Fabric energy efficiency in housing retrofit:
the role of whole-life operational and embodied carbon emissions

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ABSTRACT: UK housing decarbonisation through retrofit faces massive challenges to be consistent with 2050 Zero Carbon targets, considering the large proportion of inefficient building stock. As the design for fabric-energy-efficiency and the demand for energy consumption from modern lifestyle increases, its trade-off with the embodied carbon investment and the unintended consequences from a high-performance building envelope becomes increasingly important. We developed a model which considered both building performance metrics and existing UK Energy Performance Certificates (EPCs) metrics to investigate long-term quality and acceptability of retrofits, i.e., overheating mitigation and ventilation improvement, considering a 20- and 50-year building lifespan. The model combines energy demand assessment, indoor environmental assessment, the Future Homes Standard and EPC's cost-energy-carbon metric. A dynamic simulation study for seven predominant built forms in the South Yorkshire housing stock was designed to investigate deep retrofit results under predicted future climate conditions in the 2030s, 2050s and 2080s. The study focused on whole-life emissions from operational and embodied carbon over different timescales whilst considering a healthy indoor environment in buildings. The findings present an efficient way of combining building performance metrics and EPC metrics in a housing retrofit model that aids decision-making for homeowners, stakeholders and policymakers.
KEYWORDS: Domestic retrofit; Housing stock; Energy Performance Certificate; Retrofit metrics; Energy efficiency.

1. INTRODUCTION

In the context of the UK government's legally binding 2050 Zero Carbon targets, rapid mass retrofit is imperative, given the age and inefficiency of homes across the UK [1]. This mass retrofit is a significant multifaceted challenge to address fabric energy efficiency, fuel poverty, cold home-related health problems and associated embodied carbon from refurbishments.

The Energy Performance Certificate (EPC) is a policy instrument aiming to improve the operational energy performance of buildings through its cost-energy-carbon index from A to G in rating [2]. It acts as a primary source of data in reviewing potential domestic retrofits. The EPC's cost-energy-carbon metric, however, may not be fit for the UK's whole-life-carbon roadmap due to assumptions in the way energy consumption is estimated and the lack of consideration for thermal comfort and indoor air quality [3]. Studies have suggested ways of combining the existing EPC cost-energy-carbon index with performance assessment metrics such as comfort and indoor air quality are worthwhile to extend assessments beyond immediate retrofit delivery to improve their fitness for purpose [3].

The robustness of retrofit measures relies on how the various facets of building performance are balanced against one another. The Future Homes Standard (FHS) and Approved Document L (AD-L) recommend limiting the maximum U-values for the fabric energy efficiency of homes to avoid heat losses and air leakages [4]. However, increased insulation can increase overheating in poorly designed buildings with airtight buildings because they often rely on the careful use of natural and mechanical ventilation to achieve acceptable indoor air quality.

Prior to a retrofit, if a household has an under-consumption of energy services, or the pre-retrofit construction of a dwelling is better than its EPC record, the pre-bound effect occurs and the energy savings gap between pre- and post-retrofit could be smaller than the expected [5]. Post retrofit, if a household's daily rhythm of heating and ventilation needs are changed or a technology failure is found in construction, the rebound effect occurs, and an energy efficiency increase may also lead to an increase in the final energy consumption [5]. These effects could lead to inaccuracies in calculating the retrofit payback period and the subsequent national retrofit and decarbonisation policy.

Our exploratory case study investigates whole-life emissions from operational and embodied carbon whilst considering a healthy indoor environment in buildings. We present fabric retrofit measures for seven archetype-based models by incorporating the current SAP metrics, FHS and AD-L guidance, and additional lifetime metrics, e.g. overheating mitigation and indoor environmental conditions, over different timescales. This study aims to understand how these metrics affect the long-term quality and acceptability of retrofits, and how the rebound and prebound effects influence pre- and post-retrofit comparisons.

2. METHODOLOGY

The South Yorkshire (SY) housing stock, which houses 1.8% of the UK's residential stock, was selected for a case study. Most properties were constructed between the early 1900s to 1970, with semi-detached and terraced houses being the predominant built forms (Figure 1). Seven archetypes were selected for a deep retrofit investigation of the SY housing stock (Figure 3). Besides the 1930s semis, all other houses have heated attic rooms. The architectural drawings of the archetypes were traced from local property advertisements whilst their applicability and generalisability were further assessed. The relationship between the treated floor areas (TFA) to heat loss form factors (HLFF) and the window area (WA) to window-to-floor area (WWR) of the selected archetypes are shown in Figure 2.

Cavity walls or solid brick walls, an uninsulated ground floor, an uninsulated suspended wooden floor, a pitched roof with insulation at joints, and double-glazing are found in most of the SY housing [2]. Solid brick walls were considered in Victorian houses whereas cavity walls were considered in other houses. The U-values of the building envelopes were derived from the RdSAP 2012, as shown in Table 1. The post-retrofit U-values were derived from the FHS and the latest AD-L.

For the pre-bound scenario (Table 4) with better insulation than the base model, the U-value of walls was considered as 0.8 W/m2K, and the U-value of windows was considered as 2.5 W/m2K. For the rebound scenario (Table 4) with technical failures in retrofit construction, the U-value of walls as 0.228 W/m2K and air permeability 10m3/h.m2@50Pa were considered.

To consider the impacts of future worst-case climatic conditions on retrofit scenarios, three scenarios, the medium emissions (RCP 6.0, A1B) for 2030 and high emissions (RCP 8.5, A1FI) for 2050 and 2080, were chosen for this work [6].

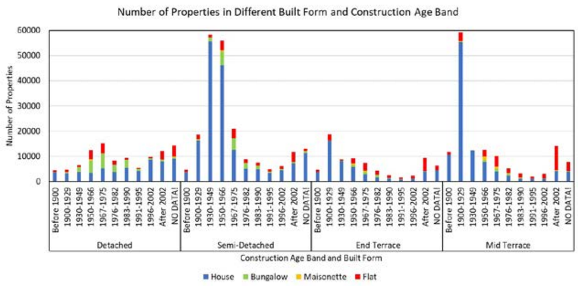

Figure 1. Construction ages and built forms of the South Yorkshire housing stock.

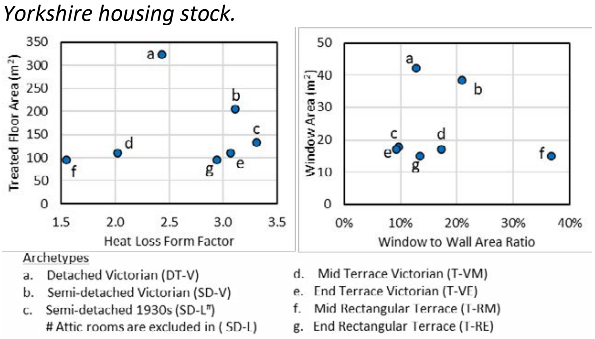

Figure 2. Archetype information used in the study.

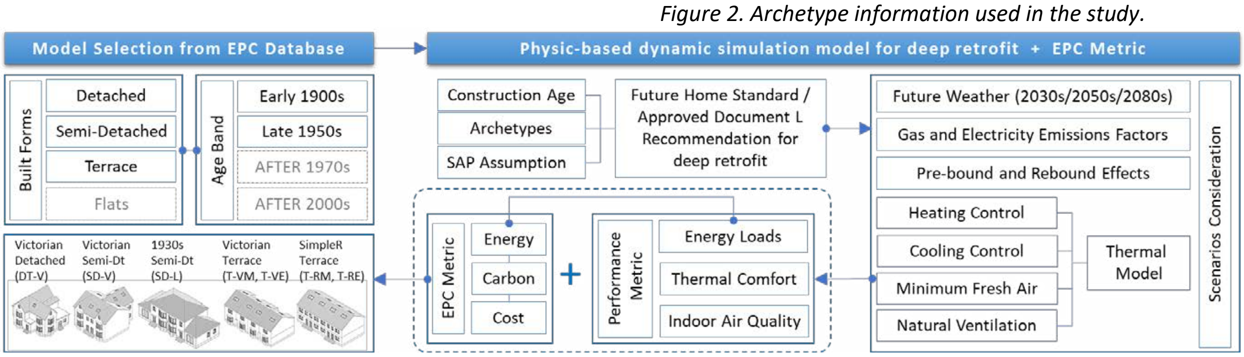

Figure 3. Overview of deep retrofit investigation using the archetype-based models for the South Yorkshire housing stock.

Table 2 presents the operational settings used in pre-retrofit and post-retrofit models. Table 3 presents the heating scenarios under both rebound (RB) and pre-bound (PB) effects.

Electricity marginal greenhouse gas (GHG) emissions factors from 2023 to 2100 were taken from BEIS [7], which is an optimistic prediction for grid decarbonisation. For instance, the GHG emissions from the UK electricity generation in 2023 is 0.207 kgCO2e per kWh whilst the BEIS prediction (published in November 2023) is 0.133 kgCO2e per kWh for 2023 and 0.120 kgCO2e per kWh for 2025 and decreased down to 0.002 kgCO2e per kWh in 2050. Emission factor changes from 2025 to 2080 were considered to calculate accumulated carbon emissions from heat pumps and gas boilers. Regarding the standard variable tariff for electricity and gas prices, the current energy price per unit from 1 October to 31

December 2023 [8] was considered in this study to compare energy costs for pre-retrofit and post-retrofit scenarios. These were £0.27 and £0.07 for electricity and gas respectively for 1kWh.

The retrofit embodied carbon emissions were calculated from the cradle-to-gate (A1-A3) and construction (A4-A5) stages. This included (i) different insulation materials such as EPS, PIR, PUR, XPS, glass wool, stone wool and wood fibre, (ii) material finishes, vapour control membrane, airtight membrane and paints, (iii) window and door replacements, and (iv) upgrading service systems such as heat pumps and gas boilers. For this work, we chose the EPS insulation for comparison. Factors used for global warming potential (GWP) and embodied carbon calculation for individual houses were taken from [9].

Table 1. U-values used in the study.

U-value (W/m²K)	Reference model (SAP)	Deep retrofit model (AD-L)
Roof	0.68	0.15
External Wall (Solid)	2.10	0.18
External Wall (Cavity)	1.60	0.18
Ground Floor	1.60	0.18
Internal Partition	2.25 (assumption)	
Window	3.10	1.4
Door	3.00	1.4
Air permeability	15	8 m³/hm²@50Pa

Table 2. Operational settings used in the simulation models.

Parameters	Values	Ref.
Indoor operative temperature		
Heating (Category II)	on if T > 20°C	[10]
Cooling (Category II)	on if T > 26°C	[10]
Natural ventilation (windows)	22°C < T < 26°C	
Fresh air and (continuous) mechanical ventilation		
Min fresh air (other rooms)	0.49 l/s/m²	[10]
Bathroom extract ventilation	8 L/s	[11]
Kitchen extract ventilation	13 L/s	[11]
CO2 generation rate	0.005 L/s	[11]
Building usage and schedules		
Occupancy (Bedroom)	Single bedroom	[12]
Occupancy (Others)	Follow rooms	[12]
Equipment and lighting	Follow rooms	[12]
HVAC Systems		
Boiler CoP	0.85 (assume)	-
Heat Pump CoP for heating	2.8 (assume)	[13]
Heat Pump CoP for cooling	3.5 (assume)	[13]
Heat recovery	Enthalpy	-
Internal heat gain	2.1 W/m²	[14]
Shading (assumption): Apply if solar radiation > 120 W/m² in the daytime and apply it during the night		
Orientation: South-facing rear garden, north-facing entrance, east and west sides for party walls.		
Suburbs terrains with no adjoining buildings.		

The operational carbon emissions from different archetypes were calculated from the results of physics-based dynamic simulation models. The energy cost and carbon emissions were calculated following EPC metric and grid decarbonisation scenarios based on modelled energy loads. Finally, the results of both metrics were reviewed for whole-life operational and embodied carbon emissions to understand energy, cost and carbon emissions versus acceptable indoor conditions for thermal comfort and indoor air quality in different timescales. The simulation results were calculated using dynamic energy and thermal simulation programs (EnergyPlus / Design Builder) considering variations in fabric-energy efficiency, thermal models and weather files for the studied houses.

Table 3. Pre-bound and rebound scenarios in heating.

Case	Heating scenarios
Base	The heating is on at all times if T < 20°C.
PB-1	The heating is on if T < 20°C and is off during sleeping hours.
PB-2	The heating is on if T < 20°C and is off during sleeping hours + daytime.
PB-3	The heating is on if T < 20°and is off in some spare/unoccupied rooms.
PB-4	If building insulation is slightly better than the based model while the heating is on if T < 20°C.
PB-5	The heating is on if T < 18°C.
RB-1	The heating is on if indoor T < 21°C.
RB-2	If retrofit construction has technical failures; the heating is on if indoor T < 20°C.
PB: Pre-bound effects. RB: Rebound effects	

3. RESULTS

3.1 Operational carbon emission for heating

The accumulated operational carbon emissions in seven studied archetypes from 2025 to 2080 are presented in Figure 4 and Figure 5. The operational carbon emissions could be reduced by a factor of 7.5 by deep-retrofit construction while the same gas boilers were used in Figure 4. As the detached Victorian house has a larger floor area, its operational energy consumption was the highest among the seven houses whereas the rectangular plan mid-terrace had the lowest demand.

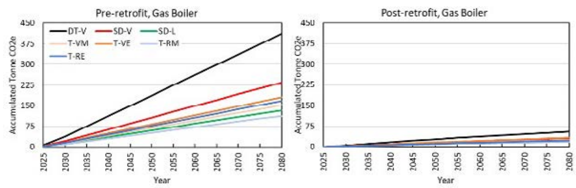

*Figure **4**. Accumulated operational carbon emissions for heating in seven houses from 2025 to 2080, considering the same consumption-based emission factor for natural gas.*

By switching the gas boiler to a heat pump, as shown in Figure 5, if the energy consumption for cooling and ventilation is also added, the operational carbon could be reduced by a factor of 10 using current national grid emission factors or reduced by a factor of 113 using grid decarbonisation scenarios.

3.2 Indoor environmental conditions

The consequence of the deep-retrofit scenario, which intended to reduce heating energy consumption from highly insulated and airtight construction, was a higher median indoor air temperature and a greater summer overheating risk than in less insulated homes. Figure 6 presents a comparison of annual hourly indoor temperatures and indoor carbon dioxide (CO_2) concentrations in three houses for five scenarios (a-e), considering 3.5m^2 differences in areas in the main bedrooms of the houses, with south-facing windows. Mechanical ventilation (MV) has an important role to play in removing indoor pollutants in retrofitted buildings. When the MV was applied in scenarios (d) and (e), the annual mean temperatures and indoor CO_2 concentrations were also reduced. The smaller the room the higher CO_2 concentration.

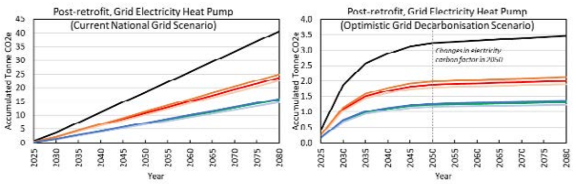

Figure 5. Accumulated operational carbon emissions for heating, cooling and mechanical ventilation in seven houses from 2025 to 2080, based on current national grid and future decarbonised grid for electricity.

Figure 7 shows the annual distribution of indoor operative temperature and indoor air CO_2 concentration, yielding a total of 8760 hours a year, for a bedroom in a 1930s semi-detached house. As shading was applied in the rooms, summer overheating did not exceed 25°C for more than 10% (876 hours) of the year, as the Passivhaus suggested [14], f the house is considered fully occupied. However, higher annual median temperatures were found if the post-retrofit construction had no MV. A high frequency of temperature distributions was found near ±2°C of the heating set point, and small distributions of temperatures above 25°C were found in Figure 7. If shading is excluded in the pre-defined scenarios, overheating could be expected as the unintended consequence of highly insulated, airtight buildings. Variations in hourly occupancy patterns affect the indoor CO_2 generation rate while temperature and air pressure differences between indoors and outdoors affect the air change rate of a room. If the room had no MV, high air CO_2 concentrations above 900ppm were observed as the windows were closed. One could argue that daily window opening could remove indoor pollutant concentrations, instead of following the pre-defined input from Table 2. When the MV was added in the post-retrofit model, the indoor air CO_2 concentration was lower than 1000ppm, as [10] suggested, despite inconsistent distributions in its frequency.

3.3 Cost saving

A deep-retrofit could reduce annual heating demand up to 5 to 6.8 times whereas the coefficient of performance (COP) of the heat pump is 3.29 times more efficient than the gas boiler. However, the tariff for electricity is nearly 4 times higher than gas for 1kWh. As a result, energy cost-saving was not directly proportional to reducing energy demand if a gas boiler was switched to a heat pump. Figure 8 presents energy-cost savings from seven houses.

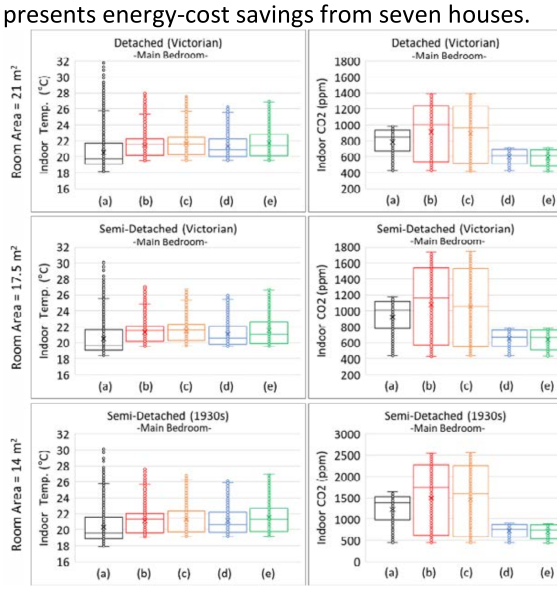

Figure 6. Annual indoor temperature and air CO2 concentration for south-facing bedrooms in three houses. [(a) Pre-retrofit in 2030 (b) post-retrofit in 2030 (c) post-retrofit in 2050 (d) post-retrofit in 2050 and MV added (e) post-retrofit in 2080 and MV added.]

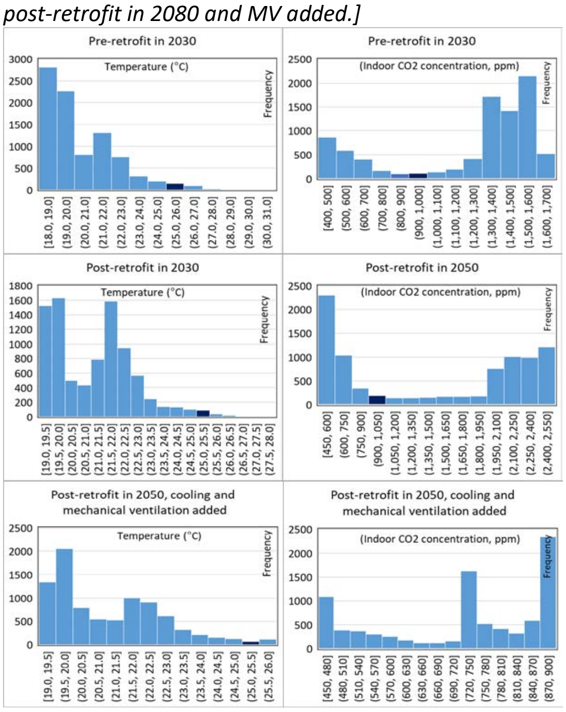

Figure 7. The frequency of annual hour distribution in indoor temperature and indoor air CO2 concentration, an example of a bedroom room in a 1930s semi-detached house.

3.4 Pre-bound and rebound effects

Figure 9 presents a comparison of pre-bound (PBE) and rebound (RBE) effects considering scenarios described in Table 3 that result in energy-saving before a pre-retrofit (-value) and overconsumption after a retrofit (+value).

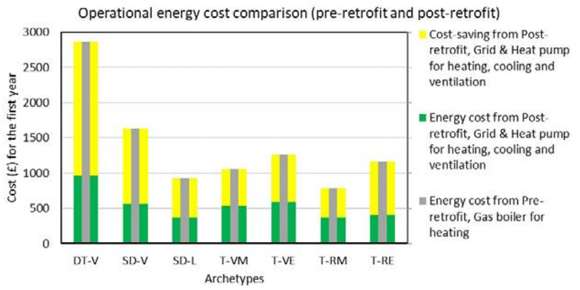

Figure 8. Annual energy cost saving in seven houses.

Reducing heating hours (PB-1) could save more energy in a pre-retrofit model than in a post-retrofit model. The length of heating hours is not a direct measure of heating energy-saving as the temperature differences between indoors and outdoors contribute to the variation of heating demand that causes different results of pre-bound scenarios. Reducing heating set points to 18°C (PB-5) could save more energy in a post-retrofit model than in a pre-retrofit model; however, this may not be realistic as energy efficiency in a post-retrofit condition can lead to an increase in the consumption of energy services due to the rebound effects [5].

Increasing heating set points to 21°C (RB-1) could bring more overconsumption in a post-retrofit model than in a pre-retrofit model; however, the personal preference of the individual could affect variation in heating set point temperatures. The most uncertain overconsumption for heating is unknown technical failures from a post-retrofit model. In this work, the RB-2 resulted in the highest overconsumption of heating. Due to differences in the number of rooms, TFA, HLFF and WWR between the DT-V and SD-V, their pre-bound and re-bound results were different.

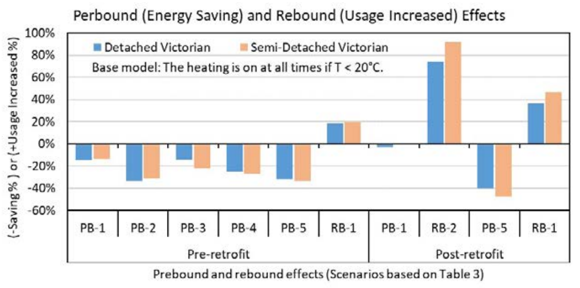

Figure 9. Pre-bound and rebound effects according to the scenarios shown in Table 3.

3.5 Carbon reduction

Figure 10 presents accumulated whole-life operational and embodied carbon emissions over different timescales for the SY housing stock. Significant carbon reduction was found by adding a deep retrofit construction to the current housing stock which has domestic heating from gas boilers. It needs to be highlighted that the results of whole-life carbon emissions from heat pump scenarios contained the energy demand for cooling and ventilation whereas the whole-life carbon emissions from gas boilers scenarios were considered for heating energy demand only. Nonetheless, switching to a heat pump from a gas boiler has benefits in carbon reduction and maintaining necessary indoor environmental conditions. The projected amount of CO_2e emissions is indicative only, as it is based on average energy consumption requirements from seven archetypes. The approximate projections from operational and embodied CO2e emissions, however, showed evidence of a promising decarbonisation path from retrofit and electrification of heating systems using heat pumps.

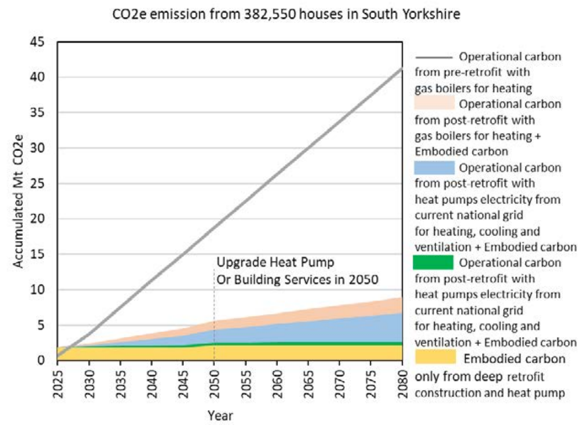

Figure 10. Operational carbon emissions and embodied carbon emissions over time, presented from 2025-2080.

4. DISCUSSION

This study aimed to address reducing domestic operational carbon emissions originating from gas boilers, and an inefficient building fabric. The method was structured to combine EPC metrics, FHS and AD-L guidance and carbon factors from a decarbonised electricity grid, considering the impacts of future weather years, lifespan of deep-retrofit construction, related embodied carbon emissions, maintenance and replacement of MEP over different timescales. Deep-retrofit fabric-first approach, heat pumps for heating, cooling and ventilation and current energy prices for pre-and-post-retrofit scenarios compared to seven archetypes.

The thermal efficiency and airtightness of the building fabric influence the indoor air temperature and air CO2 concentration, which can be improved in the post-retrofit models; however, unintended consequences of an over-heating risk and a lack of fresh air demand a potential need for cooling in extreme summer temperatures and mechanical ventilation. In the results, a higher annual median temperature in the post-retrofit scenario revealed that the end users need an adaption for changes in indoor thermal comfort. Overheating was not reported in the results shown in scenarios (d) and (e) of Figure 6 and Figure 7 due to the use of shading in the simulation models. Further studies on the effects of external and internal insulations together with thermal mass and the end user's behaviour in using shading are needed to understand potential overheating in retrofitted homes to ensure they can adapt to changing climate conditions. Whilst the energy demand for cooling and ventilation is expected in a post-retrofit scenario to maintain necessary ventilation for indoor air quality, the annual energy cost-saving figure showed a promising result from deep retrofit and switching a gas boiler to a heat pump. The monetary payback time for an energy-saving retrofit can vary by several factors; therefore, further studies are necessary to understand how different archetypes affect retrofit ROI (return on investment).

The use of static occupancy schedules and equipment schedules is common in building energy and thermal simulation models whereas the drawback of a "typical" schedule needs to be acknowledged as a problematic limitation in the results. Physiological, psychological and random factors of the end users are not "typical" while the energy usage behaviour of a household could be varied according to the environmental factors, time-related factors, and contextual factors. Further studies are necessary to investigate how those factors found in the prebound and rebound effects of energy consumption as their consequences influence indoor environmental conditions and carbon reduction. Further studies will explore the impact of these factors on energy use by conducting post-occupancy evaluation surveys for a sample of the SY housing stock and integrating these findings into the modelling.

5. CONCLUSION

The exploratory case study focused on whole-life operational and embodied carbon emissions over different timescales for the SY housing stock whilst considering a healthy indoor environment in post-retrofit scenarios. Whilst the EPC database can be undoubtedly used as a primary source in reviewing potential domestic retrofits, additional performance-related metrics and carbon emissions-related factors are necessary to consider ensuring the long-term quality and acceptability of retrofit project delivery, to tackle fuel poverty, health inequalities, and achieve wider societal benefits in cost-saving and decarbonisation. The findings present how the resilience of housing can be achieved by integrating careful ventilation mechanisms and necessary shading in housing retrofit, as well as adapting the transition between heat balance modes (the use of heating and cooling) to free-running modes for adaptive thermal comfort.

The comparison of the projected amount of CO_2e emissions could vary as the rebound effects arise from the improvement of energy efficiency while carbon factors for grid electricity and fuels change over time. For policymakers, this work also can be used to understand deep retrofit of homes at scale, the need for an in-depth cost-benefit analysis for retrofit, the need for deployment in low-and-zero energy HVAC systems for UK homes and relevant solutions and to understand making mass retrofit a reality.

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