Title	Indoor air quality, thermal comfort and ventilation in deep energy retrofitted Irish dwellings
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Publication Date	2022-05-28
Publication Information	Coggins, Ann Marie, Wemken, Nina, Mishra, Asit Kumar, Sharkey, Martin, Horgan, Liam, Cowie, Hilary, Bourdin, Emmanuel, McIntyre, Brian. (2022). Indoor air quality, thermal comfort and ventilation in deep energy retrofitted Irish dwellings. Building and Environment, 219, 109236. doi:https://doi.org/10.1016/j.buildenv.2022.109236
Publisher	Elsevier
Link to publisher's version	https://doi.org/10.1016/j.buildenv.2022.109236
Item record	http://hdl.handle.net/10379/17201
DOI	http://dx.doi.org/10.1016/j.buildenv.2022.109236

Building and Environment 219 (2022) 109236

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Indoor air quality, thermal comfort and ventilation in deep energy retrofitted Irish dwellings

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ARTICLE INFO

Keywords:
Deep energy retrofit
Indoor air quality
Energy efficient homes
Formaldehyde
PM2.5

ABSTRACT

Residential building stock energy retrofits will play a key role in EU climate actions. The impact of these retrofits on indoor air quality (IAQ) and occupant comfort needs to be assessed to inform future renovation programmes. This study evaluated IAQ and occupant satisfaction in a sample (n = 14) of deep energy retrofitted Irish residences, at least 12 months post retrofit. Measurements of PM2.5, formaldehyde, total volatile organic compounds (TVOCs), carbon monoxide, radon, and carbon dioxide were made in the main bedroom and living area over a period of two days to three months (depending on the pollutant). Temperature and humidity in most homes were within design comfort limits. Higher concentrations of all pollutants were measured in bedrooms. Only 30% of bedroom data met EN16798 Category I limits for CO_2 (within 380 ppm of outdoor concentrations), suggesting that bedrooms maybe under ventilated. Median formaldehyde concentrations of 25.4 and 20.7 μg/m^3 were detected in bedroom and living rooms respectively, with building materials likely being the major source. All radon data (apart from one home located in a high radon area) was less than the national reference value of 200 Bq/m^3. Measured ventilation extract flow rates in most participating homes would not meet the minimum performance requirements in Irish Regulations of 2019 – introduced post completion of the retrofits in this study. Greater compliance with the ventilation requirements of retrofits and the promotion and use of low emitting construction materials are recommended.

1. Introduction

It is estimated that approximately 75% of Europe's existing building stock is inefficient [1]. Additionally, one out of every three European children is likely living in unhealthy homes, with structural or environmental issues that affect indoor air quality [2]. The European Commissions 'renovation wave strategy' [3] aims to double Europe's annual building renovation rate over the next ten years, offering thousands of citizens an opportunity to improve the energy performance of their dwelling and their living conditions leading to improved indoor air quality (IAQ) and related health outcomes such as respiratory health [2].

The decarbonisation of Ireland's residential and commercial building stock presents a significant challenge. The built environment alone accounted for 12.7% of Irelands greenhouse gases in 2018. Irish residential buildings use 7% more energy and emit 58% more CO_2 than the EU average and are 70% reliant on fossil fuels. Approximately 80% of Irish homes have a Building energy rating (BER) of C1 or less (primary energy use intensity (EUI) of >150 kW h/(m^2.year)) [4]. Ireland plans to retrofit 0.5 million residential dwellings by 2030 to a BER B2 standard (EUI of less than 125 kW h/(m^2.year) [5], this would be equivalent to a reduction in CO_2 emissions of approximately 68% [6]. The Deep Retrofit Pilot Programme, was introduced in 2017, managed by the Sustainable Energy Authority of Ireland (SEAI) it aimed to test whole-house retrofits, including the requirement for a high performing fabric, reduced thermal bridging, improved air tightness (≤5 m^3/h.m^2 @ 50 Pa), use of

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https://doi.org/10.1016/j.buildenv.2022.109236
Received 29 March 2022; Received in revised form 29 April 2022; Accepted 23 May 2022
Available online 25 May 2022

renewable fuels, and mechanical ventilation to support air quality [7].

Given that we spend 80–90% of our life indoors, and up to two thirds of this time at home, IAQ in our homes has an important role to play in our health and wellbeing [8,9]. Adequate ventilation, mitigation of indoor and outdoor pollution sources, and promotion of safe, low chemical emitting construction materials in energy efficient airtight buildings are important to avoid potential negative impacts on the indoor environment and its occupants [10–16]. In Europe the Energy Performance of Buildings Directive requires member states to take account of indoor climate conditions, including good ventilation and the comfort and health of building occupants, when developing building energy policy [17]. The COVID-19 pandemic has re-ignited a global debate on the need to define health-based building ventilation standards [18], instead of ones based on occupant perception and sensory discomfort. The indoor environment contains a complex mix of pollutants, of both indoor and outdoor origin, many of which have well defined impacts on health [19]. Indoor air quality in homes is an area of significant importance given the effects of indoor air pollutants (IAPs) on respiratory, cardiovascular, neurodevelopment, and cognitive function [20–23]. Particulate matter ($PM_{2.5}$), radon, formaldehyde, nitrogen dioxide, benzene and carbon monoxide are among some of the many health relevant pollutants, that have been measured in retrofitted buildings, often at concentrations exceeding guidance values [11,24–27]. In US residences, exposure to IAPs is thought to be responsible for up to 1100 DALYs per 100,000 persons, with pollutants such as $PM_{2.5}$, acrolein and formaldehyde dominating and exposure to second-hand tobacco smoke and radon making a significant impact when present [9]. In Europe (EU-26), an annual burden of 2.1 million DALYs (dominated by cardiovascular, lung cancer and various respiratory diseases and symptoms) has been attributed to exposure to indoor air pollution [28]. Exposure to radon is an important priority for Ireland due to the prevalence of igneous rock formations with it accounting for up to 300 cases of lung cancer per year [29]. Recent international research on retrofitted homes suggests that radon concentrations can be higher post retrofit [25,30,31], most likely due to increased building air tightness with poor building ventilation or poor design causing increased infiltration from soil beneath the building. Research in this area stresses the importance of including a radon risk assessment as part of home energy efficiency upgrade [25].

The significant health burdens from exposure to $PM_{2.5}$ (outdoors) are well documented [28,32]. It is also a priority pollutant for Ireland, as a significant proportion of residential dwellings still use solid fuel burning for home heating [33]. In wintertime, outdoor $PM_{2.5}$ concentrations regularly exceed the WHO daily limit in Irish urban areas, largely due to residential solid fuel use [34]. Indoor exposure to $PM_{2.5}$ mainly occurs from infiltration of outdoor $PM_{2.5}$ [35] and when outdoor PM2.5 concentrations are elevated, unfiltered home ventilation systems can result in high concentrations indoors, adversely impacting health [36]. Indoor exposures can also arise when cleaning, lighting, and re-fuelling stoves or open fires, or cooking and cleaning activities, burning candles and incense, and tobacco smoking [16,37,38].

Elevated levels of formaldehyde have been often noted post retrofit, most likely due to increased temperature and the addition of new furnishings and building materials [39]. Formaldehyde is classified as a 1B carcinogen by IARC [39]. Reported indoor concentrations for residential buildings post moderate or basic retrofits vary from, 33 μg/m^3 in retrofitted multi-family buildings in Lithuania [25] to up to 67 μg/m^3 in retrofitted multi-family residential buildings in Slovakia [27] and up to 22 μg/m^3 in Irish homes post moderate retrofits [26].

Most of the research to date on residential energy retrofits has focused on energy efficiency and few have looked at the impact of the retrofit measures on IAQ and health [10,38]. Of the studies which have focused on IAQ, many have looked at moderate, basic, or simple retrofits with few evaluations on deep energy retrofit or ventilation added retrofits [39].

Mechanical ventilation has an important role to play in removing IAPs in retrofitted buildings. Studies comparing IAQ in mechanically ventilated with naturally ventilated buildings have found lower concentrations of formaldehyde [25] TVOCs, CO_2, fungi, mould spores and radon [41,42] in mechanically ventilated homes. Improving the ventilation rate or filtering inlet air can result in better health outcomes for occupants from lower exposure [28]. However, if the ventilation systems are inadequate or if the systems are not used correctly by the occupants, IAQ concentrations can often exceed levels before the energy retrofit [11,27,39].

This paper describes results from the ARDEN research study - indoor air, ventilation and comfort in Irish domestic dwellings post deep energy retrofit. Concentrations of $PM_{2.5}$, radon, carbon monoxide, formaldehyde, carbon dioxide, and TVOCs, along with measurements of temperature and relative humidity were collected. Environmental measurements were supplemented with information on measured ventilation rates, building characteristics, and occupant feedback, collected using a questionnaire and occupant diaries. ARDEN aimed to characterise IAQ and thermal comfort in a sample of deep energy renovated Irish dwellings and make comparisons with IAQ guidelines and other data from energy efficient domestic dwellings were available.

2. Methodology

2.1. Recruitment of study dwellings

Homes which had participated in the SEAI Deep Energy retrofit pilot programme were recruited to participate in the study [6]. Fourteen dwellings (ARDEN 20–33); detached (N = 7), semi-detached (N = 5) and one apartment (a top floor apartment in a semi-detached dwelling), were surveyed. Dwellings were located across Ireland in both urban, sub-urban and rural locations. Three of the participating homes were part of national housing association (ARDEN 25–27), two homes were rented (ARDEN 20, 21), and the remaining were owner occupied. Six of the homes had pets in the home (ARDEN 26–30, 33) at the time of the surveys. Participants were non-smoking households with at least two adults living in the premises. Measurements were collected in two homes over the winter period (March 2020, also the heating period in Ireland), and the remaining 12 homes over the summer period (July––August 2020 and June–August 2021, non-heating period in Ireland, these homes did not have any cooling system). All homes underwent a deep energy retrofit between 2018 and 2020 and were between 12- and 36-months post retrofit at the time of the study. Ethical approval for the study was obtained from the Research Ethics Committee of the National University of Ireland, Galway (Ref: 19-Jan-15).

2.2. Indoor air quality monitoring

Within each dwelling, the concentrations of six IAPs were measured in the main living room and master bedroom. Surveys were completed over the period February 2019–August 2021, only two (ARDEN 20 & 21) of the 14 homes were surveyed during the heating season. Instrumentation was placed approximately 1.0–1,5 m (seated head height) above floor level, and at least 1 m away from direct sources of pollutants or exposure modifiers (windows, ventilation extracts etc.). Every effort was made to collect measurements in the area of the room most frequented by occupants. Temperature, humidity and the concentrations of the following IAPs were measured at 5-min intervals: CO, CO_2, total volatile organic compounds (TVOC). Concentrations of $PM_{2.5}$ were measured at 1-min intervals. Taking homeowner preferences into account, for most rooms 44–48 h of data was collected for the above parameters. Average concentration of formaldehyde were measured over 3 days using a passive sampler. Radon concentrations were measured over a 3-month period. A summary of the sampling methodologies and sampling instrumentation and instrument resolution is presented in Table 1. All instrumentation (TSI SidePak AM510 & Graywolf IQ-610), were within 1 year of factory calibration and was zero calibrated before and after each use. A primary standard (DryCal® DC Lite; BIOS International, NJ,

Table 1
Summary of indoor air quality pollutant/thermal parameters monitored, and sampling methodology employed.

Parameter	Sampling method	Accuracy/ uncertainty	Sampling duration
TVOC	Photoionization 10.6 eV detector, Graywolf TG-502, Graywolf IQ-610	±9.9%	Every 5 min over 48 h
CO_2	Non-despersive infra-red probe, Graywolf TG-502, Graywolf IQ-610, LOD = 1 ppm	±3%	Every 5 min over 48 h
CO	Electrochemical sensor, Graywolf TG-502, Graywolf IQ-610, LOD = 0.3 ppm	±2.0 ppm	Every 5 min over 48 h
PM2.5	90° light scattering, laser diode TSI SidePak AM510 fitted with a PM2.5impactor	Res: 1 μg/m^3	Every 1 min over 48 h
Temperature	Pt100 sensor, Graywolf TG-502, Graywolf IQ-610	±0.3 C	Every 5 min over 24 h/ 48 h
Humidity	Capacitive detector, Graywolf TG-502, Graywolf IQ-610	±2.0%	Every 5 min over 24 h/ 48 h
Formaldehyde	UME^X 100 passive sampler. Post sampling analysed by solvent extraction and analysis by HPLC (high-performance liquid chromatography) with UV detection	7-day LOD: 0.2 ppb (0.0002 mg/m3)	3 days
Radon	Alpha track passive detector	±15% rdg	3 months

USA) was used to calibrate the TSI SidePak AM510 flow rate, before and after sampling. A correction factor was not applied to the $PM_{2.5}$ data, due to the range of PM sources in the field, therefore absolute values could vary (be slightly lower) depending on the sources measured [43]. For two rooms (one bedroom and one living room), no $PM_{2.5}$ data could be recorded due to instrument issues. Additionally, for one living room, less than 24 h of PM data could be recorded. For three bedrooms and one living room, less than 24 h of CO, CO_2, TVOC, temperature, and RH data was recorded. Outdoor 24-h average $PM_{2.5}$ and temperature data were obtained from the nearest Irish Environmental Protection Agency's National Ambient Air Quality monitoring site [44] and Met Éireann (Irish National Meteorological Service) respectively [45].

Participants were asked to complete an activity diary during the measurement period, which documented occupant activities which may impact on IAPs e.g., burning scented candles, presence of pets, opening window and doors etc. In homes with demand control ventilation (DCV) systems, building ventilation rates were calculated using measured air flows from ventilation extracts in wet rooms and in the kitchen. As the DCV systems installed were humidity controlled, a KIMO MP50 manometer (accuracy of ±0.5% of reading ±2Pa and resolution of 1Pa) was used to measure air pressure in the extract units, which was then converted to air flow (litres/second). In homes with mechanical ventilation with heat recovery (MVHR) units, a Flowfinder MK2® (uncertainty 3% of the reading with a minimum of 3 m^3/h) was used to measure air flow in each air extract and supply terminals (litres/second). Ventilation rates were compared to the minimum levels of extract and supply ventilation in S.R. 54:2014, the Code of Practice for the energy efficient retrofit of dwellings at the time the participating homes were retrofitted [46]. Measured ventilation flow rates were also compared to ventilation requirements in Part F of the Irish Building Regulations (2019) for major renovations [47]. Part F ventilation requirements (in L/s) for dwellings stipulate that the maximum of two values, one evaluated based on floor area of the residence (0.3 × Floor Area, in m^2) and the other based on number of occupants (5 + 4 × Number of occupants). The 0.3 L/s per m^2 corresponds to an air exchange rate of approximately 0.45 h^{-1} (assuming a ceiling height of 2.4 m).

Building air exchange rates (h^{-1}) were calculated in the bedrooms using logged timeseries of CO_2. For all calculations only CO_2 levels over 600 ppm were used since under that value, the levels are too close to outdoor values, leading to large variability and hence an appropriate estimate cannot be carried out. Three bedrooms did not meet these requirements. Based on the CO_2 data in each specific bedroom, three different methods were used [48]. If the CO_2 levels reached a steady state, the steady-state method was used, based on number of occupants and average CO_2 generation rate for sleeping occupants [49,50]. When a perceptible decay period was observed for CO_2, the decay method was used. When a clear decay or steady state was not observed, a transient decay method was used, again assuming average CO_2 generation rate for sleeping occupants.

2.3. Occupant comfort

Participants completed a short questionnaire, which was based on a questionnaire used in a previous study [26], with some modifications needed to reflect the additional features present in an A-rated home. The purpose of the questionnaire was to collect information on demographics, occupant behaviour, the heating and cooking appliances used in the home, ventilation strategy, energy use and occupant feedback on the retrofit and their perception of indoor air quality (including day light, noise, and odours) in the home. The questionnaire also included questions on thermal comfort, participants were asked to rate their comfort on a seven-point thermal comfort scale, they were asked to consider their comfort in winter and summer (if relevant) and also reflect on how their thermal comfort has changed since their retrofit.

2.4. Data pre-treatment and analysis

Survey data was collated using a spreadsheet application (Microsoft Excel). Subsequently, all analysis was carried out using the R statistical software [51]. After importing data into R, indoor air pollutant data were all brought to a 5-min frequency log, using averaging where needed. Timestamps of data entries were used to filter between daytime and night-time data (10 p.m.–7 a.m.). Correlations between different measured physical parameters were tested using both Pearson and Spearman correlations. Correlations were taken for data from all homes taken together, split by room type (bedrooms and living rooms) as well as for each individual home's data, split by room type. For correlation between radon and formaldehyde and the other IAPs, median values were used as the former two pollutants only had single timepoint data. Correlations were also calculated between subjective responses from the occupants regarding different aspects of indoor thermal conditions and air quality to examine how much occupants associate their overall comfort satisfaction with aspects of air quality and thermal environment satisfaction or how well thermal comfort satisfaction related to satisfaction with aspects of air quality.

3. Results

3.1. Retrofit measures and energy consumption

All homes had a post-retrofit Building Energy Rating Certificate (BER) rating [52] of between A3 and A1, Fig. 1 a). Building air tightness values were between 2.4 and 5 $\frac{m^3}{m^2 \cdot hr}$, Fig. 1 b). A summary of the building characteristics, energy measures included as part of the retrofit are provide in Table 2. ARDEN 20 and 21 had solar PV installations (~4 kW) and more wall insulation (U-value of <0.15 W/m^2K) than the other homes, resulting in a lower post-retrofit EUI than other homes, achieving a BER of A1. All dwellings were cavity wall construction, inner and outer masonry leaf with a cavity of 110 mm, ranging in age from 20 to 52 years, with floor areas in the range of 50 m^2 to 281 m^2.

All the retrofits involved the substitution of the previously used solid

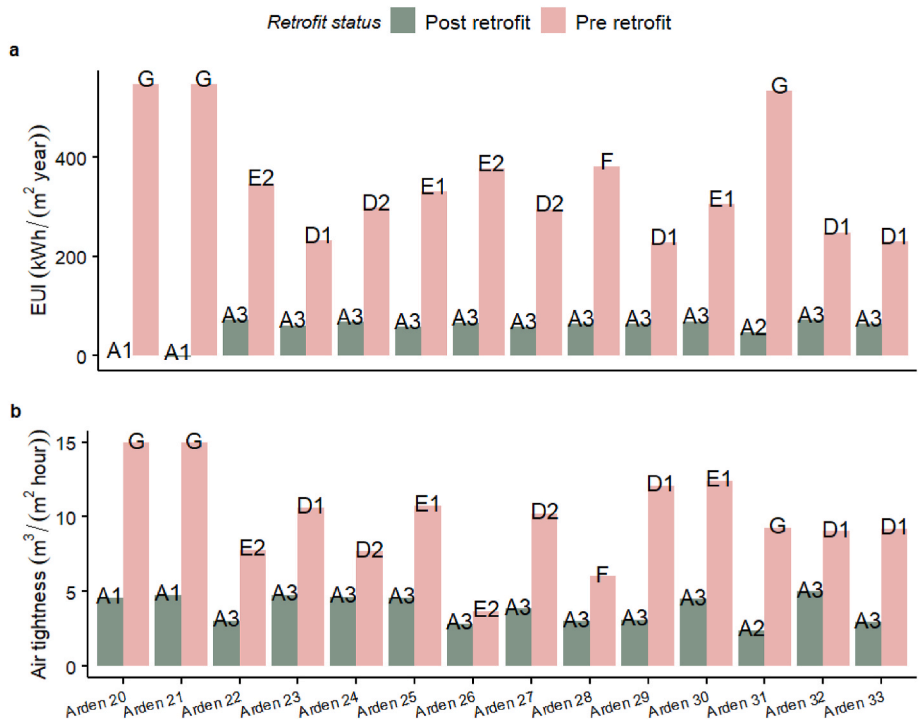

Fig. 1. Arden homes a) energy use intensity and b) air tightness, pre and post retrofit. Each home is labelled by its BER certification, both pre- and post-retrofit.

Table 2
Deep retrofit measures completed in participating dwellings. (EWI: external wall insulation, CWI: cavity wall insulation, IWI: internal wall insulation, DCV: demand control ventilation, A2W: air to water, n.a.: not applicable).

Home	Original construction period	Floor area m^2	Wall Insulation	Roof Insulation	Floor Insulation	Windows/Doors (U-values, $Wm^2{\bullet}K$)	Ventilation	Heat Pump	Wood Burning Room Heater
Arden 20	1967–77	120	EWI + CWI	Ceiling	N/a	1.1/n.a.	DCV	A2W	n.a.
Arden 21	1967–77	120	EWI + CWI	Ceiling	N/a	1.1/n.a.	DCV	A2W	n.a.
Arden 22	1983-93	100	CWI	Ceiling	N/a	n.a.	DCV	A2W	Wood Stove
Arden 23	1950–66	95	IWI	Ceiling	Solid to insulated solid	1.4/1.4	DCV	A2W	Wood Stove
Arden 24	1983–93	140	CWI	Ceiling	N/a	n.a. (2.2)/1.0	DCV	A2W	n.a.
Arden 25	1983–93	70	CWI	Ceiling	N/a	1.1/1.4	DCV	A2W	Wood Stove
Arden 26	1994–99	50	CWI	N/a	N/a	1.1/1.4	DCV	A2W	Wood Stove
Arden 27	1994–99	90	CWI	Ceiling	N/a	1.1/1.4	DCV	A2W	Wood Stove
Arden 28	1978–82	130	IWI + CWI	Ceiling + slope	N/a	1.4/1.4	DCV	A2W	Wood Stove
Arden 29	1994–99	225	EWI	Ceiling + slope	Solid to insulated solid	1.4/1.4	DCV	A2W	Wood Stove
Arden 30	1983–93	180	IWI	Ceiling + flat	Solid to insulated solid	1.4/1.4	DCV	A2W	Wood Stove
Arden 31	1967–77	170	EWI + IWI + CWI	Ceiling + slope	Partial STF to insulated partial STF	1.2/1.2	MVHR	A2W	Wood Stove
Arden 32	2000–04	300	EWI + CWI	Ceiling + slope	N/a	1.0/1.0	DCV	A2W	n.a.
Arden 33	1983–93	105	IWI + CWI	Ceiling	Solid to insulated solid	1.4/1.4	MVHR	A2W	n.a.

fuel-based heating system with an air to water heat pump, nine of the homes had a wood stove installed post retrofit (the wood stoves were not used at the time of the surveys). External wall insulation included 100 mm of a National Standards Authority of Ireland certified external wall insulation (EWI) system to achieve a U-value of 0.27 W/m^2K. Any roof upgrades at the ceiling level involved the installation of 300–350 mm mineral wool insulation. Floors were not commonly upgraded, however, where floors were upgraded (both suspended timber floors and solid floors) polyisocyanurate (PIR) insulation with a thickness of 120–150 mm was typically used. Where underfloor heating pipework was being installed, the typical thickness was 150–200 mm in order to achieve the required U-value of 0.15 W/m^2K. A mechanical ventilation system was installed in all homes, either demand control where airflow volume was adjusted based on humidity (N = 12) or mechanical ventilation with heat recovery (N = 2).

The SEAI Deep retrofit Pilot programme estimate that the average CO_2 emissions post retrofit estimated from the homes participating in the programme was 9.9 KgCO_2/m^2/yr, equal to approximately 91% reduction in CO_2 emissions [6]. Energy consumption data was available for 8 of the 13 homes was obtained from the Project Management Consultancy M.CO [52]. Participating homes reported an annual saving of between 171 and 550 kW h/(m^2•year) post retrofit.

3.2. Indoor air quality

Table 3 shows the summary concentration distribution of measured thermal and IAQ parameters, by room type. Higher concentrations of all pollutants were measured in the bedrooms, compared to living rooms. Negligible concentrations of CO were measured across all homes (median values for both bedrooms and living rooms were approaching the limit of detection of the sensor). Median CO_2 concentrations of 680 ppm and 540 ppm were detected, respectively, in the 14 bedrooms and 14 living rooms surveyed.

The cumulative frequency distribution of CO_2 measurements for the rooms has been provided in Fig. 2. All the living rooms had more than 80% of the measured data within Category I limits for CO_2, as provided by EN 16798 [53] for living area, i.e., within 550 ppm of the outdoor levels (approximated at 415 ppm). On the other hand, there were only four bedrooms where 80% of the data points were within the Category I limits for CO_2 in bedrooms, from EN 16798 (within 380 ppm of outdoors). In 31% of bedrooms surveyed, median concentrations were greater than this Category I limit over the measurement period. One home had CO_2 levels in Category III or beyond, as per EN 16798, for 100% of the time.

Higher median concentrations of TVOCs and $PM_{2.5}$ were also measured in bedrooms, compared to living rooms. Median bedroom TVOC concentrations of 146 ppm (97.5%ile: 1640 ppm), and bedroom $PM_{2.5}$ concentrations of 20 μg/m^3 (97.5%ile: 78 μg/m^3), were detected. However, the highest $PM_{2.5}$ concentrations were detected in the living room areas (97.5%ile: 167 μg/m^3).

Mean $PM_{2.5}$ concentrations are higher than 25 μg/m^3, the WHO 24-h air quality guideline value [55], in 33% of rooms surveyed and greater than the 2021 revised WHO air quality guideline for outdoor air of 15 μg/m^3 in 58% rooms surveyed [56]. Mean concentrations were higher than the US EPA National Ambient air quality primary and secondary standards for $PM_{2.5}$ [57] of 12 μg/m^3 and 15 μg/m^3 in 85% of rooms surveyed, however this comparison guideline is based on a calculated annual mean, averaged over 3 years.

Fig. 3 provides the cumulative frequency distribution of $PM_{2.5}$ measurements for the rooms.

Median TVOC concentrations exceeded 300 μg/m^3 (EN16798, Category I limit and Hygienically safe level defined by the German Environment Agency [58]) in eight bedrooms and three living areas. Four homes (22, 23, 32 & 33) had wooden floors in both the living area and bedroom, and two homes had laminate flooring in the bedroom (ARDEN 28 & 31).

Formaldehyde concentrations (3-day average) exceed the ATSDR 1-year long-term health-based guideline value of 10 μg/m^3 which is also recommended by Public Health England [59,60] in all rooms surveyed. Median bedroom formaldehyde concentrations were slightly higher, 25.4 μg/m^3 than living room concentrations (20.7 μg/m^3).

Radon data for ten homes was available, one home's radon measurement exceeded the Irish National reference level of 200 Bq/m^3 or the US EPA action level of 148 Bq/m^3 [61,62]. This home was in a high radon area where more than 20% of the homes in a 10 km grid square are estimated to be above the National reference Radon levels [61]. Radon levels measured in the remaining nine homes surveyed for radon were all less than the National reference level.

In contrast to the trends in objective measurements of the IAQ parameters, subjective perception of the occupants regarding the air quality in their homes post retrofit was mostly positive. Respondents in six homes rated their experience with IAQ factors – odour, freshness, humidity rating, and IAQ satisfaction – on the negative side of the respective Likert scales. Possible sources of occupant dissatisfaction are explained using the measured IAQ data and presented in Table 4.

Table 3
Summary IAQ data for all 14 homes taken together, for bedrooms and living rooms.

	Bedrooms		Living rooms	
	Mean (s.d.)	Median (2.5%ile, 97.5%ile)	Mean (s.d.)	Median (2.5%ile, 97.5%ile)
CO_2 (ppm)	840 (445)	680 (400,2065)	580 (165)	540 (390,995)
CO (ppm)	0.6 (0.8)	0.6 (0.2,1.4)	0.8 (0.5)	0.7 (0.3,2.4)
TVOC (ppb)	289 (460)	146 (0,1640)	176 (166)	111 (14,690)
Temperature (°C)	23.5 (2.0)	23.7 (18.7, 26.9)	24.5 (2.9)	24.6 (19.7,30.4)
RH (%)	50 [8]	51 [35,61]	47 [7]	47 [35,60]
$PM_{2.5}$ (μg/m^3)	22 [48]	20 (3,78)	30 [70]	17 (4167)
Formaldehyde (μg/m^3)	27 [12]	25.4 [14,53]	25 [13]	21 [13,54]
Radon (Bq/m^3)	90 (116)	64.5 (13.3, 340.2)	77 [63]	55.0 (23,203)

3.3. Thermal comfort

Fig. 4 provides the temperature distribution in all living rooms and bedrooms in the form of stacked bar plots, with the fraction of readings in each Category of EN16798 shown. Overall median indoor temperature was within Category I limits for residential buildings, between 21 and 25.5 °C. In ten of the fourteen homes, median temperatures in living rooms were warmer than the median temperatures in bedrooms. Of the living rooms, 50% had their median temperature outside the Category I limits, six on the warm side and one on cool side. Of the bedrooms, 28% had median temperatures outside Category I; of them three rooms on the warm side and one on the cool side. The majority of the bedrooms (N = 9) were within the Category I limit for 80% or more of the time. For two bedrooms (Arden 28, 30) conditions were warmer than 26 °C for more than 80% of the time, indicating possible issues of overheating. Similar trends were also observed for the living rooms of these two homes. Six living rooms were within Category I temperature limits for 80% or more of the time. Four living rooms were warmer than 26 °C and two were cooler than 21 °C for more than 80% of the time.

Humidity in all rooms except three (two bedrooms and one living room) remained within 30 and 60% for 80% or more of the logged time. Humidity levels greater than 70% RH were not recorded in any room. With temperature mostly between 20 and 25 °C, humidity is unlikely to have any impact on thermal comfort perception [48].

Analysis of the questionnaire data showed that the majority (100% both winter and summer period respectively) of homeowners were satisfied with the comfort level in their home post retrofit, compared to their pre retrofit experience, most especially in the winter period (38% & 50% winter and summer period respectively. In terms of indoor temperature, >85% of participants were satisfied with indoor temperature in their home in the winter, and just one homeowner expressed dissatisfaction with indoor temperature levels (ARDEN 28) in the summer period. Just one homeowner reported a problem with air movement post retrofit (in winter and summer). Where homeowners felt an issue with the thermal conditions, no connection could be made with objectively measured values of temperature or humidity.

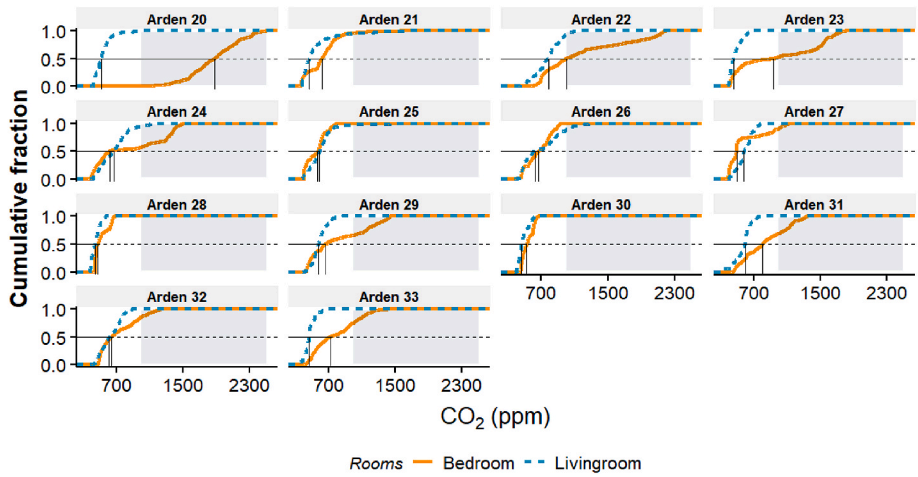

Fig. 2. Cumulative fractions of the CO_2 data logged in the different rooms, for each Arden home. The median positions for each distribution have been marked by vertical lines. The shaded portion represents CO_2 levels over 1000 ppm.

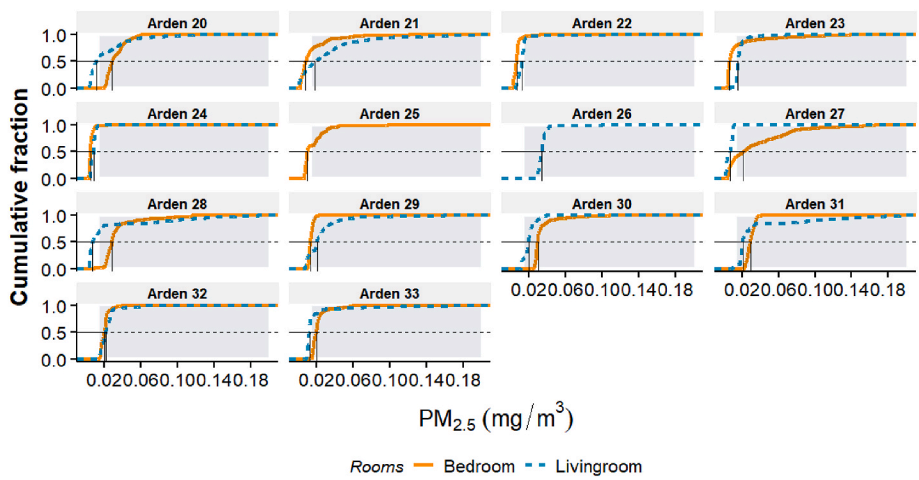

Fig. 3. Cumulative fractions of the $PM_{2.5}$ data logged in the different rooms, for each Arden home. The median positions for each distribution have been marked by vertical lines. The shaded portion represents $PM_{2.5}$ levels over 15 μg/m^3. For convenience of presentation, values over 200 μg/m^3 have been filtered out for these plots.

Table 4
IAQ satisfaction issues in homes and possible relation with objective data.

Home	Subjective perception complains	Objective IAQ measurements in Bedrooms
Arden22	Air freshness	CO_2 (53% > 965 ppm) TVOC (96.8% 300–1000 μg/m^3)
Arden23	Air freshness	CO_2 (37.6% > 1360 ppm)
Arden24	Odour	CO_2 (44.3% > 965 ppm)
Arden25	Air freshness & Humidity	RH (62.5% > 60)
Arden28	Air freshness & Humidity	TVOC (57.7% > 1000 μg/m^3) and $PM_{2.5}$ (99% > 15 μg/m^3)
Arden30	Air freshness	TVOC (78% 300–1000 μg/m^3) and $PM_{2.5}$ (100% > 15 μg/m^3)
Arden33	Odour & Overall Satisfaction	TVOC (79% 300–1000 μg/m^3) and $PM_{2.5}$ (96% > 15 μg/m^3)

Most homeowners (85%) reported satisfaction with their new home heating system post retrofit compared to just 23% satisfaction rating with the heating system pre retrofit. Homeowners (85%) were also mostly satisfied with the perceived air quality and the amount of natural light in the home post retrofit. Satisfaction with both these factors significantly improved post retrofit, compared to pre retrofit ($p <$ 0.005). Only two homes, both 2 years post retrofit, reported minor condensation and mould issues post retrofit. All participants reported that there was less noise (from the building systems) in their home post retrofit ($p < 0.005$).

3.4. Ventilation

S.R. 54:2014 (recommended at $< 5 \frac{m^3}{m^2 \cdot hr}$) and Part F of the Irish Building Regulations specify that airtight dwellings (recommended at $< 3 \frac{m^3}{m^2 \cdot hr}$)) must have some form of mechanical ventilation system [46,47]. Measured total flow rates from extract terminals located in kitchens, bathrooms, and utility rooms, were compared with minimum performance requirements in S.R 54:2014. Details of the measured flow rates at the different extraction points in the home has been provides in Table S2. A comparison of measured and required ventilation data has been provided in Fig. S1. Ventilation levels for bedrooms, calculated from the CO_2 data, have been reported for the different bedrooms in Fig. S2, along with a comparison to the measured data in bedrooms that had en-suites.

Five of the participating homes met the minimum ventilation requirements in S.R. 54:2014, and only three of the 14 mechanical ventilation systems had minimum boost extract flow rates which meet

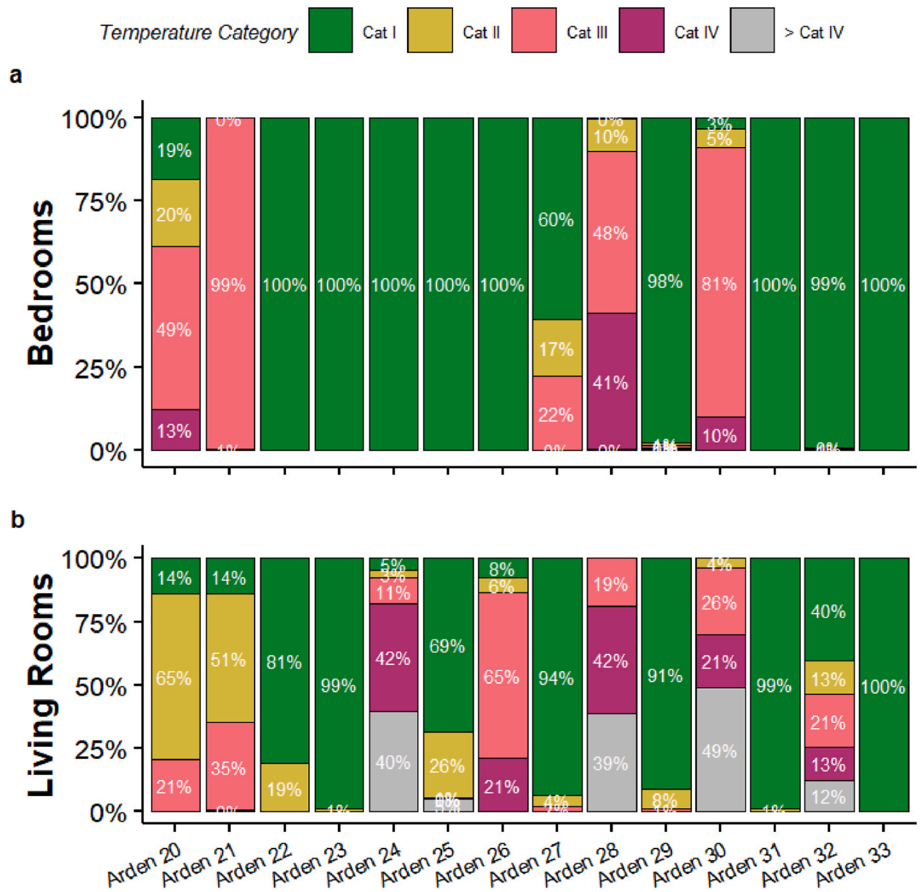

Fig. 4. Stacked bar plots representing the distribution of temperatures recorded in a) Bedrooms and b) Living rooms, across the categories classified as per EN16798.

the minimum requirements of Part F, two homes had an MVHR system installed as part of the retrofit, supply and extract flow rates did not meet the minimum requirements of Part F. In one case, measurements of air flow in all extract terminals was not possible, as the extract cover was plastered to the wall, in a second home one air inlet was positioned behind a wardrobe in a bedroom and the kitchen extract point was in a difficult to reach location and so could not be checked. In another home, the system was not working at the time of the survey, however the researcher re-visited the home a few weeks later after the unit was repaired and values from the second visit are the ones reported.

Over 85% of participants reported opening bedroom and living room windows daily to ventilate, however only 2 homes (15%) reported opening bedroom windows at night. During the IAQ surveys, window opening in the living area, varied from not opening to having living room windows open from 6 a.m.–12 midnight (ARDEN 31), and bedroom windows were left closed in all homes at night during surveys.

Greater than 60% of participants reported not having received a handover regarding the newly installed ventilation system, and 50% of participants reported that they did not understand how the system worked; 70% reported that they did not know when or how the system should be serviced/cleaned or filters replaced, and 40% reported having no access to system controls.

3.5. Inter-correlation between occupant subjective feedback

Subjective feedback collected using the project questionnaire recorded occupant experience with thermal comfort, air quality, and overall satisfaction. The occupant thermal comfort ratings correlated well with their air quality satisfaction ratings ($r = 0.77$, $p < 0.0001$). Ratings regarding lack of odours had good correlation with air quality satisfaction ratings ($r = 0.85$, $p < 0.0001$). Temperatures being perceived as stable correlated well with thermal satisfaction ($r = 0.72$, $p < 0.0001$). Overall comfort satisfaction correlated well with temperatures being perceived as stable ($r = 0.74$, $p < 0.0001$) and air quality satisfaction ratings ($r = 0.78$, $p < 0.0001$).

4. Discussion

CO_2 is an extensively used when it comes to describing IAQ. But it is just one of the parameters and a holistic description of indoor air quality requires multiple parameters [63], depending on different sources of pollutants. Living room and bedroom median concentrations of TVOC and formaldehyde were strongly correlated ($r = 0.83$, $p < 0.001$; $r = 0.66$, $p = 0.03$, respectively) suggesting that the building fabric and furnishings maybe the main source of those pollutants in the home, hence the correlated levels in each home, across two room types. Median concentrations of bedroom and living room $PM_{2.5}$ and CO_2 were not significantly correlated, indicating these pollutants occurred from different sources within the home.

While ventilation rates estimated based on extract measurements (not including infiltration) suggest a ventilation rate of between 4 and 12 L/s per person, in addition CO_2 measurements were used to identify poorly ventilated rooms. Among the bedrooms, there were two (Arden 28 and Arden 30) that had the CO_2 levels within EN16798 Category I requirements for 100% of the time while two others met Category I requirements for CO_2 levels more than 85% of the time. However, it was later found out that the occupants in Arden 30 did not use the bedroom during the data logging period. In general CO_2 levels in the bedrooms were higher than the living room levels. This is expected considering we spend nearly 50% of our time at homes inside bedrooms [8]. Highest CO_2 concentrations were recorded in Bedroom 20 (median 1878 ppm, 5%ile = 1341 ppm, 95%ile = 2353 ppm), which had a total volume of

27 m^3, and included an en-suite bathroom with a ventilation extract. Based on CO_2 data, an ACH of 0.42 was estimated for this bedroom. Using the measured ventilation flow rate in the en-suite extract an ACH of 1.3 was estimated. Discrepancies in calculated vs measured ACH values are likely due to many factors including, the bedroom is not an isolated space, the door between the bedroom and en-suite is likely to disrupt air flow, and the extract flow rate is likely to vary over the night, compared with the point in time measured flow. The bedroom was also used as an office by two persons for the full duration of the monitoring period, which partly explains the higher levels. Measurements in this home were completed during the heating season and windows were not open during the monitoring period. High concentrations of CO_2 were also recorded in Bedroom 22 and 23 (95%ile = 2135 ppm, 1710 ppm respectively). Neither had an en-suite and relied on window opening in the bedroom for ventilation. The bedroom door was open while measurements were recorded in Bedroom 22, and wall and window vents were open in both 22 and 23. The homeowner reported opening the bedroom windows for 3–4 h during the daytime in bedroom 23, but windows were closed at night. The DCV system (ARDEN 23), which extracts from the wet rooms in the home, and not from the bedroom, was non-functional during the IAQ surveys. In view of hybrid working becoming more prevalent, it is likely that bedrooms will more often serve as part-time offices, in addition to the place for sleeping. Our observations indicate that bedrooms may require to have a provision for mechanical ventilation. Depending on ventilation from an ensuite or the occupant-controlled opening of windows may no longer be sufficient.

The homes included in this study were a minimum of 12 months post retrofit. Laboratory studies on VOCs such as formaldehyde emissions in test chambers on particle board and MDF, suggest that concentrations decrease by 60%, two years after production. Continued off gassing from the building fabric and furnishings is likely to contribute to levels of TVOCs detected. Higher TVOC concentrations were recorded in the bedrooms (median; 146 ppb, 97.5%; 1640 ppb). 80% of the rooms with median concentrations >300 μg/m^3, also had higher median CO_2 concentrations (>800 ppm). This suggests under ventilation may be a contributing factor. Highest TVOC concentrations were recorded (median 1198 ppb, 95%ile: 2395 ppm) in Bedroom 31. This room had just been redecorated two months prior to the sampling and had laminate flooring. 100% of TVOC concentrations recorded over the measurement period were greater than 300 μg/m^3, most likely due to paints, varnishes, and glues. This home had one of the lowest calculated ventilation flow rate, (0.1 L/m^2). An MVHR system was installed as part of the retrofit, however supply air flow rates were significantly less than ventilation rate requirements in Part F. Extract rates were also less, likely impacting removal of pollutants from the dwelling. Notable decreases in TVOC concentration are observed (<500 ppb) when occupants opened the bedroom windows, however concentrations increased (>1000 ppb) again once windows were closed, this room also had higher levels of formaldehyde (44 μg/m^3 versus median (N = 14) bedroom concentration of 25 μg/m^3). Higher TVOC concentrations were also recorded in the living area of this home (median 452 ppb, 95%; 832 ppb) probably also influenced by the redecorating two months earlier and the poorly performing MVHR unit. Median TVOC concentrations in this study (N = 28) are higher than values reported for green-Minergie certified homes in Switzerland but comparable to levels reported in Swiss energy renovated homes without mechanical ventilation [64], reported values are less than values reported in moderately retrofitted naturally ventilated Slovakian and Irish homes [26,27].

Indoor concentrations of formaldehyde are likely to arise from both occupant and building related sources [65] including building materials (particle board, laminate), paints, adhesives and furnishings, and indoor combustion of scented candles and incense and use of personal care products. Previous research suggests that formaldehyde concentrations tend to increase (up to 29%) post retrofit due to the addition of new building materials furnishings etc [39]. Concentrations reported in this study are at the higher end of the values reported for European dwellings [65]. Highest concentrations were recorded in home 32 (bedroom, 57.35 μg/m^3, living area, 56.17 μg/m^3). Arden 32 had laminate flooring in the bedroom and was redecorating upstairs a possible reason for the higher concentrations detected. Furthermore, the DCV extract in the kitchen in 32 was not working. Bedroom 31 has already been discussed previously; it was recently redecorated and had a poorly performing MVHR system. Regarding the living area in ARDEN 24, the occupant reported cleaning and polishing for up to 6 h over the three-day sampling period, and the kitchen extract did not meet the minimum boost requirements of Part F. When comparing formaldehyde concentrations in this study with other studies on energy retrofitted homes, concentrations are within the range of those reported for deep energy retrofitted naturally ventilated Lithuanian multifamily homes [25]. Some of the higher values in this study are comparable to those reported for moderately retrofitted naturally ventilated Slovakian homes [27] but higher than concentrations reported for moderated Irish retrofitted homes [26] and also French energy efficient dwellings [66], and Finnish deep energy retrofitted, mechanically ventilated multifamily buildings [25].

The $PM_{2.5}$ concentrations reported in this study, are higher than values reported for Irish moderately retrofitted homes [26]. Calibration factors for the laser photometer used in this study, for indoor sources, are reported to range from 0.32 to 0.70 [43]. When applied to the data collected in this study reported $PM_{2.5}$ concentrations are within the range of those collected using gravimetric methods, reported for energy efficient French homes sampled during both the heating and non-heating season [66]. Indoor $PM_{2.5}$ can arise from indoor combustion sources such as tobacco smoking, cooking, or burning scented candles, and infiltration from outdoor combustion or traffic sources. In this study, outdoor $PM_{2.5}$ concentrations, where available (ARDEN 20, 24, 28, 30, 33), were mostly less than 10 μg/m^3, apart from during one week in 2020, which was during the Irish heating season, and when two homes were surveyed (ARDEN 20 & 21). During this period outdoor $PM_{2.5}$ concentrations of between 12 and 20 μg/m^3 (median 24-h averages) were recorded at an air quality monitoring station located 500 m from both homes and are much less than those measured indoors.

In many cases higher living room $PM_{2.5}$ concentrations are influenced by occupant behaviour such as cooking or burning scented candles or incense. Bedroom night-time $PM_{2.5}$ concentrations (between 10 p.m. and 7 a.m.) were negatively correlated with CO_2 concentrations in seven bedrooms, significant negative correlations ($p < 0.001$) and $|r|$ values greater than 0.5. This suggests that occupant activity is a source of the $PM_{2.5}$, and not just occupant presence – sleeping occupants being inactive led to a lowering of particulate matters while CO_2 levels in the bedrooms rose from occupant presence. Occupant activity diaries further corroborate this. Across all homes monitored, few occupants reported using their cooker hood when cooking. In Arden 31 elevated concentrations >1700 μg/m^3 were detected during a cooking event when food was burnt in the kitchen. The smoke generated by the source dominated $PM_{2.5}$ concentrations for almost 12 h in the living room. When concentrations associated with the cooking event are removed, average $PM_{2.5}$ concentrations over the measurement period are reduced from 80 μg/m^3 to 22 μg/m^3. As discussed previously the MVHR system did not meet minimum supply or extract air flow rates, and this may have contributed to a longer clearance time.

Similar trends are also observed in other homes, such as ARDEN 20 and 21, where distinct peak $PM_{2.5}$ concentrations (as high as 200 μg/m^3 (in ARDEN 20) and 600 μg/m^3 in ARDEN 21) are observed in the living area during lunch or dinner preparation. Although flow rates in the kitchen area meet the minimum boost requirements in Part F, residents rarely used the cooker hood.

Another homeowner reported burning scented candles and incense during the measurement period (ARDEN 28). Average $PM_{2.5}$ concentrations in the living area over the measurement period were 40 μg/m^3, concentrations rose to a peak of 326 μg/m^3 when burning incense, this source dominates the concentration for almost 10 h. When concentrations associated with this event are removed, average concentrations drop to 10 μg/m^3. A shorter cooking event was also reported by the homeowner, which generated peak $PM_{2.5}$ concentrations of 150 μg/m^3 in the kitchen. When this event is also removed the overall average concentration during the measurement period drops to <10 μg/m^3. It is important to remember that cooking events can be associated with an increase in particulate matter, irrespective of the nature of the cooking hob [67]. Similar increases in $PM_{2.5}$ concentrations (peak 120 μg/m^3) are also observed in the bedroom of ARDEN28, possibly also due to incense burning. Due to the uncertainty associated with the use of unadjusted optical photometric data, future studies can consider collecting gravimetric PM2.5 measurements for more accurate estimation of true PM2.5 concentrations, using more controlled set-ups.

The global COVID-19 pandemic has given a renewed focus on the important role of building ventilation in reducing exposure indoors, including to biological agents like SARS-CoV-2 virus. It is of equal importance for other IAPs, especially as homes are renovated to higher levels of air tightness. With increased numbers of individuals choosing to adopt hybrid working practices, some will spend more time at home, and exposure at home will have an even greater impact on health and wellbeing. Improving the ventilation rate of our dwellings will ensure better long-term health outcomes for occupants. Mechanical ventilation has an important role in providing clean air in future more energy efficient, airtight, retrofitted buildings. However mechanically ventilating domestic dwellings is a relatively new concept for Irish domestic dwellings. In the current study, only two of the fourteen homes had ventilation systems which complied with minimum boost extract rates recommended in the 2019 Irish Building Regulations, suggesting that their homes are under ventilated. Only four homeowners reported having received a handover on the newly installed ventilation system from the retrofit provider, and just three homeowners understood how the system worked and necessary maintenance requirements. Mechanical ventilation involves added energy use and increased implementation of such systems will likely impact the BER certifications of homes. However, in the current study, the issues noted were with the operational phase of the buildings – improper handover, inadequate cleaning and maintenance, and operational systems unable to meet the requirements. Improvements in these fronts will not impact the BER awarded to the homes and while improving the indoor air quality.

This study highlights the importance of the validation and testing of mechanical ventilation systems by independent third-party competent persons post retrofit, for major renovations where a new mechanical ventilation system is installed, now a requirement in Ireland, since November 2020 [68]. This scheme only applies to the mechanical ventilation system, the performance of local extract ventilation systems such as cooker hoods, are also critical for the removal of combustion related pollutants such as PM2.5. Study results highlight the necessity to provide homeowners with sufficient information about the ventilation system so that it can be operated in an efficient and effective manner. For example, the owner should be provided with a suitable set of operating and maintenance instructions on the centralized continuous mechanical extract ventilation system in format that the householder can understand. The instruction should be directly related to the system installed in the dwelling without prejudice to the need to comply with relevant regulations. The instructions should explain the important function of the system to provide adequate ventilation, how the system is intended to work, why the system should not be turned off, how the controls should be used and how and when the system should be cleaned and maintained. The location of the continuous centralized mechanical ventilation unit in the dwelling and the location of the filters on the unit should be identified in the document. Boost and normal operation of the unit should be explained and the effects of opening windows. Guidance on the operation of controls and how a fault is indicated, location of fault alarms and their meaning should also be included. Although most participants perceived the indoor air quality in their home to be good, many of the homes had measured concentrations of IAPs which exceeded recommended guideline values in either the living area, bedroom, or both. At the same time, thermal environment (both temperature and humidity) in most homes were well within design comfort limits and occupant feedback thermal satisfaction of the occupants suggested comfortable thermal perception. Thermal environment of an occupied space can have a significant effect on indoor air quality satisfaction [69], with IAQ acceptability improving when the air is cool and dry [70]. In a thermally comfortable environment, air quality issues can get masked. At lower air temperature, the air quality perception can improve even if the ventilation has not improved [71]. Humans are accepted to be a good sensor for thermal conditions like temperature and humidity, but they are not very good at perceiving insufficient levels of ventilation [72]. Occupants are incapable of sensing when levels of IAPs such as formaldehyde (odour threshold 50–500 μg/m^3 ppm [19,40], 10 μg/m^{3}health based guideline value) are unacceptable from health and wellbeing point of view. Increasing occupant awareness regarding indoor air pollution via the use of IoT based low cost IAQ sensors and data platforms could help occupants become more aware of indoor activities that impact on indoor air quality and help drive behaviour change.

Of the ten homes that participated in the radon survey, only one was in a high radon area, and had concentrations (320 Bq/m^3) greater than the National Reference level. Given the significant risks associated with exposure to radon, it is recommended that radon monitoring be conducted post retrofit, with priority to those dwellings located in a high-risk radon area.

Subjective ratings of satisfaction with overall comfort correlated well with the subjective ratings of satisfaction with air quality. This association between overall satisfaction with comfort in a home and the satisfaction with air quality means retrofits need to be careful about any impact on IAQ. The subjective perception of indoor temperatures being considered stable was also strongly associated with the subjective votes of overall comfort satisfaction. This positive association with stable temperatures agrees with the finding that amount of time spent outside a "comfort" temperature range is an excellent index for long term monitoring of thermal comfort [73].

4.1. Study strengths and limitations

The study characterises the concentration of several priority IAPs, including $PM_{2.5}$ for which there is little published data, in deep energy retrofit homes with mechanical ventilation, under real living conditions. The collection of subjective data from the occupants over the short monitoring period of 48 h, while short, minimises the impact of recall bias, and allows direct comparisons to be made with the pollutant concentrations measured. The study has many limitations, including the short sampling period, and the small number of dwellings, and so collected data may not be fully representative of the Irish deep energy retrofitted building stock. Furthermore, data was collected in different seasons, impacted by the COVID Pandemic, which didn't allow for seasonal effects on thermal comfort or pollutants to be evaluated, higher concentrations of volatile organic compounds might be expected during the winter months with less frequent window opening and airing. Further radon surveys are recommended, prioritising homes located in high radon areas.

Despite the small sample size, common trends in both pollutant concentrations and participant subjective feedback, particularly related to occupant knowledge regarding the newly installed ventilation systems, along with similar research findings from other jurisdictions [8,9,23,37,39] should form part of the knowledge base used to inform the future development of the energy retrofit of domestic dwellings in Ireland and Europe.

5. Conclusions

Indoor air pollutant concentrations in 14 deep energy retrofitted Irish dwellings, at least one-year post retrofit are presented. Higher concentrations of CO_2 (>800 ppm), TVOCs and formaldehyde were detected more frequently in bedrooms than living areas. Given that occupants spend a considerable proportion of their time in the main bedroom, improved bedroom ventilation maybe required as part of the retrofit to remove occupant and building generated pollutants. TVOC and formaldehyde concentrations are comparable to those reported for naturally ventilated energy efficient dwellings and are within the range of the higher concentrations reported for European dwellings. The promotion of safer low emitting construction materials and furnishings in energy retrofit is key to reducing indoor concentrations of formaldehyde and other TVOCs at source. $PM_{2.5}$ concentration frequently exceed the WHO 24-h guideline value for outdoor air, with higher concentrations during occupant activities such as cooking or burning candles or incense. In most homes, measured ventilation flow rates in extracts installed in wet rooms were less than those recommended in the current Irish Building Regulations, and some systems did not function at all, which highlights the need for greater compliance with requirements to provide adequate ventilation as part of the retrofit. To maximise the benefits of energy retrofit, related to improved health from reduced exposure to IAPs, a multi-faceted approach to retrofit is required which includes the designer and regulatory requirements but also end user, occupant needs.

Further improvement in the handover of knowledge and instruction regarding the maintenance and use of newly installed ventilation systems to homeowners is required. The current requirement in Ireland introduced in 2019 for third party compliance checks on ventilation system post retrofit is welcome, to ensure the design ventilation flow rates are achieved, but some dwellings may also require repeat performance-checks on their ventilation systems to ensure the systems are operating in an efficient and effective manner. Indoor air quality assessments, or the use of low-cost sensor technology could play an important role in identifying aspects of the renovation, which may need adjusting to maximise the benefits of the renovation process. The variation in pollutant concentrations in this current study, between the living area and the bedroom highlights the importance of measuring pollutants other than CO_2 in indoor air quality investigations post energy renovations. Pollutants typically associated with; the occupant (CO_2), but also occupant activities ($PM_{2.5}$), building fabric and furnishings (TVOCs & formaldehyde), and outdoor sources (radon and $PM_{2.5}$) should form part of the post retrofit investigation.

CRediT authorship contribution statement

Ann Marie Coggins: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization. **Nina Wemken:** Writing – review & editing, Methodology, Investigation. **Asit Kumar Mishra:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Martin Sharkey:** Writing – review & editing, Formal analysis, Data curation. **Liam Horgan:** Writing – review & editing, Investigation. **Hilary Cowie:** Writing – review & editing, Formal analysis, Conceptualization. **Emmanuel Bourdin:** Writing – review & editing, Methodology. **Brian McIntyre:** Writing – review & editing, Methodology.

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.

Acknowledgements

The ARDEN study was funded by the Sustainable Energy Authority of Ireland (SEAI) - 2018 National Energy Research, Development & Demonstration Funding Programme through research Grant No. RDD204. Radon monitoring was funded by the Irish Environmental Protection Agency (EPA). The project team would like to thank the homes who participated in this study. AKM is supported by Sustainable Energy Authority of Ireland (SEAI) through research Grant No. RDD/492.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.109236.

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