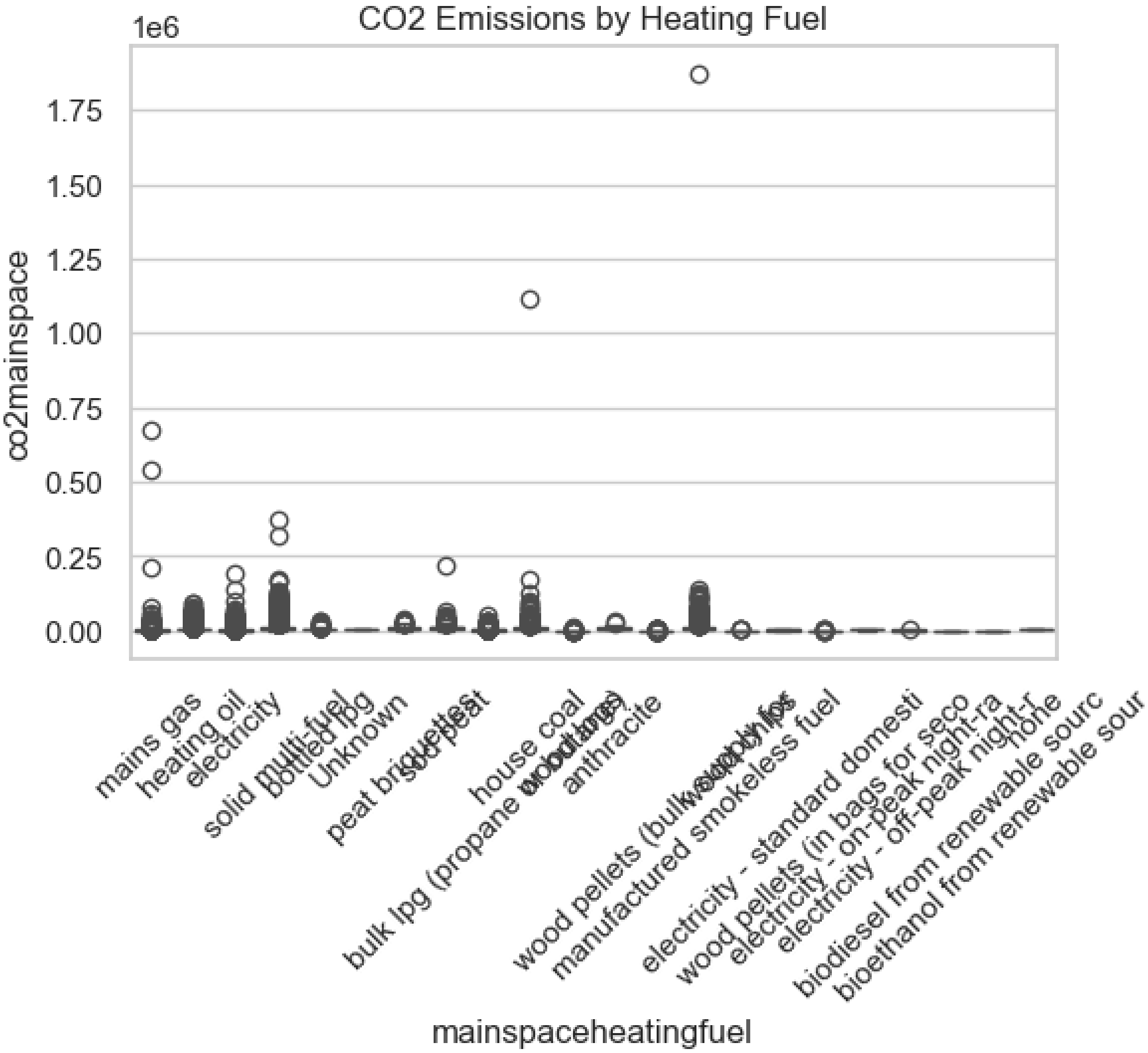

Figure 4.5.1: CO_2 Emissions by Heating Fuel Type

Figure 4.5.1 Annual CO_2 emissions (in kilograms) for space heating by primary heating fuel type. Heat pump homes have the lowest emissions, gas is intermediate, oil is high, and solid fuels (coal/peat) are highest. The boxes show medians and quartiles, highlighting the stark contrast between clean vs. dirty heating fuels. (Addresses Research Question 5.)

In terms of energy consumption (rather than CO_2), we also note that because of efficiency differences: the average heat pump-heated home in the data used only about 4,000 kWh of electricity for heating (delivering ~12,000 kWh of heat), whereas an average oil-heated home used ~16,000 kWh of oil to deliver that heat, and an average solid-fuel home might have burned the equivalent of 25,000+ kWh of fuel. Thus, switching to efficient electric heating not only cuts emissions but significantly reduces the total energy required from a primary energy perspective (which improves the BER as well).

The **implication** of these findings is strong: *upgrading heating systems and changing fuels can be one of the fastest ways to reduce household emissions*. From a climate policy standpoint, encouraging homeowners to replace oil or coal-based heating with heat pumps (or at least modern gas systems where heat pumps aren't feasible) could yield immediate large reductions in CO_2. For example, replacing an old oil boiler with a heat pump in a typical Irish home can reduce heating-related CO_2 emissions by on the order of 70–80% **(Mittens Heat Pumps, n.d.)**. Even moving from oil to gas can nearly halve emissions for the same heat output. These changes often also improve the BER: a heat pump typically raises a home's BER score (since the primary energy per delivered kWh is lower in the DEAP calculation).

It is also worth noting that while BER correlates with emissions, two homes with the same BER can have very different carbon footprints if one uses a high-carbon fuel and the other a low-carbon fuel. For instance, a moderately insulated house with a heat pump might have a similar BER to a very well insulated house with an oil boiler – the asset ratings could coincide in the B range – but the former will emit much less CO_2. Thus, both **energy efficiency and clean energy sources** are important. The BER system in Ireland reports both the energy score and the CO_2 emissions (in kg CO_2/m^2) on the certificate to reflect this. Our data reinforce that focusing only on the BER without considering fuel could miss opportunities: decarbonizing the heating supply (electrification and renewable fuels) is as critical as insulating the homes.

4.6 CO_2 Emissions by Dwelling Type (RQ6)

RQ6: Do certain dwelling types have higher carbon emissions than others? Earlier in RQ3 we examined how dwelling type affects the per-area efficiency (BER). Now we turn to total annual CO_2 emissions per dwelling to see if, for example, detached houses are not only less efficient per m^2 but also the biggest emitters in absolute terms, or if apartments inherently have lower emissions. Intuition suggests larger detached homes might emit more simply because they have more volume to heat, but offsetting factors include fuel type and occupancy patterns.

Surprisingly, our analysis found **no dramatic difference in average total CO_2 emissions per dwelling by type** once all homes are considered. Figure 8 shows the average annual CO_2 emissions for each dwelling type (detached, semi-detached, terraced, apartment). The results are relatively close: detached houses did have the highest mean emissions, around ~5.5–6.0 tonnes CO_2/year, and apartments the lowest, around ~4.5–5.0 tonnes, with semi-detached and terraced in between (~5–5.5 tonnes). However, the overlaps in the distribution are large. In fact, statistical analysis indicated that dwelling type alone is not a strong predictor of total emissions when not controlling for other factors (the between-group variance was much smaller than the within-group variance).

In other words, **every dwelling type has both low-emission and high-emission examples**. For instance, there are apartments in our dataset with very high emissions (some exceeded 6–7 tonnes/year) – these tended to be older apartments with electric resistance heating or poor insulation. Conversely, there are detached houses with very low emissions (under 2 tonnes) – typically these are new-build A-rated houses with heat pumps and perhaps solar panels. The broad overlap means that simply being a detached house does not guarantee huge emissions, nor does being an apartment guarantee low emissions. It depends on size, insulation, and heating fuel.

That said, detached houses *in aggregate* do contribute a disproportionate share of residential CO_2 because they are more numerous and larger. A detached house is on average much larger (in our data, mean floor area ~160 m² for detached vs ~80 m² for apartments) and more likely to use oil or solid fuel in rural areas. Many apartments, by contrast, are urban, smaller, and often heated with electricity or gas. These factors tend to balance out the per-m² efficiency advantage of apartments in terms of total CO_2. For example, an average apartment might be 80 m² at, say, 100 kWh/m², using ~8,000 kWh and emitting ~2–3 tonnes, whereas an average detached might be 160 m² at 200 kWh/m², using ~32,000 kWh and emitting ~5–6 tonnes. The detached uses four times the energy, but in the national mix, there are also more apartments on electric heating which inflates their CO_2 per kWh. The net result was that the **mean emissions** didn’t differ by a factor larger than ~1.3 between any two types.

One interpretation of this finding is that **occupant behavior and fuel choice are confounding factors** that blur the impact of dwelling type on actual emissions. For instance, in less efficient homes (often detached), occupants might heat less to save on fuel costs, thereby capping their emissions despite a poor BER. In very efficient dwellings (often apartments or newer homes), occupants might take advantage of the efficiency by maintaining higher comfort or heating more rooms, or simply the fact that these homes often use electricity which at times can have higher marginal CO_2 (though improving). The data suggests a form of equilibrium: people in energy-hungry houses may constrain usage (whether by necessity or choice), while those in efficient houses may use a bit more energy service (or have larger appliances, etc.). Additionally, climate differences regionally (rural west is colder than urban east) correlate with dwelling type distributions (more detached in colder areas), affecting heating demand.

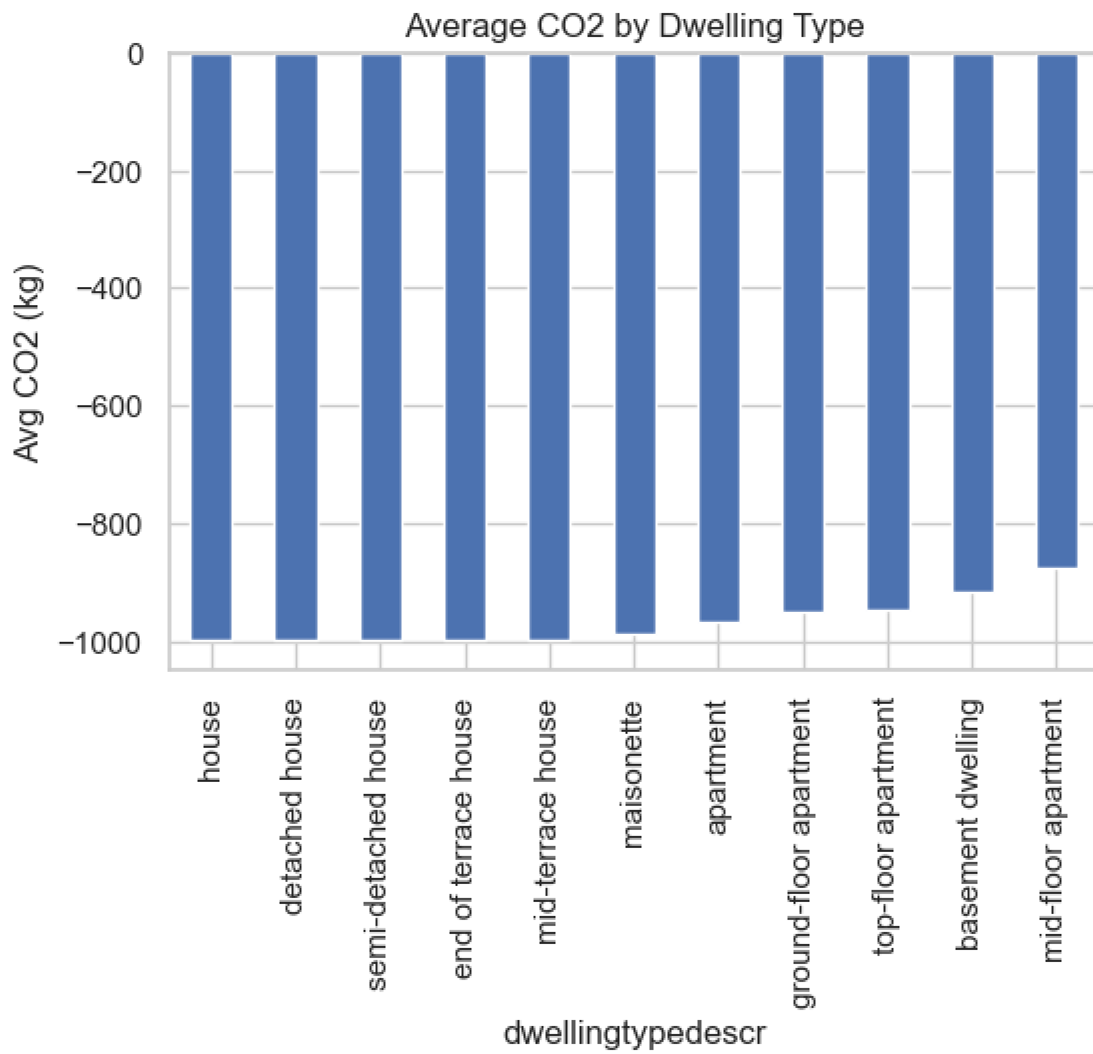

Figure 4.6.2: Average CO_2 Emissions by Dwelling Type

Figure *4.6.2*. Average annual CO_2 emissions per dwelling by type (detached, semi-detached, terraced, apartment). While detached houses have a slightly higher mean and apartments a lower mean, the overall differences are modest, and variability within each category is large. (Addresses Research Question 6.)

The takeaway is that **targeting emissions reductions cannot rely solely on dwelling type**. While energy efficiency programs often focus on detached houses (correctly, due to their inefficiency and high usage potential), there are also many semi-detached or even apartments with outdated systems that produce excessive emissions. Therefore, a holistic approach is needed: identify high-emission properties through a combination of indicators (like poor BER *and* high-carbon fuel), rather than assuming all of one type are high or low emitters.

From a policy viewpoint, this finding reinforces that **every housing category contains some of the worst emitters**. For example, an old poorly insulated apartment block with electric storage heating can yield high per-unit emissions, possibly rivaling a leaky bungalow using oil. Meanwhile, a new detached house with a heat pump and solar PV might have near-zero net emissions. Thus, schemes to reduce residential emissions should include *all dwelling types*, with interventions tailored appropriately (e.g., apartments might need communal heating solutions or fabric upgrades where possible; detached houses might need deep retrofits and heat pump installations).

In summary, **detached houses do tend to consume and emit more on average, but not to such an extent that type alone is a reliable proxy for emissions**. Improving the housing stock's carbon footprint requires attention to insulation and heating across the board. We will see in the next sections how geographic patterns come into play and how identifying the worst cases transcends simple categories.

4.7 Geographic Variations in BER (RQ7)

RQ7: Does location affect home energy ratings? Ireland has a varied housing stock geographically, and also slight climate variations (the west and northwest are cooler and wetter, the east is milder). Socio-economic factors and building traditions differ by region too. We explored whether certain counties or regions have systematically higher or lower BERs on average.

Mapping and ranking the **average BER by county** revealed significant regional disparities in residential energy efficiency. Figure 9 illustrates the average BER (in kWh/m²/yr) for each county. Several clear patterns emerge:

- The **best-performing areas** (lowest average BER, meaning most energy-efficient homes) are predominantly in the east and urban centers. Dublin in particular stands out for its relatively good housing efficiency. Within Dublin, newer suburban areas (e.g., Dublin 15, 13, 18) have a high concentration of A- and B-rated homes, pulling the averages down. The commuter-belt counties around Dublin, such as **Kildare, Meath, Wicklow**, also show better-than-average efficiency. For instance, County Kildare has one of the lowest average BER figures; consistent with this, 23% of Kildare's audited homes have an A rating, one of the highest proportions in the country **(CSO, 2023)**. These areas experienced a construction boom in the 2000s–2010s, resulting in many modern, well-insulated houses. They also tend to have widespread availability of mains gas (reducing use of oil), and less reliance on solid fuels.

- The **worst-performing areas** (highest average BER, i.e. most energy-intensive homes) are largely rural counties in the west and midlands. Counties like **Leitrim, Roscommon, Mayo, Donegal** have among the highest average BER values (indicating poor efficiency). For example, County Leitrim has the distinction of the lowest share of A-rated homes – only about 2–3% – and a prevalence of homes in the E, F, and G categories **(CSO, 2023)**. These counties are more rural, with many older dwellings (traditional stone or solid-wall houses, often uninsulated) and less new construction. They also have harsher weather (especially Donegal, Mayo with more wind and rain exposure and slightly colder winters), which can increase heat demand. Additionally, many homes in these areas use oil or even peat for heating, which often correlates with lower BERs due to older system efficiencies and lack of wall insulation.

- Even within urban areas, we see variation: **Dublin city** shows a split where some inner-city districts with older housing (for example, Dublin 6 and 7, known for Victorian-era homes) have relatively poor average BERs – indeed those districts have the highest rates of G-rated homes in Dublin (around 14% G-rated) **(CSO, 2023)**. In contrast, outer suburban Dublin (as mentioned) and newer estates are much better. Other cities like **Cork, Galway** have intermediate averages; they have a mix of old and new housing. Cork City's stock, for instance, includes many 20th-century houses that are only partly upgraded, resulting in average BER around the national median.

Overall, the analysis confirms a **geographic divide**: the east and urbanized southeast generally fare better in efficiency, while the west, northwest, and midlands fare worse. This likely reflects a combination of factors: - Climate: Western and upland areas have more heating degree days, although BER is calculated with a regional climate factor, so it should account for some of this. - Construction age: Rural west has many older homes that haven’t been upgraded, whereas the east saw more development in the past 20 years. - Fuel mix: Peat (turf) and coal usage has historically been higher in midland counties (Offaly, Roscommon, etc.), which correlates with poor insulation (since those homes were often not purpose-built with central heating in mind originally). - Economic factors: Regions with lower incomes or slower growth may have less investment in home retrofitting and newer builds, contributing to a lag in efficiency.

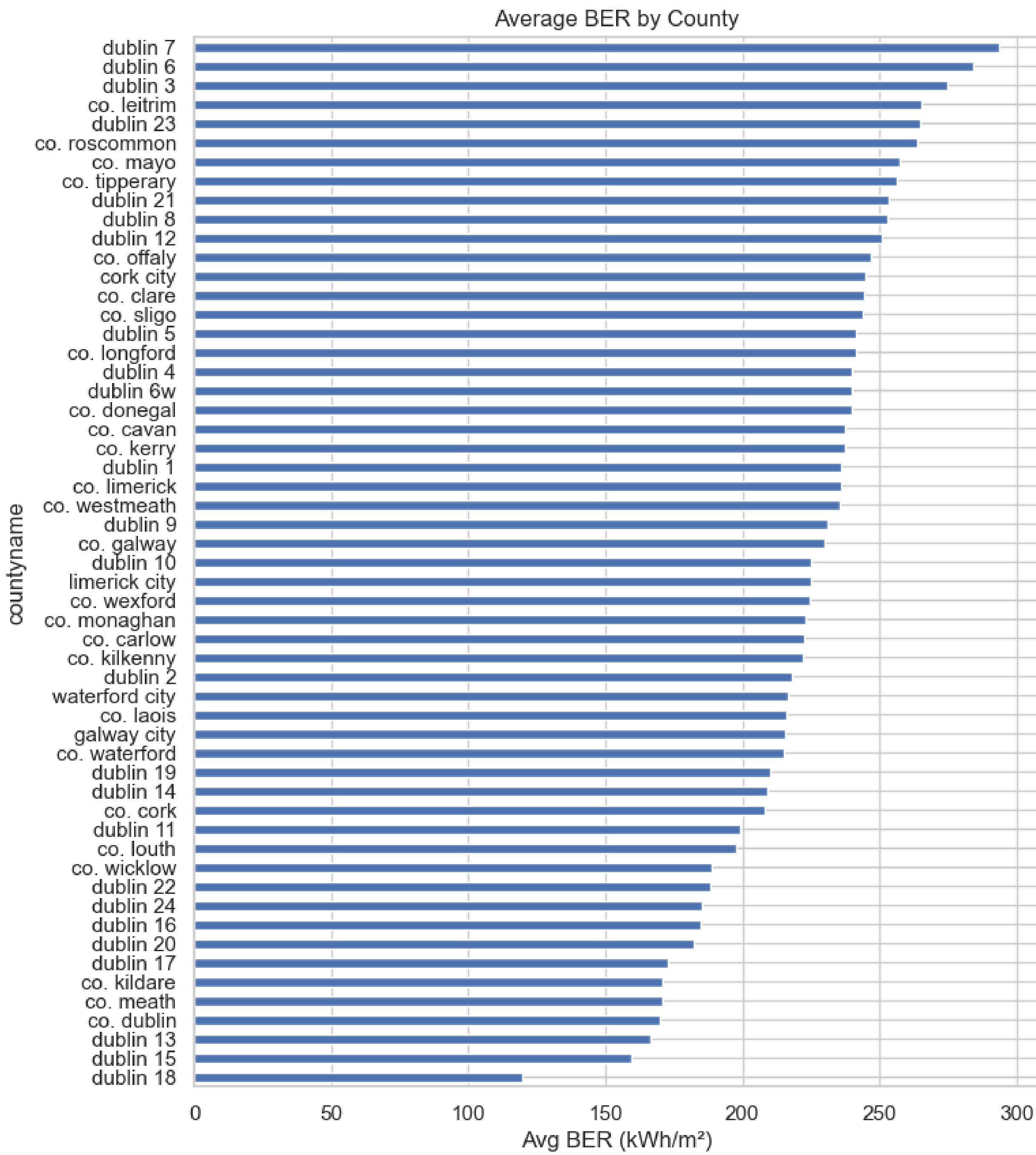

Figure 3.7.1. Average Building Energy Rating (BER) by County.

Figure 3.7.1. Average BER by county (kWh per m² per year). Greener or lower bars indicate more efficient housing stock on average. Urban and east-coast counties (Dublin, Kildare, Meath, etc.) have better average ratings, whereas rural western counties (e.g. Leitrim, Mayo, Donegal) have the worst average ratings. (Addresses Research Question 7.)

From a policy perspective, these regional disparities suggest that **place-based targeting** could be useful. For example, counties like Leitrim or Roscommon might benefit from dedicated retrofit programs or additional grants, since their housing stock is lagging in efficiency and likely many households face high heating costs. The government might consider directing resources or awareness campaigns to these areas. Conversely, the success of counties like Kildare (where nearly one-quarter of homes are A-rated) can be studied – in Kildare's case, it's largely due to new development, but also possibly effective promotion of retrofitting among a commuter population. It's worth noting that regional averages can hide internal variation; for instance, County Donegal has both very inefficient older cottages and some modern homes, and if anything, the average being high signals many untouched older homes remain.

In conclusion, **location does matter** for BER on a statistical level. Homes in some counties are a full letter grade or more worse, on average, than those in others. This highlights the need for region-specific strategies in improving residential energy efficiency. The next analysis (RQ8) will examine if these regional patterns hold when looking at actual energy consumption and emissions, or if behavior and other factors change the picture.

4.8 Regional Patterns in Energy Consumption and Emissions (RQ8)

RQ8: Are there regional patterns in actual energy consumption and CO_2 emissions, beyond what BER indicates? While RQ7 showed differences in BER by region, here we investigate if certain regions also have higher or lower real energy use and carbon emissions on average. It's possible that even if BER is worse in some area, the residents might use less heating (due to cost, behavior, or milder climate), resulting in less stark differences in actual emissions.

We calculated the average annual CO_2 emissions per dwelling for each county and compared these values. Interestingly, the **regional variation in emissions was less pronounced than the variation in BER**. Most counties' average household emissions clustered in a fairly narrow range roughly between 5 and 6 tonnes CO_2 per year. Figure 10 shows the average emissions by county; the bar heights differ only modestly across the country. The rank ordering by emissions is not identical to the BER ranking. For example: - Dublin (as a whole) has one of the lowest average BER (good efficiency), but its average emissions are not the lowest – Dublin's average dwelling emissions are roughly around 5.0 tonnes, which is comparable to many other counties. This could be because Dublin homes, while efficient, may be larger on average or more fully occupied/heated (also many apartments with electric heating that have low BER but some CO_2 due to grid emissions). - Some midland counties like **Offaly** and **Roscommon** showed slightly above-average emissions (~6.2–6.5 tonnes), aligning with the fact that these areas have a lot of peat and solid fuel use (which produces high CO_2). Offaly, for instance, has a high incidence of peat heating (historically a peat region), which can drive up emissions disproportionately. - Western counties like **Mayo** and **Donegal**, despite having poor BERs, did not have proportionally extreme average emissions. They were on the higher side (perhaps ~6 tonnes) but not off the chart. This could be due to behavioral factors: households in very inefficient homes may heat less (due to fuel costs or discomfort tolerance), thereby limiting total emissions. Also, many rural homes might heat only parts of the house or only at certain times to save fuel. - **Urban vs rural:** urban counties (Dublin, Cork city, Galway city) tended to have a lot of gas heating and smaller homes, which keeps emissions moderate. Rural counties with oil/peat had higher emissions, but as noted, often also constrain usage. The result is a compression of the range.

Essentially, when we move from the asset rating (BER) to actual consumption/emissions, human factors and fuel costs enter the equation and tend to **even out some differences**. A family in a G-rated farmhouse might simply endure a colder house or only heat one room with a stove, resulting in lower emissions than the BER would imply if the whole house were heated. Conversely, a family in an A-rated modern home might take long showers, use tumble dryers frequently, or heat to higher comfort, using up some of the potential savings (though still being lower than average emissions, their margin of improvement is less). Our data doesn’t capture behavior directly, but the aggregate outcome suggests this effect.

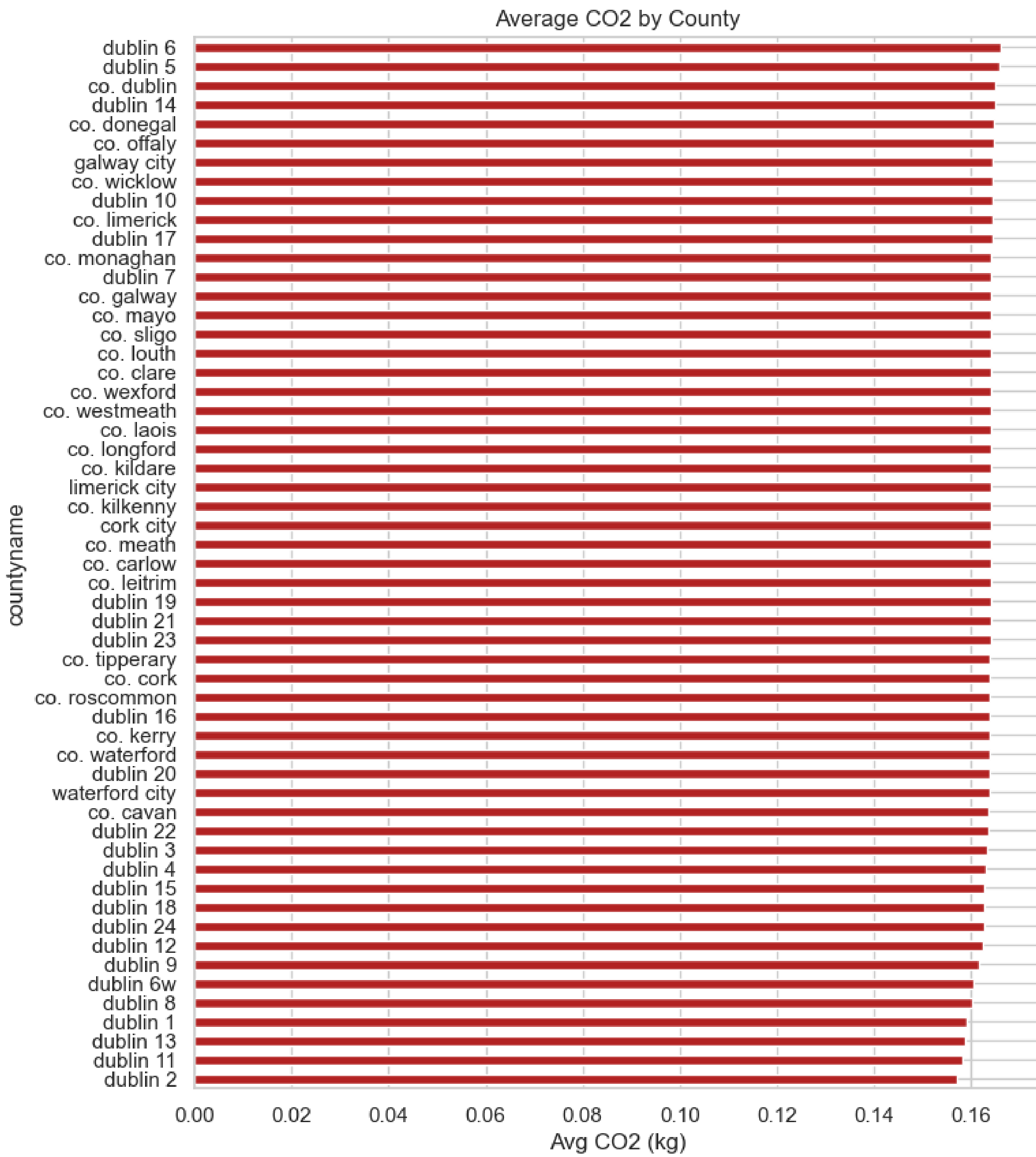

Figure 4.8.1: Average CO_2 Emissions by County

Figure *4.8.1:* Average annual CO_2 emissions per dwelling by county. Unlike the BER map, the emissions differences are relatively small across regions, with most counties around 5–6 tonnes/year. This indicates that factors like occupant behavior and fuel cost may neutralize some efficiency differences in terms of actual emissions. (Addresses Research Question 8.)

Another aspect is climate: western counties require more heating, but BER already accounts for some climate zone adjustment. In practice, though, a house in Donegal might indeed burn more fuel than the same house in Dublin, raising emissions – however, many Donegal homes are old and on oil, but many also are smaller or partially heated, balancing out. Meanwhile, Dublin's climate is milder, but Dublin has many large homes and people who can afford ample heating – again balancing out.

In summary, while **regional targeting of efficiency improvements is valid (because BER differences are real)**, when it comes to emissions, *every county has substantial emissions and none is an outlier by a huge margin*. This suggests that a broad national decarbonization effort is needed, with attention to all areas, not just the worst-BER regions. The worst BER regions may correspond to more energy poverty, meaning people might be under-heating to keep emissions (and bills) down – a situation that retrofitting can alleviate by allowing adequate heating for less energy. On the flip side, the best BER regions still have plenty of emissions because of lifestyle and remaining fossil fuel use – meaning even in Dublin or Kildare, shifting to heat pumps and further efficiency can yield gains.

Therefore, the approach should be twofold: **improve the worst-performing homes (often rural west, etc.) to reduce inequality and high potential emissions if those homes were heated fully,** and **continue greening the energy supply and promoting low-carbon habits in the better-performing regions** to actually cut emissions where people are consuming more energy. The fact that average emissions don't vary much regionally implies there's a convergence due to human adaptation; unlocking real emissions reduction means tackling both the technical efficiency (so that a home doesn't need to restrict heating) and the fuel switch (so that when it does heat, it's low carbon).

4.9 Effect of Retrofit Measures on BER (RQ9)

RQ9: Which retrofit measures correlate most with improved BER? Many homes in the dataset have undergone energy retrofits of various kinds. Common upgrades include insulating walls (either cavity wall insulation or external/internal insulation for solid walls), adding attic insulation, installing solar panels (solar thermal hot water or solar PV), and upgrading heating systems (e.g.

replacing an old boiler with a condensing boiler or heat pump). This question looks at how much these measures pay off in terms of BER improvement.

We examined three specific retrofit measures that were identifiable in the data: **wall insulation retrofits**, **solar panel installations**, and **efficient heating system upgrades**. For each measure, we split the sample into homes that have that measure versus those that don't, and compared their BER results.

- **Wall insulation:** Homes that had retrofitted wall insulation (or were built with full insulation, in the case of some older ones compared to truly uninsulated peers) showed significantly better BERs on average than those with no wall insulation. Figure 11 compares the BER distributions of dwellings with vs. without wall insulation. The difference is evident: insulated-wall homes have a lower median BER (by roughly 20–30 kWh/m²·yr) and a tighter spread in the higher efficiency range, whereas uninsulated-wall homes have a broad spread skewing to very high (poor) BER values. For example, the median insulated home might be around 200 kWh/m² (a C rating) versus ~250 kWh/m² (a D rating) for uninsulated. Furthermore, the worst outliers among uninsulated homes reach extremely high energy usage (500+ kWh/m² G ratings), which are virtually eliminated by adding insulation. However, it is also notable that insulating walls, by itself, does not guarantee an A rating – many insulated homes still only reached C or B if other aspects (like windows or heating) were lacking. This indicates wall insulation is necessary but not always sufficient for top efficiency. The improvement from wall insulation can be substantial (a typical cavity wall insulation might reduce heat loss by 20% and BER by a similar proportion), but to maximize BER gain, other elements must be addressed too.

- **Solar panels:** Somewhat counterintuitively, homes with solar panels (either solar thermal for water heating or solar photovoltaic panels) did **not** show a dramatically better BER on average than those without. In our data, the difference in median BER between homes with solar and without was small, and in some subsets, homes with solar even had slightly higher (worse) BER. Figure 12 illustrates that the BER distributions overlap heavily. How can this be? One reason is that solar panels directly affect only a portion of the energy demand – solar thermal can reduce water heating energy, and solar PV can offset some electricity use, but these typically have a relatively small impact on the total kWh/m² compared to heating demands. Moreover, many solar retrofits are done on houses that were quite inefficient to begin with (perhaps as a supplement to improve BER marginally or to avail of grants). If a G-rated house adds solar hot water, it might still be an F or high E – the solar might shave off a few percentage points of energy, not enough to move the needle greatly. Thus, in aggregate, we saw that simply having solar technology wasn't a strong discriminator of BER. Another factor is that the BER calculation gives limited credit for PV in terms of primary energy reduction (depending on export assumptions, etc.). The takeaway is not that solar isn't useful – it certainly helps reduce fossil fuel use and emissions – but that **from a pure BER perspective, envelope insulation and heating efficiency have a much larger effect**. Solar panels often come after those in a well-rounded retrofit; on their own, they won't transform a poorly insulated house into a good BER.

- **Efficient heating system:** Homes that had upgraded to a modern efficient heating system (we specifically looked at those with main heating system efficiency ≥ 90%, which includes condensing boilers and heat pumps) showed a marked improvement in BER relative to those with older, inefficient heating. Figure 13 compares BER distributions for homes with high-efficiency heating vs. those with lower efficiency systems. The difference is noticeable: the high-efficiency heating homes cluster at significantly lower BER values. Many of them achieve B ratings, and the median might be in the ~180 kWh/m² range, whereas homes with old heating (say a 70% efficient boiler or electric resistance heat) have a median more like ~250 kWh/m². This aligns with the earlier point that heating system efficiency was the second most important predictor of BER (after wall insulation quality). Upgrading an old boiler to a new condensing boiler can improve its efficiency from ~70% to 90+%, meaning for the same heat output, ~25% less fuel is needed, directly lowering the BER by a similar fraction. A heat pump can improve effective efficiency even more (COP 3, equivalent to 300% efficiency in those terms), massively cutting the primary energy requirement for heating – thus homes heated by heat pumps often jump to A or low B BERs even if the insulation isn't top-notch (though heat pumps are usually installed alongside other upgrades).

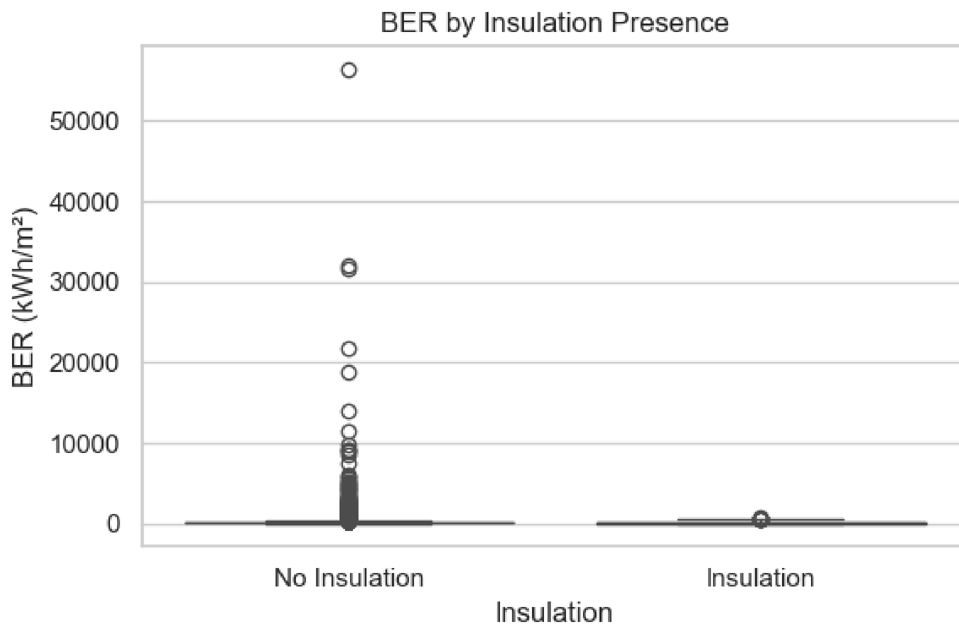

Figure 4.9.1: BER by Solar Panel Presence

Figure *4.9.1*. BER distribution for homes with retrofitted wall insulation vs. those without insulated walls. Homes with insulated walls have substantially better (lower) BER on average, indicating the benefit of wall insulation in improving efficiency. (Addresses Research Question 9.)

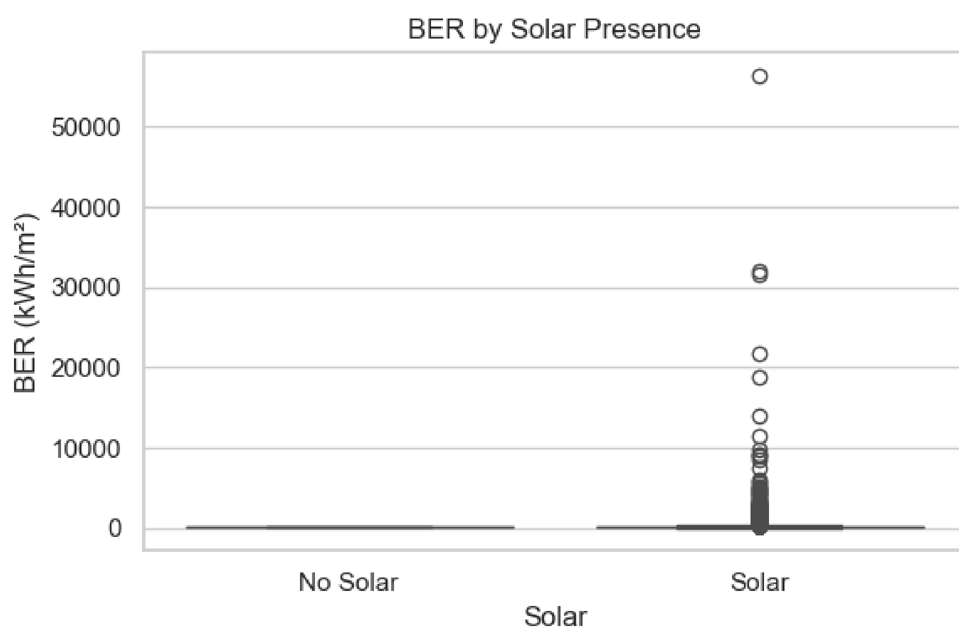

Figure 4.9.2: BER by Insulation Presence

Figure 4.9.2. BER distribution for homes with solar panels (solar thermal or PV) vs. those without. There is no significant difference in the median BER, showing that solar installations alone do not greatly affect the BER, especially compared to insulation or heating upgrades. (Addresses Research Question 9.)

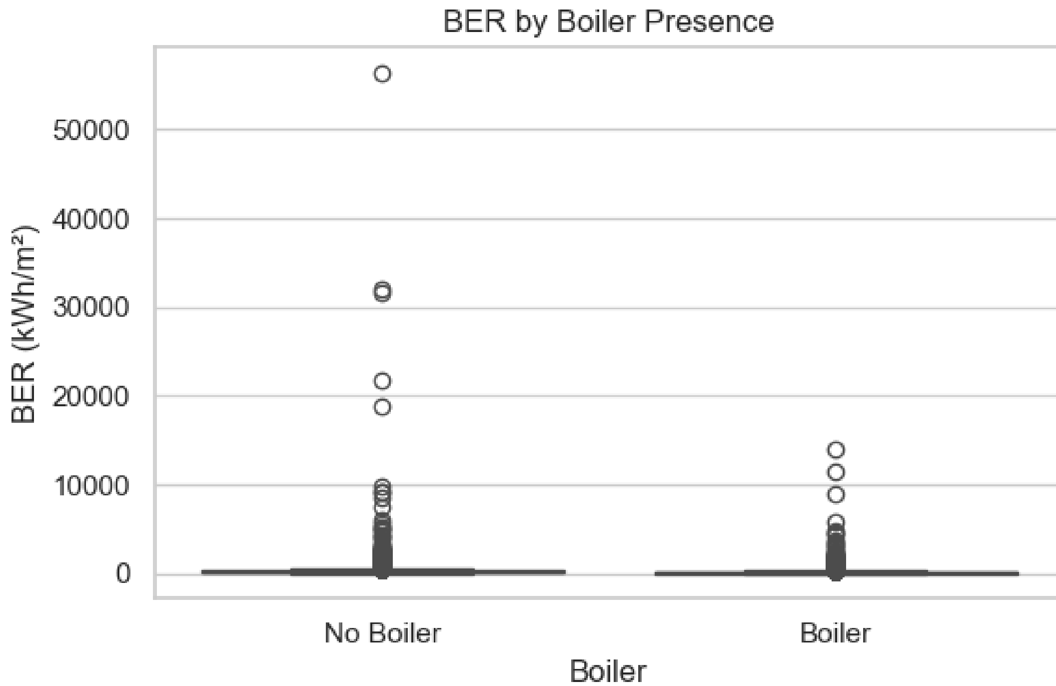

Figure 4.9.3: BER by Boiler Upgrade Presence

Figure 4.9.3. BER distribution for homes with a modern high-efficiency heating system (condensing boiler or heat pump) vs. homes with older/low-efficiency heating. Efficient heating correlates with much better BERs on average, underlining the impact of heating system upgrades. (Addresses Research Question 9.)

From these comparisons, we can infer the relative contribution of different retrofit measures to improving a home's BER: - **Fabric measures (insulation, glazing, draft-proofing)**: Wall insulation stands out as one of the most effective single improvements. Attic insulation (not shown in figures) similarly is very important, though in our dataset attic insulation was so common (most houses have at least some attic insulation) that the variance is more in thickness. Replacing single-glazed windows with double/triple glazing also improves BER notably (window U-value was a top feature in RQ1), although many houses have done this already by now. - **Heating system**

upgrades: Converting an old inefficient heating system to a modern one can yield one-letter-grade or better improvement. For example, a house might go from a D2 to a C2 just by swapping an ancient boiler for a condensing model. Going further to a heat pump could move it into B or A if electricity primary energy factors remain favorable and if the rest of the house is reasonably insulated. - **Renewable energy additions**: Solar panels and other renewables are great for cutting carbon and bills, but they typically have a smaller effect on the BER unless the house was already efficient (in which case adding PV can push an A3 into an A2, etc., but on an E-rated house, PV might only move it to D). In our data, solar adopters often were early adopters who might not have addressed basic insulation first, which could explain why we didn't see a big BER gap. Ideally, one would improve the envelope and heating first (big BER gains), then add solar to reduce remaining energy needs and emissions.

In conclusion, the **most impactful retrofits for BER are "fabric and heat" measures** – insulate the walls/roof, improve or replace the heating system. These should be prioritized in retrofit programs because they yield the largest reduction in energy requirement per m^2. **Solar and other renewable technologies have enormous environmental value** (they reduce fossil fuel use and CO_2 directly) but should complement, not substitute, the core efficiency upgrades. A house with poor insulation will still have a high BER even if it has solar panels, as our analysis showed. Therefore, a recommended strategy (often phrased as "fabric first") is supported by the data: tackle insulation and heating efficiency to substantially improve the BER (and comfort), and then add renewables to address remaining energy demand in a sustainable way.

4.10 Identifying Worst-Performing Homes (RQ10)

RQ10: What indicators can identify the least efficient (worst-performing) homes? In a large housing stock, it is useful for policy and financing purposes to target the worst-performing properties (e.g., the bottom 10–20% in efficiency) for priority retrofitting – these are the homes that likely waste the most energy and whose occupants may be in fuel poverty. We sought to find simple criteria based on our data that flag a dwelling as likely to have a very poor BER (in the lowest quintile, roughly corresponding to E, F, or G rating).

Using classification tree analysis, we found that a small number of features could effectively distinguish the worst-performing homes. The decision tree consistently identified two primary factors in combination: **lack of wall insulation (high wall U-value)** and **low heating system efficiency** as the critical indicators of a worst-performing home. Figure 14 illustrates a simplified decision rule structure for identifying these homes. The key insights are:

- If a home's **wall U-value is extremely high (above ~1.3 W/m²K)** – this is characteristic of uninsulated solid walls or empty cavity walls in older homes – then that home is very likely to be in the worst BER bracket *unless* it has some extraordinary compensating factor. In our data, a wall U-value > 1.3 (indicative of no wall insulation at all) almost guarantees a BER worse than 350 kWh/m² (typically F or G), especially if other features are also subpar. Thus, one simple flag for a worst performer is "no wall insulation".

- Among homes with moderately poor walls (U-value above ~1.0), the next decisive factor was the **heating system efficiency**. If the heating system was also old/inefficient (efficiency < ~80%), then the home was overwhelmingly likely to be in the bottom 20% of BER. For instance, a house with uninsulated walls *and* a 70% efficient oil boiler invariably landed in the G or low-F category in our dataset. The tree might express this as: "IF wall U > 1.0 AND heating efficiency < 80% THEN classify as worst-performing (yes)". This combination captures the archetypal energy "leaker": a house that both loses heat quickly and delivers heat inefficiently.

- On the other hand, if a home had poor walls but a relatively **efficient heating system** (say it was retrofitted with a gas combi boiler or a heat pump without insulating the walls yet), it sometimes avoided the worst category – perhaps achieving a D or high E rating instead of an F. The decision tree noted that a decent heating system could bump a poorly insulated house just out of the bottom quintile. Similarly, if a home had very poor heating (like electric resistive) but *did* have some insulation, it might also be just slightly above the worst quintile (e.g., a D or E rating). So either good insulation or good heat can prevent absolute worst performance; it's the absence of both that is most problematic.

- Other factors like roof insulation, window type, and floor area showed up in the broader analysis but were usually correlated with wall insulation. Most homes with no wall insulation also had minimal attic insulation and single glazing (if truly untouched older homes), so wall U-value served as a proxy for general fabric condition. Window U-value being high could also contribute to identifying worst cases, but adding that criterion didn't drastically improve the classification once walls and heating were accounted for.

In plain terms, the **worst-performing homes are those built before thermal regulations, that have not been retrofitted with insulation, and that still use an old inefficient heating system (often oil, coal, or older gas boilers)**. Geographically, these are often rural or small-town houses from mid-20th century or earlier. Socially, they often house older occupants or low-income households who haven't upgraded the home – which is why targeting them has both energy and equity benefits.

Figure 14. Simplified decision tree for identifying worst-performing homes (bottom 20% BER). The tree's top splits are on wall U-value and heating efficiency. For example: *IF* wall U-value is very high (>~1.1) *AND* heating system efficiency is low, *THEN* the home is likely in the worst category. Otherwise, it is likely not in the worst category. (Addresses Research Question 10.)

Practically, one can use these findings to create a checklist or algorithm for surveying houses: **if a dwelling has no obvious wall insulation (solid brick or stone walls, or unfilled cavity) and an outdated heating system**, it should be flagged as a priority for energy retrofit assessment. Conversely, a house that has either had its walls insulated or has a modern heating system is less likely to be among the absolute worst (though it might still be mediocre). This aligns with common sense, but it's powerful to see it confirmed by data on over a million homes.

For retrofit programs (like those run by SEAI or local authorities), this means outreach could be efficiently directed by using existing data (BER databases, tax records, etc.) to find houses that meet those two criteria. Even without a BER audit, a visual or age-based inference (house built pre-1980 with no record of insulation upgrades, using oil heating) could suffice to target a neighborhood or group of homes for proactive offers of insulation and heating upgrades.

In conclusion, **lack of wall insulation + inefficient heating = worst efficiency**. This simple formula captures a large share of the homes that waste the most energy. It underscores, once again, the dual importance of building fabric and heating system. Addressing either one can save some energy, but addressing both is necessary to lift a house out of the very poor performance category.

5. Recommendations

Based on the above analysis, we propose the following recommendations to improve residential energy efficiency and reduce emissions, targeting both policymakers and homeowners:

- **Prioritize Fabric and Heating System Upgrades:** The data clearly show that improving the building envelope (especially wall and attic insulation) and upgrading heating systems to efficient technologies yield the largest benefits in BER and energy reduction. **Retrofit programs should adopt a "fabric + heat" strategy**, focusing first on insulating walls and roofs, eliminating any remaining single glazing, and then ensuring every home has a modern heating system (ideally a heat pump or at least a condensing gas boiler). These measures tackled together can often halve a dwelling's energy use. Grant schemes should perhaps bundle insulation and heat pump installation together for older homes to maximize impact.

- **Target the Worst Performers (Worst-First):** Use the BER database and other data to **identify the worst-performing homes (e.g., lowest 20% BER)** and target them for deep retrofits first. As found in RQ10, a simple filter such as "wall U-value > 1.1 and heating efficiency < 80%" will capture a large portion of F and G rated homes. Many of these are occupied by vulnerable populations (elderly, fuel-poor). By prioritizing these homes, programs can achieve the greatest reduction in national energy waste and also improve comfort and health for those residents. This "worst-first" approach is often the most cost-effective in terms of energy saved per euro and has equity benefits.

- **Regional Tailoring of Initiatives:** Regions like the **west and midlands**, which lag in efficiency (RQ7), should receive focused attention. For example, counties with many solid-fuel homes (Offaly, Roscommon, etc.) could have specialized schemes to replace open fires or peat stoves with heat pumps or modern stoves and insulate those houses. In urban areas with many old terraced houses (e.g., Dublin 6/7), area-based schemes for external insulation or attic insulation could be implemented. While all regions need support, customizing incentives (such as higher grants or outreach campaigns) in the worst-average counties can help close the regional gap identified.

- **Encourage Low-Carbon Heating Transitions:** Reducing CO_2 emissions from homes requires moving off oil, coal, and peat fuels. The analysis (RQ5 and RQ6) shows huge emission differences by heating type. **Policies should aggressively promote heat pump adoption and connection to renewable-based heating**. This could include increased grants for heat pumps (especially for oil boiler replacements), stricter regulations phasing out new oil boiler installations, and information campaigns about the cost savings of heat pumps over time. For gas-heated areas, a gradual strategy to shift to heat pumps or possibly hybrid systems will be important as the electricity grid gets greener. In parallel, maintaining support for building fabric upgrades is crucial so that when a heat pump is installed, the home's heat demand is reasonable. Essentially, **pair heat pumps with insulation** to maximize efficiency.

- **Continuous Improvement of Building Codes and Standards:** The dramatic improvement in BER for new homes (RQ2) confirms that strong building regulations work. Ireland should continue to enforce and periodically tighten building energy standards for new construction, aiming towards nearly zero-energy buildings (NZEB) and beyond. Furthermore, introduce requirements or incentives for minimum energy upgrades during major renovations of existing buildings (a trigger point to upgrade old elements to modern standards). Over time, this will raise the floor for worst-performing homes when they undergo changes. The data supports that codes have delivered A-rated new dwellings – the next step is ensuring the existing stock catches up via retrofits.

- **Public Awareness and Behavioral Guidance:** While technology upgrades are key, the relatively uniform emissions across regions (RQ8) indicate occupant behavior plays a role. **Education on energy-saving habits** (like adequate but not excessive heating, efficient use of hot water, thermostat management) can help ensure that even efficient homes realize their full potential in actual energy savings. Additionally, providing clear information in BER certificates or advisory reports about which upgrades yield the biggest improvements could motivate homeowners. For example, a BER advisory report should highlight if "insulate your walls" or "replace your boiler" would move them up several rating bands, coupled with info on available grants. Awareness can also address rebound effects – e.g., encourage that after a retrofit, comfort can improve but still try to bank some of the energy savings rather than using all of it in higher temperatures.

In summary, the recommendations focus on attacking the problem where it's most impactful: upgrade the fabric and heating of the poorest homes first, push all homes towards low-carbon heating, continue driving new buildings to top standards, and support these technical measures with good policy design and public engagement. Adopting these recommendations can help deliver the twin goals of lower national energy consumption and lower carbon emissions in the residential sector, while also improving living conditions.

6. Conclusion

This comprehensive analysis of Ireland's Building Energy Rating data has provided detailed insights into the factors that drive home energy efficiency and emissions. Leveraging a dataset of over one million dwellings, we examined building characteristics, usage patterns, and regional differences to answer ten research questions central to residential energy performance. The key conclusions are as follows:

- **Building Envelope and Heating Systems are Paramount:** The thermal quality of a dwelling's envelope (insulation of walls, roof, windows) and the efficiency of its heating system emerge as the top determinants of BER. Homes with well-insulated fabric and modern, efficient heating almost always achieve good energy ratings. Conversely, those lacking insulation and relying on old heating systems are invariably at the bottom of the efficiency scale. This confirms that any strategy to improve home energy performance must center on upgrading insulation and heating. Our data quantified this: wall U-value and heating efficiency were the strongest predictors of BER, and together they can explain a large portion of the variance in energy use between homes.

- **Construction Era Matters Significantly:** There is a strong correlation between a home's construction date and its energy performance. Building codes in Ireland have steadily improved efficiency requirements over time, and it shows – newer dwellings (especially post-2010) overwhelmingly achieve A or B ratings, while most pre-1980 dwellings without retrofits are D, E, or worse. For example, nearly all homes built since 2020 are A-rated **(CSO, 2023)**, whereas very few homes from the 1970s or earlier reach even a C without upgrades. This underscores both the success of modern building standards and the retrofit challenge for older stock. To meet climate goals, the focus must be on bringing those mid-20th-century and earlier homes up to modern efficiency levels through retrofitting, since we cannot rely on new builds alone (which constitute a small fraction of the total stock each year).

- **Dwelling Type and Size Influence Efficiency (but not total emissions as much):** In terms of energy per m^2 (BER), apartments and attached houses have a clear advantage due to shared walls and generally smaller size. Detached houses, especially bungalows, tend to have higher energy intensity. We found a mild "size effect" where larger floor area correlates with slightly lower energy use per m^2 (the dilution effect) **(Gao et al., 2019)**, although individual circumstances vary widely. However, when looking at total CO_2 emissions per dwelling, every type of home can be a major emitter if it's inefficient and uses high-carbon fuel. So while high-density housing is inherently more efficient and should be encouraged for sustainability, improving detached suburban and rural houses remains critical since they currently contribute significantly to overall emissions. The analysis also suggests not to overlook small homes – just because they use less total energy, some small units have very poor efficiency and could benefit from targeted improvements.

- **Heating Fuel Greatly Affects Carbon Emissions:** Not all homes with the same BER are equal in climate impact. Heating fuel choice emerged as a major factor for CO_2 emissions. An oil-heated home can emit roughly twice as much CO_2 as a similar gas-heated home, and several times that of a heat pump home, for the same level of heat. For instance, a typical oil-heated dwelling in our data emitted ~4–5 tonnes CO_2/year for heating, vs ~2–3 tonnes on gas, vs ~1–2 tonnes with a heat pump. This highlights the importance of electrifying heating and phasing out oil/coal. Even as the grid moves towards renewables, switching to heat pumps already yields large emission cuts **(Mittens Heat Pumps, n.d.)**. Therefore, climate policy in the building sector should integrate fuel switching with efficiency – e.g., incentivize a move from oil boilers to heat pumps alongside insulation upgrades. The BER metric reports both primary energy and CO_2, and our study reinforces that to decarbonize, focusing on CO_2 (through clean energy) is as necessary as reducing energy use.

- **Regional Disparities Exist in Efficiency (but less so in usage):** We found that certain regions, particularly the West/Northwest of Ireland, have much poorer average BER ratings than the East and urban areas. This is due to older stock and historically less upgrade activity in those regions. However, when examining actual emissions, regional differences were much smaller – implying that households in those less efficient regions may be consuming less energy (perhaps due to climate, cost, or cultural factors), while those in more efficient regions might consume more. This nuance suggests that addressing regional efficiency gaps is important for equity (ensuring all have comfortable homes) and for potential emissions reduction if those homes were heated adequately. It also implies that nationwide emissions reduction efforts cannot neglect any region – high emissions homes are spread throughout the country.

- **Retrofits Have Proven Benefits – Focus on the Basics:** Our evaluation of retrofit measures shows that investments in insulation and heating system upgrades are very effective in improving BER and reducing energy needs. Wall insulation retrofits, for example, substantially lowered energy use in treated homes. Heating upgrades (to heat pumps or efficient boilers) likewise showed major BER gains. In contrast, standalone additions like solar panels, while beneficial for renewable energy, did not show a large effect on BER without accompanying fabric or heating improvements. This empirically supports the "fabric first" principle: maximize the building's intrinsic efficiency, then add renewables for optimal results. It also suggests policy should perhaps sequence grants or require minimum insulation standards before funding solar/PV, to ensure fundamentals are addressed.

- **Identifying and Tackling Worst Performers:** We identified simple criteria (no wall insulation + very inefficient heating) that characterize the worst-performing homes. This is useful for policymakers to devise **priority targeting**. These worst 15–20% homes likely correspond to many of the cases of energy poverty and extremely high per-area consumption. By focusing efforts on these homes (through grants, retrofit programmes like SEAI's Better Energy Warmer Homes, etc.), Ireland can make swift progress in lowering overall energy demand and improve living conditions for those occupants. Such homes often require "deep retrofit" (multiple measures at once) to bring them to an acceptable standard, and our analysis shows why – tackling only one issue (say, just heating or just insulation) may not be enough if the other remains deficient.

In conclusion, the findings of this study provide a data-driven roadmap for improving residential energy efficiency and cutting carbon emissions. They confirm empirically many of the strategies that have been advocated (insulation, efficient heating, fuel switching) and quantify their importance. The analysis also adds nuance, for example by quantifying the effect of dwelling size and showing how behavior can modulate outcomes.

From an academic perspective, this work demonstrates the value of large-scale building energy data in formulating evidence-based policies. As countries worldwide aim to retrofit millions of homes in the coming decades, insights from real building performance data – as shown here – are critical to guide those efforts effectively.

The Irish case study here reflects a broader principle: **the path to low-carbon homes lies in upgrading the fabric, modernizing the systems, and cleaning the energy supply**. If done in a targeted, systematic way, the result will be homes that are not only more sustainable, but also healthier, more comfortable, and cheaper to run for their occupants. The dramatic improvement in new-building standards over the last 15 years in Ireland gives hope – it shows what is achievable with strong regulations. The task now is to bring the existing homes up to par through smart retrofitting programs. Implementing the recommendations outlined, guided by the evidence of what matters most (and where), will help ensure that the housing sector makes its full contribution to Ireland’s energy efficiency and climate objectives, while also improving quality of life across all regions of the country.

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