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C66

R1-C1 Residential Retrofitting: Integrated Building Performance Evaluation

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ABSTRACT

In the current global scenario, there exists a significant surge in the pursuit of retrofitting endeavors within residential infrastructure, driven by the essential need to mitigate carbon emissions at a national level. A critical aspect within this retrofitting context involves substituting conventional heating systems with the electrification of heat, particularly through the adoption of heat pump technologies. The primary objective of this study is to analyze the retrofitted residential built form from energy, carbon, and thermal comfort perspectives, providing an overview of the renovated built form. Moreover, particular emphasis will be placed on the operational phase, with a focus on improving thermal comfort and reducing carbon emissions based on monitored indoor parameters. In this study, a deeply retrofitted dwelling from the pre-1978 period, upgraded to achieve an A2 BER rating, is examined. The annual primary energy consumption in the post-retrofitted house is 49.5 kWh/178 MJ/m^2/annually, while in the pre-retrofitted house, the primary energy consumption is 83.8 kWh/301.7 MJ/m^2/annually, including electricity and gas. The pre- and post-retrofitted operational carbon footprints are identified as approximately 15.9 kgCO2eq./m^2/annually and 6.4 kgCO2eq./m^2/annually. Furthermore, in the post-retrofitted building, the thermal comfort level is determined by the PMV index, which ranges from 0 to -1.5. Overall, this analysis provides a comprehensive view of the post-retrofitted house, encompassing energy, carbon, cost, and thermal comfort.

INTRODUCTION

Globally, the urgency to reduce carbon emissions has increased significantly to foster an environmentally sustainable future. Many countries have implemented initiatives and measures to achieve this goal. Within the European Union, the primary energy-consuming sectors are buildings, industry, and transport (European Commission 2022). Specifically, buildings account for nearly 40% of global energy-related CO_2 emissions. Existing residential buildings alone contribute approximately 17% of these emissions, representing about 25% of the total energy consumption (IEA, Paris 2023). Most of these homes were constructed before the establishment of energy efficiency regulations (Ma et al. 2012). Ambitious climate targets and national sustainability policies drive residential retrofitting efforts worldwide (Dowson et al. 2012; Fylan et al. 2016). Reports indicate that over 97% of existing buildings in the EU require renovation, highlighting the Renovation Wave strategy as a central pillar of the European Green Deal (O'Hegarty, Amedeo, and Kinnane 2024; Directorate-General for Communication (European Commission) 2021; BPIE; 2017). With these renovation strategies, improving thermal comfort in buildings has also become increasingly significant. Heating and cooling systems are crucial for thermal comfort, and making these systems carbon-efficient aligns directly with climate targets. A core element of retrofitting strategies is replacing traditional, fossil fuel-based

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heating systems with electrified solutions such as heat pumps, recognized for their efficiency and substantial potential in reducing residential heating-related emissions (EHPA, n.d.). Additionally, these heating system upgrades and renovation efforts positively impact energy cost-effectiveness. Given this heightened environmental awareness and structured renovation approach, accurately measuring and analyzing the carbon impacts of residential retrofitting has become critical (Shove 2018). This research examines the carbon footprint associated with residential heating by comparing pre- and post-retrofit scenarios in detail. It emphasizes the impact of heat pump electrification on carbon emissions. The analysis focuses on a semi-detached house in Dublin, Ireland. A key issue is that nearly half of Ireland's existing housing stock was built before the introduction of thermal building regulations in 1979, when there were no official rules for insulation or energy-saving design; it was not until 2006 that large-scale thermal retrofitting efforts began (Ahern and Norton 2019a). Furthermore, since there is no regulation, thermal comfort is not considered, despite being an important concept from the user's perspective, and it is essential to integrate it into the design of the built form. Ireland has introduced several policies to meet its climate targets and address this issue, including the installation of 680,000 heat pumps and the retrofitting of 500,000 homes by 2030 (Government of Ireland 2023). The CO2 emissions in 2005, associated with gas and electricity, were approximately 1443 ktCO2 eq. and 4775 ktCO2 eq., while in 2022, emissions related to gas and electricity are approximately 1280 ktCO2 eq. and 2752 ktCO2eq. (SEAI 2022a). This represents a reduction of approximately 11% in emissions associated with gas and approximately 42% in electricity over a 17-year period. This shows the impact of policies and measures considering population growth. R2-C1 This study evaluates energy consumption and carbon emissions, as well as the assessment of thermal comfort using the Predictive Mean Vote (PMV) index, to assess improvements resulting from enhanced building envelope and heating system upgrades. PMV is a key component that assesses built form factors directly or indirectly through assessment of enclosed geometry, thermal zoning, spatial layout, insulation, and thermal mass based on six core factors: air temperature, mean radiant temperature, mean air velocity, air humidity, clothing insulation, and metabolic rate (Humphreys and Nicol 2002; Broday et al. 2019; Moreno Santamaria et al. 2020). While embodied carbon significantly impacts lifecycle emissions, current research primarily focuses on operational carbon, as well as energy consumption and cost assessment from actual bills and metered monitoring. This research investigates the reductions achievable through enhanced thermal storage and system improvements. For the PMV analysis, sensor-based monitoring is utilized to provide an assessment based on the dwelling environment. Overall, this study will explore how retrofitting an old home can enhance energy efficiency, reduce carbon emissions, and improve thermal comfort efficiency.

REVIEW OF HOUSEHOLD ENERGY CONSUMPTION

R1-C2/R1-C3 Numerous studies have examined factors influencing household energy consumption, particularly in buildings. Key determinants include household characteristics (e.g., age, household size, income level), housing attributes (e.g., ownership status, house size, sunlight exposure), and geographic location (e.g., climate region, urban/rural). Households with children consume more energy, whereas those with older adults typically use less (Kavousian, Rajagopal, and Fischer 2013). Owner-occupied homes generally spend less on energy than rented homes due to more significant investments in energy-efficient measures (Rehdanz 2007). However, lower introductory energy prices may encourage higher consumption; building characteristics, such as sunlight intensity and larger dwelling size, correlate with higher energy use (Tso and Guan 2014). Along with these factors, geographical factors like urban and rural placement and warm and cold climates were also identified as significant factors for energy variations (Kuzemko et al. 2025). Research has increasingly emphasized energy-efficient buildings, which were previously less explored. Numerous green building certifications have emerged globally, regionally, and nationally to enhance building efficiency (Karamoozian and Zhang 2025), such as the Global Leadership in Energy and Environmental Design (LEED), the European Union's Energy Performance Certificate, and Switzerland's Minergie label (Filippini and Obrist 2022; Economidou et al. 2020). Ireland also has the Irish Green Building Council (IGBC), which introduced the Home Performance Index (HPI), a framework for evaluating the sustainability of residential projects, in 2016 and was last updated in 2022 (IGBC 2018). One uncertainty that remains unresolved is the extent to which housing renovation improves energy efficiency. Several retrofit approaches can influence residential energy use, including the installation of advanced windows and exterior wall insulation. Insulation methods have been applied to roofs, walls, floors, ceilings, and windows (Hung Anh and Pásztory 2021). Studies focusing on window retrofitting found significant benefits. For instance, Csaszar et al. (Csaszar, Kinnane, and O'Hegarty 2023) observed that window upgrades significantly impact the total heat flux when retrofitting details with full-height window slab insulation might make no difference in energy saving. Similarly, after replacing windows with multilayer energy-efficient

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options, Bjørneboe et al. (Bjørneboe, Svendsen, and Heller 2017) observed notable energy savings in older Danish buildings. Similarly, insulating building envelopes and adjusting heating systems significantly reduced energy usage in Poland (Cholewa et al. 2020). Omrany et al. (Omrany et al. 2016) systematically reviewed passive wall systems, confirming their effectiveness in enhancing thermal performance and lowering energy consumption. However, conflicting results exist; for example, Kavousian et al. (Kavousian, Rajagopal, and Fischer 2013) reported increased energy consumption in insulated homes in the US, potentially explained by larger house sizes. Furthermore, Buso et al. and Far et al. identify that, along with the thermal envelope, the significant causes of energy consumption are occupant and building envelope design (Buso et al. 2015; Far, Ahmed, and Mackee 2022). This may explain the underlying cause of increased energy consumption and size, as occupant behavior plays a crucial role in the built environment.

The case featured in the current study utilizes a deeply retrofitted house, offering a unique approach to analyzing its overall impact through actual bills and metered readings, along with monitoring of indoor parameters. This provides a practical method for assessing energy consumption related to housing renovations.

METHODOLOGY

The methodology of this study involves analyzing utility energy data from pre- and post-retrofitted buildings, along with real-time monitoring of post-retrofitting for thermal comfort analysis, as shown in Figure 1.

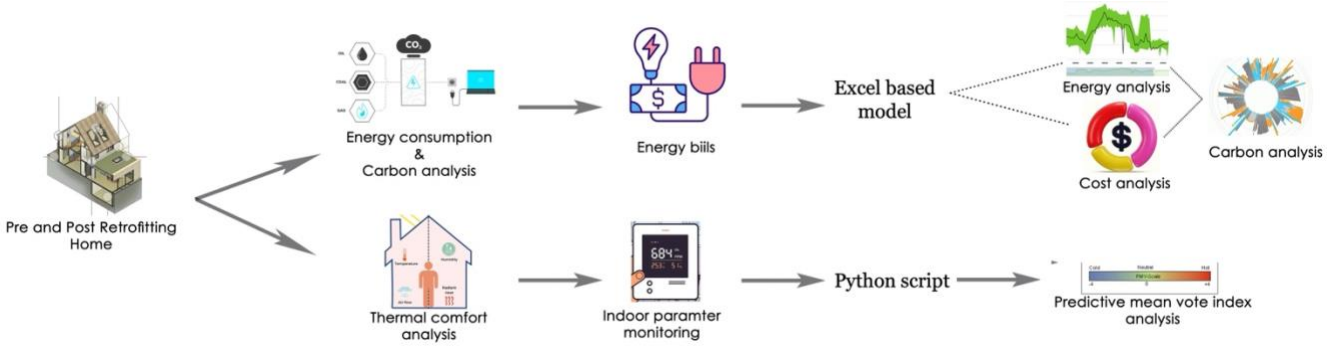

Figure 1: Methodology adaptation R2-C2

Case Background

For this study, a semi-detached house in Dublin, Ireland, has been chosen as the case study to analyze improvements in energy efficiency and carbon emissions. In Ireland, residential buildings are given energy ratings from A (most efficient) to G (least efficient). Figure 2 shows the criteria for the energy rating assessment, along with the CO2 emission indicator with respect to the BER (Building Energy Rating) systems (Government of Ireland 2020). Another classification of typologies is the construction period through which the envelope's U-value can be assessed. The house selected for this study belonged to the pre-1978 construction period, which means it was highly inefficient and lacked proper ventilation to control indoor air quality, leading to high CO2 and humidity levels. After undergoing deep energy retrofitting, the house was upgraded to an A2 rating, just one level below the highest possible rating (A1) in the Irish system. The deep retrofitting measures follow domestic technical standards and specifications defined by SEAI, which outline a general approach to achieving home energy upgrade measures (SEAI 2024). R3-C2 Based on generalized U-value following the construction period in pre retrofit, the U-values are as follows (Ahern and Norton 2019b), roof - 2.3 (0.4), wall - 2.1 (0.37), floor - 1.2 (0.21), window - 3.5 (0.62), door - 2.8 (0.49), W/m^2.K (Btu/h·ft2·°F), while in post retrofit, the U-values are as follows: roof - 0.16 (0.03), wall - 0.2 (0.04), floor - 0.18 (0.03), window - 1.6 (0.28), door - 1.4 (0.25), W/m^2.K (Btu/h·ft2·°F). Furthermore, the floor area of the dwelling in its pre-retrofit state is 170 m² (1830 sq ft), and the number of occupants is 2. In the post-retrofit state, the area increased to 189 m² (2,034 sq ft) due to the conversion of garage space into dwelling space, and the number of occupants also increased to 3. Along with improved insulation and energy efficiency, the retrofit also included a modern heating system and an air source heat pump (ASHP). The heating system was upgraded from a natural gas boiler (NGB) with an efficiency of 90% (as specified by the manufacturer) to a 12 kW (40946 Btu/h) ASHP with a coefficient of performance (COP) of 3.42 (as specified by the manufacturer). Furthermore, measures to regulate humidity and CO2 levels, such as an automated roof window that operates based on indoor CO_2 concentration levels in the enclosed space, enhance occupant comfort.

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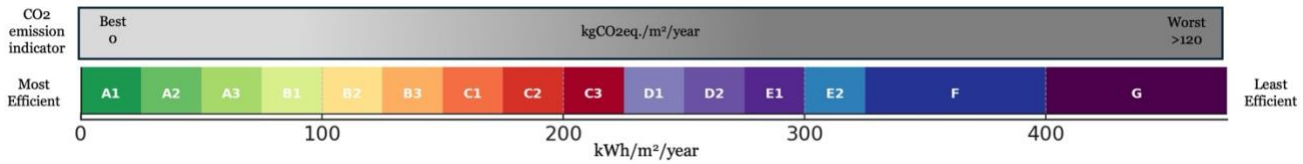

Figure 2: BER rating criteria adapted from (Government of Ireland 2020)

Energy Measuring & Carbon Assessment

Energy consumption data collection typically relies on two methods: self-reporting, which involves estimating consumption based on homeowner information, and utility billing. However, self-reported data are subjective and prone to inaccuracies and limited reliability (Jiang, Li, and Zheng 2024). For this analysis, utility billing data were systematically collected from the pre-retrofit and post-retrofit phases of the dwelling. In the pre-retrofit phase, annual electricity and natural gas bills were analyzed to assess the yearly consumption in both scenarios. In the pre-retrofit phase, natural gas was primarily used for space heating and part of the domestic hot water (DHW) demand through an NGB. In contrast, electricity consumption reflected non-heating loads (e.g., appliances, lighting) along with partial DHW demand. Following the retrofit, the heating system transitioned from gas to an ASHP, which operates on electricity for both space and water heating. To provide more granular consumption insights, sub-monitoring systems were installed to isolate the energy consumption of critical components, including the ASHP, with a time frequency of 1 minute. This subcategorization approach enabled a detailed analysis of energy use by the heating system. Furthermore, a carbon footprint comparison is conducted between the pre- and post-retrofit scenarios, based on energy consumption patterns and floor area. For the analysis, the carbon footprint is calculated according to Equation 1, R1-C5 where G is the carbon footprint (kg CO2eq./m^2/annually); E_g is the consumption of gas in kWh/annually, and C_g is the carbon coefficient of the gas in kg CO2 eq./kWh, E_e is the electricity consumption in kWh/annually, C_e is the carbon coefficient of electricity in kgCO2 eq./kWh. A is the area in per or post retrofit. The values of the carbon coefficient are based on the present scenario instead of the values from which the pre-retrofit is functioning, because the pre-retrofit scenario represents the houses that are in the present and can be retrofitted. The comparison will provide a baseline for determining how much carbon reduction can be achieved through retrofit measures. The carbon coefficient of electricity is 0.255 kg C02eq./kWh, and gas is 0.23 kgCO2eq./kWh, for Ireland following SEAI (SEAI 2022a).

$$G = (E_g \times C_g + E_e \times C_e)/A \quad R1 - C4 \qquad \ldots\ldots\ldots\ldots\ldots\ldots Equation\ 1$$

Thermal Monitoring

Thermal comfort is a crucial factor in the analysis of residential buildings, and achieving a balance between comfort and energy efficiency is essential for optimal energy use. To analyze thermal comfort, sensor-based monitoring was conducted in the living room of the selected house, with sensors measuring temperature, relative humidity, and carbon component levels at an hourly time frequency after retrofit. Several thermal comfort models are available, accounting for environmental, cultural, lifestyle, and age-related differences (Rupp, Vásquez, and Lamberts 2015). Fanger's model is the most commonly applied thermal comfort model for indoor conditions, which forms the basis for several international standards, including ISO 7730, ASHRAE, and the Chinese standard GB/18049 (Zhao, Lian, and Lai 2021). The PMV index based on Fanger's model is utilized in this study. The PMV index is derived from Fanger's comfort equation (Equation 2), which incorporates several factors: the metabolic rate (M), the partial pressure of water vapor (P_a), the ambient air temperature (t_a), the clothing area factor (f_{cl}) reflecting the ratio of clothed to unclothed body surface the temperature at the outer surface (t_{cl}) of the clothing, the mean radiant temperature (T_r), and the convective heat transfer coefficient (h_c), which is influenced by indoor air velocity.

$$\begin{aligned} PMV = {} & (0.303e^{-0.036M} + 0.028) \\ & \times [M - 3.054 \times 10^{-3} \times (5733 - 6.99M - P_a) - 0.42 \times (M - 58.15) \\ & - 1.7 \times 10^{-5} \times M \times (5867 - P_a) - 0.0014 \times M \times (34 - ta) - 3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 \\ & - (t_r + 273)^4] - f_{cl} \times h_c \times (t_{cl} - t_a)] \qquad R1 - C4 \quad \ldots\ldots\ldots\ldots\ldots\ldots Equation\ 2 \end{aligned}$$

In practice, the PMV equation is often applied through dedicated software; this study implements it via a Python script (Tartarini and Schiavon 2020). Required inputs include the monitored indoor parameters, temperature and humidity, metabolic rate (considered 1.1, representing sitting and standing without activity), a clothing insulation level of 0.67, and an air velocity of 0.2 m/s, considering living-room conditions with mechanical ventilation. These parameters align with ASHRAE 55 standards (ASHRAE 2017). Under ASHRAE 55, the PMV scale spans from -3 (cold) to +3 (hot), with 0 signifying neutral comfort.

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ANALYSIS AND DISCUSSION

Energy saving performance

R1-C5/R1-C6/R2-C3/R3-C4 The energy-saving performance was evaluated by comparing: (i) the energy performance before and after the retrofit, and (ii) the associated cost savings under both scenarios. One year of metered electricity and gas consumption data, along with utility bills, was used to account for seasonal variation and dwelling's fabric improvements. For the energy performance comparison of two system typologies, energy generation or primary energy (PE) is utilized, which considers the fuel change in accordance with the system. The PE factor for electricity consumption is 1.77, while for gas, it is 1.1 for Ireland (SEAI 2023). Furthermore, cost analysis is based on €/kWh, derived from actual bills, with sensitivity analysis accounting for inflation.

Figure 3 presents the energy performance for the pre- and post-retrofit scenarios. Based on PE, the pre- and post-retrofit consumption are 83.8 kWh/301.7 MJ/m^2/annually and 49.5 kWh/178 MJ/m^2/annually, respectively. Overall, the analysis indicates that the post-retrofit scenario shows an efficiency of 40% in PE consumption. For the in-depth analysis, the results identified that the pre-retrofit's primary electricity consumption is approximately 29.3 kWh/105.5 MJ/m²/annually. In comparison, gas consumption is 54.5 kWh/196.2 MJ/m²/annually, indicating that gas accounts for 65% of the primary energy consumption. In the case of post-retrofit, approximately 80% is due to space and water heating, of which DHW accounts for approximately 63% or 22.4 kWh/80.6 MJ/m^2/annually, and space heating is 13.2 kWh/47.5 MJ/m^2/annually and 8.9 kWh/ 32 MJ/m^2/annually accounts for other activities. One interesting observation in the analysis is that despite the dwelling belonging to pre 1978 period, the analysis identified that the kWh/m^2 of the pre scenario is within the range of B1-B2 BER rating, which is primarily because of the number of users is only 2 in pre and while the post aligns with the A2 energy rating the number of users is 3. For the cost analysis, the pre-retrofit bills totaled 940€/1046$, within which gas represented 0.06€/kWh and electricity represented 0.15€/kWh. In the case of post-retrofit, the cost slightly increased to 960 €/1068$ (0.2€/kWh); these final costs are based on end-use energy, including any night or other tariffs for electricity or cost incentives provided by the government in winter for gas. Based on the analysis, the electricity cost increases by approximately 40% after retrofit, which is due to several factors, including investment in renewable energy, network and grid modernization, supply and demand imbalance, and other policy-related factors. Although gas is not used in the post-retrofit period, based on the market rate, the cost of gas has increased by 65%, primarily due to the significant increase in the carbon tax, which rose by approximately 200% from 2017 (the pre-retrofitting period) to 2024 (the post-retrofitting period), and also because of the geo-political events surrounding the fuel. Although from a per-unit cost perspective, the post-retrofit value is approximately 150% higher than that of the pre-retrofit. However, the difference in the overall cost of pre- and post-retrofit is approximately 2%, which can be directly attributed to the performance factor of the ASHP, where it is assumed that the efficiency of the NGB is 90%. At the same time, in ASHP, a COP of approximately 3.42 applies.

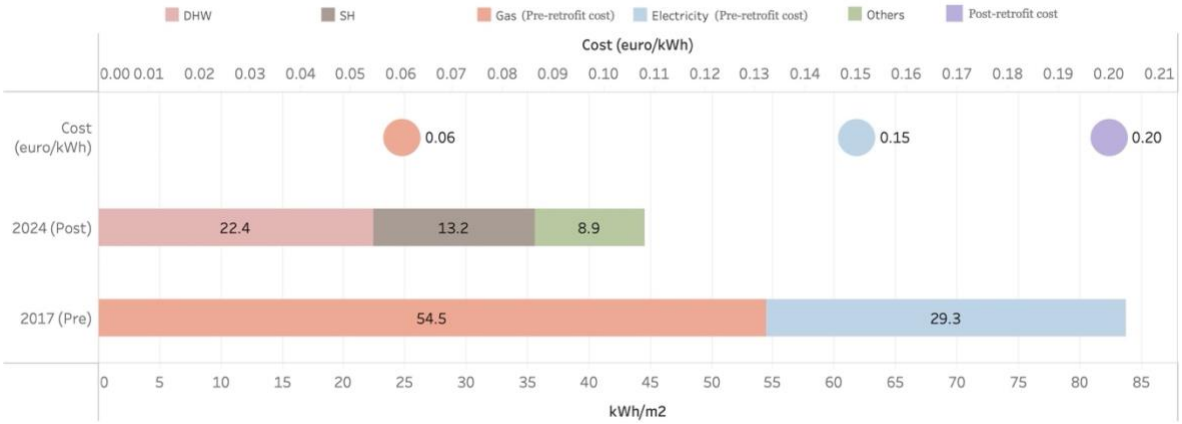

Figure 3: Primary energy performance R2-C4

Carbon footprint

R1-C6/R2-C7 Based on energy use and carbon coefficients, utilizing Equation 1, Figure 4 compares the carbon footprints before and after retrofit. Post-retrofit operational emissions are 6.4 kgCO_2eq./m²/year, representing a 60% reduction from the

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pre-retrofit value of 15.9 $kgCO_2eq./m^2/year$. Within the post-retrofit breakdown, DHW is highest at 3.1, followed by space heating (2.1) and other uses (1.2) $kgCO_2eq./m^2/year$. Pre-retrofit, gas contributed 11.2 and electricity 4.7 $kgCO_2eq./m^2/year$. Compared to the average Irish dwelling's carbon footprint of ~4.6 $tCO_2/year$ (SEAI 2022b), which includes a mix of energy ratings and fuels (electricity, oil, gas, peat, coal), the post-retrofit footprint is ~75% lower. This suggests the retrofitted house performs significantly better than average. However, further analysis is needed to assess whole-life carbon performance, especially embodied impacts. While operational emissions are often targeted through heating upgrades and electricity decarbonization, embodied carbon is increasingly critical, projected to exceed operational emissions by 2030, accounting for ~60% of residential sector emissions (O'Hegarty and Kinnane 2022).

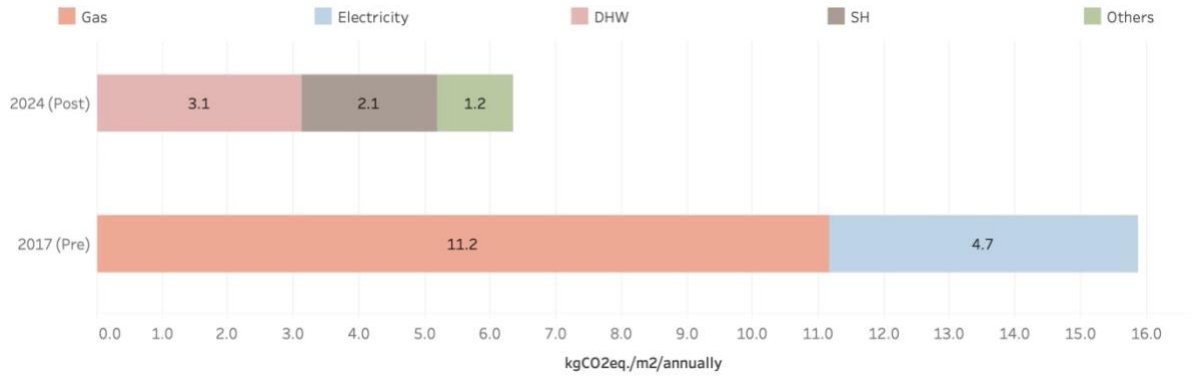

Figure 4: Carbon footprint analysis R2-C4

Thermal comfort analysis

R2-C1/R2-C3 For thermal comfort assessment, sensors were installed in the living room of the selected house to track both relative humidity and indoor temperature, as shown in Figure 5, which also includes outdoor temperature data. As observed in the figure, the outdoor temperature (light blue line) declines steadily from 18-20 °C in early September to below 5 °C by early December, following the transition from autumn to winter. Correspondingly, the indoor temperature (green line) remains more stable, averaging around 20–22°C, due to the presence of space heating systems that maintain comfort despite falling outdoor temperatures. This thermal buffering is characteristic of well-insulated dwellings with active heating during colder months. Indoor relative humidity (purple line) exhibits a slightly inverse trend to temperature, rising gradually through autumn and peaking above 70% in late November. Importantly, humidity appears moderately controlled indoors, mainly remaining within the recommended 40–60% range. Spikes and dips in humidity can be linked to ventilation patterns.

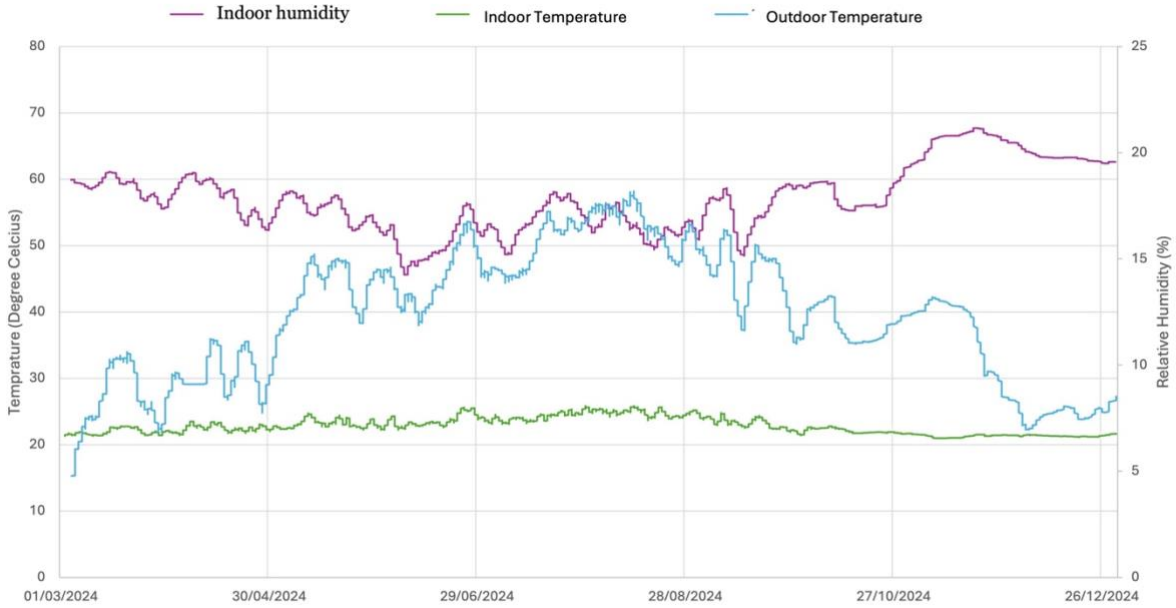

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Figure 5: Monitored parameters R2-C5

R2-C9/R3-C3 Figure 6 displays the PMV and indoor CO_2 levels; the PMV reflects thermal comfort, while the CO_2 levels indicate air quality and occupancy patterns. The green-shaded zone represents the acceptable PMV comfort band (–0.5 to +0.5), along with the acceptable range for indoor CO_2 levels, aligned with thermal neutrality as per ISO 7730 and ASHRAE 55 (ASHRAE 2017; ISO 2005, 77). From March to early September, the PMV gradually shifts from slightly cold (–1.5 to –0.5 °C) to near-neutral, remaining within the comfort zone during mid-summer. This aligns with warmer outdoor conditions and likely reduced heating demand. However, from September onward, the PMV drops significantly below -1, indicating persistent thermal discomfort due to underheating, possibly caused by an insufficient heating response as cooler months approach. Simultaneously, indoor CO_2 levels mostly remain below 600 ppm, suggesting adequate ventilation and moderate occupancy throughout the year. These levels are well within typical indoor air quality standards, further supported by the absence of sharp CO_2 spikes. Despite generally good air quality, the PPD (Predicted Percentage of Dissatisfied) is around 25%, which is calculated utilising the PMV results and corresponds to PMV values around ±0.5. This means that even under "acceptable" conditions, one in four occupants is still likely to be thermally dissatisfied. Thermal comfort is influenced by several factors, not just indoor air temperature, but also humidity, clothing level, metabolic rate (activity level), and air movement. In Figure 5, indoor temperatures stayed relatively stable (around 20 - 22 °C), but outdoor temperatures dropped steadily, especially from September to December, and indoor humidity fluctuated moderately (rising through the autumn). Considering Figure 5 further, it is observed that PMV values dropped significantly below -1 during late autumn and early winter, indicating a shift toward thermal discomfort. This aligns with the outdoor temperature trend seen earlier, falling below 10 °C by November, while the indoor temperature appears to remain only marginally adjusted. This suggests inadequate heating or slow diurnal heating response as the external temperatures drop. Furthermore, in addition to this seasonal variation, there is an automated window that operates based on indoor CO_2 concentration, which also aligns with the finding of acceptable CO_2 readings and may be the cause of the varied PMV range during the cooler months. In summary, the system may benefit from more dynamic heating control or adaptive setpoints during shoulder seasons, even when ventilation appears sufficient. These results underline the need for integrated thermal and air quality strategies to maintain year-round comfort.

Figure 6: PMV analysis R2-C5

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CONCLUSION

R2-C6/R2-C8/R2-C10 This study investigates the impact of retrofitting on energy consumption, carbon footprint, and thermal comfort. The analysis evaluates energy consumption data and utility bills, allowing for a thorough assessment of energy use and its associated operational carbon emissions. Based on Primary Energy (PE) consumption from pre-retrofit, which is 83.8 kWh/301.7 MJ/m^2/annually, there is an improvement of approximately 40% compared to post-retrofit PE consumption, which is approximately 49.5 kWh/178 MJ/m^2/annually. Before the retrofit, approximately 65% of the energy was from gas, while the remaining 35% was from electricity. Furthermore, comparing the electricity consumption except for heating between the pre- and post-scenarios, which are approximately 29.3 kWh/105.5 MJ/m^2/annually and 8.9 kWh/ 32 MJ/m^2/annually, there is a decrease of 70%, which is primarily because in the pre retrofit water heating partially dependent on electricity. In contrast, in the post retrofit, the water heating is an integral part of the ASHP. Considering the PE factor of the respective scenario periods, the difference is approximately 31% if the conversion factors of the pre- (2.06) and post-periods (1.77) are utilized, which underscores the improvement in electricity generation toward a cleaner future, with an increased share of renewable energy, and future growth toward a more sustainable future. The operational cost of the pre-retrofitted scenario is 0.08€ or 0.09$/kWh, while in the case of post-retrofitting, it is 0.2€ or 0.22$/kWh, representing an approximate 120% increase in the per-unit cost, with a 2% increase in the overall cost. This increase in cost is partly due to the heating system's dependency on electricity. When evaluating carbon emissions, the post-retrofit scenario yields a notable decrease of around 60% in operational carbon footprint compared to the pre-retrofit scenario, which is approximately 6.4 kg CO2eq./m²/annually and 15.9 kg CO2eq./m²/annually. In pre-retrofit homes, the bulk of emissions stemmed from gas consumption related to heating, whereas in the post-scenario, heating is done by an ASHP, which operates on electricity. Although the analysis shows a positive impact, as the study covers only the operational aspect of carbon footprint, further analysis from the whole-carbon perspective, encompassing the embodied aspect, is also required.

Based on the initial analysis, thermal comfort was assessed using the Predicted Mean Vote (PMV) index, which ranged between 0 and -1.5 in the post-retrofit scenario. This range indicates conditions trending toward slightly cool, along with a Predicted Percentage of Dissatisfaction (PPD) of approximately 25%, which is based on the PMV. According to ASHRAE & ISO guidelines, an ideal PMV range is between -0.5 and +0.5; however, except for the summer period, the PMV is not in the ideal range, which is partly because of the presence of the automated window that operates based on the level in carbon concentration, which affects the indoor humidity level and partly from inadequate heating. Maintaining the balance between thermal comfort and carbon concentration is an important aspect that needs further assessment. However, based on preliminary analysis, improved ventilation systems, coupled with more dynamic heating control, may help achieve the desired thermal comfort range. Overall, these findings demonstrate the preliminary benefits of residential retrofits in reducing energy consumption, decreasing carbon footprint, and maintaining thermal and carbon levels from a broader perspective. However, following a robust methodological framework, further detailed analysis of contributing factors is necessary. This includes evaluating energy consumption, occupant behavior, and envelope design perspectives, as well as assessing the carbon footprint from a whole-life viewpoint to capture the embodied potential, especially given that some retrofit interventions may lead to increased embodied emissions. Additionally, the impact of mechanical ventilation and retrofitted indoor materials on maintaining thermal comfort and regulating indoor air quality needs further investigation. Nonetheless, considering that a substantial portion of Europe’s housing stock needs renovation, embracing such retrofit measures could decrease the residential sector’s environmental impact, underscoring the necessity for comprehensive analysis and evidence-based retrofitting practices.

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REFERENCES

Ahern, Ciara, and Brian Norton. 2019a. “A Generalisable Bottom-up Methodology for Deriving a Residential Stock Model From Large Empirical Databases.” *Articles*, December. https://doi.org/10.1016/j.enbuild.2020.109886.

———. 2019b. “Thermal Energy Refurbishment Status of the Irish Housing Stock.” *Energy and Buildings* 202 (November):109348. https://doi.org/10.1016/j.enbuild.2019.109348.

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ASHRAE. 2017. "ASHRAE Standard 55-2017." https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/55_2017_d_20200731.pdf.

Bjørneboe, Matilde Grøn, Svend Svendsen, and Alfred Heller. 2017. "Evaluation of the Renovation of a Danish Single-Family House Based on Measurements." *Energy and Buildings* 150 (September):189–99. https://doi.org/10.1016/j.enbuild.2017.04.050.

BPIE. 2017. "State of the Building Stock Briefing. Buildings Performance Institute Europe." 2017. https://bpie.eu/wp-content/uploads/2017/12/State-of-the-building-stock-briefing_Dic6.pdf.

Broday, Evandro Eduardo, Jéferson Aparecido Moreto, Antonio Augusto de Paula Xavier, and Reginaldo de Oliveira. 2019. "The Approximation between Thermal Sensation Votes (TSV) and Predicted Mean Vote (PMV): A Comparative Analysis." *International Journal of Industrial Ergonomics* 69 (January):1–8. https://doi.org/10.1016/j.ergon.2018.09.007.

Buso, Tiziana, Valentina Fabi, Rune K. Andersen, and Stefano P. Corgnati. 2015. "Occupant Behaviour and Robustness of Building Design." *Building and Environment* 94 (December):694–703. https://doi.org/10.1016/j.buildenv.2015.11.003.

Cholewa, Tomasz, Constantinos A. Balaras, Sandro Nižetić, and Alicja Siuta-Olcha. 2020. "On Calculated and Actual Energy Savings from Thermal Building Renovations – Long Term Field Evaluation of Multifamily Buildings." *Energy and Buildings* 223 (September):110145. https://doi.org/10.1016/j.enbuild.2020.110145.

Csaszar, Bernadett, Oliver Kinnane, and Richard O'Hegarty. 2023. "Renovation of 20th Century Modern Buildings: Some Common Challenging Architectural Details Analysed to Find Optimal Insulating Solutions." *Journal of Physics: Conference Series* 2654 (1): 012002. https://doi.org/10.1088/1742-6596/2654/1/012002.

Directorate-General for Communication (European Commission). 2021. *European Green Deal: Delivering on Our Targets*. Publications Office of the European Union. https://data.europa.eu/doi/10.2775/595210.

Dowson, Mark, Adam Poole, David Harrison, and Gideon Susman. 2012. "Domestic UK Retrofit Challenge: Barriers, Incentives and Current Performance Leading into the Green Deal." *Energy Policy* 50 (November):294–305. https://doi.org/10.1016/j.enpol.2012.07.019.

Economidou, M., V. Todeschi, P. Bertoldi, D. D'Agostino, P. Zangheri, and L. Castellazzi. 2020. "Review of 50 years of EU Energy Efficiency Policies for Buildings." *Energy and Buildings* 225 (October):110322. https://doi.org/10.1016/j.enbuild.2020.110322.

EHPA. n.d. "EHPA Stats." Accessed December 30, 2023. https://stats.ehpa.org/annex.

European Commission. 2022. "Eurostat Statistics." 2022. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:F8Structural_shares_of_energy_use_in_main_categories_of_energy_balances,_EU,_1990-2022.png.

Far, Claire, Iftekhar Ahmed, and Jamie Mackee. 2022. "Significance of Occupant Behaviour on the Energy Performance Gap in Residential Buildings." *Architecture* 2 (2): 424–33. https://doi.org/10.3390/architecture2020023.

Filippini, Massimo, and Adrian Obrist. 2022. "Are Households Living in Green Certified Buildings Consuming Less Energy? Evidence from Switzerland." *Energy Policy* 161 (February):112724. https://doi.org/10.1016/j.enpol.2021.112724.

Fylan, F., D. Glew, M. Smith, D. Johnston, M. Brooke-Peat, D. Miles-Shenton, M. Fletcher, P. Aloise-Young, and C. Gorse. 2016. "Reflections on Retrofits: Overcoming Barriers to Energy Efficiency among the Fuel Poor in the United Kingdom." *Energy Research and Social Science* 21 (November):190–98.

Government of Ireland. 2020. "Long-Term Renovation Strategy – Ireland (2020)." European Commission. https://energy.ec.europa.eu/document/download/5cf8a54b-ed5f-41c6-afc2-e2df796c5b4e_en?filename=ie_2020_ltrs.pdf&utm.

———. 2023. "Climate Action Plan 2023: Changing Ireland for the Better." Dublin. https://www.gov.ie/pdf/?file=https://assets.gov.ie/256997/b5da0446-8d81-4fb5-991e-65dd807bb257.pdf#page=null.

Humphreys, Michael A, and J Fergus Nicol. 2002. "The Validity of ISO-PMV for Predicting Comfort Votes in Every-Day Thermal Environments." *Energy and Buildings*, Special Issue on Thermal Comfort Standards, 34 (6): 667–84. https://doi.org/10.1016/S0378-7788(02)00018-X.

Hung Anh, Le Duong, and Zoltán Pásztory. 2021. "An Overview of Factors Influencing Thermal Conductivity of Building Insulation Materials." *Journal of Building Engineering* 44 (December):102604. https://doi.org/10.1016/j.jobe.2021.102604.

IEA, Paris. 2023. "CO2 Emissions in 2022." 2023. https://www.iea.org/reports/co2-emissions-in-2022, License: CC BY 4.0.

IGBC. 2018. "What Is the Home Performance Index?" *Irish Green Building Council* (blog). March 12, 2018. https://www.igbc.ie/home-performance-index-2.

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ISO. 2005. “ISO 7730: Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria.” https://www.iso.org/standard/39155.html.

Jiang, Lu, Jinrou Li, and Yingsheng Zheng. 2024. “The Impact of Thermal Comfort Requirements on Household Heating Energy Consumption.” *Journal of Building Engineering* 90 (August):109426. https://doi.org/10.1016/j.jobe.2024.109426.

Karamoozian, Masood, and Hong and Zhang. 2025. “Obstacles to Green Building Accreditation during Operating Phases: Identifying Challenges and Solutions for Sustainable Development.” *Journal of Asian Architecture and Building Engineering* 24 (1): 350–66. https://doi.org/10.1080/13467581.2023.2280697.

Kavousian, Amir, Ram Rajagopal, and Martin Fischer. 2013. “Determinants of Residential Electricity Consumption: Using Smart Meter Data to Examine the Effect of Climate, Building Characteristics, Appliance Stock, and Occupants’ Behavior.” *Energy* 55 (June):184–94. https://doi.org/10.1016/j.energy.2013.03.086.

Kuzemko, Caroline, Blondeel ,Mathieu, Bradshaw ,Michael, Bridge ,Gavin, Faigen ,Erika, and Louis and Fletcher. 2025. “Rethinking Energy Geopolitics: Towards a Geopolitical Economy of Global Energy Transformation.” *Geopolitics* 30 (2): 531–65. https://doi.org/10.1080/14650045.2024.2351075.

Ma, Zhenjun, Paul Cooper, Daniel Daly, and Laia Ledo. 2012. “Existing Building Retrofits: Methodology and State-of-the-Art.” *Energy and Buildings*, Cool Roofs, Cool Pavements, Cool Cities, and Cool World, 55 (December):889–902. https://doi.org/10.1016/j.enbuild.2012.08.018.

Moreno Santamaria, Belen, Fernando del Ama Gonzalo, Benito Lauret Aguirregabiria, and Juan A. Hernandez Ramos. 2020. “Evaluation of Thermal Comfort and Energy Consumption of Water Flow Glazing as a Radiant Heating and Cooling System: A Case Study of an Office Space.” *Sustainability* 12 (18): 7596. https://doi.org/10.3390/su12187596.

O’Hegarty, Richard, Gianmarco Amedeo, and Oliver Kinnane. 2024. “The Impact of Compromised Insulation on Building Energy Performance.” *Energy and Buildings* 316 (August):114337. https://doi.org/10.1016/j.enbuild.2024.114337.

O’Hegarty, Richard, and Oliver Kinnane. 2022. “Whole Life Carbon Quantification of the Built Environment: Case Study Ireland.” *Building and Environment* 226 (December):109730. https://doi.org/10.1016/j.buildenv.2022.109730.

Omrany, Hossein, Ali Ghaffarianhoseini, Amirhosein Ghaffarianhoseini, Kaamran Raahemifar, and John Tookey. 2016. “Application of Passive Wall Systems for Improving the Energy Efficiency in Buildings: A Comprehensive Review.” *Renewable and Sustainable Energy Reviews* 62 (September):1252–69. https://doi.org/10.1016/j.rser.2016.04.010.

Rehdanz, Katrin. 2007. “Determinants of Residential Space Heating Expenditures in Germany.” *Energy Economics* 29 (2): 167–82. https://doi.org/10.1016/j.eneco.2006.04.002.

Rupp, Ricardo Forgiarini, Natalia Giraldo Vásquez, and Roberto Lamberts. 2015. “A Review of Human Thermal Comfort in the Built Environment.” *Energy and Buildings* 105 (October):178–205. https://doi.org/10.1016/j.enbuild.2015.07.047.

SEAI. 2022a. “ENERGY IN IRELAND.” https://www.seai.ie/sites/default/files/publications/Energy-in-Ireland-2022.pdf.

———. 2022b. “Residential | Energy Statistics In Ireland | SEAI.” 2022. https://www.seai.ie/data-and-insights/seai-statistics/residential.

———. 2023. “SEAI Statistics.” 2023. https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors.

———. 2024. “Domestic Technical Standards and Specifications.” 2024. https://www.seai.ie/sites/default/files/publications/Domestic-Technical-Standards-and-Specifications.pdf.

Shove, Elizabeth. 2018. “What Is Wrong with Energy Efficiency?” *Building Research & Information* 46 (7): 779–89. https://doi.org/10.1080/09613218.2017.1361746.

Tartarini, Federico, and Stefano Schiavon. 2020. “Pythermalcomfort: A Python Package for Thermal Comfort Research.” *SoftwareX* 12 (July):100578. https://doi.org/10.1016/j.softx.2020.100578.

Tso, Geoffrey K. F., and Jingjing Guan. 2014. “A Multilevel Regression Approach to Understand Effects of Environment Indicators and Household Features on Residential Energy Consumption.” *Energy* 66 (March):722–31. https://doi.org/10.1016/j.energy.2014.01.056.

Zhao, Qiantao, Zhiwei Lian, and Dayi Lai. 2021. “Thermal Comfort Models and Their Developments: A Review.” *Energy and Built Environment* 2 (1): 21–33. https://doi.org/10.1016/j.enbenv.2020.05.007.