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Energy retrofits: Factors affecting a just transition to better indoor air quality

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A B S T R A C T

In comparison with other European countries, Ireland has a disproportionately high number of poorly performing energy-inefficient buildings. Consequently, Ireland has one of the most ambitious energy retrofit programmes in Europe. The aim of this study was to evaluate the impact of deep energy renovation measures i.e. (replacement of heating system and upgrade to building envelope) on indoor air quality, thermal comfort and ventilation in a sample of primarily social housing in Ireland. A mixed methods approach including measurement of indoor air quality and a thermal comfort questionnaire survey was employed. Indoor concentration measurements of $PM_{2.5}$, carbon dioxide, formaldehyde, and radon along with measurements of air temperature and relative humidity were made (N=14). Occupants (n=56) completed a thermal comfort questionnaire survey pre- and post-retrofit. Data collection ran from autumn 2020 until autumn 2023.

Thermal comfort improved post-retrofit along with occupant satisfaction with the indoor thermal environment and heating-systems. Post-retrofit, higher bedroom CO_2, and higher $PM_{2.5}$ concentrations were recorded in both living areas and bedrooms. Occupant behaviours e.g. blocking wall vents were significant predictors of poorer ventilation while smoking indoors was related to higher concentrations of $PM_{2.5}$. In general, homes that had mechanical ventilation systems installed were better ventilated. Underventilation, as indicated by visible condensation or mould was observed in half of the social homes surveyed and reported by questionnaire respondents (26 %). Tailored communications to occupants regarding the important role of ventilation and indoor air quality is required as part of retrofit to optimise impacts on IEQ.

1. Introduction

The European Commission (EC) has set ambitious climate action targets under its 'Fit for 55' legislative programme. These targets include achieving net zero greenhouse gas (GHG) emissions for the built environment by 2050 [1]. This sector currently accounts for almost 40 % of the energy use and 36 % of GHG emissions across the EU [2]. Europe's 'renovation wave', supported by funding of up to €72.2 billion, aims to retrofit 35 million buildings by 2030, and decarbonise the building stock by 2050. Retrofitting can not only improve a building's energy performance but also its indoor environmental quality (IEQ) [3] and health outcomes for its occupants [4].

Fabric upgrades, i.e. replacing windows, adding facade insulation and roof insulation, can reduce energy use in the residential building stock by almost 25 % [5]. However, retrofits also need to address ventilation so that the improved airtightness from the fabric upgrades does not lead to build-up of indoor pollutants concentrations and moisture. Reduced ventilation as a result of poorly designed and installed energy retrofit can result in increased concentrations of volatile organic compounds [6,7] radon [8] and increased levels of moisture which favours mould growth [9]. Improved airtightness can reduce the infiltration of outdoor pollutants like particulate matter (PM) [10,11].

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However, unfiltered mechanical ventilation can lead to increased ingress of outdoor $PM_{2.5}$ [12]. Occupant behaviours such as smoking can also lead to build-up of smoking generated pollutants indoors [12], including PM, and more so in airtight homes. Smoking negatively impacts respiratory health of occupants, but impacts are further exacerbated when smokers live in poor quality housing [13,14]. Fine particulate matter accounts for a significant proportion of the negative health impacts caused by exposure to poor indoor air [15,16] and its imperative that a singular energy focus or a 'fabric first' approach does not negatively impact on exposure to PM and other indoor air pollutants [17–19].

Research suggests that energy retrofit measures can have a positive impact on temperature and comfort aspects of IEQ in both social and private housing stock [4,8]. They can also positively impact physical and mental health from improvements in indoor temperatures [20–22]. A recent study on the impact of New Zealand's 'Warm Up New Zealand: Heat Smart (WUNZ) programme', (an insulation and heater subsidy programme) which involved the analysis of medical prescription data for over one million residents of WUNZ renovated homes, showed reduced incidence of new chronic respiratory disease and reduced exacerbations of pre-existing respiratory disease among residents of renovated homes [23]. This finding supports the positive impact of energy retrofit initiatives on the health of occupants in both social and private housing stock [4].

Recognising the link between energy inefficient housing and energy poverty, EU member states, including Ireland have prioritised a just transition towards climate neutrality in the recently recast Energy Performance of Buildings Directive (EPBD) [2]. It is estimated that 30 % of low-income households and 10 % of the EU population spend more than 40 % of their income on housing related costs [3]. Low-income housing has long been associated with poor IEQ due to factors such as the age of the building, poor building maintenance and higher smoking prevalence [24,25]. Poor IEQ negatively impacts physical and mental health of residents of these homes, who may be more vulnerable due to factors such as age and socioeconomic status [25]. It is estimated that improving daylight and reducing damp and mould could bring health and wellbeing benefits worth €100 billion per year in the EU [26].

The Irish Government retrofit programme includes a range of measures to support low-income households. In 2023 over half of the annual retrofit budget targeted fully funded retrofits for low-income homes [27] under schemes such as the Warmer Homes Scheme, the Energy Efficiency Retrofit Programme and the Midlands Retrofit Programme. In Ireland, social housing options for those on low incomes is mainly provided by Local Authorities or Approved Housing Bodies, approximately 10 % of the population resides in social housing [28] and the Irish National Retrofit Programme aims to retrofit close to 40,000 Local Authority dwellings by 2030 [29]. Current schemes in Ireland are designed to bring the homes to the cost-optimal retrofit level of B2 (estimated EUI of $\leq$ 125 kWh/m^2). In Ireland, ventilation requirements for major renovations are outlined in the Building Regulations, Part F (S.I. No. 263/2019) [30] and a Code of Practice for the Energy Efficient Retrofit of Dwellings (S.R. 54:2014&a2:2022) published by the National Standards Authority of Ireland [31].

With an enhanced focus on decarbonization targets for the built environment and the impact of same on IEQ, studies that examine the impact of energy renovation on IEQ in vulnerable housing are timely. Ireland is in a unique position within the European context, as it has a disproportionately high number of poorly performing energy-inefficient buildings compared to other EU states [32]. Consequently, Ireland has one of the most ambitious energy retrofit programs in Europe, with a goal to retrofit a quarter of the housing stock by 2030. Despite this, there is a significant lack of indoor air quality (IAQ) data for deep energy retrofitted social housing dwellings in western Europe including Ireland [25]. The majority of the IAQ research on social housing retrofits have been conducted in North America [8,25]. Due to differences in climate and housing stock, these studies are not directly applicable to the western European context. Much of the previous research on IAQ in social housing in Europe has focused on the impact of shallow or basic retrofits on apartments or multi-unit developments, or on new energy efficient dwellings [6,7,32–36]. However, 86 % of Irish dwellings consist of detached, semi-detached, or terraced construction styles which will require different combinations of solutions which will likely have a bigger impact on air permeability than multi-unit developments. The current study, the Health Impact Assessment of Energy Renovations on Irish Domestic Dwellings (HAVEN) research project, aimed to address the latter knowledge gap, by examining indoor air quality, thermal comfort, and associated health benefits of energy retrofitting among a sample of detached, semi-detached and terraced social housing dwellings in Ireland. To the authors' knowledge, this is the first study to examine indoor air quality in deep retrofitted social housing in western Europe.

The objectives of this study were to measure indoor air pollutant concentrations pre- and post-retrofit, including: $PM_{2.5}$, radon, carbon monoxide, formaldehyde, and carbon dioxide, and the thermal parameters: air temperature and relative humidity. Subjective perceptions of thermal comfort were also measured to contextualise the objectively measured thermal environment. In addition, another objective of the study was to evaluate the impact of ventilation and occupant behaviour on IAQ in the newly renovated homes. This is the first comprehensive analysis of the impact of the Irish climate action plan target related to home energy retrofits (to upgrade the energy performance of dwellings to BER B2 energy rating) on IAQ, thermal environment, and occupant perceived thermal comfort.

2. Methods

The aim of this study was to evaluate the impact of deep energy renovation measures on indoor air quality, thermal comfort and ventilation in a sample of primarily social housing in Ireland. The study employed a mixed methods approach, combining environmental monitoring of homes and a questionnaire survey exploring thermal comfort in homes pre and post energy retrofit. Ethical approval was obtained from the Research Ethics Committee of the University of Galway (Ref: 09-March-20).

2.1. Participant recruitment

2.1.1. Indoor Air Quality (IAQ) survey recruitment

Participating homes were recruited via engagement with Approved Housing Bodies (AHBs), the Sustainable Energy Authority of Ireland (SEAI)-accredited retrofitting providers, and Local Authorities involved in the Irish Government funded Midlands Retrofit Programme. Nineteen social housing properties were recruited to the IAQ surveys, comprising detached (N=3), semi-detached (N=10), and terraced (N= 6) configurations. Nine homes were single-storey (N=9), and the remaining were two-storey. Due to the COVID-19 Pandemic, some renovations were delayed or did not proceed, and an extra 3 privately owned homes (detached N=3; two storey N=2, single storey N=1) were recruited to the study. A total of 14 homes participated at both pre- and post-retrofit surveys, 3 of them private and 11 social housing properties. A further 13 social housing properties were recruited and surveyed for radon only. Dwellings were located in both suburban and rural areas across Ireland. Ten homes had pets living within the house. Table A.1 in the supplementary material (S.I. A.1) provides an overview of the characteristics of all participating homes.

The inclusion criteria for the study stipulated that home occupants were required to be non-smokers; however, it became evident during fieldwork that smoking/vaping was occurring in some of the participating homes (N=4). Pre-retrofit measurements were completed between January 2021 and July 2023; post-retrofit measurements commenced in November 2022 and were completed in June 2024. The majority of IAQ surveys were completed between 9 and 20 months post-retrofit works; one home was surveyed 33-months post-retrofit (HAVEN 03). Participating homes had pre-retrofit building energy ratings (BER) between F and C1. More information on Irish BER scheme has been provided in Supplementary material (S.I. A.2). Homes were scheduled for energy retrofit to a BER category B2 or better. The three private homes and three of the social housing properties who participated in the IAQ survey also participated in the thermal comfort questionnaire survey.

2.1.2. Thermal comfort questionnaire survey recruitment

The inclusion criteria for individuals participating in the survey were (1) their homes were due to receive a retrofit to a minimum of BER B2 standard (2) respondents were over the age of 18 and (3) informed participant consent was obtained. Invitations to participate, including the participant information sheet, were distributed to 700 homes via Local Authorities, AHBs, retrofitting contractors and energy agencies. In total, 112 homes agreed to participate in the questionnaire survey. However, attrition occurred between the pre-retrofit and post-retrofit phases, with 56 post-retrofit questionnaires returned. Out of the 56 participating houses, 44 were from Local Authorities or AHBs (79 %).

2.2. Indoor air quality (IAQ) and thermal environment monitoring

Within each residence, the objective was to measure concentrations of five pollutants and the thermal parameters temperature and relative humidity in two rooms - the main bedroom and the kitchen/ living room area, for 24–72 hours pre- and post-retrofit. In each room, the instrumentation was placed 1.0–1.5 m from the floor and away from sources of pollution, ventilation (such as windows and vents), and heat sources. Temperature, humidity, CO, CO_2 and TVOC were measured at 5-min intervals for 24–72 hours using GrayWolf IAQ-610 sensing probes. Post-retrofit, additional carbon dioxide data was collected using ARANET CO_2 sensors. $PM_{2.5}$ was measured at one-minute intervals for 24–72 hours using a TSI SidePak AM520. The SidePak was calibrated using a primary standard (DryCal® DC Lite; BIOS International, NJ, USA) before and after each use, and a daily zero check was performed using the TSI zero filter. All instrumentation (TSI SidePak and Graywolf IQ-610) was within 1 year of factory calibration at the time of sampling. A correction factor was not applied to the $PM_{2.5}$ data, due to the range of potential PM sources in homes. Absolute values could vary depending on the sources present [37]. Passive samplers were utilized for formaldehyde and radon, which remained in situ for 72 hours and three months, respectively. A comprehensive breakdown of sampling methods is provided in S.I. (Table A.3).

In mechanically ventilated homes (three private and two social housing) a KIMO MP50 manometer was used to measure air pressure in the extract units in all wet rooms. The measured pressure differences were converted to air flow (litres/second) and air change rate (h^{-1}), following the NSAI Agrément certificate for the specific ventilation systems installed in the homes [38]. Outdoor hourly average $PM_{2.5}$, temperature, humidity, and wind speed data were gathered from closest EPA air quality and Met Eireann monitoring sites, where possible [39].

Due to factors like equipment failure, power outages, and noise complaints from participants regarding the instrumentation, it was not possible to obtain 24 hours of data for all parameters in every home. During the field surveys participants were asked to complete a contextual information questionnaire adapted from Coggins et al. [40] to obtain information on occupant demographics, typical household activities, space heating and ventilation methods and reported thermal satisfaction and perception of indoor environmental quality (including odour and hygrothermal condition). During the sampling period, participants completed an activity diary to document household activities (occupant behaviour) that may influence pollutant concentrations e.g., cooking, opening windows, burning candles, and cleaning. Ventilation rates were calculated using bedroom night-time (10 pm-7 am) CO_2 data using the steady-state method [41]. Further details regarding the steady state method along with associated method uncertainty are provided in S.I.(A.4).

2.3. Thermal comfort questionnaire survey

The questionnaire was designed with reference to previous research [7,42] and used the ASHRAE 7-point thermal sensation scale [43]. The complete questionnaire is provided in S.I. (A.5). The questionnaire was piloted before use and modified based on feedback received from both Local Authorities and relevant Governmental Agencies. All participating homes in the survey received a study information sheet and an informed consent form which could be returned via stamped-addressed envelope. Upon receipt of written consent to participate, pre-retrofit questionnaire surveys were distributed by post or by Local Authority employees who were visiting homes selected for the retrofit process. Pre-retrofit questionnaires were issued to participants four to six weeks before the retrofit took place, and the post-retrofit questionnaires were distributed seven to thirteen months after the renovation was complete. The pre-retrofit questionnaires were distributed between autumn 2020 and winter 2021/2022. The post-retrofit questionnaires were distributed between spring 2022 and summer 2023.

2.4. Data pre-treatment and analysis

Data from IAQ and thermal parameters monitoring, participant diaries, and survey contextual information were collated in MS Excel spreadsheets. Data clean-up, pre-treatment and analysis was completed using R statistical software [44]. Where $PM_{2.5}$ data points were recorded at zero due to the limit of detection for the method at 0.001 mg/m^3, these were replaced with 0.0005 mg/m^3, half the limit of detection. Carbon dioxide levels recorded <400 ppm were replaced with blank ('NA') values. Summary statistics (median, mean, minimum, maximum, standard deviation, 5th percentile and 95th percentile) were calculated for indoor environmental data, for each room type, pre- and post-retrofit. Considering typical occupancy patterns, we focused on analysing daytime data (7 am to 10 pm) for living rooms and nighttime data (10 pm to 7 am, next day) for bedrooms. Pearson's correlation coefficient was calculated between living and bedrooms for the means for the first and second 24 hours of data, measured in each room. Data was excluded from the correlations where less than 80 % of the data was recorded. Statistical significance of the correlations was assessed using t-tests. For indoor environmental data, $\alpha < 0.05$ was used for statistical significance. Radon and formaldehyde concentrations pre- and post-retrofit values were compared using paired t-tests. For temperature, carbon dioxide, and $PM_{2.5}$ values, linear mixed effects models (LMEs) were used to compare the impact of retrofit [45]. The LMEs included outdoor weather data to account for the different monitoring periods. Home ID number was used as the random effect in the models. Further information regarding the LMEs has been provided in S.I. (A.6).

The thermal comfort questionnaire survey responses were compared pre- and post-retrofit using Wilcoxon signed rank test for ordinal data (e.g. Likert style questions). For binary data (e.g. number of residents who considered solar glare to be an issue, pre- and post-retrofit) Chi square analysis was used and where binary data was paired the McNemar test was employed. For statistical analysis involving the questionnaire responses, an α of <0.1 was used to identify statistically significant results.

3. Results

3.1. Retrofit measures and energy consumption

All dwellings that participated in the IAQ monitoring had cavity walls (110 mm cavity) with an inner and outer masonry leaf. Dwellings were originally built between the 1970's and 2006 and had floor areas of 48.8–77 m^2 (Local Authority dwellings) or 173 – 270 m^2 (private dwellings). A summary of the measures completed as part of the retrofit are presented in S.I. (Table A7.1). Homes had a post BER between B2 and A2 (Fig. 1). Only the three private dwellings had post retrofit air tightness tests completed (1.52 – 3.51 $m3/hr/m^2$). Four of the homes (HAVEN 7, 11, 13, 14) had no fabric upgrades undertaken during the current retrofit works as they previously had a shallow retrofit (attic and cavity wall insulation and replacement doors and windows) completed in 2015.

Mechanical ventilation systems (humidity-based demand control ventilation system) were installed in the three private homes, and in two of the local authority homes. All other homes were naturally ventilated with background ventilation (wall ventilators) and intermittent extract ventilation in the kitchen and wet rooms, as per the Irish Code of Practice for the Energy Efficient Retrofit of Buildings SR.54 [30]. Humidity-controlled wall ventilators were installed in two homes (HAVEN 5 and 19). A summary of the range of energy upgrades provided for the dwellings of the 56 participants of the thermal comfort questionnaire survey is provided in S.I. (Table A.7.2). All 56 homes had their legacy heating system replaced with a heating pump and most homes received an upgrade to their building envelope (better fenestration, insulation, etc.).

3.2. Indoor environmental quality parameters –summary statistics

Table 1 shows summary statistics of the measured IAQ and thermal parameters, pre- and post-retrofit, by room type. The CO_2 and $PM_{2.5}$ data has further been grouped by homes which had blocked vents and homes with residents who smoked, respectively.

3.3. Indoor air quality

3.3.1. Indoor carbon dioxide levels

Based on the linear mixed effect models (LMEs), retrofit status was a significant predictor of bedroom ($\chi^2(1) = 58.8$, $p < 0.001$) and living room ($\chi^2(1) = 66.1$, $p < 0.001$) CO_2 concentrations. Accounting for outdoor conditions, post-retrofit, CO_2 in living rooms reduced from 804 ppm (95 % CI: 639,1022) to 652 ppm (95 % CI: 513, 821) and in bedrooms they increased from 871 ppm (95 % CI: 735,1033) to 1002 ppm (95 % CI: 846, 1200).

Pre-retrofit, three homes had bedroom CO_2 concentrations greater than EN16798 Category IV limits (> 1350 ppm) (Fig. 2) [46] for 75 % of the measurement period, compared to five homes (four naturally ventilated and one mechanically ventilated) post-retrofit. Highest bedroom CO_2 concentrations were recorded in HAVEN 19 (maximum nighttime concentration of 4586 ppm) and a bedroom ventilation rate of 1.74 and 3.42 $L.s^{-1}.p$ was calculated for the two nights of sampling, which is lower than recommended for undisturbed sleep quality [47, 48].

Pre-retrofit, bedroom CO_2 concentrations were greater than Category III limits (within 950 ppm of outdoors, 415 ppm) for more than 18 % of the measurement period in the 22 homes compared to 57 % of the measurement period in the 14 homes post-retrofit. The five homes with bedroom CO_2 concentrations greater than Category IV limits for 75 % of sampling time, had visible mould growth since the retrofit in either the living area, bedroom, or both at the top of the skirting board or ceiling cornice area. One of the five homes, a mechanically ventilated social housing property (HAVEN 22) had visible mould in the porch area, which also occurred post-retrofit.

In living rooms of the current study, the proportion of CO_2 concentrations falling into Category III limits or above (for greater than 50 % of measurement period) also increased post-retrofit, (16 %, N=2 versus no home pre-retrofit), both houses had blocked wall vents post-retrofit and high bedroom CO_2 concentrations (S.I. Figure A9.1).

3.3.2. Particulate matter concentrations ($PM_{2.5}$)

Adding the retrofit status as a predictor significantly improved the LME model for bedrooms ($\chi^2(1) = 584.3$, $p < 0.001$) and living rooms ($\chi^2(1) = 26.6$, $p < 0.001$). Accounting for outdoor conditions, post-retrofit, $PM_{2.5}$ in bedrooms increased from an average of 13 $\mu g/m^3$ (95 % CI: 9, 19) to 25 $\mu g/m^3$ (95 % CI: 17, 37) and in living rooms increased from 28 $\mu g/m^3$ (95 % CI: 16, 49) to 33 $\mu g/m^3$ (95 % CI: 19, 57). Fig. 3 shows the proportion of PM2.5 measurements pre- and post-retrofit, in bedrooms and living areas relative to the WHO limits for

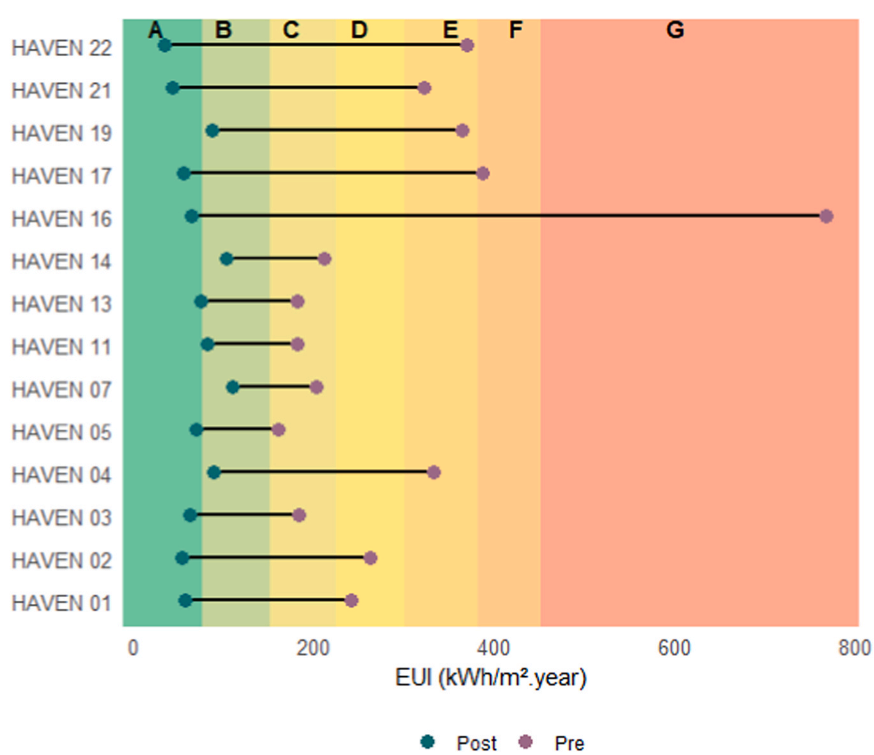

Fig. 1. Impact of the energy retrofit on study homes energy use intensity values (EUI (kWh/m2.year) and BER certification (letter's A-G).

Table 1
Summary of measured pollutant concentrations and thermal parameters, pre- and post-retrofit, across participant homes.

	Bedroom (BR)				Living Room/Kitchen (LR)			
Parameter	Pre-Retrofit		Post-Retrofit		Pre-Retrofit		Post-Retrofit	
	Mean (SD)	*Median (5 %ile, 95 %ile)*	*Mean (SD)*	*Median (5 %ile, 95 % ile)*	*Mean (SD)*	*Median (5 %ile, 95 %ile)*	*Mean (SD)*	*Median (5 %ile, 95 %ile)*
Carbon Dioxide (CO_2) (ppm) Pre-retrofit: N=18 (BR), N=18 (LR) Post-retrofit: N=9 (BR), *N*=8(LR)	733 (485)	540 (485, 1714)	967 (635)	802 (418, 2295)	642 (215)	578 (419, 1107)	714 (247)	698 (425, 1194)
Carbon Dioxide (CO_2) (ppm) *Visible blocked wall vents* Pre-retrofit: N=3 (BR), N=3 (LR) Post-retrofit: N=5 (BR), *N*=5 (LR)	1119 (563)	981 (411, 2200)	1405 (592)	1425 (480, 2466)	748 (230)	748 (423, 1157)	1018 (473)	859 (476, 1985)
Particulate Matter (PM2.5) (μg/m^3) *Smoking residences* Pre/post BR: N=2,4; Pre/post LR: N=2,4	410 (870)	53 (6, 2790)	228 (440)	58 (5,1070)	427 (809)	75 (7,2700)	258 (427)	56 (3, 1220)
Particulate Matter (PM2.5) (μg/m^3) *Non-smoking residences* Pre/post BR: N=18,10; Pre/post LR: N=21, 10	47 (143)	14 (3115)	61 (130)	15 (2, 312)	38 (157)	13 (1, 130)	41 (105)	17 (2, 150)
Formaldehyde (μg/m^3) Pre/post-retrofit BR & LR: *n*=21,14	21 (8)	21 (10, 32)	26 (11)	23 (15, 44)	21 (11)	19 (10, 33)	36 (17)	34 (20, 62)
Radon (Bq/m^3) Pre/post-retrofit, BR/LR N= 17/18, N=19,20	124 (315)	38 (15,380)	71 (40)	50 (34, 154)	111 (284)	30 (19,296)	68 (46)	46 (28,151)
Relative Humidity (%) Pre-retrofit BR/LR: N=22/23; Post-retrofit: N=14	55 (10)	57 (37, 71)	60 (9)	62 (45, 71)	51 (10)	52 (33, 66)	60 (9)	62 (45,71)
Temperature (°C) Pre-retrofit BR/LR: N=22/23; Post-retrofit: N=14	22 (2)	22 (19, 25)	21 (2)	21 (18,23)	22 (2)	22 (20, 26)	21 (2)	21 (19, 24)

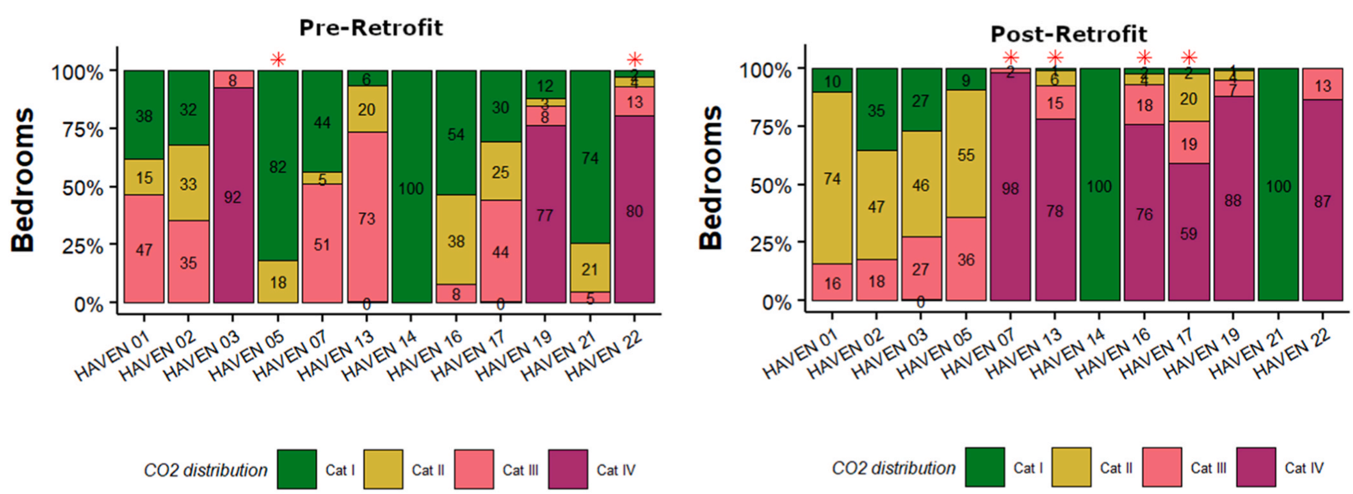

Fig. 2. Distribution of CO_2 in bedrooms pre- and post-retrofit (*marked homes indicate presence of blocked vents).

PM2.5 [49].

In the current study, the highest $PM_{2.5}$ concentrations pre-retrofit were recorded in a social housing property (HAVEN 05), (median bedroom and living room concentrations over the measurement period were 181 μg/m^3, and 244 μg/m^3 respectively). The tenant reported having their kitchen and bedroom windows open for greater than 50 % of the measurement period, and outdoor $PM_{2.5}$ concentrations were low (approximately 5 μg/m^3). Therefore, ingress of $PM_{2.5}$ from outdoors is unlikely to be a significant source. Higher concentrations are likely due to the presence of a fossil fuel (wood) based heating system, candle and incense burning, tobacco smoking in the presence of reduced ventilation due to closed wall vents during the sampling period. Post-retrofit $PM_{2.5}$ concentrations recorded in this home were significantly lower, (median concentrations 20 μg/m^3 in both rooms). Smoking was still reported post-retrofit. However, ventilation had improved (as indicated by bedroom CO_2 concentrations), wall vents were open, and the fossil fuel-based heating system had been replaced with a heat pump.

Post-retrofit highest $PM_{2.5}$ concentrations are reported in social housing property HAVEN 04 (260 μg/m^3 and 233 μg/m^3 in the living area and bedroom respectively). Smoking in the home post-retrofit may have contributed to the higher concentrations detected, coupled with low ventilation (bedroom ventilation rate of between 2 and 3.5 $L.s^{-1}$.p.). High $PM_{2.5}$ concentrations were also recorded in the bedroom of HAVEN 13 (median value 316 μg/m^3), this bedroom (22 m^3) had two occupants and was under ventilated (1.8–2.5 $L.s^{-1}$.p.) most likely due to blocked wall vents. All of this may have contributed to the high $PM_{2.5}$ concentrations recorded.

3.3.3. Formaldehyde and radon concentrations

A pairwise comparison of bedroom formaldehyde levels, pre- and

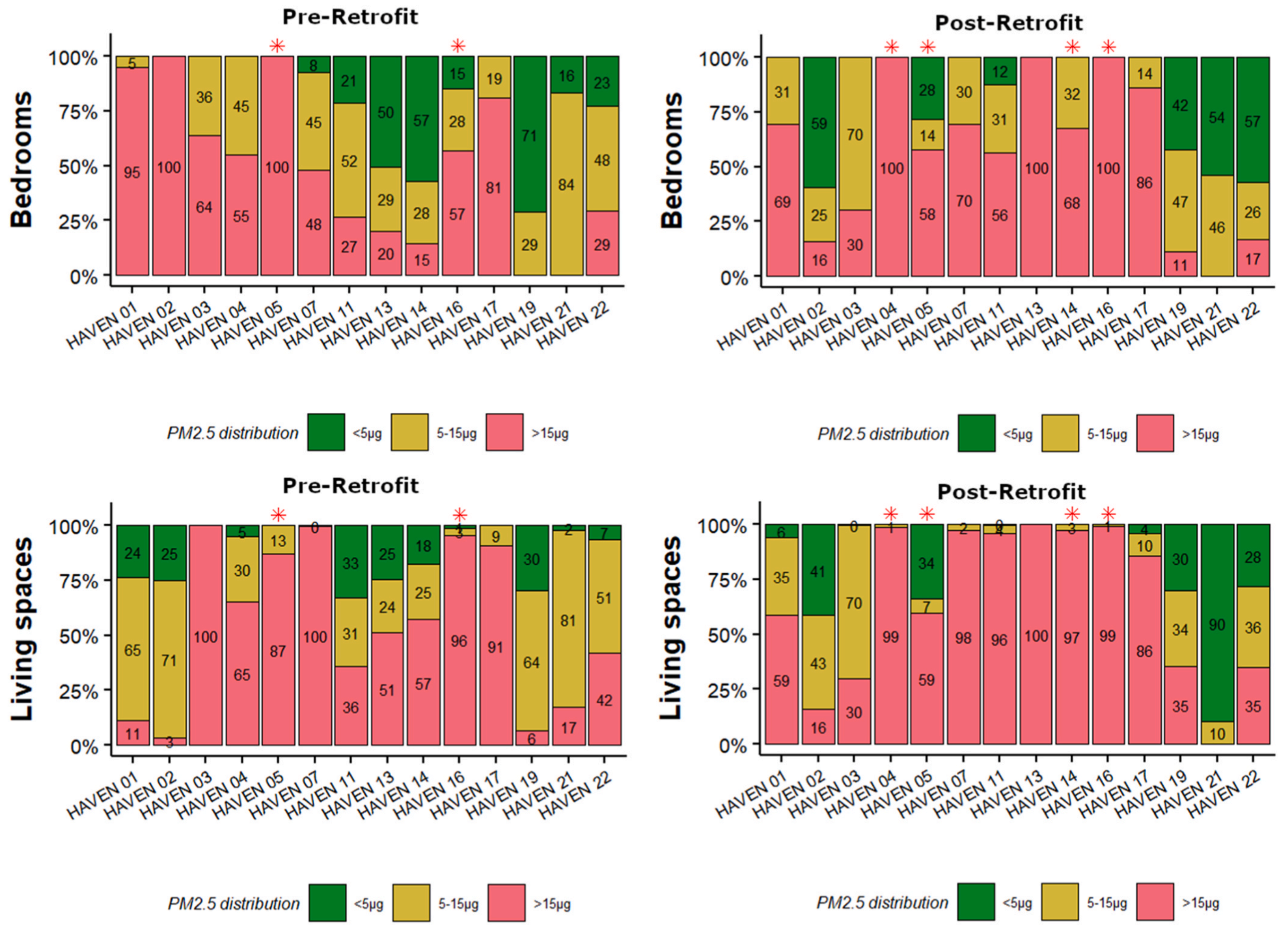

Fig. 3. (a) Distribution of $PM_{2.5}$ in bedrooms pre- and post- retrofit (*marked homes indicate the presence of smoking) Fig. 3 (b) Distribution of $PM_{2.5}$ in living rooms pre- and post- retrofit (*marked homes indicate the presence of smoking).

post-retrofit, indicated a non-significant difference (p = 0.06, V = 15). For living rooms, there was a significant increase post-retrofit (p = 0.016, V = 28), most likely due the extensive renovations associated with removing the fossil fuel heating systems in the living area. Pre- and post-retrofit formaldehyde concentrations exceed the ATSDR 1-year long term health-based guideline [50] value of 10 μg/m^3. No measurements, either pre- or post-retrofit exceed the WHO 30-minute limit of 100 μg/m^3 [51].

Previous research has shown indoor formaldehyde concentrations to vary seasonally, with higher concentrations detected during the summer period [52,53]. Only three of the 24 pre-retrofit formaldehyde samples were collected in the winter period, compared to nine of the 14 post-retrofit samples. A mixed effects model, with the room type, retrofit status, and average outdoor temperature during sampling as fixed effects and the Home ID as random effects was constructed for formaldehyde data. The model explained overall 49 % (conditional R^2) of the variations while the fixed effects explained only 19 % (marginal R^2). Of the fixed effects, the outdoor temperature had the smallest standardized beta value, 0.13 as opposed to 0.33 of room type and 0.90 of retrofit status. This implied that formaldehyde levels primarily varied due to the retrofit and outdoor temperature had little influence. Highest concentrations of formaldehyde were detected in HAVEN 17 post retrofit (50 μg/m^3 in the bedroom, and 63 μg/m^3 in the living area). At the time of the post-retrofit survey the retrofit provider had returned to the home to fix a final sealant to windows. Additionally, in this home the tenant was burning candles and incense. All these factors could have contributed to the higher formaldehyde concentrations.

Radon measurements were collected both pre- and post-retrofit in 9 homes, and in an additional 8 and 12 homes pre- and post-retrofit respectively. In all but two homes that pre- and post-retrofit measurements were made (N=9) concentrations increased post-retrofit, with the largest increase (275 % increase from a pre-retrofit value of 36 Bq/m^3 to a post-retrofit value of 135 Bq/m^3) observed in a home located in a high-risk area. The highest post-retrofit radon concentration was detected in a low radon risk area (pre-retrofit 82 Bq/m^3, post-retrofit 178 Bq/m^3). None of the 21 post-retrofit measurements exceeded the Irish EPA reference level of 200 Bq/m^3 even though eleven of the homes were in high radon risk locations [54]. One home recorded a pre-retrofit radon concentration of 1290 Bq/m^3. This home was in a high radon-risk area. Although the home did not proceed to retrofit, the survey highlighted a significant radon issue which need to be addressed. This highlights the importance of including a radon risk assessment as part of retrofit.

3.4. *Impact of ventilation type on indoor air quality*

In naturally ventilated homes, the frequency of occurrence of higher indoor CO_2 concentrations increased following the retrofit. Measured extraction rates in two of the three mechanically ventilated private homes complied with minimum boost extract rates recommended in Part F of the 2019 Irish Building Regulations [31]. At the time of the IAQ survey, there was a leak in the duct work supplying four extract terminals in one of the homes, which was later repaired. Measured extraction rates in the mechanically ventilated systems installed in the two social housing homes met minimum boost extract rates in Part F at commissioning stage [31]. The performance of the ventilation systems was not checked during surveys, as tenants were unable to supply details or information on the systems installed. The system installed in one of the social housing properties did not include a control indicator, which is a requirement in Part F [31], to ensure that the occupant can check if the system is operating correctly and whether a fault has occurred.

The switch from natural to mechanical ventilation for the three private homes resulted in a decrease in the occurrence of higher bedroom CO_2 measurements (> EN16798 Category III) (HAVEN 1–3), from 47 %, 35 % and 100 % pre-retrofit naturally ventilated status, to 16 %, 18 % and 27 %, respectively. However, the switch from natural to mechanical ventilation in one of the social housing properties resulted in poorer ventilation, 93 % of CO_2 concentrations pre-retrofit were > Category III compared to 100 % of measurements post-retrofit. The tenant in the second mechanically ventilated social home reported leaving windows and doors open during most of the day during sampling, which may account for the lower concentrations measured. A previous study [35] on IAQ in mechanically and naturally ventilated social housing in the UK identified significant under ventilation in both ventilation types, largely driven by poor knowledge of use and maintenance of MVHR systems among tenants.

Of the five naturally ventilated homes with higher CO_2 concentrations and poor ventilation (referred to in Section 3.3.1), three homes had blocked the wall vents at the time of sampling. A fourth home, also naturally ventilated, had humidity-controlled wall vents installed in the bedroom and living area, the tenant in this home did express concern regarding the poor performance of the vents.

For both radon and formaldehyde, linear mixed effect models were used to compare the impact of ventilation on the pollutant concentration post-retrofit. Ventilation type (MV vs NV) and Room type were used as fixed effects while Home ID was used as the random effect. Least square means using 'lsmeans' were used to compare the impact of ventilation type on the pollutant levels. For both pollutants, MV homes had a lower pollutant concentration. Formaldehyde concentrations were lower in the MV homes (0.030 ppm, 95 % CI: 0.010–0.050), compared to the NV homes (0.032 ppm, 95 % CI: 0.021–0.043). Radon concentrations were also lower in the MV homes (35 Bqm^{-3}, 95 % CI: 2–69), as compared to the NV homes (80 Bqm^{-3}, 95 % CI: 62–99).

3.5. Impact of occupant behaviour on indoor air quality in energy retrofits

We examined the impact of four behaviours, viz., opening of windows (percentage of time), blocking wall vents (Y/N), smoking (Y/N), and burning of incense, candles, or solid fuel (Y/N).

3.5.1. CO_2 and occupant behaviour

CO_2 concentration data is presented separately for homes with blocked wall vents in Table 1, which had higher median CO_2 concentrations across both room types (bedroom and living area 1425 and 802 ppm respectively, versus 859 and 698 ppm respectively). Figure A8.1 (S.I.) shows an example of the impact of blocked wall vents on the hourly CO_2 profile in the bedroom of one participant home, comparing it with the CO_2 profile for a similar home with unobstructed wall vents.

Adding behaviours (window opening and blocked vents) significantly improved the bedroom CO_2 model compared to the model with retrofit status and outdoor conditions ($\chi^2(2) = 120.8$, $p < 0.001$). The standardized coefficients indicated that among the fixed effects, retrofit status was the most important, followed by blocking of vents, outdoor wind speed, and window opening (0.35::0.23::0.13::0.12). For living rooms, adding behaviours did not significantly improve the CO2 model ($\chi^2(2) = 0$, $p = 1$).

3.5.2. $PM_{2.5}$ and occupant behaviour

Higher median $PM_{2.5}$ concentrations (Table 1) were recorded in the bedrooms of smoker homes compared to non-smoking residences pre-retrofit (median, 53 $\mu g/m^3$ versus 14 $\mu g/m^3$), bedroom concentrations increased post-retrofit in smoker homes, and only marginally increased in non-smoking dwellings (58 $\mu g/m^3$ versus 15 $\mu g/m^3$). Median $PM_{2.5}$ concentrations in living areas decreased in smoker and marginally increased in non-smoking residences post-retrofit (75–56 $\mu g/m^3$, and 13–17 $\mu g/m^3$ respectively). Figure A8.2 (S.I.) shows an example of the impact of smoking and vaping on the hourly $PM_{2.5}$ profile in the bedroom and living area of one participant home. Mean $PM_{2.5}$ concentrations in smoking residences were within the range of those reported previously for Irish smoker homes (mean concentration range 21 – 463 $\mu g/m^3$) [55] and social housing retrofits in the US [17]. They are slightly higher than concentrations (median value 35 $\mu g/m^3$) reported in energy efficient French smoker homes [10], and are slightly lower than those reported for [18] Canadian retrofits however the latter differences are more likely due to different sampling strategies.

Adding behaviours (window opening, blocked vents, smoking, and burning candles/incense/solid fuel) significantly improved the bedroom $PM_{2.5}$ model compared to the model with retrofit status and outdoor conditions ($\chi^2(4) = 8822.9$, $p < 0.001$). The standardized coefficients indicated that among the fixed effects, blocking vents was the dominant effect, followed by window opening, smoking, and burning candles/incense/fossil fuels (0.67::0.39::0.33:0.16). For living rooms, adding behaviours also significantly improved the $PM_{2.5}$ model ($\chi^2(4) = 7168.3$, $p < 0.001$). The standardized coefficients indicated that blocking vents (0.91) was also the dominant fixed effect for living rooms $PM_{2.5}$ model, followed by smoking (0.85), window opening (0.64), and burning (0.43).

3.6. Thermal environment - environmental surveys

Based on the linear mixed effects model, the retrofit status had a significant contribution to the temperature models in both bedroom ($\chi^2(1) = 1752.6$, p < 0.001) and living rooms ($\chi^2(1) = 1462.1$, p < 0.001). After accounting for outdoor conditions, post-retrofit, temperatures in bedrooms reduced from 22.4 °C (95 % CI: 21.4, 23.4) to 20.3 °C (95 % CI: 19.3, 21.3). For living rooms, the reduction was from 22.5 °C (95 %CI: 21.7, 23.2) to 20.4 °C (95 %CI: 19.7, 21.2). Post-retrofit, median air temperatures in bedrooms and living areas were still within EN16798 Category I limits [46], between 21 and 25.5 °C. Median relative humidity values were between 52 % and 62 %, both pre- and post-retrofit. Pre- and post-retrofit, 23 % of bedroom air temperature measurements were within Category 3 limits or worse (< 20° C or > 26° C) mostly < 20°C category. Post-retrofit most of the bedroom air temperature measurements, which were within Category III limits, were recorded in the social housing home which had the humidity-controlled wall vent (60 % of measurements). Post-retrofit, 24 % of living room air temperature measurements were within Category III limits or less, compared to 13 % pre-retrofit (S.I. Figure A9.2 and A9.3).

Most participants in the environmental surveys (85 %) expressed satisfaction with the heating in their home post-retrofit, compared to 55 % pre-retrofit. Post-retrofit several tenants (36 %) expressed concern regarding draughts that could cause heat to escape but this number had reduced since pre-retrofit from 63 % to 36 %. In both pre-retrofit (44 %) and post-retrofit (47 %), a number of occupants identified the ventilation system as a source of draught in their home.

Pre-retrofit five of the six homes that identified the ventilation system as a source of draughts in their home had blocked wall vents. Only two participants reported blocking wall vents in the questionnaire, compared to an observed five homes with blocked wall vents during the field studies.

Pre-retrofit, 28 % of bedroom relative humidity measurements were between 60 % and 80 %, compared to 55 % between 60 % and 100 % post-retrofit. Pre-retrofit higher bedroom RH values are recorded in HAVEN 5, 17, 19 and 21, post-retrofit higher RH values (between 60 % and 80 %) are recorded again in HAVEN 5, 17, 19 and a further 3 homes (HAVEN 7, 16 and 22). Highest RH values (83 % values > 80 %) were recorded in the bedroom of HAVEN 19. Four of the six homes with higher RH readings post-retrofit had visible and reported mould issues since the retrofit (Figure S.I. A9.4 and 9.5).

3.6.1. Thermal Questionnaire data

Fig. 4 shows that post-retrofit 51 % of respondents reported that, in general, their thermal comfort was ‘Warm’ compared to just 26 % of respondents pre-retrofit. This was mirrored to a certain degree by a decrease in those reporting that in general they were ‘Cold’ and or ‘Cool’ from 34 % pre-retrofit to just 6 % post-retrofit. Occupant satisfaction (respondents reporting “Satisfied” and “Fairly satisfied”) with temperature in their home also improved post-retrofit. Compared to 15 % of respondents pre-retrofit, 44 % of respondents post-retrofit reported being “satisfied” with the temperature in their home ($p<0.01$) (Fig. 5). Post-retrofit, a higher proportion of respondents (86 % vs 58 %) reported that the temperature within their home during warm/hot weather was ‘Occasionally too hot’ or ‘Often too hot’. Significant reductions in reported levels of condensation in homes after retrofitting works were reported ($p<0.01$) with over 46 % of respondents reporting no problems with condensation after the retrofit. This is a reduction from 86 % of respondents who identified some level of condensation issue pre-retrofit. Similarly, fewer respondents reported mould on windows/ceilings/walls post-retrofit, compared to pre-retrofit (31 % versus 45 % (N=54, $p<0.1$)). Unfortunately, levels of condensation and the presence of mould was not solved for all homes post-retrofit. Twenty six percent (26 %) of respondents identified condensation as a continuing issue (moderate to very severe level) post-retrofit, and many of those who reported issues with condensation also reported the occurrence of mould, specifically 94 % of those who reported presence of mould (N=16) had condensation issues.

3.6.2. Sources of thermal discomfort

Overall, there was a reduction in the reported (thermal comfort questionnaire) number of sources of thermal discomfort post-retrofit (Fig. 6). The most significant reductions were in reports of ‘draughts from windows’ ($p<0.05$), ‘temperature changes between rooms’ ($p<0.01$) and ‘hot/cold surrounding surfaces’ ($p<0.05$). Draught from windows was a source of local thermal discomfort, pre-retrofit, for almost a third of the participants and perhaps contributed to the overall thermal discomfort registered by participants, pre-retrofit. Similar to feedback received during the IAQ surveys (Section 3.6), draught from vents was still a point of concern for some survey respondents post-retrofit (N=20 post-retrofit).

There was also a reduction (-59 %) in the number of homeowners identifying ‘deficient windows’ ($p<0.05$) as a source of discomfort that caused air movement or draughts. These improvements post-retrofit likely reflect the improved window quality, wall insulation, and weather sealing of doors and windows that were completed as part of the retrofit.

In the thermal comfort questionnaire survey, 44 homes were naturally ventilated and included sleeved wall ventilators/humidity-controlled wall ventilators and trickle vents in the windows in each habitable room. Post-retrofit, with the newly installed, functional wall vents, the makeup air coming from outdoors through the vents was likely more noticeable. It was also a cause of discomfort, unfortunately.

Following retrofitting, homes get more airtight envelopes hence adequate ventilation must be ensured. Only 12 of the homes participating in the questionnaire survey had mechanical ventilation installed as part of retrofitting. Mechanical ventilation is not funded currently under the Irish Energy Efficiency Retrofit Programme for social housing [56].

There was a significant increase in the number of occupants reporting satisfaction with the new heating system (heat pump) installed, 81 % reporting being ‘satisfied’ or ‘fairly satisfied’ post-retrofit versus 42 % pre-retrofit ($p<0.01$) (Fig. 5). Only two of the 14 participants in the IAQ aspect of the study reported being unsatisfied with the new heat pump.

4. Discussion

Indoor air quality (IAQ) is an important component of IEQ, and post retrofit occupancy IAQ studies in social housing are a pressing priority. Such studies, including the current work, provide exposure data required to evaluate the impact of DER on the health of building occupants [16,22]. While studies of residential energy retrofits have evaluated the role of occupant behaviour in the success of such interventions [57], i.e, energy use, few exposure assessment studies have looked at how occupant behaviour impacts on exposure to indoor air pollutants (IAPs) in deep energy retrofitted social housing in western Europe. Results from this study contribute to our understanding of how the current deep energy retrofit measures which are being applied to residential social housing in Western Europe impact on the concentrations of indoor air pollutants, and thermal comfort.

4.1. Retrofits and improved thermal comfort

Results from the questionnaire survey showed that thermal comfort (p-value <0.01), and warmth perception improved post retrofit while the predicted energy usage of these homes reduced dramatically, which aligns with previous studies on thermal comfort post-energy retrofits [8, 58]. Retrofitting provided more airtight and better insulated windows, reduced chances of hot/cold surfaces around the homes, and more uniform thermal conditions. The retrofits thus helped reduce local sources of thermal discomfort and ensured improved thermal comfort perception with reduced energy use. The improvement of thermal comfort perception combined with lower temperatures post-retrofit suggest that pre-retrofit, occupants were using higher temperature as a

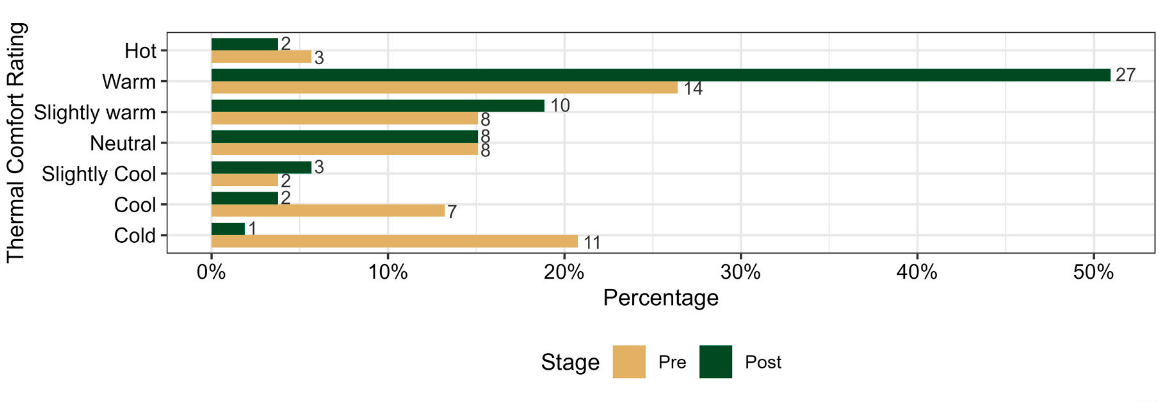

Fig. 4. Change in occupant thermal comfort sensation, pre- and post-retrofit.

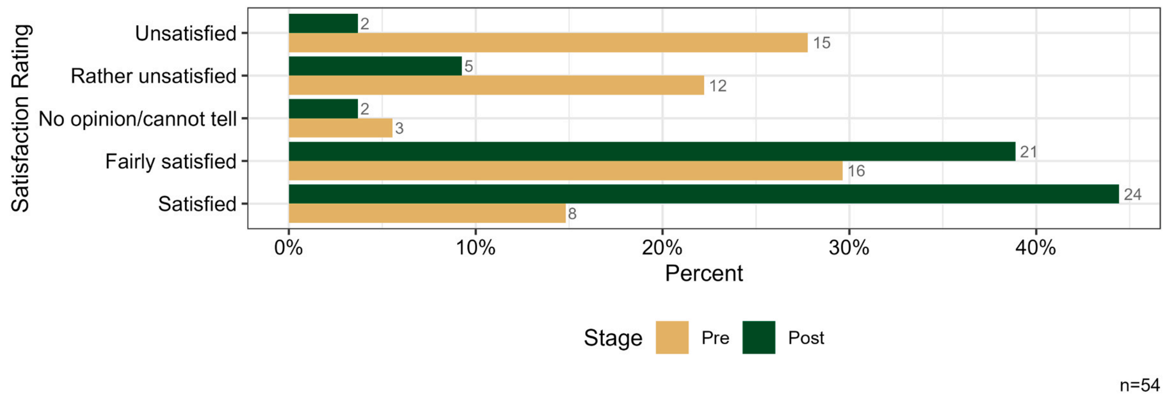

Fig. 5. Change in temperature satisfaction pre- and post- retrofit.

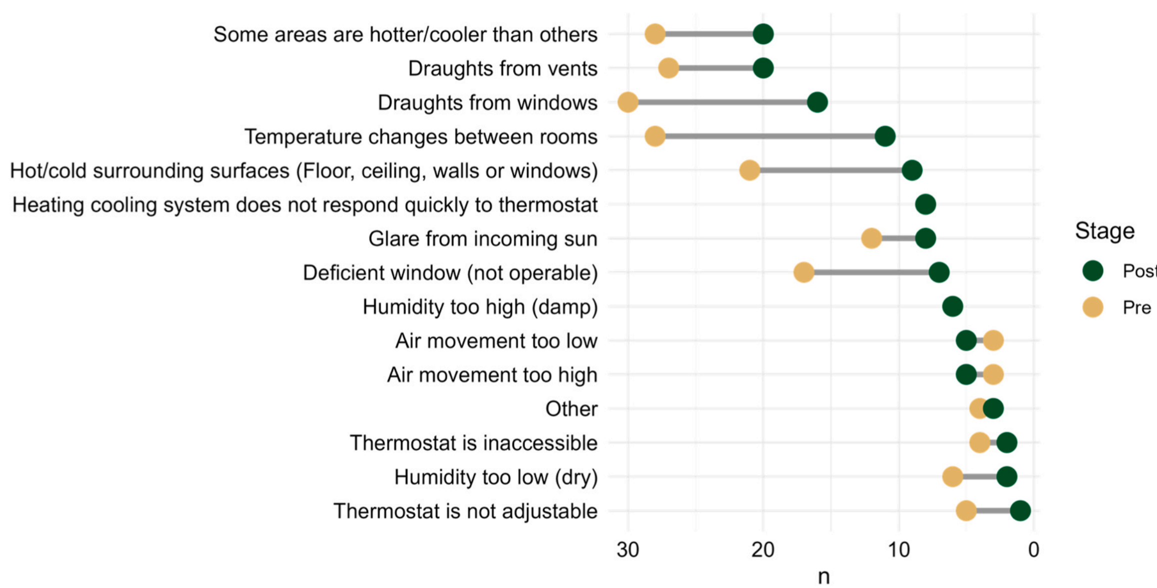

Fig. 6. Change in sources of thermal discomfort pre- and post-retrofit.

buffer against sources of thermal discomfort. discomfort and non-uniformities could be examined, as these aspects of thermal comfort cannot be assessed solely based on monitoring air temperature. Further studies should consider including targeted questionnaires, as used in this survey, and measurement of draught and radiant asymmetry can be employed to better evaluate the benefits of retrofitting to occupant comfort.

Only a small minority of study participants (Fig. 7) reported issues related to regulating the heating system in the home, (e.g., 'thermostat is not adjustable', and to a lesser extend 'thermostat is inaccessible', 'Heating/cooling system does not respond quickly to thermostat') pre- or post-retrofit. Recent research on social housing retrofits has shown that providing occupants with better control over their indoor environment, in this case heating regulation systems, improves satisfaction

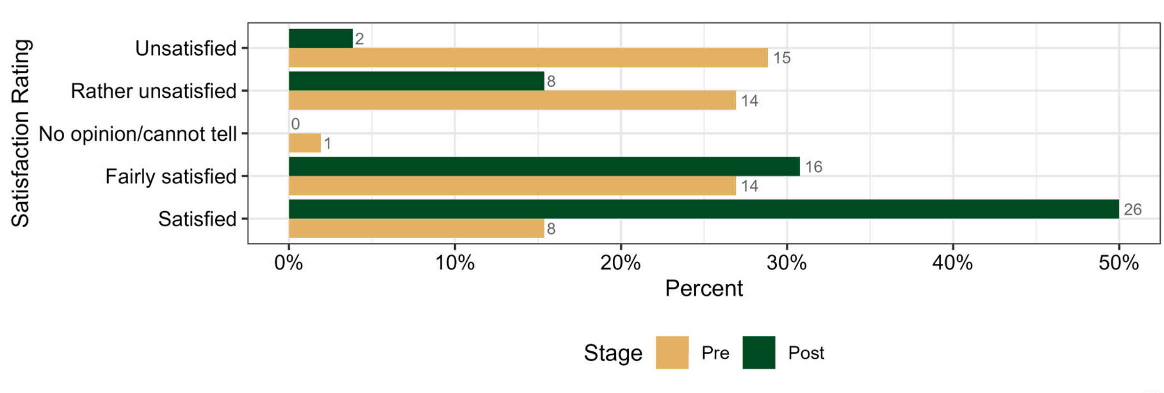

Fig. 7. Change in satisfaction with heating in the home pre- and post- retrofit.

[59]. It also improves overall perception of the positive impact of the renovation on IEQ. Like the current work, studies on Irish (privately owned) energy-retrofitted dwellings [40,45] and social housing [7] have reported significant improvements in occupant comfort and satisfaction with the newly installed home heating systems post-retrofit, particularly during the heating season.

Several respondents (post-retrofit) also reported feeling 'hot' in their homes during the summer months, which suggests that retrofitted homes may be susceptible to overheating during summer. The risk of overheating in newly renovated domestic dwellings has already been identified as an area of concern [6,34]. This concern is likely to grow as more extreme weather events are predicted in future years, due to climate change [60,61].

4.2. Retrofits and indoor air quality

Although non-smoking homes were invited to participate in the current study, evidence of tobacco smoking and vaping was observed in a number of homes (N=4) during fieldwork. Pre-and post-retrofit mean $PM_{2.5}$ concentrations in smoking residences, across all room types, were higher than the WHO 24-hr air quality guideline value of 15 μg/m^3 [49]. Concentrations in non- smoking dwellings were less than 15 μg/m^3 pre-retrofit, and at the limit (bedrooms) or just exceeding the limit (living areas) post-retrofit. Previous research has shown that $PM_{2.5}$ concentrations can be up to 10 times higher in smoker homes compared to non-smoker homes [18,55]. Therefore, those involved in the management of retrofit programmes need to ensure that occupants of energy efficient homes understand the consequence of their behaviours and practices such as smoking indoors in a more airtight home. Although deep energy retrofits offer the potential to significantly lower combustion-generated particulate matter (PM) through the decarbonization of the building heating system [27], our findings provide evidence that unchanged occupant smoking practices post retrofit, in a newly renovated decarbonised, more airtight home, can lead to increased $PM_{2.5}$ exposure. There is also a role for public health officials leading smoking cessation policy who need to consider the potential impact of increased exposure to second-hand tobacco smoke following energy retrofit particularly among vulnerable communities. Recent Irish Census data shows that 34.1 % of social housing residents smoke regularly compared to 14.9 % of the rest of the population, and so smoking is potentially a significant source of indoor PM in Irish social housing [28].

The average radon concentrations measured post-retrofit in this study were lower than the national average for domestic dwellings in Ireland [62]. The increased airtightness of ground-level building envelopes, combined with reduced ventilation after retrofitting, can result in higher radon levels [6,63–66]. Previous research evaluating the impact on retrofitting strategies on radon in UK and Irish homes [66,67] has largely employed model simulations, and there have been limited field studies focusing on radon exposure post retrofit in social housing [68, 69]. Our research, although based on a small sample size, indicates a median increase in radon concentrations of 105 % (ranging from −13–275 %) post-retrofit. This supports the modelled predictions for Irish homes and slightly exceeds projections for UK homes. Together with computational predictions [66], our findings significantly enhance the understanding of how deep energy retrofit measures impact radon exposure in naturally ventilated Irish housing. Given that Ireland has recorded some of the highest radon levels in Europe, controlling radon is essential, particularly in social housing, where due to higher smoking prevalence, any increase in radon levels could elevate lung cancer risks [54].

Higher formaldehyde concentrations were recorded post-retrofit which is in line with previous energy retrofit studies [7,8,40,45]. Occupants need to be reminded to 'air out' their homes more frequently following retrofit to remove elevated VOC concentrations arising from the off gassing from recently used construction products.

Decreased ventilation post retrofit either as a result of poor occupant engagement with newly installed systems or underperforming ventilation, could lead to the accumulation of indoor pollutants from indoor sources. In this study, post-retrofit indoor air pollutant concentrations (CO2, PM2.5, Formaldehyde and radon) were higher in naturally ventilated homes compared to mechanically ventilated homes and also higher than in previously reported mechanically ventilated deep energy retrofits in Ireland [40,45]. Post-retrofit, higher ventilation rates (S.I. Figure A8.1) and lower median CO_2 concentrations were recorded in the mechanically ventilated homes compared to naturally ventilated homes (699 ppm and 660 ppm for bedrooms and living areas in mechanically ventilated versus 887 ppm and 780 ppm for same rooms in naturally ventilated homes). Previous studies [17] report improved indoor air quality, and reduced $PM_{2.5}$ when retrofit included replacement and repair of source ventilation and the provision of mechanical ventilation. Our study alongside previous research [9] adds to a growing body of evidence supporting the inclusion of mechanical ventilation as part of deep energy retrofit of domestic dwellings.

4.3. IAQ and occupant behaviour

Multiple studies have shown occupant behaviour to be an important predictor of indoor air quality [70–72]. Our research indicates that achieving optimal indoor air quality (IAQ) benefits through deep energy retrofitting in social housing is complicated by the significant impact of occupant behaviours, such as blocking wall vents and smoking. In our study tenants reported blocking the vents in response to perceived draught or heat loss, or to prevent ingress of tobacco smoke from outdoors. Many of the homes with blocked wall vents and compromised ventilation also had visible mould growth. Occupants may have been unaware of the important role of the wall vents in providing ventilation to their home and that under ventilation can lead to mould growth. Similar to this current study, previous work in Irish energy renovated social housing [73] also reported occupant dissatisfaction with newly installed wall vents and study participants reported blocking wall vents due to the perceived draughts and heat loss. Taken together with the conclusions from [73] our results suggest that use of wall vents is not a reliable ventilation option for deep energy retrofitted social housing.

Migration of indoor air pollutants between social housing units has previously been identified as concern for some [17,18]. Installing mechanical ventilation, improving building air tightness along with sealing individual compartments has been recommended to mitigate this issue. However, most of the social housing homes in this study did not have mechanical ventilation.

If occupants do not modify their behaviour, activities and habits that impact the home thermal environment and IAQ, retrofits can only have a limited positive impact and at worst a negative impact [33]. For example, in this study, it was found that smoking behaviour had a greater effect on $PM_{2.5}$ concentrations than retrofit status. Studies on social housing retrofits in Canada [18], found no significant difference in $PM_{2.5}$ concentrations pre- and post-retrofit, and highlighted smoking behaviour to have a significant effect on levels of indoor $PM_{2.5}$. The UK Smartline project [74] also among social housing properties, showed that occupant behaviour, particularly smoking and vaping were significantly associated with higher levels of $PM_{2.5}$. In that study 25 % of the exposure levels monitored over a one-year period among 279 households were higher than the WHO $PM_{2.5}$ annual guideline value of 5 μg/m^3.

Occupant behaviour following retrofit is easier to influence when the behaviour change is perceived to be easy and socially accepted [74]. Retrofit programmes will need to consider tailored messaging for vulnerable groups such as social housing tenants, that considers their specific needs and preferences that highlights the importance of indoor pollutant sources, such as smoking and to promote positive engagement with ventilation as part of the retrofit roll out to tenants. Previous US based energy retrofit projects [17] have shown the positive impact of such educational programmes on lowering exposure to indoor pollutants such as $PM_{2.5}$ post retrofits.

4.4. The retrofit handover

While installed mechanical ventilation systems (n=5) were mostly adequately designed and commissioned, our interactions with the home occupants showed that there is frequently a lack of proper handover regarding technical aspects of the retrofit e.g. the ventilation systems and other new systems such as the heat pump. Previous research has shown that inadequate handover of the physical or technical aspects of a retrofit can lead to a perceived lack of control, encourage energy-inefficient behaviour, and cause dissatisfaction with indoor environmental quality (IEQ) [59]. Our findings indicate that this remains a persistent issue. Detailed handover and tailored messaging for different resident groups, not just a technical guide on the ventilation system, [75] is needed to accompany the retrofit so that tenants or homeowners understand the importance of ventilation in a retrofitted, airtight home. The retrofit handover should include details of the design and commissioning records and instructions on how to correctly maintain the systems. Ventilation systems are an essential component of any building, but especially in energy efficient buildings to ensure improved air quality given the increased level of building air tightness [76,77].

4.5. Limitations of the current study

As previously noted, the COVID-19 pandemic and associated public health restrictions in Ireland impacted on both the roll-out of the national retrofitting programme and recruitment and data collection for this project. Low engagement in the study initially necessitated the inclusion of both private and Local Authority homes within the sample, thereby increasing the variability in the range of homes included and retrofit measures applied. The data collection period was also extended beyond the initial plan, with some homes choosing to withdraw their participation, due to the non-completion of the retrofit works during the specified timeline. The use of questionnaire survey data is beneficial; however, it is subject to biases including recall bias and social desirability bias which may influence findings. The small sample size and limited monitoring period limits generalisability of the results and so findings must be interpreted with caution.

5. Conclusions

Results from our study showed a substantial reduction in predicted energy use along with improved thermal comfort and increased satisfaction with both the indoor thermal environment and heating.

However, occupant behaviours such as blocking wall vents were significant predictors of poorer ventilation and smoking indoors was related to higher concentrations of $PM_{2.5}$ in social housing properties. It is crucial to the success of the retrofit programme that those engaged in the construction and delivery of an energy retrofit understand the varied factors, including occupant related preferences and needs, that impact IAQ and thermal comfort, to avoid the unintended consequences which may arise if following solely a 'fabric first' approach.

In general, homes which had mechanical ventilation systems installed as part of the retrofit were better ventilated. This adds to a growing body of research evidence supporting the inclusion of mechanical ventilation as part of the deep energy retrofit of social housing. Almost half of the social housing tenants surveyed, residing mainly in naturally ventilated homes had visible condensation or mould issues following retrofit, and 26 % of the thermal comfort questionnaire respondents also reported condensation or mould issues following retrofit, indicating possible issues with under ventilation and/or thermal bridging.

Post-retrofit occupancy studies, such as HAVEN, are required to help capture potential unintended consequences related to the technical measures installed as part of the retrofit and/or occupant activities. In the interim, tailored communications regarding the important role of ventilation and indoor air quality following energy retrofit will need to be provided to homeowners and or tenants following retrofit.

CRediT authorship contribution statement

Victoria Hogan: Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ann Marie Coggins:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Edel Doherty:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Cowie Hilary:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Wemken Nina:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Declan Foster:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Norton:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Asit Kumar Mishra:** Writing – review & editing, Methodology, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indenv.2024.100058.

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