



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

Title	Energy retrofits: Factors affecting a just transition to better indoor air quality
Author(s)	Coggins, Ann Marie;Hogan, Victoria;Mishra, Asit Kumar;Norton, Daniel;Foster, Declan;Wemken, Nina;Cowie, Hilary;Doherty, Edel
Publication Date	2024-10-19
Publisher	Elsevier
Repository DOI	<a href="https://doi.org/10.1016/j.indenv.2024.100058">https://doi.org/10.1016/j.indenv.2024.100058</a>

## Supplementary Material

Energy retrofit: factors affecting a just transition to better indoor environmental quality

### A1: Characteristics of dwellings that participated in the IAQ Surveys

Table A1: Characteristics of dwellings that participated in the IAQ Surveys

Home ID	Property type	Year of Construction	Pre-retrofit BER rating	Social / Private housing	Pre-retrofit sampling	Post-retrofit sampling	Radon Sampling
HAVEN 01	Detached, two storey	2006	D1	Private	Yes	Yes	Yes
HAVEN 02	Detached bungalow	2003	D2	Private	Yes	Yes	Yes
HAVEN 03	Detached two storey	2001	C2	Private	Yes	Yes	Yes
HAVEN 04	Semi-detached Bungalow	1997	E2	Social	Yes	Yes	Yes
HAVEN 05	Detached bungalow	2006	C1	Social	No	Yes	Yes
HAVEN 07	Semi-detached Bungalow	1998	C3	Social	Yes	Yes	Yes
HAVEN 08	Semi-detached bungalow	1998	G	Social	Yes	No	Yes
HAVEN 09	End of Terrace	1950	E2	Social	Yes	No	Yes
HAVEN 10	Semi-detached bungalow	1998	G	Social	Yes	No	Yes
HAVEN 11	Terraced	2001	C2	Social	Yes	Yes	Yes
HAVEN 12	Terraced	2001	C2	Social	Yes	No	Yes
HAVEN 13	Terraced	2001	C2	Social	Yes	Yes	Yes
HAVEN 14	Semi-detached	2001	C3	Social	Yes	Yes	Yes
HAVEN 15	Terraced	1970's	F	Social	Yes	No	Yes
HAVEN 16	Semi-detached	1970's	G	Social	Yes	Yes	Yes
HAVEN 17	Terraced	1970's	F	Social	Yes	Yes	Yes
HAVEN 18	Semi-detached two storey	2008	C2	Social	Yes	No	Yes
HAVEN 19	Semi-detached bungalow	2000	E2	Social	Yes	Yes	Yes
HAVEN 21	Bungalow	1990	E1	Social	Yes	Yes	Yes
HAVEN 22	Bungalow	1992	E2	Social	Yes	Yes	Yes

<b>INTERRE G23</b>	Detached, two storey	2003	C2	Social	Yes	No	No
<b>INTERRE G24</b>	Terraced, two storey	2003	C2	Social	Yes	No	No

## A.2 Building Energy rating (BER)

A Building Energy Rating (BER) certificate allows for the comparison of the energy performance of dwellings. It is calculated following the Domestic Energy Assessment Procedure (DEAP) calculation framework, which is based on IS EN 13790 [1], and is compliant with the methodology framework in the EU Energy Performance of Buildings Directive (EPBD). The BER is based on the building itself, the fabric and systems installed, it is not based on its operational performance. It rates the dwelling on a scale of A to G, with A-rated homes being the most energy efficient while G-rated are the least energy efficient. There are three subdivisions of the A, B and C grade, two for D and E grade. A dwelling with an A3 rating has a calculated energy consumption  $>50$  kWh/m<sup>2</sup>/yr and  $\leq 75$  kWh/m<sup>2</sup>/yr. A dwelling with a B<sup>+</sup> rating has a calculated energy consumption  $>100$  kWh/m<sup>2</sup>/yr and  $\leq 125$  kWh/m<sup>2</sup>/yr [2].

## A.3 Summary of indoor air quality pollutant/thermal parameters monitored, and sampling methodology employed

Table A3. Summary of indoor air quality pollutant/thermal parameters monitored, and sampling methodology employed.

<b>Parameter</b>	<b>Sampling Method</b>	<b>Accuracy/Uncertainty</b>	<b>Sampling interval and duration</b>
<b>PM<sub>2.5</sub></b>	90° light scattering, laser diode TSI SidePak <sup>TM</sup> Personal Aerosol Monitor (AM520)	Range 0.001 to 100 mg/m <sup>3</sup> Minimum resolution 1 µg/m <sup>3</sup>	Every 1 min over 48 h -72 h
<b>CO<sub>2</sub></b>	Gray Wolf DirectSense II probe with smart °C/°F, %RH sensors Aranet 4 monitor	Range: 0 – 10,000 ppm Accuracy ± 35 ppm Sensor LOD: 1.0 ppm Range: 0 - 9999 ppm Resolution - 1ppm Accuracy: ± 30 ppm ± 3 % of reading	Every 5 min over 48 h -72 h 5 minutes (historic data availability 7 days)
<b>TVOC</b>	Gray Wolf DirectSense II probe with photoionization detector 10.6 eV lamp smart °C/°F, %RH sensors	Range 0 – 20000 ppm Sensor LOD 0.005 ppm Resolution 0.001 ppm	Every 5 min over 48 h -72 h

<b>CO</b>	Gray Wolf DirectSense II probe with smart Electrochemical sensor	Range: 0.0 to 500 ppm Accuracy $\pm 2\%$ rdg $\pm 1$ ppm	Every 5 min over 48 h -72 h
<b>Temperature</b>	Gray Wolf DirectSense II probe with smart $^{\circ}\text{C}/^{\circ}\text{F}$ , Pt100	Range $-25^{\circ}\text{C}$ to $70^{\circ}\text{C}$ Accuracy $\pm 0.3^{\circ}\text{C}$	Every 5 min over 48 h -72 h
	Aranet 4 monitor with SHT3x-DIS CMOSens <sup>®</sup> Sensor Chip,	Range: 0 - 85 % Accuracy: $\pm 3$ %	5 minutes (historic data availability 7 days)
<b>Relative humidity</b>	Gray Wolf DirectSense II Capacitive	Range 0 – 100% Accuracy $\pm 2\%$ RH < 80%RH ( $\pm 3\%$ RH > 80%RH)	Every 5 min over 48 h -72 h
	Aranet 4 monitor with SHT3x-DIS CMOSens <sup>®</sup> Sensor Chip,	Resolution RH: 1% Accuracy RH: $\pm 3$ %	5 minutes (historic data availability 7 days)
<b>Formaldehyde</b>	UMEX 500-100 passive badges	7-day LOD: 0.2 ppb ( $2\ \mu\text{g}/\text{m}^3$ )	Mass collected over 72 h
<b>Radon</b>	Closed alpha-track detector (Radtrak)	$\pm 15\%$ rdg	3-9 months
<b>Ventilation flow rates</b>	Kimo MP50 Manometer by Sauermann	Range: -1000 to +1000 Pa Accuracy: $\pm 0.5$ % of reading $\pm 2$ Pa	Measured once or twice at the time on sampling

#### A.4 Bedroom ventilation calculations using carbon dioxide concentration data

The Steady state method assumes that CO<sub>2</sub> concentrations increase as occupants sleep until the influence of ventilation leads to a plateau. Recorded CO<sub>2</sub> levels are influenced by the number of occupants, their age, gender, and the volume of the room. These factors are accounted for in this method. Ventilation capabilities are presented in terms of building air exchange rates (h<sup>-1</sup>) and litres/per second/per person [3]. Only night-time CO<sub>2</sub> data recorded whilst occupants were sleeping was utilised to calculate ventilation rates.

The steady-state method was preferred over the decay method since the decay method would be highly sensitive to occupant behaviour after waking up, such as opening doors and/or windows. The steady state method uses the following formula to estimate outdoor air ventilation:

$$V \left( \frac{L}{s} \right) = \frac{G \left( \frac{L}{s} \right)}{C_{SS} - C_o}$$

where  $V$  is the outdoor air ventilation rate in litres per second,  $G$  is carbon dioxide generation rate from all the occupants in the bedroom (litres per second),  $C_{SS}$  is the steady-state  $CO_2$  levels reached in the bedroom, and  $C_o$  is the outdoor  $CO_2$  level, both  $CO_2$  levels expressed in parts per million. We assume that the bedrooms did not have any other sources of  $CO_2$ , apart from the occupants, during the nighttime, which is a logical assumption for these homes.

The associated uncertainty with this formula is,

$$\frac{\delta V}{V} = \sqrt{\left(\frac{\delta G}{G}\right)^2 + \left(\frac{\delta C_{SS}}{C_{SS}}\right)^2 + \left(\frac{\delta C_o}{C_o}\right)^2}$$

Where  $\delta G$  is the uncertainty associated with the occupants'  $CO_2$  generation,  $\delta C_{SS}$  and  $\delta C_o$  are the uncertainties associated with the indoor and outdoor  $CO_2$  levels. For occupant  $CO_2$  generation, a 10% uncertainty is assumed, deriving from occupants' self-reported height and weight (age and sex are determined without any uncertainty). The met rate, while occupants slept, was estimated at 1 met, assumed to be determined without any uncertainty.  $\delta C_{SS}$  and  $\delta C_o$  are respectively taken at 35 and 50 ppm. Using these values, the average uncertainty of bedroom ventilation estimates post-retrofit was found to be 22.4% and for pre-retrofit estimates, the average uncertainty was 22.8%.

Apart from the uncertainty associated with the measurements, the process also relied on assuming the bedrooms (in some cases, the bedroom-ensuite combination) as a single zone, with negligible interzone transport of  $CO_2$  – between the bedroom and the rest of the home. Considering that living room  $CO_2$  levels were consistently lower than bedroom values, there is a likelihood of air from the rest of home leaking into the bedroom or vice versa. The implication would be the estimated bedroom ventilation levels are conservative values.



## A.5 Thermal comfort questionnaire survey

The questionnaire survey examined: thermal comfort and temperature satisfaction (8 questions), sources of thermal discomfort (5 questions), perceived indoor air quality (1 question), odour perception and response (2 questions), observance of mould and/or condensation (2 questions), and noise disturbance (1 question). Five-point Likert scale response formats ranging from 'satisfied' to 'unsatisfied' were employed for satisfaction questions e.g., "how satisfied are you with the temperature in your home". Multiple response options where participants could check all the items that applied, were used to explore aspects of thermal comfort in more depth e.g., sources of thermal discomfort, causes of draughts, locations of mould, window opening behaviour, sources of odours, noise disturbance sources, etc. Some yes/no response options were also employed, e.g. "Are there any unpleasant odours present in your house that bother you?"

A copy of the survey is provided below:

### **HAVEN STUDY - THERMAL COMFORT QUESTIONS**

**(Note: The thermal comfort questions have been extracted from a larger questionnaire instrument, the results of which are reported elsewhere)**

#### **Section 2: This section asks about your home**

1. Have you noticed mould on walls / ceilings in your house?  
YES  NO
2. How much of a problem would you say that you have with condensation in your house? Please tick one only.  
Not a problem  Minor problem  Moderate problem   
Severe problem  Very severe problem

#### **Section 4: This section asks about your Thermal Comfort**

Thermal comfort is very difficult to define, but aims to describe a person's state of mind in terms of whether they feel too hot or too cold. Your thermal comfort can be influenced by environmental factors such as air temperature, air movement, or relative humidity but also personal factors such as your clothing and also your activity. In this questionnaire we ask you

a number of questions about the thermal environment in your home so that we can try and evaluate the impact of your energy renovation on your thermal comfort.

1. How would you rate your thermal comfort in general? (Check the one that is most appropriate)

Hot	<input type="checkbox"/>
Warm	<input type="checkbox"/>
Slightly warm	<input type="checkbox"/>
Neutral	<input type="checkbox"/>
Slightly cool	<input type="checkbox"/>
Cool	<input type="checkbox"/>
Cold	<input type="checkbox"/>

2. How satisfied are you with the temperature in your home? (Check the one that is most appropriate)

Satisfied  Fairly satisfied  No opinion/Cannot tell  Rather unsatisfied   
Unsatisfied

3. Overall, how satisfied are you with the heating in your home? (Please tick one only)

Satisfied  Fairly satisfied  No opinion/Cannot tell  Rather unsatisfied   
Unsatisfied

4. In warm/hot weather, how would you describe the temperature in your home: (Check the one that is most appropriate)

Always too hot  Often too hot  Occasionally too hot  Occasionally too cold   
Often too cold

5. In cool/cold weather, how would you describe the temperature in your home: (Check the one that is most appropriate)

Often too hot  Occasionally too hot  Occasionally too cold  Often too cold   
Always too cold

6. On cooler days, would you consider the thermal comfort of your home to be a problem? (Check all that apply)

Morning (before 11am)	<input type="checkbox"/>	No particular time	<input type="checkbox"/>
Midday (11am-2pm)	<input type="checkbox"/>	Always	<input type="checkbox"/>

Afternoon (2-5pm)	<input type="checkbox"/>	Never	<input type="checkbox"/>
Evening (after 5pm)	<input type="checkbox"/>	Other	<input type="checkbox"/>

7. Following on from question 6, on cooler days how would you best describe the source of thermal discomfort in your home? (Check all that apply)

Humidity too high (damp)	<input type="checkbox"/>	Glare incoming from sun	<input type="checkbox"/>
Humidity too low (dry)	<input type="checkbox"/>	Draughts from windows	<input type="checkbox"/>
Air movement too high	<input type="checkbox"/>	Draughts from vents	<input type="checkbox"/>
Air movement too low	<input type="checkbox"/>	Some areas are hotter/cooler than others	<input type="checkbox"/>
Thermostat is inaccessible	<input type="checkbox"/>	Heating/cooling system does not respond quickly enough to the thermostat	<input type="checkbox"/>
Thermostat is not adjustable	<input type="checkbox"/>	Hot/cold surrounding surfaces (floor, ceiling, walls, windows)	<input type="checkbox"/>
Temperature changes between rooms	<input type="checkbox"/>	Deficient window (not operable)	<input type="checkbox"/>
Other:	<input type="checkbox"/>		<input type="checkbox"/>

8. Within your home, are any of the following a source of discomfort causing air movement or draughts (Please tick all that apply)

	Summer	Winter
Leaky windows	<input type="checkbox"/>	<input type="checkbox"/>
Cold window panes	<input type="checkbox"/>	<input type="checkbox"/>
Mechanical ventilation (extract ducts (bathroom) or cooker hood (kitchen))	<input type="checkbox"/>	<input type="checkbox"/>
Doors to the outside	<input type="checkbox"/>	<input type="checkbox"/>
Doors within the house	<input type="checkbox"/>	<input type="checkbox"/>
Stairways or landing	<input type="checkbox"/>	<input type="checkbox"/>
Wall vents	<input type="checkbox"/>	<input type="checkbox"/>
Other places (please specify)	<input type="checkbox"/>	<input type="checkbox"/>

--	--	--

9. How satisfied are you with your indoor air quality within your house? (please tick one only)

Satisfied  Fairly satisfied  No opinion/Cannot tell  Rather unsatisfied   
 Unsatisfied

10. How often do you need to open your windows in the following rooms in winter to be comfortable? (Please tick all that apply)

	Daily	Weekly	From time to time	Never
Kitchen	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bedroom(s)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Living room	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bathroom	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other areas	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

11. How often do you open your windows in the following rooms in summer to be comfortable? (Please tick all that apply)

	Daily	Weekly	From time to time	Never
Kitchen	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bedroom(s)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Living room	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bathroom	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other areas	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

12. Over the last 3 months did you suffer at any time at home from dry eyes?

Daily  Weekly  From time to time  Never

13. Over the last 3 months did you suffer at any time at home from a dry throat?

Daily  Weekly  From time to time  Never

14. Over the last 3 months did you suffer at any time at home from a headache?

Daily  Weekly  From time to time  Never

15. During the past month, how would you rate your sleep quality overall?

Very good  Fairly good  Fairly bad  Very bad

16. Are there any unpleasant odours present in your house that bother you?

Yes  No

If yes, what type? (please tick all that apply)

Food odours	<input type="checkbox"/>	General stuffiness	<input type="checkbox"/>
Cigarette smoke	<input type="checkbox"/>	Sewer odour	<input type="checkbox"/>
Mould odour	<input type="checkbox"/>	Smoke odour	<input type="checkbox"/>
Construction materials	<input type="checkbox"/>	Odours from traffic	<input type="checkbox"/>

17. Following on from question 16, what do you do if you notice any unpleasant odours?

Open windows	<input type="checkbox"/>	Spray air freshener (Febreze, etc.)	<input type="checkbox"/>
Open inside doors	<input type="checkbox"/>	Turn on electric air diffuser	<input type="checkbox"/>
Open outside doors	<input type="checkbox"/>	Aroma diffuser (oils, etc.)	<input type="checkbox"/>
Light scented candles	<input type="checkbox"/>	Nothing	<input type="checkbox"/>

18. Do you experience noise disturbances from the following sources? (Please tick all that apply)

	Daily / almost daily	Weekly	From time to time	Never
Inside the house (from different rooms)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Building ventilation, plumbing, etc.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Immediate surroundings (e.g. neighbours, yard)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Surrounding areas (traffic, industry, etc.)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

19. Have you noticed any mould in your house

Yes  No

If yes, location of mould?

Around the windows	<input type="checkbox"/>
At cornice level (ceiling)	<input type="checkbox"/>
Middle of ceiling	<input type="checkbox"/>
At skirting level	<input type="checkbox"/>

Middle of the wall	<input type="checkbox"/>
--------------------	--------------------------

20. Do any of the following cause you discomfort? (Please tick all that apply)

	Summer	Winter
Natural light (daylight from outside) (too bright)	<input type="checkbox"/>	<input type="checkbox"/>
Natural light (daylight from outside) (too dark)	<input type="checkbox"/>	<input type="checkbox"/>
Lighting overall (too bright)	<input type="checkbox"/>	<input type="checkbox"/>
Lighting overall (too dark)	<input type="checkbox"/>	<input type="checkbox"/>
Vibration from inside the building (appliances, etc.)	<input type="checkbox"/>	<input type="checkbox"/>
Vibration from outside the building (traffic, etc.)	<input type="checkbox"/>	<input type="checkbox"/>

## A.6 Linear mixed effects models for indoor parameters

Linear mixed effects models (LMEs) were chosen for analysing the impact of retrofits on the indoor air quality and thermal environmental parameters that were recorded as time series. We also used LMEs to examine the impact of different occupant behaviours on these parameters. Since multiple data points corresponded to the same homes, to account for non-independence of data (data from the same home) LMEs were the appropriate choice, with HomeID being modelled as a random effect. The LMEs allowed us to explicitly specify the impact of occupant behaviour and retrofit status in the model, along with outdoor weather data (temperature, humidity, wind speed, and PM<sub>2.5</sub>). Since participating homes may often drop out of such long-term studies or even withdraw consent regarding use of their data, it is further advantageous to use LMEs. These models do not depend on having the exact same population before and after intervention.

Separate linear mixed effect were developed for living rooms and bedrooms. For bedrooms, data between 10 pm and 7 am was used and for living rooms, data between 7 am and 10 pm was used. A model (Eq. A.1) without the Retrofit Status as one of the

predictor variables was compared to a model (Eq. A.2) with retrofit status added to the list of predictors.

*Predicted Parameter ~ Temp.Out+RH.Out+Wind.Out+PM2.5.Out+ 1 HomeID)*  
(Eq A.1)

*Predicted Parameter ~ Temp.Out+RH.Out+Wind.Out+PM2.5.Out+Retrofit Status+1 HomeID)*  
(Eq A. 2)

If addition of retrofit status significantly improved the model, it meant the energy retrofit had a significant effect on the indoor environmental parameter. If a difference was found, we proceeded to pairwise comparisons using the “lsmeans” package in R, computing contrasts between pre- and post-retrofit values.

To address non-uniform residuals, we log-transformed PM<sub>2.5</sub> and CO<sub>2</sub> parameters before fitting the model. For temperature data, no transformation was required.

To examine the impact of occupant behaviour on CO<sub>2</sub>, window opening percentage (as gathered from the participant activity diary, percentage) and blocking of vents (Yes or No) was added to the model. For PM<sub>2.5</sub> model, window opening, blocking of vents, smoking (Yes or No), and burning of wood fire or incense/candles (Yes or No) were added. The occupant behaviour models were examined to see if addition of these behaviours significantly improved the model over the model with retrofit (Eq,A.2). If the model with behaviours was significantly better then we examined which behaviours had the leading contribution to the model, using standardized coefficients.

## A.7 Summary of the Retrofit measures completed across the 14 participant homes

Five homes (HAVEN 01-03, 21, 22) received extra cavity wall insulation, five homes (HAVEN 04, 5, 21 and 22) received 100 - 160 mm external wall insulation (U value 0.12 -0.13 W/m<sup>2</sup>K). Eight of the homes received extra attic insulation (300 – 400 mm fibre glass wool, typical U value of 0.13 W/m<sup>2</sup>K), and nine received new windows and doors (both double and triple glazed). All homes had their fossil fuel-based heating systems (stoves or fireplace) replaced with a heat pump, and chimneys and flues were filled. Three homes (HAVEN 5, 21 and 22) had solar PV installations (»2kW), resulting in a

higher post retrofit BER rating (A3 and A2). The three private dwellings (HAVEN 1-3) had wood burning stoves installed as secondary heating sources post retrofit.

Table A.7.1 Deep retrofit measures completed in participating dwellings.

Home ID	Construction year	Floor area (m <sup>2</sup> )	Wall insulation	Roof insulation	Windows/ Doors (U-values, Wm <sup>2</sup> .K)	Post ventilation system	Heat pump	Wood burning/ Room heater
HAVEN01	2006	270.1	300mm CW, 0.36 W/m <sup>2</sup> K	300mm FG, 0.13 W/m <sup>2</sup> K	2.3/1.2	DCV	A2W350 %	Yes
HAVEN02	2003	178.8	300mm CW, 0.31 W/m <sup>2</sup> K	300mm FG, 0.13 W/m <sup>2</sup> K	0.7/0.9	DCV	A2W350 %	Yes
HAVEN03	2001	173.7	300mm CW, 0.30 W/m <sup>2</sup> K	300mm FG, 0.13 W/m <sup>2</sup> K	0.7/3.0	DCV	A2W350 %	Yes
HAVEN04	1997	48.8	150mm EWI, 0.12 W/m <sup>2</sup> K	400mm FGW, 0.26 W/m <sup>2</sup> K	0.8/1.8	NV	A2W6kW 350%	No
HAVEN05	2006	97.5	160mm EWI + 50mm CW, 0.13 W/m <sup>2</sup> K	300mm FG, 0.13 W/m <sup>2</sup> K	1.2/1.2	NV	A2W6kW 350%	No
HAVEN07	1998	73.0	-	-	-/-	NV	A2W350 %	No
HAVEN11	2001	76.0	-	-	-/-	NV	A2W350 %	No
HAVEN13	2001	76.0	-	-	-/-	NV	A2W350 %	No
HAVEN14	2001	76.0	-	-	-/-	NV	A2W350 %	No
HAVEN16	1970's	76.0	-	-	1.2*/1.0	NV	A2W175 %	No
HAVEN17	1970's	76.0	-	-	1.2*/1.0	NV	A2W175 %	No
HAVEN19	2000	55.0	-	400mm MWI, 0.11 W/m <sup>2</sup> K	0.7*/-	NV – RH controlled	A2W	No
HAVEN21	1990	74.2	100mm EWI, 0.25 W/m <sup>2</sup> K + 50mm CW	300mm FG	1.1*/1.2	NV	A2W8kW 350%	No
HAVEN22	1992	77.0	100mm EWI, 0.25 W/m <sup>2</sup> K + 50mm CW	300mm FG	1.1*/1.2	DCV	A2W8kW 350%	No

**Note.** \*=triple glaze windows (double glaze otherwise), CW = cavity wall insulation, EWI = external wall insulation, FG = fibre glass, FGW = fibre glass wool, MWI = mineral wool insulation, DCV = demand control ventilation, NV = natural ventilation, A2W = air to water.

Table A7.2. Retrofit measures for houses participating in the thermal comfort survey questionnaire.

Retrofit measures	Number of houses
Heat pump	56
New doors	36
New windows	31
Insulation added within the roof space	18
External wall insulation	11
Wall cavity insulation	11
Hot water tank/Internal pipework insulated	6
Internal wall insulation	5
Demand control ventilation	12*
Floor insulation added	2*

---

\*These measures were only applied in private homes

A.8 Indoor air pollutant profiles showing the impact of occupant behaviours, blocking wall vents and smoking on concentrations of carbon dioxide and PM2.5 respectively

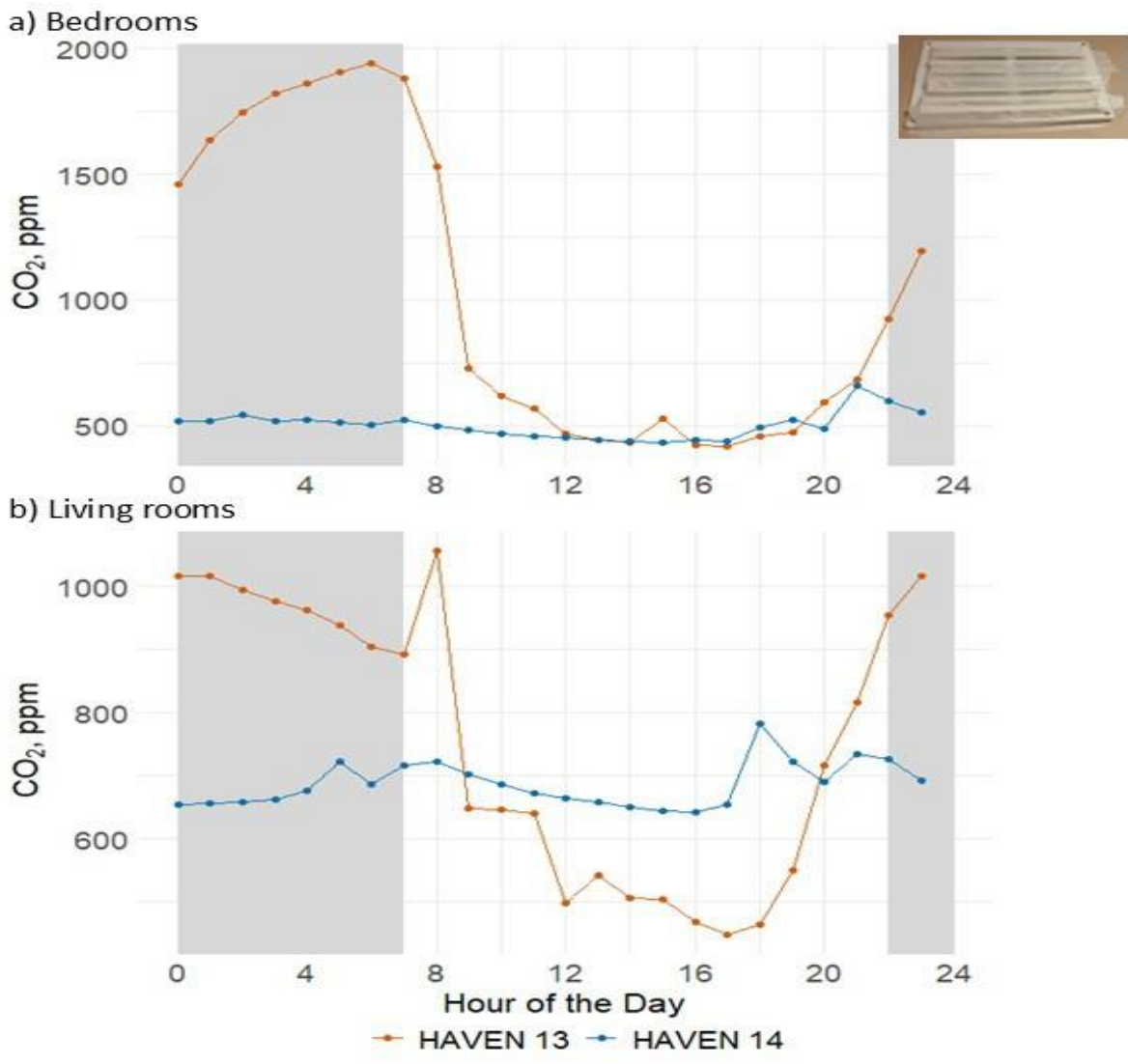


Figure A.8.1 Hourly bedroom CO<sub>2</sub> concentration profile for HAVEN 13, compared to HAVEN 14, showing the impact of blocked wall vents on (a) bedroom and (b) living room concentrations post retrofit. Both dwellings have the same construction style. At the time of the surveys two adults occupied the bedroom in both homes. Both dwellings were monitored at the same time period.

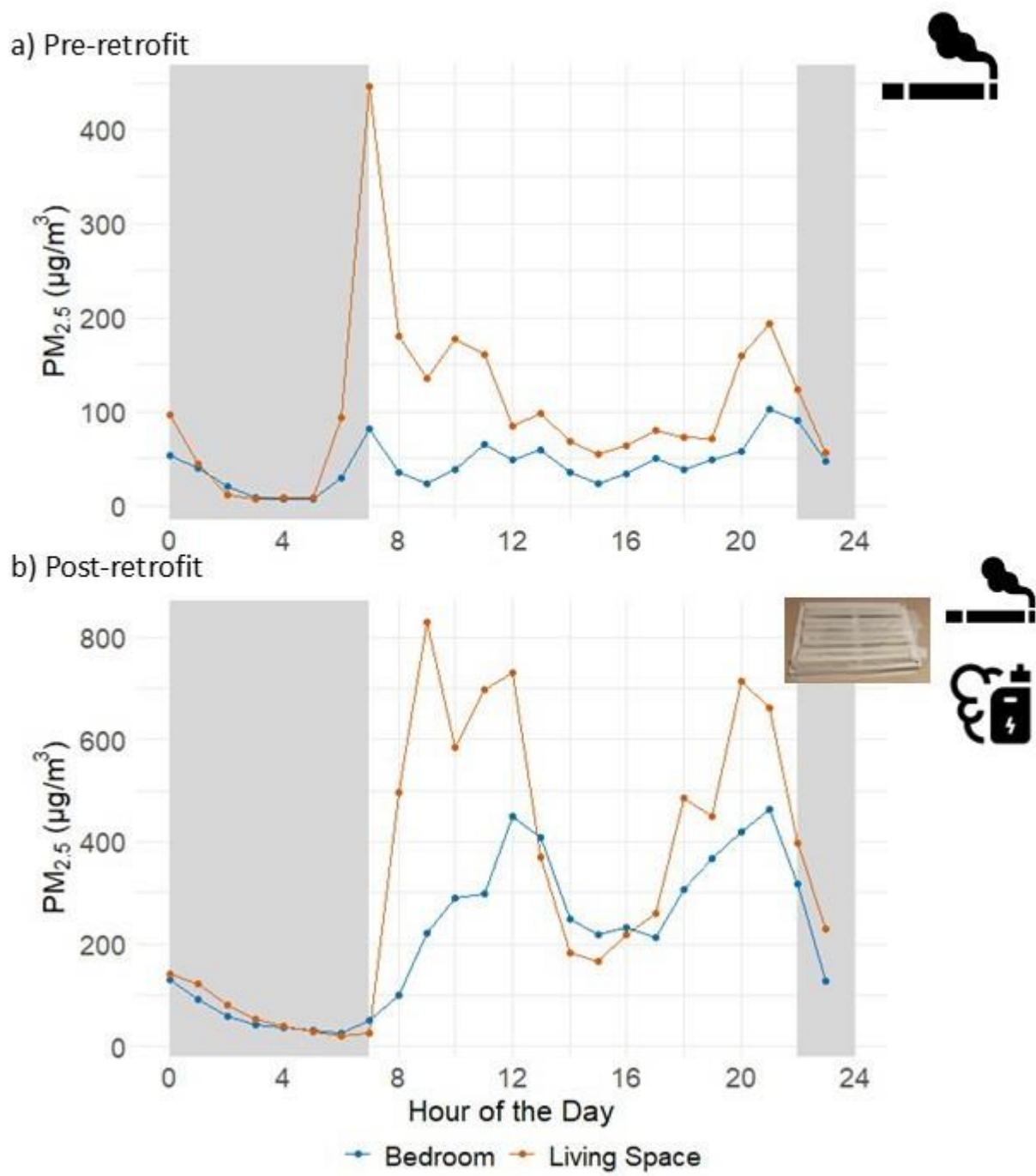


Figure A8.2 Hourly bedroom PM<sub>2.5</sub> concentrations (a) pre-retrofit and (b) post-retrofit in HAVEN 16, showing the impact of tobacco smoking in the living area (pre- and post-retrofit), and vaping in the bedroom (post-retrofit only) on nighttime and daytime concentrations. Occupants had blocked the wall vents in this dwelling post retrofit.

### A.8.1 Ventilation in indoor environments

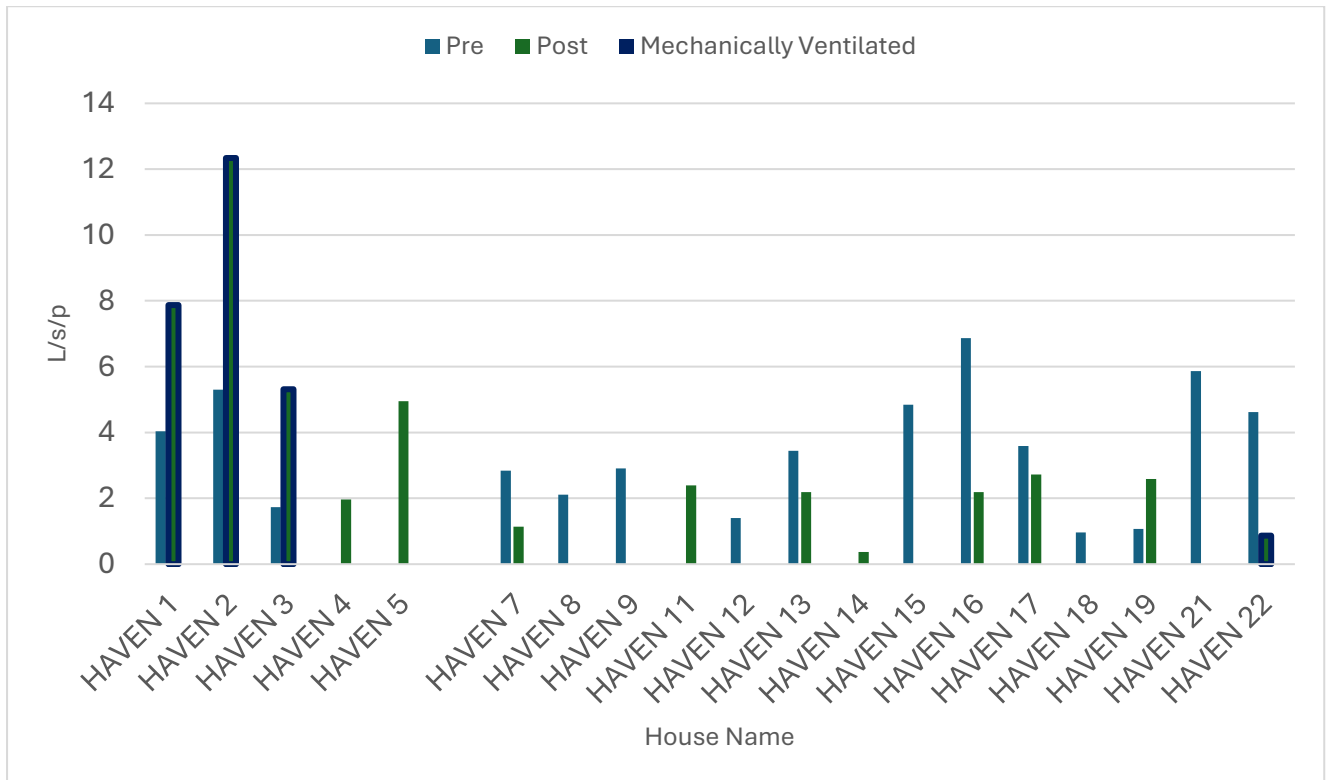


Figure A8.1. Pre/post-retrofit nighttime ventilation rates (night time, L/s/p)

### A.9 Distribution of indoor air quality and thermal environment parameters across sampled houses.

We present stacked plots of distribution for indoor air quality and thermal environment data for the homes pre- and post-retrofit. These plots present “paired” data, that is, only homes for which we had data both pre- and post-retrofit for a given parameter have been included in the plots.

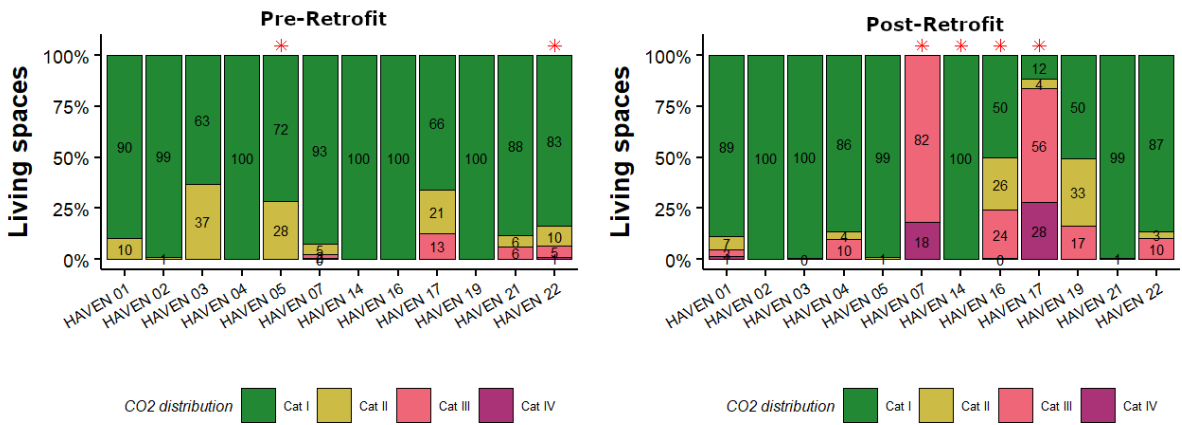


Figure A9.1. CO<sub>2</sub> distribution in living rooms pre- and post-retrofit (\* marked homes had blocked vents).

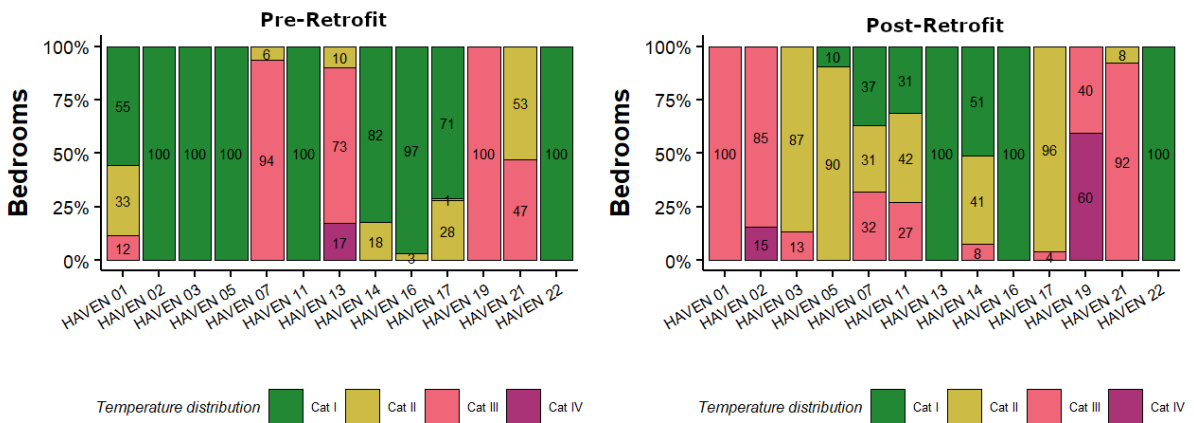


Figure A9.2. Temperature distribution in bedrooms pre- and post-retrofit.

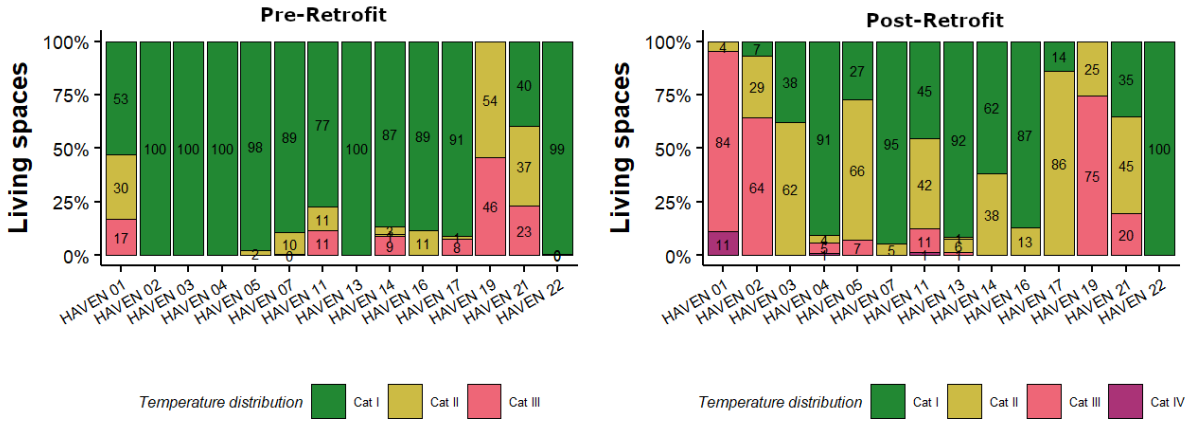


Figure A9.3. Temperature distribution in living rooms pre- and post-retrofit.

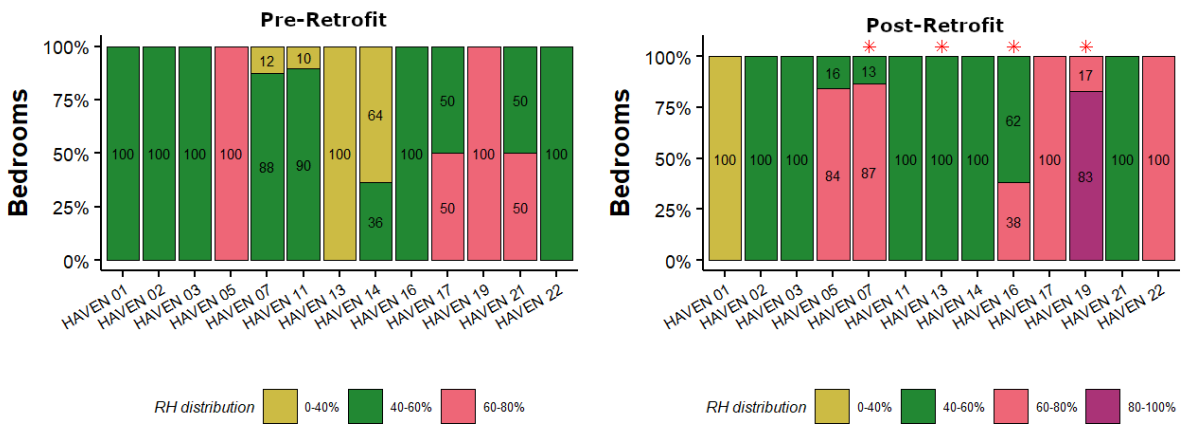


Figure A9.4. Relative humidity distribution in bedrooms pre- and post-retrofit. (\* marked homes had visible mould issues)

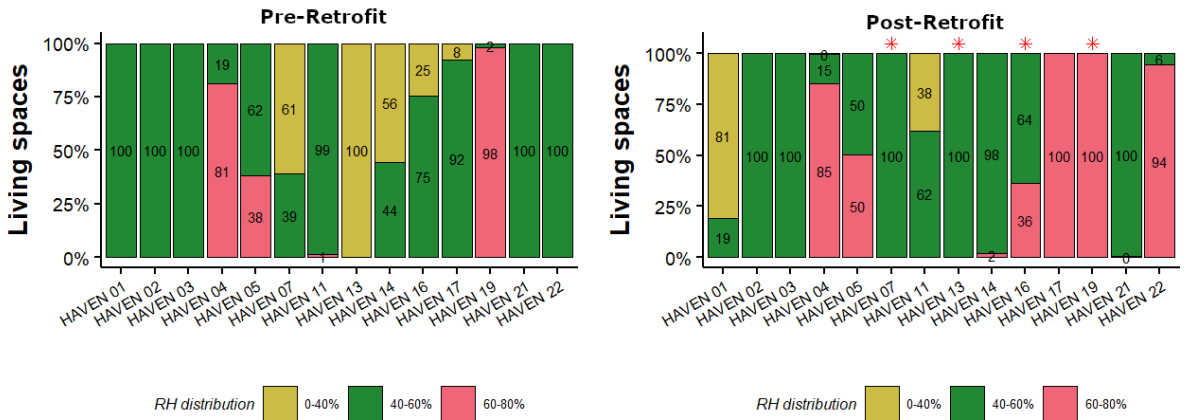


Figure A9.5. Relative humidity distribution in living rooms pre- and post-retrofit. (\* marked homes had visible mould issues)

References

- [1] SEAI, ISEN 13790: Energy performance of buildings - Calculation of energy use for space heating and cooling.
- [2] SEAI, Building Energy Rating Certificate (BER). 2024 (accessed May 2024).
- [3] S. Batterman, Review and Extension of CO<sub>2</sub>-Based Methods to Determine Ventilation Rates with Application to School Classrooms, *Int. J. Environ. Res. Public Health* 14(2) (2017) 145.