Research to identify if changes to guidance in standard 3.14 ventilation in 2015 have been effective in improving ventilation and indoor air quality

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This report is published electronically to limit the use of paper, but a hard copy will be provided on request to Building Standards Division.

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1. Executive Summary

1.1 The overall purpose of this work has been to investigate the effect the 2015 changes to guidance in Standard 3.14 has had on: ventilation design solutions and their implementation; occupant interaction with ventilation components; occupant experiences and observations on ventilation systems and indoor air quality; measured levels of indoor air quality within a representative selection of dwellings; and to provide clear reporting of outcomes and recommendations for where improvements can be made.

1.2 The brief specified a start date of March 2021, with the project due to be completed by the end of August 2022. However, restrictions due to the Coronavirus pandemic heavily impacted on the project's delivery since substantial elements of the work relied on access to households. The project has effectively completed in October 2022.

1.3 The literature review (WP1) was completed in April 2021, identifying best practice, emerging trends in this field, and other regulatory standards for ventilation. It highlighted a possible conflict between indoor and outdoor pollution sources when opening windows to dilute and expel indoor pollutants in urban locations.

1.4 The original intention had been to undertake the face to face survey work (WP2) in spring 2021 and to start monitoring (WP3) soon after. However, due to Covid restrictions about essential work, concerns about undertaking fieldwork, and potential reluctance of participants, this work was postponed to Autumn 2021.

1.5 However, with continuing cases, restrictions for fieldwork remained in place, therefore a decision was taken to deliver the WP2 survey as a postal survey. A larger pool of survey addresses (2000 in total) were obtained from records of Energy Certification (SEPCR) - Domestic Extract Apr 2019 To Mar 2020.

1.6 The postal survey was developed, based on previous similar work (REF 2014 Survey), augmented with a face to face survey when restrictions were lifted producing a final total of 138 returns, identifying 57 households interested in participating in the long term monitoring (WP3).

1.7 The survey identified a high proportion of households reporting not having a Carbon Dioxide ($CO_{2)}$ monitor fitted. In fact only 59% of respondents claimed to have CO_2 monitors in their bedrooms. All the households who expressed an interest in participating in the long term monitoring were contacted to check that this was the case. In a small number of instances occupants had been mistaken, confusing Carbon Monoxide (CO) and CO_2 monitors, as well as heating controls and CO_2 monitors. Some of these homes were included in the study as a comparison.

1.8 Key findings from the survey were:

- 59% of respondents reported the presence of a CO_2 monitor installed in bedrooms.

- Of those households who have CO_2 monitors installed, only 30% had received advice on how to use the CO_2 monitor.

- The survey found an increase in reported window opening (27% in living rooms and 36% in bedrooms), when compared to the results of the 2014 survey (around 19% in living rooms and around 12% in bedrooms).

- The survey found a significant increase in reported trickle vent opening (75% in living rooms and 69% in bedrooms), when compared to the results of the 2014 survey (around 25% in living rooms and around 28% in bedrooms).

- The main drivers for ventilation include thermal comfort (26% in both living rooms and bedrooms), indoor air quality or “fresh air” (33% in living rooms and 40% in bedrooms) and energy consumption (26%).

- Of those households who have CO_2 monitors installed, 60% stated that they use the monitors and 80% reported taking action when CO_2 levels are high. For action, the majority open the windows but still a minority misunderstood the purpose of a CO_2 monitor (some believed it was a carbon monoxide detector or heating control).

1.9 The 57 households identified were contacted to verify suitability and willingness to participate in the project. By January 2022, monitoring commenced in 16 homes as part of WP3.

- The long term monitoring component of this study (WP3) began in winter 2022 on 16 homes. The ventilation audit undertaken in these homes, included testing mechanical systems and found that extraction rates below government recommendation (13 homes), insufficient door undercuts (9 homes), unclear labelling of switches (6 homes), systems turned off (8 homes), and lack of ventilation advice (12 homes). Reported issues with mechanical systems were noise, draughts, costs of running.

- Long term monitoring (WP3) began in Winter 2022 on 16 homes. Seasonal analysis took place and data analysis during winter and spring evidenced 6 homes with indication of poor indoor air quality throughout the dwelling, despite the presence of CO_2 monitors in some of the bedrooms.

- In terms of measured air quality in the homes that were provided with CO_2 monitors (12 out of 16), seasonal means of CO_2 concentration during occupied hours in both living rooms and bedrooms in winter, spring were above 1000 parts per million (ppm) (see WP3-Chapter 5). Whilst it may be concluded that not all homes with CO_2 monitors installed maintain indoor concentrations below 1000 ppm, the underlying causes of this were driven more by the ventilation provision and compliance.

- For temperatures, it was found that during July 2022, several homes reported excessively high temperatures. In two homes occupied by vulnerable people, living room temperatures exceeded 26°C for more than 60-70% of the time. In bedrooms, overheating assessment against TM59-criterion-2[1] showed overheating on 8 homes out of 16.

1.10 Following initial data analysis of the winter season, 9 households were selected out of the 16 homes for detailed indoor air quality (IAQ) monitoring (WP4) that took place in April 2022 (see Chapter 6 for details). All of the dwellings under the detailed monitoring regime have TVOC levels that would be considered to be relatively low. There was no indication of PM levels being generated from external sources, but was more positively correlated with periods where cooking was likely to be taking place.

1.11 The industry workshop (WP5) explored possible causes of the lack of compliance regarding installation of CO_2 monitors in August 2022. Whilst there is an indication of confusion about CO alarm/ CO_2 monitors in some local authority verifiers, it was identified that a high proportion of homes, primarily owner-occupied homes, may have been subject to stage warrants for pre 2015 Standards. This was verified in the 4 homes (those with no CO_2 monitors) out of 16 that were monitored, where the building warrant was submitted before 1 October 2015 for homes built in 2019.

1.12 The survey had identified a lack of advice to householders as part of the handover information about how to use the CO_2 monitors and the workshop identified limitations on this. During the workshop the need for providing ventilation advice gradually, i.e. after occupants were settled in the homes, was also discussed.

1.13 A concern raised at the time of the introduction of the revised standards is that it may result in widespread complaints from occupants (i.e. complaints relating to a presumed energy consumption from the CO_2 monitor, visual disturbance, or any generic mistrust from having this equipment in bedrooms). The feedback from the workshop and elsewhere is that this has not been the case. Given the earlier evidence of user interventions, it may be concluded that the overall effect has been positive.

1.14 The overall conclusions are broadly as follows:

- There is increased awareness of issues of ventilation and health. This may have been due to a general increase of interest, but the Covid-19 pandemic may also have impacted on awareness and behaviour. Underlying health issues among occupants (especially respiratory diseases such as asthma as well as chronic obstructive pulmonary disease) were also important drivers for ventilation awareness, as evidenced from the household survey

- Whilst the survey indicated that, compared to the 2014 research, there is a greater awareness of the importance of ventilation, including of air quality as a driver for ventilation. Though, many of the barriers to effective ventilation remain, which includes issues of noise and security. Thermal comfort and energy use remain the main drivers for window opening and closing.

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[1] TM59-criterion-2: for bedrooms only, from 10 pm to 7 am, operative temperatures shall not exceed 26°C for more than 1% of annual hours

- There was evidence of the use of the CO_2 sensors in homes as a catalyst for ventilation behaviours and raising awareness for occupants and there were no significant unintended consequences identified. Their continued use in regulations is supported. However, this could be further supported by better provision of advice about their purpose, and effective use of ventilation systems

- Issues of compliance remain the significant barrier. A large proportion of the homes tested, did not meet minimum Building Standard requirements but it was also clear that house builders have the tendency to submit greater than normal levels of applications before changes in Building Standards come into effect to avoid having to build to the new standards for as long as possible.

- These issues were the predominant drivers for incidences of poor ventilation identified during the long-term monitoring, which remain commonplace.

2. Research outline

The overall purpose of this work is:

2.1 To investigate the effect the 2015 changes to guidance in Standard 3.14 has had on: ventilation design solutions and their implementation; occupant interaction with ventilation components; occupant experiences and observations on ventilation systems and indoor air quality; measured levels of indoor air quality within a representative selection of dwellings; and to provide clear reporting of outcomes and recommendations for where improvements can be made.

Specific objectives include:

2.2 To identify to what extent ventilation systems installed following these changes achieve the minimum recommended ventilation performance; and where dwellings do not, identify the root cause(s) of this non-compliance. To provide a comparison of performance of post change performance against pre-change performance.

2.3 To identify how guidance is being interpreted by designers, the design solutions being implemented, design methodologies being used, the performance of these design methodologies in practice including end user perceptions and delivered indoor air and environmental quality, and to identify where potential improvements to guidance are required to deliver robust solutions.

2.4 To establish indoor environmental performance and how this relates to occupant interactions with available means of ventilation, such as trickle ventilators, windows, doors and extract fans in dwellings constructed under the 2015 building regulations and Technical Handbook guidance through: identification of a large sample of representative dwellings, a broad snapshot study of more than 200 to establish system types, occupant perceptions and monitored performance, and perform in-depth monitoring of at least 20 dwellings for a period of 12 months.

2.5 To provide clear robust and justified evidence underpinning the outcomes from the work in the required formats to best fit the needs of the clients.

Progress on the agreed work packages is described below.

WP1

2.6 This was an initial project setup phase, including an initial meeting with the client organisation to refine the scope, timescales, deliverables, and to set up and procure the following work packages. The WP also undertook a literature review to identify best practice, emerging trends in this field, and other regulatory standards.

2.7 This stage confirmed the key research questions, a refinement of the methodology in relation to this, and identification of timescales and deliverables over the course of the project. This WP has been completed and the literature review is contained in Appendix 1. The project timescale has been significantly affected by the impacts of the COVID pandemic and these are described in the following section.

WP2

2.8 This WP2 (household survey) is aimed to gather data about occupant's awareness of their ventilation provision, use of the CO_2 indicators and how this affects their air quality. The objective was to gather this through a general survey of 200 homes built to the 2015 regulations.

2.9 The survey was based on the questionnaire used in the 2014 study of Occupant Interactions with Ventilation[2], and the 2018 dMEV study[3]. This allows some longitudinal comparison of responses, for example to identify changes in awareness. This survey included occupancy patterns, building information and use, awareness of ventilation systems, the frequency of use of these systems, awareness of indoor environmental conditions, and barriers and drivers for use of ventilation. The survey preparation included the development of additional survey content to address the specific questions raised in this study concerning use of CO_2 sensors and consequent interaction with ventilation provision, including mechanical and natural systems. This included awareness of the sensors, how it affects household ventilation behaviours, value of the alert systems and unintended or negative consequences.

2.10 The survey was developed and agreed with Building Standards Division (BSD) in Spring 2021. Following the methodology used in the 2014 study, the intention was to deliver this through a face-to-face doorstep survey, however we did identify that this could be undertaken as an online, postal or telephone survey, with some refinement of the questionnaire.

2.11 The team commissioned a professional survey company to undertake the survey. Based on similar research, this required identification of approximately 800 addresses of suitable homes. After the scoping exercise in WP1 we identified the requirements for representation of responses in the study, for example dwelling types, construction systems, ventilation provision, geographical location, and tenure type. The team used existing contacts with developers and housing associations to identify suitable sites for the survey. The original intention was to conduct these on a limited series of selected developments which would make the survey and the monitoring much simpler and reduce the number of other variables in the survey. We identified 5 housing developments, which represented typical construction types and common ventilation provision.

2.12 The ongoing restrictions in the Spring of 2021 prevented the survey being carried out at that time. Given on-going limitations, and different behavioural patterns of

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[2] Sharpe T, McQuillan J, Howieson S, Farren P, Touhy P (2014) Research Project To Investigate Occupier Influence On Indoor Air Quality In Dwellings, Scottish Government Technical Report (Local Government and Communities Building Standards Division), 21 August 2014. https://strathprints.strath.ac.uk/50463/

[3] Sharpe et al. 2018, Ability of decentralized mechanical ventilation to act as 'whole-house' ventilation systems in new-build dwellings', The Scottish Government, http://radar.gsa.ac.uk/7085/1/Final%20report%20dMEV.pdf

home use and ventilation in the summer, it was agreed the survey would be postponed to the end of August 2021 for two reasons; firstly, a survey about ventilation in the summer months may give a skewed picture and secondly an expectation that restrictions would be relaxed by the Autumn. However, this was not the case and the research company which was bound by the requirements of the Market Research Society (MRS) was not able to conduct face to face surveys.

2.13 Given the pressure on time, after consultation with BSD and negotiations with the survey company, it was decided to change the mode of delivery to a postal survey, with possible face-to-face follow-up when this was possible. As a postal survey has a lower rate of return (approximately 10:1) so a larger number of addresses were required. To facilitate this, we used a dataset provided by BSD that included addresses of properties with certification in 2019 and 2020.

Selection Criteria:

2.14 This dataset was very large with 38057 addresses in the sample, so some selection was undertaken to narrow this down. This included using the 2019 addresses as these would be beyond a defects liability period and occupants would have settled in; location in the central belt; inclusion of both houses and flats, but exclusion of some less common typologies such as bungalows and maisonettes. It also excluded properties larger than 100m^2 on the grounds that larger homes are less likely to be adversely affected by poor ventilation issues. Selection criteria consisted of:

- Certification in 2019
- Central Belt Location: Postcodes E, ML, PA1 and G
- Houses and flats
- Excluded Detached Houses and Bungalows, Maisonettes,
- Total Floor Area (TFA) <100m^2

2.15 This provided 2525 sample addresses for use in the survey, and this was used as the basis for the survey delivery and headline results of this are reported in Section 3. The survey was sent out at the end of August 2021. One of the disadvantages of a postal survey is that it takes longer for returns to be collected with returns coming in over September and October. This had a knock-on effect for the identification of homes for participation in the monitoring study in WP3. By November 115 returns had been achieved and so measures were put in place to undertake face to face surveys. The Housing Associations for these sites had agreed to contact the occupants ahead of the survey when this was first planned for August, and for the later survey, these communications had to be re-established. Further face-to face surveys were commenced in late November and were on-going. Unfortunately, the emergence of the Omicron variant resulted in the MRS withdrawing face to face survey permissions. After consultation with BSD, it was agreed that rather than waiting for these restrictions to be lifted, the remainder of the survey would be conducted as a postal survey – we have used the Housing Association addresses for these as they are likely to produce better returns. By February 2022 there are 138 surveys completed with 57 households that had expressed interest in participating in the long monitoring. The results of the survey to date are provided in Section 3.

WP3

2.16 The aim of WP3 is to undertake actual monitoring of environmental conditions in homes to investigate what effects the new regulations have had on actual ventilation use. The survey in WP2 had included a question to ask the respondents if they would be willing to participate in a monitoring programme.

2.17 As outlined in the previous section, the slower response rate to the survey meant that availability of locations was also slower to materialise, and this delayed the deployment of the monitoring installation. Part of the initial discussions in WP1 had identified general parameters for investigation, for example, comparison of homes who do or do not make use of the systems; or those that do use the systems, which may then compare effectiveness in different construction types or with different ventilation provision and it was agreed that this would be refined from the survey data.

2.18 A key issue arose in an initial analysis of the survey returns in that a high proportion (37%) indicated that they did not have a sensor or were unsure (7%). The properties that had expressed an interest were followed up by telephone and these responses were tested, but it would appear that they were reliable. After consultation with BSD, it was agreed that some houses without CO_2 sensors would be included in the monitoring study. Whilst the main aim is to test effectiveness of the use of the sensors, these properties may provide comparator sites for evaluation. The deployment of the detailed monitoring is described in more detail in Section 4 but at the time of writing (April 2022) 16 homes are being monitored.

2.19 Although the monitoring has commenced much later than planned, with it running to August 2022, we are confident that reliable data from the winter, spring and summer seasons will provide a robust picture of environmental condition in these homes.

2.20 The installation also included the collection of further data about the homes. This included verification of the construction and ventilation system, testing of the mechanical ventilation provision, identification of undercuts, and verification of patterns of occupancy. The outline findings for this and sample data are shown in Section 4.

2.21 At the end of March 2022 the detailed monitoring study began (WP4) to capture detailed data on a time-limited period. A total of 3 weeks of intense monitoring are capturing more granular data on occupancy and behaviour. The locations of these homes were identified through analysis of the long term monitoring, with a focus – but not exclusively - on homes that appear to be poorly ventilated. Specific sensors system is been employed, will focus on the presence of particulates (PM_{10}) and tVOCs.

2.22 WP5 was intended to gain an understanding of the industry awareness and application of the 2015 requirements. This included collection of insights from 48 members of the industry sector, including designers, contractors and building control officers. The results of the household survey (WP2) have been the basis to conduct a focus group that was conducted in August 2022 online to explore more detail how guidance is being interpreted by designers, the design solutions being implemented, design methodologies being used. One new issue that has been explored in the light of findings to date was about ensuring compliance and guidance for users.

2.23 WP6 is the work package for preparation of written reports and findings for BSD and related agencies, collation of interim reports, production of a final report and wrap up workshop for BSD

3. Literature review

Background and context

3.1 The University of Strathclyde has been commissioned to undertake research to identify whether the changes to the 2015 Building Standard (Scotland) Regulations, that required the installation of CO_2 monitors, has produced any changes in occupant behaviour regarding the opening of trickle vents, windows and/or internal doors. This is founded on the fundamental principles enshrined in Section 3.14 of the Technical Standards that, “Every building must be designed and constructed in such a way that ventilation is provided so that the air quality inside the building is not a threat to the building or the health of the occupants.”

3.2 This investigation represents the third phase of research into indoor air quality (IAQ) that has attempted to quantify the impact increasing building envelope air tightness standards, have had on background air infiltration rates. The previous report (Sharpe, 2014) was founded on research work (Sharpe, 2015) (Howieson, 2014) into low ventilation rates in contemporary Scottish dwellings that confirmed high levels of CO_2 , particularly in bedrooms. This literature review adds to the introduction that prefaced the 2014 report and will attempt to survey, synthesize, analyse and present our current understanding of the cognate area.

3.3 The research undertaken in Scotland built on investigations in England (Raw GJ, 2004, Davis, 2008; Crump, 2009) and Europe (Stranger, 2012; Kaunelienė, 2016) that highlighted the drive for energy efficiency by reducing ventilation rates through the mechanism of increasing the building fabric’s air tightness, was likely to lead to a significant reduction in IAQ with potential implications for long term public health. The 2014 research was therefore designed to measure the impact on IAQ in contemporary dwellings, where trickle vents in conjunction with intermittent mechanical wet zone extraction, was the sole ventilation technique to be employed.

3.4 The 2014 report (Sharpe, 2014) confirmed that there was minimal occupant interaction with the trickle ventilators (i.e. 63% were always closed and 28% always open in bedrooms). In only 9% of cases did the occupants intervene to make occasional adjustments. In a sub-set of dwellings that were the subject of more detailed monitoring, average bedroom CO_2 levels of 1520 ppm during occupied (nighttime) hours were observed. Where windows were open the average bedroom CO_2 levels were 972 ppm. With windows closed, the combination of ‘trickle ventilators open plus doors open’ gave an average of 1021 ppm. ‘Trickle ventilators open with doors closed’ gave an average of 1571 ppm. All other combinations gave averages of 1550 to 2000 ppm. Ventilation rates and air change rates were estimated from measured CO_2 levels, calculated the ventilation rate was less than 8 l/s/p in all dwellings, with 42% of cases having air change rates less than $0.5ach^{-1}$. The report concluded that trickle ventilation with occasional wet zone extraction does not provide an effective strategy to protect against poor IAQ.

3.5 This was in line with two previous studies undertaken in Scotland (Sharpe, 2015; Howieson, 2014) that confirmed a significant reduction in air infiltration rates through the building fabric, have had a deleterious effect on IAQ, with indoor CO_2 levels in new dwellings monitored at concentrations approaching 5000ppm. These studies provided an evidence base to stimulate a change to the standard that was designed to address - or at least ameliorate - the concerns surrounding poor IAQ, that is likely to be particularly acute in single aspect, small, flatted dwellings with high occupancy densities.

3.6 In 2015 a new requirement was embedded in the Building Standards (Scotland) Regulations, Technical Standards (Domestic), in an attempt to address the issue of poor IAQ in modern air-tight dwellings, that was designed to inform the occupant when IAQ was deteriorating, and it was hoped would stimulate action to increase ventilation rates (opening windows and internal doors):

"The regulation requires CO_2 monitoring equipment to be provided in the apartment expected to be the main or principal bedroom in a dwelling where infiltrating air rates are less than $15m^3/hr/m^2$ @ 50 Pa. This should raise occupant awareness of CO_2 levels (and therefore other pollutants) present in their homes and of the need for them to take proactive measures to increase the ventilation. Guidance on the operation of the monitoring equipment, including options for improving ventilation when indicated as necessary by the monitor, should be provided to the occupant."

3.7 The standard did not prescribe the specifics of the guidance; however an associated reference (Scottish Gov., 2017) provided the following recommendations for occupants with advice being given using a 7point scale:

CO_2 level	Action
0-349ppm	Check monitor is working
350-779ppm	Do nothing
800-999ppm	No immediate action
1000-1199ppm	Partially open trickle ventilators or open door
1200-1499ppm	Fully open trickle vents or open door
1500-1999ppm	Partially open window
Over 2000ppm	Open window and door

3.8 Although these recommendations may be considered to lack specificity, the monitor's primary function was to act as an IAQ 'traffic light'. CO_2 levels were to be used as a proxy metric to stimulate occupants to take action to increase internal air movement within the dwelling or to introduce external air via adjustable trickle vents or opening windows. These instructions are offered on the presumption that the installed windows have the facility to be held firmly in a partially open position, to ensure that they remain unaffected by capricious wind action.

3.9 The research protocol and methods to be adopted must therefore take into account a variety of confounding variables and be designed to answer the following questions:

1. Has the dwelling been built to the specified air tightness standard i.e. below $15m^3/hr/m^2$@50 Pa?
2. Has the monitor been installed in the recommended location and position?
3. Have the occupants been provided with appropriate guidance?

4. Have the occupants understood the guidance?
5. Have the monitors encouraged behavioural change re. window/door opening?
6. Have these changes in behaviour produced the required improvement in IAQ (i.e. CO_2 levels been maintained below the 1000ppm target threshold)?

Background

3.10 In 1992, Perera (1992) put forward the concept of ‘build tight- ventilate right’. This was a proposition that dwellings should be designed and constructed to be as tight as practicable and incorporate a ‘planned’ ventilation strategy. The paper emphasised that a building cannot be too ‘air-tight’, but it can be under ventilated. This approach built on a BRE publication (Building Research Establishment, 1995) that claimed there was wide acceptance that a whole house ventilation rate of $0.5ach^{-1}$ - supplemented by mechanical air extraction during cooking and bathing - was sufficient to dilute indoor pollutant concentrations and suppress relative humidity below 70% - a threshold associated with condensation and mould growth. The view was re-confirmed in 2012, in the 2014 study report commissioned by Building Standards Division (BRE, 2012). Subsequent work by the University of Strathclyde (Howieson, 2014) however highlighted aspects of the testing regime undertaken at the BRE HQ in Watford, which undermined the view that trickle vents alone could ensure ‘healthy’ IAQ in ‘air-tight’ dwellings.

3.11 It appears from these studies, that dwellings built to the new prescribed air tightness standard that rely solely on trickle ventilators supplemented with mechanical wet zone extraction, for background ventilation, do not satisfy the requirement of Technical Standard 3.14 that states:

Ventilation should have the capacity to:

- provide outside air to maintain indoor air quality sufficient for human respiration.
- remove excess water vapour from areas where it is produced in sufficient quantities in order to reduce the likelihood of creating conditions that support the germination and growth of mould, harmful bacteria, pathogens and allergens.
- remove pollutants that are a hazard to health from areas where they are produced in significant quantities.

3.12 Reducing ventilation rates to improve energy efficiency and lower carbon emissions, without providing a planned and effective ventilation strategy is likely to result in a more toxic and hazardous indoor environment, with a concurrent and significant negative long term and insidious impact on public health. The observed data from ‘real life’ conditions, where dwellings have been built to the prescribed Building Standards for air tightness ($5m^3/m^2$@50Pa) with trickle ventilation as the sole ‘planned’ ventilation strategy, produced CO_2 levels indicative of poor indoor air quality.

3.13 When considered as a discrete volume, an occupied apartment will require a substantially greater ventilation rate than can be provided solely by trickle ventilators with a free vent area of $12000mm^2$. Air infiltration rates through trickle vents are likely to be further compounded by occlusion from curtains or blinds and where controllable they are invariably closed due to ‘whistling’ in high winds (Sharpe, 2015). Whilst it may be argued that elements such as occupants closing vents, or occlusion by curtains are beyond the remit of the building standard regulations (albeit that they are specified as being ‘controllable’), these are nevertheless predictable behaviours which require to be addressed, on the same basis as ‘safety factors’ are applied in structural engineering regulations to account for occasional and/or accidental overloading.

3.14 If the CIBSE recommendation of 8l/s/p to keep CO_2 at under 1000ppm (CIBSE, 2005) is applied to an occupied living room designed for 5 persons, 40l/s of ambient air (that equates to circa 150m^3/hr) will have to enter, and more crucially, exit the room through the trickle vents. To drive such a flow in a room that has been designed for cross ventilation, will require an air speed of approximately 3.3m/s, equivalent to a pressure differential of 18Pa (Howieson, 2014). Where rooms have a window vent in only one elevation, cross ventilation will not occur. Without a potential exhaust route on an opposite or adjacent wall, it is difficult to conceive how trickle vents could provide anything close to ‘healthy’ ventilation rates, as the air will have to both enter and exit via the same opening. In still conditions where no pressure differential occurs, there will be little or no transfer and IAQ is therefore likely to deteriorate rapidly.

3.15 A study by Biler (2018) that looked specifically at the efficacy of trickle vents reported on the impact of a variety of design parameters. These were listed as: ventilation capacity, controllability, actuation, thermal insulation, air permeability, water tightness, climatic adaptation, security, and acoustic attenuation. Other important parameters in trickle vent design are positioning, equivalent area and the interaction with the occupants. It is clear from this work that the performance of trickle vents can vary markedly depending on a multiplicity of interacting factors. This undermines the view that a ‘one size fits all’ regulatory approach will prove adequate for all locations and dwelling typologies.

3.16 There are no specific air quality standards in the UK for residential buildings. A guide by the Chartered Institution of Building Services Engineers (CIBSE, 2005) concentrating on health issues in building services recommends that ventilation rates should never fall below 5 l/s, however, in a major literature review of a range of building types, ventilation rates below 25 l/s/p increased the risk of sick building syndrome, short term sick leave and decreased perceptions of productivity[4]. It is thus highly likely that relatively tight, energy efficient, modern dwellings will not only suffer from poor indoor air quality, but they will also be subject to progressive and cumulative increases in humidity, during the winter months if windows remain closed; an increasingly likely scenario given recent cost inflation in energy supply. Furthermore, diurnal temperature variations – particularly in lightweight construction incorporating polythene vapour barriers – will be greater, increasing overnight internal relative humidity and condensation rates, which will be absorbed by carpets, bedding and soft furnishings; the key habitat of the house dust mite; a species that produces 15 high allergenic proteins in its faecal pellets (Wright, 2009). HDM levels in new timber frame dwellings constructed since 1990 had allergen levels equal to that of the older stock signifying that the new stock has taken only 10 years or so, to develop HDM colonies that have taken over 70 years to develop in the older stock (Howieson, 2005). Howieson maintained that although dwellings have become warmer they have also become more

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[4] Jaakkola, J. J. & Miettinen, P., 1995. Ventilation Rate in Office Buildings and Sick Building Syndrome. *Occupational and Environmental Medicine*, 52(11), pp. 709-714.

humid allowing HDM to colonise and proliferate. It is this change in the indoor environment (from cold and draughty to warm and humid) that has driven a 6-fold increase in child asthma prevalence that has occurred in Scotland over the last 40 years.

3.17 The move towards higher insulation and greater sealing of houses from accidental and on occasion, fortuitous air leakage and infiltration rates, is projected to exacerbate the problem over the next decade where modern methods of construction such as factory sealed SIP panels are likely to be deployed in greater numbers. Improvements to fabric U-values, has resulted in ventilation now being the major route for heat losses. Increased sealing of buildings to reduce inadvertent air movement invariably leads to low air change rates that will result in:

a) Still and stale internal air
b) Increased concentrations of toxins, Volatile Organic Compounds (VOCs) and off gassing from materials and furnishings
c) Increased humidity resulting in mould growth and ideal conditions for HDM colonization and proliferation
d) Increased susceptibility to pre-disposed health issues of residents such as asthma and viral infections transmitted by aerosol concentrations (Covid-19)

3.18 Ventilation of dwellings and the requirement to do this without increasing energy use is a priority for the house building industry. Current options include natural ventilation, consisting of intermittent mechanical ventilators in kitchen and bathroom and trickle ventilators in the window frames and various forms of mechanical ventilation from continuous extract, to whole house balanced systems with heat recovery options. There appears to be a lack of interest and take up in ventilation systems within the house building industry. This possibly stems from the lack of detailed inclusion in building regulations going back to the early 1990s. Lack of industry research into ventilation strategies during this period, and a reluctance from architects and developers alike to develop planned natural or hybrid ventilation strategies has meant that the Building Standards, *de facto* become the default position. Given the UK government's planning prediction (Ministry of Housing, Communities and Local Government 2020) that 5 million new dwellings will be required to satisfy demographic changes, it is vital that research into the epidemiological relationships between existing domestic environments, ventilation rates and respiratory health is undertaken to inform the design specification of what amounts to a £500 billion house building programme.

3.19 In domestic environments, recommendations on ventilation are largely driven by the control of humidity levels, as well as pollutants from combustion (e.g., gas cooking hobs) and odours. Guidance can be found in CIBSE Guide A (2015) Table 1.5 and CIBSE TM60: Good Practice in the design of homes (2018) and is generally aligned with or higher than the minimum values recommended in Approved Document F (MHCLG, 2013b) (or equivalent in Scotland and Wales). These include minimum whole dwelling rates and minimum rates in kitchens and wet rooms. The recommended range in Guide A is 0.4 to 1 air changes per hour (ach) in living rooms and bedrooms, with higher extract rates in kitchens and wet rooms. These should also be checked against guidance for the control of HDM, for which 0.5 ach with regular purge ventilation (e.g., extract fans) to provide 1.3 ach to enable dilution of indoor pollutants and the expulsion of moisture build-ups particularly associated with the now common practice of internal clothes drying (Howieson, 2005; Porteous, 2013).

3.20 Exposure to air pollutants can have both acute and chronic health effects, from mild to severe and pollutants may or may not be perceived by occupants (Wargocki, 2002). The likelihood and severity of effects occurring depends on age, pre-existing medical conditions and individual sensitivity. The effects can also include temporary discomfort and annoyance from odours, and from some pollutants can have negative impacts on cognitive performance (Dimitroulopoulou 2015a&b). The UK for instance has seen the market for 'air fresheners' significantly increase over the last 20 years. The primary function of these products is not to freshen but to mask odours, by introducing more pungently odoriferous compounds, some of which contain VOCs.

3.21 Indoor air quality is also associated to a large extent with outdoor air pollution. The indoor environment contains many sources of air pollutants from building materials, consumer products, occupants and their activities. Occupants are therefore exposed to a mixture of pollutants (Dimitroulopoulou, 2015; Trantallidi, 2015; EC, 2014; RCP, 2016), as illustrated in Figure 9.1. These compounds can of course act in additive, antagonistic and synergistic combinations. Indoor sources have become more significant as airtightness standards have become more exacting in recent years. Substantial work has been done over the past few decades to assess the health impacts of outdoor air pollutants, and this work has placed increasing emphasis on indoor sources of pollution. Exposure to air pollution has health effects at every stage of life. The symptoms may develop gradually as a result of long term or repeated exposure. Overall, the World Health Organization (WHO) estimates that approximately seven million people worldwide die each year as a result of air pollution exposure from outdoor and indoor sources (one in eight deaths), with a large proportion in developing countries due to indoor combustion. It considers air pollution to be the world's largest single environmental health risk (WHO, 2014b) and has produced exposure guidelines for a large number of pollutants (see table 9.3 Appendix 1). In many countries where smoking bans have been put in place, significant improvements in public health have been measured. The challenge is how best to apply this legal maxim to other ubiquitous indoor toxins.

3.22 In the UK it is estimated that ambient air pollution results in the premature death of between 28000 and 36000 each year, based on the combined effects of particulate and NO_2 pollution (COMEAP, 2018). Exposure of the developing foetus and young children is of particular concern (RCP, 201; RCPCH, 2020; Hänninen, 2013). This highlights the significance of outdoor air pollution on the overall health burden, evidenced by indoor levels of pollutants such as particulate matters (PM) being above WHO guidelines (EC, 2004; Mandin, 2017). Overall, the majority of the burden falls on cardiovascular diseases, followed by asthma and lung cancer.

3.23 There is a hierarchy of importance in the range of pollutants exposure. Some pose a known and severe health and even death hazard through short-term exposure (e.g., CO). For some pollutants, long term effects may show up years after exposure has occurred or only after longer repeated periods of exposure (e.g., radon, particulates, NO_2). These long term hazards may be respiratory diseases, such as asthma and chronic obstructive pulmonary disease aggravated by pollutant exposure, cardiovascular disease, or lung cancer related to radon exposure. Other pollutants may not be severe and immediate health hazards, but become irritants if concentrations are sufficiently high and/or exposure sufficiently long, with sensitivities depending on individuals (e.g., many VOCs). Others may have limited health effects but are considered useful indicators of indoor air quality. CO_2 concentrations are recognised as a good predictor of total VOC (TVOC) exposure.

3.24 Oxides of nitrogen (NOx) and PMs (PM_{10}, $PM_{2.5}$, and smaller) from combustion processes, are generated from outdoor sources, such as traffic and industrial processes, and by indoor sources such as cooking and fireplaces. NOx includes NO and NO_2, both being closely linked with NO_2 typically used as a marker for overall levels of associated compounds. There are a wide range of pollutants found in the domestic environment that are generated by sources such as: chemicals used for cleaning, off-gassing from building materials (chipboard flooring etc), ventilation ducts, furnishing (fire retardants), interior finishes (solvent based paints), electrical appliances, radon from soil, heating and combustion appliances, water systems, dampness and mould and external air quality.

3.25 Modern methods of construction such as SIP panels can contain a variety of bonding compounds (glues) that off-gas VOCs. There are thousands of VOCs and many have known health effects. The most common requiring attention in buildings is formaldehyde, a known (IARC Group I) carcinogen, that is emitted from building materials such as laminated wood products, varnishes and glues. The effects of exposure to VOCs include, mucosal irritation in eyes and upper airways, lower respiratory symptoms (coughing), central nervous system (neuropsychological) symptoms (headache), and tiredness. Sources of VOCs include the outdoor air (e.g. benzene and toluene from traffic sources and industrial activities) and indoor sources (e.g. xylene from combustion sources, formaldehyde and hexanal from building materials, d-limonene from cleaning products, acetaldehyde from plants, ripe fruit and consumer fragrances. Indoor VOC levels are therefore normally significantly higher than outdoors. Total VOCs (TVOC) concentrations also vary significantly with the season, affected by ventilation and by variations in off-gassing driven by increases in temperature and humidity (Coward, 2002; Dimitroulopoulou, 2005; Jamieson, 2005; Geiss, 2011; Holøs, 2019). Primary emissions are from building products and normally dominate for a period of a few weeks to months in new and newly renovated buildings. As the materials age, secondary emissions from the reaction of VOCs with other pollutants may increase (Wolkoff and Nielsen, 2001). VOCs from consumer products are a rising source of concern, especially in residential environments (Dimitroulopoulou et al., 2015a/b; Trantallidi et al., 2015; Geiss et al., 2011) but they are also found in non-domestic environments such as workplaces and schools, where sources include cleaning products, equipment (printers) and educational activities (paints, glues, etc.) (Wolkoff, 2013; Mandin et al., 2017; EC, 2014; Geiss et al., 2011).

3.26 In addition to VOCs, occupants are exposed to a number of other components present in the air through outdoor and indoor sources, such as polybrominated diphenyl ethers (PBDEs) that act as flame retardants; in electronic equipment and furnishings, and hormone disrupters such as phthalates from plastic. Knowledge on the health effects of these is still evolving however hormone disrupting compounds (false oestrogens) are now implicated in falling fertility particularly in younger males who have been affected *in utero*. Other products may not currently be considered pollutants because of a lack of information on their effects, especially those related to long term exposure. Additional compounds may emerge through new industrial and manufacturing processes (e.g. nanoparticles), or through chemical reactions between pollutants forming complex new organic substances, as is known to be the case for ozone reactions with VOCs.

3.27 The role of microbiological contaminants in indoor air is becoming more important as buildings become more airtight. This applies both to the home, where dampness can cause severe infestation, and to buildings with mechanical ventilation and/or cooling systems, which can harbour moulds and bacteria that are now known to have a causal link with lung function (McSharry, 2015). There is growing evidence that building design and occupant behaviour can affect the type and diversity of bacteria found indoors (Kembel et al. 2012). A study by Sharpe et al. (2020) found associations between ventilation provision and use on the presence of Gram-negative bacteria, with increased window opening reducing the likelihood of finding Gram-negative isolates. Covid-19 has also highlighted the role of ventilation rates and their relationship to micro-aerosol concentrations. It is becoming clear from infectivity patterns in various countries, that poorly ventilated indoor spaces play a major role in infection transmission. Poorly ventilated dwellings may very well be proven to be the greatest source of cross-infection (Noorimotlagh, 2021).

3.28 Building occupants are constantly exposed to numerous substances from multiple sources. Most assessments evaluate risks on a substance-by-substance basis and do not consider the combined adverse health effects due to exposure to multiple pollutants. They do not take account for instance of additive, synergistic or antagonistic effects that can occur between various compounds, nor of exposure through routes other than inhalation. These synergistic effects are mostly unknown, but there is growing evidence that such interactions do occur; for example, between radon and tobacco smoking in the causation of lung cancer; between NO_2 and formaldehyde in increasing the effects of exposure to allergens such as house dust mites (RCP, 2016), and between particles and ozone (Wolkoff, 2013).

3.29 In most countries there is currently no comprehensive regulatory framework on indoor air quality, with the exception of radon. The default position is therefore to refer to the WHO air quality guidelines as presented in Table 9.1. Appendix A. This approach should help align the project with best practice guidance, provide an element of future-proofing against possible future legislation, as well as reducing future litigation risk. Table 9.1 (Appendix A) covers a selection based on the following rationale: pollutants covered by ambient and indoor air quality guidelines from the WHO (2006a, 2010a) and pollutants covered by EU and UK ambient air quality objectives (OJEU, 2008b; Defra, 2007; TSO, 2010b), which are themselves largely similar to or less stringent than WHO guidelines. Key pollutants that are known to be common in the built environment and to have serious adverse health effects include: asbestos, radon, second-hand ETS, carbon monoxide and mould (RCP, 2016). In urban locations, the main pollutants likely to require attention over and beyond regulatory requirements (e.g. in addition to carbon monoxide and radon regulations) are particulate matters and NOx from outdoor sources, formaldehyde and TVOCs.

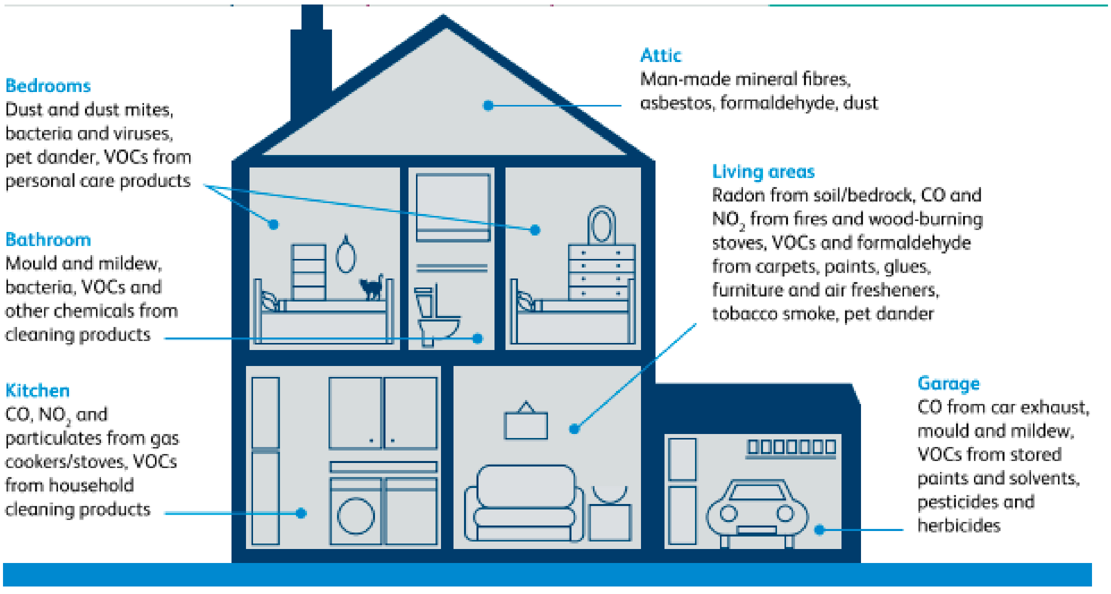


Figure 9.1 Sources of pollutants indoors (including indoor and outdoor sources) (RCP, 2016)

Figure 3.1 Sources of pollutants indoors (including indoor and outdoor sources) (RCP,2016)

The Scottish Dimension

3.30 Five Strategic Objectives were set out in 2008 by the Scottish Parliament outlining the vision for a, 'Wealthier & Fairer, Smarter, Healthier, Safer & Stronger and Greener Scotland'. The Framework would last over 10 years before being updated with the introduction of the National Performance Framework in 2018, that reformulated the original objectives to correspond with the United Nations Sustainable Development Goals as proposed in the 2030 Agenda for Sustainable Development (UN, 2015). This project aims to deliver on these objectives and to meet challenges raised by the Low Carbon Building Standards Strategy for Scotland (Sullivan, 2007) and subsequently enshrined in law by the Climate Change (Scotland) Act, 2009. The initial ambition contained in the Sullivan report was to achieve zero carbon if practical by 2016/17. This however did not turn out to be practical and was revised to meet a target reduction of 34% on 1990 emission rates by 2020 and a more realistic target of an 80% reduction by 2050.

3.31 The Scottish Government also recognises the link between physical environment and health and wellbeing in the implementation plan for, 'Good Places, Better Health – A new approach to environment and health in Scotland, 2008'. Working in partnership with health boards, local authorities, broader community planning partnerships, third sector organisations, community based organisations and communities themselves, the Scottish Government stated aim is to target toxic, infectious, allergic, and physical threats. The demand to reduce CO_2 emissions through reduced energy use needs to be balanced with the ambition to promote health and well-being. The intent is to achieve affordable warmth within a healthy environment, free from toxins, volatile organic compounds and house dust mite infestation that are a significant driver for asthma in Scotland, may not be compatible with a carbon neutral development unless the conflict with healthy indoor air quality, can be resolved or at least the conflict optimised.

3.32 Increasing ventilation leads directly to an increase in heat loss and this in many modern dwellings that require to have low U values, for the opaque areas of the building envelope, air changes can now account for up to 80% of the total dwelling's heat loss. The industry has always viewed minimum standards as maximum targets, and it is highly unlikely that they will choose to incorporate measures that may have cost implications that will in turn affect price points and profit margins. History has proven that this challenge will only be met by the design and construction industry, in response to statutory regulation.

3.33 In an attempt to encourage infiltration via the trickle ventilators, by creating a negative pressure in the dwelling, a technique was developed (dMEV – decentralised mechanical extract ventilation) and implemented in a number of Scottish dwellings. A study that surveyed 223 homes (Sharpe 2018) aimed to generate responses from the occupants regarding their knowledge and operation of the fitted ventilation system. A subset of these homes was subsequently monitored to examine the system 'in-use' and identify any confounding variables that may impact on overall performance and efficacy. A further study was undertaken in one dwelling to experiment with different dMEV configurations. The survey reported that although there was good awareness of the presence of ventilation provisions, there was a lack of knowledge regarding how these systems were controlled. Many households did not know how to boost the ventilation rate in the dMEV system, nor did they feel the need to intervene with the controls. The survey also highlighted a lack of engagement with the trickle ventilators situated in the window frames.

3.34 As some of these dwellings were constructed after the 2015 regulation change, the survey was able explore the impact of this change in 21 homes that were reported to have a CO_2 monitor installed in their main bedroom. Of these, 19 households stated that they understood the purpose of the CO_2 monitor. The responses varied from i) to measure/ monitoring CO_2 (16 homes), ii) for health and safety (2 homes), or iii) gas poisoning (1 home). This suggests there may have been some confusion regarding the purpose of the monitor, confusing it with the carbon monoxide detector. The majority of homes with carbon dioxide monitoring equipment stated that they did not receive any guidance on how to use the CO_2 monitors (11 homes). Further responses confirmed that the monitors had been ineffective in driving any significant behavioural changes regarding increasing ventilation rates when CO_2 levels triggered the red warning light.

3.35 Over 50% of these homes appeared to have poor overnight ventilation (where carbon dioxide levels exceeded 1,000ppm for the majority of the time) in bedrooms. These included the type of the trickle vents, the window coverings, the path between the room and the dMEV (including the door opening or undercut, and the arrangement of the home) and the installation and performance of the system. Dwellings with shorter, more open pathways for air movement had better IAQ. Where the dMEV systems were more remote, IAQ was noticeably poorer.

3.36 Inspection of the monitored homes found a high number of installed dMEV systems (42-52% - depending on location), were sub-optimal (exceeding recommended airflow rates by >15%), or non-compliant with the guidance (17-48%). Flow rates were highly variable. This was due in the main to system setup and commissioning. Given that bedroom doors were often closed (41%) due to occupant preference or fire requirements, the strategy relies on door undercuts, but these were undersized in 20% of properties.

3.37 There were a number of homes (51%) where trickle vents were installed in wet rooms with dMEV systems. Whilst this may improve the efficacy of extract and moisture control in these rooms, this undermines the ability of the system to assist with ventilation in more remote rooms. Whilst dMEV systems in en-suite bathrooms provided the best outcomes for adjacent bedrooms, problems with systems being disabled were encountered in 56% of homes with the predominate problem being reported as acoustic nuisance. The findings would suggest that whilst there are some situations where a dMEV system can assist with the ventilation provision of modern airtight homes, the ability to act as a whole house system is limited, particularly in larger more complex layouts and where ventilation loads are higher.

3.38 Although trickle ventilation provision in habitable rooms did not appear to be a major determinant of carbon dioxide concentrations in the monitored dwellings, these results should be interpreted with caution, given the small sample size and large number of confounding variables identified. It is likely that the impact of reduced area of trickle ventilation was overshadowed by other key components such as air flow pathways, pressure differentials, dMEV extract rates etc. As such, the system as a whole requires careful design, taking into account the house layout, air movement routes (including undercuts and pass vents), the nature of the mechanical system and greater consideration of rooms that are more remote.

Contemporary research findings

3.39 Indoor air is comprised of a complex mix of both indoor and outdoor sources of pollutants. Ventilation should act to dilute, disperse and remove indoor pollutants while limiting the ingress of outdoor pollutants into the internal environment. This balancing act is further complicated by the fact that, for both a building designer and occupant, strategies for managing good IAQ must compete with the need to provide thermal comfort, avoiding overheating and noise pollution, economic costs, and to meet energy use and carbon reduction targets.

3.40 Despite most dwellings having to conform to the standards laid down in the building regulations there are many additional variables that can influence the complex interactions between the building fabric, internal layouts, windows type, occupant behaviour and air movement. Significant differences have been observed between apartments and houses (Langer, 2013) ventilation systems, (Järnström, 2006; Tuomainen, 2001; Yoshimo, 2006; Yang, 2020) ventilation rates, (Langer, 2013 and 2016, Godish, 1996; Kaunelienė, 2016; Guyot, 2018) or dwellings with gas cookers (Raw, 2004) or emissions associated with the storage of paints and cleaning materials within garages (Langer, 2016). These studies have highlighted the influence upon IAQ of occupancy and human activity (Logue, 2011; Ai, 2015), the presence of indoor sources of pollutants (Raw, 2004; Yoshimo, 2006; Jones, 2000) and ventilation rates (Langer, 2013, 2016; Godish, 1996; Dimitroulopoulou, 2016; Deng 2020). Seasonal variations have also been identified and may be associated with occupant ventilation behaviour, outdoor conditions, ventilation rates (Langer, 2016; Aubin, 2011) or varying emission rates from building products (Haghighat, 1998; Wolkoff, 1998).

3.41 Recent studies have examined IAQ in both conventional and low-energy dwellings in a number of countries (Yang, 2020; Logue, 2011). Few comparisons have been made within the UK context, where the most significant study of 867 homes occurred between 1997-1999 (Raw, 2004). As low-energy and ventilation practices have moved on significantly in the subsequent 20 years, the implications of a shift towards, airtight dwellings upon IAQ needs to be better understood, both in respect to the relationship with outdoor air and the need to control emissions inside dwellings (Yu 2011, 2012).

3.42 A more recent UK Government survey (HM Government 2019) of 10 new homes indicated high concentrations of total volatile organic compounds (TVOCs), formaldehyde and carbon dioxide (CO_2), but only included 7-day passive sampling of one apartment dwelling and did not capture seasonality. Despite advances in measurement technologies, a recent review of 'Passivhaus' studies indicated very few studies included physical IAQ measurements beyond CO_2 , (Moreno-Rangel, 2020) with just one UK based study (McGill, 2016) capturing formaldehyde concentrations. This indicates a lack of comprehensive UK based IAQ studies on low-energy dwellings with little or no data on flatted dwellings.

3.43 The recent IEA-EBC Annex 68, 'Indoor Air Quality Design and Control in Low Energy Residential Buildings', that has proposed a set of IAQ metrics, identified key pollutants from previous studies and developed guidelines for the design and operational strategy of domestic dwellings (Rode 2019). This work has included setting target exposure limit values (ELVs) corresponding to recognised concentration thresholds, above which exposure potentially presents a risk to health. This allows an assessment of the measured concentrations against their respective health risks, providing a clearer comparison across pollutants. Defining appropriate ELVs is not straightforward, varying between regions, exposure periods and evolving health risks. The study aligns itself with the ELV values set in IEA Annex 68 (Abadie 2017). There is therefore a further compounding variable to take into account, where dwellings are located close to major road junctions where the external air is heavily polluted with the outputs from internal combustion engines or in the vicinity of industrial processes, off-gassing specific pollutants from flues and smoke stacks.

3.44 The London Air Quality Network stations reported annual mean concentrations of both roadside and urban background as: PM2.5(13.2 $\mu g/m^3$ – 12.2 $\mu g/m^3$), PM10 (23.7 $\mu g/m^3$ – 21.1 $\mu g/m^3$) and roadside NO2 (50.9 $\mu g/m^3$) . These levels are well above the World Health Organisation (WHO 2006) limits (PM2.5 - 10 $\mu g/m^3$, PM10 - 20 $\mu g/m^3$). Short-term, 24hour, limits for background PM2.5 are breached 23 times annually. Annual mean urban background NO_2 (31.9 $\mu g/m^3$) is reported at three-quarters of the WHO limit (40 $\mu g/m^3$), with significant seasonality, dropping from around 35 $\mu g/m^3$ in the heating season to 25 $\mu g/m^3$ in the summer months.

3.45 Criteria for pollutant inclusion is based upon both the health risk posed and the likely levels to be encountered in a residential setting. Under IEA-EBC Annex 68, (Abadie 2017) reviewed several studies that had aimed to create priority indices and metrics for residential buildings. The key indicators were listed as: Particulates $PM_{2.5\text{-}10}$, Carbon monoxide, NO_2, TVOC, Ozone, Formaldehyde. Of the VOCs the most common that affect health are, Benzene, Naphthalene, Trochloroethylene, Tolene, Styrene, d-limonene and alpha-Pinene.. Radon and PAHs both feature as key pollutants identified by the WHO (WHO 2010) whilst sulphur dioxide maybe a significant ambient source in some locations. Finally, IEA Annex 68 further included Acrolein and mould within its full scope (Abadie 2019).

3.46 Stamp (2021) has recently undertaken longitudinal indoor air quality monitoring in five low-energy London apartments. 16 key pollutants were monitored using continuous and diffusive methods across all seasons. The results indicate strong seasonal variations driven by increased natural ventilation rates over the summer period. A combined metric for indoor and outdoor pollutants (Itot), suggests the IAQ in the winter (Itot=17.7) is more than twice as bad as that seen in the summer (Itot=8.6). Formaldehyde concentrations were lower in the non-heating season, indicating increased ventilation rates more than offset increased off-gassing. Increased summertime ventilation rates were observed to increase the proportion of outdoor pollutants entering the internal environment. This resulted in higher indoor concentrations of NO_2 in the summer than the winter, despite significant reductions in outdoor concentrations.

3.47 These results demonstrate the impact of ventilation practices upon IAQ, the influence of occupant actions and the complex relationship ventilation rates play in balancing indoor and outdoor sources of air pollution. Following this, strong seasonal patterns can then be observed within CO_2 concentrations, with mean summertime concentrations significantly below those during the heating season and only marginally above external levels. The indication here is that there is a significant increase in window opening and natural ventilation during the summer to provide additional cooling and air movement, a strategy to combat the rising internal temperatures. Conversely, across the heating season CO_2 concentrations approach 1000 ppm, indicating that significantly lower ventilation rates are achieved when background MVHR is operating alone during the winter. This may then lead to a higher build-up of internal contaminants across the heating season. Across all pollutants, (excluding CO_2) differences in ventilation practices affect the I/O ratio that is significantly higher in the non-heating season. The median I/O ratio increases from the winter to the summer from 0.32 to 0.70 for $PM_{2.5}$, 0.50 to 1.42 for PM_{10} and 0.55 to 0.98 for continuously measured NO_2 and 0.39 to 0.85 for passively measured NO_2. This last result helps explain the unexpectedly higher indoor NO_2 levels seen in the summer, with increased ventilation rates increasing the proportion of ambient NO_2 entering the indoor environment. Therefore, whilst increased ventilation rates act to dilute many internal pollutants, this is somewhat offset by the increased exposure to NO_2 from the ambient air. Although not measured in this survey it is likely that SO_x will be found in similar concentrations to oxides of nitrogen.

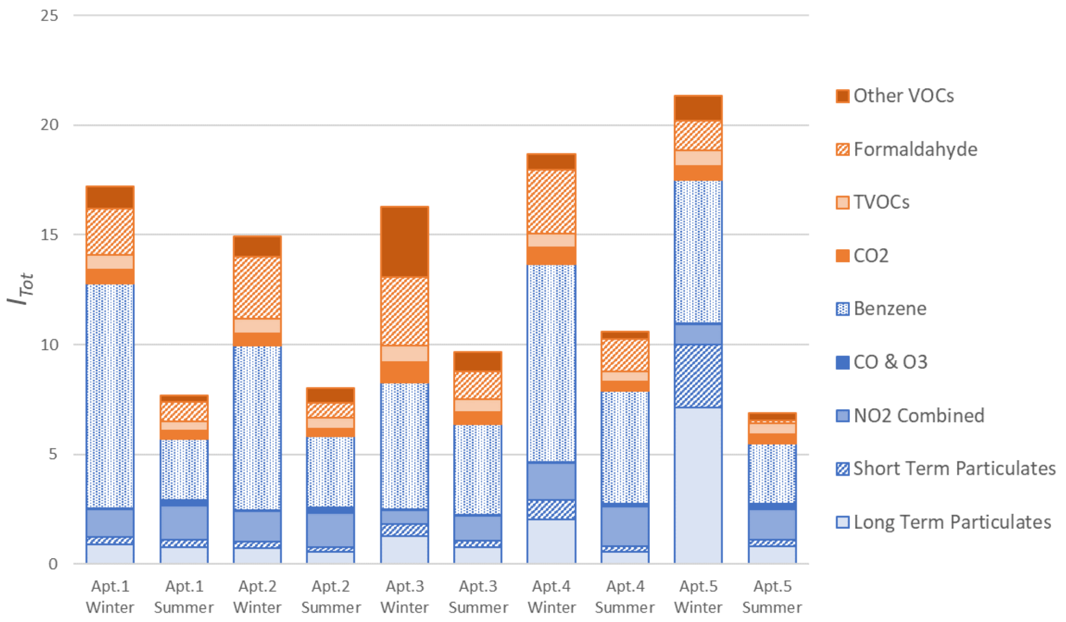


Figure 3.2 Seasonal variations of pollutants concentrations

3.48 Strong seasonal differences in ventilation practices were seen, with increased natural ventilation doubling the average ventilation rate from $0.7h^{-1}$ in the heating season to $1.6h^{-1}$ in the summer. Similar seasonal effects were observed in indoor CO_2 concentrations.

3.49 The study points at the need for improved MVHR filtration for dwellings in polluted urban environments. This should include improved filtration of fine particulates and further consideration of measures to reduce or control NO_2. This points to the importance of adopting measures to control indoor sources and remove or filter out, black carbon particulate matter and oxides of nitrogen and sulphur. The study concluded that the impact of window opening behaviour must be more holistically considered, with mechanisms to inform occupants of the impact of their actions upon IAQ. The scope of any feedback mechanisms must not therefore be restricted to CO_2 as the sole proxy for IAQ.

3.50 Wargocki, (2016) claimed that people in the developed world spend between 85-90% of their time indoors. Of this, most is spent in homes. To minimize health risks from pollutants occurring in homes, exposures should be controlled. The most effective way to achieve this is to control sources of pollutants and to reduce emissions. This strategy is however difficult to control as occupants will bring with them many potential sources of indoor pollutants. Exposure can therefore only be controlled by providing sufficient, ventilation air to dilute and expel any contaminants. The paper concludes that there are very few studies on this issue and many of them suffer from deficient experimental design, as well as a lack of proper characterisation of actual exposures occurring indoors. Newly installed mechanical ventilation systems were observed to improve health conditions. In homes with existing ventilation systems however, this positive effect was less evident, probably due to poor performance of the system (ventilation rates inadequate and/or poor maintenance). The author called for better research in which exposures are characterised (for example measuring the pollutants used by the WHO Guidelines). Exposures should also be controlled using different ventilation methods for comparison. Future studies should advance the understanding of how ventilation systems could be operated to achieve optimal performance. This is one of the key aims of Annex 86, to improve the energy efficiency of indoor air quality management strategies and to improve their acceptability, installation quality, control and long term reliability (see www.annex86.iea-ebc.org). Moreover, these data would create further input and support to the guidelines for ventilation based on health developed currently in the framework of the HealthVent project (www.healthvent.eu).

3.51 Kinnane (2016) recognised that optimising the conflict between energy efficiency and IAQ is proving to be challenging in many European countries. This study assesses the efficacy of passive ventilation strategies designed to comply with building regulations and imposed after housing energy-efficiency retrofits. In particular, it focuses on the provision of ventilation using background through-wall vents, which remains a common strategy in a number of European countries, where vent sizes are related to floor area that are prescribed in the building regulations. A case study based on social housing typologies reported that occupants were decidedly unhappy with through-wall vents with many being blocked to limit perceived draughts and heat loss. A wide range of effective air change rates are observed when vents are sized without reference to building airtightness, and significant energy penalties result for the leakier homes.

Summary

3.52 Optimising the potential trade-offs between energy efficiency and IAQ particularly in small single aspect family flats, may prove to be an intractable problem unless a properly working and well-maintained mechanical ventilation system is used.

3.53 Recent published research highlights the challenge between diluting internal sources of pollution whilst avoiding ingress of external sources. Opening windows to dilute and expel indoor pollutants in urban locations is likely to result in an increase in internal concentrations of PM_{10} as well as the ingress of oxides of nitrogen, sulphur and benzene (e.g. locations near busy roads, etc.).

3.54 The findings demonstrate the impact of ventilation practices on IAQ and the complex role ventilation plays in balancing indoor and outdoor sources of air pollution. Assessing and managing the risk of ingress of external pollutants therefore will be critical when designing a solution, particularly concerning the application of CO_2 sensors as a proxy indicator of IAQ. If testing against a range of IAQ parameters can be established, they can form the basis of performance specifications that architects, engineers and the volume house builders will have to meet both in theory and practice (similar to blow door testing), if they are to be granted a building warrant and have a completion certificate accepted by local authority verifiers.

4. Household survey

Aims and objectives

4.1. The main aim of WP2 (household survey) is to gather data about occupants' awareness of their ventilation provision, use of the CO_2 indicators and how this affects their air quality. The objective was to undertake a general survey of 200 homes built under the 2015 regulations.

4.2. The survey was based on the questionnaire used in the 2014 study (Sharpe, 2014). This enabled some longitudinal comparison of responses, for example, to identify changes in awareness of trickle vents. The questionnaire has been complemented with additional survey content to address the specific questions raised in this study concerning the use of CO_2 sensors and consequent interaction with ventilation provision, including mechanical and natural systems. Such questions included awareness of the sensors, how it affects their ventilation behaviours, the value of the alert systems and any unintended or negative consequences. For logistical reasons a commercial research company, Research Resource was used to conduct these surveys, based on a survey design and brief developed by the team and approved by BSD.

The Survey

4.3. The proposed figure of 200 household surveys proved to be challenging. Challenges related to timescale and budget were exacerbated by the limitations on face-to-face surveys posed by the governmental restrictions due to the Covid Pandemic.

4.4. As a result, the original plan of identifying 800 addresses in order to complete doorstep face-to-face survey was changed to 2000 addresses for a postal survey, in order to attain the original figure of 200 completed surveys. The postal survey resulted in 115 responses.

4.5. Following the restrictions posed by the Government, from 13 December 2021, the professional survey company stopped carrying out in-home interviews. After discussions, the Building Standards Division agreed that the survey could proceed via postal surveys until the ban on doorstep surveys was lifted. The doorstep interviews were resumed in January 2022. As a result, the postal survey was supported by 23 additional face-to-face interviews, bringing the total number of responses to 138 responses.

Results

4.6. The questionnaire presented questions regarding the household characteristics, awareness of ventilation systems (including pattern of ventilation in living room, bedroom and bedroom at night in winter and provision of ventilation advice), provision of a CO_2 monitor (including occupants' understanding and use of the monitor) and the availability for long term monitoring.

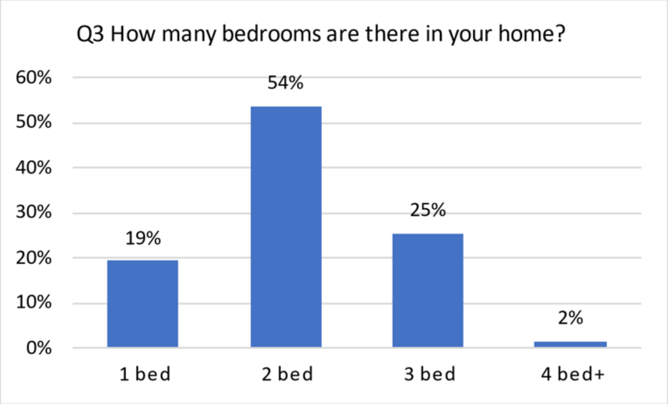
4.7. The following section will focus on the responses related to engagement with ventilation systems and ventilation awareness. A complete set of responses is available in Annex A.

Table 3.1: overview of household survey responses obtained by January 2022

	method	responses obtained	interested in follow up monitoring
postal survey (Sept. 2021):	2000 addresses contacted via post	115	39
face-to-face (Nov.-Jan 2022):	50 addresses visited	23	18
	total	138	57

Household information

4.8. The main observation regarding the household survey is that more than half of the households were rented from a Council or Housing association while a small proportion (7%) were rented privately. 37% of properties were owner-occupied. In addition, over half of the households surveyed (54%) had 2 bedrooms.



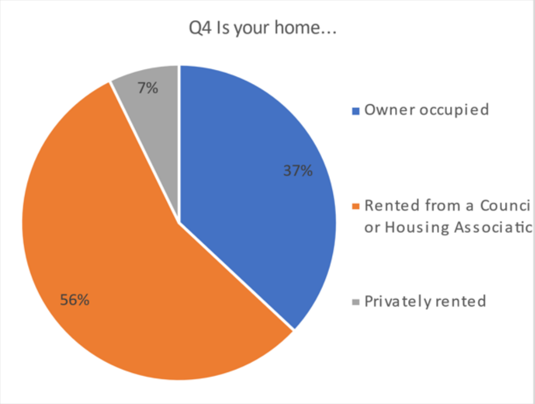


Figure 4.1: Average number of bedrooms in households surveyed.

Figure 4.2: Tenancy type

4.9. In total 13% of homes reported health conditions linked to the respiratory system, of which the majority (11%) live in social housing. Of all those households reporting health issues, the majority reported issues with asthma.

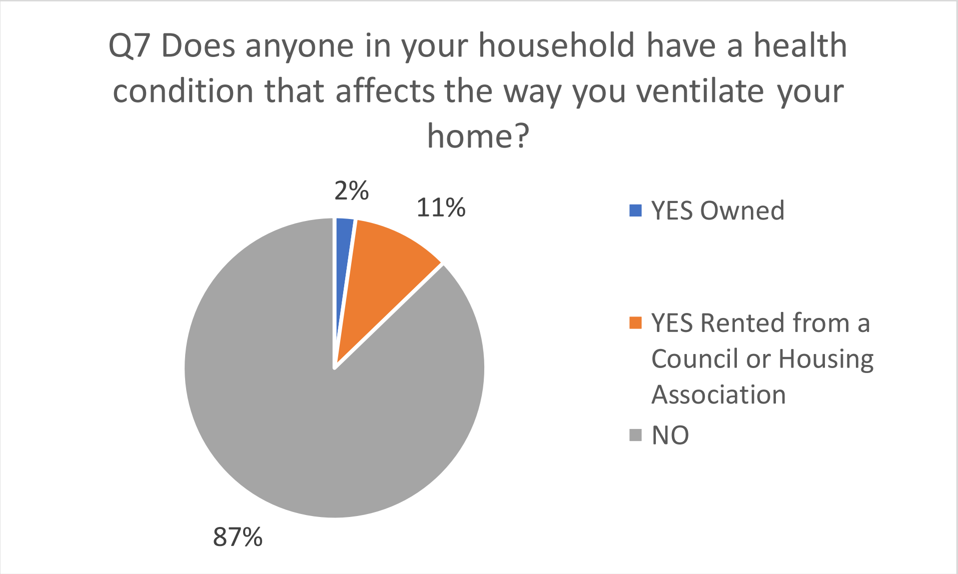


Figure 4.3: Health issues

Awareness of ventilation systems

Trickle vents

4.10. When shown the trickle vents in figure 4.4 below, and asked whether respondents know what this is, the vast majority (93%) confirmed that they knew what it is and what it is for. Results therefore suggest that there has been an increase in awareness of trickle ventilation compared to the 2014 study when about 80% of respondents stated their awareness of trickle vents.

Figure 4.4 Images of different trickle vents included in the questionnaire.

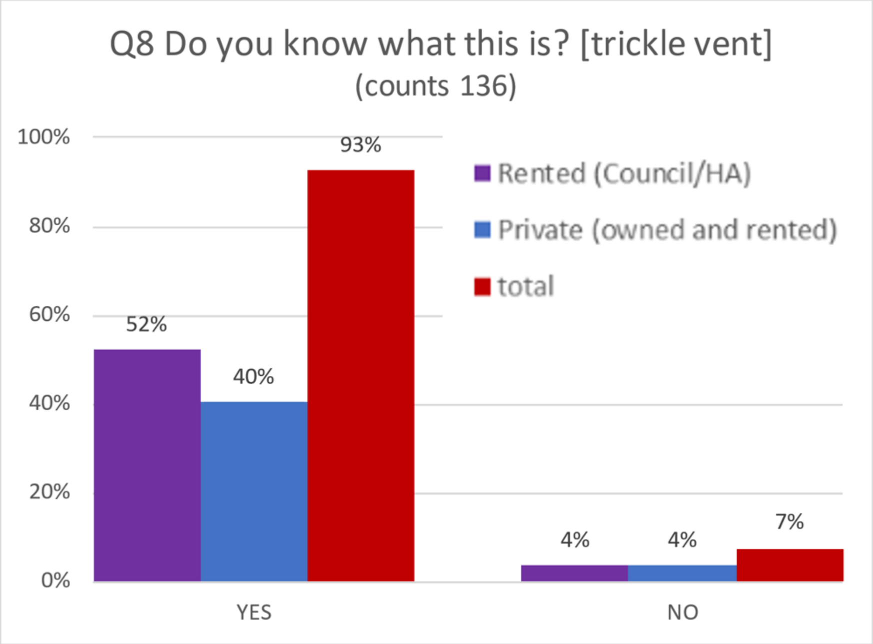


Figure 4.5: Q8 Do you know what a trickle vent is?

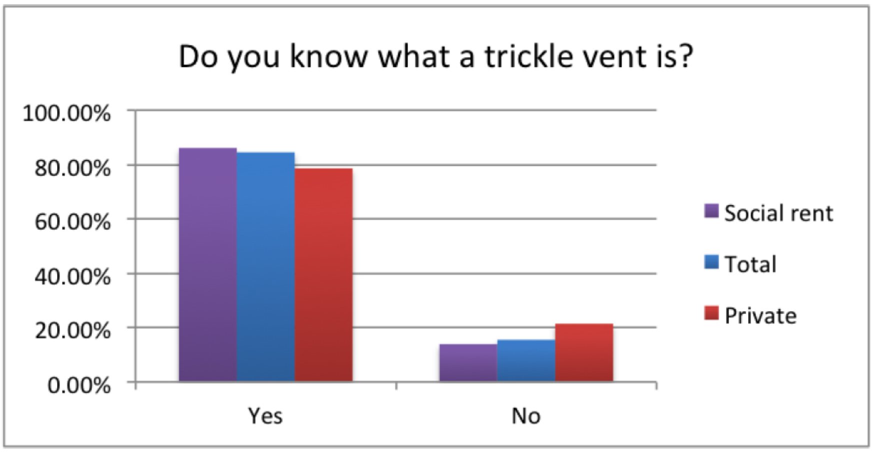


Figure 4.6: 2014 survey – Do you know what a trickle vent is? (Sharpe, 2014)

4.11. In question Q9, when asked what a trickle vent is for, 93% of responses were grouped under the generic category '*ventilation'* (93%). Other responses include statements such as "*to stop/help with condensation*".

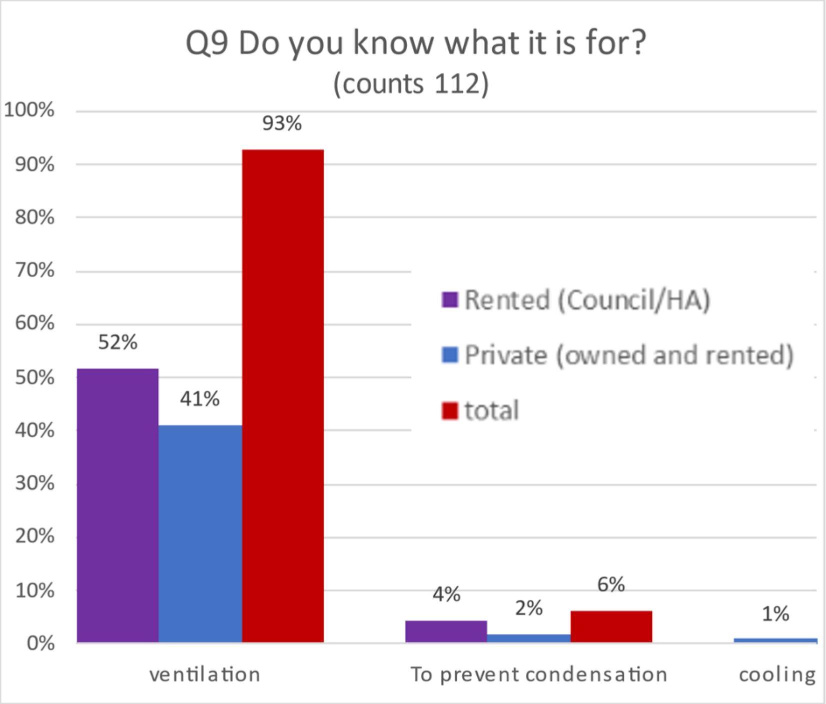


Figure 4.7: Do you know what a trickle vent is for?

4.12. Q9a asks to detail what exactly trickle vents are for. For the majority (50%) trickle vents are part of the ventilation (generic concept). On the other hand, 29% stated the trickle vents provide 'fresh air', indicating that occupants consider the air hygiene aspects of ventilation. In addition, 13% stated the trickle vents provide air circulation when windows are closed, therefore suggesting that occupants consider trickle vents as an option to not open the windows. Then, 6% view trickle vents as a means to avoid condensation. Finally, 1% view trickle vents as means for ventilative cooling.

4.13. The different aspects nuanced for ventilation suggests that occupants have different levels of understanding of ventilation, strongly supporting the claim that occupants are increasingly aware of trickle vents and ventilation. While in the 2014 study (Sharpe, 2014) 15% of respondents stated to not know what trickle vents are, results of the current survey (2022) show that only a 7% don't know what a trickle vent is. This further strengthens the claim that occupants are increasingly aware of their ventilation systems. Whilst the survey did not include explicit questions about the influence of Covid, there has been increased messaging about ventilation from Government and the media, including the Hands, Face, Space, Ventilate [5] campaigns and this may be impacted on occupant awareness.

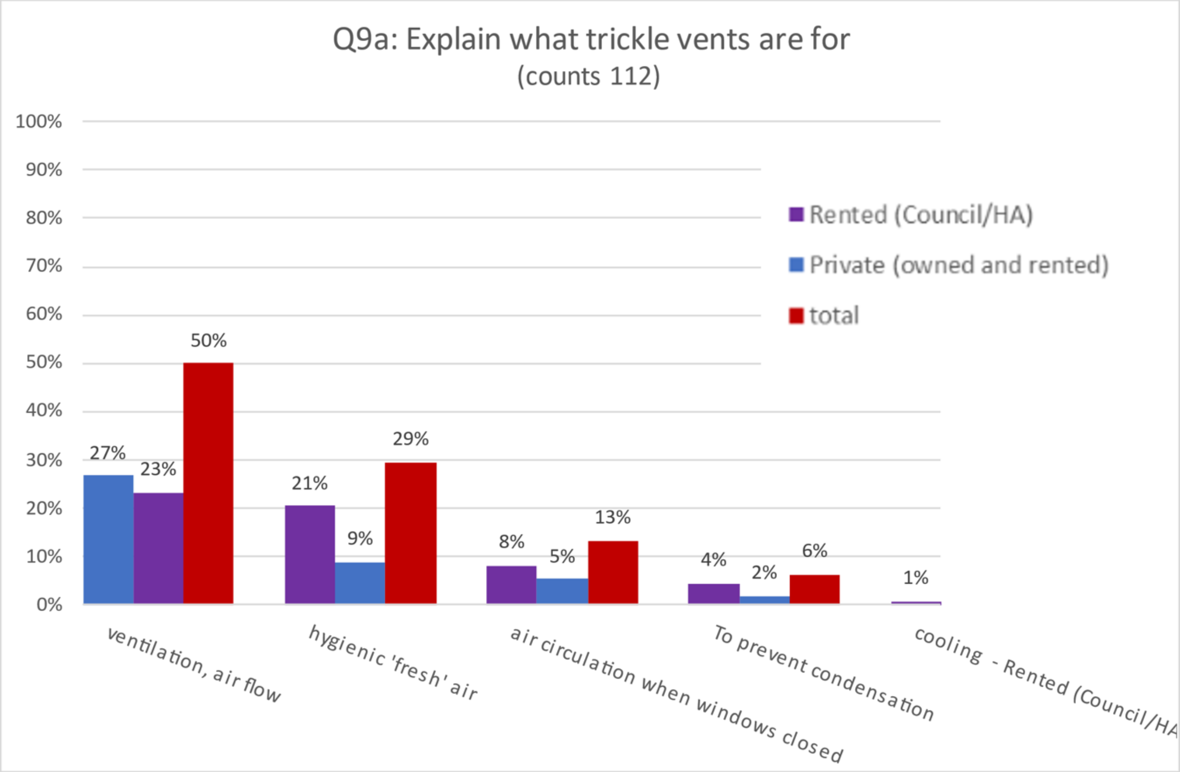


Figure 4.8: Explain what trickle vent are for

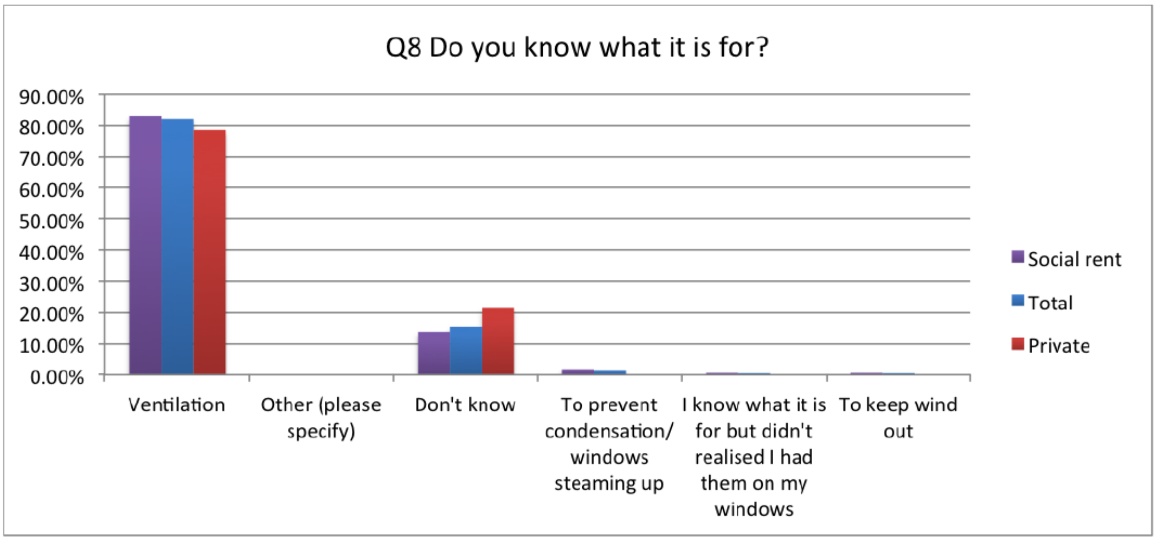


Figure 4.9: 2014 survey – Explain what trickle vent are for (Sharpe, 2014)

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[5] https://www.gov.uk/government/news/new-film-shows-importance-of-ventilation-to-reduce-spread-of-covid-19

Extract fans

Figure 4.10 Images of mechanical extract fan included in the survey

4.14. With regards to mechanical fan extracts, out of 138 responses, most households (88%) had a mechanical extract fan installed in both the kitchen and bathroom. Also, it was found that only a minor portion were unaware of the existence of a mechanical extract fan.

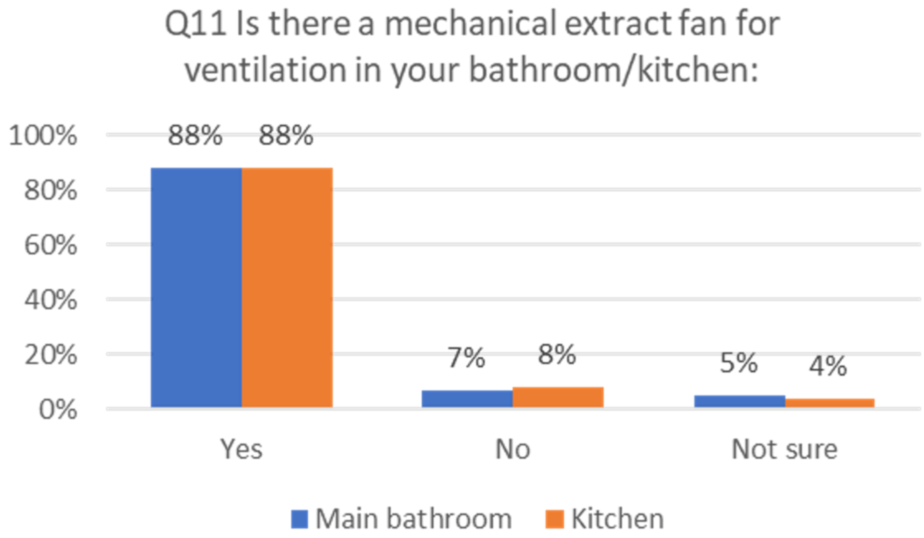

Figure 4.11: Presence of mechanical extract fan for ventilation in your bathroom/kitchen

4.15. For those that stated they had an extract fan, more than half reported some problems with the fans, the main issue being noise. ‘Other problem(s)’ reported included: “Seems a waste of material when ventilation can be resolved with simpler/ natural solutions”, “Downstairs toilet is freezing” and “an infestation of maggots so all my vents had to be closed off”.

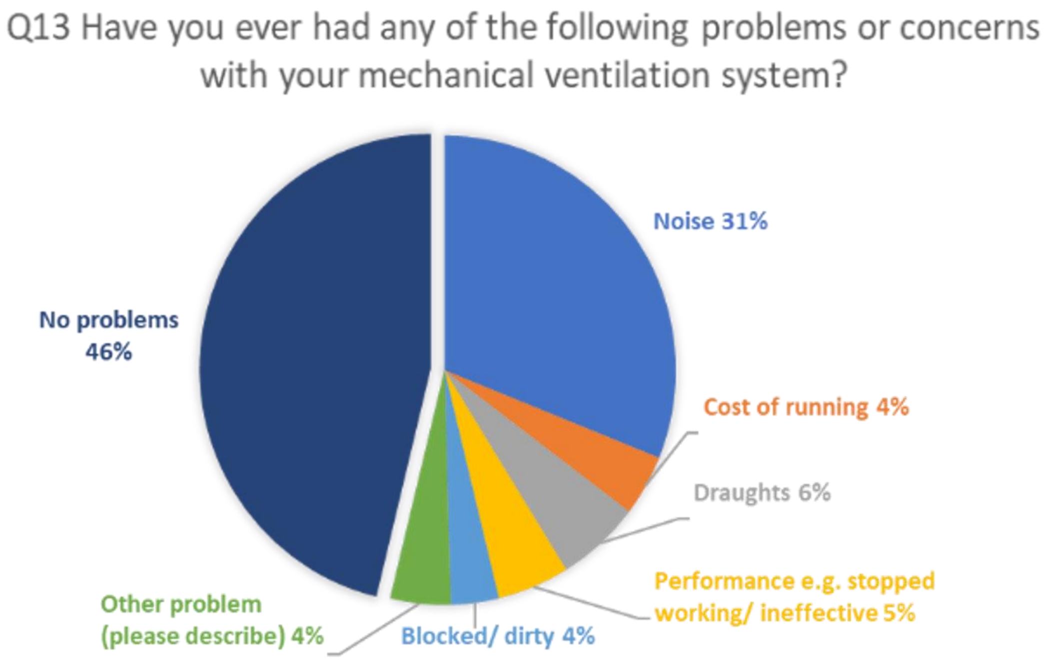

Figure 4.12: Problems with the mechanical ventilation

Practices of ventilation in living rooms and bedrooms

Trickle vents

4.16. The majority of households are aware of the presence of trickle vents in their homes (73% in the living room and 70% in bedrooms). However, there is a significant portion of households (13-14%) that do not know if their windows are equipped with trickle ventilators.

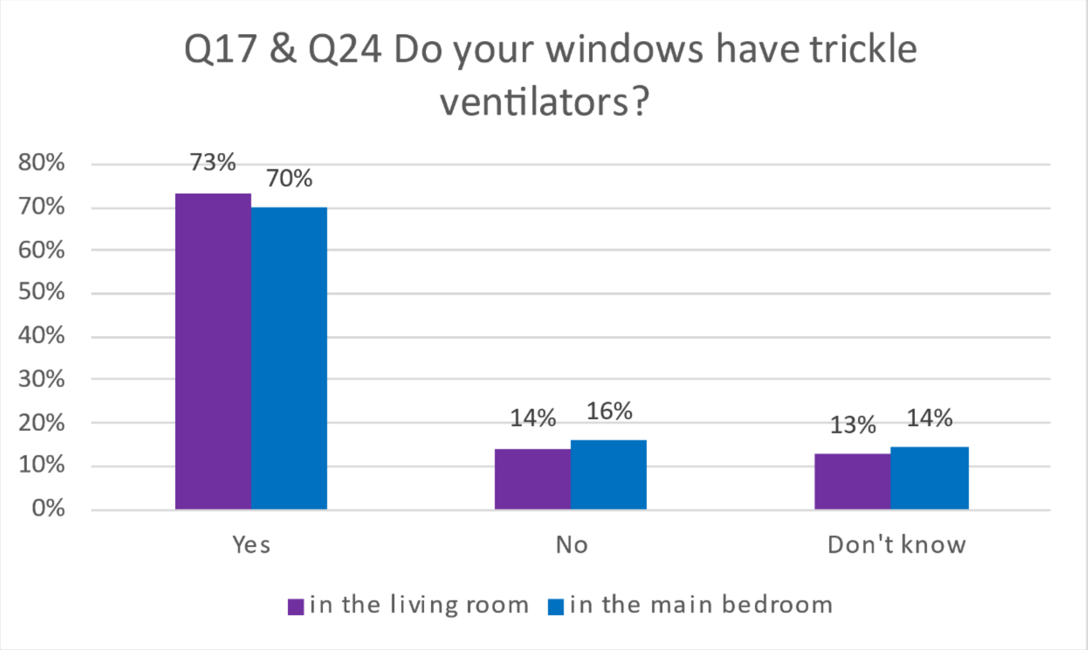

Figure 4.13 Presence of trickle vents

4.17. Regarding trickle vent opening frequency, when asked ‘how often are the vents open during the day’, respondents largely (75% in living room and 69% in bedroom) left them open all of the time while a small portion (13% in living room and 12% in bedroom) never open. Looking at the 2014 study submitted between January and March 2014 (Sharpe, 2014), where the question was phrased differently ‘how often do you open the trickle vents during the day?’, respondents lean towards not opening the trickle vents, suggesting a change in tenency from "never open" to "open all the time".

4.18. This figure is in contrast with the responses obtained during the 2014 study depicting a noticable switch between "open all the time" and "never open".

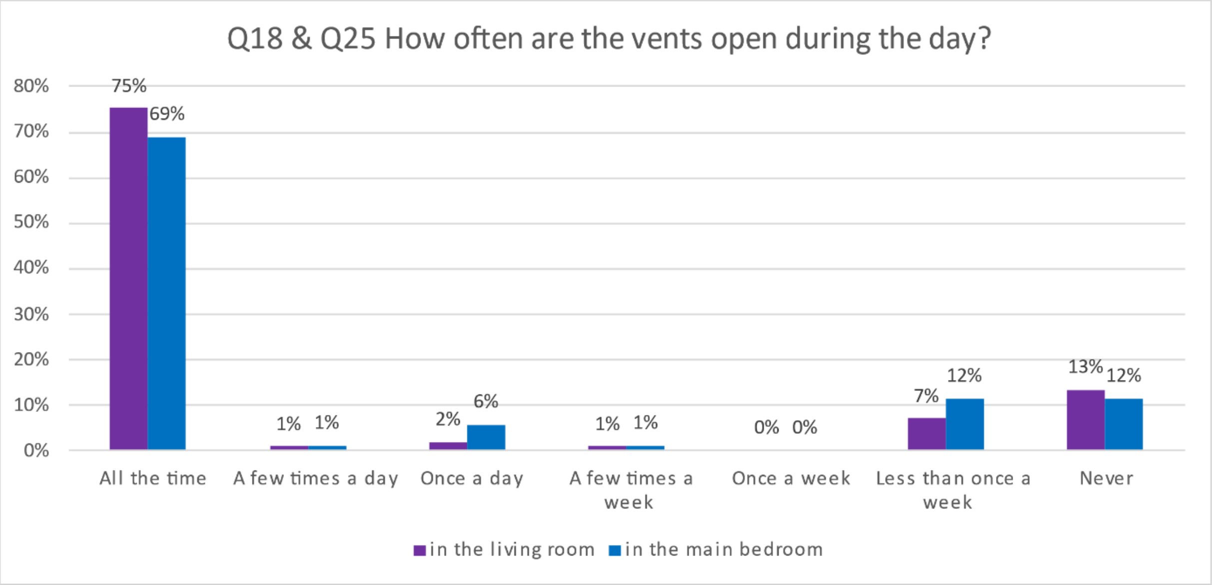

Figure 4.14 Trickle vents opening frequency

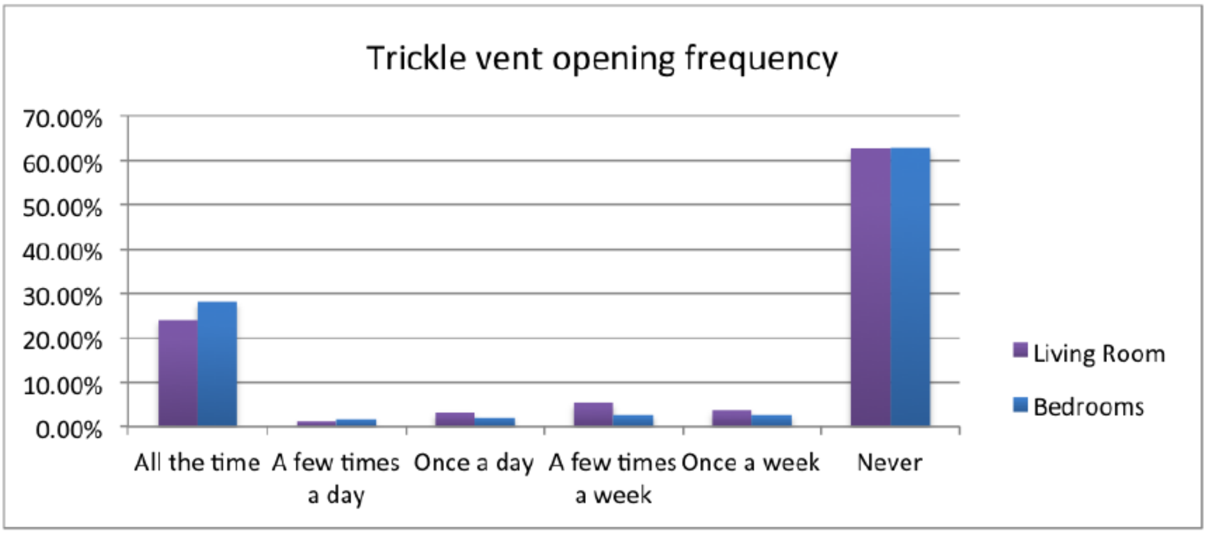

Figure 4.15: The 2014 survey – Trickle vents opening frequency (Sharpe, 2014).

Occupants were asked how frequently they used the trickle vents in the bedrooms and living rooms.

4.19. Of those that do not use trickle vents, reasons for not using the trickle vents remain similar to the 2014 study (Sharpe, 2014), where the most reported reasons to not use trickle vents are noise, drafts and don't feel the need to.

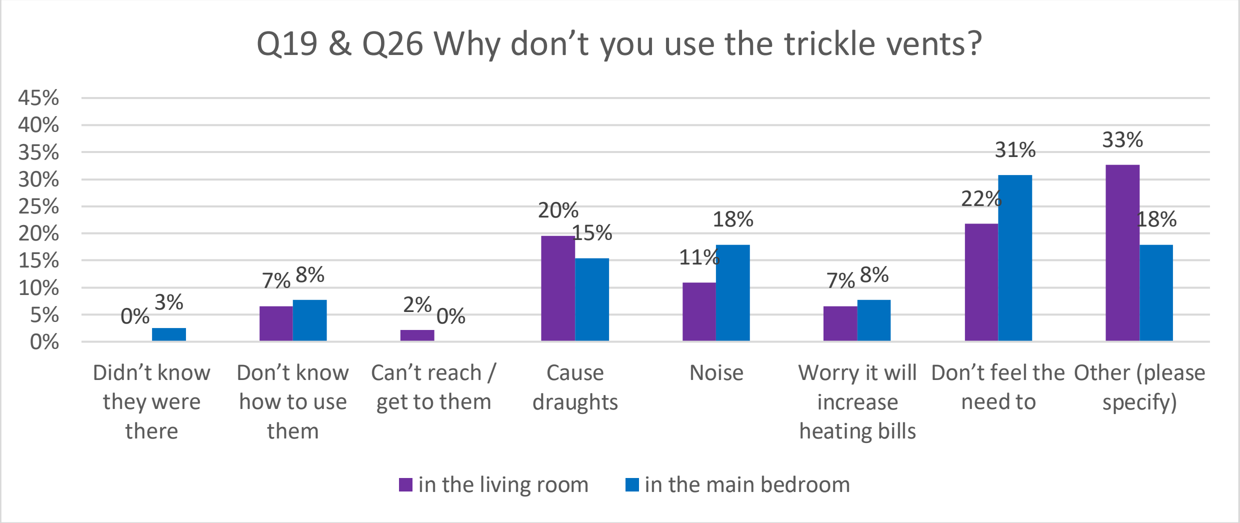

Figure 4.16 Reasons for not using trickle vents

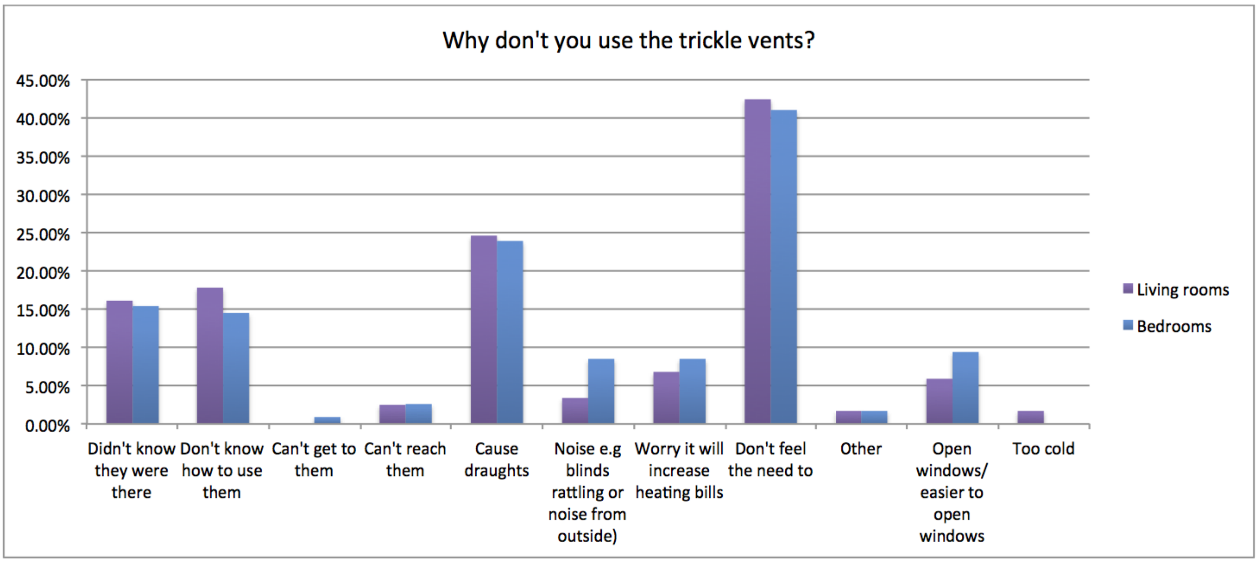

Figure 4.17 Phase II survey – Reasons for not using trickle vents (Sharpe, 2014)

Windows

4.20. Occupants were asked about window opening use in the living room and bedroom. In general, people showed engagement with window opening. In fact, the majority of occupants (27%) open the living room windows all the time, in contrast to 8% never opening them. Bedrooms showed a similar response with 36% opening windows all the time, and 3% never opening them.

4.21. This represents a major change from the 2014 survey (homes built to 2010 regs), with a considerable increase in reported window opening. This could be due to an increased awareness of indoor air quality or increased need to open windows due to indoor environments being stuffier. The latter hypothesis however is not supported by evidence provided in paragraph 4.26 in which responses, in general, reported a satisfactory perception of the indoor environment, but as noted above, the Covid pandemic may have increased awareness of ventilation use.

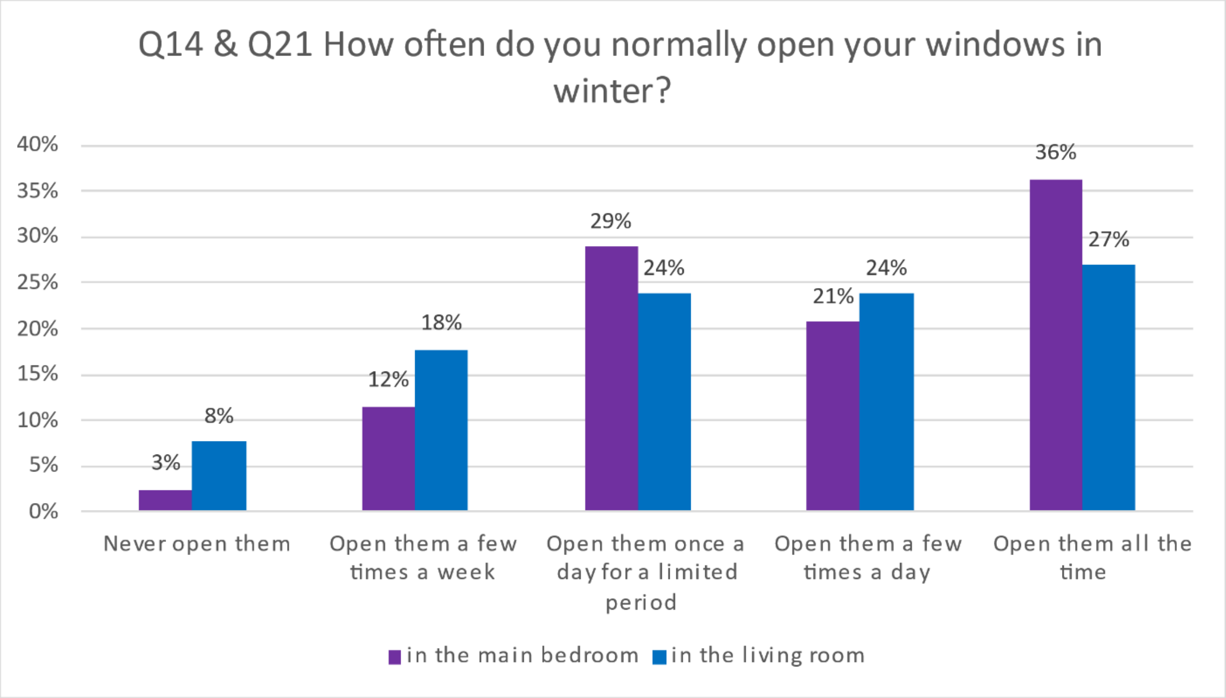

Figure 4.18: Frequency of window opening in winter

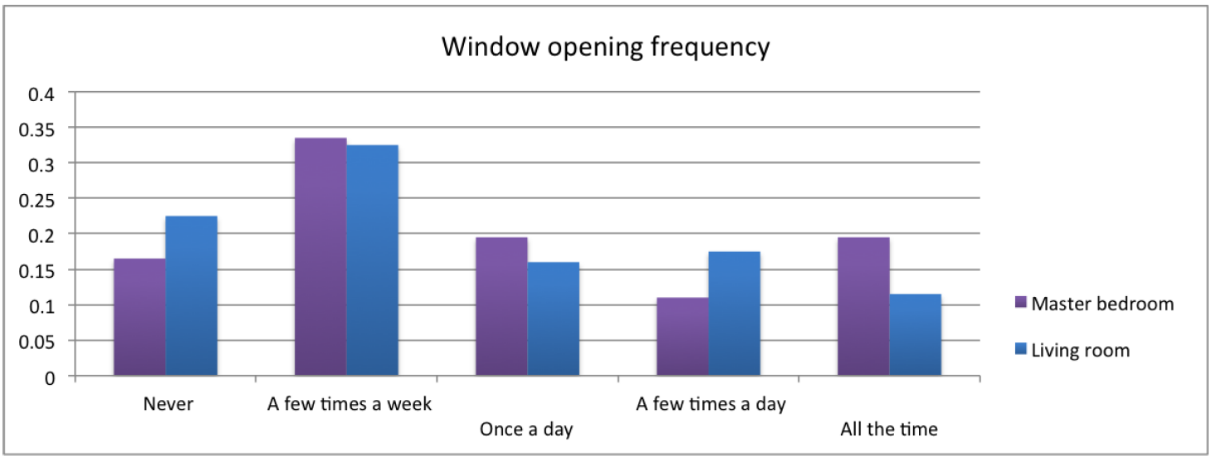

Figure 4.19: Phase II survey – Frequency of window opening (Sharpe, 2014)

4.22. Occupants were also asked about the drivers and barriers for opening windows. The predominant driver was to provide “fresh air”, followed by “too warm”. In comparison, the main driver reported in the 2014 survey (2014) was “too warm”.

4.23. At the time, the 2014 survey which included addresses completed after 2014 (to meet Building regulations 2010) the specified air tightness requirement was of a maximum 10m^3/hr/m^2 @ 50 Pascals (Pa.) The current survey is based on addresses completed by 2019 (to meet Building regulations 2015) with a requirement of a maximum air loss figure of 5m3/hr/m2 @ 50 Pascals.

4.24. To provide “fresh air” is one of the main drivers for window opening. Linking this answer to the one provided in paragraph 4.20, may be an indication of an increased need to ventilate homes, especially bedrooms. This hypothesis is strengthened by the fact that the response “to provide fresh air” has grown when compared to the 2014 study (in bedrooms from about 10% to about 40%).

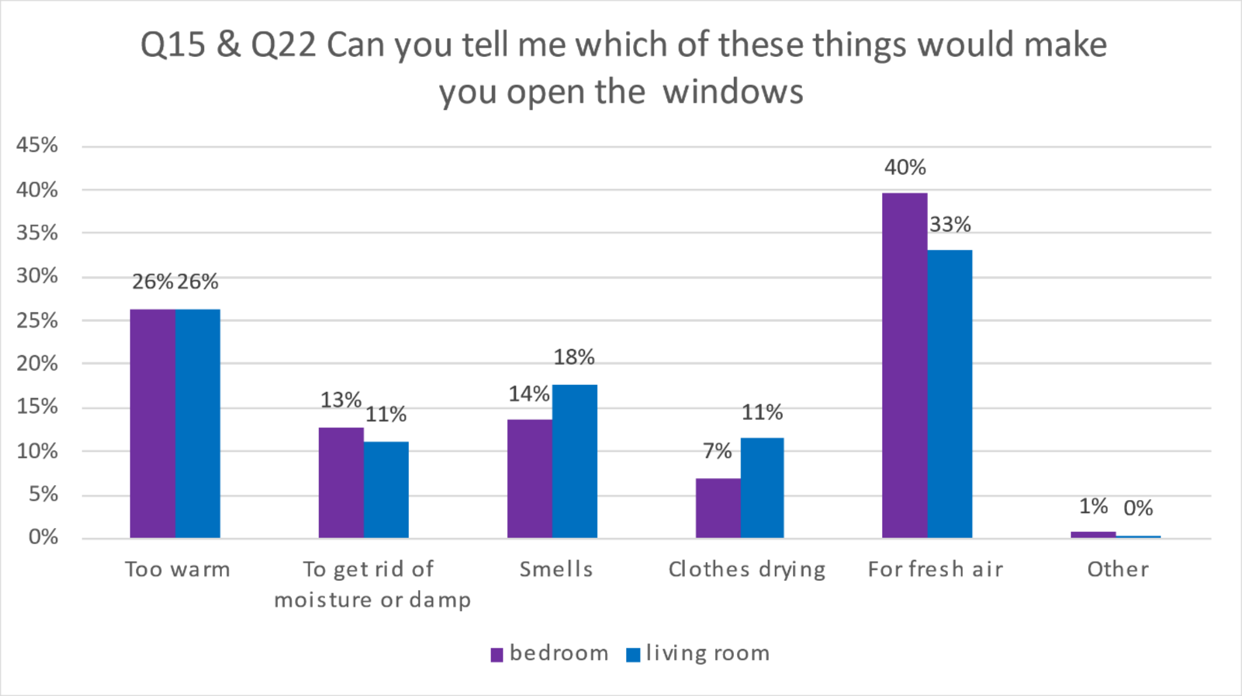

Figure 4.20: Window opening drivers

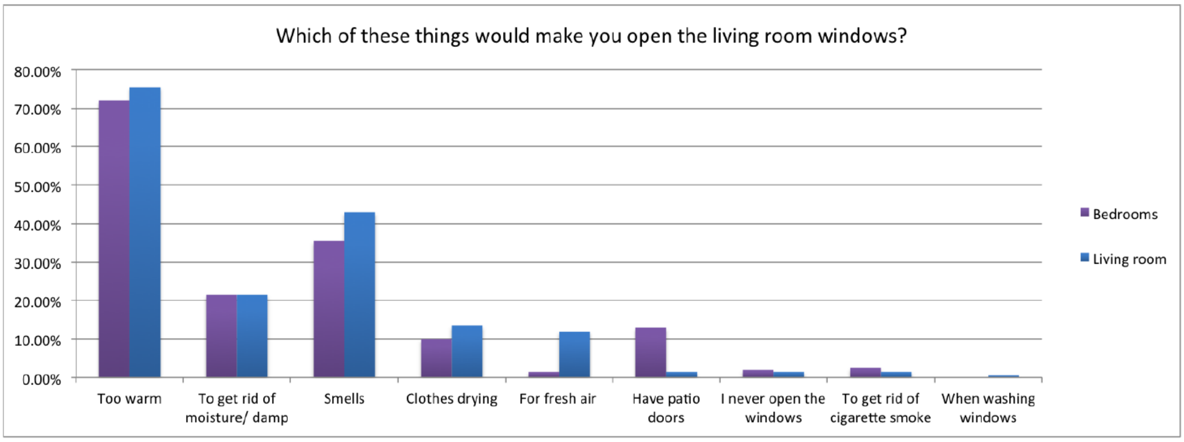

Figure 4.21: 2014 survey - Window opening drivers (Sharpe, 2014)

4.25. In comparison to the 2014 survey, “heat loss” as a barrier to window opening has significantly reduced (from 60% to 26%). “Noise” as a barrier remains unchanged.

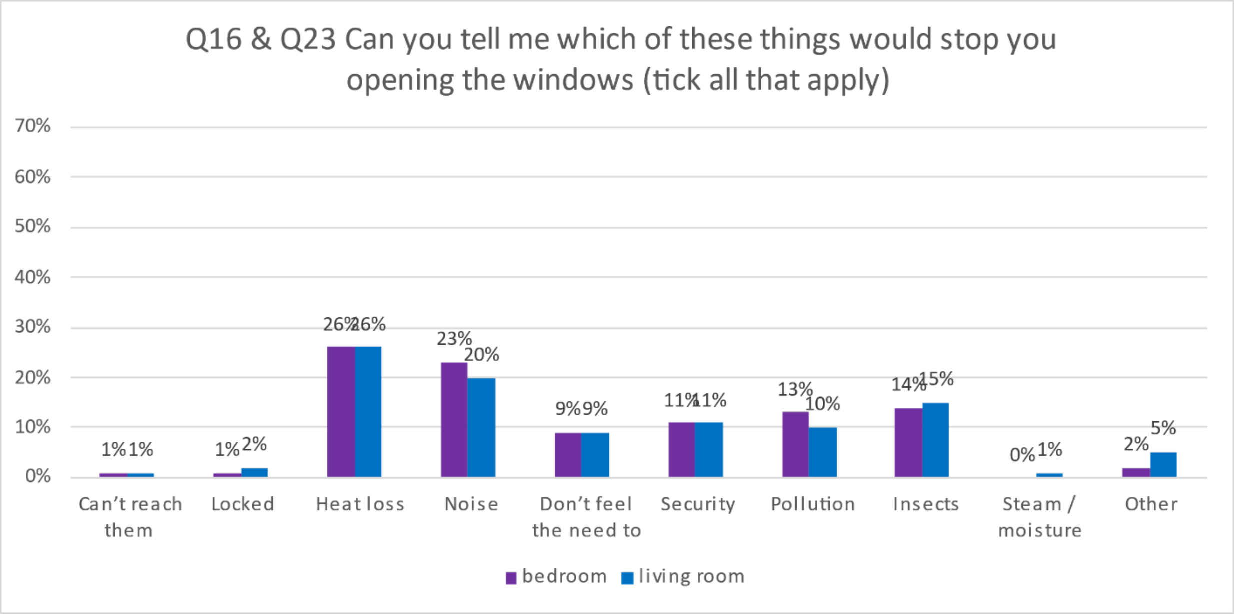

Figure 4.22: Window opening barriers

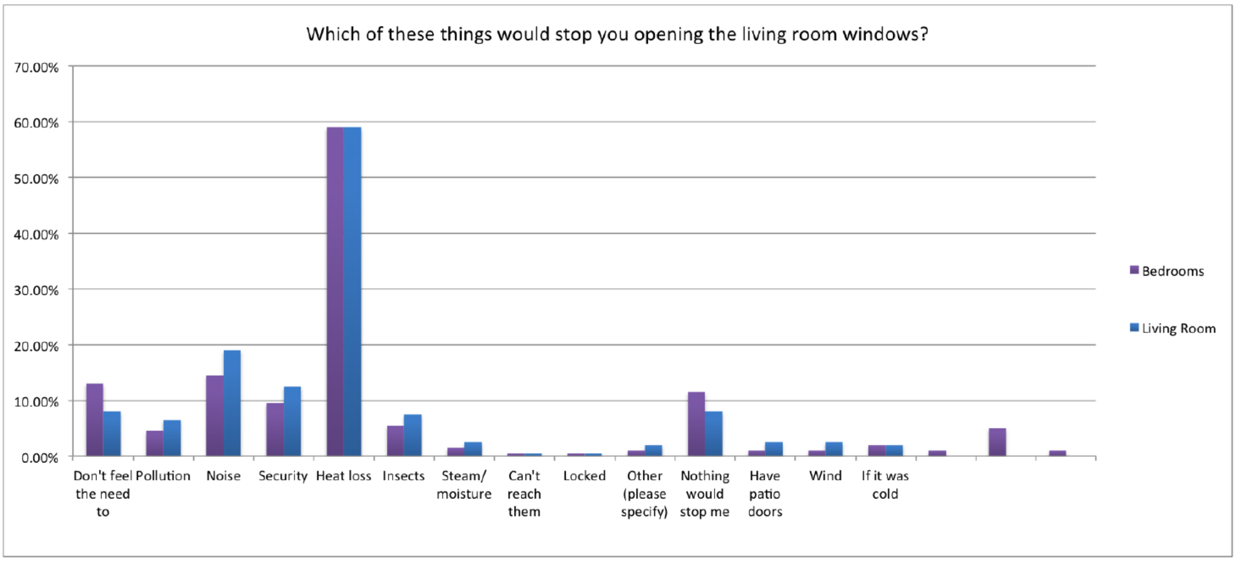

Figure 4.23: 2014 survey - Window opening barriers (Sharpe, 2014)

Bedroom conditions at night in winter

4.26. The majority of respondents keep windows closed at night (63%). While 39% of respondents keep bedroom door closed at night, a combined 61% keep the door either open or open a little. Similarly, for trickle vents, while 41% keeps the trickle vents closed at night, a combined 59% leaved them either open wide or open a little.

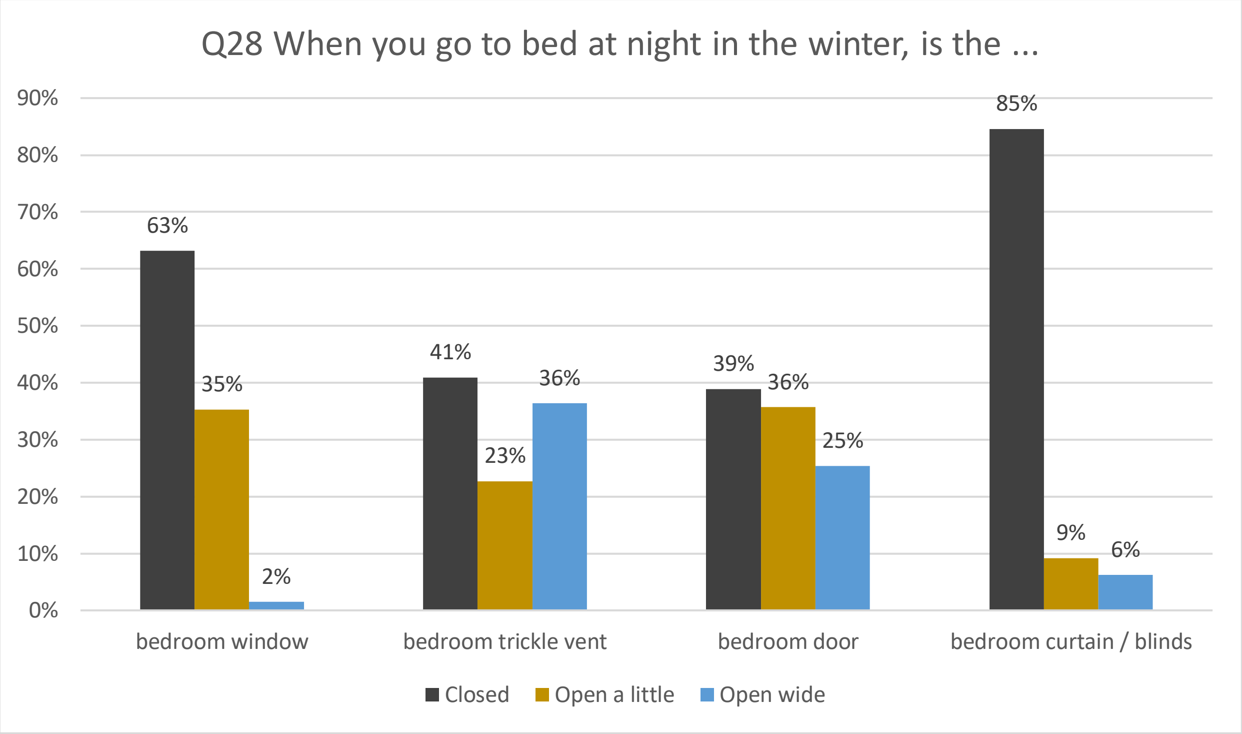

Figure 4.24 Bedroom at night

Indoor air quality perception

4.27. The majority of respondents perceived the quality of air in their home as 'very good'. This is similar to the 2014 survey, however the perception of air quality in bedrooms has decreased.

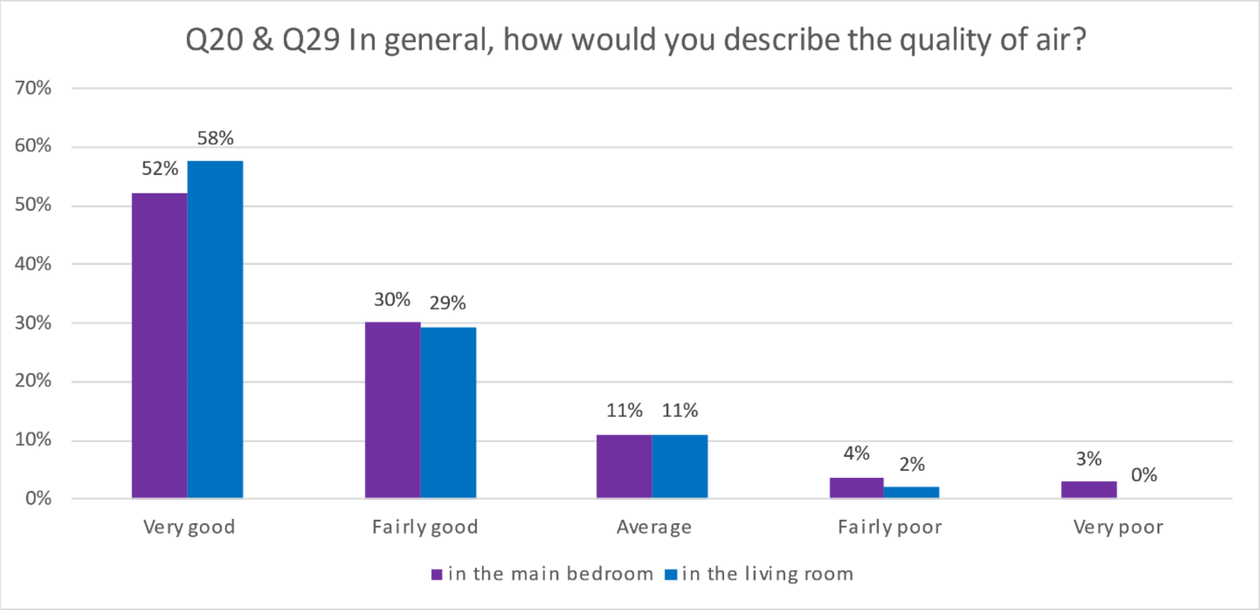

Figure 4.25: Indoor air quality perception

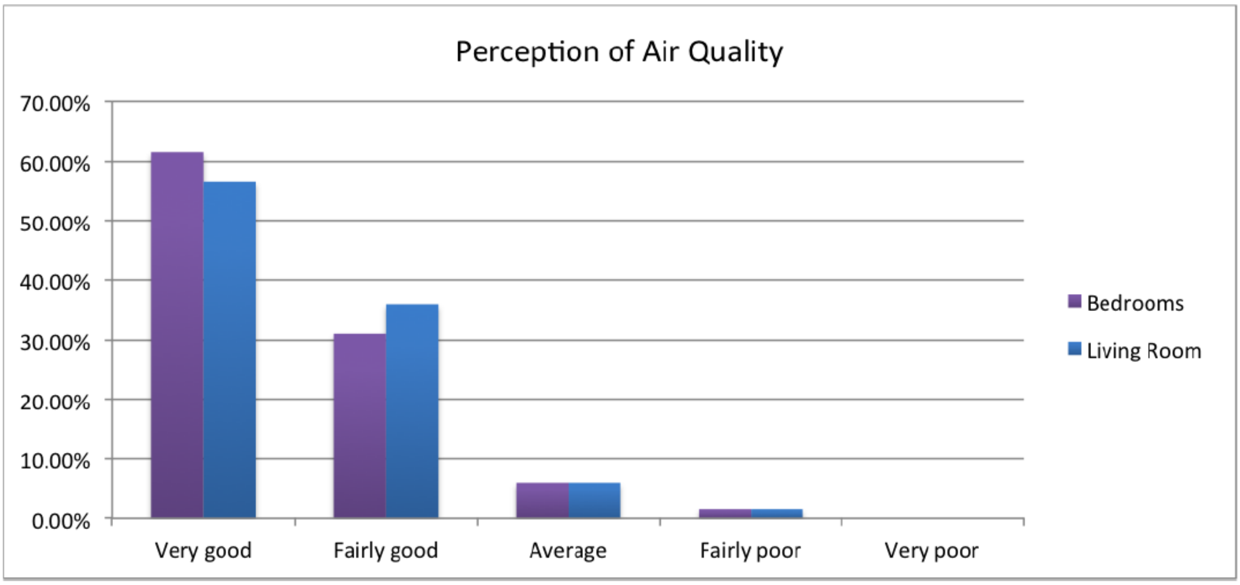

Figure 4.26: 2014 survey - Indoor air quality perception (Sharpe, 2014)

4.28. When asked “Is there anything that could improve the ventilation in your house?”, only a few responses (18) were obtained. It is interesting to note that the majority of responses relate to a need for increased ventilation, whether that is via more air volume or accessible/secure windows (50% of responses). This can be linked with responses in paragraph 3.23 showing an increased need to provide “fresh air”.

4.29. Some respondents stated ‘too cold’ in response to things that could improve the ventilation. This may be due to ‘cold drafts’ caused by the trickle vents. Depending on the type of construction, this could be further exacerbated by the fact that new homes with modern methods of construction cannot store heat (i.e. timber frame), so comfort in such cases relies on air temperature alone. Therefore, even though this survey shows an increased use of trickle vents (see paragraph 4.18), unless adjustments to provide comfort are made, there could be a portion of households that would avoid using trickle vents despite awareness.

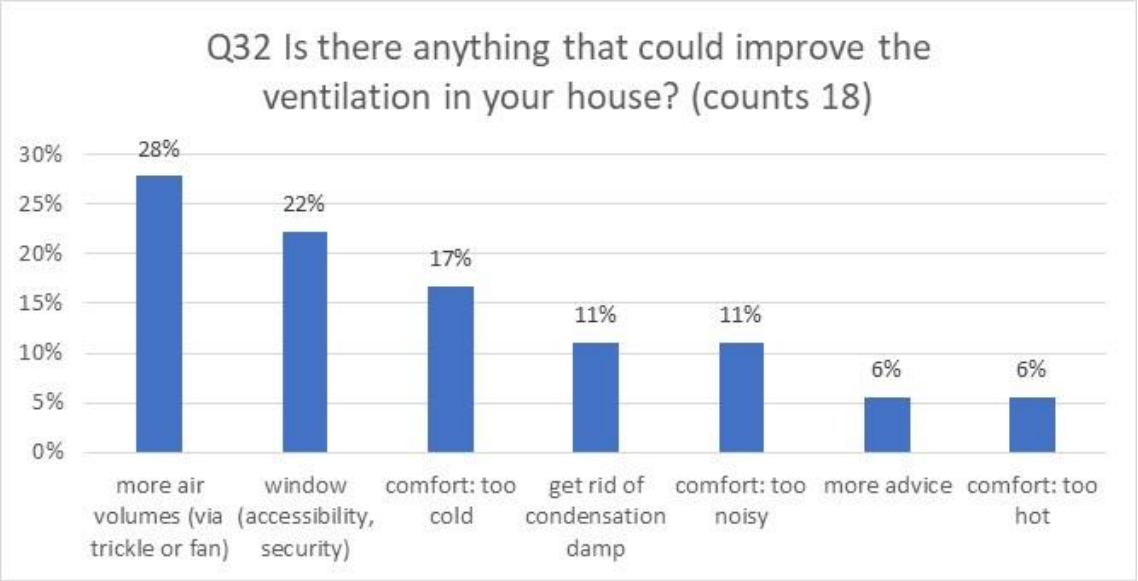

Figure 4.27: Ventilation improvement

Ventilation advice

4.30. The increased awareness of trickle ventilation and increased window opening appears to be only marginally influenced by advice provision. In fact, while awareness of ventilation systems has evidently improved, respondents experience a general lack of advice.

4.31. Of the 16% of occupants who had received advice, 52% had received specific instruction on the use of the vents (about 8% of the total). Overall, results show a slight increase in advice on trickle vents compared to the 2014 results. Common to the two surveys is that, of those that had received advice, the information provided was generally relevant.

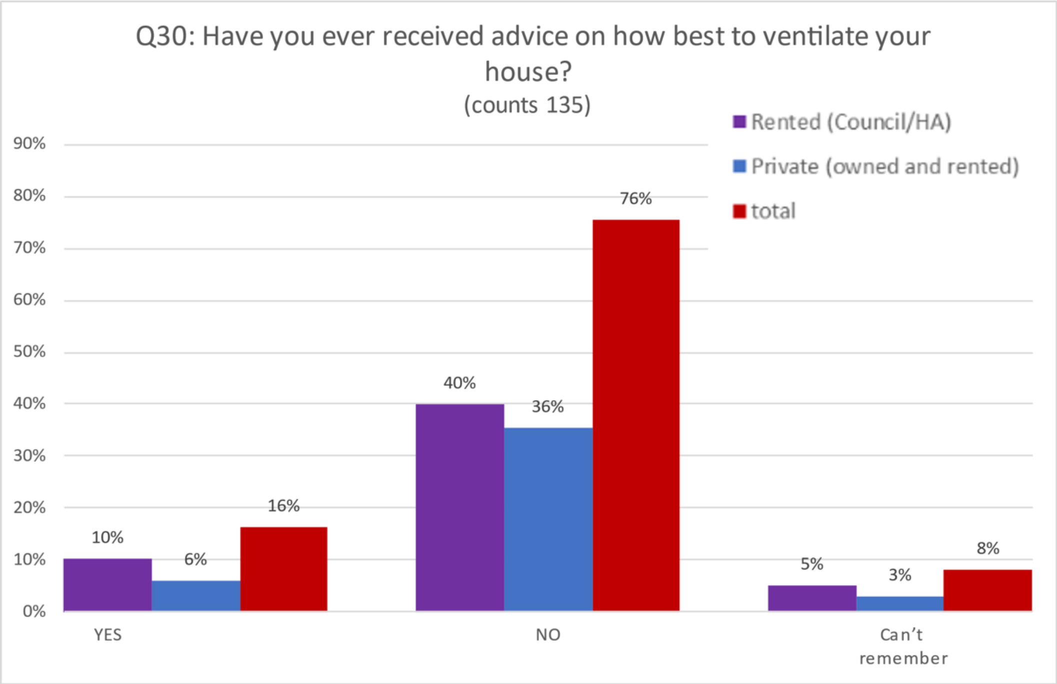

Figure 413.28: Ventilation advice

Carbon Dioxide Monitor

Figure 4.29: Carbon Dioxide monitors - examples shown

4.32. When shown images of a Carbon Dioxide monitor (figure 4.29) and asked whether respondents have one installed in their bedrooms, 59% said that they have one installed (the majority of these (44%) were in social housing).

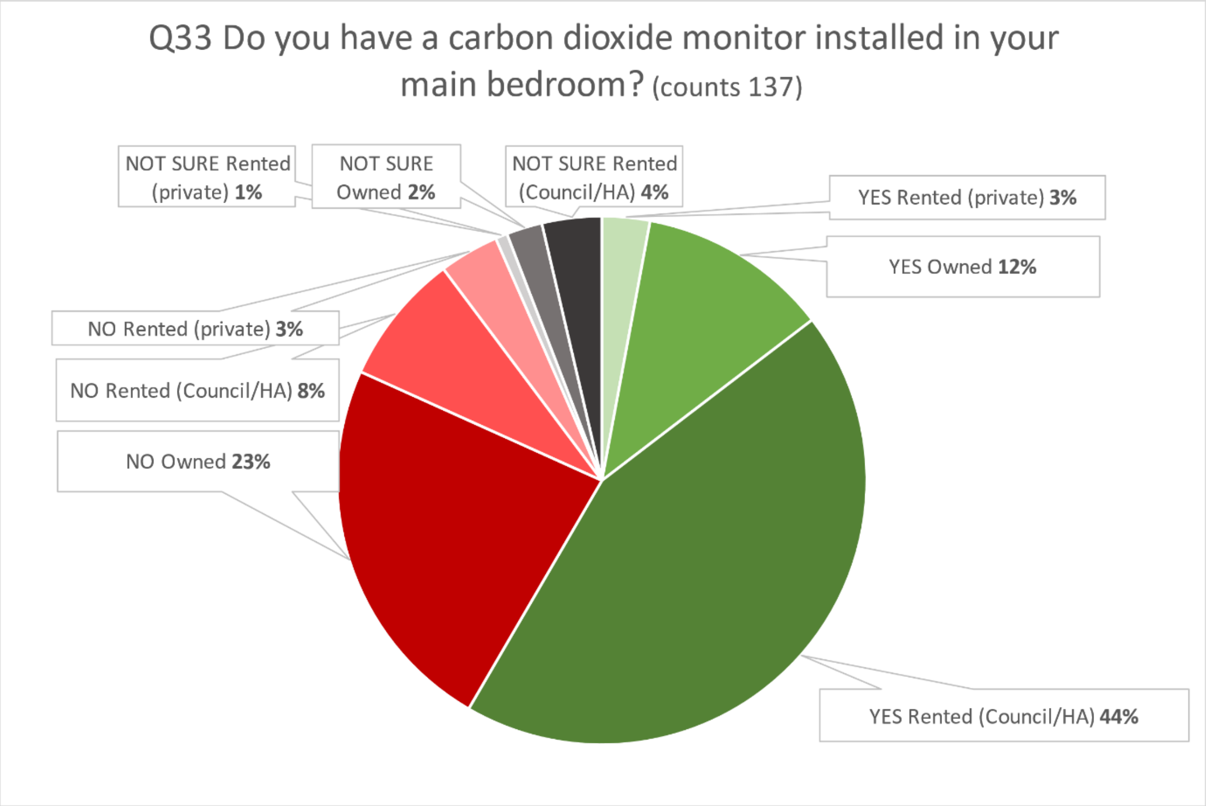

Figure 4.30: CO_2 monitors installed

4.33. The majority of respondents of those that stated they had a CO_2 monitor installed in their bedroom stated that they knew what a CO_2 monitor is for (72%). However, looking at the responses provided when asked "what that advice was", it became clear that nearly half of them didn't know what a CO_2 monitor is for. Some of the responses revealed that the CO_2 monitor was being confused with detectors for other gasses such as carbon monoxide.

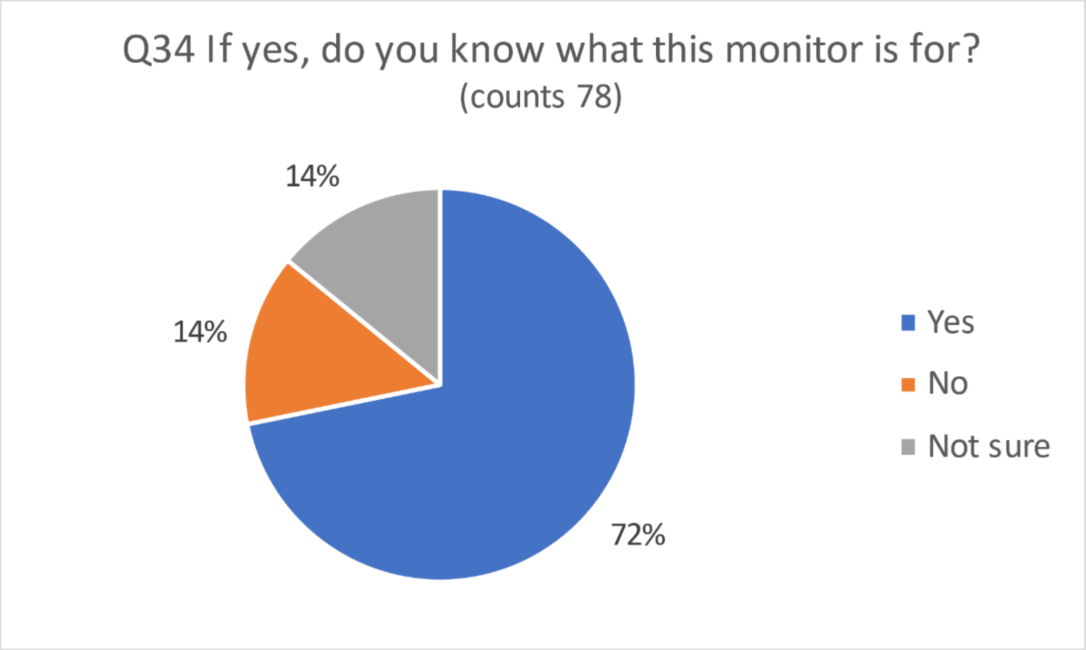

Figure 4.31: Do you know what the CO_2 monitor is for?

CO2 monitor advice

4.34. From the respondents that stated they had a CO_2 monitor installed in their bedroom, 30% of respondents stated that they were given advice on how to use the CO_2 monitor[6]. This effectively corresponds to 25 people in total. The majority are council or housing association rented properties (in figure 4.23 labeled as "Rented Council/HA).

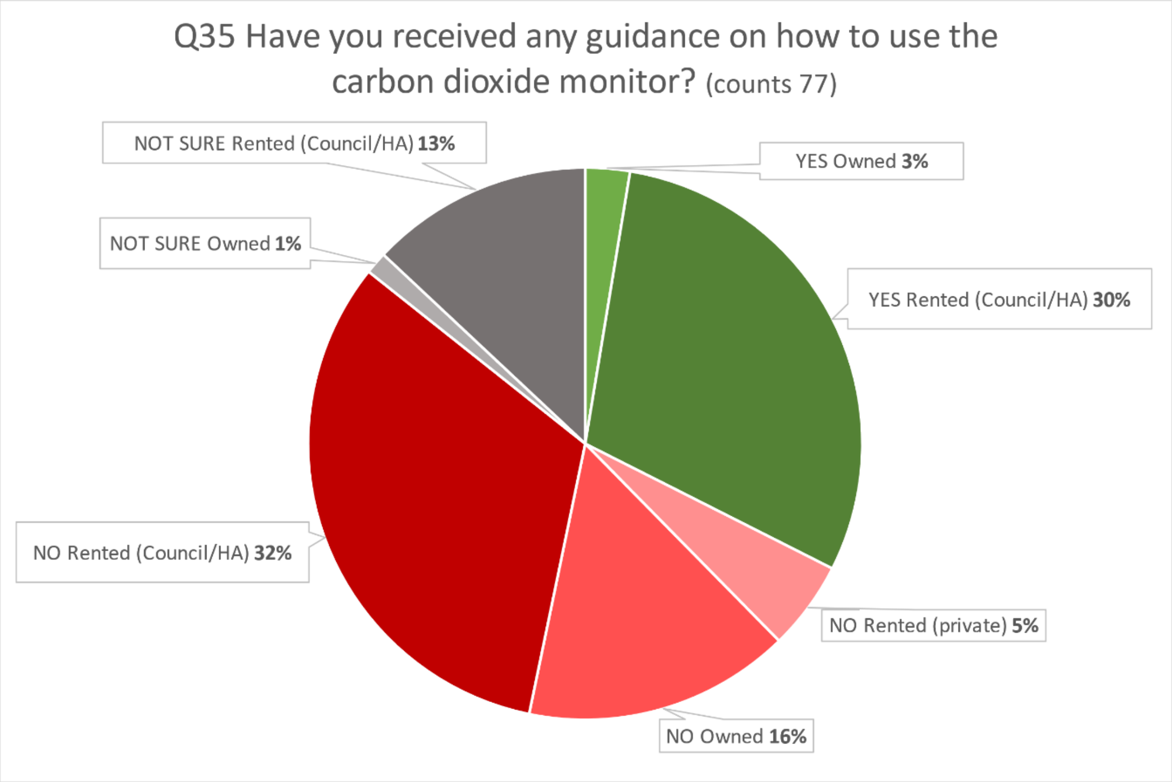

Figure 4.32: CO_2 monitor guidance

4.35. While 40% of people stated that they 'never' use the CO_2 monitor to check carbon dioxide levels, the majority (60%) stated that they use the monitors.

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[6] This percentage is in contrast with the 16% who stated that they received advice on ventilation. Conceptually, the advice of the use the CO2 monitor falls within the scope of ventilation advice. However, being CO2 monitors relatively new and not applicable to all buildings in the UK, when designing the questionnaire, we purposely kept this question separate as we know that inquiring occupants about ventilation advice, traditionally it is meant if occupants have received any explanation regarding windows, trickle vents and mechanical extracts (as shown in paragraph 3.29) and the different detailed responses in Q30 and Q35 are evidence of this meaning of ventilation advice.

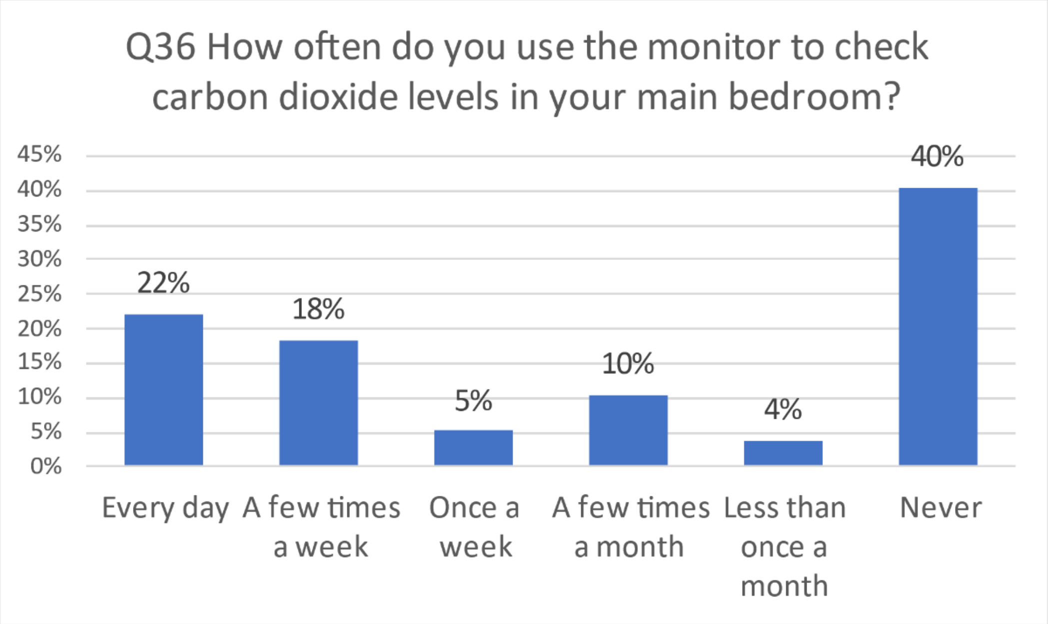


Figure 4.33: CO_2 monitor use

4.36. Of the households with a CO_2 monitor, the majority (80%) claimed to take action when carbon dioxide levels are high. For action, the majority open the windows but still a minority misunderstood the purpose of a CO_2 monitor. For instance, 6% stated they would call the gas board and 10% were not sure what to do.

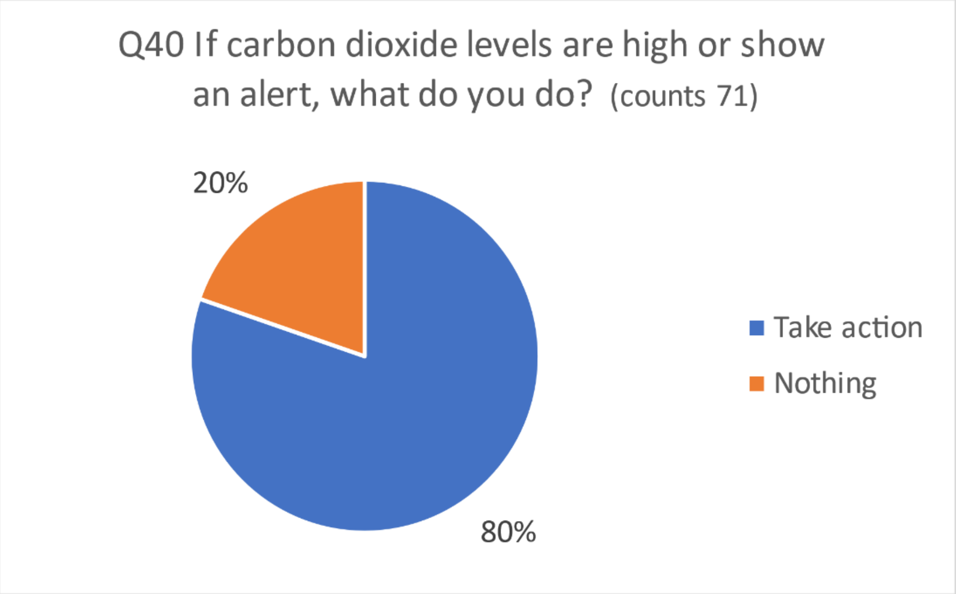


Figure 4.34: CO_2 monitor action in case of alert (1)

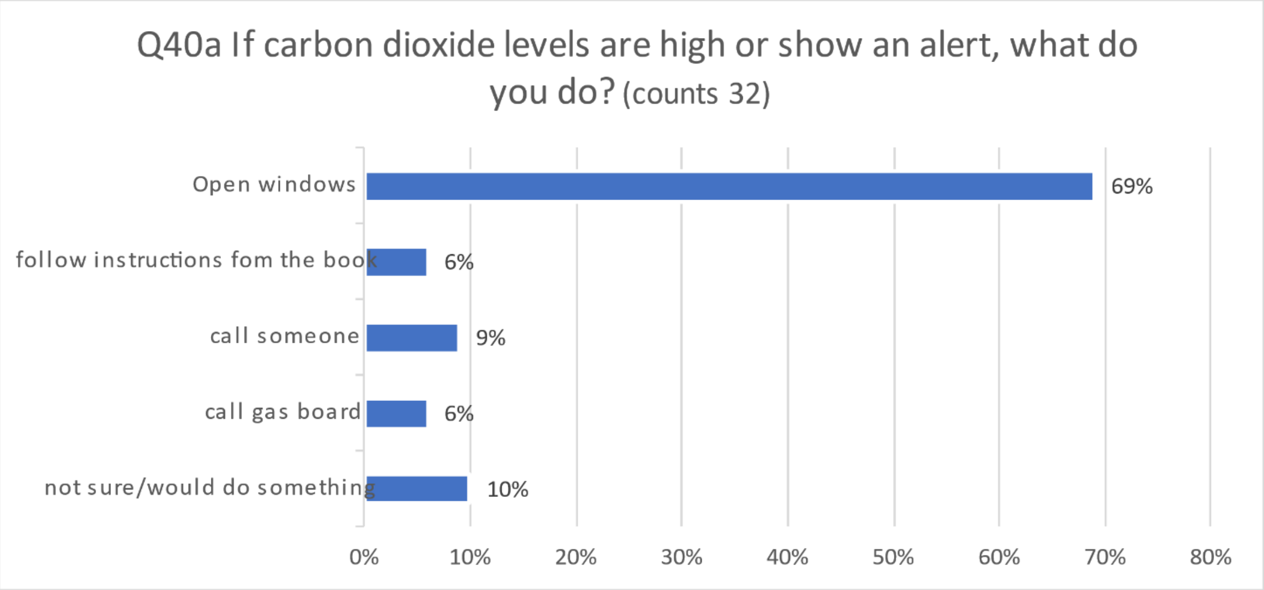


Figure 4.35: CO_2 monitor action in case of alert (2)

4.37. While respondents tend to open the windows when action is required, it is apparent that many respondents were unsure of the effectiveness of such action. Nonetheless, it can be noticed that only one third of those with CO_2 monitors find that CO_2 monitors have improved indoor air quality or has influenced the way they ventilate their homes. This has been explored in detail in the following paragraphs.

4.38. Of the subset of households who have taken action, figures 4.36 and 4.37 show people who have and who have not had advice respectively.

- Of households that have had advice, 8% reported that taking action make a difference in CO_2 levels. In households who have not had advice 15% reported that taking action make a difference in CO_2 levels. Interestingly, both groups for the majority claimed to be unsure if taking action makes a difference in CO_2 levels.

- Of households that have had advice, 19% reported that the presence of the CO_2 monitor made them aware of ventilation and indoor air quality. In households who have not had advice, 12% reported that the CO_2 monitor made them aware of ventilation and indoor air quality, albeit 9% of households did not.

- Of households that have had advice, 13% reported that the presence of the CO_2 monitor had an influence on the way they ventilate their homes. In households who have not had advice, 10% reported that the presence of the CO_2 monitor had an influence on the way they ventilate their homes, albeit 18% have had no influence.

- Of households that have had advice, 13% think that having the CO_2 monitor has improved their indoor air quality. In households who have not had advice, 9% reported that having the CO_2 monitor has improved their indoor air quality, albeit 12% of households did not.

4.39. Results above demonstrate that CO_2 monitors have had some benefit, albeit limited by advice.

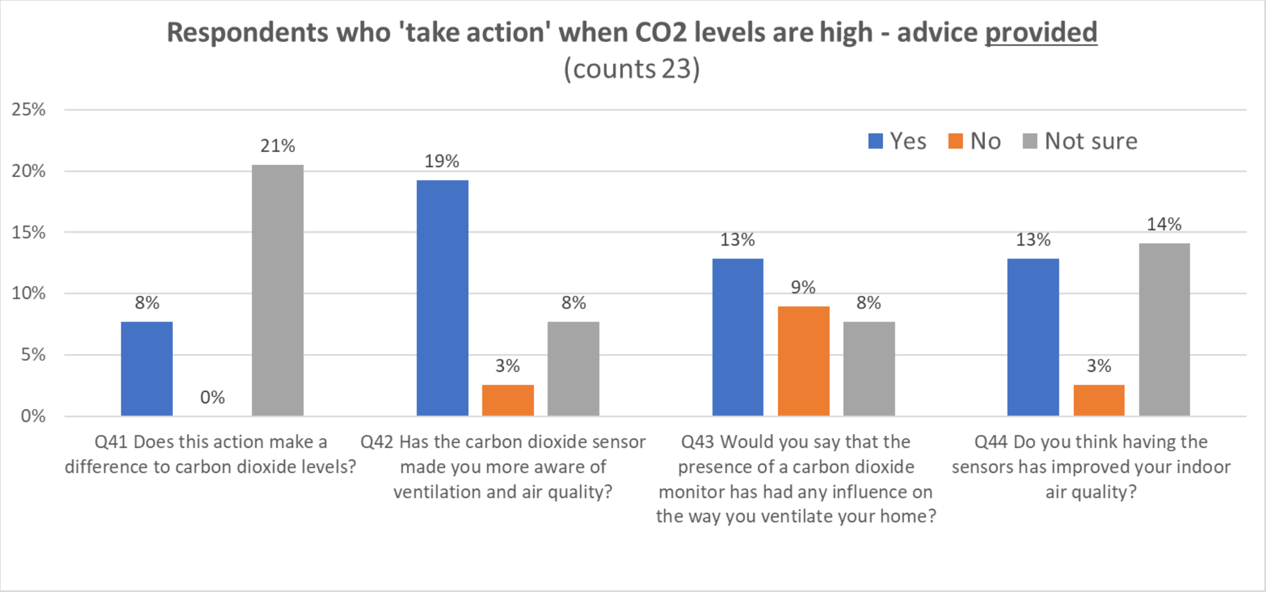


Figure 4.36: CO_2 awareness in households who have had CO_2 monitor advice

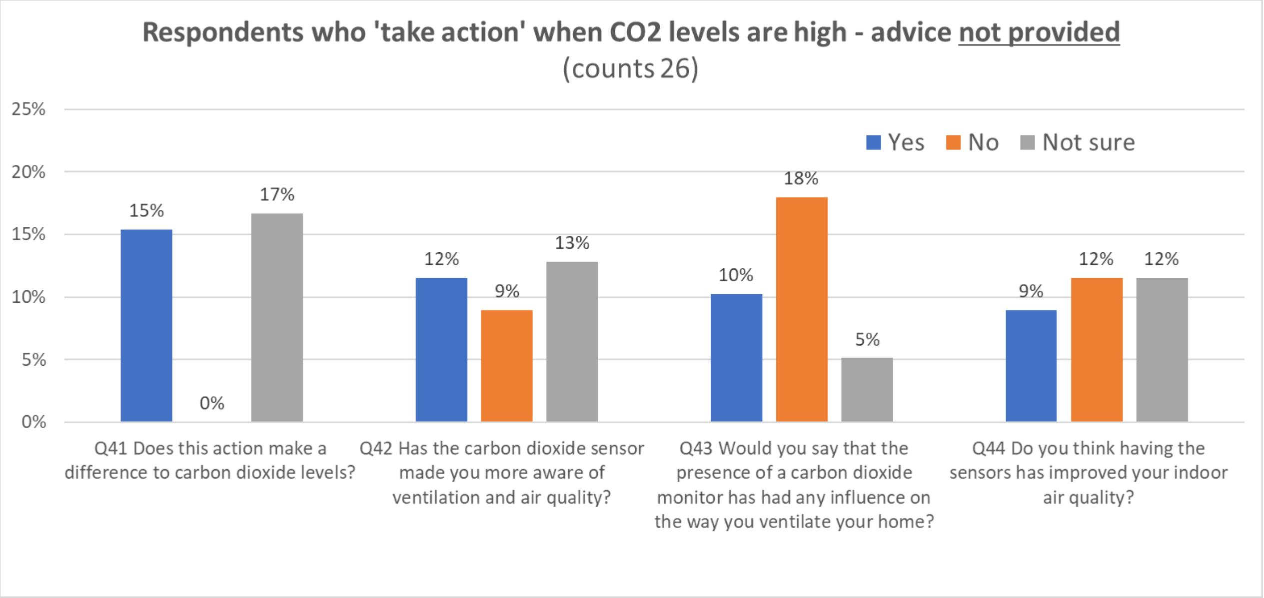


Figure 4.37: CO_2 awareness in households who have **not** had CO_2 monitor advice

Detailed monitoring

4.40. The final question reads “Would you like to be considered to participate in a detailed monitoring study?” Out of 138 responses, 57 expressed their willingness to participate in long term monitoring. Most households of this subgroup have been contacted to initiate long term monitoring, as detailed in the next chapter.

Summary

4.41. The survey provided a modified picture from the survey the 2014 study. Now, occupants are aware of the purpose of trickle vents, and the majority of trickle vents are open all the time. This show that there is a definite change in ventilation systems engagement also for windows. In fact, the trend for window opening has switched from “never opening windows” to “open all the time”. This change in behaviour appear not to be driven by improved advice about ventilation which remains low, however the external context for Covid may have change awareness and behaviours of ventilation use.

4.42. Key findings are reported below in bullet points (most important ones first):

- Only 58% of respondents reported the presence of a CO_2 monitor installed in bedrooms as requested by the building regulations.

- Of those who have CO_2 monitors installed, very few (30%, 12 households) received advice on how to use the CO_2 monitor.

- The survey found an increase in reported window opening (27% in living rooms and 36% in bedrooms), when compared to the results of the 2014 survey (around 19% in living rooms and around 12% in bedrooms)

- The survey found a significant increase in reported trickle vent opening (75% in living rooms and 69% in bedrooms), when compared to the results of the 2014 survey (around 25% in living rooms and around 28% in bedrooms)

- The main drivers for ventilation include thermal comfort (26% in both living rooms and bedrooms), indoor air quality or “fresh air” (33% in living rooms and 40% in bedrooms) and energy consumption (26%).

- Of those households who have CO_2 monitors installed, 60% stated that they use the monitors and 80% claimed to take action when CO_2 levels are high. For action, the majority open the windows but still a minority misunderstood the purpose of a CO_2 monitor.

- Of those households who take action when CO_2 levels are high, the majority claimed to be unsure if taking action makes a difference in CO_2 levels which shows that CO2 monitor advise as well as ventilation provision is limited. There were some slight differences in CO_2 monitor perception among groups who have had advise from those who have not.

5. Long term monitoring study

Aims and objectives

5.1. The specific aim of the long term monitoring component of this study is to investigate what effects the new regulations have had on actual conditions in homes. By doing so, it will be possible to compare the effectiveness of the introduction of CO_2 sensors across different construction and ventilation provisions and over varying weather conditions as well as real-world compliance and performance.

Homes selection and description

5.2. The household survey as per WP2 identified 57 households willing to participate in long term monitoring. Homes with CO_2 monitors and flats were prioritised as part of the selection process.

5.3. Out of 39 households willing to participate in the long term monitoring, only 19 claimed to have CO_2 monitors installed in the bedrooms, which constituted a potential challenge to obtain 20 case studies for the long term monitoring. To overcome this challenge, further household surveys were arranged to developments where the presence of CO_2 monitors had been confirmed by the housing association. A total of 26 new addresses were surveyed face to face obtaining further 18 households willing to participate.

5.4. Households were contacted to (a) confirm CO_2 monitor presence, (b) identify the house typology and (c) explain the mechanics of the long term monitoring. In 18 homes, occupants confirmed their willingness to continue with the study.

5.5. The first round of home visits for long term monitoring were arranged for 18 homes in total, however monitoring was set up only in 13 homes because of last minute cancellations in 5 homes (2 homes drop off due to Covid illness, 1 wrong address, 2 absent at the door and unable to contact) The home visits took place between 01/12/2021 and 10/12/2021, with 2 to 3 hours' time slots per home.

5.6. After restrictions were lifted and face to face interviews resumed, a second round of visits took place between 31/01/2022 and 04/02/2022. Out of the 7 visits booked, 4 households cancelled at the door (2 uninterested at the door, 1 absent at the door and unable to contact, 1 was unavailable due to Covid illness) and setup took place in 3 homes, adding up to a total of 16 homes. Table 5.1 sums up the homes visit efforts.

5.7. To sum up, out of the 57 homes willing to participate and 36 of them having CO_2 monitors present. Survey and monitoring set up was performed in 16 homes. From those 16 homes, 4 homes were not provided with CO_2 monitors. After consultation with BSD, it was agreed that a small number of these would be included in the study as a comparison.

Table 5.1 Homes visits scheduled and homes surveys performed.

	Number of homes' visits scheduled	Number of homes' surveys cancelled before installation	Number of homes' surveys and monitoring set up performed
Round I (01/12/2021-10/12/2021)	18	5	13
Round II (31/01/2022 - 04/02/2022)	7	4	3
		Total homes surveyed	16

Table 5.2 Homes included in the long term monitoring. The table includes CO_2 monitor and construction information.

Home ID	Carbon dioxide (CO_2) monitor	Postcode	Property Type	Dwelling Type	Total floor area (m^2)	Air Tightness (design)	Air Tightness (tested)	Mechanical Ventilation
1 (ex RR983)	No	G32 7BS	Flat	Mid-floor flat	76		0.4	MVHR
2 (ex RR1211)	yes	G43 1FF	Flat	Ground-floor flat	69	4		dMEV
3 (ex RR991)	No	G32 7BS	Flat	Mid-floor flat	55	4		dMEV
4 (ex RR1628)	No	G78 2BF	House	End-terrace house	74	4.5		dMEV
5 (ex RR25)	Yes	EH11 4FF	House	Mid-terrace house	76		2.5	dMEV
6 (ex RR575)	Yes	EH42 1ZT	Flat	Ground-floor flat	71	4		dMEV
7 (ex RR619)	Yes	EH5 1RW	Flat	Ground-floor flat	74	5		dMEV
8 (ex RR846)	No	EH7 5FQ	Flat	Mid-floor flat	64	5		dMEV
9 (ex RR12)	Yes	EH11 3US	Flat	Mid-floor flat	72		4.5	dMEV
10 (ex RR914)	Yes	G31 1AR	Flat	Ground-floor flat	65	4		dMEV
11 (ex RR1560)	Yes	G73 2DS	Flat	Mid-floor flat	51	4		dMEV
12 (ex RR1386)	Yes	G53 6ER	House	Semi-detached house	95	4		dMEV
13 (ex RR1351)	Yes	G53 6EH	House	Semi-detached house	95	4		dMEV
14	Yes	G46 8AZ	House	Semi-detached house	96	4.5		dMEV
15	Yes	ML5 3AY	Flat	Mid-floor flat	52	5		dMEV
16	Yes	G46 8AZ	Flat	Ground-floor flat	81	4.5		dMEV

Description of monitoring set up and survey process

5.8. The survey process consisted of a series of 6 steps.

STEP 1 – Consent. Before beginning with any form of data collection, and in line with the ethical procedure put in place by the University of Strathclyde, researchers obtained signed consent from occupants.

STEP 2 – Walk-through. Then an initial walk-through with the occupants was performed to identify (a) the positioning of trickle vents (when manually adjustable), (b) the mechanical system and status (i.e. fan speed dial), (c) the floor plan layout, (d) any occlusion of openings and window conditions, (e) where the sensors will be installed, in agreement with the occupant and at the same time in a position that allows for reliable data collection (away from sources of heat, solar gains, windows etc.).

STEP 3 – Occupant Questionnaire. Questionnaires were completed by each household, capturing information on the following:

- ☐ household information
- ☐ trickle vents awareness and use in winter
- ☐ windows and door interaction in winter
- ☐ mechanical ventilation awareness and use
- ☐ advice on ventilation received
- ☐ CO_2 monitors advice and interaction
- ☐ a general overall perception of the indoor environment

STEP 4 – Environmental Monitoring installation. Environmental monitoring equipment was installed during the same site visit in each bedroom and one living area. Temperature, relative humidity and carbon dioxide levels were monitored simultaneously at 15-minute intervals.

The equipment (provided by the company Aico Ltd) consisted of a SmartLINK gateway Ei1000G and HomeLINK Environmental Sensors Ei1025. These two products send readings from the sensors to an online HomeLINK dashboard. First, the desired location of the gateway was tested for a strong signal. Once confirmed, sensors were placed in the rooms using non-marking fixing tape. Each piece of equipment was labelled with the house code, installation date and room (see figures below).

UNIV. STRATHCLYDE / ARCHITECTURE
Project BSD-feb21 Home ID
____
Placed on ____________room
____
Don't remove from its location.
For any issues, please contact:
Linda Toledo linda.toledo@strath.ac.uk

Figure 5.1 Label on equipment

c

Figure 5.2 Pictures of equipment installed in the long term monitoring

STEP 5 – Ventilation survey. A ventilation survey was performed by testing the airflow measurements of the mechanical ventilation systems with the use of an air capture hood, SwemaFlow 126. Testing was performed in all outlets. The test was performed twice to improve the reliability. First, outlets were tested in *trickle* mode and then in boost mode.

STEP 6 – Dimensional Survey and Photos. After a quick draft of the home layout, the researchers recorded the dimensions of rooms, trickle vents and door undercuts. Where available, photos of the trickle vent stamp indicating equivalent area were taken, and measurements of the trickle vent length were recorded.

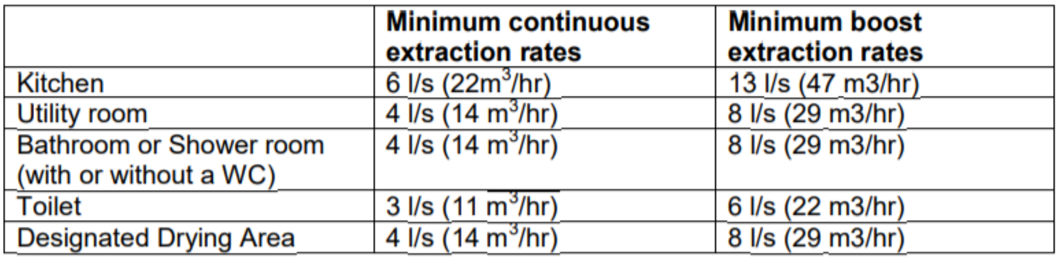
In 8 homes dMEV systems were found to be turned off from the isolators because of noise, draughts, costs of running. On such occasions, systems were turned on for the purpose of testing. Researchers also explained the purpose for them to be turned on and suggested occupants to leave the isolator on the ON position.

5.9. The results of the long term environmental monitoring, household questionnaire, building survey and ventilation audit were used to establish whether occupants use of the CO_2 monitor had any impact on their awareness and use of ventilation, and whether this resulted in improved air quality.

Ventilation system test results

5.10. Results of measured ventilation flow rates of dMEV systems in kitchens and bathrooms are reported in table 5.4. It should be noted that a large portion of dMEV systems, especially those in kitchens, were not compliant with governmental recommendations.

Table 5.3 Minimum extraction rates required [7]



	Minimum continuous extraction rates	**Minimum boost extraction rates**
Kitchen	6 l/s (22m^3/hr)	13 l/s (47 m3/hr)
Utility room	4 l/s (14 m^3/hr)	8 l/s (29 m3/hr)
Bathroom or Shower room (with or without a WC)	4 l/s (14 m^3/hr)	8 l/s (29 m3/hr)
Toilet	3 l/s (11 m^3/hr)	6 l/s (22 m3/hr)
Designated Drying Area	4 l/s (14 m^3/hr)	8 l/s (29 m3/hr)

The ventilation audit found bedroom trickle vent sizes varied considerably between homes. The trickle vents sizes found during the survey (see table 5.4).

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[7] LGCD (2017) Building Standards domestic ventilation supporting guidance version 2.1. Part of *Building, planning and design.* Available at Building Standards domestic ventilation: supporting guidance - gov.scot (www.gov.scot)

Table 5.4 Results of the ventilation audit

House ID	dMEV test				**main bedroom** conditions						
	Kitchen		Bathroom								
	trickle mode (ref. **6 l/s**)	boost mode (ref. **13 l/s**)	trickle mode (ref. **4 l/s**)	boost mode (ref. **8 l/s**)	trickle vent EA	trickle vent % of opening	door under cut	night occupancy (A-adult, C-child)	window position at night	door position at night	curtains and blinds at night
1	14.3	18.6	3.2	12.3	only tilted windows	-	-	2A	Open	Open	Closed
2	4.8	9.8	2.6	4.5	2300 mm^2 x 2 units	100%	5 mm	2A	Closed	Open	Closed
3	7.8	N/A	6.9	10.5	5000 mm^2 x 1 unit	100%	4 mm	1A	Closed	Closed	Open
4	5.3	11.5	3	5.6	4200 mm^2 x 2 units	50%	4 mm	1A	Closed	Open	Closed
5	0	3.4	4.1	6.7	2500 mm^2 x 1 unit	100%	2 mm	2A	Closed	Closed	Closed
6	2.2	2.6	6.4	7.9	2500 mm^2 x 3 units	66%	10 mm	1A	Closed	Closed	-
7	0	0	7.2	6.4	5000 mm^2 x 1 unit	100%	18 mm	1A	Closed	Closed	Closed
8	7.4	10.9	7.7	10.7	only tilted windows	-	19 mm	2A	Closed	Closed	Closed
9	2	3.7	4.5	9	2500 mm^2 x 1 unit	100%	19 mm	2A	Closed	Open	Closed
10	5.8	15.5	3.8	8.8	5000 mm^2 x 1 unit	100%	9 mm	1A	Closed	Closed	Closed
11	3	4.9	2.2	4	3200 mm^2 x 1 unit	0%	4 mm	1A	Closed	Open	Closed
12	8.6	11.8	6.6	19.8	3200 mm^2 x 1 unit	0%	4 mm	2A	Closed	Open	Closed
13	6.7	13.4	4.7	18.9	3200 mm^2 x 1 unit	0%	4 mm	2A	Closed	Closed	Closed
14*	5.5	15.2	0	7.7	4200 mm^2 x 2 units	50%	8 mm	2A 1C	Closed	Open	Closed
15	6.5	11.9	inaccessible		9600 mm^2 x 1 unit	0%	20 mm	1A	Closed	Open	Open
16	2.8	4.9	inaccessible		4200 mm^2 x 2 units	100%	16 mm	1A	Open	Open	Closed

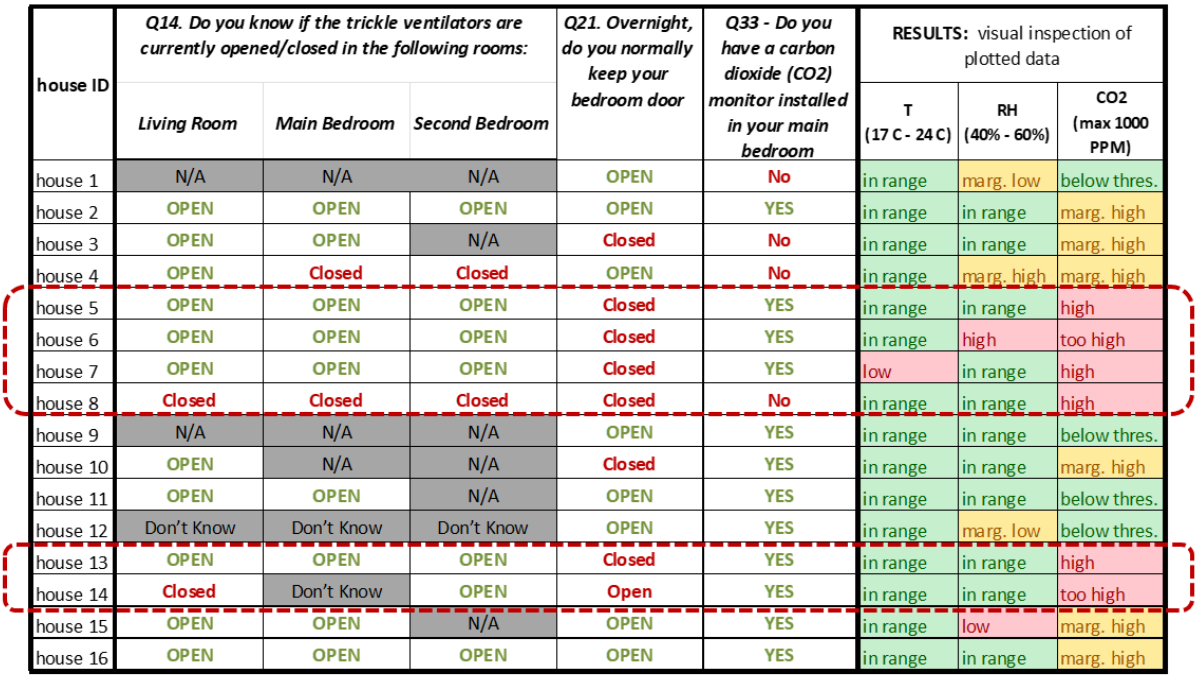
* bed 2 used as master bedroom

Seasonal analysis

5.11. The complete long term data can be found in Annex C.

5.12. The seasonal report issued on 13 April 2022 showed various homes at medium and high risk of poor IAQ (see Table 5.5).

Table 5.5 Overall evaluation of the winter performance, presented in the Seasonal Report (13/04/2022)



house ID	*Q14. Do you know if the trickle ventilators are currently opened/closed in the following rooms:*			*Q21. Overnight, do you normally keep your bedroom door*	*Q33 - Do you have a carbon dioxide (CO2) monitor installed in your main bedroom*	**RESULTS:** visual inspection of plotted data		
	Living Room	*Main Bedroom*	*Second Bedroom*			**T (17 C - 24 C)**	**RH (40% - 60%)**	**CO2 (max 1000 PPM)**
house 1	N/A	N/A	N/A	OPEN	No	in range	marg. low	below thres.
house 2	OPEN	OPEN	OPEN	OPEN	YES	in range	in range	marg. high
house 3	OPEN	OPEN	N/A	Closed	No	in range	in range	marg. high
house 4	OPEN	Closed	Closed	OPEN	No	in range	marg. high	marg. high
house 5	OPEN	OPEN	OPEN	Closed	YES	in range	in range	high
house 6	OPEN	OPEN	OPEN	Closed	YES	in range	high	too high
house 7	OPEN	OPEN	OPEN	Closed	YES	low	in range	high
house 8	Closed	Closed	Closed	Closed	No	in range	in range	high
house 9	N/A	N/A	N/A	OPEN	YES	in range	in range	below thres.
house 10	OPEN	N/A	N/A	Closed	YES	in range	in range	marg. high
house 11	OPEN	OPEN	N/A	OPEN	YES	in range	in range	below thres.
house 12	Don't Know	Don't Know	Don't Know	OPEN	YES	in range	marg. low	below thres.
house 13	OPEN	OPEN	OPEN	Closed	YES	in range	in range	high
house 14	Closed	Don't Know	OPEN	Open	YES	in range	in range	too high
house 15	OPEN	OPEN	N/A	OPEN	YES	in range	low	marg. high
house 16	OPEN	OPEN	OPEN	OPEN	YES	in range	in range	marg. high

Seasonal results

5.13. Seasonal analysis was performed, examining the average night-time temperature, relative humidity and CO_2 levels in bedrooms during three different months, representative of winter (Feb 2022), spring (Apr 2022) and summer (Jul 2022) seasons.

Carbon dioxide concentrations

5.14. With respect to CO_2 concentrations, in general, living rooms tended to perform better than bedrooms. The highest CO_2 concentrations levels are found in bedrooms at night. This trend is stable throughout the three periods examined, i.e. winter (February 2022), spring (April 2022) and summer (2022). The next paragraphs examine in detail these periods. See figures 5.6, 5.7 and 5.8, showing monthly average values for all homes monitored. On the left-hand side are the 12 homes with CO_2 monitor installed in bedrooms and on the right-hand side are the 4 homes that were not provided with CO_2 monitors.

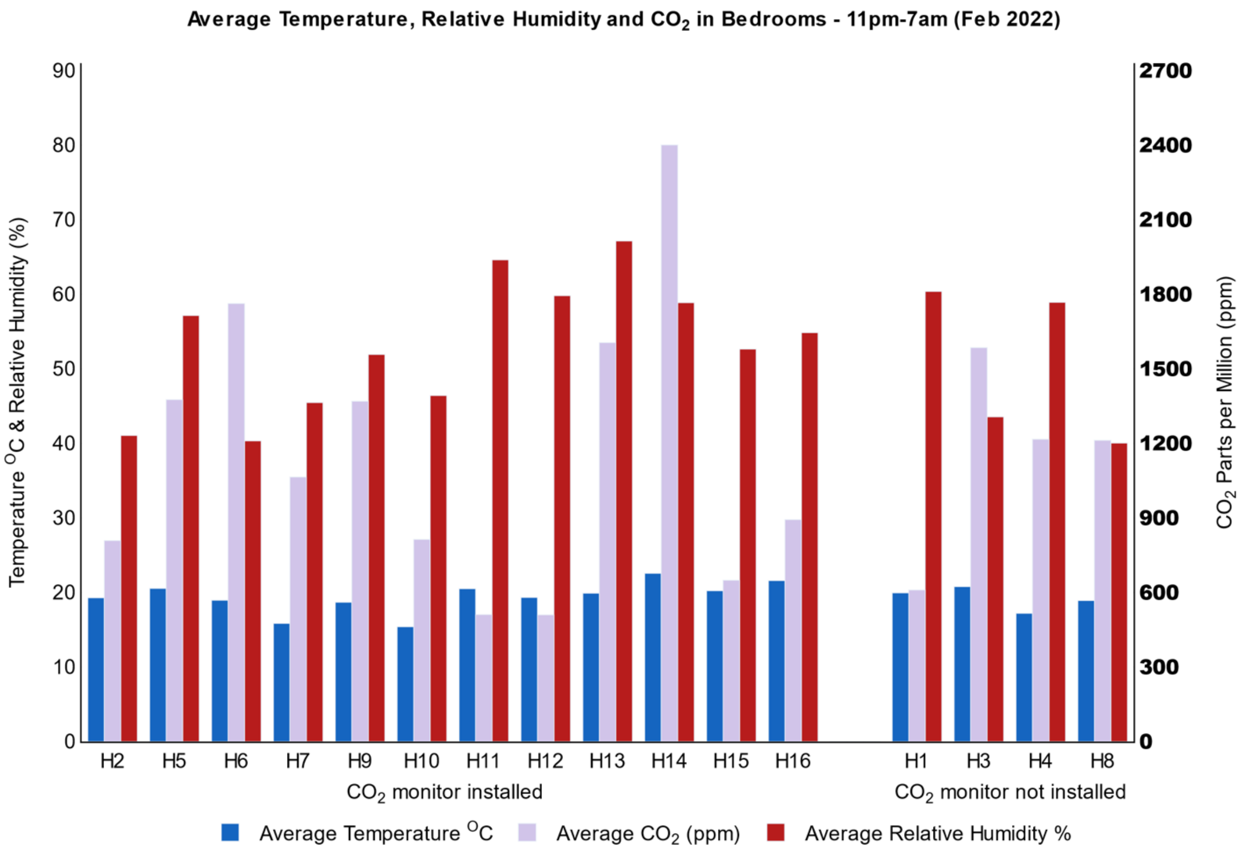


Figure 5.6 Winter period: average of Temperature, Relative Humidity and CO_2 concentrations in bedrooms at night.

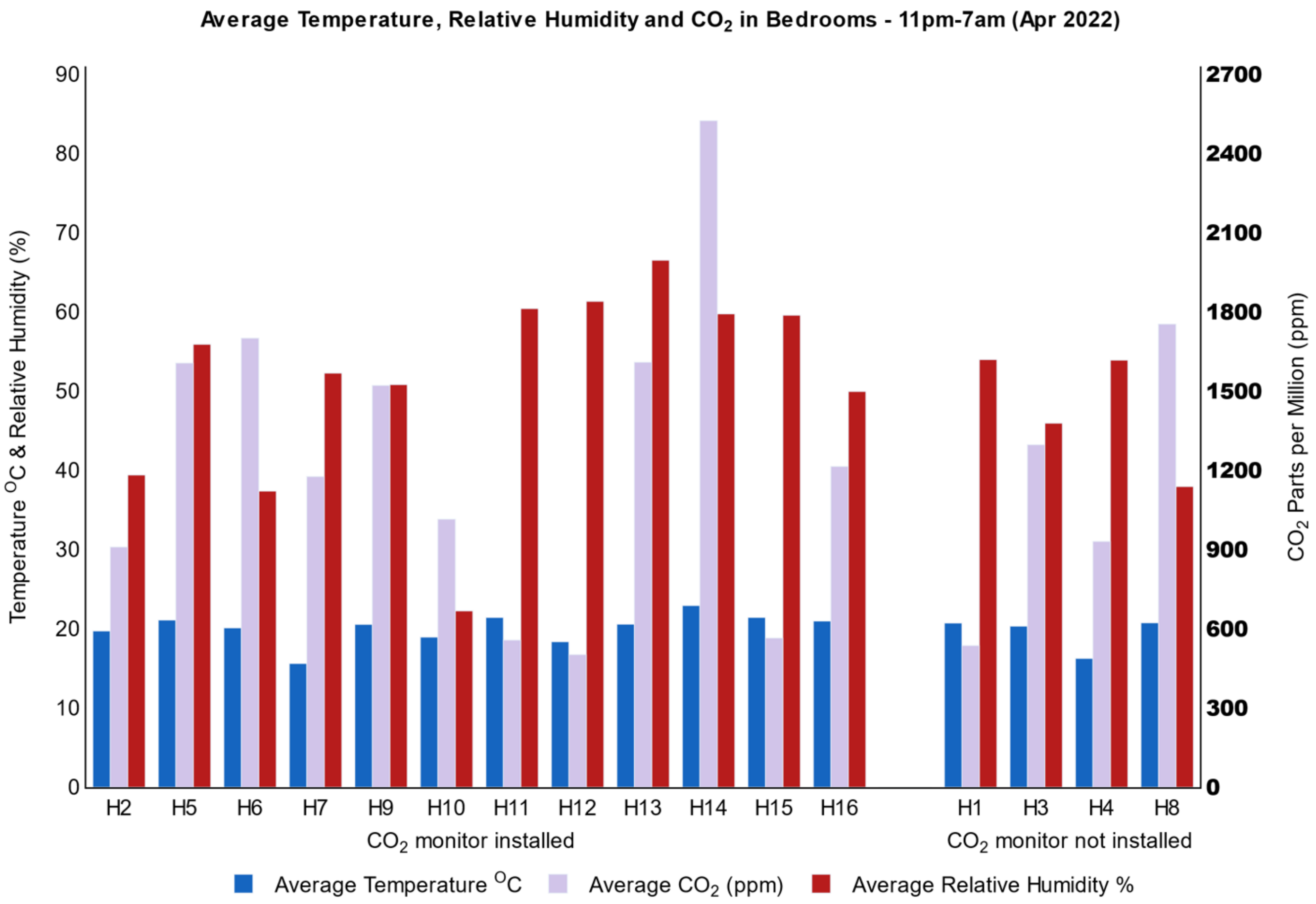


Figure 5.7 Spring period: average of Temperature, Relative Humidity and CO_2 concentrations in bedrooms at night.

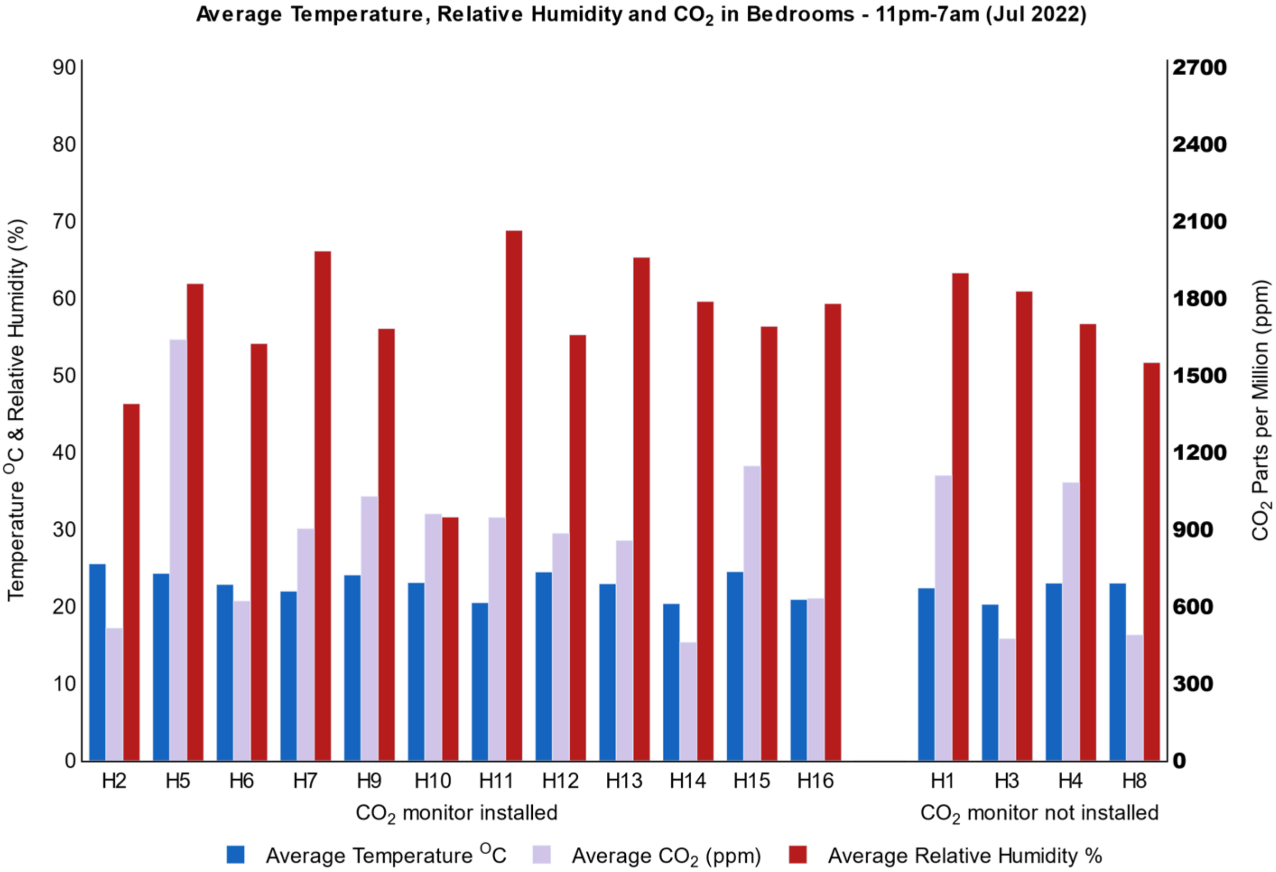


Figure 5.8 Summer period: average of Temperature, Relative Humidity and CO_2 concentrations in bedrooms at night.

Winter

5.15. In figure 5.6 and figure 5.9 it can be noticed that half of homes with CO_2 monitors in bedroom exceed the 1000 PPM. In decrescent order of concentrations, homes with CO_2 levels above 1500 PPM are H14[8] with over 80% of the time above 1500 PPM followed by H13, H6 and H3 with over 50% of the time above 1500 PPM.

5.16. In the case of H14 and H13, both cases their households have children and adults keep the main bedroom closed at night. H6 is a main bedroom occupied by one teenager, while the adult occupied bedroom 2.

5.17. For the same period, 3 out of the 4 homes with no CO_2 monitor had average night-time CO_2 concentration levels above 1000 ppm, with highest levels found in H3, followed by H4 and H8. H3 on the other hand is a one person flat in a converted church. At the time of the survey, the occupant of flat H3[9] had expressed his concern due to cold discomfort in the bedroom, so it assumed a certain reluctancy from the occupant to open the windows.

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[8] H14 is a 3-bed semi-detached, with a household of 5 family members, of which one new-born sleeping in main bedroom with the parents.

[9] H3 is a one aspect one bedroom flat on a converted church with one occupant.

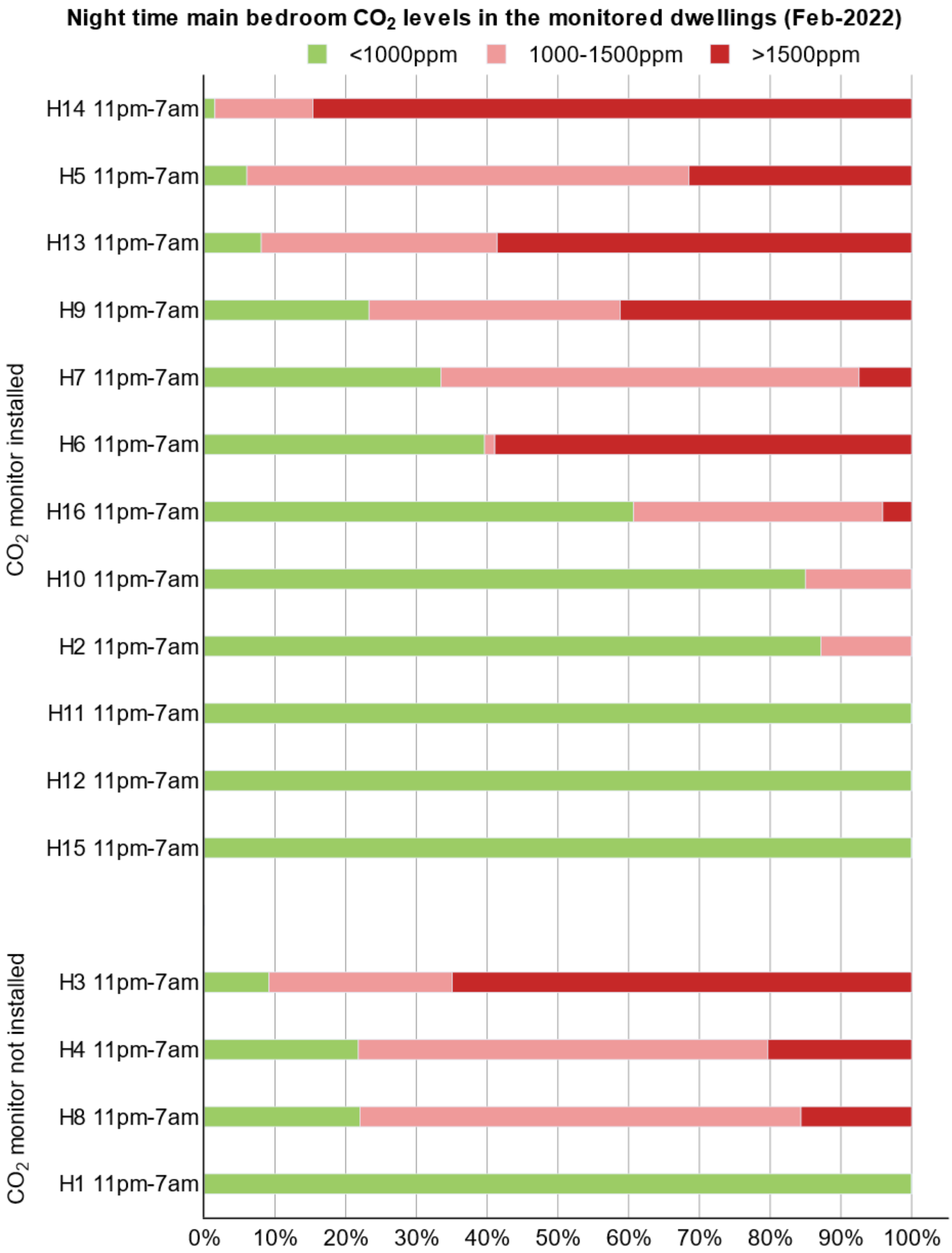

Figure 5.9 Winter period: CO_2 concentrations in bedrooms at night.

Spring

5.18. During Spring (figure 5.7 and figure 5.10), overall bedrooms and living rooms CO_2 levels were generally higher in spring compared to winter in most homes. This may be indication of a concurring phenomenon besides window-trickle vent opening

5.19. In decreasing order of concentrations, bedroom night-time CO_2 levels exceeded 1,500ppm for more than 85% of the time in H14 (family with new-born). This figure is similar to winter CO_2 concentrations.

5.20. Bedroom night-time CO_2 levels in H5[10] (couple) exceeded 1,500 ppm for 60% of the time. This figure greater that winter CO_2 concentrations (over 30% of the time exceeding 1,500ppm).

5.21. In H8[11], CO_2 concentration levels in the main bedroom exceeded 1,500ppm for over 70% of the time during Spring (a noticeable increase from 15% during Winter).

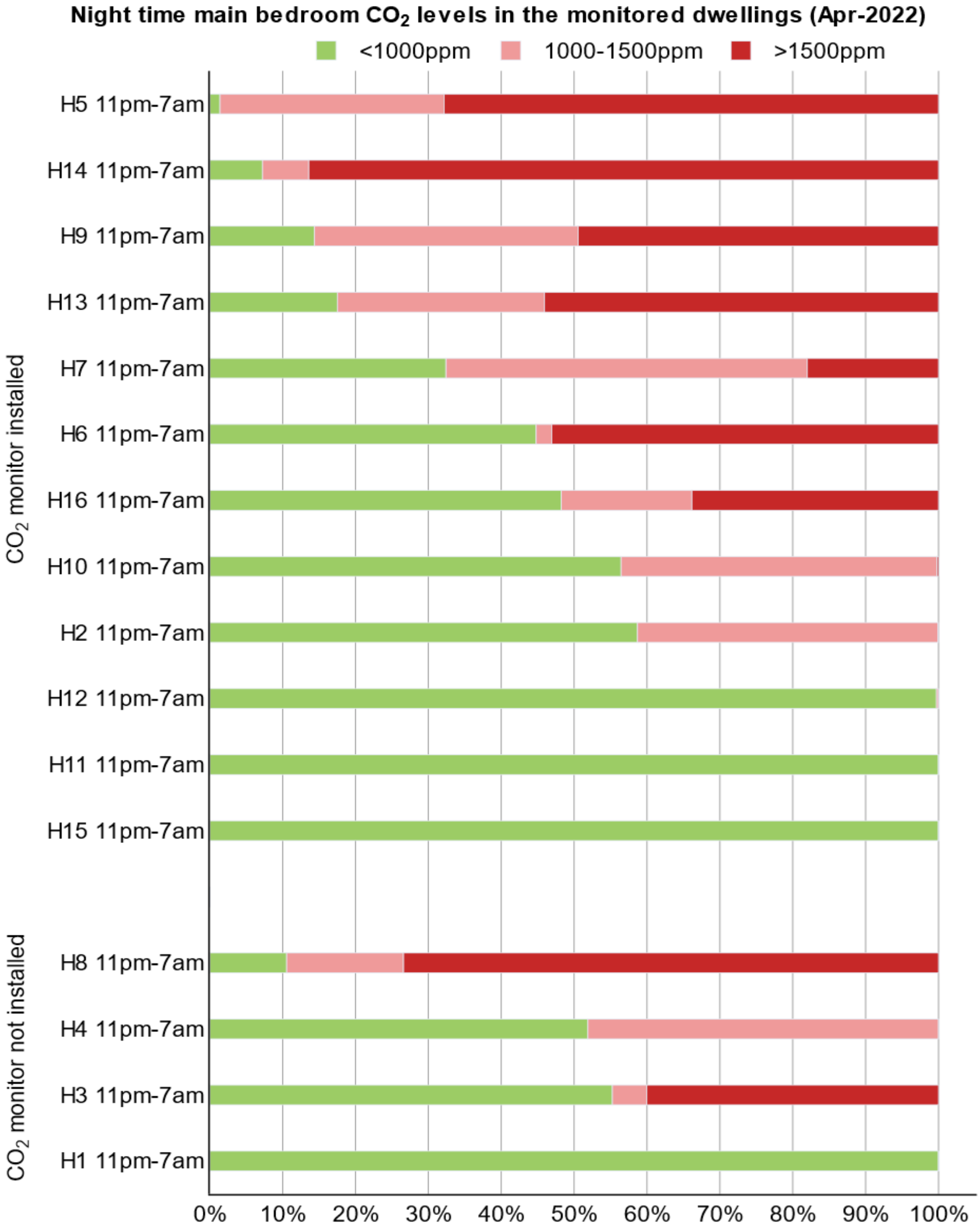

Figure 5.10 Spring period: CO_2 concentrations in bedrooms at night.

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[10] H5 is a mid-terrace occupied by a couple. During the first survey, the occupants expressed their preference for a warm environment even at the expense of indoor air quality.

[11] H8 is a flat occupied by a couple.

Summer

5.22. During summer (see figure 5.8 and figure 5.11), bedroom CO_2 levels at night decreased as expected during this season. Interestingly, most homes still show averages of CO_2 above 1000 PPM. In addition, night-time bedroom CO_2 levels in H5 were above 1500 PPM for over 50% of the time, despite the occupant reportedly sleeping with the bedroom door open.

5.23. Another interesting finding was that in H1[12] (Passivhaus), while performance in winter and spring was optimal, CO_2 levels in summer exceeded 1000 ppm for over 60% of the time. A possible explanation may be related to occupant's behaviour to keep heat out during this season.[13]

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[12] H1 is Passivhaus flat with 2 occupants.

[13] Further investigation can look at the status of the MVHR system during summer to make sense of the higher CO2 values.

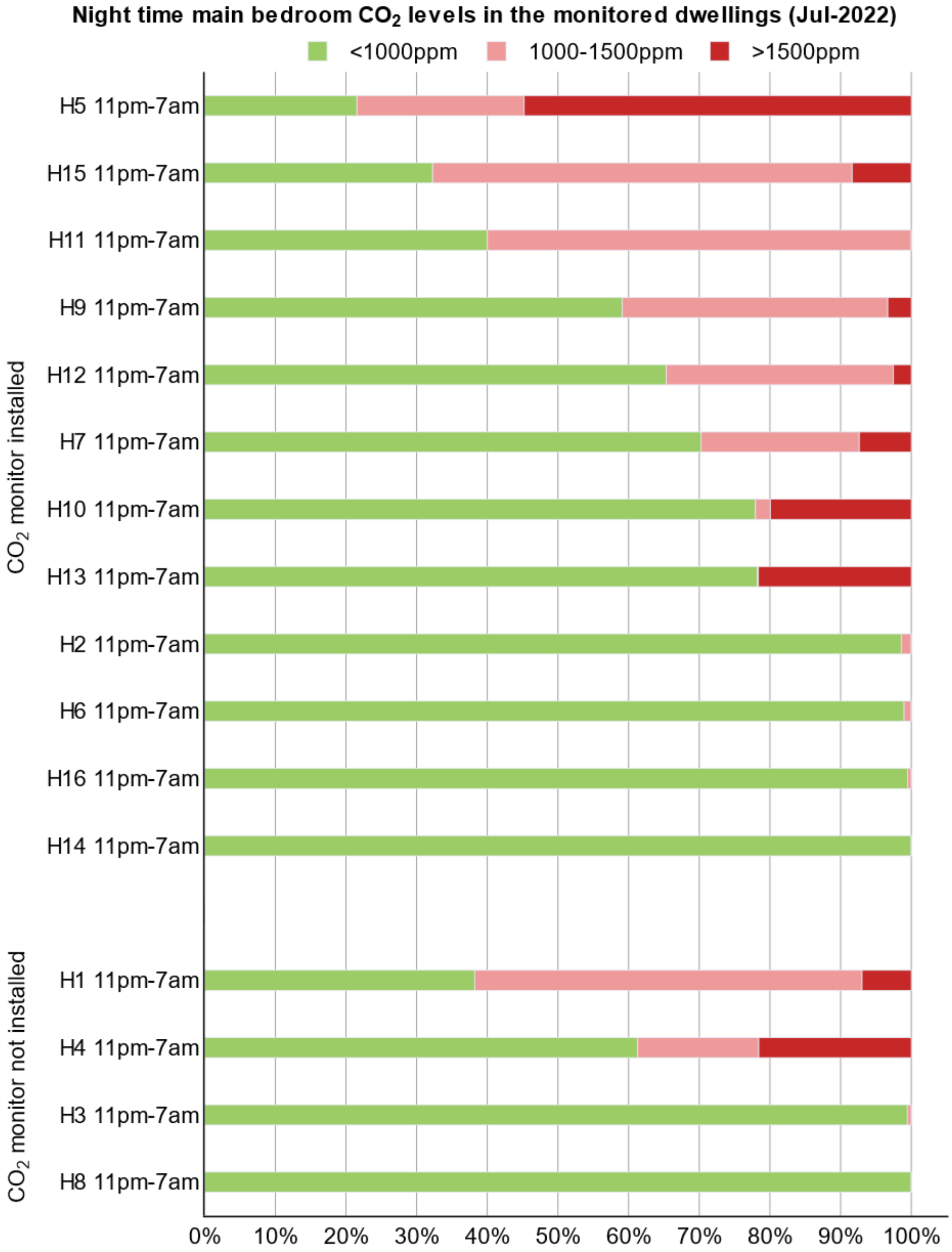

Figure 5.11 Summer period: CO_2 concentrations in bedrooms at night.

Relative Humidity

5.24. With regards to Relative Humidity in bedrooms overnight, all homes were found to be on average within a healthy range (40-60%) throughout spring, summer and winter periods. The exception is observed in H10[14] where the average levels of RH drop closed to 20% in April and 30% in July.

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[14] H10 is a ground floor flat with one occupant. The occupant suffers from asthma.

Temperature

5.25. During winter, cold temperatures were found in some homes, especially in bedrooms at night (see figure 5.6 and figure 5.12). In H7[15], living room temperatures were below 16°C for 80 % of the time. At the time of the survey the occupant complained of the flat being draughty and with a heating system control difficult to manage.

5.26. The low temperatures recorded in winter in H7 correlate with the low CO_2 concentrations recorded at the same time, suggesting high levels of (unwanted) air changes. A similar situation of low temperatures was found in H12[16], though in this case, the occupant overventilated due to concern regarding mould in the loft. The loft was not accessed for obvious health and safety reasons. Tenant from H12 pointed to the researchers at one home in the same development that had installed extra vent in the loft on their own initiative since the developer has not come to remedy this issue. Two monitored homes were affected by proliferous mould growing in the loft, which are H12 and H13.

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[15] H7 is a ground floor 2 bedroom flat. At the time of the survey, researchers found that the mechanical extract grille located in the kitchen (living-kitchen) was covered with a box by the occupant, who complained of excessive draught coming from it.

[16] H12 and H13 are two identical 3 bed-semi-detached homes from the same development. During the initial survey occupants complained of mould infestation in the lofts (confirmed by the researchers). Through discussions with the occupants it appears that the construction company has not provided sufficient ventilation in the roof with consequent mould formation in the loft. As reported by the occupant, this issue concerns all the development therefore all homes and that construction company has repeatedly deployed mould bomb foggers, but the mould has regrown. One occupant also showed us the roof vent installed only in one of the homes as a remedial action towards this unresolved issue.

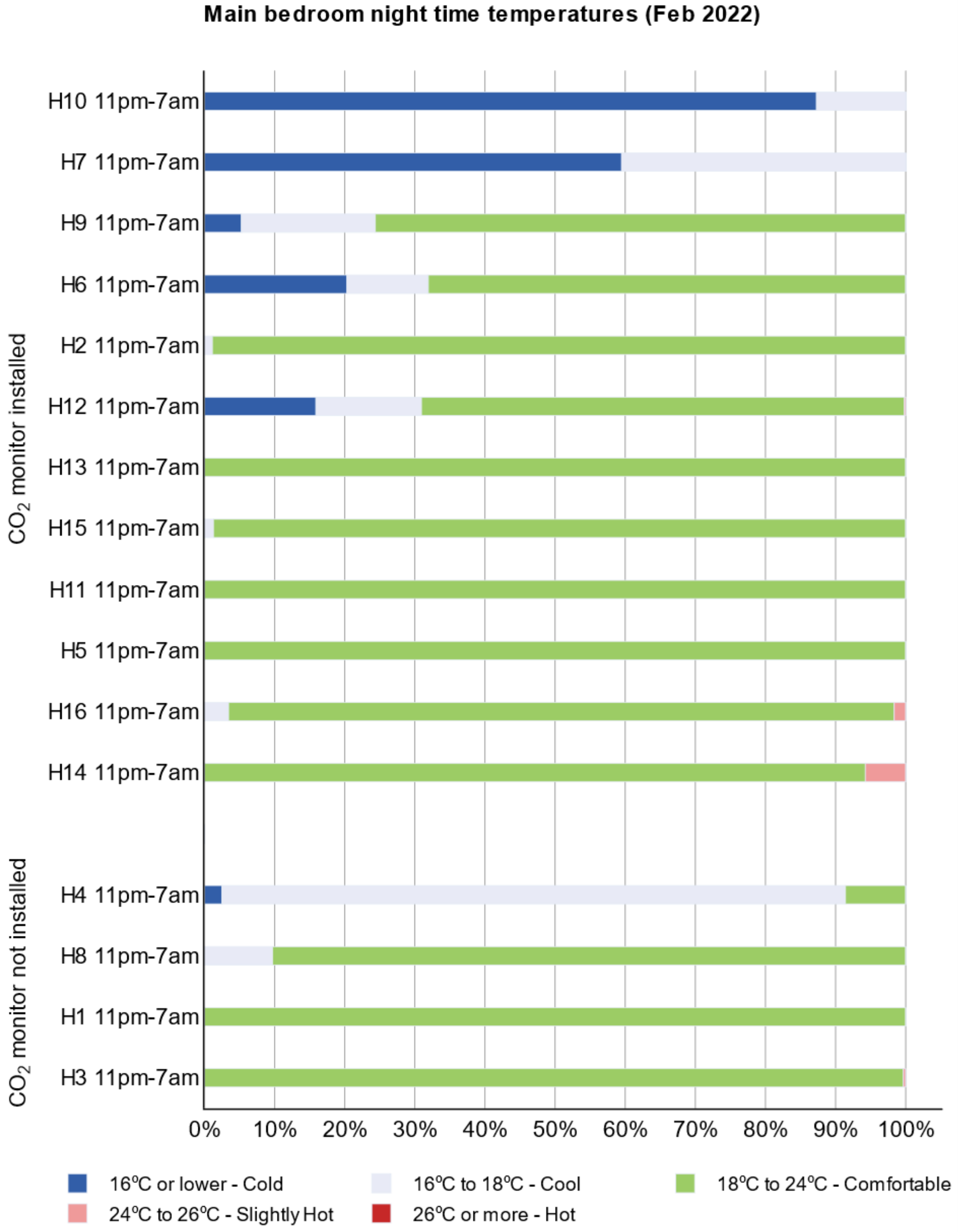

Figure 5.12 Winter period: temperature ranges in bedrooms at night.

5.27. Indoor temperatures during spring were higher than winter, as expected (see figure 5.13). H10, H11 and H14 recorded more than 30% of time between 24-26°C and H14 exceeded 26°C for 15% of the daytime in the living room.

5.28. Cold temperatures were still observed in H7 during spring, with temperatures at 16 °C or lower for 70% of the time in the main bedroom at nighttime (see figure 5.14).

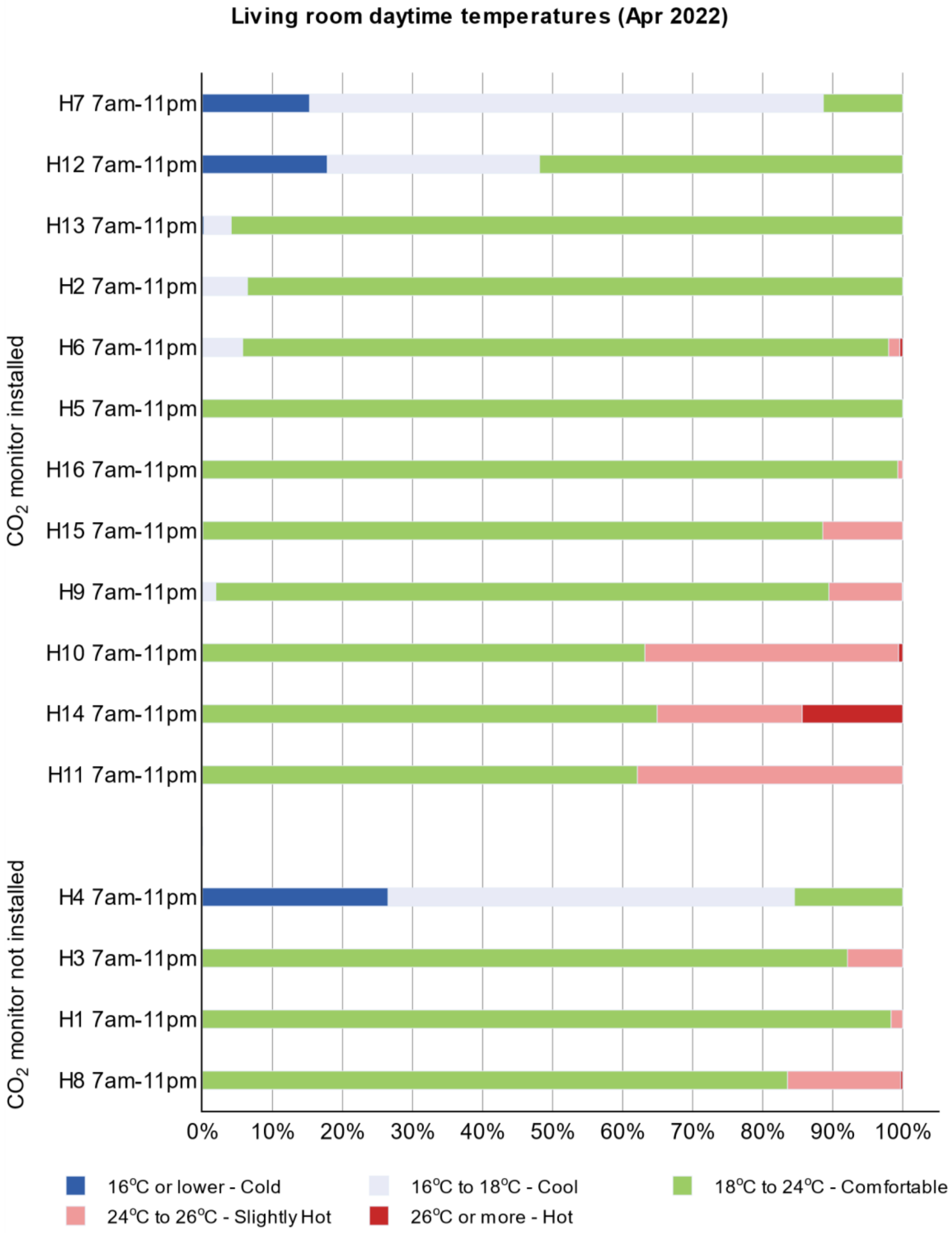

Figure 5.13 Spring period: temperature ranges in living rooms during daytime.

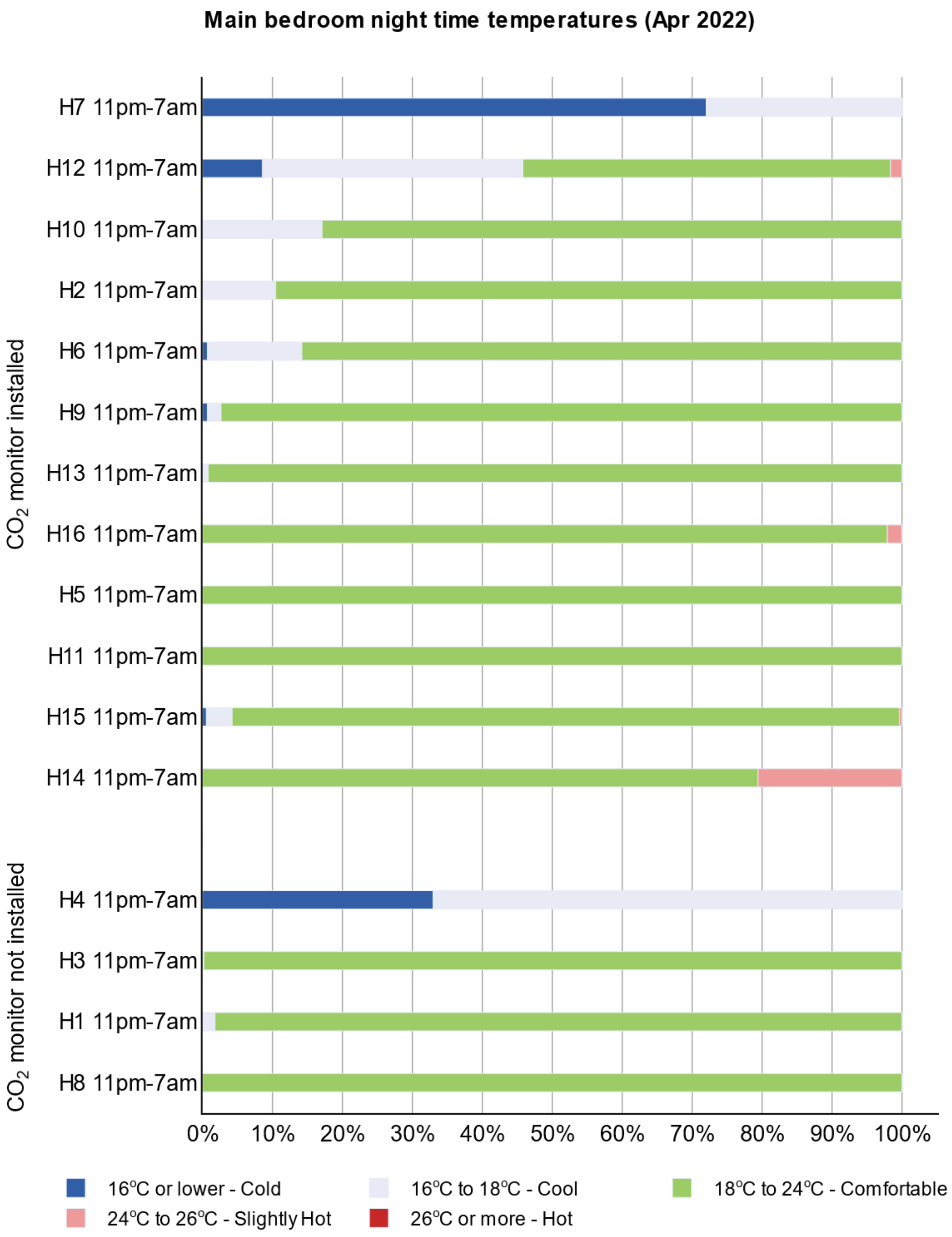

Figure 5.14 Spring period: temperature ranges in bedrooms at nighttime.

5.29. During the summer period, the UK experienced the most intense heat wave. During summer 2022, the UK experienced 2 heatwaves, in July and in August. The July heatwave reached the UK on 18th and 19th July [17] [source: 2022_03_july_heatwave (metoffice.gov.uk)]. On 19th July, a new record high temperature for Scotland of 34.8°C was recorded at Charterhall in the Scottish Borders, with temperatures in southern and eastern Scotland exceeding 30°C on

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[17] Met Office 2022, 2022_03_july_heatwave. Available at https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2022/2022_03_july_heatwave_v1.pdf

the 18th and 19th July. The August heatwave in Scotland was not as intense, with temperatures reaching 28°C on the 13th and 14th August. [18] Importantly, during both heatwaves, air quality deteriorated across much of the UK, with the highest ground-level ozone concentrations observed in rural locations and furthest south. Although not experiencing the highest temperatures, Scotland did not escape the deterioration in air quality with significantly elevated ground-level ozone across South-East Scotland. [19]

5.30. Generally, temperatures were mostly found to be high, and higher in the living rooms when compared to bedrooms (day and night). See figures 5.15 and 5.16.

5.31. The measurement data found three homes to be overheating. In H2, living room temperatures exceeded 26°C for more than 70% of the time and in H15 for more than 60% of the time. Living room temperatures in both homes were consistently between 24°C and 26°C. This is worrisome since both homes are occupied by vulnerable people. H12 also showed high temperatures but mostly in the range of 24-26°C. The low CO_2 concentrations recorded for that same period suggest that all 3 cases (H2, H15 and H12) opened windows to a great extent.

5.32. In bedrooms, overheating assessment against TM59-criterion-2[20] showed overheating on 8 homes out of 16. Further investigation is required to establish the main cause of overheating in these homes (i.e. whether due to layout and orientation, or other sources of uncontrolled heat gains).

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[18] https://www.heraldscotland.com/news/20269129.scotland-heatwave-2022-expect-met-office-records-highest-temperature-year/

[19] https://www.heraldscotland.com/news/20269129.scotland-heatwave-2022-expect-met-office-records-highest-temperature-year/

[20] TM59-criterion-2: for bedrooms only, from 10 pm to 7 am, operative temperatures shall not exceed 26°C for more than 1% of annual hours.

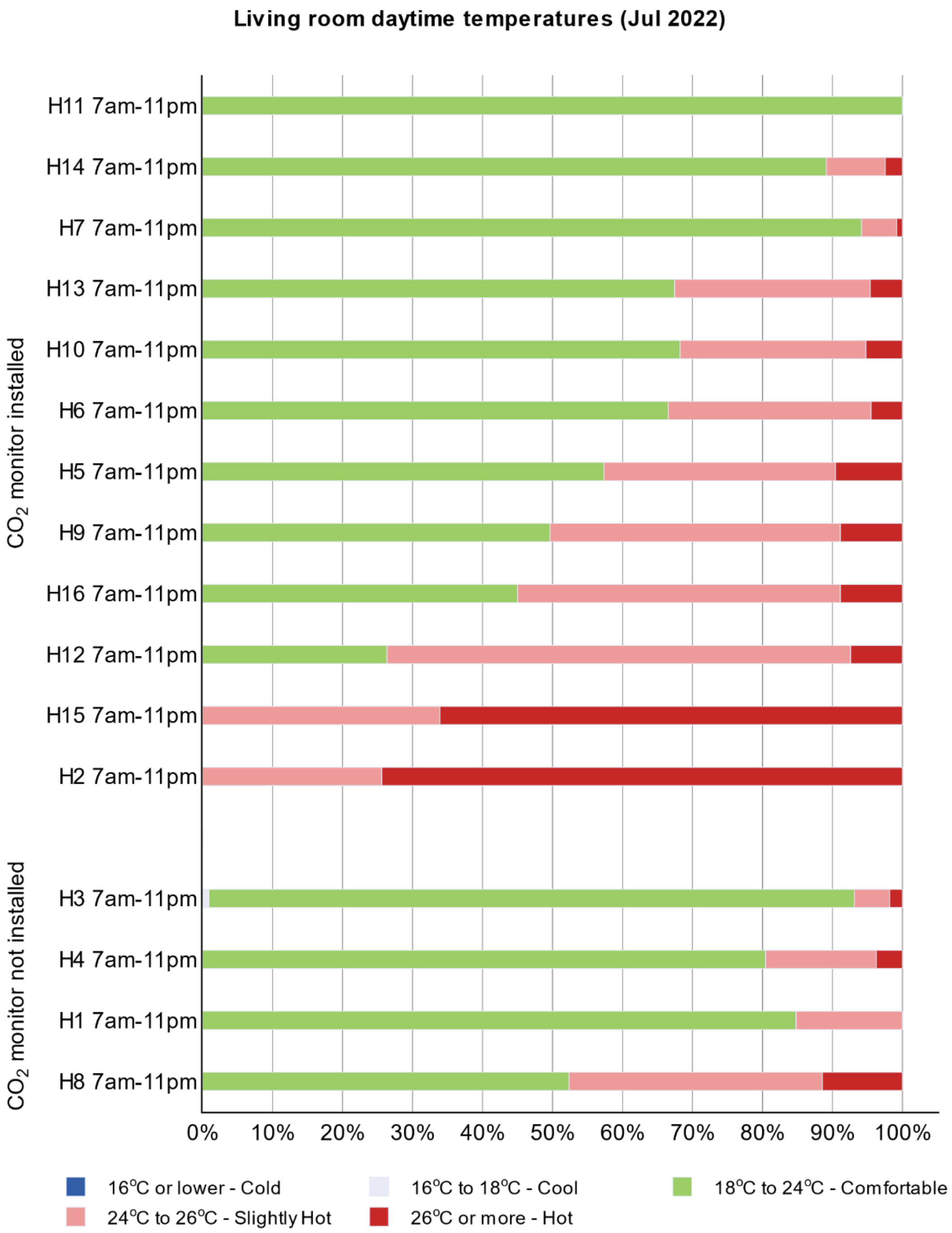

Figure 5.15 Summer period: temperature ranges in living rooms during daytime.

5.33. In H2, bedroom night-time temperatures were between 24-26°C for over 90% of the time, with levels exceeding 26°C for over 30% of the time. Similarly, H15 and H2 recorded bedroom night-time temperatures between 24-26°C for over 70% of the time. The CO_2 concentrations recorded in H2 for that same period suggest the room was adequately ventilated (the flat can perform cross ventilation) despite being a ground floor.

5.34. It is worth noting the results of H3. This is a converted church flat where the resident complained that the bedroom was too cold. During winter and spring, CO_2 values were high, indicating poor ventilation. During summer H3 is the only home showing nighttime temperatures between 16-18°C in the bedroom at night. Looking at the CO_2 levels for the same period, there is indication that the occupant provided ventilation throughout the night.

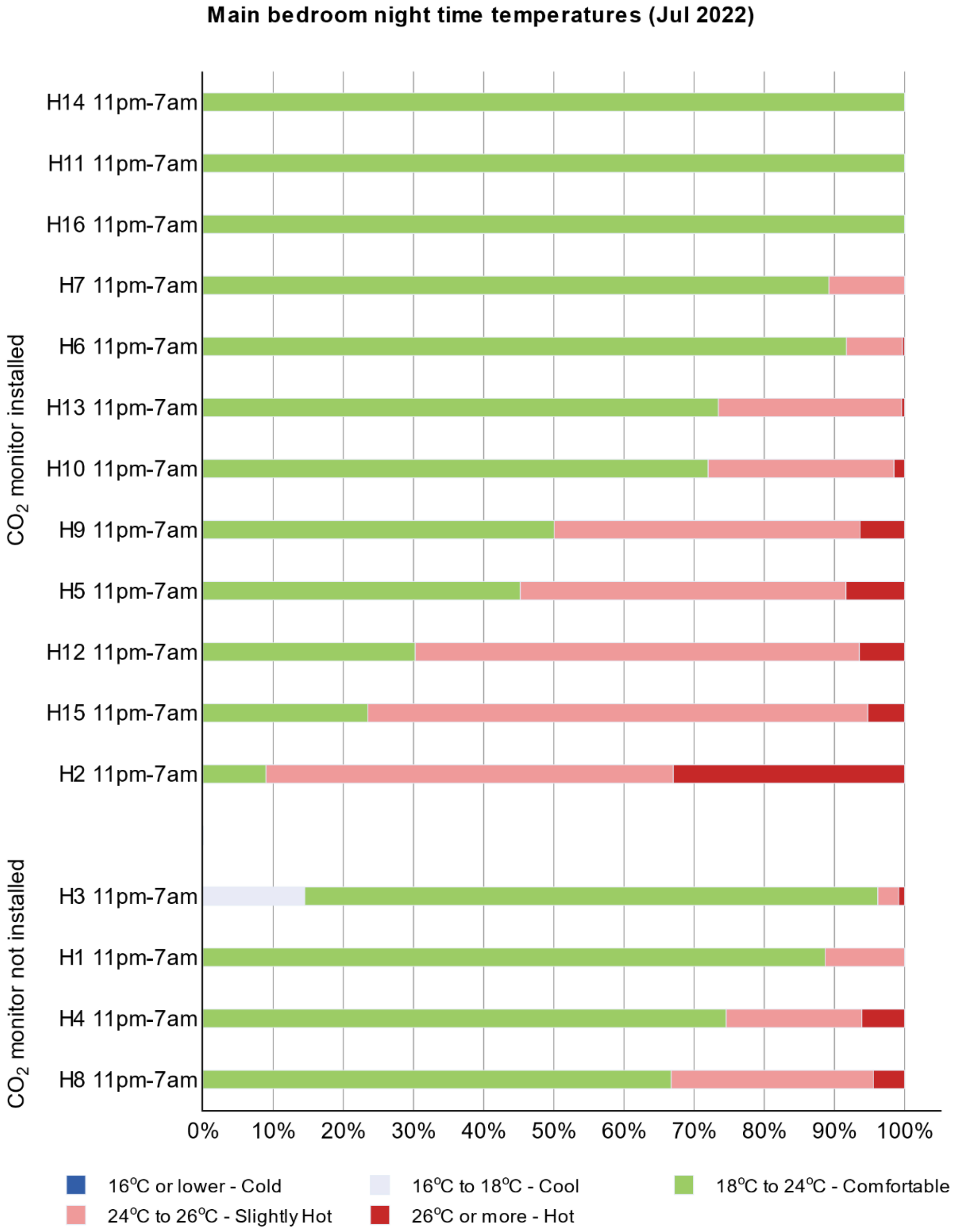

Figure 5.16 Summer period: temperature ranges in bedrooms at night.

Summary

5.35. The ventilation audit performed in 16 homes show that ventilation design is not adequately provided. The ventilation audit performed in 16 homes found that dMEVs extraction rates below government recommendation (13 homes), insufficient door undercuts (9 homes), unclear labelling of dMEV switches(6 homes), dMEV systems turned off (8 homes), and lack of ventilation advice (12 homes)[21]. Householders reported several concerns with the dMEV system, including noise, draughts, and costs of running. Some of these concerns were evidenced, in particular noise and draughts.

5.36. From the results of CO_2 concentrations in both living rooms and bedrooms in winter, spring, and summer it can be concluded that not all homes with CO_2 monitors installed maintain indoor concentrations below 1000 ppm. Long term monitoring (WP3) began in Winter 2022 on 16 homes. Seasonal analysis took place and data analysis during winter and spring evidenced 6 homes with indication of poor indoor air quality throughout the dwelling, despite the presence of CO_2 monitors in some of the bedrooms.

5.37. In terms of measured air quality throughout the 3 seasons, of the homes that were provided with CO_2 monitors (12 out of 16), the results of peak CO_2 concentrations in both living rooms and bedrooms in winter, spring were above 1000 ppm (see WP3-Chapter 5). Whilst it may be concluded that not all homes with CO_2 monitors installed maintain indoor concentrations below 1000 ppm, the underlying causes of this were driven more by the poor ventilation implementation and poor ventilation compliance.

5.38. For temperatures, it was found that during July 2022, several homes suffer excessively high temperatures. In H2, living room temperatures exceeded 26°C for more than 70% of the time and in H15 for more than 60% of the time. This is worrisome since both homes are occupied by vulnerable people. The low CO_2 concentrations recorded for that same period suggest that both homes (H2 and H15) opened windows to a great extent. In bedrooms, overheating assessment against TM59-criterion-2[22] showed overheating on 8 homes out of 16.

5.39. Whilst there is evidence that occupants use CO_2 monitors to take actions, for bedrooms this would be reactive (i.e. in the morning) and less likely to affects overnight conditions. Nevertheless, some of the households with CO_2 monitors (such as H2) did interact with the monitors various times a day.

5.40. Given that the homes surveyed were built to a higher standard of air tightness, the requirement of CO_2 monitors is further justified and needed.

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[21] Many homes reported not having received ventilation advice. However, after inspecting some of these homes' house manuals (where available), in some cases, written advice was provided. Nonetheless, it was noted that in many cases the householders felt it was not explained to them.

[22] TM59-criterion-2: for bedrooms only, from 10 pm to 7 am, operative temperatures shall not exceed 26°C for more than 1% of annual hours.

6. Detailed IAQ monitoring study

Aims and objectives.

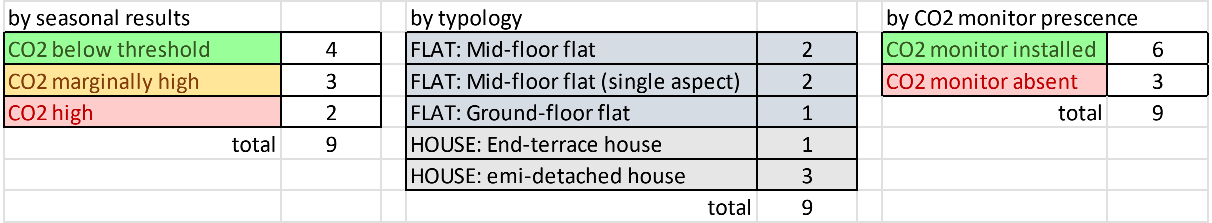
6.1. The aim of the detailed IAQ monitoring is to capture granular data on occupancy and behaviour. This includes the use of additional and specific pollutant monitoring equipment (see below section "*Description of monitoring set up*" for details). Detailed analysis of this data will examine the effectiveness of the regulatory measures that have been installed. This will provide information including indicative ventilation rates, comparison with threshold levels of IAQ, pollutants and environmental conditions such as temperature and moisture. It will also compare with this occupant comfort and energy use. It will use the data to examine use and effectiveness of the CO_2 sensor, occupant awareness, behaviours and examine impacts on IAQ and ventilation.

Homes selection and description

6.2. The original idea was to deploy such sensors in 4-6 selected homes to identify specific risks or activities (for instance, homes identified as poorly ventilated from WP3).

6.3. The seasonal (winter) report from the monitored data found various homes at medium and high risk of poor IAQ. Out of 6 homes performing poorly (i.e. homes with measured bedroom CO2 levels above the 1000 PPM threshold for most of the time) only 2 homes (H13 and H14) were included in the detailed monitoring. This is because some occupants were unavailable at the time of monitoring setup.

6.4. The detailed monitoring included a valuable mixed sample of homes whose seasonal (winter) analysis of seasonal results, typologies, and CO_2 monitors, as show in figure 6.1.



by seasonal results	
CO2 below threshold	4
CO2 marginally high	3
CO2 high	2
total	9

by typology	
FLAT: Mid-floor flat	2
FLAT: Mid-floor flat (single aspect)	2
FLAT: Ground-floor flat	1
HOUSE: End-terrace house	1
HOUSE: emi-detached house	3
total	9

by CO2 monitor prescence	
CO2 monitor installed	6
CO2 monitor absent	3
total	9

Figure 6.1 Homes included in the short-term monitoring sorted by various characteristics

6.5. It should be noted that among the well performing homes (i.e. homes with measured bedroom CO2 levels below the 1000 PPM threshold for most of the time, from the winter analysis) there is one Passivhaus flat and one single aspect flat with a smoker. The interest in performing short term monitoring of the Passivhaus flat is to assess the effect of the constant provision of fresh air through the inlets provided in bedrooms and living rooms on indoor pollutant concentrations. The single aspect flat with a smoker, on the other hand, provides an insight of a flat categorised as "well performing", though this result is influenced by the constantly open windows to remove smoke and odours.

Table 6.1 Homes included in the detailed term monitoring

Home ID	Carbon dioxide (CO_2) monitor	Postcode	Property Type	Dwelling Type	Total floor area (m^2)	Air Tightness (design)	Air Tightness (tested)	Mechanical Ventilation
1 (ex RR983)	No	G32 7BS	Flat	Mid-floor flat	76		0.4	MVHR
2 (ex RR1211)	yes	G43 1FF	Flat	Ground-floor flat	69	4		dMEV
3 (ex RR991)	No	G32 7BS	Flat	Mid-floor flat	55	4		dMEV
4 (ex RR1628)	No	G78 2BF	House	End-terrace house	74	4.5		dMEV
9 (ex RR12)	Yes	EH11 3US	Flat	Mid-floor flat	72		4.5	dMEV
11 (ex RR1560)	Yes	G73 2DS	Flat	Mid-floor flat	51	4		dMEV
12 (ex RR1386)	Yes	G53 6ER	House	Semi-detached house	95	4		dMEV
13 (ex RR1351)	Yes	G53 6EH	House	Semi-detached house	95	4		dMEV
14	Yes	G46 8AZ	House	Semi-detached house	96	4.5		dMEV

Description of monitoring set up and survey process

6.6. The monitoring set up consisted of the following three steps:

STEP 1 – Consent. Before beginning with any form of data collection, and in line with the ethical procedure put in place by the University of Strathclyde, researchers obtained signed consent from occupants for this specific detailed monitoring.

STEP 2 – Environmental Monitoring installation. The equipment used was provided by the company Duomo Ltd, marketed as LoRaWAN Wireless Indoor Air Quality Sensor. It is composed by a LoRawan multi sensor, a LoRa aerial and a gateway. The sensor measures temperature, relative humidity, carbon dioxide levels, pressure, tVOCs, PM1, PM2.5, PM4, PM10 and Typical Particle Size. These factors are monitored at 5-minute intervals. The equipment was installed only in the living rooms (i.e. one sensor per home). Equipment was placed near the TV for space convenience and to make sure that no sources of heat would affect readings. As for the long term monitoring, sensors were placed without drilling into walls and all equipment contained a label with a house code and the researchers contact details (see figures below).

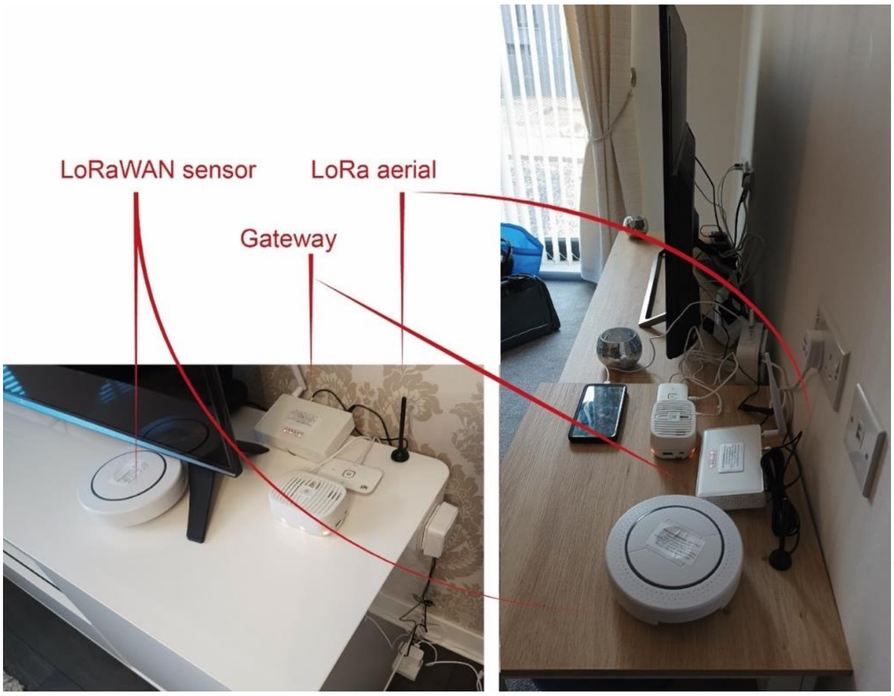
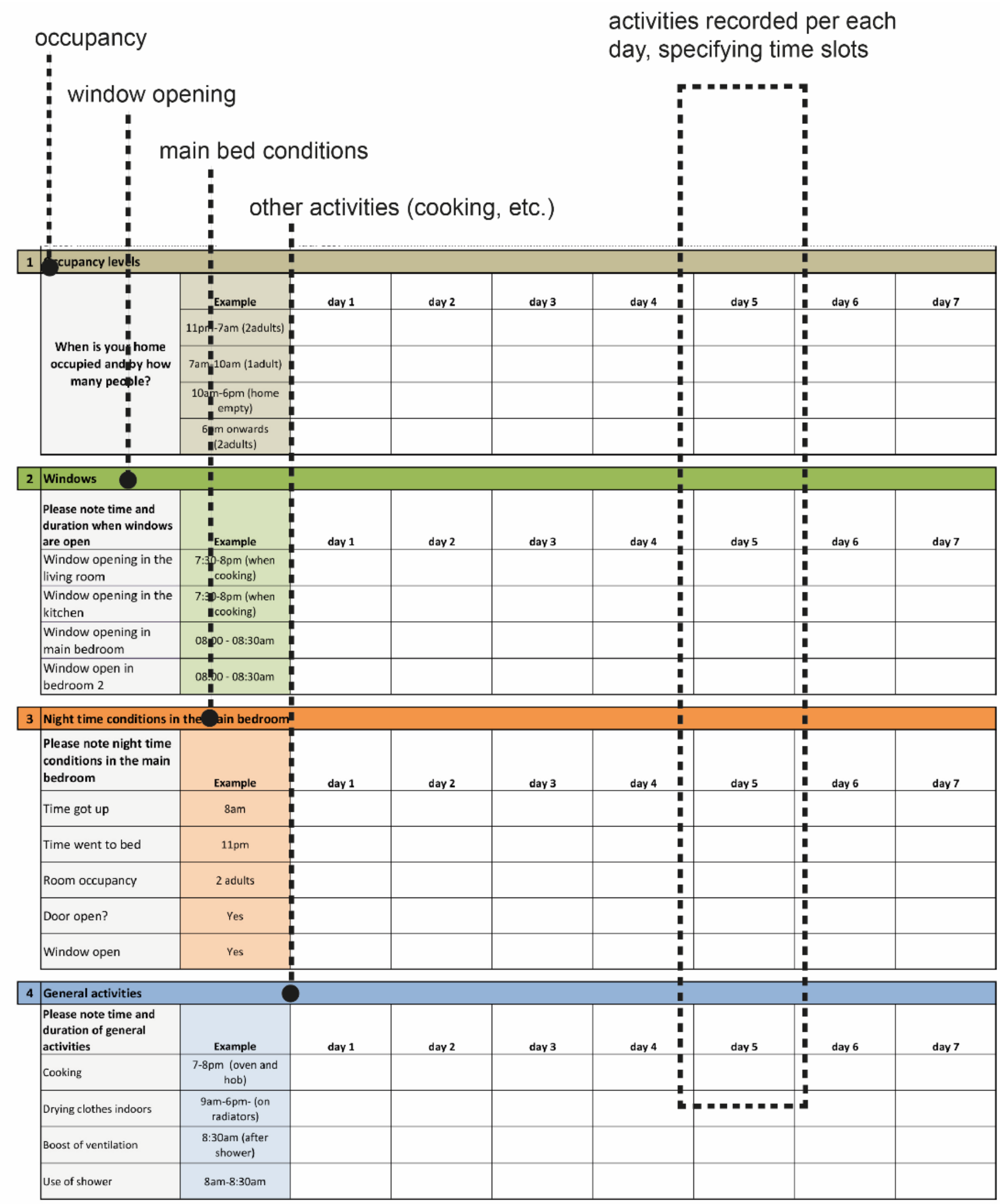


Figure 6.2 Pictures of equipment installed

STEP 3 – Occupant diaries. This step consists of the production of daily diaries for occupants that identify ventilation habits and activity for specific spaces. Occupant diaries were disseminated to occupants and occupants were briefed on how to complete these. A total of 3 copies were left in each home.

The occupant diary (figure 36) contained detailed daily questions about:

- dwelling occupancy;
- room window opening;
- main bedroom conditions: occupancy, night-time window and door opening;
- a general activities section, to record activities such as cooking, showering, drying clothes, etc.
- additionally, a blank space was provided to add any additional activity the occupants may want to highlight.



1 Occupancy levels								
When is your home occupied and by how many people?	**Example**	**day 1**	**day 2**	**day 3**	**day 4**	**day 5**	**day 6**	**day 7**
	11pm-7am (2adults)							
	7am-10am (1adult)							
	10am-6pm (home empty)							
	6pm onwards (2adults)							
2 Windows								
Please note time and duration when windows are open	**Example**	**day 1**	**day 2**	**day 3**	**day 4**	**day 5**	**day 6**	**day 7**
Window opening in the living room	7:30-8pm (when cooking)							
Window opening in the kitchen	7:30-8pm (when cooking)							
Window opening in main bedroom	08:00 - 08:30am							
Window open in bedroom 2	08:00 - 08:30am							
3 Night time conditions in the main bedroom								
Please note night time conditions in the main bedroom	**Example**	**day 1**	**day 2**	**day 3**	**day 4**	**day 5**	**day 6**	**day 7**
Time got up	8am							
Time went to bed	11pm							
Room occupancy	2 adults							
Door open?	Yes							
Window open	Yes							
4 General activities								
Please note time and duration of general activities	**Example**	**day 1**	**day 2**	**day 3**	**day 4**	**day 5**	**day 6**	**day 7**
Cooking	7-8pm (oven and hob)							
Drying clothes indoors	9am-6pm- (on radiators)							
Boost of ventilation	8:30am (after shower)							
Use of shower	8am-8:30am							

Figure 6.3 Picture of the occupant diary

6.7. The use of occupant diaries were instrumental in identifying whether occupants use of the alert system affected their awareness and use of ventilation, and whether this had resulted in improvements to indoor air quality in their home. Monitors were collected after the measurement period, along with the occupant diary.

Analysis

6.8. Analysis was carried after the monitors and diaries were collected. The aim was to identify poor indoor air quality in the surveyed homes, to examine pollutants presence in relation to the diaries and to examine the correlation between behaviour variables and measurements. Graphical summaries of key observations and findings were produced.

Table 6.2 Pollutants thresholds considered

Pollutant	**Recommendations related to health** WHO air quality guidelines 2005 guidelines - UK regulations - CIBSE TM40 recommendations	**short term threshold used**
PM10	• 20 µg/m3 - annual mean • 50 µg/m3 - 24-hr mean (Reduce as much as possible, as no safe level is known)	**50 µg/m3**
PM2.5	• 10 µg/m3 - annual mean • 25 µg/m3 - 24-hour mean (Reduce as much as possible, as no safe level is known)	**25 µg/m3**
Formaldehyde (a VOC)	100 µg/m3 - 30-min average	(included in TVOCs)
TVOC (as indicator)	300 µg/m3 - 8-hour average	**300 µg/m3**

6.9. Several previous studies have shown that CO_2 levels are directly correlated with TVOCs and negatively correlated with PM_{10} levels[23][24]. While good indoor air quality requires relatively high ventilation rates, if the external air is heavily polluted with PM_{10}, the challenge is reducing the concentration of pollutants of indoor origin while inhibiting the infiltration of external air pollutants, especially at locations where external particulate burdens are high (main road junctions where traffic may be regularly queuing).

6.10. The sub-set of 9 dwellings that underwent more detailed monitoring were selected to provide some comparisons between rural and urban locations and house type/ventilation regimes (4 dwellings were selected with relatively low CO_2 levels and 5 dwellings with CO_2 levels regularly on/exceeding the 1000ppm threshold). With such a small sample and a multiplicity of confounding variables (volume, occupant behaviour (smoking), construction type, location, air tightness, orientation, cooking facilities (gas v electricity) and furniture, fittings and fixtures), any comparison between data sets should not be considered as statistically significant and extrapolations or generalisations should therefore be avoided. The monitoring was restricted to 14 days in March/April and external weather conditions may also have had an impact on occupant behaviour. The effects of outdoor temperature and wind conditions, that can play a major part in particulate concentrations, were not monitored and therefore any possible impacts cannot be accounted for in the analysis. The data sets do, however, give some insight into the relationship between internal air change rates, pollutants being generated internally and those that may be infiltrating from external sources (fuel combustion).

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[23] Howieson, S. G., Sharpe, T. & Farren, P (2014) How are new air tightness standards affecting indoor air quality in dwellings? *Building Services Engineering Research and Technology*. 35, 5, p. 475-487 13 p. Building tight – ventilating right?

[24] Stamp S, Burman E, Shrubsole C. et al (2021) Seasonal variations and the influence of ventilation rates on IAQ: A case study of 5 Low-Energy London Apartments.

Results

6.11. The complete survey results can be found in Annex D.

6.12. In general, the dwellings maintained CO_2 levels below the target threshold of 1000ppm and the relationship between CO_2 and TVOC concentrations was found to be closely correlated. The relationship with PM levels however is more complex as several dwellings had a combined living/kitchen configuration and particulate matter from cooking (either smoke or gas combustion) produced a notable rise in the levels around meal times.

Example 1: H1

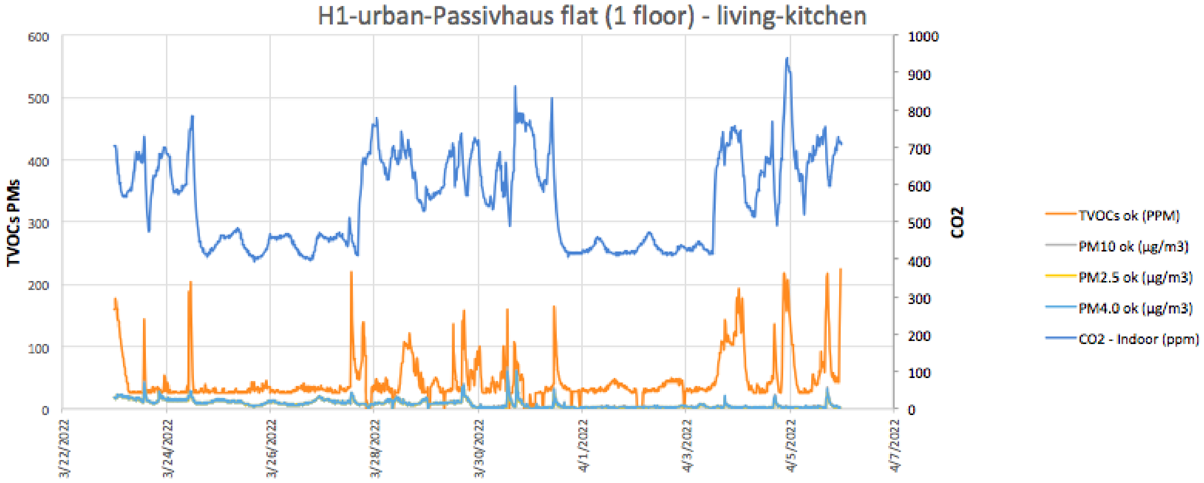


Figure 6.4 Example 1: H1

6.13. The graph shows that the whole house ventilation system maintained CO_2 levels well below the threshold for poor IAQ of 1000ppm. The occasional peak in TVOC levels closely followed CO_2 concentrations and occurred during typical mealtimes. PM_{10} levels were relatively low in this home despite it's urban location, suggesting that the MVHR system had an effective air filter. Although there is no known safe threshold for PM_{10} levels, the average concentration was well below the 20 ug/m^3 benchmark, with levels only rising above the short term 50 ug/m^3 for circa 30 minutes over the entire 14-day period, and this is again likely to be associated with cooking activities. The MVHR system maintained CO_2 levels well below the 1000ppm threshold. This is in contrast to the dMEV systems, that did not appear to be quite as effective.

Example 2: H13

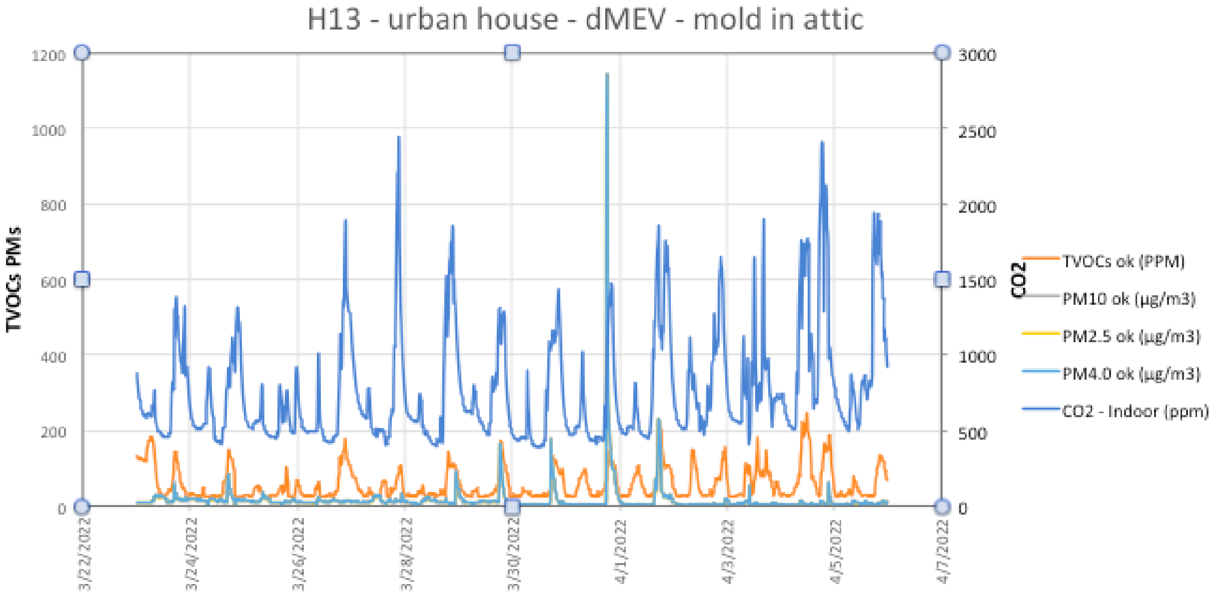


Figure 6.5 Example 2: H13

6.14. The graph shows that the dMEV system in H13 was unable to keep the CO_2 levels consistently below the threshold of 1000ppm (average 875 ppm) with many peaks above 1500ppm. H13 was unoccupied for most days during 8.30 until 3 pm. TVOC levels closely followed CO_2 concentrations and peaked when cooking activities were being undertaken. PM_{10} levels were low for an urban environment and associated with cooking times. This would suggest that the major source of particulate matter in this home was smoke from cooking or methane combustion.

Example 3: H11

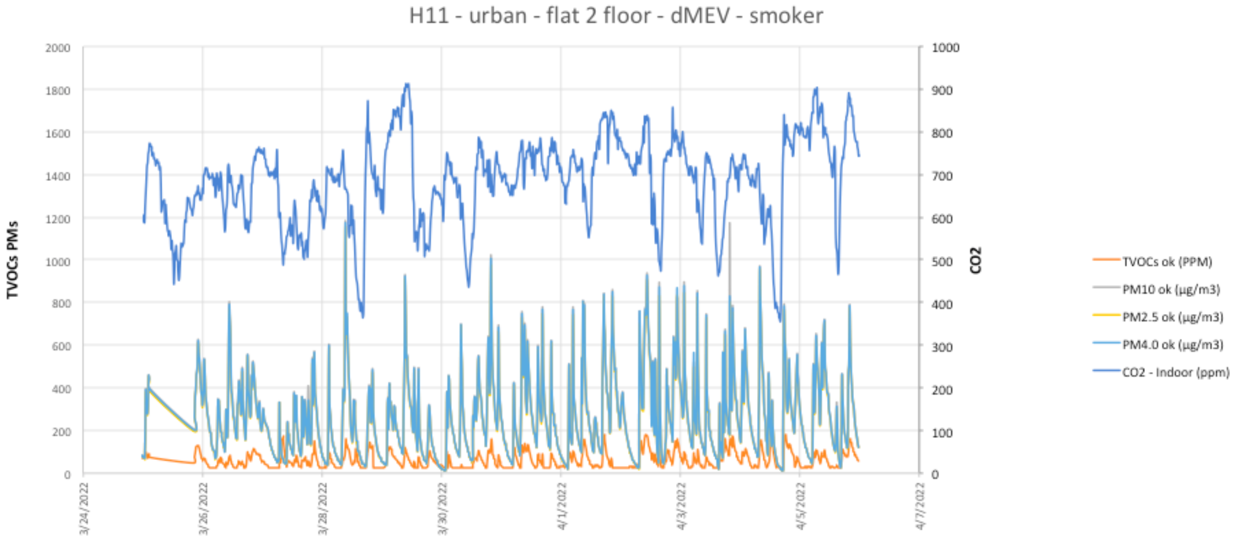


Figure 6.6 Example 3: H11

6.15. H11 was occupied at all times during the detailed survey. Windows were reported to be open 24/7 to mitigate the occupant's heavy smoking habits (there is no specific information on times smoking occurred indoors). No specific information was collected to times when the occupant smoked. Smoking in H11 is clearly a major factor affecting PM_{10} concentrations despite the ventilation system maintaining CO_2 below 1000ppm. Air change rates would therefore have to increase significantly to extract this level of internal particulate pollution.

Example 4: H14

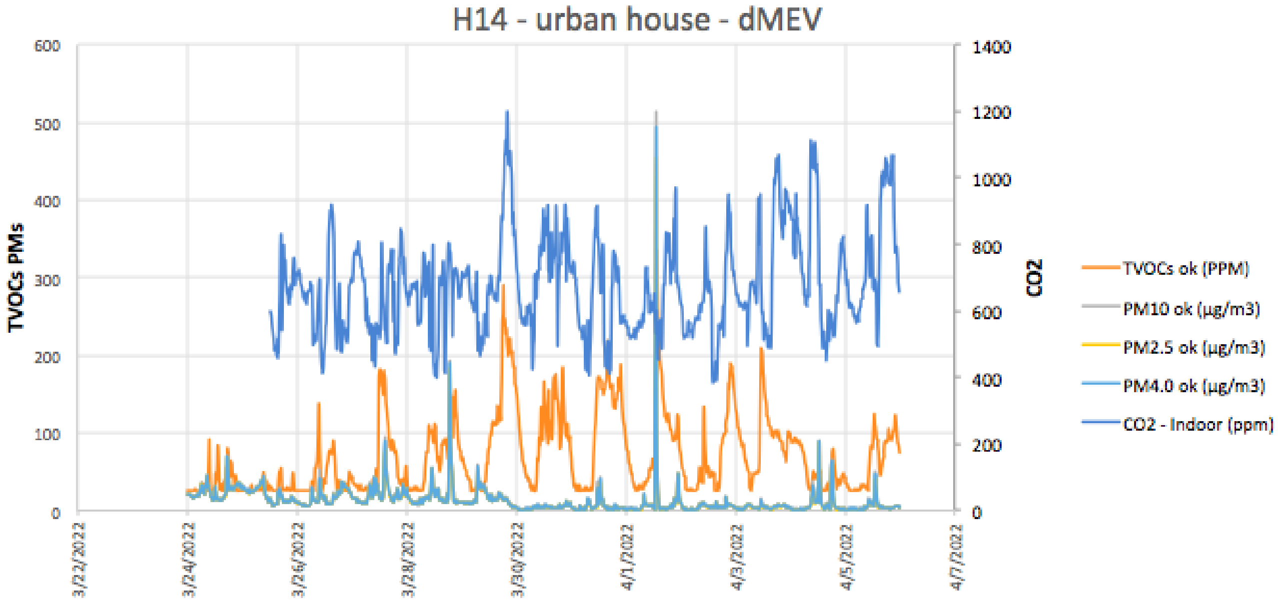


Figure 6.7 Example 4: H14

6.16. Most of the dwellings under the more detailed monitoring regime have TVOC levels that would be considered to be relatively low (i.e. under 300ug/m^3). As many dwellings have open plan kitchen and living rooms, the levels tend to rise when cooking is taking place as VOCs copen plan kitchen or living room and TVOC levels have a closer correlation with CO_2. When the CO_2 level reaches 1000ppm we can note that TVOC levels are on occasion approaching the 300ug/m^3 threshold.

Summary – What can we take from these results?

6.17. MVHR and dMEV systems are relatively effective in maintaining internal CO_2 levels below the target threshold of 1000ppm.

6.18. TVOCs are positively correlated with CO_2 however, levels were generally below the recommended threshold of 300 ppm. It is worth noting that TVOC cannot provide an indication of health effects, as it doesn't measure VOCs individually.

6.19. The PM levels did not have a particularly strong negative correlation with CO_2 levels across all 9 dwellings. This would suggest that external traffic pollution was not a major factor over the monitoring period due either to the dwellings' suburban locations or relatively high wind speeds effectively dispersing localised traffic fumes. The particulate matter, if anything, had a positive correlation during periods where cooking was likely to be taking place. This of course could be dealt with by better wet zone extraction (cooker hoods).

Future research

This small sub-set did not demonstrate a problematic negative correlation between PM_{10} particulates and air change rates than many studies have shown to be in operation in heavily polluted urban environments (see literature review). It remains unclear as to whether this was primarily due to the dwellings location and external weather conditions dispersing pollutants. There were no significant differences between the urban and rural dwellings. This result requires further measurement to compare urban and rural locations and classify the type of particulate matter and VOCs that may be both infiltrating and off-gassing.

7. Industry workshops

Aims and objectives.

7.1. The aim of the detailed industry workshop is to gain an understanding of industry awareness and use of the 2015 requirements. This includes collection of data from industry participants, including designers, contractors and building control officers, through an industry workshop to establish in more detail how guidance is being interpreted by designers, the design solutions being implemented, and design methodologies being used.

7.2. The industry workshop was conducted (with BSD approval) at later stages of the project, to present the findings of the research, and to identify and scope out further revisions or changes with the industry's input.

7.3. The industry workshop was organised through the Scottish Federation of Housing Association (SFHA) online platform ("webinar"). Researchers provided SFHA with information in order to publicise the online event and gain a broad audience. The information provided to SFHA is listed below and the leaflet is shown in figure 7.1.

Title: Understanding the role of ventilation in healthy homes

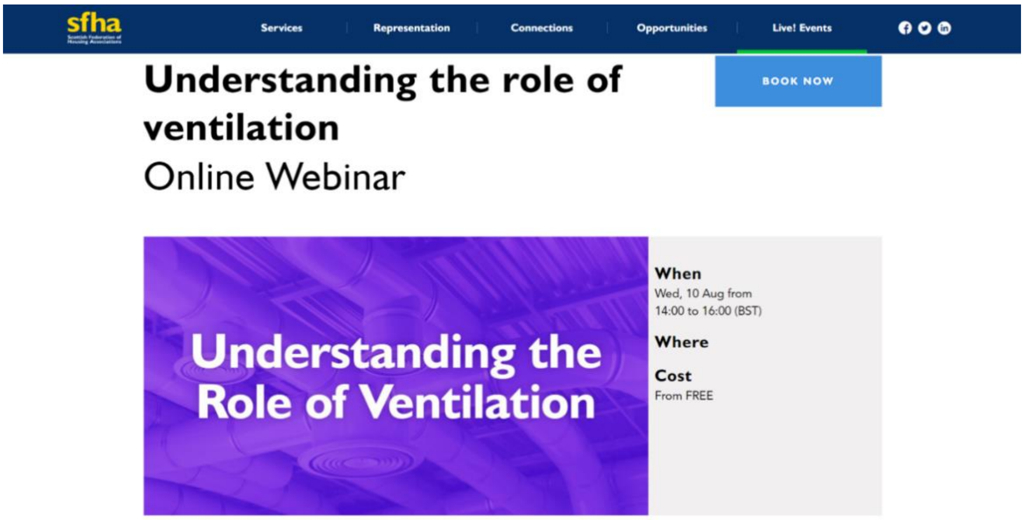
Brief : The University of Strathclyde on behalf of the Building Standards Division has been conducting research to understand if changes to guidance in Standard 3.14 Ventilation in the 2015 Building Regulations have been effective in improving ventilation practices and indoor air quality.

Come along to find out more about the preliminary findings from the research team and the key learnings for social landlords in managing indoor air quality, supporting healthy living environments and providing appropriate advice to tenants.

Benefits of Attending:

- Understand the role of ventilation practices in improving indoor air quality
- Learn about the key findings from ongoing academic research
- Discuss approaches to engaging with tenants on ventilation
- Discuss how the design guidance is being used at the design stages and to identify potential improvements.

Target Audience: Asset managers, housing officers, energy advisors, designers, contractors, building control officers. This event is open to non-members.



Understanding the role of ventilation
Online Webinar

When
Wed, 10 Aug from 14:00 to 16:00 (BST)
Where
Cost
From FREE

Figure 7.1 Leaflet promoting workshop [25]

Structure of the workshop

7.4. The industry workshop was organised in two parts. The first part focused on presenting the BSD project and presenting key interim results from the household survey. The second part of the workshop consisted of a focus group with the audience to explore industry's view of the introduction of the CO_2 monitors. Table 7.1. presents the workshop structure.

Table 7.1 Structure of the industry's workshop

14:00		Welcome and house keeping	Cassandra Dove
PART I: BSD research to identify if changes to guidance in standard 3.14 ventilation in 2015 have been effective in improving ventilation and indoor air quality			
14:05		Introduction to the project and expectations for the day	Prof. Tim Sharpe
14:15		Presentation of the household survey results	Dr Linda Toledo
PART II: Focus group The audience will be asked some questions through the zoom chat, and they are invited to respond verbally (by raising their hand first) or via chat (responses will be read by one of the researchers). Each question will be allocated 15-20 minutes max.			
14:35		With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided… ❖ Q1-what is your perception of that regulation? ▪ are you confident that your department has the knowledge of CO_2 monitor requirement? ▪ are you confident that CO_2 monitors are being installed?	Dr Grainne McGill

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[25] SFHA (2022). *What's on*. Available at https://www.sfha.co.uk/whats-on/event-details/understanding-the-role-of-ventilation

		❖ Q2-Have you encountered resistance from occupants to install CO_2 monitors? ▪ has the installation of CO_2 monitors resulted in any complaints from occupants? ▪ Or has it helped to identify any problems? ❖ Q3-What is been done to explain the CO_2 monitor to occupants? ▪ what instructions are provided to occupants?	
15:35		Sum up conclusions and closure	Prof. Tim Sharpe

Workshop

7.5. The workshop was well attended (48 delegates in total, excluding organisers and presenters), thanks to the marketing and support provided by SFHA. The audience was composed by a mix of government / local authority representatives, housing associations and construction professionals, as illustrated in Figure 7.2.

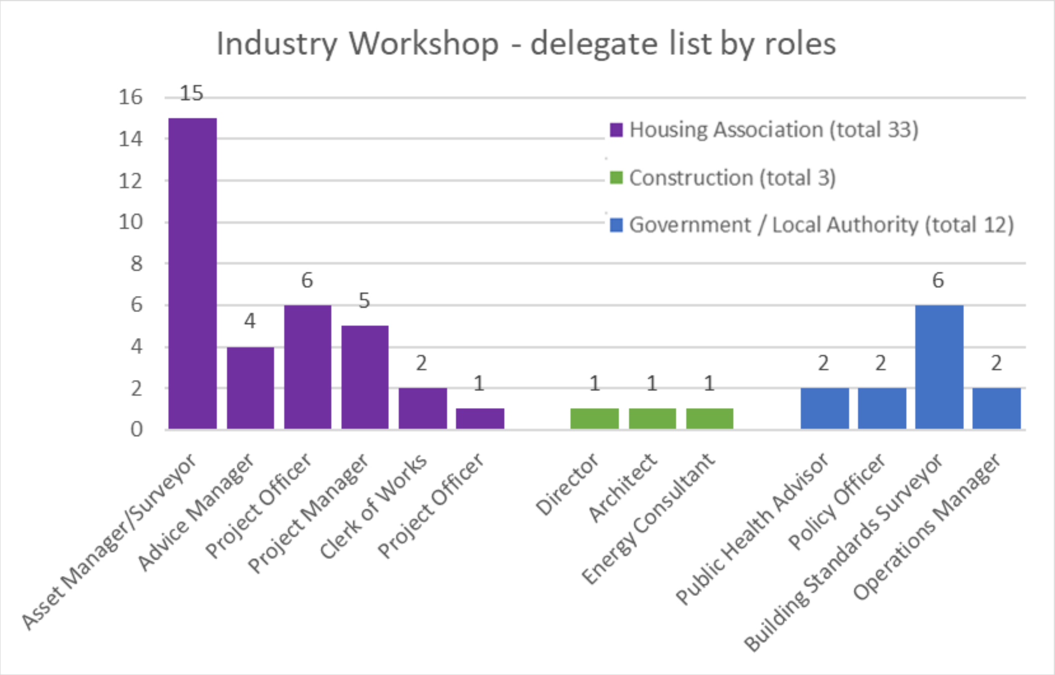

Fig. 7.2 Delegate list by sector

7.6. The findings from the industry workshop are discussed below. The focus group was recorded and is privately accessible in the SFHA YouTube channel.

Q1: With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided, what is your perception of that regulation?

7.7. In response, participant 1 from the Scottish Government (P1-gov) stated that a possible reason for non-compliance may lie in the fact that the building warrants of households contacted might have been submitted prior to the changes to building regulation Standard 3.14. The same participant also explained that despite having 3 years to build after approval, such time is often extended. As a result, some of the addresses contacted may have had their building warrants submitted just before the introduction of changes in October 2014, which would help to explain the high level of non-compliance observed.

7.8. The research team investigated this possibility through communication with a member of Building Standards referred by Mr Thomas Lennon (Alan McAulay from the Building Standards Hub Director). Out of the 16 homes monitored in WP3, those with no CO_2 monitor (4 in total) provision were further investigated to verify building warrant submission.

7.9. Mr McAuley checked the date of building warrant submission of the 4 monitored homes with no CO_2 monitor. He confirmed that 4 out of 4 addresses had their building warrant submitted before the changes to the regulations introduced on 1st October 2015 and henceforth did not require to provide CO_2 monitor (see fig. 7.3). These 4 homes were highlighted in the WP3 chapter seasonal analysis. Besides one that is Passivhaus, the other 3 homes with no CO_2 monitors were performing poorly in winter and spring. However, a direct comparison with those built post 2015 could not be drawn.

House code	typology	Date of warrant submission	Application reference	Description of work
H1	1 bed flat CONVERTED	23-Apr-14	14/01013/BW	Global - Conversion, alteration and extension to former church and hall to form 19 dwellings.
H3	2 bed flat (NEW PASSIVHAUS)	As above	As above	As above
H4	2 bed flat	08-Sep-2015 (made valid)	2015/0771/ERD	Erection of 154no. Dwellinghouses and associated works
H8	2 bedroom flat	18- Sep-2015 (made valid)	15/04051/STAGEA	Erect 31 flats - foundations, underground drainage, substructure up to DPC level (CERTIFICATE Q RECEIVED)

Fig. 7.3 Investigation of warrant submission of 4 monitored homes

7.10. Participant 2 from the construction sector (P2-const) brought to the discussion the conflict between regulation requirements, such as fire doors that must be kept closed and ventilation. This is especially relevant if considering that door undercuts were found to be insufficient (i.e. < 8,000mm^2) in 9 out of the 16 homes monitored under WP3. Participant P2-const also highlighted the fact that the 2015 Ventilation Regulations are based on a room-by-room ventilation analysis and not whole house analysis. He explained that the British Standards requires a whole house because it results in better performance, and henceforth the Royal Incorporation of Architects in Scotland (RIAS) has developed a practice notice [26] with a strategy flow chart for Section 3.0 Guidance to select the correct strategy and that could be useful in case for the building requirements change to a whole house strategy.

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[26] RIAS Practice Information for Chartered practices. (2016) *OS1612: Ventilation Design Strategy – Flowchart Section 3.0 Guidance.* Available at https://rias.org.uk/for-practices/practice-notes

Are you confident that your department has the knowledge of the requirement for CO_2 monitoring? Are you confident that CO_2 monitors are being installed?

7.11. Participant 1 from the Scottish Government (P1-gov) reminded of the multiple energy efficiency measures introduced at the time that building controllers had to absorb in a short amount of time. They also reminded that just in 2013 the requirement to use CO alarms was introduced.

7.12. To question 2, participant 3 from a housing association (P3-ha), stated that they, as a housing association, do perform the checks to verify that CO_2 monitors are installed. They also confirmed that their housing association do explain to occupants how the CO_2 monitor is to be used and how to engage with the trickle vents. They try to create a partnership with tenants and, on this basis the housing association is interested in explaining to tenants to get them more engaged. This participant is from a housing association in Skye where humidity levels are extremely high, therefore tenants must be better at ventilation and humidity management. He stated that they would also like to have humidity sensors so that tenants are more observant and more in control of their indoor environments.

Q2. With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided, have you encountered resistance from occupants to install CO_2 monitors? has the installation of CO_2 monitors resulted in complaints from occupants or has it helped to identify any problems?

7.13. Participant 4 from a housing association (P4-ha) explained they regularly adopt a whole house ventilation strategy claiming they didn’t have any issues from occupants, but he stated that they as a housing association would not build without a whole house ventilation system with heat recovery.

7.14. Participant P3-ha underlined those homes equipped with less known technologies, such as air source heat pump, have a much higher level of engagement,

7.15. Participant P4-ha explained that on occasions they receive phone calls from tenants which they use as opportunity to ask questions and to check if they are having any issues with the ventilation system. He stated that they do an annual service in which they revisit the ventilation systems with the occupants.

The audience was asked whether there has been any reported cases of people confusing CO_2 monitor with CO alarm sensors.

7.16. Participant 5 from the construction sector (P5-const) highlighted the fact that in the case of retrofits they haven’t been fitted CO_2 monitors. He stated that because CO_2 sensors are located in the bedroom and CO monitors in the kitchen, it should not represent an issue. It should be highlighted however that this is not always the case, for instance in flats that have a boiler in the bedroom (e.g. case study H4).

Q3: With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided, what is been done to explain the CO_2 monitor to occupants? What instructions are provided to occupants?

7.17. Participant 5 from the construction sector (P5-const) explained that on day 1 of moving in, tenants receive 3 large packs of information: one pack from the housing officer on tenancy regulations and obligations, one pack from the development department, covering the basics aspects of the property, including utilities, fire doors, thermal performance, general advice on how to get the best out of the building and advice on fire prevention, and finally one pack of information from architects or contractors covering the **technical** aspects on how to use the components of the property, which is not ideal as the tenant is mostly concern with moving in.

7.18. Participants P5-contr and P4-ha stated that some housing associations perform follow ups with tenants, after 6 weeks, 8 weeks or 3 months. These follow ups are called *settlement visits* or *tenancy sustainment* and their aim is to ask tenants how well they are settling in. Participant P5-const stated that this is probably the best opportunity to reinforce information on how to get the best out of the building. This point was reinforced by participant P4-ha, who also stressed the importance of the *technical induction* which is best done after the tenants have lived in the property for a period of time.

Participants were asked how they explain the traffic light system of the CO2 monitor

7.19. Participant P4-ha explained that housing officers must first explain at a level that people can understand so as not to generate anxiety. He stated that in northern parts of Scotland the humidity levels are 12%-13% higher which often results in instances of mould, especially in bedrooms. He stated that, especially in older buildings, there is a real tension between humidity management and indoor air quality.

Participants were asked if CO_2 monitors should stay in the building regulation

7.20. Participant P5-const brings the reflection that in case of MVHR, and in the case of power cuts. This makes further sense if we think that homes might be required to be equipped with MVHR.

7.21. The discussion moved to fuel poverty and the effects it may take in rural areas with no gas provision as opposed to urban areas. Participant P4-ha elaborated on providing access to tenants to clear their own MVHR filters. He also claimed that doing this would require extra $2m^2$ to each flat to be able to access their own which added much financial fear.

Summary

- The low compliance issue was further investigated thanks to the points made during the focus group. During such further investigation it became clear that many homes in the list of 200 addresses built in 2019 may not have been constructed to 2015 regulations. That notwithstanding, it remains an issue if Building regulations change, such changes can take up to 5 years to be built. This also generates some form of injustice between the large and the smaller development, with larger developers with land banks and greater resources able to more readily stage warrant applications. This practice will also slow progress to the delivery of new standards and performance

- Another aspect of compliance discussed in the workshop is the lacking provision of advice on how to use the CO_2 monitors. Tenant engagement from small housing associations was confirmed through the workshop, though it remains unclear why there is little guidance delivered to tenants, despite the requirement for Quick start guides being in place before changes to Standard 3.14 Ventilation. For those who delivered advice effectively (i.e. not on the day or moving in, after several weeks and repeatedly), it became clear the crucial role that social landlords have on both securing tenant understanding and on performing regular checks to the ventilation systems, which is lacking in the private sector.

- It can also be concluded that participants have not had any obstacles or complaints from occupant regarding the installation of the CO_2 monitor. Occupant complaints have not been a barrier. However technical inductions should be avoided on the day of moving in and they should be repeated periodically to verify that instructions are understood and that systems are working properly.

- There is some evidence, both from the survey but also the workshop about confusion between CO and CO2 monitors.

8. Conclusions

8.1. This research gives an insight of the effect the 2015 changes to guidance in Standard 3.14 have had on ventilation design, on occupant interaction and experiences on ventilation systems, on measured indoor quality.

8.2. The first objective was set out to identify to what extent ventilation systems installed following these changes achieve the minimum recommended ventilation performance and where dwellings do not, identify the root cause(s) of this non-compliance.

Ventilation provision and information

8.1. Whilst study cohort had a limited number of properties that were equipped with the sensor, and a smaller number that has information on their use, the study found clear evidence of use of the monitors to help manage ventilation and their inclusion in standards is justified.

8.2. However, the research gives evidence that CO_2 monitors on their own do not constitute a mitigating strategy for healthy indoor environment. Further support is required for the provision of advice on information about the purpose of the sensors, and actions which may be taken to improve ventilation

8.3. The ventilation audit performed in 16 homes show that ventilation design is not adequately provided, providing evidence of compliance issues. The ventilation audit performed in 16 homes found that dMEVs extraction rates below government recommendation (13 homes), insufficient door undercuts (9 homes), dMEV had no clear labelling of switches (6 homes), dMEV systems turned off (8 homes), and lack of ventilation advice (12 homes). Reported issues with dMEV were noise, draughts, costs of running.

8.4. The ventilation audit depicted a landscape of ventilation systems that may not be able to achieve healthy indoor environments. On this premise, the requirement of CO_2 monitors can aid occupants to spot if anything is wrong and manage or ask for advice in the case of council or housing association rented homes.

8.5. To secure an adequate provision of ventilation, ensuring flow paths (trickle vents open, adequate door undercuts and dMEV properly working) has proven to be a challenge. In fact, only 1 out of the 14 homes built to 2015 Standards (within the 16 surveyed homes) met the 2015 standards in their entirety. Moreover, in the few cases where the system did meet standards, the system remains vulnerable to occupants' interaction (dMEV turned off due to noise, undercuts reduced by carpets, trickle vents closed due to drafts). The exception and comparison was the Passivhaus dwelling.

8.6. Whilst this may indicate a benefit of MVHR, other standards of construction and performance are better demonstrated through a Passivhaus approach. During the industry workshop there was discussion of other vulnerabilities that MVHR systems may carry during building use, such as loss of power supply and MVHR maintenance (filter cleaning), with concerns raised that if the industry is unable to provide simple mechanical systems, there may be inherent risks in more complex systems without a more robust compliance and maintenance requirement.

8.7. The long term monitoring component of this study (WP3) illustrates that is still a critical number of homes with sub-optimal conditions in homes. The ventilation survey showed that many dMEV systems were not to specification as well as many were turned off (due to cold and noise concerns). Given that the homes surveyed were built to a standard of airtightness where improved ventilation provision is required (compared to the traditional housing stock) - the requirement of CO_2 monitors is further justified and needed.

Implementation of published solutions/guidance

8.8. The second objective was set out to identify how guidance is being interpreted by designers, the design solutions being implemented, design methodologies being used, the performance of these design methodologies in practice including end user perceptions and delivered indoor air and environmental quality, and to identify where potential improvements to guidance are required to deliver robust solutions.

8.9. The large postal survey (WP2) provided suggested an apparent lack of compliance to provide CO_2 monitors in households with them being present on in 59% of the households.

8.10. Further investigation following feedback from the industry workshop (WP5) found that for homes with a 2019 energy certification (EPC, issued on completion), there is no guarantee that the building was constructed to 2015 regulations, as building warrants may have been submitted prior to 1 October 2015 (date of changed to the regulations). In fact, when investigating further the 4 homes under long-term monitoring that did not have CO_2 monitor, the search concluded that for all 4 homes, building warrants were submitted before changes to the Standard. This supports the hypothesis raised during the workshop.

8.11. The change process and development lag for building regulations is known and is identified in any supporting Impact Assessment to provide adequate lead-in time before new requirements are imposed on the construction sector and the practical need to build out projects already submitted/approved. The evidence from the workshop is that this may be used as a cost-saving exercise, and will necessarily impact on the rate of implementation of new standards and consequent Government targets for energy reduction and improvements in ventilation provision. Lack of adoption of new regulations for homes being built up to 4 years after construction seems excessive and measures to reduce or avoid this would therefore be useful. Once aspect of this is that there was no evidence that homeowners were aware of the standards to which their homes had been built, so a requirement for this to be provided may aid transparency.

8.12. The issue of provision of advice was discussed during the industry workshop. The survey has indicated a general lack of advice, on ventilation provision in general and on CO_2 monitors in particular. It was considered that the process to provide technical induction and with it the ventilation advice should be provided at an appropriate time and followed up on. In this respect, the role of the social landlord is potentially major, since they have a direct interest of a two-way communication with tenants for a properly managed home. The private sector instead lacks that continual engagement. However, there was also limited evidence of the use of Quick-start guides observed through the household survey. Whilst in some cases these were provided, as observed through the monitoring setups, they accompanied large amounts of other information provided at hand-over.

Assessing indoor environmental performance in practice.

8.13. The third objective was to establish indoor environmental performance and how this relates to occupant interactions with available means of ventilation, such as trickle ventilators, windows, doors and extract fans in dwellings constructed under the 2015 building regulations and Technical Handbook guidance through: identification of a large sample of representative dwellings, a broad snapshot study of more than 200 to establish system types, occupant perceptions and monitored performance, and perform in-depth monitoring of at least 20 dwellings for a period of 12 months.

Measured indoor quality

8.14. In terms of measured air quality, of the homes that were provided with CO_2 monitors (12 out of 16), the results of peak CO_2 concentrations in both living rooms and bedrooms in winter, spring were above 1000 ppm (see WP3-Chapter 5). Whilst it may be concluded that not all homes with CO_2 monitors installed maintained indoor concentrations below 1000 ppm, the underlying causes of this were driven more by lack of system compliance identified in Section 5:10.

8.15. The results of temperature monitoring indicated instances of overheating in 6 homes during July 2022. There is scope to further examine such homes and the influences of design (layout, orientation, construction materials, etc.) on indoor temperatures but this was not evaluated as part of this work.

8.16. Restating what was found in the literature review, balancing the needs of both energy efficiency and IAQ particularly in small single aspect family flats, may prove to be an intractable problem unless a properly working and well-maintained MVHR system is used. However, given the apparent challenges with implementation of simpler ventilation provision, more robust standards for design, installation, compliance, and-over and maintenance would be required.

8.17. Inefficient ventilation provision was found also in lofts. Even though these are beyond the scope of this research project, mould growth in two of the monitored homes from the same development suggests that constructors and developers are overlooking at these spaces exposing occupants to health hazards. Further research should verify to what British Standard these homes have been constructed. At the moment Section 3.15

Condensation of the Building standards technical handbook 2020: domestic reads: “3.15.3 Control of condensation in roofs. Section 8.4 of BS 5250: 2002 provides guidance on the control of condensation in the principal forms of roof construction. Clause 8.4.1 of BS 5250 lists various issues that should be considered in the design of roofs to reduce the possibility of excess condensation forming that might damage the building and endanger the health of the occupants.”[27] It should be noted that the BS 5250: 2002 has been withdrawn by versions 2011, first, and recently by BS 5250:2021[28] which requires for vents to be provided on warm roofs. The 2002 document was unretrievable therefore it remains unclear the reason for avoiding the use of roof vents in the affected homes.

8.18. In addition, such short-term monitoring showed no difference in PM levels suggesting that external traffic pollution was not a major factor over the monitoring period.

Occupants’ awareness and interaction with their ventilation systems

8.19. The large household survey (WP2) provided comparable insights to a baseline study from 2014. In terms of occupant use of the ventilation systems (windows and trickle vents) a significant improvement in occupant engagement was found, compared to the 2014 study (Sharpe et al. 2014). Specifically, a noticeable increase in reported trickle vent opening was identified (more than double then 2014 study).

8.20. In terms of trickle vent opening frequency, respondents largely (75%-living room and 69%-bedroom) left them open all of the time while a small portion (13% in living room and 12% in bedroom) left them open. This figure is in contrast with the responses obtained during the 2014 study submitted depicting a noticable switch between “open all the time” (around 25%) and “never open (around 60%)”.

8.21. This shift in trickle vent opening is not supported by an increase in ventilation advice, which suggests other factors may be at play. In fact, among the drivers for window opening in the bedroom we find a noticeable increase in choices of driver “open for fresh air” in the bedrooms (from less than 5% in the 2014 study to 40% in the current study).

8.22. Since the previous study there may have been a general increase in awareness of ventilation. However the COVID-19 pandemic may also have impacted, with Government and Public Health messaging about the importance of ventilation. The main drivers for ventilation were to provide

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[27] https://www.gov.scot/publications/building-standards-technical-handbook-2020-domestic/3-environment/3-15-condensation/

[28] BSI Standards Publication.. BS 5250:2021 Management of moisture in buildings — Code of practice. 2021

"fresh air" as one of the main drivers for window opening (40%-bedroom and 33%-living room) and rooms being "too warm" (26% in both bedroom and 3 living room).

8.23. In terms of barriers for ventilation, reasons to not use trickle vents are "noise" (11%-bedroom and 18%-living room), "draughts" (20%-bedroom and 15%-livingroom), and "don't feel the need to" (22%-bedroom and 31%-livingroom). When it comes to windows, the main barriers for window opening are "heat loss" (26% in both bedroom and living rooms) and "noise" (23%-bedroom and 20%-living room).

8.24. From the above, there is some evidence of an increased need-to manage indoor air quality. In fact, when asked about their perception of their indoor environment in the household survey, 3% found the quality of the air very poor in bedrooms, when in the previous household survey 2014, this figure was 0%. Although 3% is not a significant increase, when asked "Is there anything that could improve the ventilation in your house?", of the few responses (18) obtained, the majority of responses relate to a need for increased ventilation, whether that is via more air volume or accessible/secure windows (50% of responses).

8.25. Within the survey, of those homes that had a CO_2 sensors, there was a significant proportion (45%) who reported using these sensors at least weekly, and 80% of respondents reporting undertaking activity – primarily window opening – as a result of this. Whilst the size of the study and the underlying issues of compliance means that there is a not a clear demonstration of an effect of this activity, it nevertheless indicates that the introduction of the sensors has increased awareness and interaction, albeit limited by advice and ventilation provision.

Doing research during the pandemic

8.26. As a result of the COVID-19 pandemic, timescales had to be shifted and methods of data collection adapted to accommodate restrictions posed at a national level. That notwithstanding, home occupants showed outstanding interest in the research and trusted researchers' protocols to avoid transmission.

9. Recommendations

9.1. In terms of the key research question, the study found clear examples of benefits derived from the provision of the CO_2 sensors, including increased awareness of air quality and use of the sensors to inform ventilation behaviours. There was no evidence seen of negative impacts, in terms of increased complaints. It is therefore recommended that the provision of CO_2 sensors should be maintained. The monitoring indicated that poor ventilation remains prevalent in bedrooms, but there were also instances of poor ventilation in other occupied rooms. A limitation in bedrooms is that the insights are retrospective as occupants are generally asleep, so opportunities for interaction are limited. Expanding their use to other rooms such as living rooms, where interaction may be more likely, would potentially increase opportunities for interaction. This may also have benefits in terms of providing occupants with information to balance heating and ventilation.

9.2. Clearer guidance is required for ventilation in general and the CO_2 sensors specifically to enable more informed use. There was limited evidence of use of quick-start guides, and the nature and timing of advice provision requires consideration.

9.3. The study found evidence of poor compliance with regulations. These included delays to the implementation of standards, poor compliance with performance standards for ventilation provision, the lack of provision of CO_2 monitors in bedrooms, and associated guidance to occupants.

9.4. A key issue is that of non-compliance and related to that maintenance of compliance. More robust measures are clearly needed to ensure that the minimum standards are delivered at hand-over, but also consideration of how these standards may be maintained over time, recognising that under the building standards system, there is limited scope for action to be enforced post acceptance of the completion certificate.

9.5. At present the scope of powers available under the building standards system is the submission of the completion certificate, beyond which there is limited scope for action. Given the widespread nature of non-compliance, a requirement to make good, that is to meet the standard may not be a sufficient driver for action. Punitive measures for non-compliance may act as a catalyst for improved compliance.

9.6. The evidence provided by this research shows that there are some areas for improvement in the ventilation provision. It is suggested to provide minimal revisions to the guidance supporting Standards to provide a protocol for ventilation induction and follow up to improve occupant understanding and ability to interact effectively with the ventilation strategy employed within their home.

9.7. Problems with on-going maintenance of ventilation systems was identified. Whilst at present regulations cannot mandate onward maintenance, the introduction of a requirement to provide a maintenance plan may be helpful. Further recommendation for providers would be a requirement for regular servicing of mechanical systems, mirroring the one currently being adopted for boilers.

9.8. In this study the prevalence of new dwellings with an EPC provided in 2019, but being built to pre 2015 standards, suggest that latitude to enable industry to adopt to new standards may be being used to avoid these unnecessarily. This could delay governmental efforts to improve buildings in terms of energy demand (and associated CO2 emissions) and heath for residents of Scottish homes. Measures may therefore be required to reduce the lag time between building warrant submission and actual construction to avoid homes being built today under the building standards of 5 years ago.

9.9. There was little evidence of occupant knowledge of the standards to which their homes had been built, so a requirement for this information to be made available, may also act as a driver to faster adoption of new standards. New build dwellings should have information or certification provided to owners and occupants about the Standards to which they are constructed to evidence ‘new’ buildings built to superseded standards – this could potentially be incorporated into Quickstart Guides.

Further research

9.10. External conditions may be major drivers for ventilation use in homes. This may include detrimental external conditions such as noise or pollution and there has not been any research that attempts to measure indoor and outdoor pollutants or other nuisances concurrently.

9.11. Related to this are strategies for ventilation in rural areas of Scotland where external weather and moisture is a major issue and practices of ventilation are influenced and at time restricted by it. The limitations of this study were the relatively restricted geographical location of homes, and lack of external contextual data which may be relevant.

9.12. Currently mandated mechanical ventilation systems are based on standard assumptions of occupancy for moisture control. There is little information on loads derived by different types of occupancy (for example larger households, family with young children, or people with special needs) that may result in higher moisture loads, which may present challenges for existing systems. An understanding of the performance envelope of systems may be useful as a means of determining risks.

9.13. The use of MVHR as an energy efficient ventilation system is becoming more established, but there is little data on their longer term effectiveness, particularly in more mainstream housing (i.e. not Passivhaus). Related to this may be investigations of alternative strategies, for example demand control driven systems.

9.14. Research to underpin the appropriateness of ventilation systems to cope with an increased demand for ventilation during heatwaves. This links to the new Mandatory Standard “3.28 Overheating risk” introduced on 1 February 2023. Here, the Simple method for assessing and mitigating overheating recommends – alongside solar gain control – providing effective ventilation to remove the build-up of heat, indicating that the level of air change sought under standard 3.14 (4 air changes per hour) should cope in a building with cross ventilation, which was not the case in two of the monitored homes.

9.15. Further work may be required to identify the scope of warrant applications prior to implementation of new regulations to provide better data on the scale and impacts of this practice. This may be beneficial in terms of informing Impact Assessments of new regulations and identification of progress toward Government Targets for energy reduction and climate change.

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10. References

Abadie M, Wargocki P, Rode C, et al. Proposed Metrics For IAQ in Low-Energy Residential Buildings. ASHRAE J N Y 2019; 61: 62–65.

Abadie M, Wargocki P, Rode C, et al. Indoor Air Quality Design and Control in Low-energy Residential Buildings Annex 68 | Subtask 1: Defining the metrics. AIVC Contributed Report 17, International Energy Agency - Annex 68, 2017

Ai ZT, Mak CM, Cui DJ. On-site measurements of ventilation performance and indoor air quality in naturally ventilated high-rise residential buildings in Hong Kong. Indoor Built Environ 2015; 24: 214–224

Aubin D, Won D, Schleibinger H, et al. Seasonal variation in indoor air quality from a field study investigating the impact of ventilation rates on the health of asthmatic children in Québec City, Building and Environment, http://www.sciencedirect.com/science/journal/03601323

Biler et al. 2018, A review of performance specification and studies of trickle vents, Buildings journal, https://www.mdpi.com/2075-5309/8/11/152

Bryman, A. (2016). Social Research Methods (5th ed.). London: Oxford University Press.

Building Research Establishment. “Digest 297: Surface condensation and mould growth in traditionally built dwellings”. BRE Press, Garston, 1985

Building Research Establishment. “The effect that increasing air-tightness may have on air quality within dwellings”. Scottish Government, Building Standards Division, Livingston, April 2012

CIBSE TM40 2005/2020 The Chartered Institution of Building Services Engineers 222 Balham High Road, London SW12 9BS

CIBSE Guide A (2015) Table 1.5 and CIBSE TM60: Good Practice in the design of homes (2018a) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/872091/Planning_for_the_Future.pdf

CIBSE, 2017. TM59: Design methodology for the assessment of overheating risk in homes. https://doi.org/ CIBSE TM59: 2017

COMEAP (2015) The mortality effects of long term exposure to particulate air pollution in the United Kingdom (London: Health Protection Agency for the Committee on the Medical Effects of Air Pollutants) (available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/304641/COMEAP_mortality_effects_of_long_term_exposure.pdf

COMEAP (2018) Impact of long term exposure to nitrogen dioxide on mortality (Press Release, 22nd August 2018) (London: Committee on the Medical Effects of Air Pollutants)

Coward SKD, Brown VM, Crump DR, Raw GJ and Llewellyn JW (2002) Indoor air quality in homes in England; volatile organic compounds BRE Report BR433 (Garston: BRE)

Crump D, Dengel A, Swainson M. “Indoor Air Quality in Highly Energy Efficient Homes – a Review”. IHS BRE Press, Watford, England, 2009

Davis I, Harvey V. “Zero Carbon: what does it mean to homeowners and house builders?” NHBC Foundation report, NF9, 2008

Defra (2007) National air quality objectives and European Directive limit and target values for the protection of human health (London: Department for Environment, Food and Rural Affairs) (available at https://uk-air.defra.gov.uk/assets/documents/Air_Quality_Objectives_Update.pdf

Deng T, Shen X, Cheng X, et al. Investigation of window-opening behaviour and indoor air quality in dwellings situated in the temperate zone in China. Indoor Built Environ 2020;
1420326X20924746.

Dimitroulopoulou C, Crump D, Coward S, et al. Ventilation, air tightness and indoor air quality in new homes, https://www.brebookshop.com/details.jsp?id=189831 (2005)

Dimitroulopoulou, C. & Lucica, E & Johnson, A & Ashmore, Mike & Sakellaris, Ioannis & Stranger, Marianne & Goelen, Eddy. (2015). EPHECT I: European household survey on domestic use of consumer products and development of worst-case scenarios for daily use. The Science of the total environment. 536. 10.1016/j.scitotenv. 2015

Dimitroulopoulou C, Lucica E, Johnson A, Ashmore MR, Sakellaris I, Stranger M and Goelen E (2015a) 'EPHECT I: European household survey on domestic use of consumer products and development of worst-case scenarios for daily use' J. Science of the Total Environment 036 880–889

Dimitroulopoulou C, Trantallidi M, Carrer P, Efthimiou G and Bartzis J (2015b) 'EPHECT II: Exposure assessment to household consumer products' J. Science of the Total Environment 036 890–902

EC (2004) The INDEX project: Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU (Ispra, Italy: European Commission, Joint Research Centre, Institute for Health and Consumer Protection, Physical and Chemical Exposure Unit)
http://ec.europa.eu/health/ph_projects/2002/pollution/fp_pollution_2002_exs_02.pdf)

EC (2014) SINPHONIE: Schools Indoor Pollution and Health, Observatory Network in Europe (Luxembourg: Publications Office of the European Union)
https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/sinphonieschools-indoor-pollution-and-health-observatory-network-europe-final-report) (accessed 9/12/19)

Geiss O, Giannopoulos G, Tirendi S, Barrero-Moreno J, Larsen BR, Kotzias D (2011) 'The AIRMEX study - VOC measurements in public buildings and schools/kindergartens in eleven European cities: Statistical analysis of the data' Atmospheric Environment 45 (2011) 3676–3684 (available at
https://www.academia.edu/20002029/The_AIRMEX_study_-

_VOC_measurements_in_public_
buildings_and_schools_kindergartens_in_eleven_European_cities_Statistical_analysis_of_the_data)

Godish T, Spengler JD. Relationships Between Ventilation and Indoor Air Quality: A Review. Indoor Air 1996; 6: 135–145

Guyot G, Melois A, Bernard A-M, et al. Ventilation performance and indoor air pollutants diagnosis in 21 French low energy homes. Int J Vent 2018; 17: 187–195.

Haghighat F, De Bellis L. Material emission rates: Literature review, and the impact of indoor air temperature and relative humidity. Build Environ 1998; 33: 261–277

Hänninen O, Asikainen A, Sorjamaa R, Lipponen P, Wargocki P, Bischof W, Hartmann T, Fanetti A, Carrer P, Asimakopolou M, Santamouris M, Asimakopoulos D, Santos H, Leal V, de Oliveira Fernandes E, Allard F, Seppänen O, Schmidt M, Popov T and Mustakov T (2013) Impact of the implementation of the ventilation guidelines on burden of disease (Kuopio, Finland: HealthVent)
https://webgate.ec.europa.eu/chafea_pdb/assets/files/pdb/20091208/20091208_d08_oth8_en_ps.pdf

HM Government. Ventilation and Indoor Air Quality in New Homes. Aecom Limited, Ministry of Housing, Communities and Local Government, 2019

Holøs SB, Yang A, Lind M, Thunshelle K, Schild P and Mysen M (2019) 'VOC emission rates in newly built and renovated buildings, and the influence of ventilation — a review and meta-analysis' International Journal of Ventilation 18 (3) 153–166 (available at https://www.researchgate.net/publication/323296323_VOC_emission_rates_in_newly_built_and_renovated_buildings_and_the_influence_of_ventilation_-_a_review_and_meta-analysis)

Howieson 2005 Housing and Asthma, Taylor and Francis London

Howieson, S. G., Sharpe, T. & Farren, P How are new air tightness standards affecting indoor air quality in dwellings? Building Services Engineering Research and Technology. 35, 5, p. 475-487 13 p. Building tight – ventilating right? Sep 2014

Jaakkola, J. J. & Miettinen, P., 1995. Ventilation Rate in Office Buildings and Sick Building Syndrome. *Occupational and Environmental Medicine*, 52(11), pp. 709-714.

Jamieson SS, Dimitroulopoulou S, Brown VM and Colvile RN (2005) ‘Levels of indoor VOCs in workplaces in a polluted urbanarea of London’ Indoor Built Environment 14 (3/4) 259–268

Järnström H, Saarela K, Kalliokoski P, et al. Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. Atmos Environ 2006; 40: 7178–7191

Jones NC, Thornton CA, Mark D, et al. Indoor/outdoor relationships of particulate matter in domestic homes with roadside, urban and rural locations. Atmos Environ 2000; 34: 2603–2612.

Kaunelienė V, Prasauskas T, Krugly E, et al. Indoor air quality in low energy residential building in Lithuania. Build Environ 2016; 108: 63–72

Kembel, S. W. et al. Architectural design influences the diversity and structure of the built environment microbiome. Int. Soc. Microbial Ecol. J. 2012; 6, 1469–1479

Kim S, Kim H-J. Comparison of formaldehyde emission from building finishing materials at various temperatures in under heating system; ONDOL. Indoor Air 2005; 15: 317–325

Kinnane, Sinnott, Turner, 2016, Evaluation of passive ventilation provision in domestic housing retrofit, Building and Environment, https://phai.ie/wp-content/uploads/2018/05/2016-Kinnane-et-al.-2016-Evaluation-of-passive-ventilation-provision-in-domestic-housing-retrofit.pdf

Kolarik B, Gunnarsen L, Logadottir A, et al. Concentrations of Formaldehyde in new Danish
Residential Buildings in Relation to WHO Recommendations and CEN Requirements: Indoor
Built Environ. Epub 2011. DOI: 10.1177/1420326X11419872

Langer S, Ramalho O, Derbez M, et al. Indoor environmental quality in French dwellings and building characteristics. Atmos Environ 2016; 128: 82–91

Langer S, Bekö G. Indoor air quality in the Swedish housing stock and its dependence on
building characteristics. Build Environ 2013; 69: 44–54.

LGCD (2017) Building Standards domestic ventilation supporting guidance version 2.1. Part of *Building, planning and design.* Available at Building Standards domestic ventilation: supporting guidance - gov.scot (www.gov.scot)

Logue JM, McKone TE, Sherman MH, et al. Hazard assessment of chemical air contaminants measured in residences. Indoor Air 2011; 21: 92–109

Mandin C, Trantallidi T, Cattaneo A, Canha N, Mihucz V G, Szigeti T, Mabilia R, Perreca E, Spinazzè A, Fossati S, De Kluizenaar Y,Cornelissen E, Sakellaris I, Saraga D, Hänninen O, De Oliveira Fernandes E, Ventura G, Wolkoff P, Carrer P, Bartzis J (2017).
Assessment of indoor air quality in office buildings across Europe - The OFFICAIR study, Science of The Total Environment 579 169–178 https://www.ncbi.nlm.nih.gov/pubmed/27866741)

McGill G, Qin M, Oyedele L. A Case Study Investigation of Indoor Air Quality in UK Passivhaus Dwellings. Energy Procedia 2014; 62: 190–199

McGill G, Oyedele LO, McAllister K. Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing. Int J Sustain Built Environ 2015; 4: 58–77

McSharry, C., Vesper, S., Wymer, L., Howieson, S., Chaudhuri, R., Wright, G. R.& Thomson, N. C. Clinical and Experimental Allergy. 20 p. Decreased FEV1% asthmatic adults in Scottish homes with high environmental relative moldiness index values, 2015

Moreno-Rangel A, Sharpe T, McGill G, et al. Indoor Air Quality in Passivhaus Dwellings: A Literature Review. Int J Environ Res Public Health 2020; 17: 4749

Noorimotlagh 2021 Noorimotlagh Z, Jaafarzadeh N, Silva S and Environironmental Research. 2021 A systematic review of possible airborne transmission of the COVID-19 virus (SARS-CoV-2) in the indoor air environment

OJEU (2008b) 'Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe' Official Journal of the European Union (available at http://eur-lex.europa.eu/legal-content/en/ TXT/?uri=CELEX%3A32008L0050)

Perera, E. & Parkins, L. "Build tight - ventilate right", Building Services, Chartered Institution of Building Services Engineers, London, June 1992, pp 37-38

Porteous 2013 Porteous C, Sharpe T, Menon R, Shearer D, et al. Domestic laundering: Environmental audit in Glasgow with emphasis on passive indoor drying and air quality Domestic laundering: Environmental audit in Glasgow with emphasis on passive indoor drying and air quality. Indoor and Built Environment 2013

Raw GJ, Coward SKD, Brown VM, et al. Exposure to air pollutants in English homes. J Expo Sci Environ Epidemiol 2004; 14: S85–S94

RIAS Practice Information for Chartered practices. (2016) *OS1612: Ventilation Design Strategy – Flowchart Section 3.0 Guidance.* Available at https://rias.org.uk/for-practices/practice-notes

RCP (2016) Every breath we take: the lifelong impact of air pollution — Report of a working party (London: Royal College of Physicians) https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution)

RCPCH (2020) The inside story: Health effects of indoor air quality on children and young people (London: Royal College of Paediatrics and Child Health) https://www.rcpch.ac.uk/resources/inside-story-health-effects-indoor-air-qualitychildren-young-people

Rode C, Qin M, Grunewald J, et al. Key findings of IEA EBC Annex 68 - indoor air quality design and control in low energy residential buildings. In: ResearchGate, https://www.researchgate.net/publication/336747000_Key_findings_of_IEA_EBC_Annex_68_- indoor_air_quality_design_and_control_in_low_energy_residential_buildings (2019)

SFHA (2022). *What's on*. Available at https://www.sfha.co.uk/whats-on/event-details/understanding-the-role-of-ventilation

Sharpe T, Farren P, Howieson S. et al. Occupant interactions and effectiveness of natural ventilation strategies in contemporary new housing in Scotland, UK, International Journal of Environmental Research and Public Health. 12, 7, p. 8480-8497 Jul 2015 https://www.mdpi.com/1660-4601/12/7/8480

Sharpe T, McQuillan J, Howieson S, Farren P, Touhy P (2014) Research Project To Investigate Occupier Influence On Indoor Air Quality In Dwellings, Scottish Government Technical Report (Local Government and Communities Building Standards Division), 21 August 2014 https://www2.gov.scot/Resource/0046/00460968.pdf http://www.gov.scot/publications/building-standards-domestic-ventilation-supporting-guidance/

Sharpe et al. 2018, Ability of decentralized mechanical ventilation to act as ‘whole-house’ ventilation systems in new-build dwellings’, The Scottish Government, http://radar.gsa.ac.uk/7085/1/Final%20report%20dMEV.pdf

Sharpe, T., McGill, G., Dancer, S., King, M-F., Fletcher, L., Noakes, C., Influence of ventilation use and occupant behaviour on surface microorganisms in contemporary social housing, Scientific Reports, 2020: 10 (11841), https://www.nature.com/articles/s41598-020-68809-2#ref-CR15

Stamp S, Burman E, Shrubsole C. et al (2021) Seasonal variations and the influence of ventilation rates on IAQ: A case study of 5 Low-Energy London Apartments

Stranger M, Verbeke S, Täubel M, et al. Clean Air, Low Energy - Exploratory research on the quality of the indoor environment in energy-efficient buildings: the influence of outdoor
environment and ventilation. 2012; 346

Sullivan 2007 https://www.gov.scot/publications/a-low-carbon-strategy-scotland-sullivan-report/

TSO (2010b) The Air Quality Standards Regulations 2010 (London: The Stationery Office) (available at http://www.legislation.gov.uk/uksi/2010/1001)

Trantallidi M, Dimitroulopoulou C, Wolkoff P, Kephalopoulos S and Carrer P (2015) 'EPHECT III: Health risk assessment of exposure to household consumer products' Science of The Total Environment 536 903–13

Tuomainen M, Pasanen A-L, Tuomainen A, et al. Usefulness of the Finnish classification of indoor climate, construction and finishing materials: comparison of indoor climate between two new blocks of flats in Finland. Atmos Environ 2001; 35: 305–313

UN 2015 https://www.un.org/sustainabledevelopment/blog/2015/12/sustainable-development-goals-kick-off-with-start-of-new-year/

Wargocki, (2016), The effects of ventilation in homes on health, International journal of ventilation, https://www.tandfonline.com/doi/abs/10.1080/14733315.2013.11684005

Wright G, Howieson S, McSharry C, McMahon A, Chaudhuri R, Thompson J, Fraser I, Brooks R, Lawson A, Jolly L, McAlpine L, King E, Chapman M, Wood S, Thomson N. Effect of improved home ventilation on asthma control and house dust mite allergen levels, Allergy, 29th March, 2009

World Health Organization Who guidelines for indoor air quality: selected pollutants. Copenhagen: WHO, 2010

WHO (2014b) Guidelines for indoor air quality: Household fuel combustion (Geneva: World Health Organization) http://apps.who.int/iris/bitstream/10665/141496/1/9789241548885_eng.pdf?ua=1

WHO (2006a) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005: Summary of risk assessment (Geneva: World Health Organization Occupational and Environmental Health Team) (available at https://apps.who.int/iris/handle/10665/69477)

WHO (2010a) WHO guidelines for indoor air quality: selected pollutants (Copenhagen: World Health Organization Regional Office for Europe) (available at https://apps.who.int/iris/bitstream/handle/10665/260127/9789289002134-eng.pdf)

Wargocki 2002 Wargocki L. Lagercrantz T. Witterseh J. Sundell D. P. Wyon P. O. Fanger
Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office
Indoor Air 2002 https://doi.org/10.1034/j.1600-0668.2002.01101.

Wolkoff P. Impact of air velocity, temperature, humidity, and air on long term voc emissions from building products. Atmos Environ 1998; 32: 2659–2668

Wolkoff P and Nielsen GD (2001) ‘Organic compounds for indoor air: their relevance for perceived indoor air quality?’Atmospheric Environment 35 (26) 4407–17 (available at https://www.academia.edu/25184984/Organic_compounds_in_indoor_air_their_relevance_for_perceived _indoor_air_quality)

Wolkoff P (2013) 'Indoor air pollutants in office environments: Assessment of comfort, health, and performance' International Journal of Hygiene and Environmental Health 216 4 371–94

Yang S, Perret V, Jörin CH, et al. Volatile organic compounds in 169 energy-efficient dwellings in Switzerland. Indoor Air 2020; 30: 481–491

Yoshimo H, Netsu K, Yoshida M, et al. Yoshimo H, Netsu K, Yoshida M, Ikeda K, Nozaki A, Kakuta K, Hojo S, Yoshino H, Amano K, Ishikawa S (2006). Long term field survey on IAQ and occupant’s health in 57 sick houses in Japan. Proceedings of 2006, III, , Lisbon, 4–6 June 2006. In: Healthy Buildings. Lisbon, 2006, pp. 315–320.

Yu CWF, Kim JT. Low-Carbon Housings and Indoor Air Quality. Indoor Built Environ 2012; 21: 5–15.

Yu CWF, Kim JT. Building Environmental Assessment Schemes for Rating of IAQ in Sustainable Buildings. Indoor Built Environ 2011; 20: 5–15.

Annex A: guidance

CIBSE TM40 - 2020 Guide – Indoor air quality comparisons

Figure 2 Indoor air quality recommendations

Recommendations related to health (*continued*)				
Pollutant	**WHO guidelines**	**UK regulations**	**CIBSE recommendations**	**Comments**
NO_2	• 200 $\mu g/m^3$ 1-hour average • 40 $\mu g/m^3$ annual average (WHO, 2010a)	(*Ambient EU and UK objective; COSHH WEL)* AD-F performance criteria: • 288 $\mu g/m^3$ 1-hour average • 40 $\mu g/m^3$ annual average (MHCLG, 2013b)	• 200 $\mu g/m^3$ 1-hour average • 40 $\mu g/m^3$ annual average	The WHO notes that there is 'no evidence for an exposure threshold' (WHO, 2010a) It is therefore recommended to reduce exposure levels as much as possible, rather than the guideline levels being seen as 'safe'
SO_2	• 20 $\mu g/m^3$ 24-hour mean • 500 $\mu g/m^3$ 10-minute mean (WHO, 2006a)	*(Ambient EU and UK objective; COSHH WEL)*	• 20 $\mu g/m^3$ 24-hour mean • 500 $\mu g/m^3$ 10-minute mean	The WHO guidelines are for general air quality; the WHO has not identified SO_2 as a pollutant for which specific indoor air quality guidelines are required (WHO, 2010a)
PM_{10}	• 20 $\mu g/m^3$ annual average • 50 $\mu g/m^3$ 24-hour average (WHO, 2006a)	*(Ambient EU and UK objective; COSHH WEL on dust)*	• 20 $\mu g/m^3$ annual mean • 50 $\mu g/m^3$ 24-hr m Reduce as much as possible, as no safe level is known	The WHO guidelines (2006a) are currently under revision; publication is expected in 2020 (WHO, 2018a) The WHO (2010) identified the need for indoor air quality guidelines on particulate matters, and concluded that their existing ones from 2006 'are also applicable to indoor spaces' It also states that 'there is little evidence to suggest a threshold below which no adverse health effects would be anticipated' and therefore the guidelines are produced for the purpose of standard-setting on the basis of risk assessments and public health priorities, but authorities are encouraged to adopt increasingly stringent limits (WHO, 2006a)
$PM_{2.5}$	• 10 $\mu g/m^3$ annual average • 25 $\mu g/m^3$ 24-hour average (WHO, 2006a)	*(Ambient EU and UK objective; COSHH WEL on dust)*	• 10 $\mu g/m^3$ annual mean • 25 $\mu g/m^3$ 24-hour mean • Reduce as much as possible, as no safe level is known	
Ultra-fine particles (< 0.1 μm in diameter)	Currently insufficient evidence to produce guideline concentrations (WHO, 2006a)	*(COSHH WEL on dust)*	No recommended level can be proposed — project teams to remain informed of status of knowledge and guidance	
Ozone	• 100 $\mu g/m^3$ 8-hour mean (WHO, 2006a)	*(Ambient EU and UK objective; COSHH WEL)* AD-F performance criterion: 100 $\mu g/m^3$ (MHCLG, 2013b)	100 $\mu g/m^3$ 8-hour mean	The WHO guidelines are for general air quality; in 2010 the WHO identified ozone as a pollutant for which specific indoor air quality guidelines should be recommended but found that current evidence was uncertain or not sufficient (WHO, 2010a)

Table continues

Table 9.1 Indoor air quality; recommendations related to health and occupant satisfaction (*continued from previous page*)

Recommendations related to health (*continued*)				
Pollutant	**WHO guidelines**	**UK regulations**	**CIBSE recommendations**	**Comments**
CO	• 100 mg/m^3 15-min average • 35 mg/m^3 1-hour average • 10 mg/m^3 8-hour average • 7 mg/m^3 24-hour average (WHO, 2010a)	*(Ambient EU and UK objective; COSHH WEL, see comments)* AD-F performance criteria: • 100 mg/m^3 15-min average • 60 mg/m^3 30-min average • 30 mg/m^3 1-hour average • 10 mg/m^3 8-hour average • For occasional exposure in non-dwellings: 35 mg/m^3 8-hour average See also comments	• 100 mg/m^3 15-min avg • 60 mg/m^3 30-min avg • 30 mg/m^3 1-hour average • 10 mg/m^3 8-hour average • 7 mg/m^3 24-hour average • For occasional exposure in non-dwellings: 35 mg/m^3 8-hour average	See also regulatory requirements in sections 9.2 and 9.4.7 The COSHH WEL limits are higher than AD-F; the WEL for 8-hour exposure is 23 mg/m^3 and therefore lower than the AD-F for occasional 8-hour exposure, but may be present more often, as an occupational limit (HSE, 2018)
Lead	0.5 µg/m^3 annual average (WHO, 2019a)	*(Ambient EU and UK objective; Occupational Exposure Limit under Control of Lead at Work Regulations 2002)*	0.25 µg/m^3 annual mean Based on UK ambient air quality objective (Defra, 2007)	—
Formaldehyde (a VOC)	100 µg/m^3 30-min average (WHO, 2010a)	*(COSHH WEL)* AD-F: no limit except as part of TVOCs; see below	100 µg/m^3 30-min average	Consider implementing a lower target for buildings which are not yet fully fitted-out, to account for future additional emissions from fit-out elements See guidance on insulating materials in section 9.4.4
Benzene (a VOC)	No safe level of exposure can be recommended; exposure should be reduced as much as possible (WHO, 2010a)	*(Ambient EU and UK objective; COSHH WEL)*	Exposure should be avoided, and otherwise reduced to as low a level as possible	—
1,3-butadiene (a VOC)	Insufficient evidence to allow the production of a guideline value (WHO, 2000)	*(Ambient UK objective; COSHH WEL)*	Maximum 2.25 µg/m^3 (based on UK national air quality objective) Since no exposure guideline is currently available, project teams should remain informed should this be developed in the future; in the meantime, reduce exposure as much as possible based on the precautionary principle	—

Table continues

Recommendations related to health (*continued*)				
Pollutant	**WHO guidelines**	**UK regulations**	**CIBSE recommendations**	**Comments**
Trichloroethylene (a VOC)	No safe level can be determined; guidance is based on a risk estimate rather than a safe level, i.e. concentratio associated with an excess lifetime Cancer risk of 1:10 000, 1:100 000 and 1:1 000 000 for 230 $\mu g/m^3$, 23 $\mu g/m^3$ and 2.3 $\mu g/m^3$ respectively (WHO, 2010a)	*(COSHH WEL)*	2.3 $\mu g/m^3$ and reduce as much as possible as no safe level is known	—
Tetrachloroethylene (a VOC)	0.25 mg/m^3 annual average (WHO, 2010a)	*(COSHH WEL)*		—
Polycyclic aromatic hydrocarbons (PAH)	No safe level of exposure can be recommended; exposure should be reduced as much as possible (WHO, 2010a)	*(Ambient EU and UK objective; COSHH WEL for some individual substances)*	Exposure should be avoided, and otherwise reduced to as low as possible	—
Naphthalene (a VOC and a PAH)	0.01 mg/m^3 annual average (WHO, 2010a)	—	0.01 mg/m^3 annual average	—
Microbial contamination	No criteria for safe microbial exposure — addressed through control of humidity and ventilation (WHO, 2009a)	*Legionella* prevention: see chapter 13 Humidity: see section 8.3	No performance level — refer to regulations as well as design and operational best practice guidance	See also chapter 8, 'Humidity'
Odours (i.e. in the case of occupant perceptions and satisfaction (*not* health)				
Odours	Sensory comfort guidelines for a small number of substances, based on the odour detection threshold (WHO, 2000)	*N/A, other than through general ventilation requirements in Building Regulations Part F*	Investigate if this is a reported problem; if odours are linked to a known pollutant, the above limits apply	ANSI/ASHRAE (2001) offers possible benchmarking based on reported detection and annoyance
Indicators				
TVOC (as indicator)	WHO provides guidelines for individual VOCs, not total level	*(COSHH WEL for some individual substances)* AD-F performance criterion: 300 $\mu g/m^3$ 8-hour average (MHCLG, 2013b)	300 $\mu g/m^3$ 8-hour average This is only an indicator; if levels are found to be high, an analysis should be carried out to identify which VOCs are present and set targets for those known or suspected to present a health hazard See Table D.2 in Annex D for examples of some commonly found in buildings	In buildings that are not yet fully fitted-out, consider implementing a lower target to account for future additional emissions from fit-out elements

Table continues

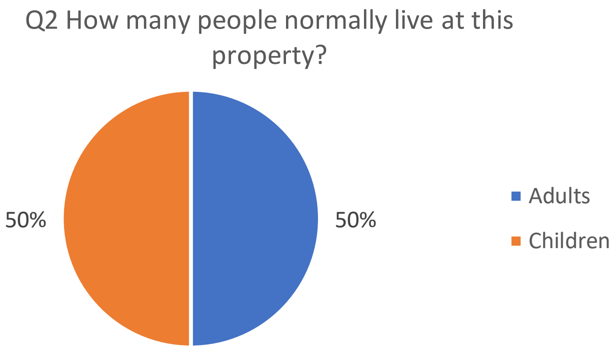
Table 9.1 Indoor air quality; recommendations related to health and occupant satisfaction (*continued from previous page*)

Indicators (*continued*)				
Pollutant	**WHO guidelines**	**UK regulations**	**CIBSE recommendations**	**Comments**
CO_2 (as indicator)	N/A	*(COSHH WEL = 5000 ppm for 8-hour exposure a 15 000 ppm for 15-min exposure)* (HSE, 2018)	850–900 ppm ('medium' air quality), or 700–750 ppm ('high' air quality); 'medium' is normally recommended. These are derived from BS EN 15251 air quality classes. The standard recommends differences with outdoor CO_2 levels, rather than absolute levels. Its replacement BS EN 16798-1:2019 allows higher differences (550 ppm for Class I and 800 ppm for Class II, which at 400 ppm outdoors would result in absolute levels of 950 ppm for Class I and 1200 ppm for Class II), but it is understood that these will be reviewed in the next update **Schools**: • mechanically ventilated buildings: daily average < 1000 ppm, and above 1500 ppm for no more than 20 consecutive minutes • naturally ventilated, or hybrid system in natural mode: daily average < 1500 ppm and > 2000 ppm for no more than 20 consecutive minutes, and < 1200 ppm (new-build) or 1750 ppm (refurbishement) for the majority of the time (ESFA, 2018)	See section 3.9 on BS indoor air quality classes See section 9.5 on whether CO_2 should be seen as pollutant on its own rather than an indicator

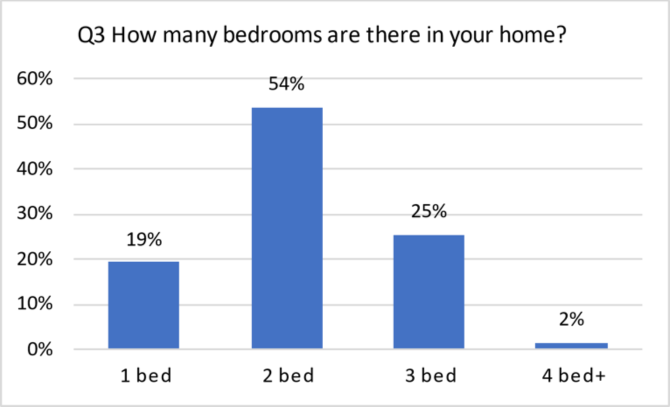
Annex B: complete household survey

Q1 How long have you been living at this property? (*If do not live here, thank you and close)

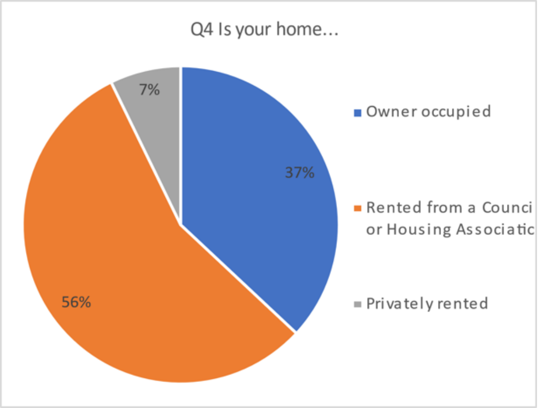
Q2 How many people normally live at this property?



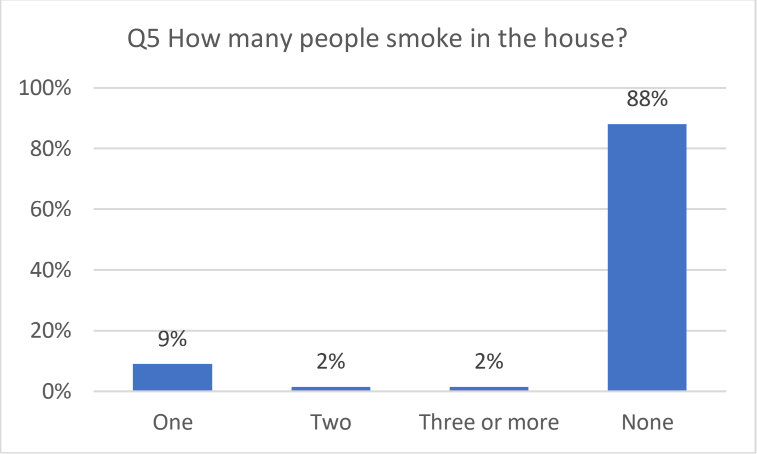
Q3 How many bedrooms are there in your home?



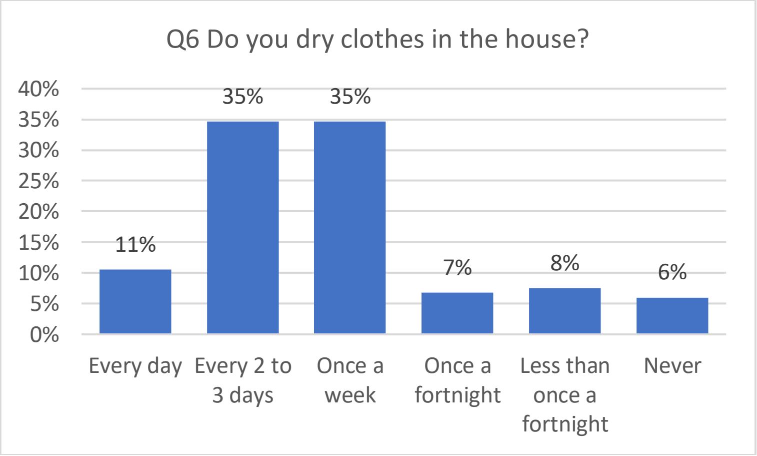
Q4 Is your home?



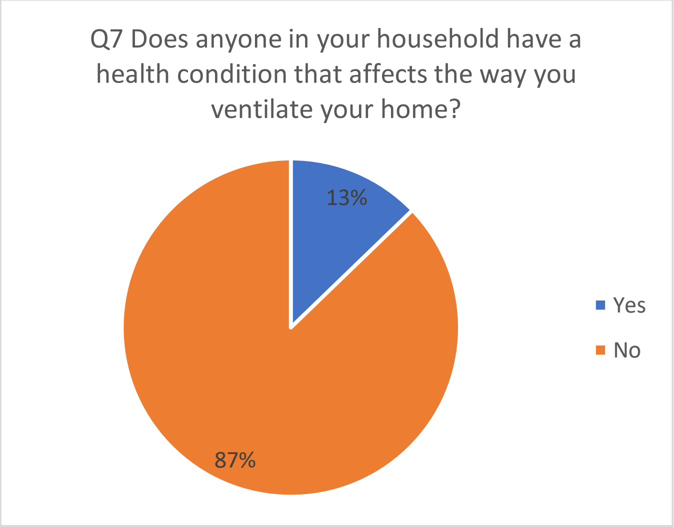
Q5 How many people smoke in the house?



Q6 Do you dry clothes in the house?



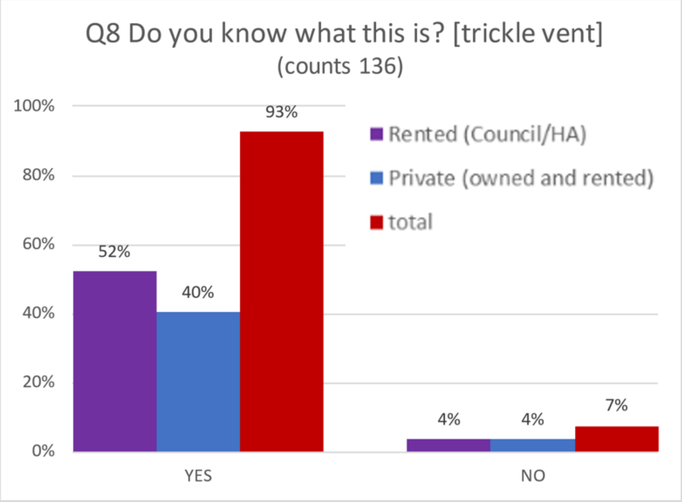
Q7 Does anyone in your household have a health condition that affects the way you ventilate your home? [IF NO, GO TO Q9]



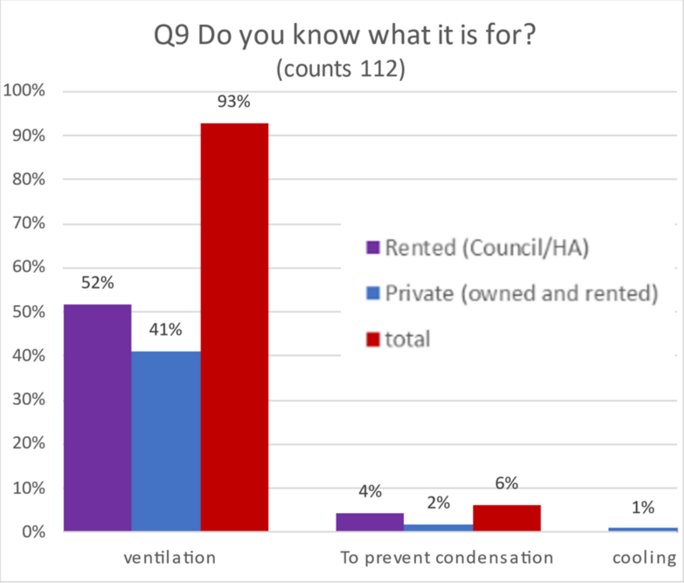
Q7a Yes (please explain)

health condition	counts
Asthma	9
Chronic obstructive pulmonary disease (COPD)	3
allergies	3
cardiovascular	2

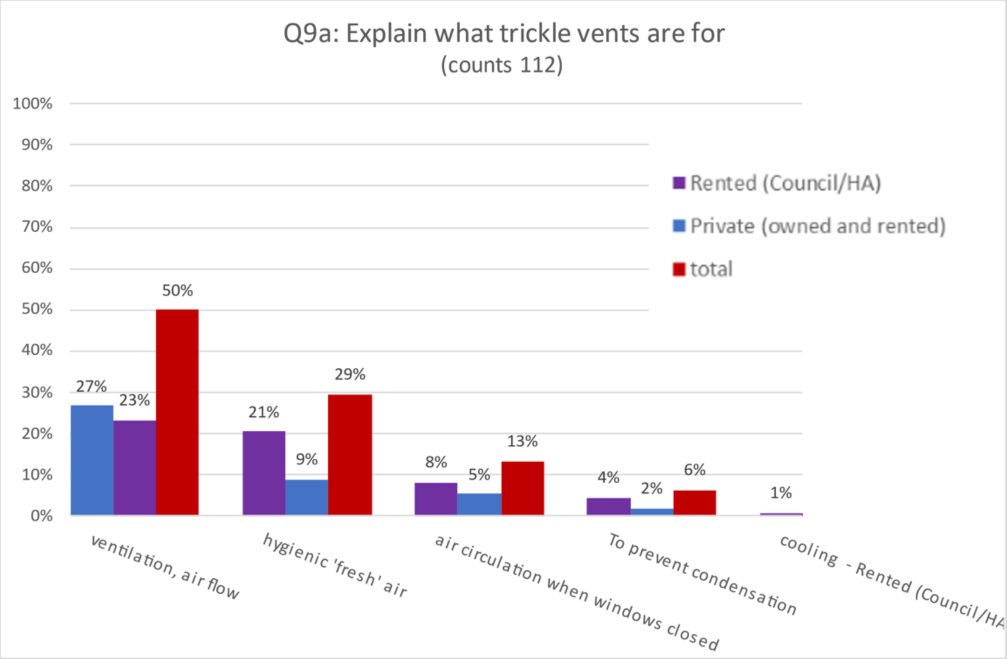
Q8 Do you know what this is? [showcard – picture of a trickle vent]



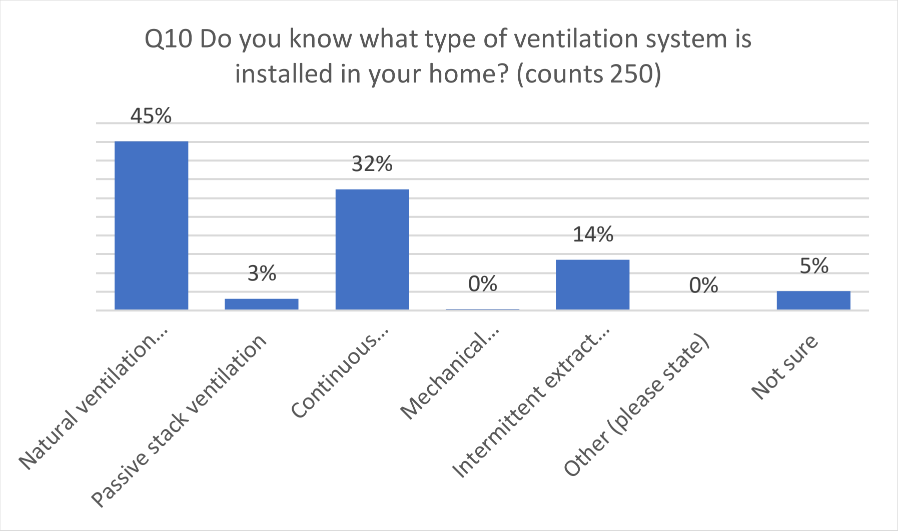
Q9 Do you know what it is for?



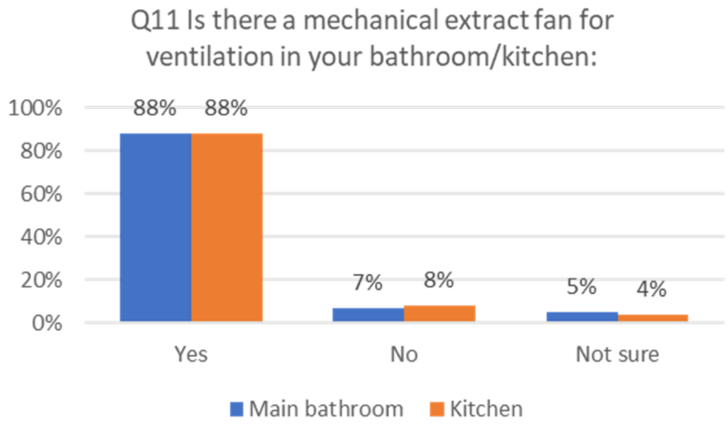
Q9a Yes (if yes, please explain)



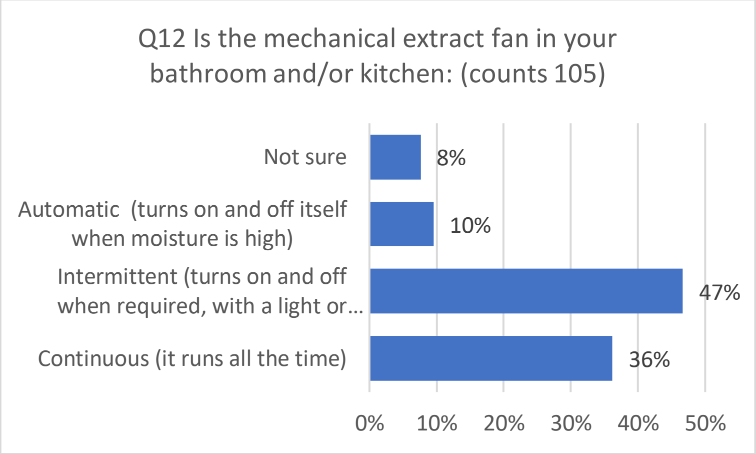
Q10 Do you know what type of ventilation system is installed in your home?



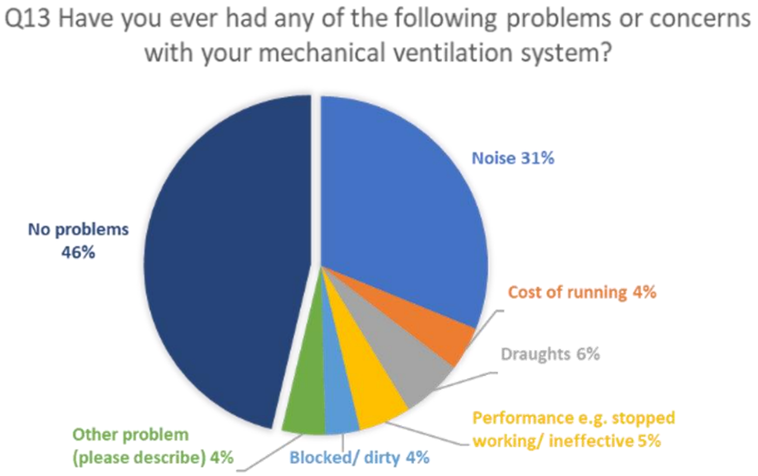
Q11 Is there a mechanical extract fan for ventilation in your:



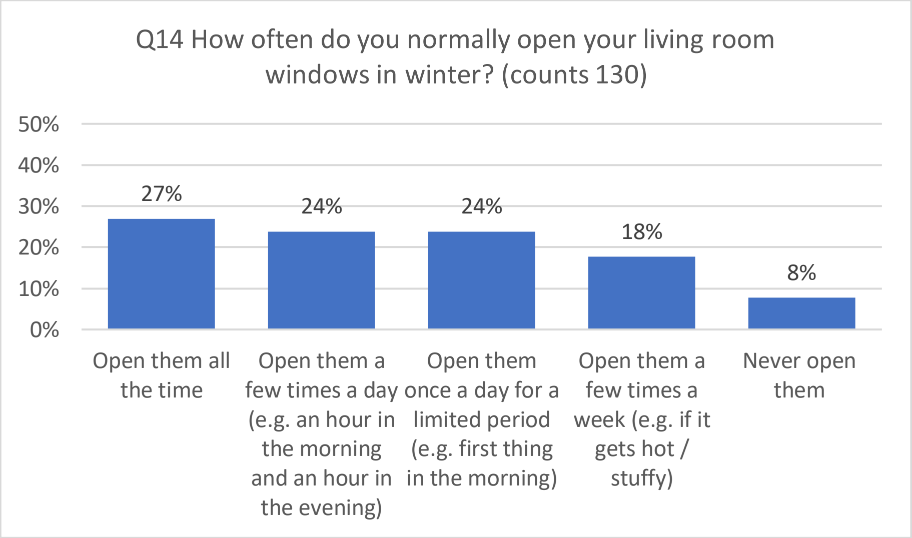
Q12 Is the mechanical extract fan in your bathroom and/or kitchen:



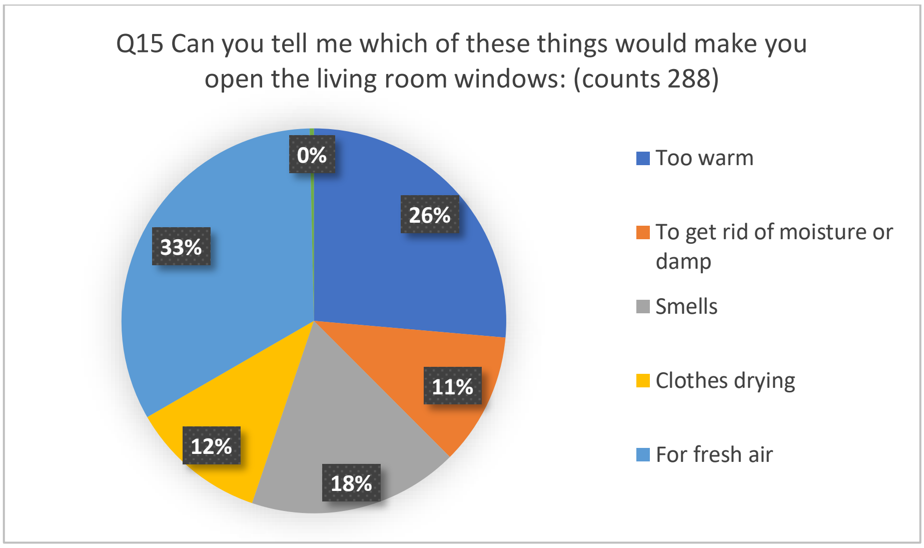
Q13 Have you ever had any of the following problems or concerns with your mechanical ventilation system?



Q14 How often do you normally open your living room windows in winter?



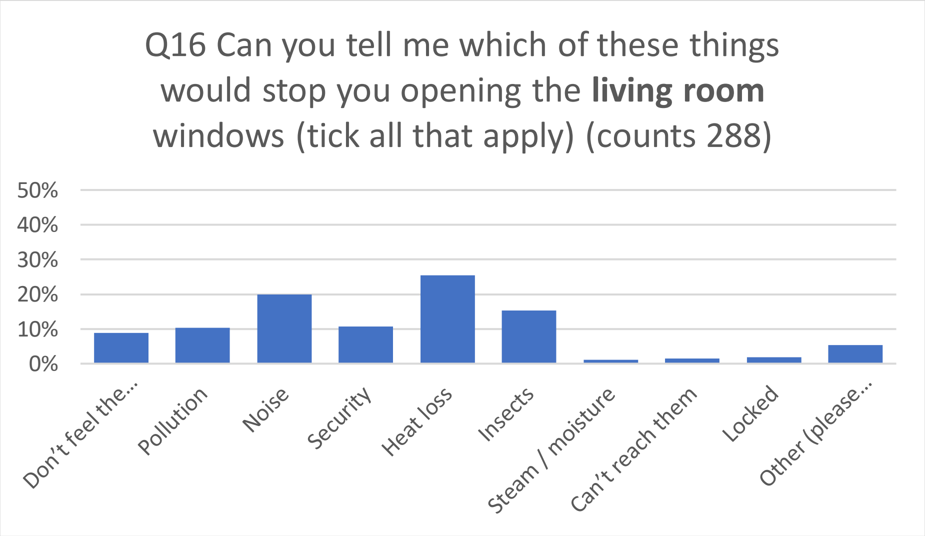
Q15 Can you tell me which of these things would make you open the living room windows:



Q15 Other (please specify)

N/A

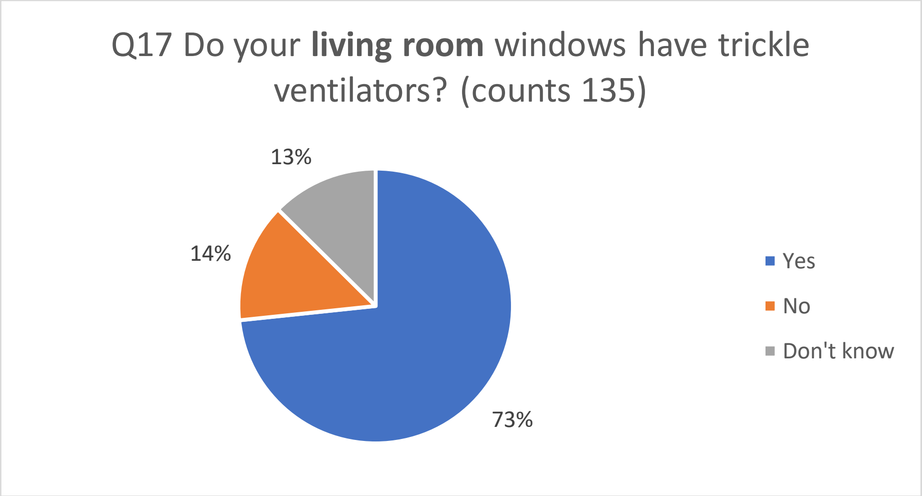
Q16 Can you tell me which of these things would stop you opening the living room windows (tick all that apply)



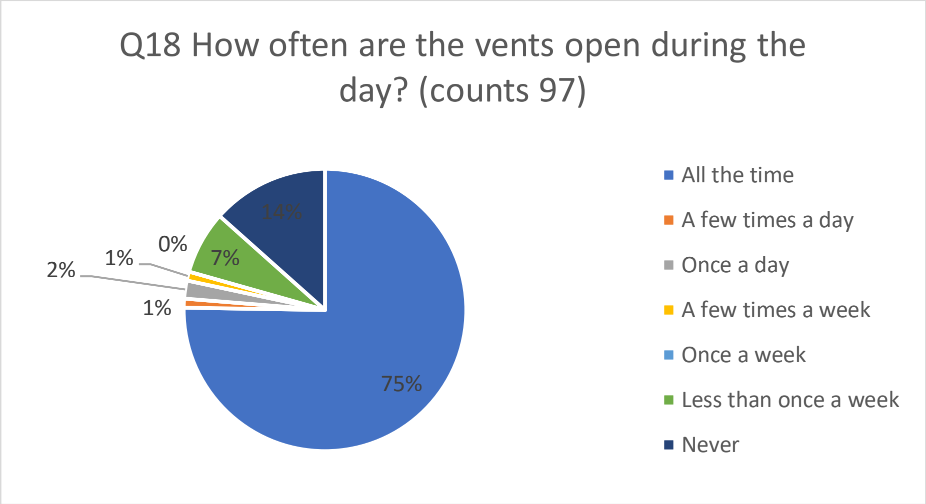
Q16 Other (please specify)

"Always open windows every day
if my guests and i are noisy
Temperature Preservation
Dust from building site.
Cold outside.
The fact that the cat might jumpout if opened too wide as on firstfloor".

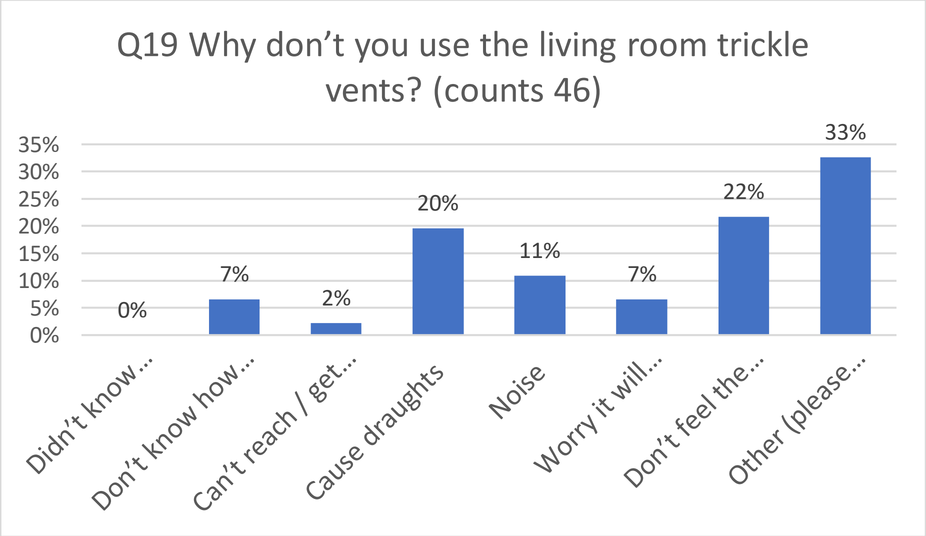
Q17 Do your living room windows have trickle ventilators?



Q18 How often are the vents open during the day?



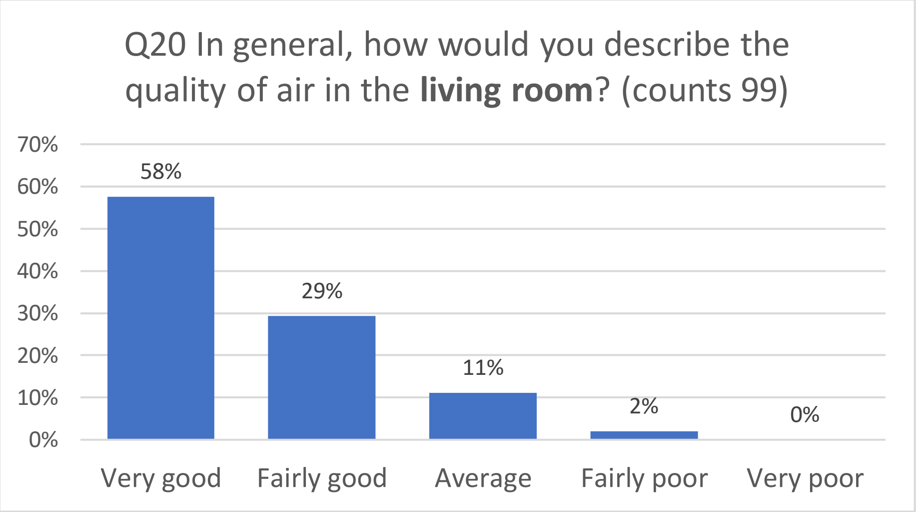
Q19 Why don’t you use the living room trickle vents?



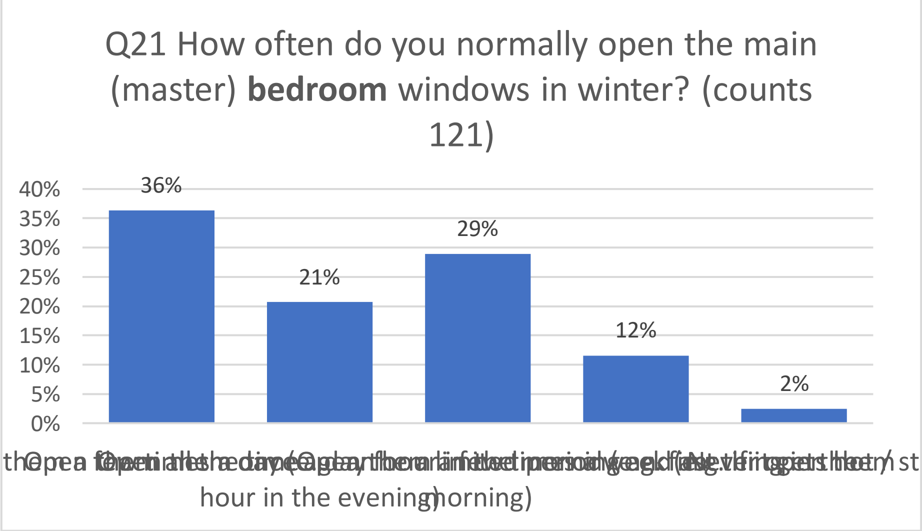
Q19 Other (please specify)

“opened
There always open
They are covert and i often discover it is too cold because i forgot to close them
I open the windows as required.
Irritating draught noise/ sound.
Windows opened frequently.
Had to be closed off because we had an infestation of maggots
Do
Prefer to just open a window
I do
I do
I do
I do

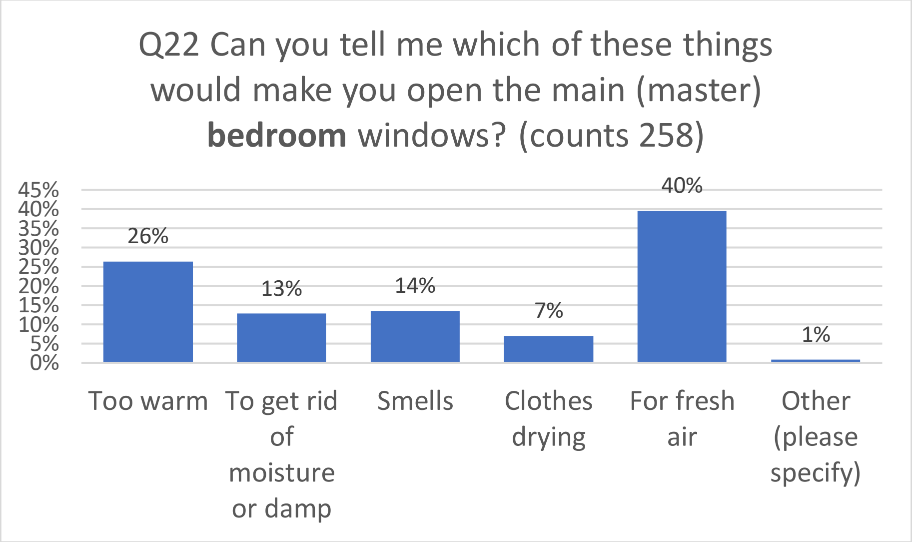
Q20 In general, how would you describe the quality of air in the living room?



Q21 How often do you normally open the main (master) bedroom windows in winter? [IF NEVER OPEN THEM, GO TO Q24]



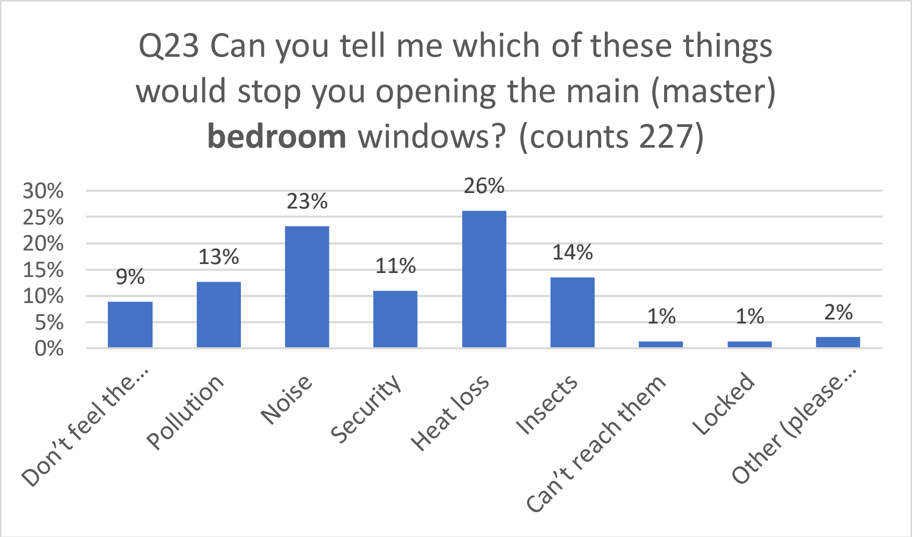
Q22 Can you tell me which of these things would make you open the main (master) bedroom windows?



Q22 Other (please specify)

N/A

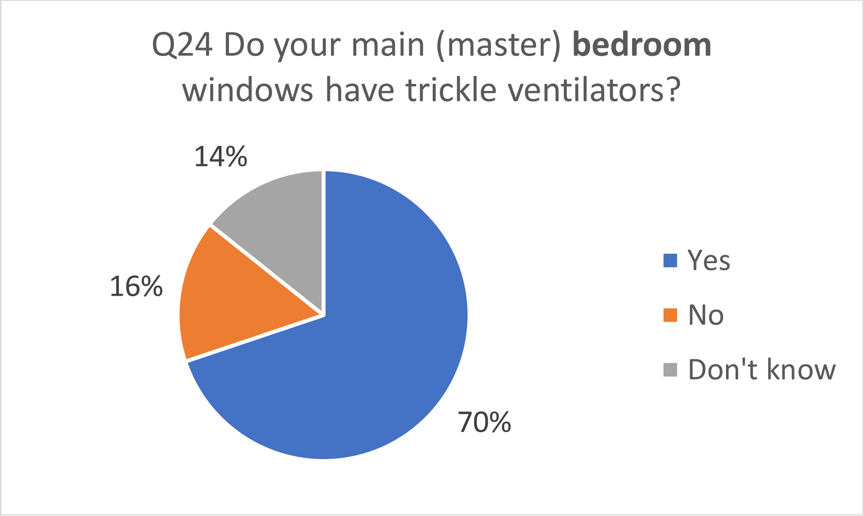
Q23 Can you tell me which of these things would stop you opening the main (master) bedroom windows?



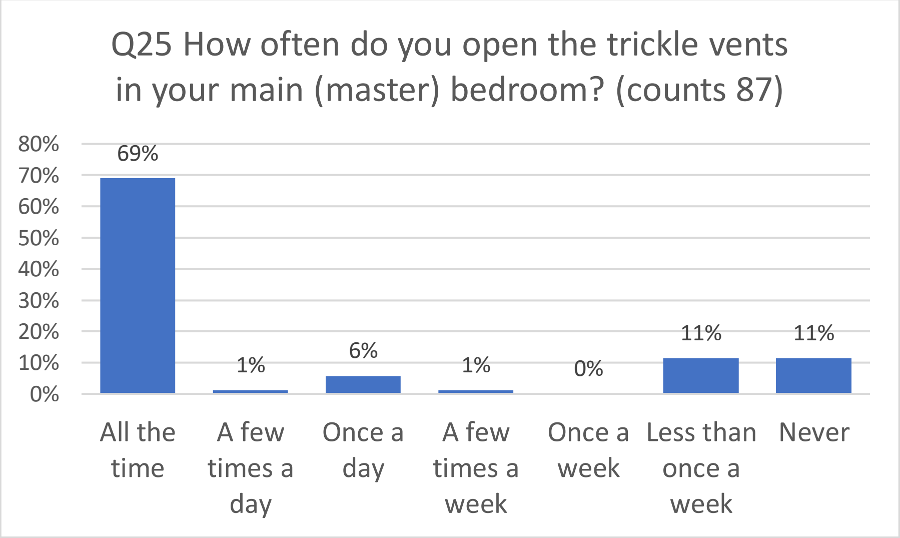
Q23 Other (please specify)

"Window open every day
N/A
The window frames are very stiff.
Cold outside.
Rain can come in at times."

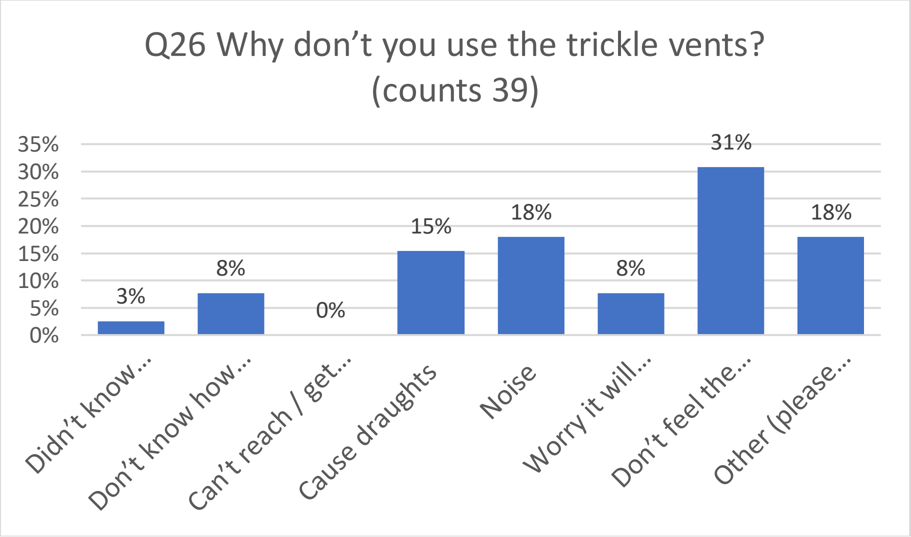
Q24 Do your main (master) bedroom windows have trickle ventilators?



Q25 How often do you open the trickle vents in your main (master) bedroom?



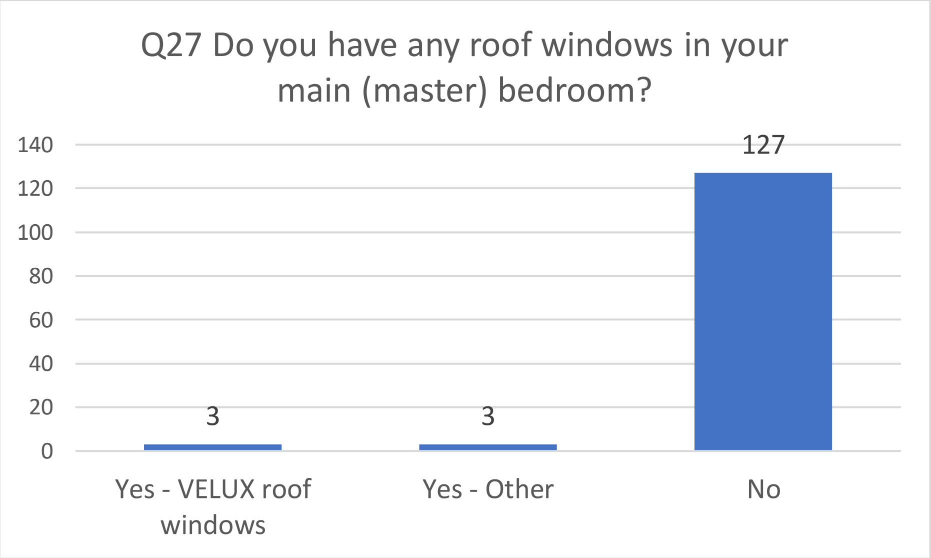
Q26 Why don’t you use the trickle vents?



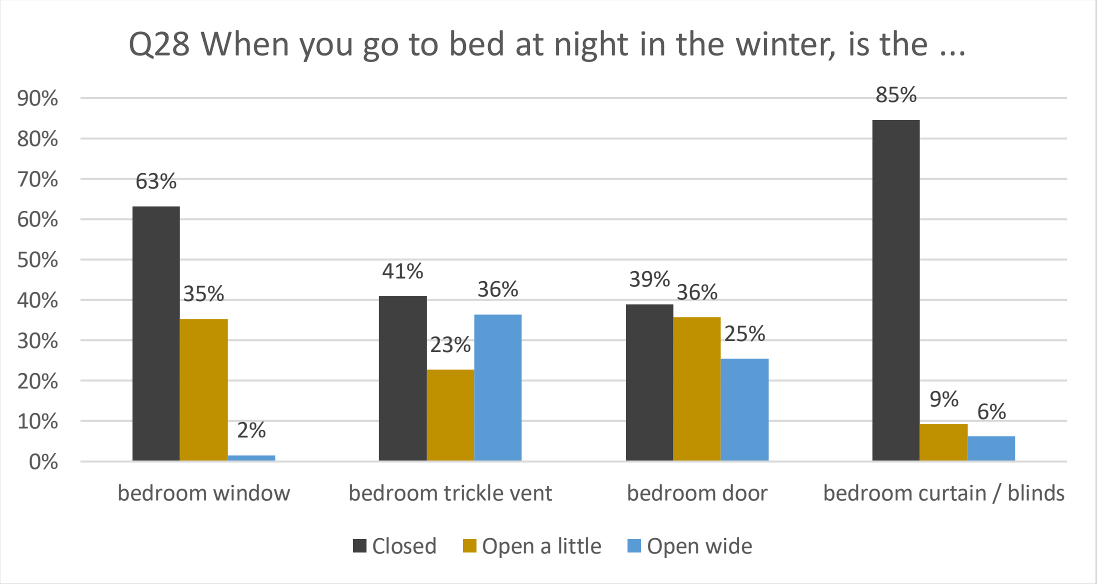
Q26 Other (please specify)

“Vents open all the time
It gets very cold
N/A
Always open.
Windows open frequently.
Had t be closed off
I do”

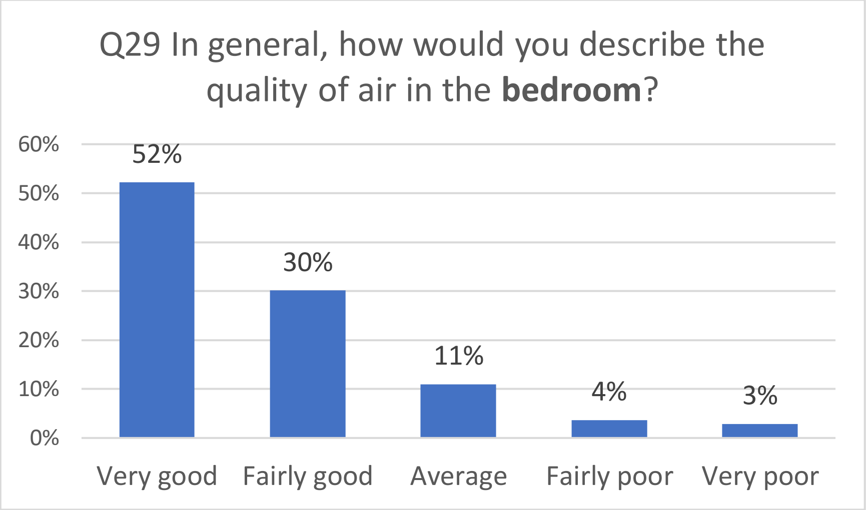
Q27 Do you have any roof windows in your main (master) bedroom?



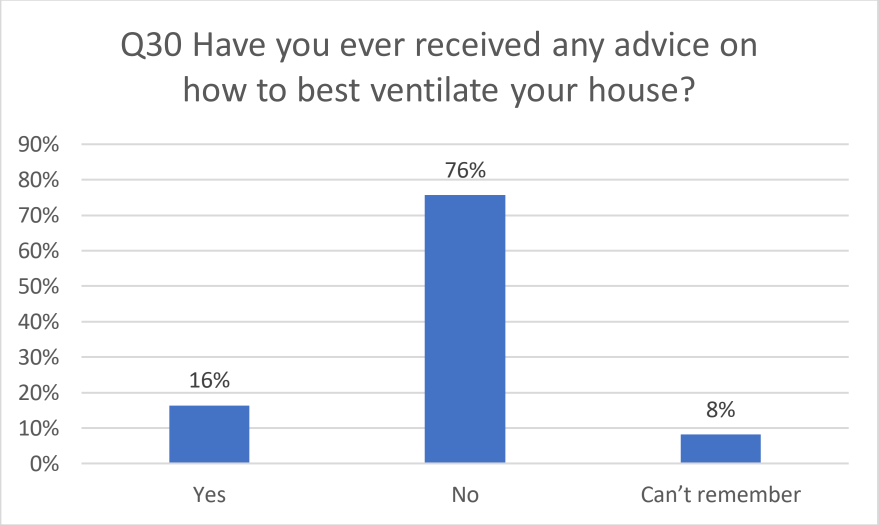
Q28 When you go to bed at night in the winter, is the bedroom window:



Q29 In general, how would you describe the quality of air in the bedroom?



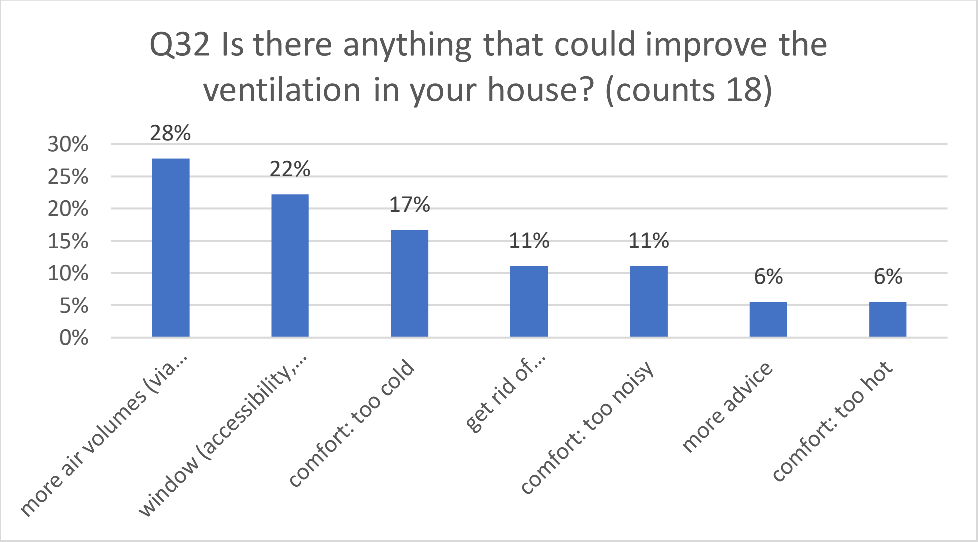
Q30 Have you ever received any advice on how best to ventilate the house?



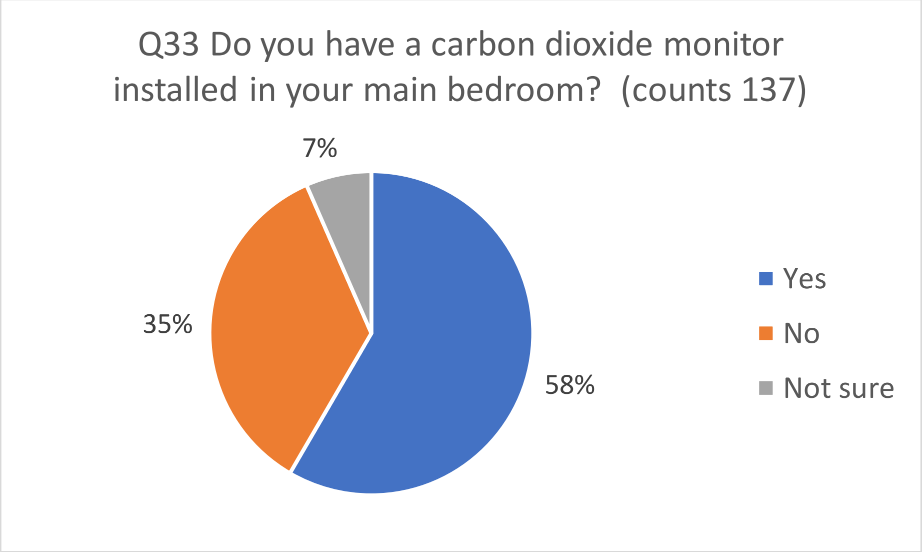
Q31 What was this advice?

“To open the trickle vents
Open the windows more often.
To leave the vents open
To air the place. Had a problem which glen oaks know about
To keep the vents open
Keep vents open
Told to keep the vents open
How to work the co2 monitor”

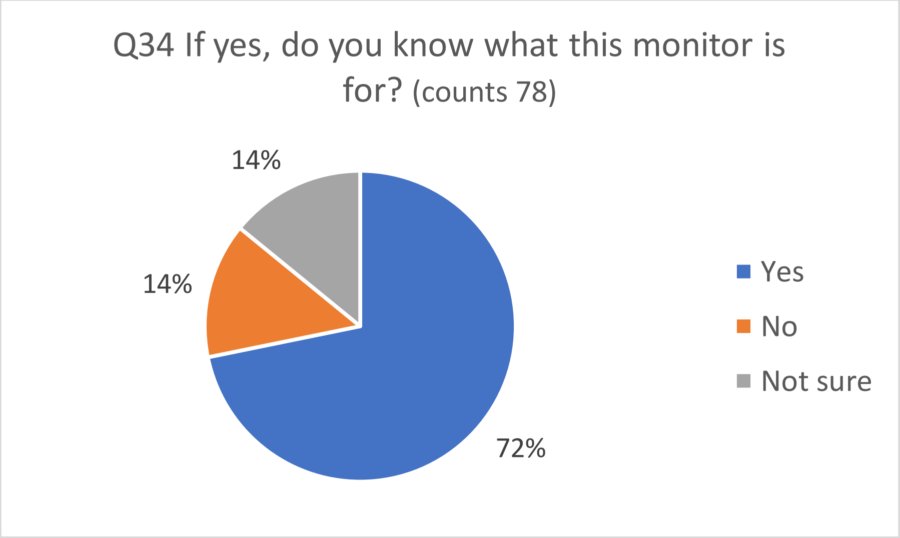
Q32 Is there anything that could improve the ventilation in your house?



Q33 [Showcard – carbon dioxide monitor] Do you have a carbon dioxide monitor installed in your main bedroom?



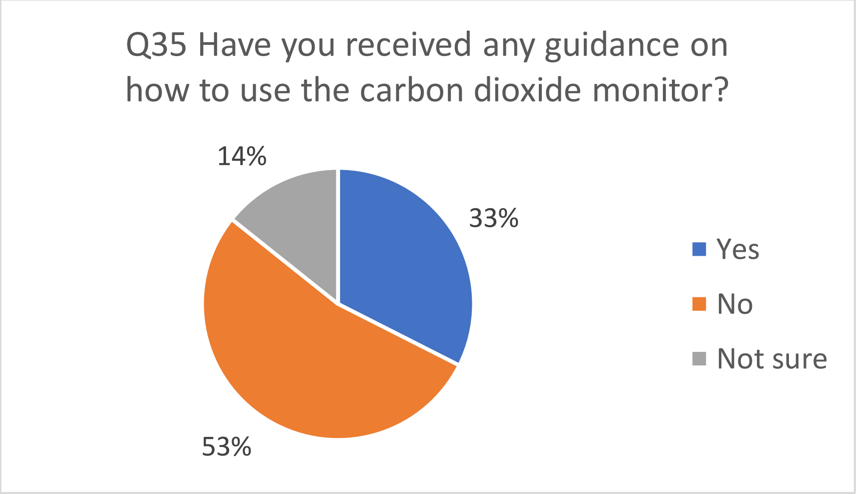
Q34 If yes, do you know what this monitor is for?



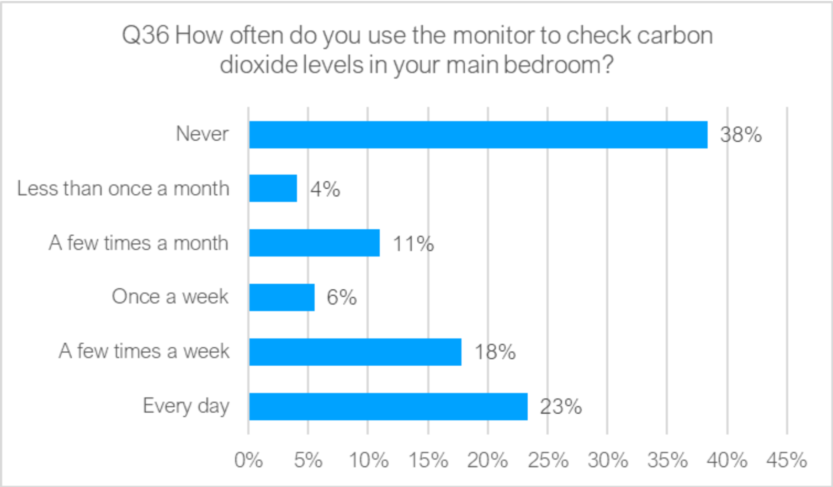
Q34a Yes (please explain)

“Should CO2 reach dangerous level it will sound
Monitor CO2 levels
Monitor air quality
To show oxygen levels
Not 100%, think it measures air in the room
To detect high levels of CO2 from gas boiler
To tell information on the pollution or contaminants
Moisture in the room
To let us know when cause it is too high
Gases
it detects gas leaks
To detect smoke or gas
In case we get poisoned
For the gas escape
Used to detect carbon monoxide levels”

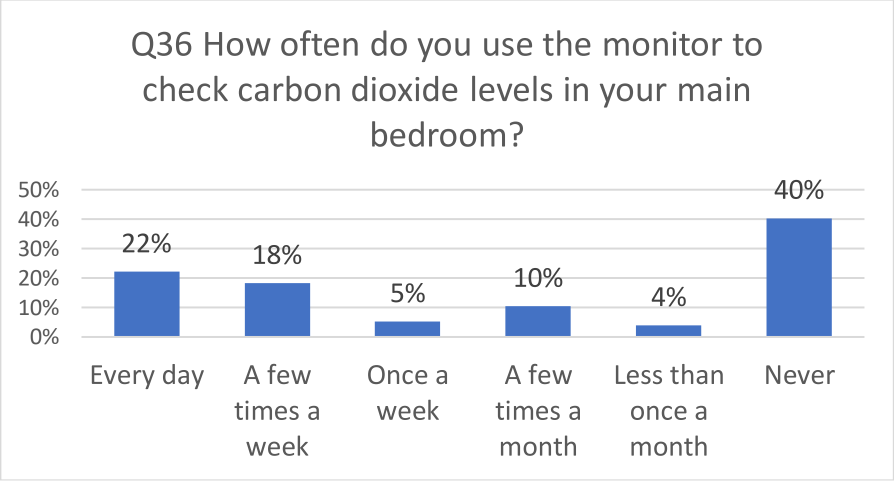
Q35 Have you received any guidance on how to use the carbon dioxide monitor?



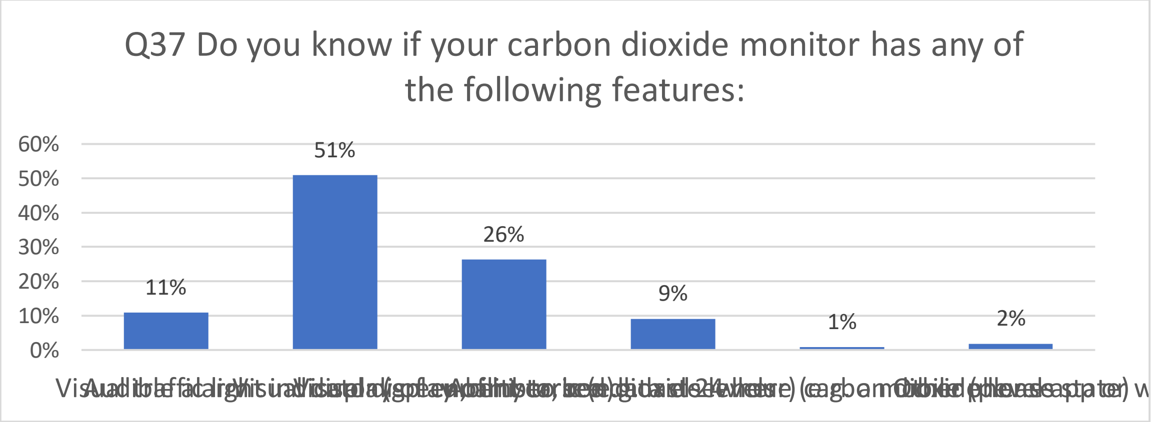
Q35a If yes, what was this advice?



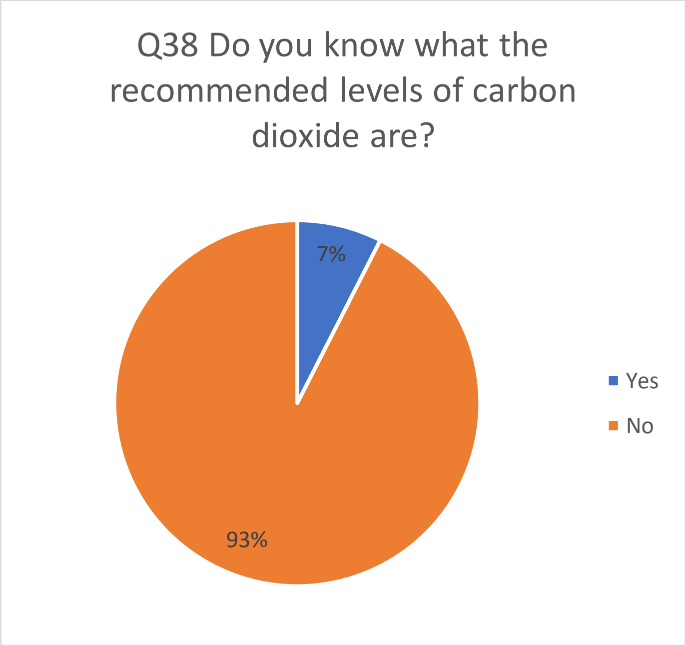
Q36 How often do you use the monitor to check carbon dioxide levels in your main bedroom?



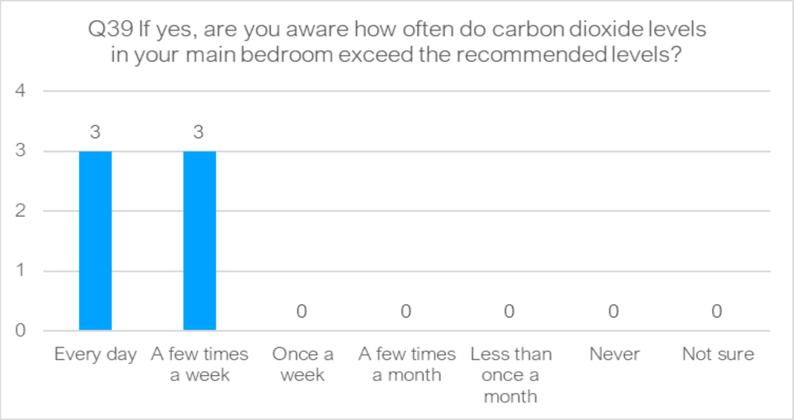
Q37 Do you know if your carbon dioxide monitor has any of the following features:



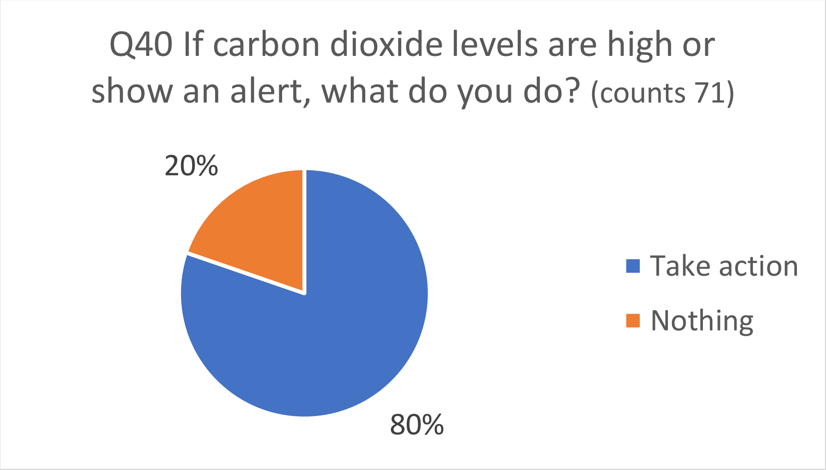
Q38 Do you know what the recommended levels of carbon dioxide are?



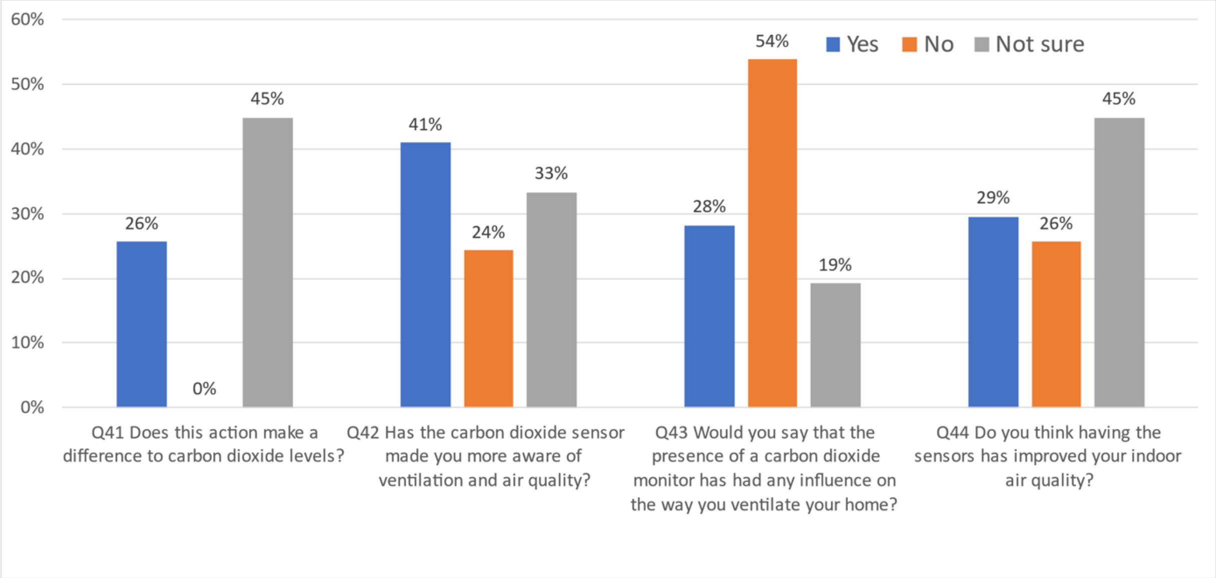
Q39 If yes, are you aware how often do carbon dioxide levels in your main bedroom exceed the recommended levels?



Q40 If carbon dioxide levels are high or show an alert, what do you do? (*If nothing, why not? - [GO TO Q48])

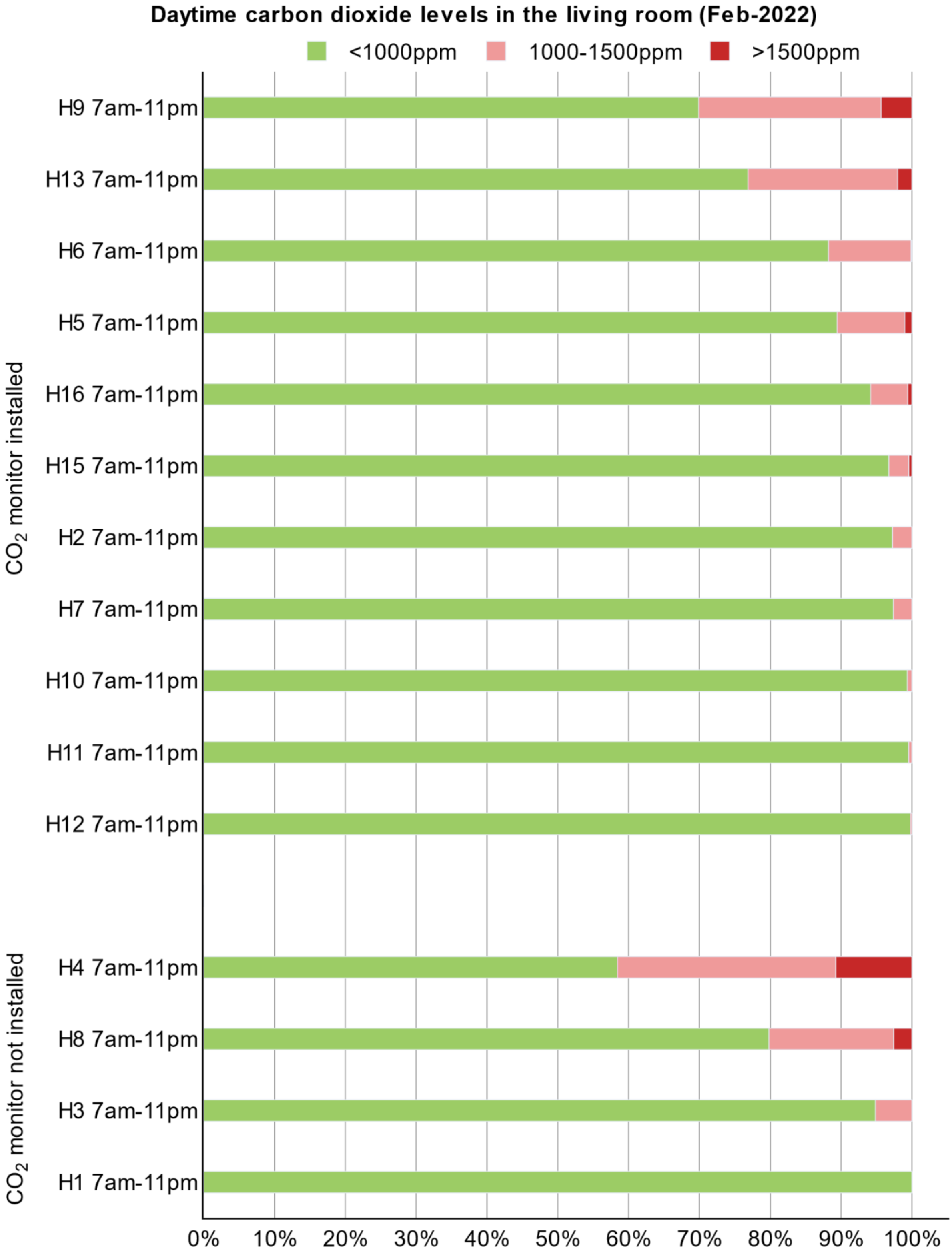


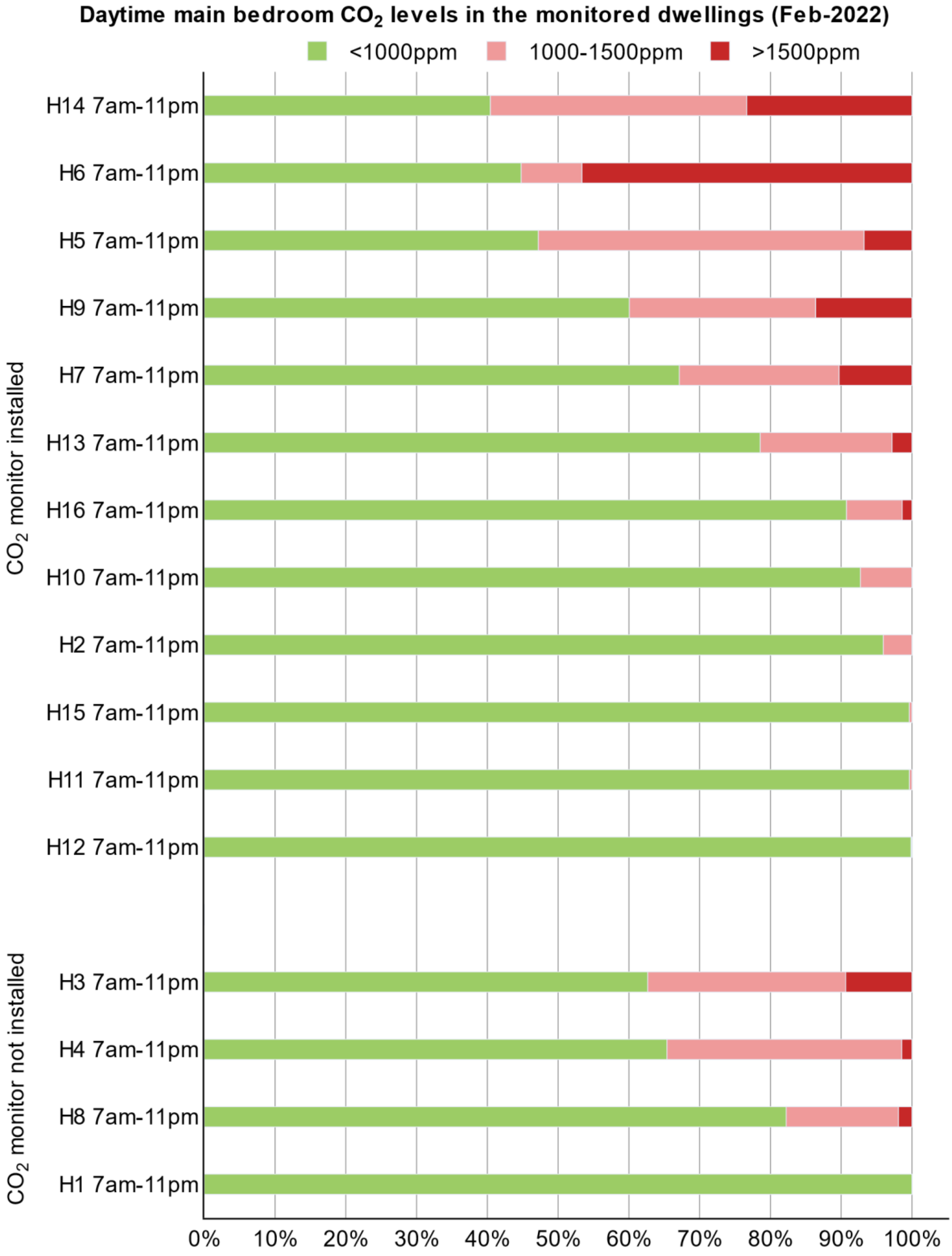
Q41 – Q44

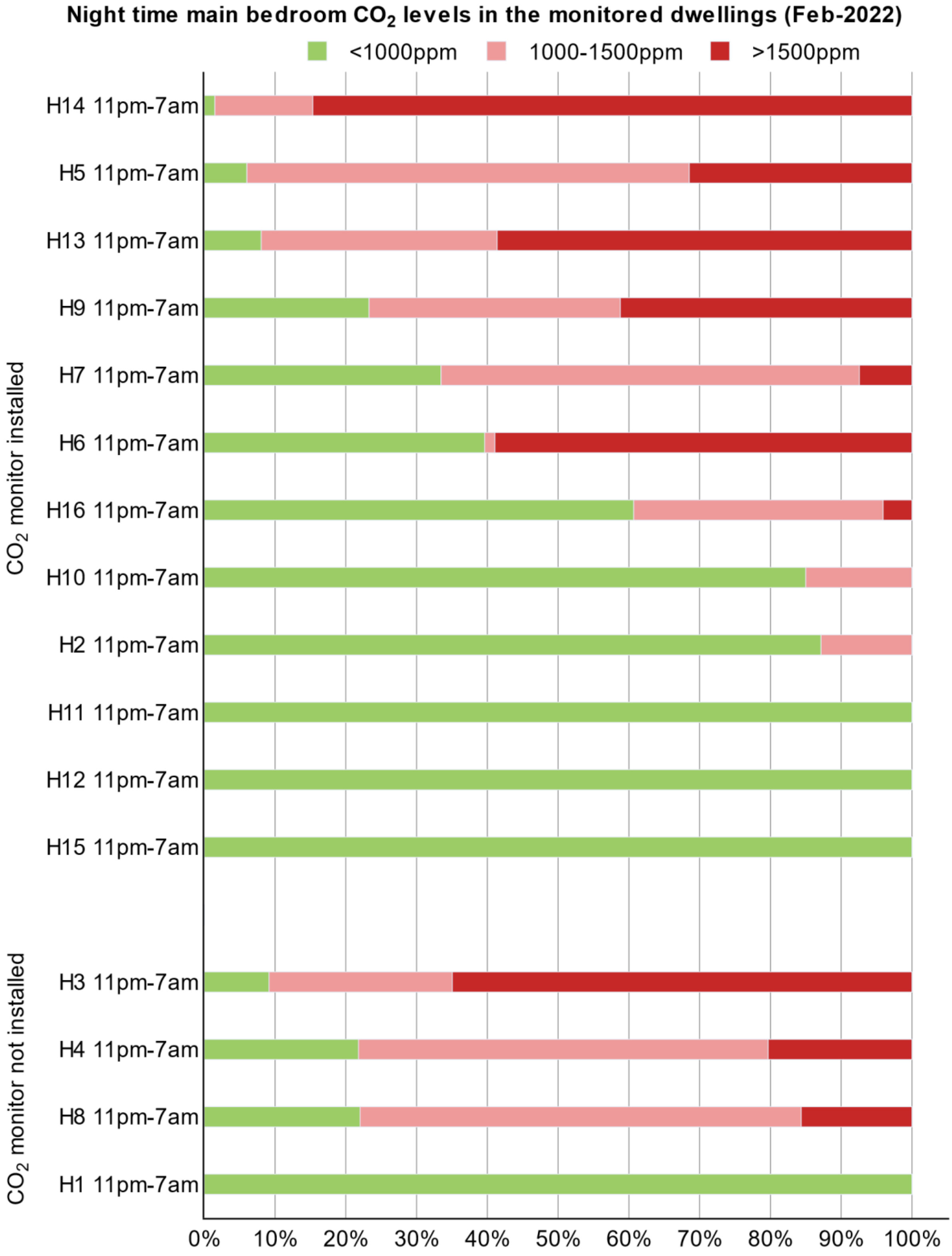


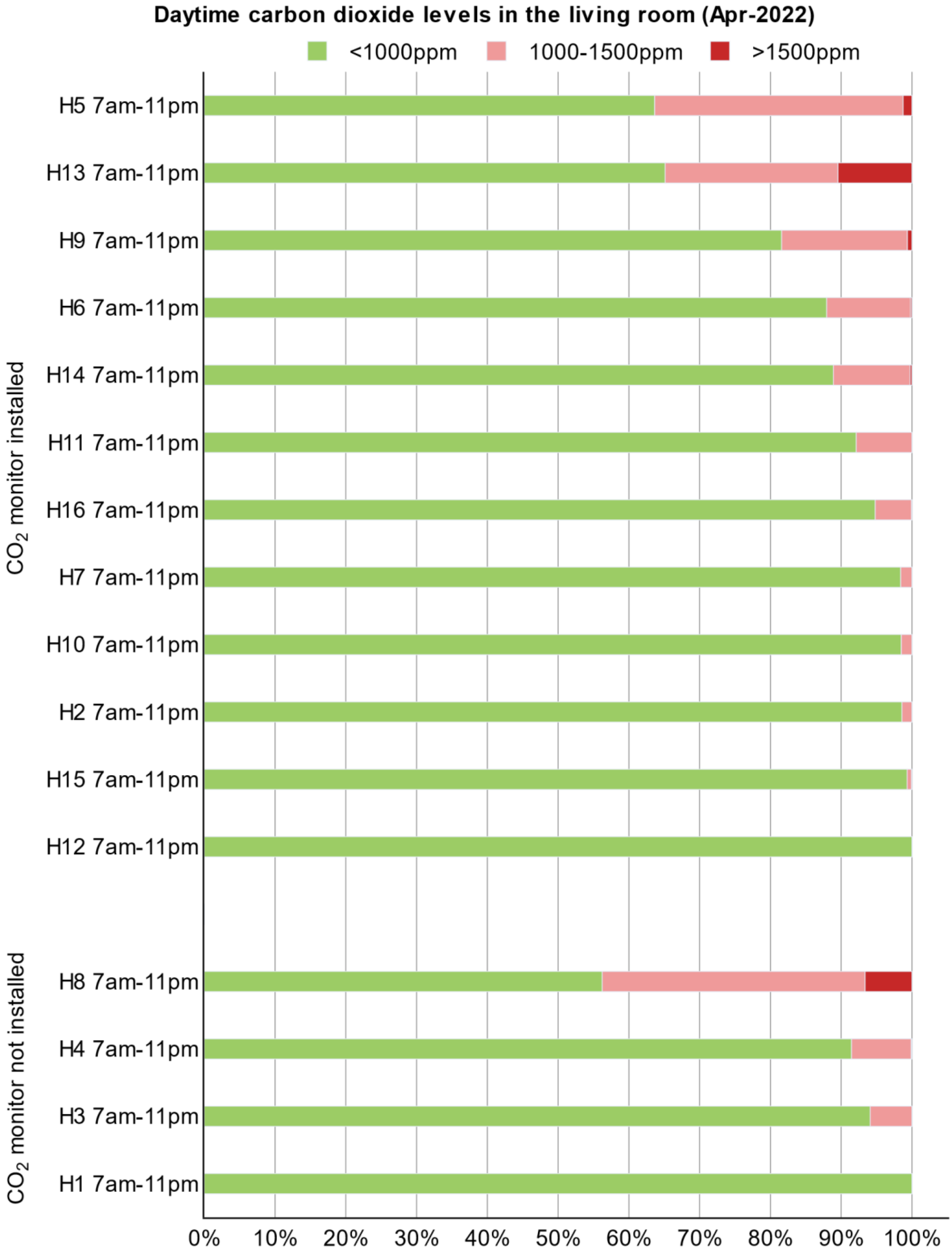
Annex C: long term monitoring

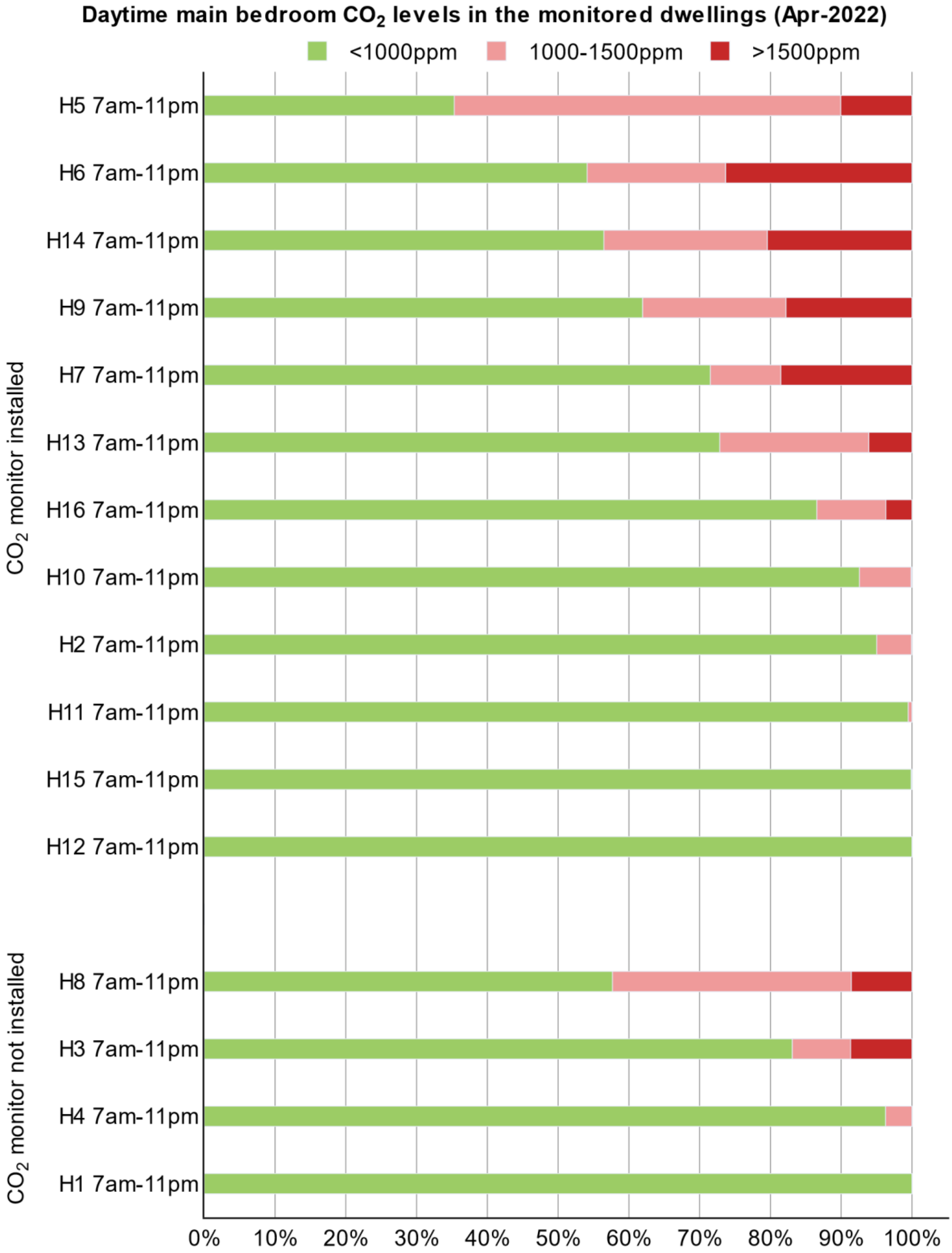
house ID	Kitchen dMEV test		Bathroom dMEV test		main bedroom ventilation system conditions				Ventilation provision according to Building Standards 2015	Q14. Do you know if the trickle ventilators are		Q18c.In winter, how often are the windows usually open in the main bedroom during the night?	Q21. Overnight, do you normally keep your bedroom door:	Q22. Overnight in your bedroom, do you normally keep curtains/blinds:	Q33 - Do you have a carbon dioxide (CO2) monitor installed in your main bedroom:	RESULTS: visual inspection of plotted data		
	trickle mode (ref. 6 l/s)	boost mode (ref. 13 l/s)	trickle mode (ref. 4 l/s)	boost mode (ref. 8 l/s)	trickle vent EA	trickle vent % of opening	door under cut (mm)	night occupancy (A-adult, C-child)		Living Room	Main Bedroom					T (17 C - 24 C)	RH (40% - 60%)	CO2 (max 1000 PPM)
1	14	18.6	3.2	12	only tilted windows	-	-	2A	N/A (pre-2015)	N/A	N/A	Daily	OPEN	Closed	No	in range	marg. low	below thres.
2	4.8	9.8	2.6	4.5	2300 mm2 x 2 units	100%	5	2A	sub-optimal	OPEN	OPEN	Never	OPEN	Closed	YES	in range	in range	marg. high
3	7.8	not availabl	6.9	11	5000 mm2 x 1 unit	100%	4	1A	N/A (pre-2015)	OPEN	OPEN	Never	Closed	OPEN	No	in range	in range	marg. high
4	5.3	11.5	3	5.6	4200 mm2 x 2 units	50%	4	1A	N/A (pre-2015)	OPEN	Closed	Never	OPEN	Closed	No	in range	marg. high	marg. high
5	0	3.4	4.1	6.7	2500 mm2 x 1 unit	100%	2	2A	sub-optimal	OPEN	OPEN	Never	Closed	Closed	YES	in range	in range	high
6	2.2	2.6	6.4	7.9	2500 mm2 x 3 units	66%	10	1A	sub-optimal	OPEN	OPEN	Never	Closed	-	YES	in range	high	too high
7	0	0	7.2	6.4	5000 mm2 x 1 unit	100%	18	1A	sub-optimal	OPEN	OPEN	Never	Closed	Closed	YES	low	in range	high
8	7.4	10.9	7.7	11	only tilted windows	-	19	2A	N/A (pre-2015)	Closed	Closed	Never	Closed	Closed	No	in range	in range	high
9	2	3.7	4.5	9	2500 mm2 x 1 unit	100%	19	2A	sub-optimal	N/A	N/A	Never	OPEN	Closed	YES	in range	in range	below thres.
10	5.8	15.5	3.8	8.8	5000 mm2 x 1 unit	100%	9	1A	sub-optimal	OPEN	OPEN	Never	Closed	Closed	YES	in range	in range	marg. high
11	3	4.9	2.2	4	3200 mm2 x 1 unit	0%	4	1A	sub-optimal	OPEN	OPEN	Never	OPEN	Closed	YES	in range	in range	below thres.
12	8.6	11.8	6.6	20	3200 mm2 x 1 unit	0%	4	2A	sub-optimal	Don't Know	Don't Know	Weekly	OPEN	Closed	YES	in range	marg. low	below thres.
13	6.7	13.4	4.7	19	3200 mm2 x 1 unit	0%	4	2A	sub-optimal	OPEN	OPEN	Never	Closed	Closed	YES	in range	in range	high
14*	5.5	15.2	0	7.7	4200 mm2 x 2 units	50%	8	2A 1C	sub-optimal	Closed	Don't Know	Never	OPEN	Closed	YES	in range	in range	too high
15	6.5	11.9	inaccessible		9600 mm2 x 1 unit	0%	20	1A	sub-optimal	OPEN	OPEN	All the time	OPEN	OPEN	YES	in range	low	marg. high
16	2.8	4.9	inaccessible		4200 mm2 x 2 units	100%	16	1A	sub-optimal	OPEN	OPEN	Daily	OPEN	Closed	YES	in range	in range	marg. high

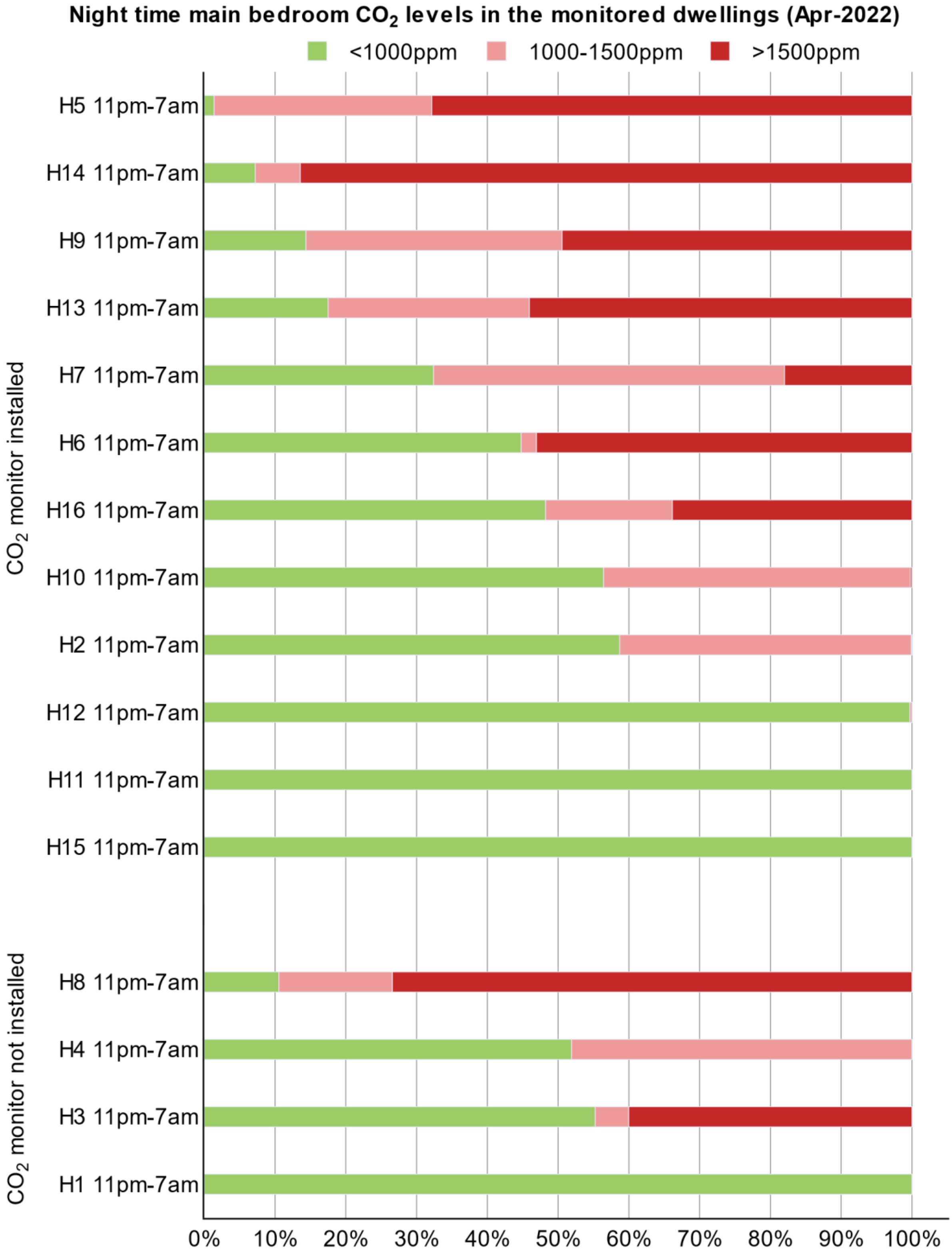

Daytime carbon dioxide levels in the living room (Feb-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO$_2$ monitor installed
H9 7am-11pm
H13 7am-11pm
H6 7am-11pm
H5 7am-11pm
H16 7am-11pm
H15 7am-11pm
H2 7am-11pm
H7 7am-11pm
H10 7am-11pm
H11 7am-11pm
H12 7am-11pm
CO$_2$ monitor not installed
H4 7am-11pm
H8 7am-11pm
H3 7am-11pm
H1 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


Daytime main bedroom CO_2 levels in the monitored dwellings (Feb-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO_2 monitor installed
CO_2 monitor not installed
H14 7am-11pm
H6 7am-11pm
H5 7am-11pm
H9 7am-11pm
H7 7am-11pm
H13 7am-11pm
H16 7am-11pm
H10 7am-11pm
H2 7am-11pm
H15 7am-11pm
H11 7am-11pm
H12 7am-11pm
H3 7am-11pm
H4 7am-11pm
H8 7am-11pm
H1 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


Night time main bedroom CO_2 levels in the monitored dwellings (Feb-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO_2 monitor installed
H14 11pm-7am
H5 11pm-7am
H13 11pm-7am
H9 11pm-7am
H7 11pm-7am
H6 11pm-7am
H16 11pm-7am
H10 11pm-7am
H2 11pm-7am
H11 11pm-7am
H12 11pm-7am
H15 11pm-7am
CO_2 monitor not installed
H3 11pm-7am
H4 11pm-7am
H8 11pm-7am
H1 11pm-7am
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


Daytime carbon dioxide levels in the living room (Apr-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO$_2$ monitor installed
H5 7am-11pm
H13 7am-11pm
H9 7am-11pm
H6 7am-11pm
H14 7am-11pm
H11 7am-11pm
H16 7am-11pm
H7 7am-11pm
H10 7am-11pm
H2 7am-11pm
H15 7am-11pm
H12 7am-11pm
CO$_2$ monitor not installed
H8 7am-11pm
H4 7am-11pm
H3 7am-11pm
H1 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


Daytime main bedroom CO_2 levels in the monitored dwellings (Apr-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO_2 monitor installed
H5 7am-11pm
H6 7am-11pm
H14 7am-11pm
H9 7am-11pm
H7 7am-11pm
H13 7am-11pm
H16 7am-11pm
H10 7am-11pm
H2 7am-11pm
H11 7am-11pm
H15 7am-11pm
H12 7am-11pm
CO_2 monitor not installed
H8 7am-11pm
H3 7am-11pm
H4 7am-11pm
H1 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


Night time main bedroom CO_2 levels in the monitored dwellings (Apr-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO_2 monitor installed
CO_2 monitor not installed
H5 11pm-7am
H14 11pm-7am
H9 11pm-7am
H13 11pm-7am
H7 11pm-7am
H6 11pm-7am
H16 11pm-7am
H10 11pm-7am
H2 11pm-7am
H12 11pm-7am
H11 11pm-7am
H15 11pm-7am
H8 11pm-7am
H4 11pm-7am
H3 11pm-7am
H1 11pm-7am
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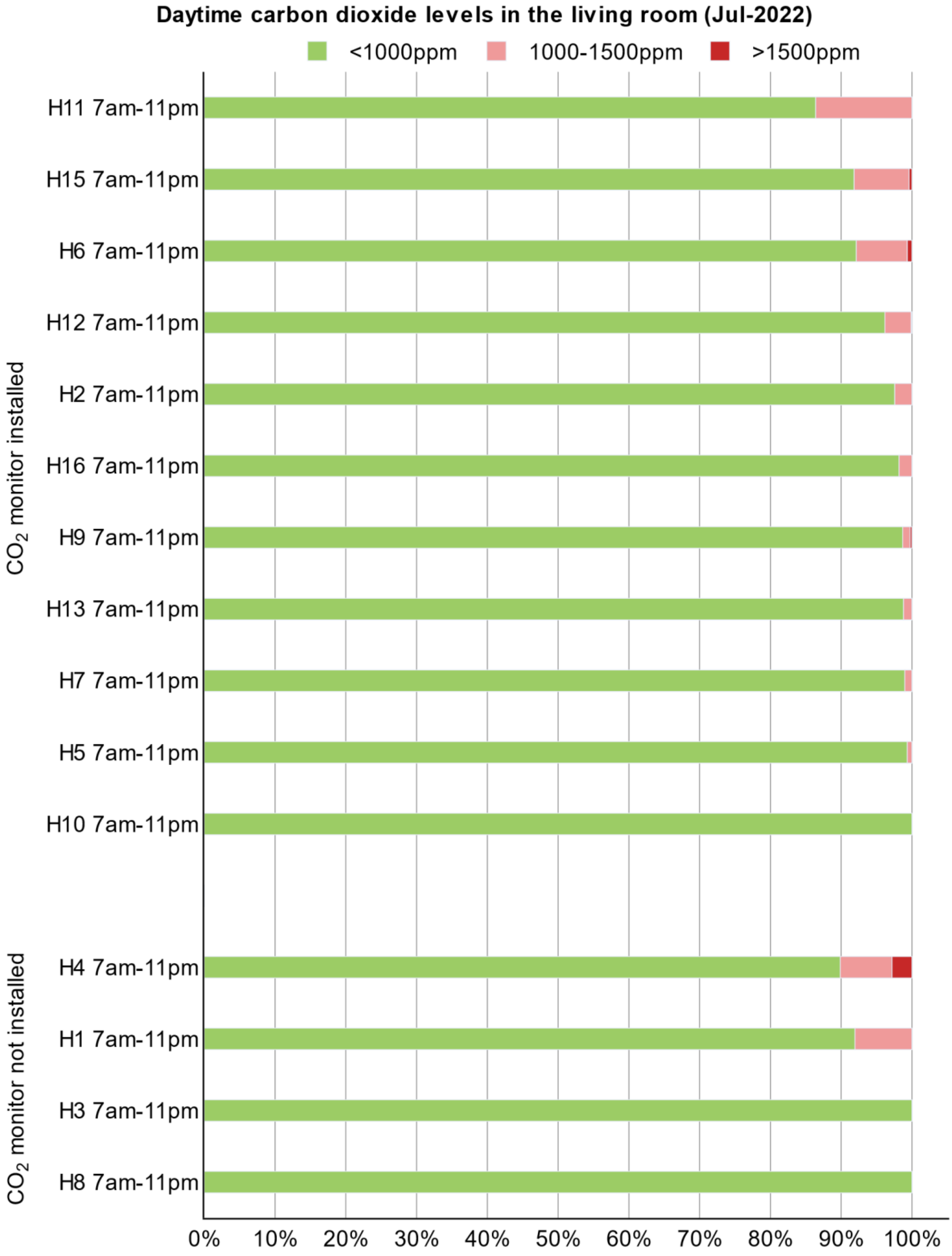
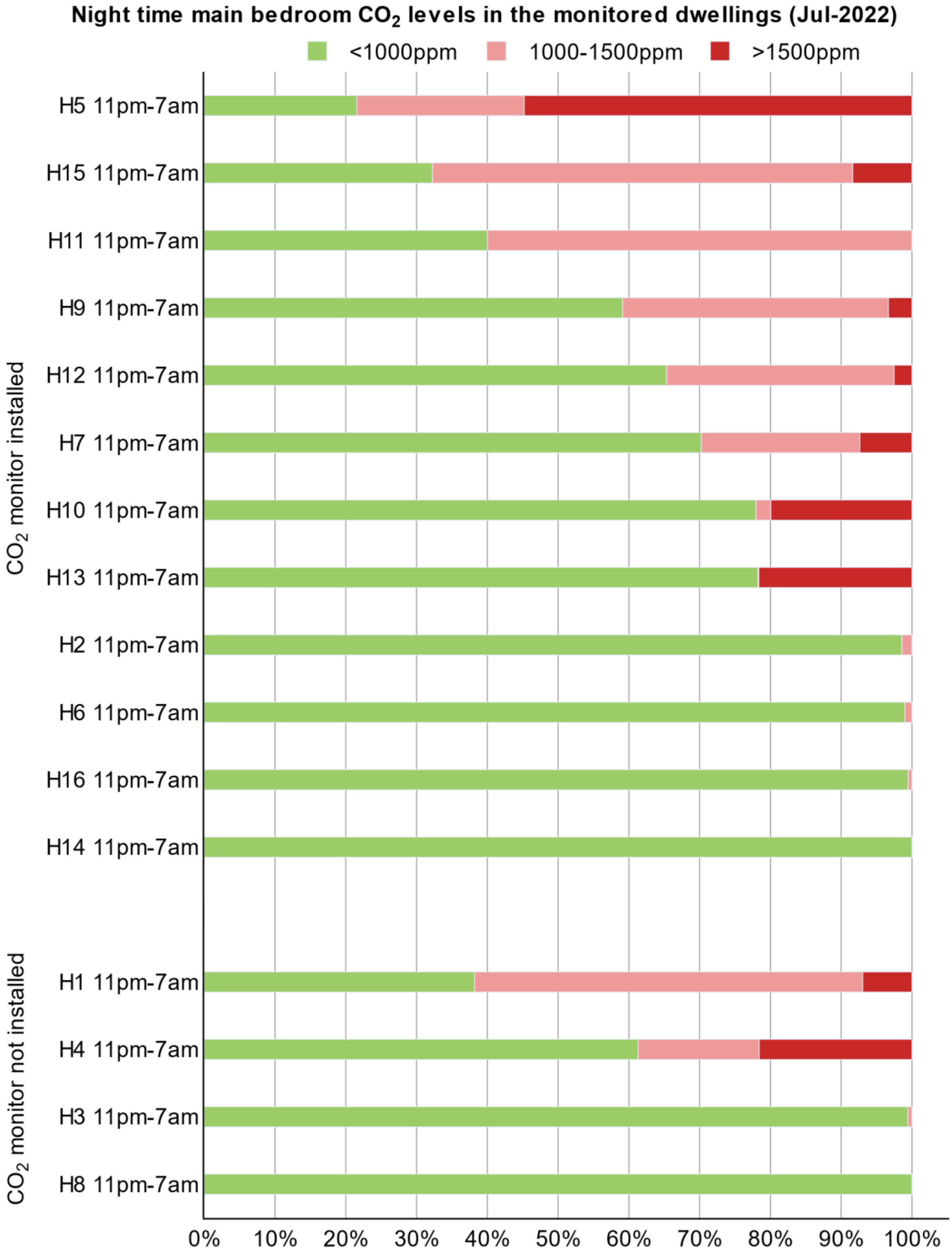
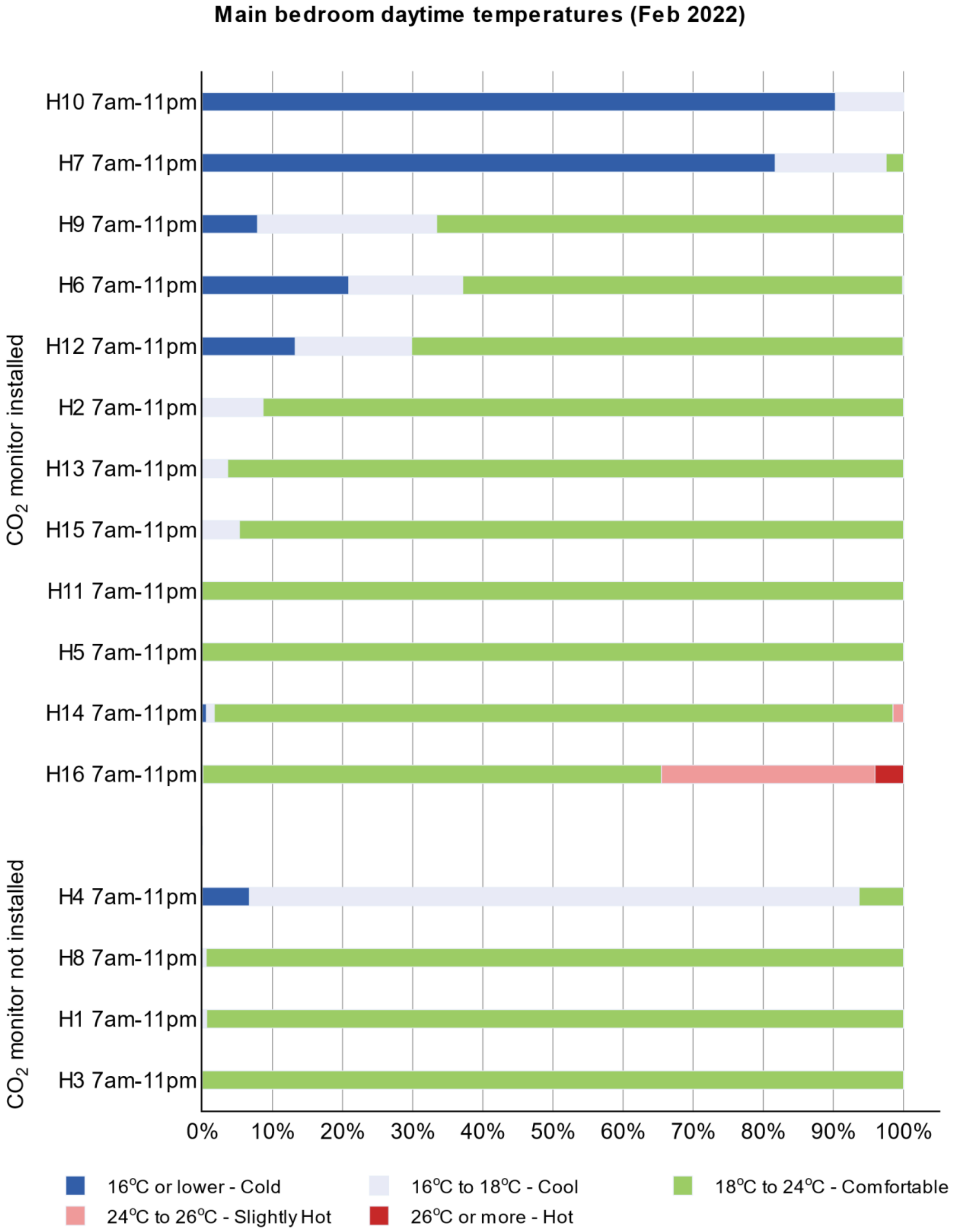
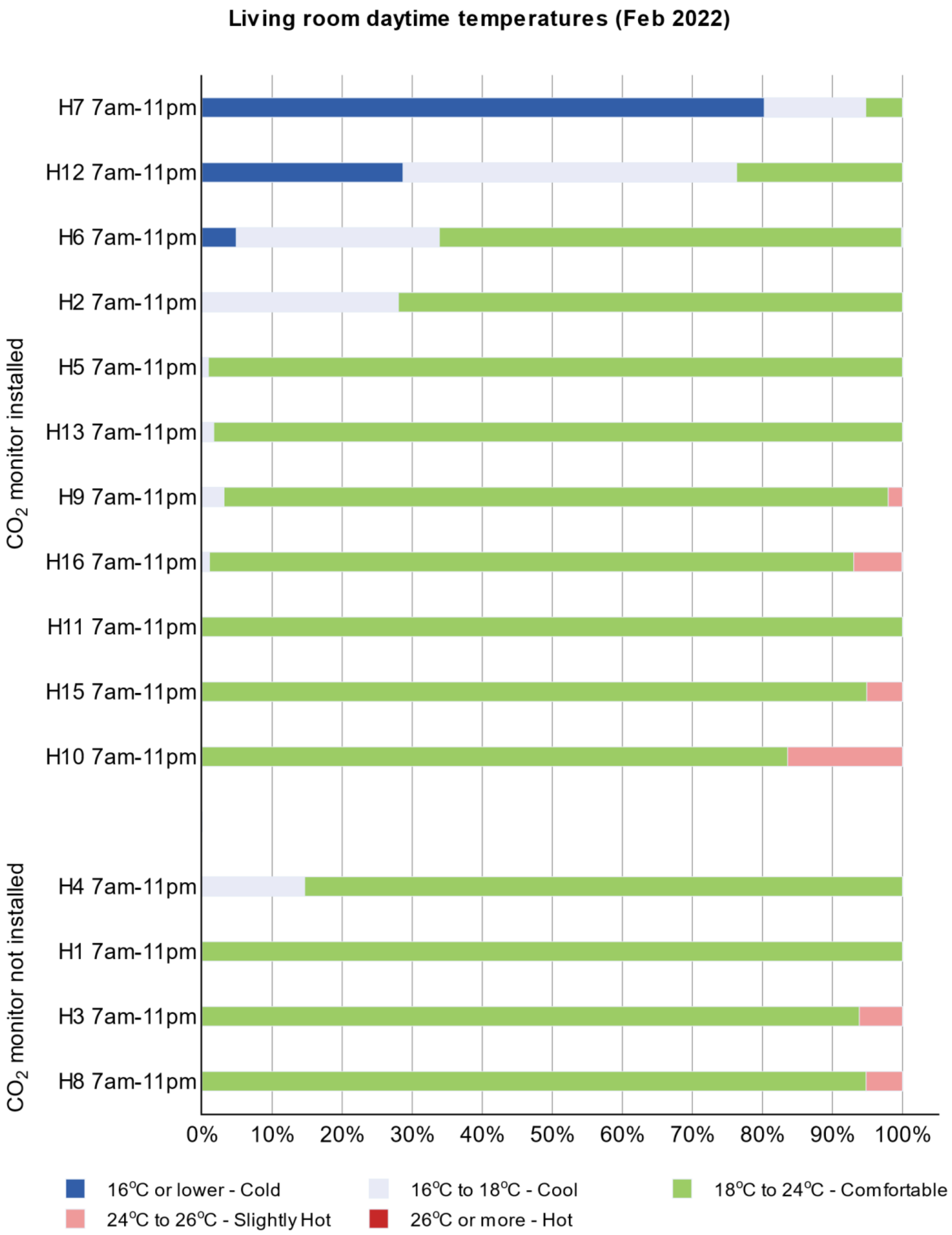
70%
80%
90%
100%

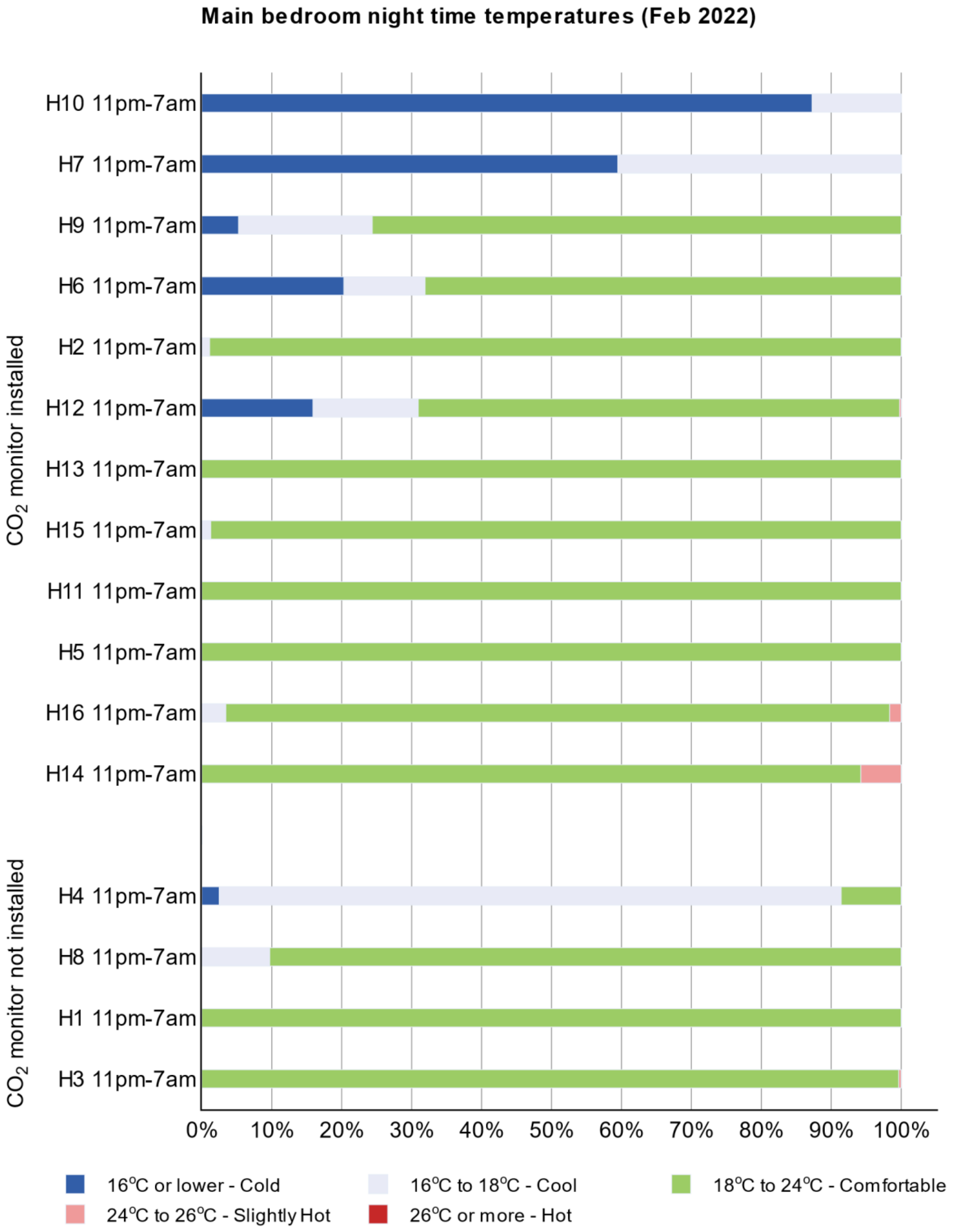

Daytime carbon dioxide levels in the living room (Jul-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO$_2$ monitor installed
H11 7am-11pm
H15 7am-11pm
H6 7am-11pm
H12 7am-11pm
H2 7am-11pm
H16 7am-11pm
H9 7am-11pm
H13 7am-11pm
H7 7am-11pm
H5 7am-11pm
H10 7am-11pm
CO$_2$ monitor not installed
H4 7am-11pm
H1 7am-11pm
H3 7am-11pm
H8 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

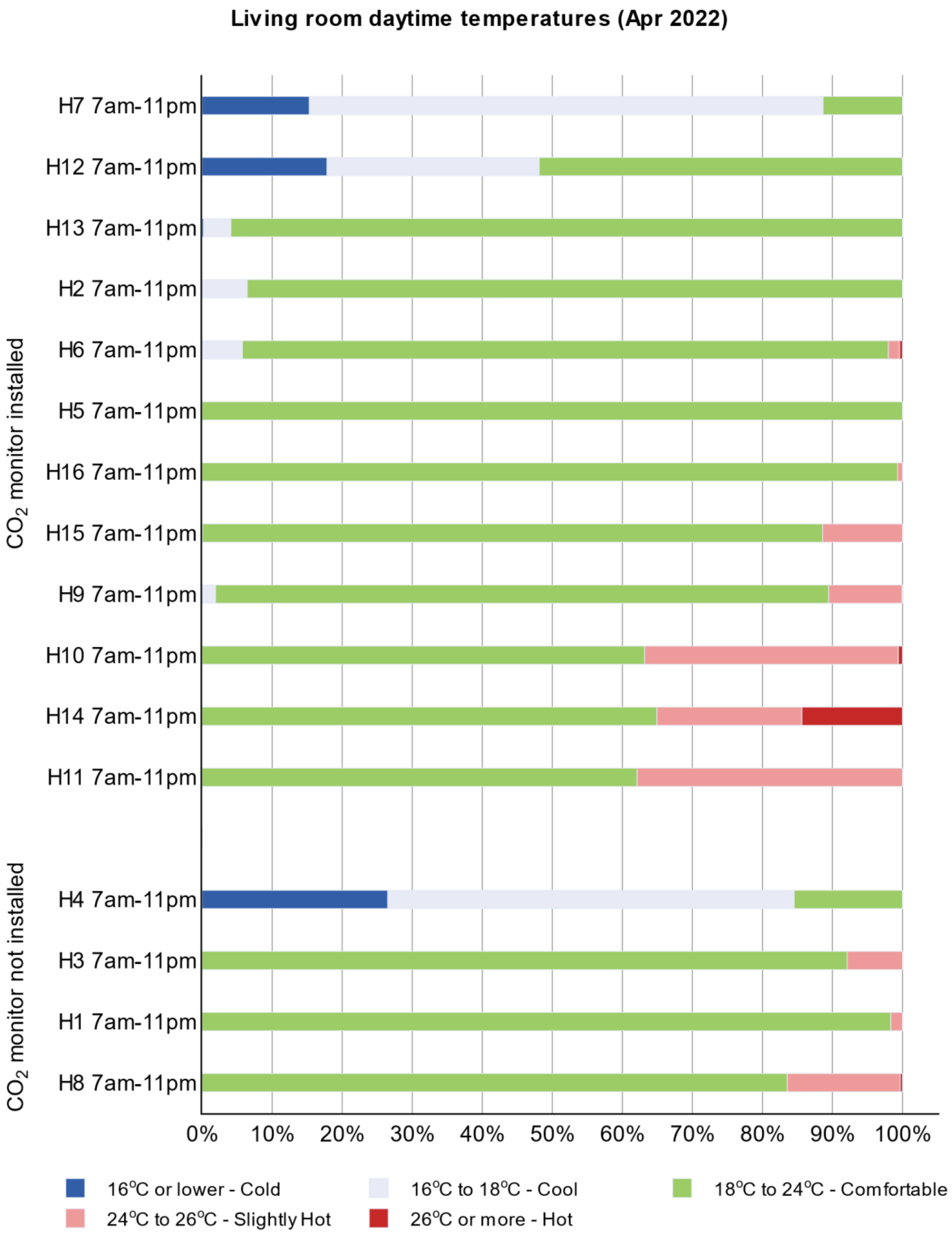

Daytime main bedroom CO_2 levels in the monitored dwellings (Jul-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO_2 monitor installed
CO_2 monitor not installed
H13 7am-11pm
H5 7am-11pm
H11 7am-11pm
H15 7am-11pm
H7 7am-11pm
H10 7am-11pm
H6 7am-11pm
H12 7am-11pm
H9 7am-11pm
H2 7am-11pm
H16 7am-11pm
H14 7am-11pm
H1 7am-11pm
H4 7am-11pm
H3 7am-11pm
H8 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

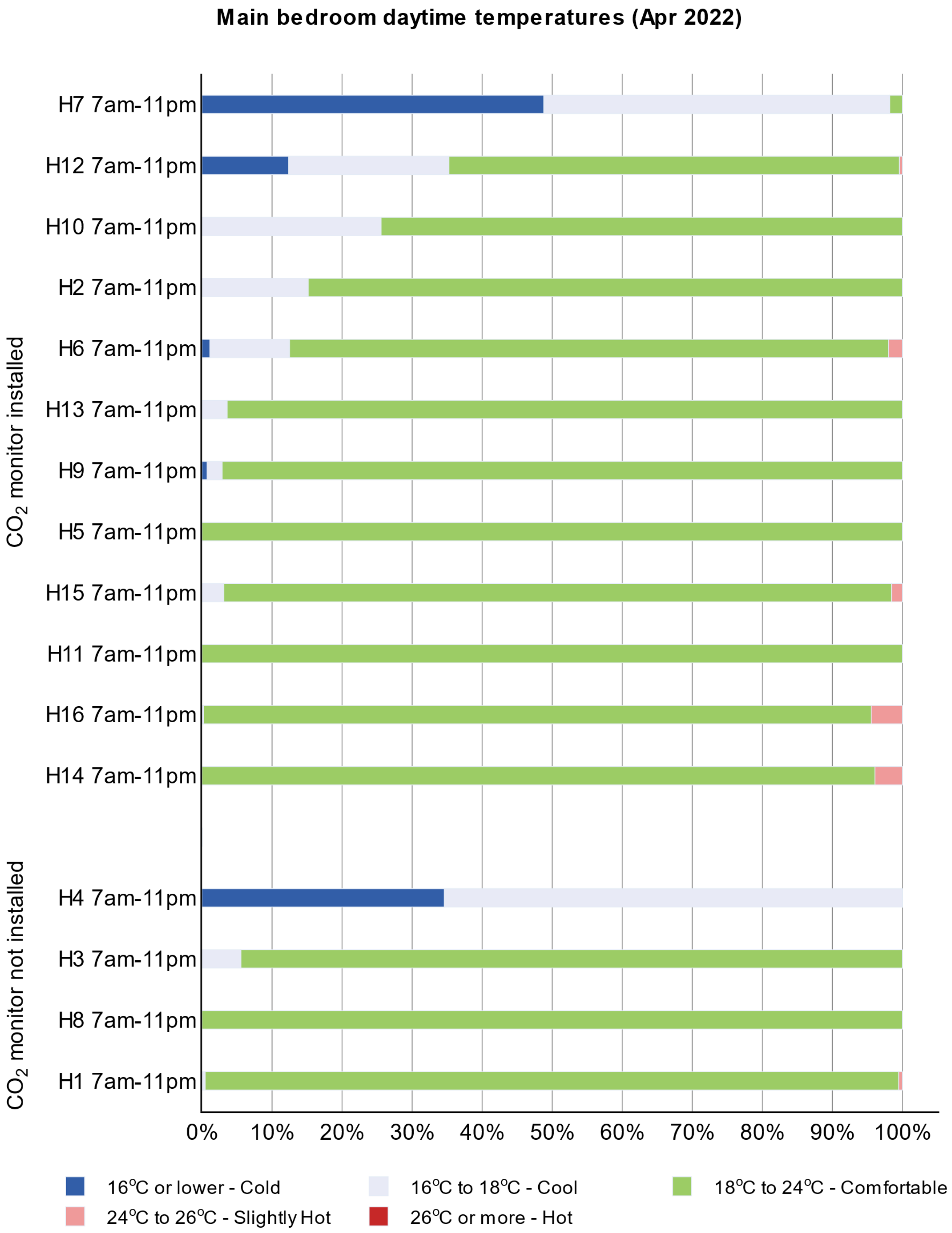

Night time main bedroom CO_2 levels in the monitored dwellings (Jul-2022)
<1000ppm
1000-1500ppm
>1500ppm
CO_2 monitor installed
H5 11pm-7am
H15 11pm-7am
H11 11pm-7am
H9 11pm-7am
H12 11pm-7am
H7 11pm-7am
H10 11pm-7am
H13 11pm-7am
H2 11pm-7am
H6 11pm-7am
H16 11pm-7am
H14 11pm-7am
CO_2 monitor not installed
H1 11pm-7am
H4 11pm-7am
H3 11pm-7am
H8 11pm-7am
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

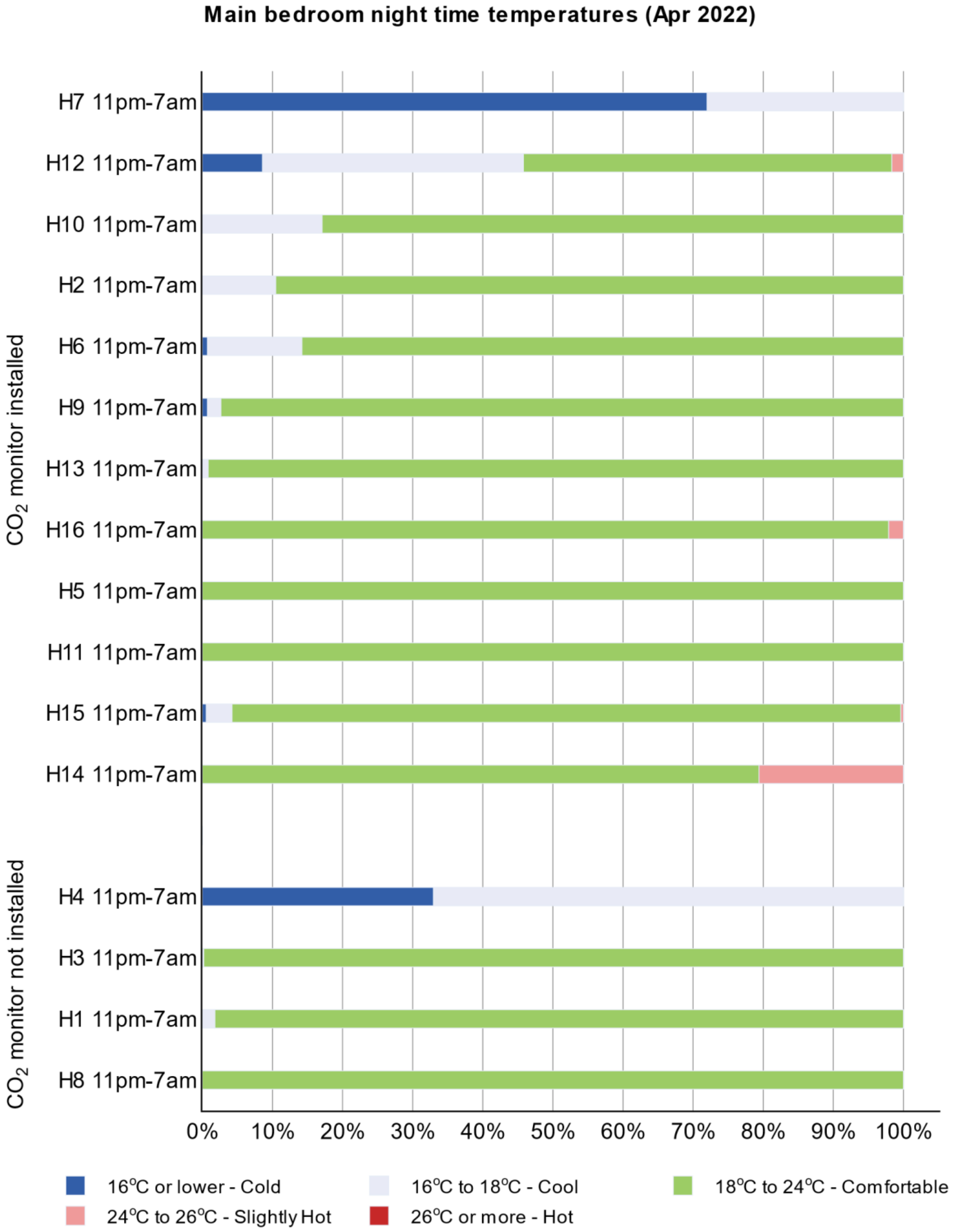

Main bedroom daytime temperatures (Feb 2022)
CO$_2$ monitor installed
CO$_2$ monitor not installed
H10 7am-11pm
H7 7am-11pm
H9 7am-11pm
H6 7am-11pm
H12 7am-11pm
H2 7am-11pm
H13 7am-11pm
H15 7am-11pm
H11 7am-11pm
H5 7am-11pm
H14 7am-11pm
H16 7am-11pm
H4 7am-11pm
H8 7am-11pm
H1 7am-11pm
H3 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot

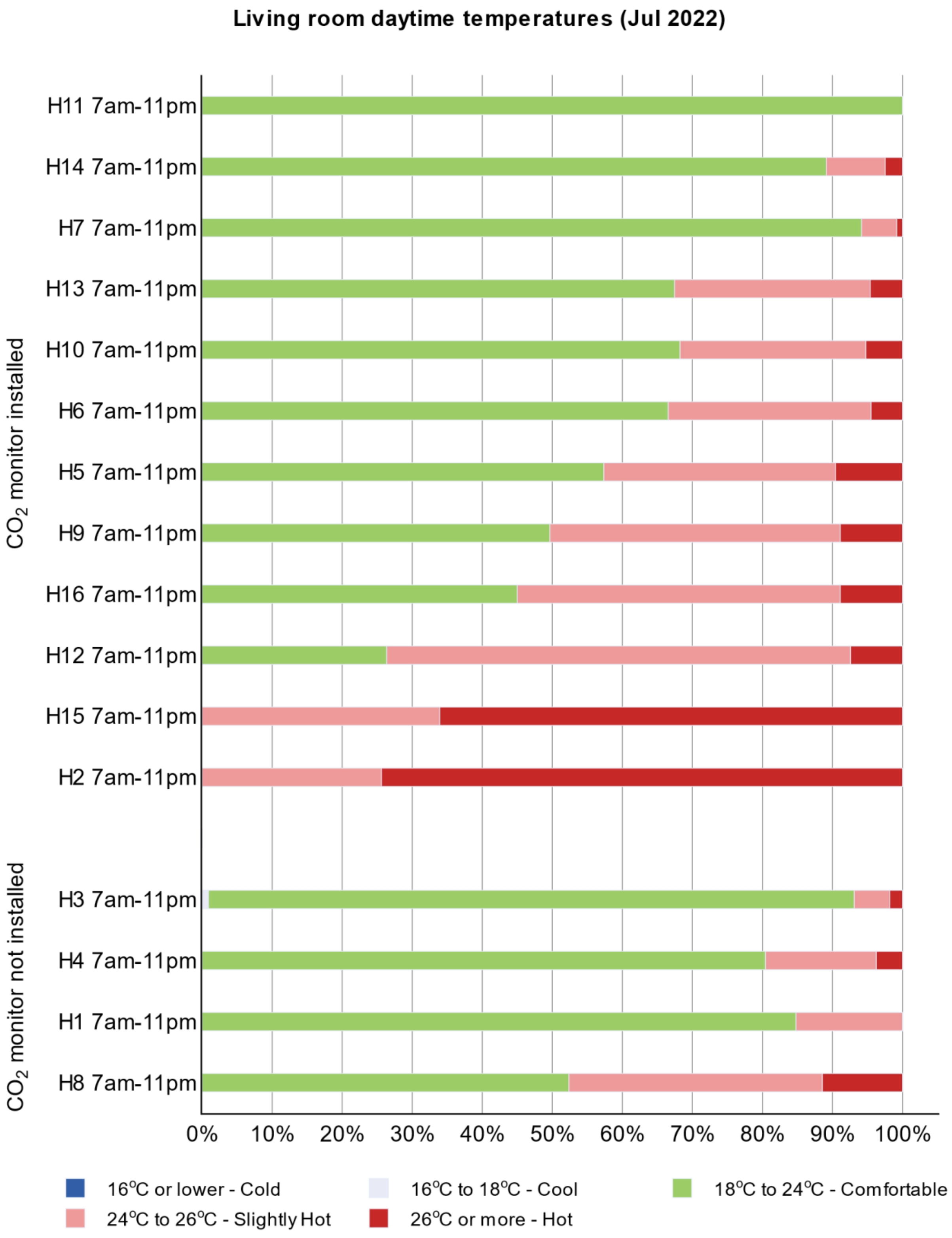

Living room daytime temperatures (Feb 2022)
CO$_2$ monitor installed
H7 7am-11pm
H12 7am-11pm
H6 7am-11pm
H2 7am-11pm
H5 7am-11pm
H13 7am-11pm
H9 7am-11pm
H16 7am-11pm
H11 7am-11pm
H15 7am-11pm
H10 7am-11pm
CO$_2$ monitor not installed
H4 7am-11pm
H1 7am-11pm
H3 7am-11pm
H8 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot

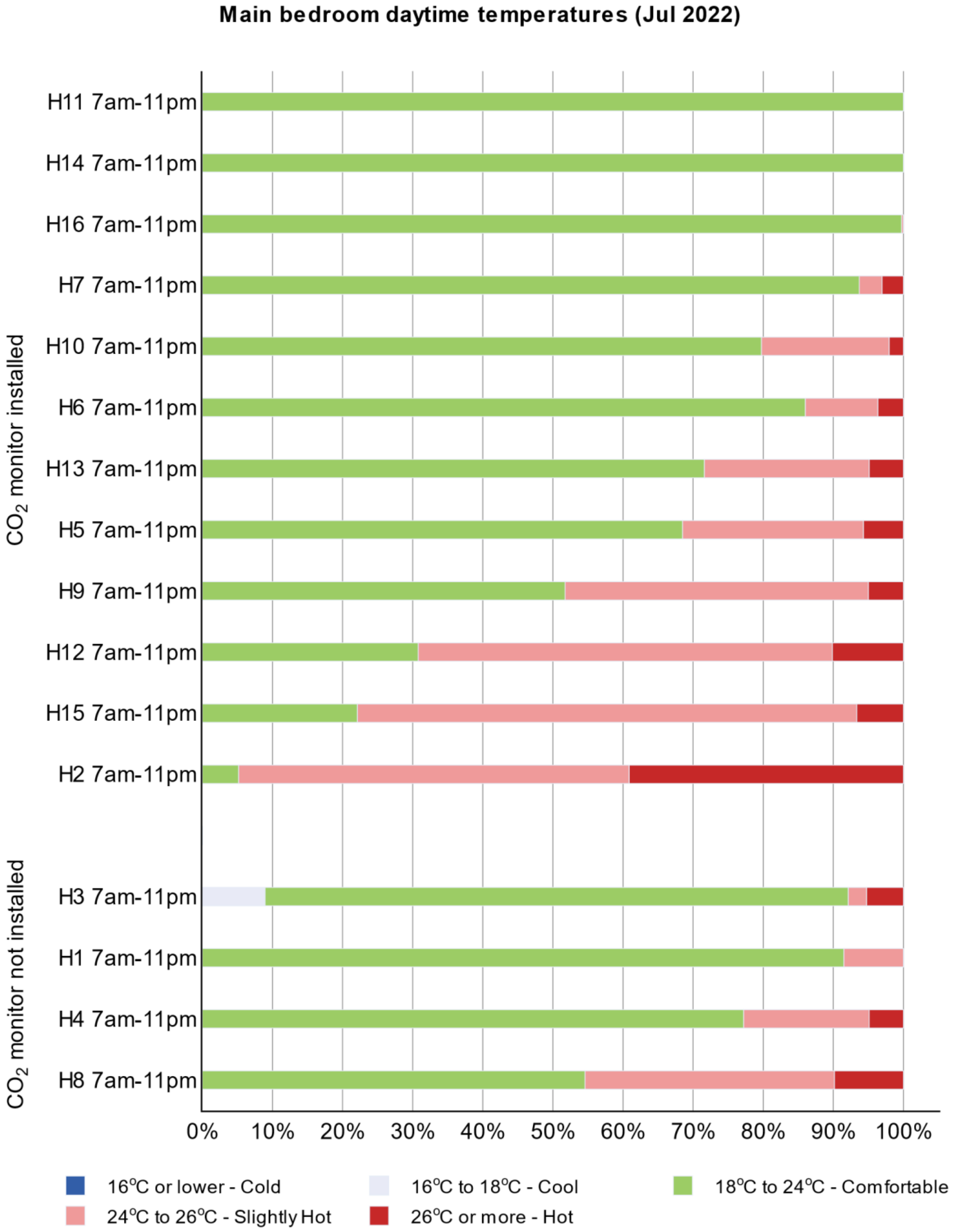

Main bedroom night time temperatures (Feb 2022)
CO$_2$ monitor installed
CO$_2$ monitor not installed
H10 11pm-7am
H7 11pm-7am
H9 11pm-7am
H6 11pm-7am
H2 11pm-7am
H12 11pm-7am
H13 11pm-7am
H15 11pm-7am
H11 11pm-7am
H5 11pm-7am
H16 11pm-7am
H14 11pm-7am
H4 11pm-7am
H8 11pm-7am
H1 11pm-7am
H3 11pm-7am
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot


Living room daytime temperatures (Apr 2022)
CO$_2$ monitor installed
CO$_2$ monitor not installed
H7 7am-11pm
H12 7am-11pm
H13 7am-11pm
H2 7am-11pm
H6 7am-11pm
H5 7am-11pm
H16 7am-11pm
H15 7am-11pm
H9 7am-11pm
H10 7am-11pm
H14 7am-11pm
H11 7am-11pm
H4 7am-11pm
H3 7am-11pm
H1 7am-11pm
H8 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot

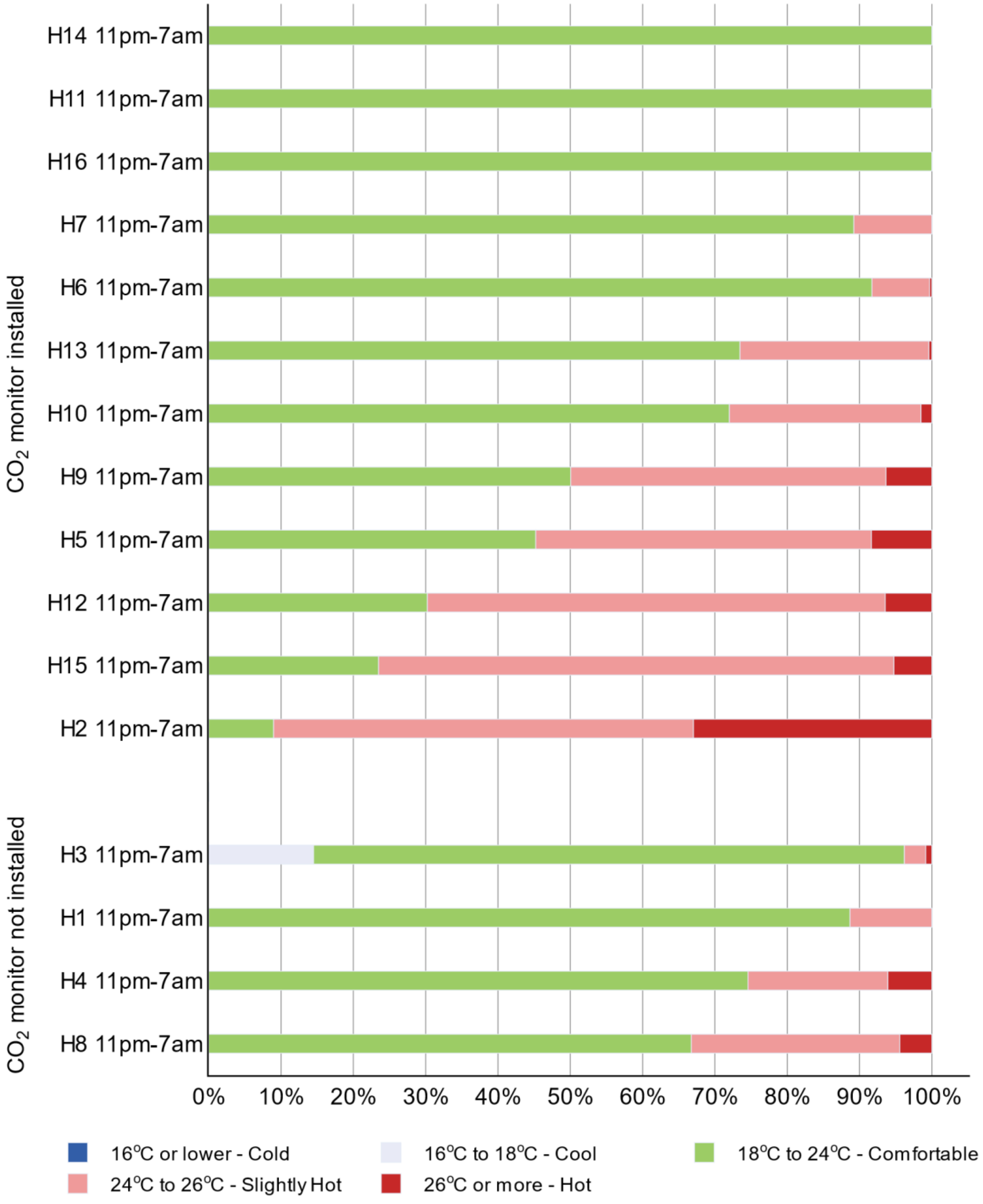

Main bedroom daytime temperatures (Apr 2022)
CO$_2$ monitor installed
H7 7am-11pm
H12 7am-11pm
H10 7am-11pm
H2 7am-11pm
H6 7am-11pm
H13 7am-11pm
H9 7am-11pm
H5 7am-11pm
H15 7am-11pm
H11 7am-11pm
H16 7am-11pm
H14 7am-11pm
CO$_2$ monitor not installed
H4 7am-11pm
H3 7am-11pm
H8 7am-11pm
H1 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot


Main bedroom night time temperatures (Apr 2022)
CO$_2$ monitor installed
H7 11pm-7am
H12 11pm-7am
H10 11pm-7am
H2 11pm-7am
H6 11pm-7am
H9 11pm-7am
H13 11pm-7am
H16 11pm-7am
H5 11pm-7am
H11 11pm-7am
H15 11pm-7am
H14 11pm-7am
CO$_2$ monitor not installed
H4 11pm-7am
H3 11pm-7am
H1 11pm-7am
H8 11pm-7am
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot


Living room daytime temperatures (Jul 2022)


Main bedroom daytime temperatures (Jul 2022)
CO2 monitor installed
H11 7am-11pm
H14 7am-11pm
H16 7am-11pm
H7 7am-11pm
H10 7am-11pm
H6 7am-11pm
H13 7am-11pm
H5 7am-11pm
H9 7am-11pm
H12 7am-11pm
H15 7am-11pm
H2 7am-11pm
CO2 monitor not installed
H3 7am-11pm
H1 7am-11pm
H4 7am-11pm
H8 7am-11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
16°C or lower - Cold
16°C to 18°C - Cool
18°C to 24°C - Comfortable
24°C to 26°C - Slightly Hot
26°C or more - Hot

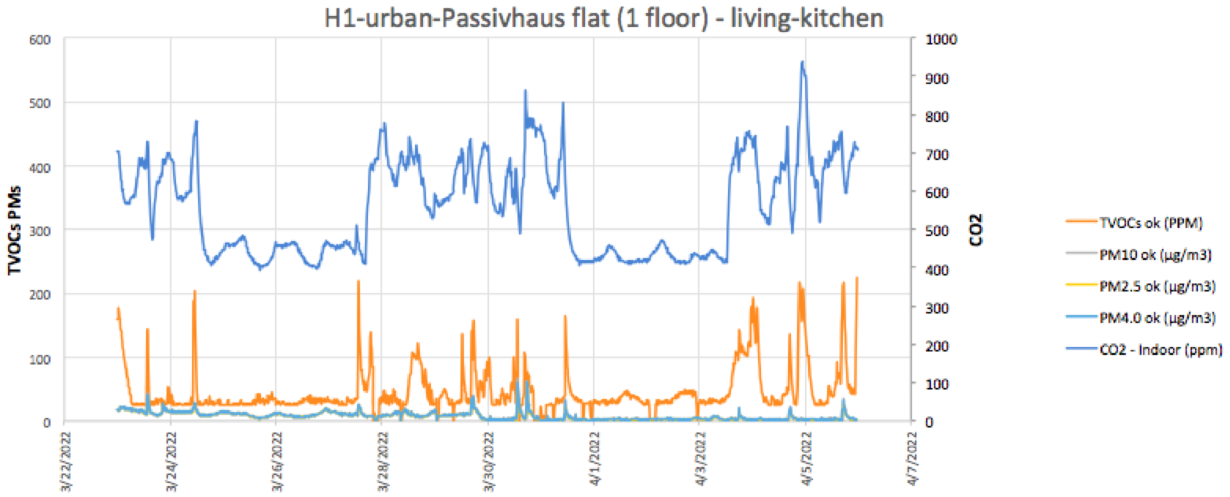
Main bedroom night time temperatures (Jul 2022)

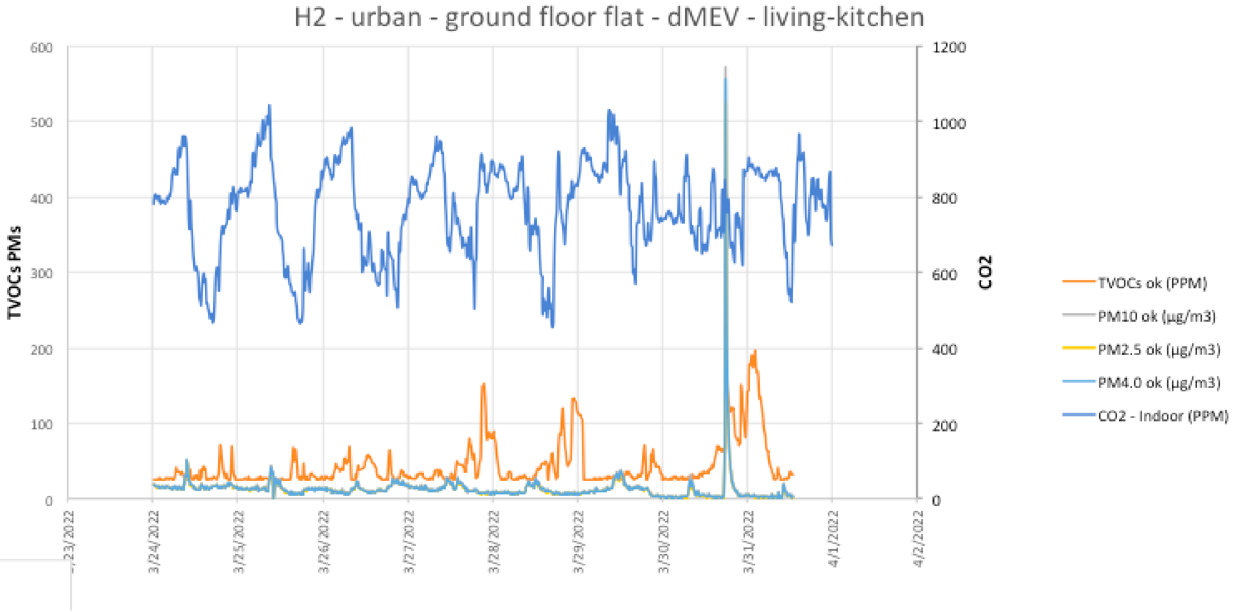


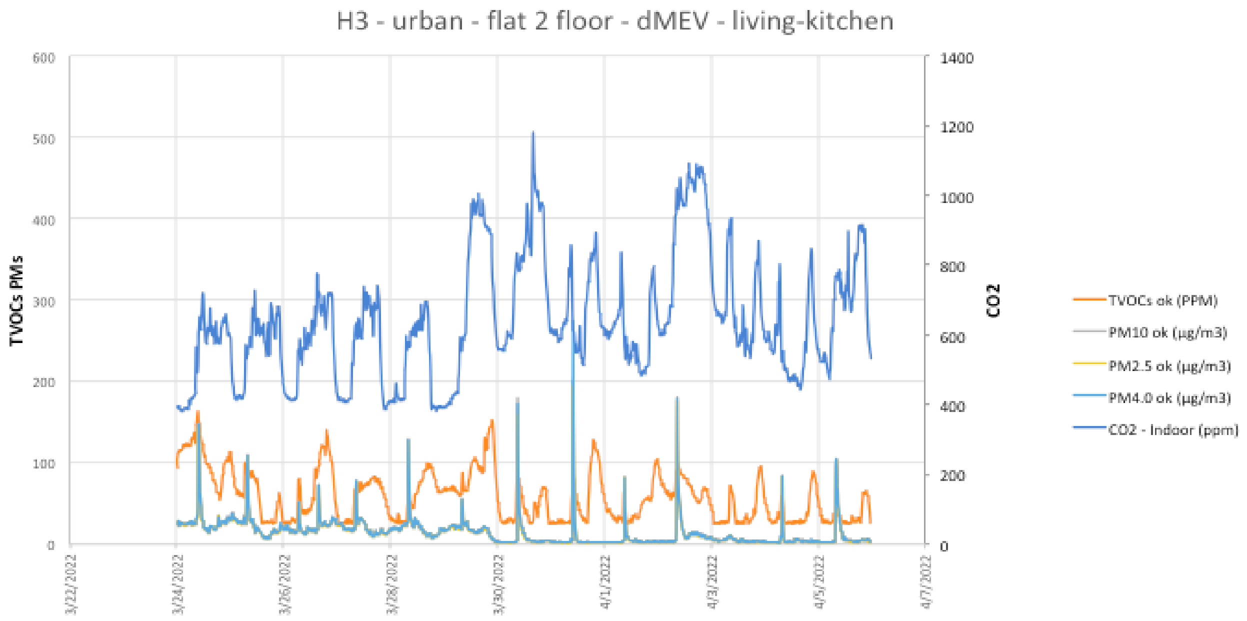
Annex D: detailed monitoring

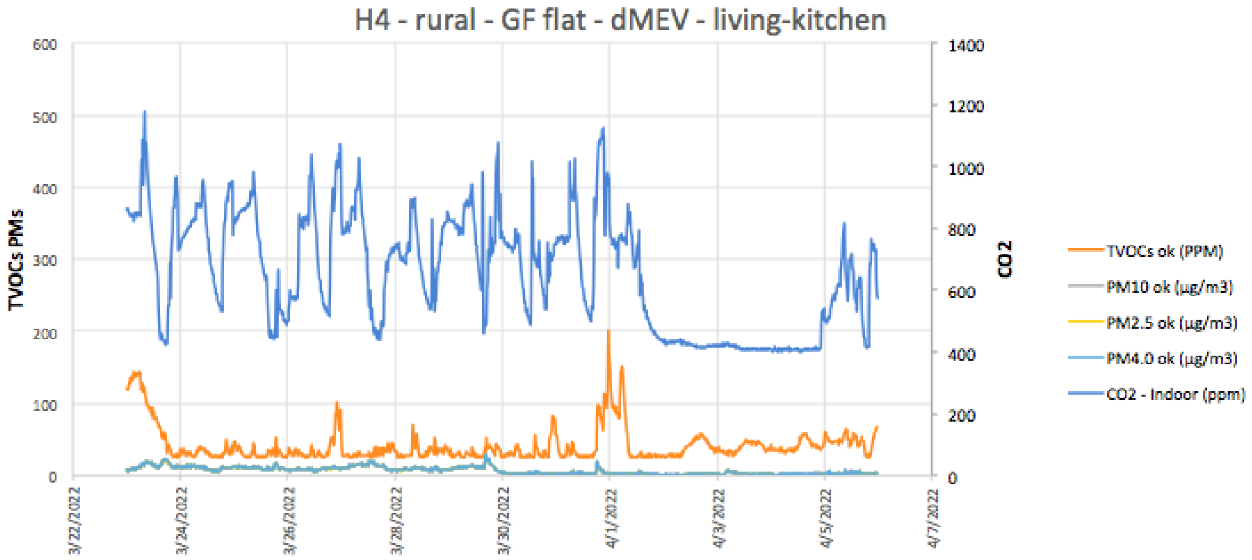
House types and graphs (CO_2/TVOCs/$PM^{2.5-10}$)

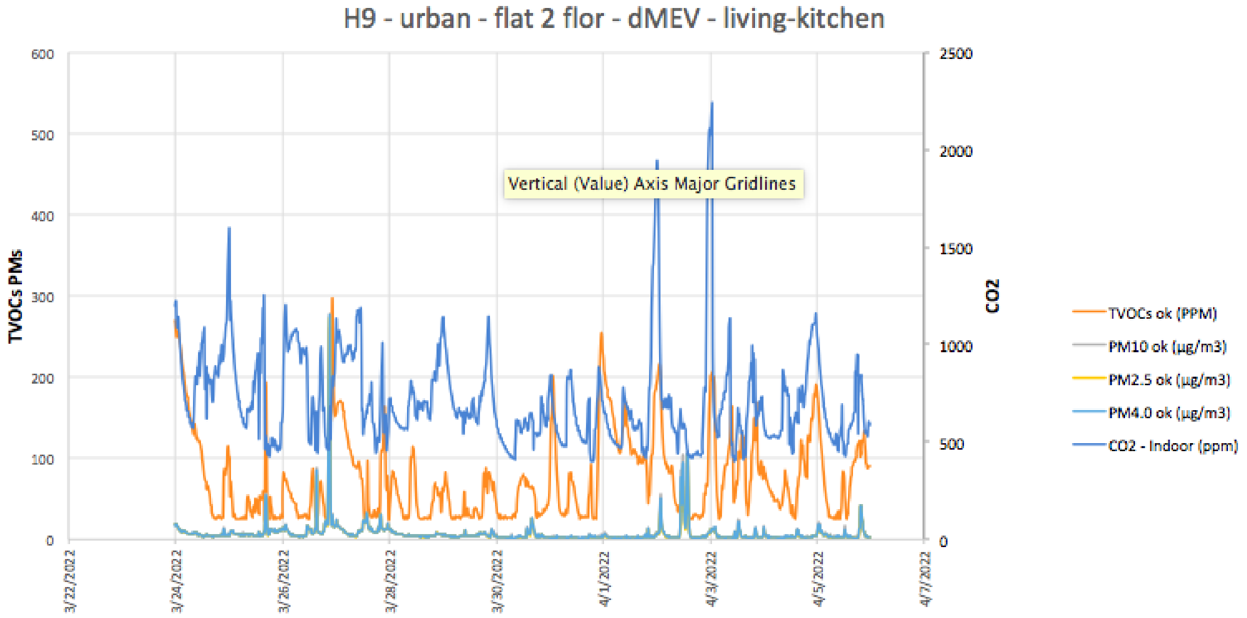
The following graphs show the relationship between CO_2 levels, TVOCs and particulate matter ($PM^{2.5-10}$).

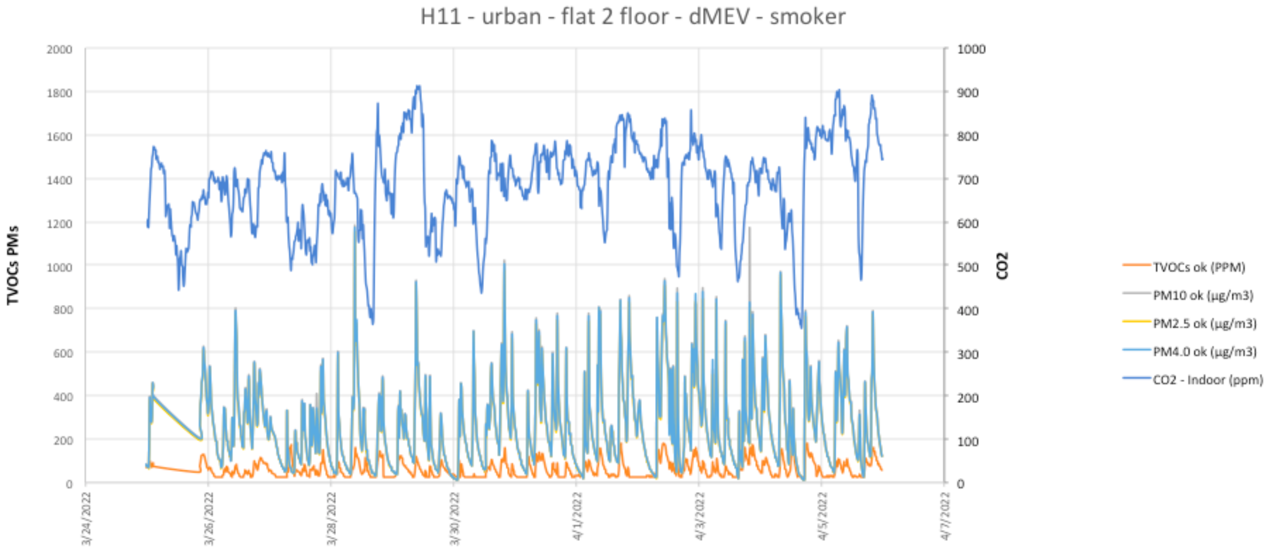


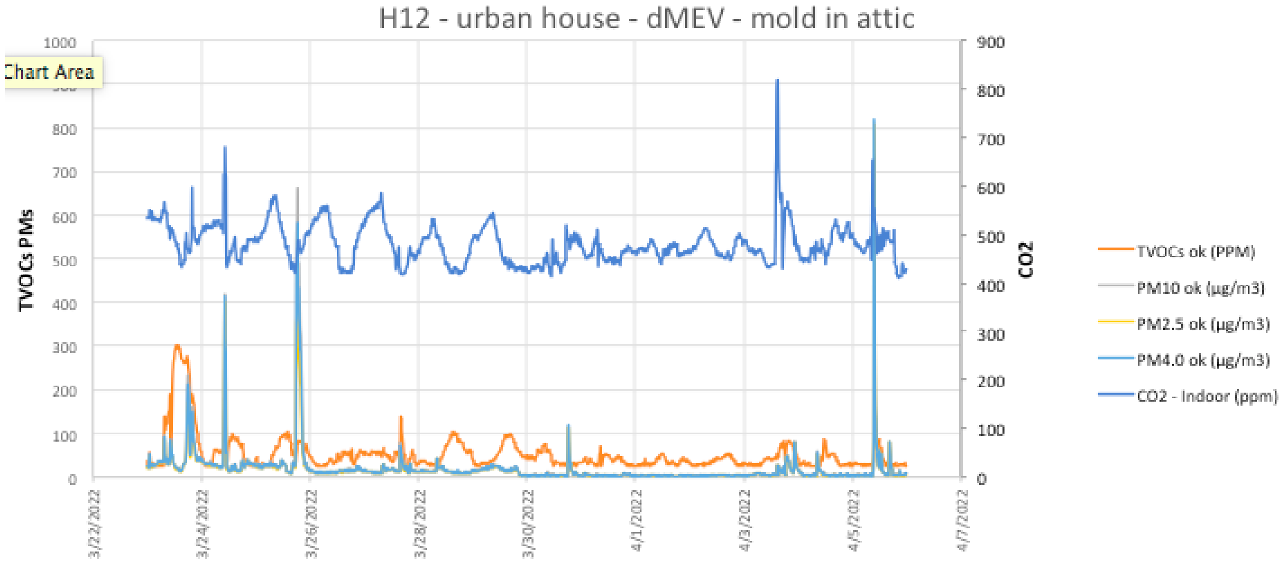


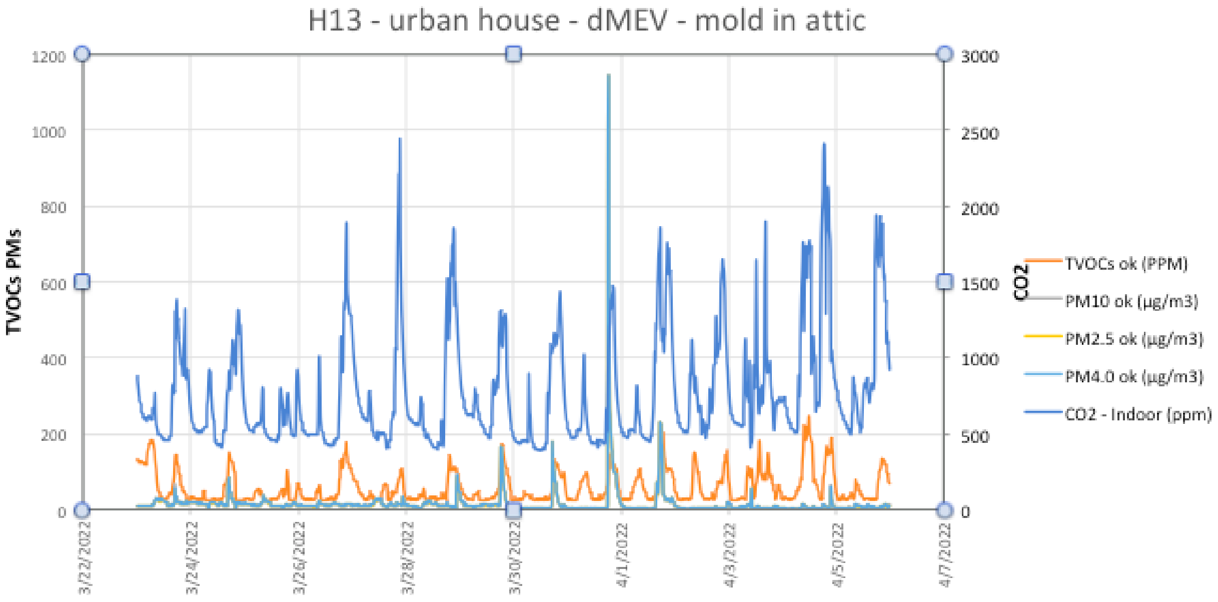

H3 - urban - flat 2 floor - dMEV - living-kitchen

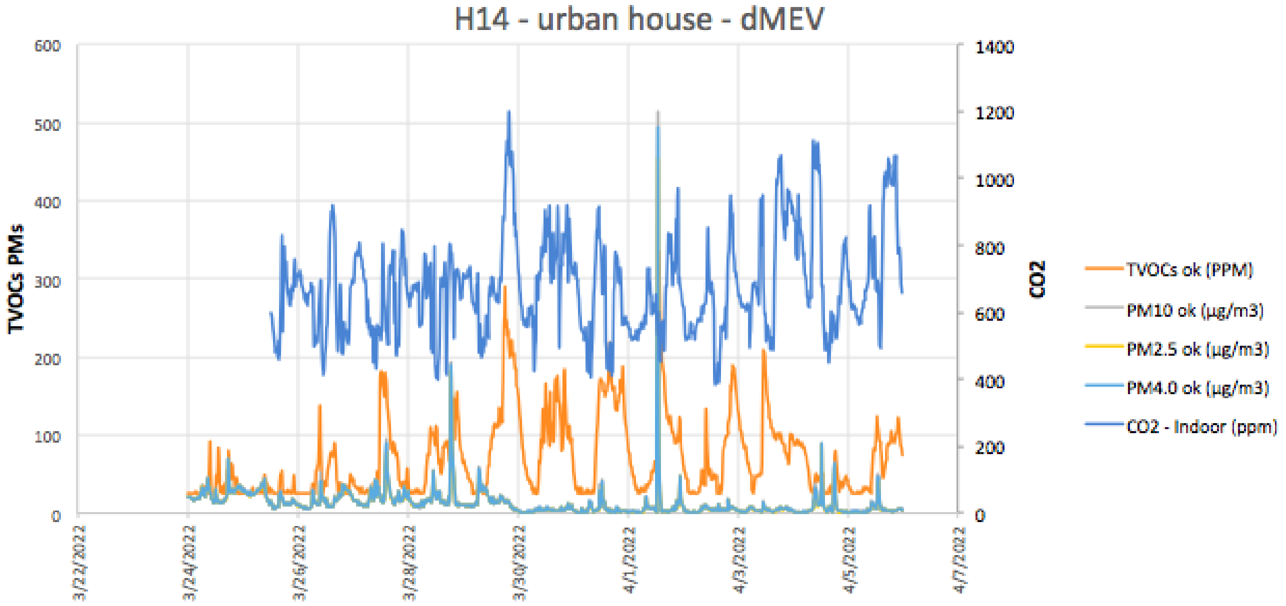

H4 - rural - GF flat - dMEV - living-kitchen


H9 - urban - flat 2 flor - dMEV - living-kitchen


H11 - urban - flat 2 floor - dMEV - smoker
TVOCs PMs
2000
1800
1600
1400
1200
1000
800
600
400
200
0
CO2
1000
900
800
700
600
500
400
300
200
100
0
3/24/2022
3/26/2022
3/28/2022
3/30/2022
4/1/2022
4/3/2022
4/5/2022
4/7/2022
TVOCs ok (PPM)
PM10 ok (µg/m3)
PM2.5 ok (µg/m3)
PM4.0 ok (µg/m3)
CO2 - Indoor (ppm)


H12 - urban house - dMEV - mold in attic
Chart Area
TVOCs PMs
1000
800
700
600
500
400
300
200
100
0
CO2
900
800
700
600
500
400
300
200
100
0
3/22/2022
3/24/2022
3/26/2022
3/28/2022
3/30/2022
4/1/2022
4/3/2022
4/5/2022
4/7/2022
TVOCs ok (PPM)
PM10 ok (µg/m3)
PM2.5 ok (µg/m3)
PM4.0 ok (µg/m3)
CO2 - Indoor (ppm)


H13 - urban house - dMEV - mold in attic
TVOCs PMs
1200
1000
800
600
400
200
0
CO2
3000
2500
2000
1500
1000
500
0
3/22/2022
3/24/2022
3/26/2022
3/28/2022
3/30/2022
4/1/2022
4/3/2022
4/5/2022
4/7/2022
TVOCs ok (PPM)
PM10 ok (µg/m3)
PM2.5 ok (µg/m3)
PM4.0 ok (µg/m3)
CO2 - Indoor (ppm)


H14 - urban house - dMEV
TVOCs PMs
CO2
0
100
200
300
400
500
600
0
200
400
600
800
1000
1200
1400
3/22/2022
3/24/2022
3/26/2022
3/28/2022
3/30/2022
4/1/2022
4/3/2022
4/5/2022
4/7/2022
TVOCs ok (PPM)
PM10 ok (µg/m3)
PM2.5 ok (µg/m3)
PM4.0 ok (µg/m3)
CO2 - Indoor (ppm)

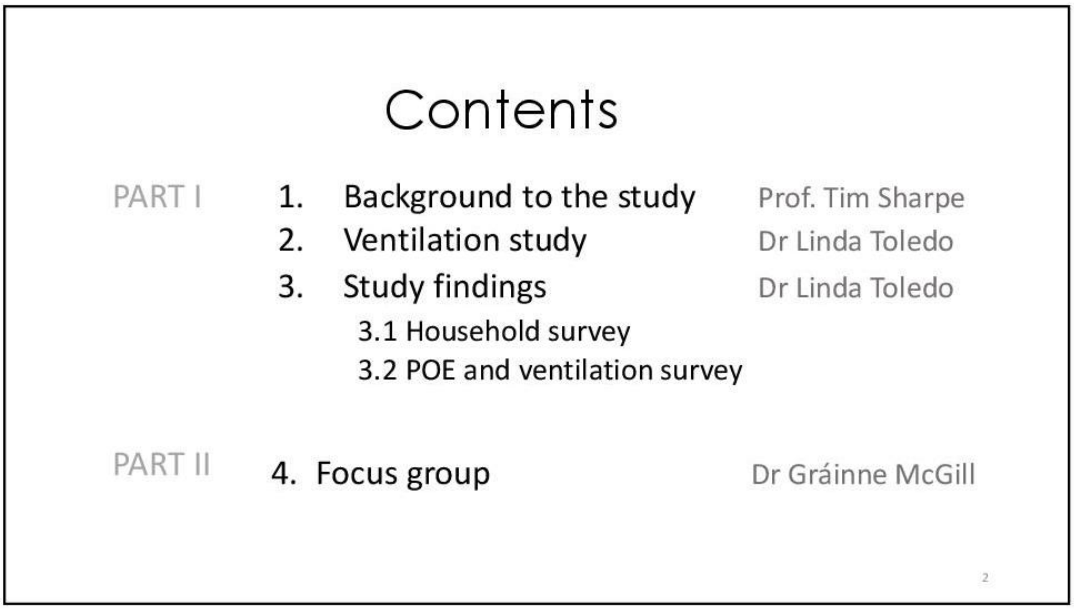
Annex E: industry workshop

Understanding the role of ventilation

10 August 2022
SFHA - Online Webinar

Prof. Tim Sharpe tim.sharpe@strath.ac.uk
Dr. Linda Toledo linda.Toledo@strath.ac.uk
Dr. Gráinne McGill Grainne.mcgill@strath.ac.uk

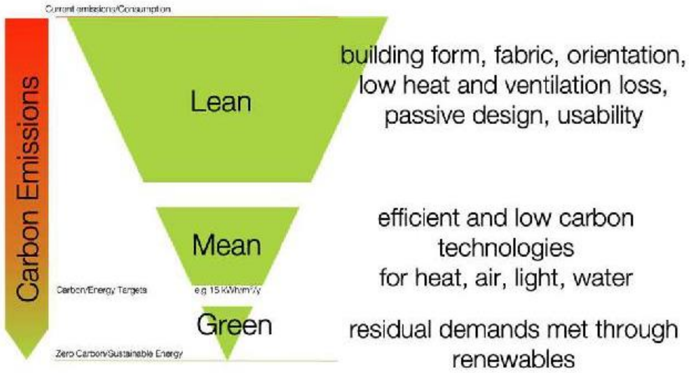
Scottish Government
Riaghaltas na h-Alba
gov.scot



Contents

PART I	1. Background to the study	Prof. Tim Sharpe
	2. Ventilation study	Dr Linda Toledo
	3. Study findings	Dr Linda Toledo
	3.1 Household survey	
	3.2 POE and ventilation survey	
PART II	4. Focus group	Dr Gráinne McGill

1. Background

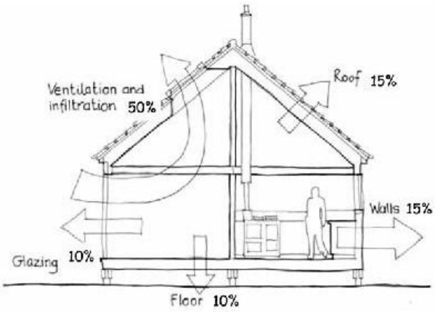


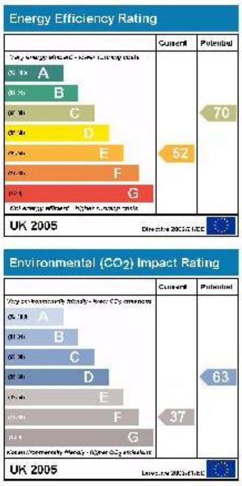
building form, fabric, orientation, low heat and ventilation loss, passive design, usability

efficient and low carbon technologies for heat, air, light, water

residual demands met through renewables

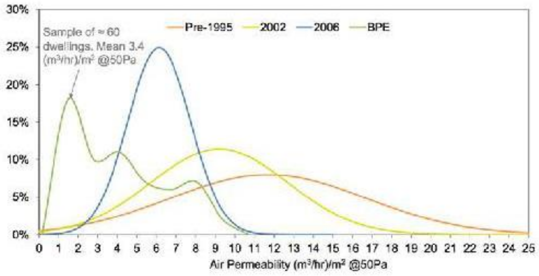
1. Background





1. Background

- Zero Carbon Agenda
- Focus on reducing heat loss
- As fabric improves ventilation losses are critical
- Airtightness - improving due to post completion testing



Source: Fourwalls, Building Sciences (RSK); Leeds Beckett University; Innovate UK BPE portfolio

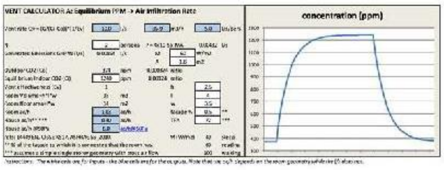
---

1. Background

- CO_2 is commonly used as an indicator of ventilation rates
- When people breathe CO_2 is exhaled
- Levels of CO_2 correlate well with human occupancy and human-generated pollutants
- Recognised as a 'proxy' for air quality – keeps 'bad company' (other pollutants)
- Evaluating levels of CO_2 can give indications of occupancy and ventilation.

- **< 1000ppm = 8 litres/s per person = good ventilation**

- *"..ventilation rates above 0.4 h-1 or CO2 below 900 ppm in homes seem to be the minimum level to protect against health risks based on the studies reported in the scientific literature"   Wargocki, P. The Effects of Ventilation in Homes on Health. Int. J. Vent. 2013; 12, 101–118*



Research Project To Investigate Occupier Influence On Indoor Air Quality In Dwellings

Building Standards Directorate

Prof Tim Sharpe University of Strathclyde U
Jonathan McQuillan Anderson Bell Christie
Dr. Stirling Howieson, University of Strathclyde
Paul Farren ASSIST DESIGN ARCHITECTS
Dr. Paul Tuohy ESRU, University of Strathclyde

The Scottish Government

Mackintosh Environmental Research Unit
Anderson Bell Christie
ASSIST DESIGN
ESRU, Dept. of Architecture, Strathclyde University

Research Project To Investigate Occupier Influence On Indoor Air Quality In Dwellings

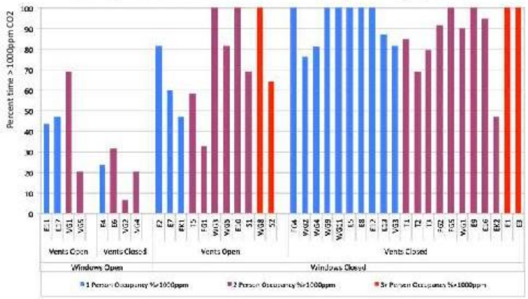
21 August 2014

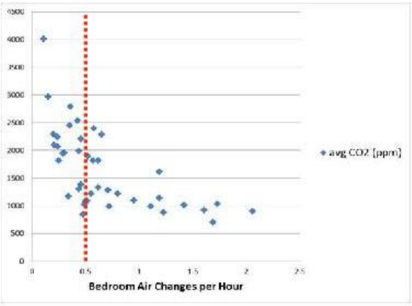
https://www.webarchive.org.uk/wayback/archive/3000/https://www.gov.scot/Resource/0046/00460968.pdf
https://strathprints.strath.ac.uk/50463/

Findings

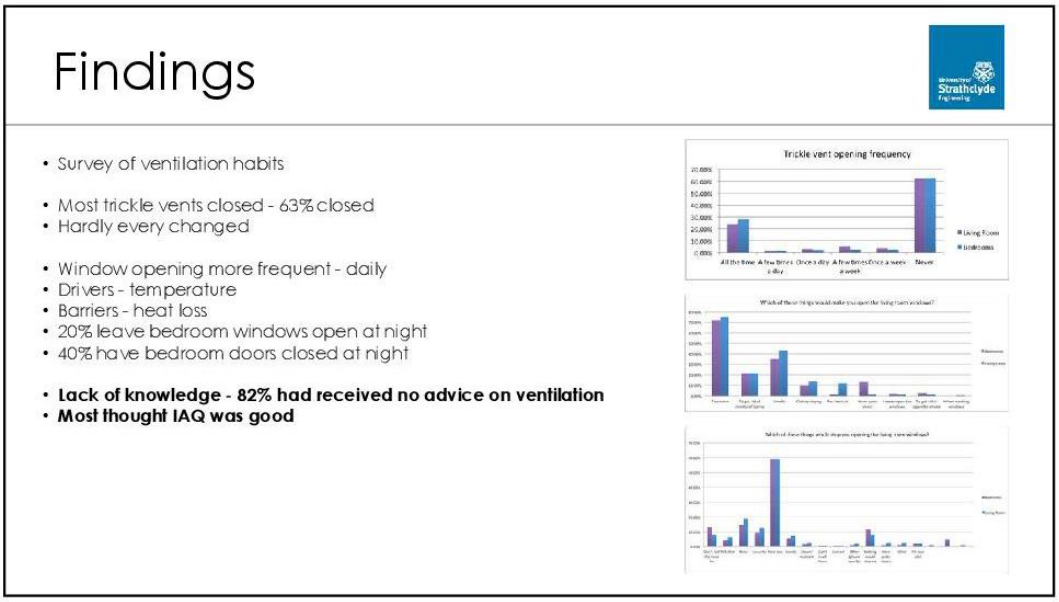
- % time over 1000ppm at night
- Significant periods of time with low ventilation
- Mitigated by window opening
- Better with open vents - but not effective

ALL BEDROOMS (TOTAL 40)
Percentage of Time Bedrooms > 1000PPM CO2 - Time Weighted Average 11pm - 7am





Sharpe, Tim, Farren, Paul, Howieson, Stirling, Tuohy, Paul and McQuillan, Jonathan (2015) Occupant Interactions and Effectiveness of Natural Ventilation Strategies in Contemporary New Housing in Scotland, UK. International Journal of Environmental Research and Public Health, 12 (7). pp. 8480-8497. ISSN 1660-4601



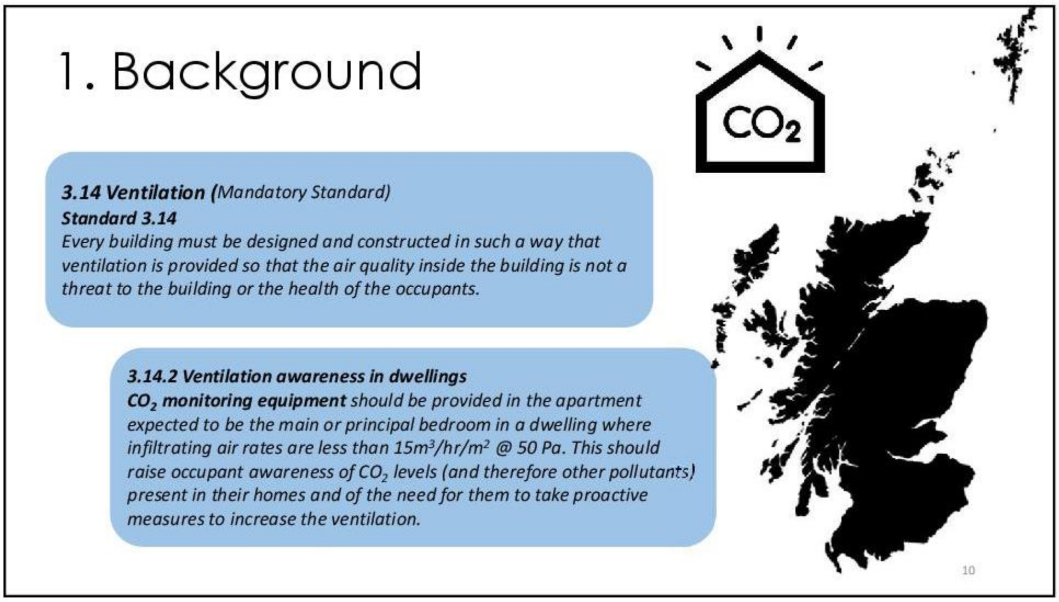
Findings

- Survey of ventilation habits

- Most trickle vents closed - 63% closed
- Hardly every changed

- Window opening more frequent - daily
- Drivers - temperature
- Barriers - heat loss
- 20% leave bedroom windows open at night
- 40% have bedroom doors closed at night

- **Lack of knowledge - 82% had received no advice on ventilation**
- **Most thought IAQ was good**

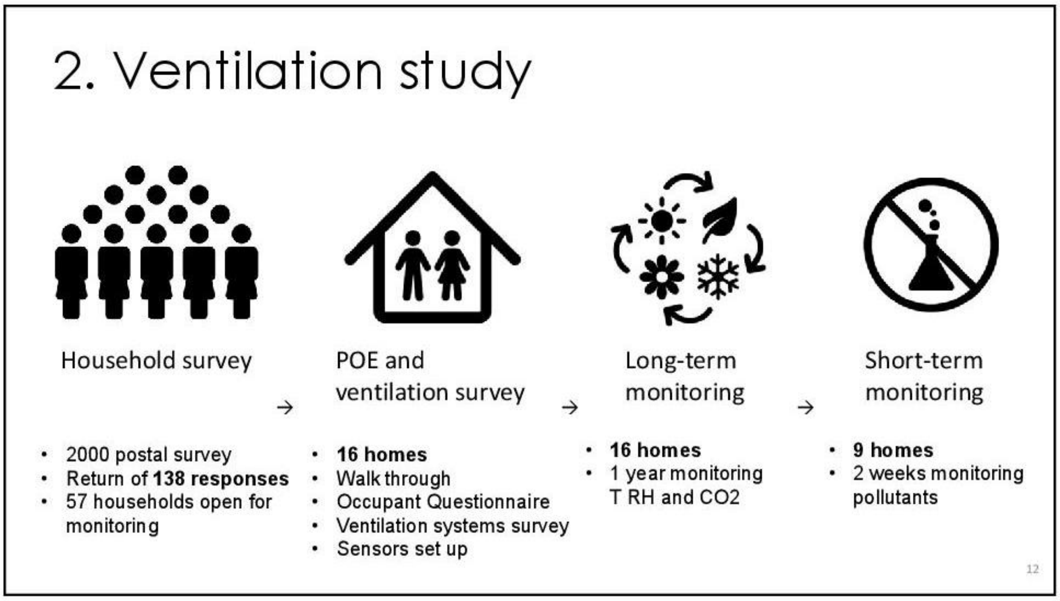


1. Background

***3.14 Ventilation** (Mandatory Standard)*
Standard 3.14
Every building must be designed and constructed in such a way that ventilation is provided so that the air quality inside the building is not a threat to the building or the health of the occupants.

3.14.2 Ventilation awareness in dwellings
***CO_2 monitoring equipment** should be provided in the apartment expected to be the main or principal bedroom in a dwelling where infiltrating air rates are less than $15m^3/hr/m^2$ @ 50 Pa. This should raise occupant awareness of CO_2 levels (and therefore other pollutants) present in their homes and of the need for them to take proactive measures to increase the ventilation.*

Research to identify if changes to guidance in *Standard 3.14 Ventilation* in 2015 have been effective in improving ventilation and indoor air quality



2. Ventilation study

Household survey →

- 2000 postal survey
- Return of **138 responses**
- 57 households open for monitoring

POE and ventilation survey →

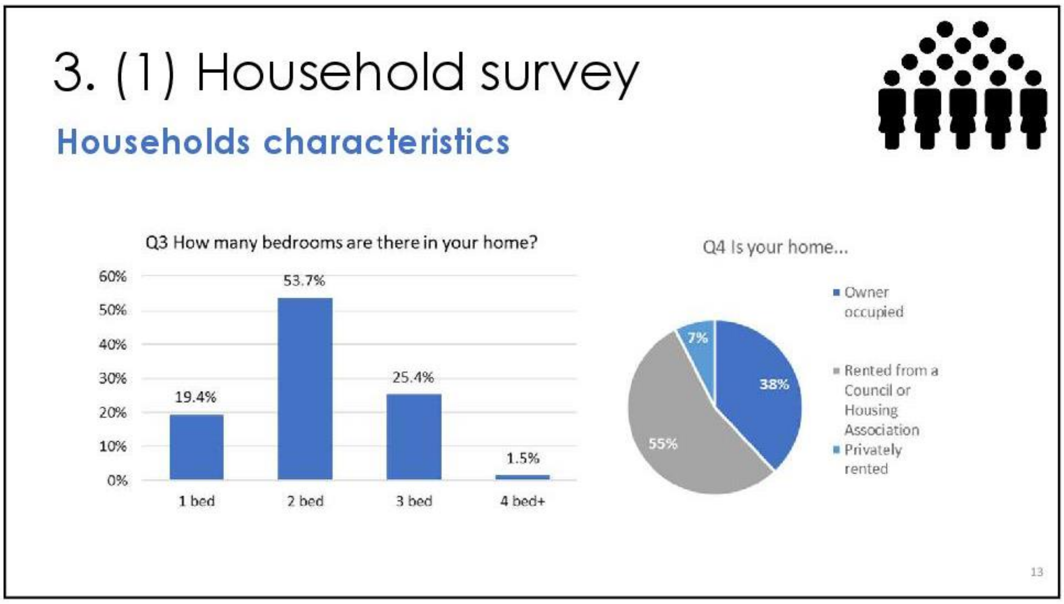
- **16 homes**
- Walk through
- Occupant Questionnaire
- Ventilation systems survey
- Sensors set up

Long-term monitoring →

- **16 homes**
- 1 year monitoring T RH and CO2

Short-term monitoring

- **9 homes**
- 2 weeks monitoring pollutants

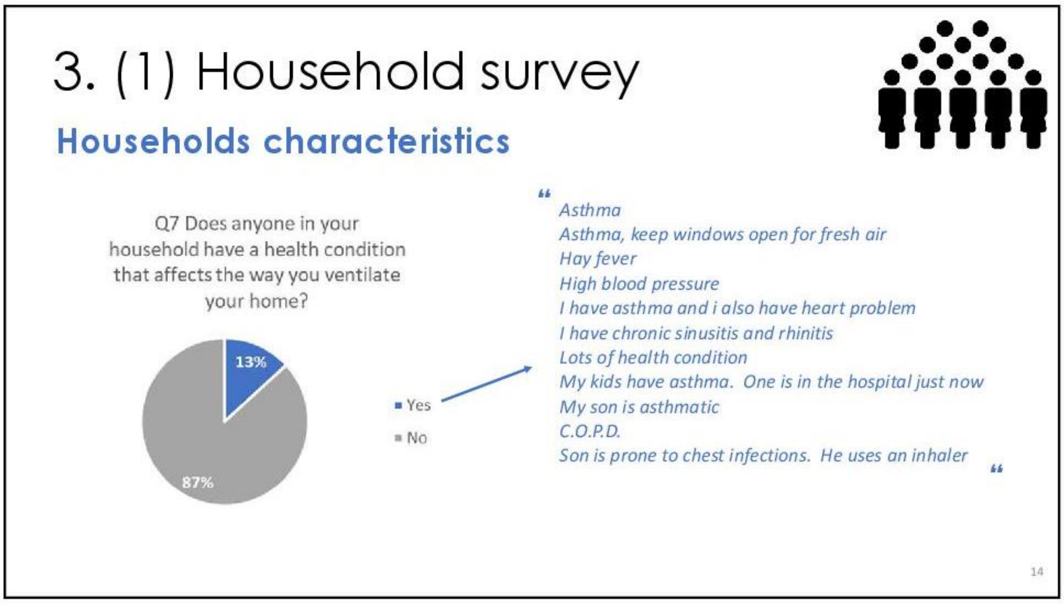


3. (1) Household survey

Households characteristics

Q3 How many bedrooms are there in your home?

Q4 Is your home...

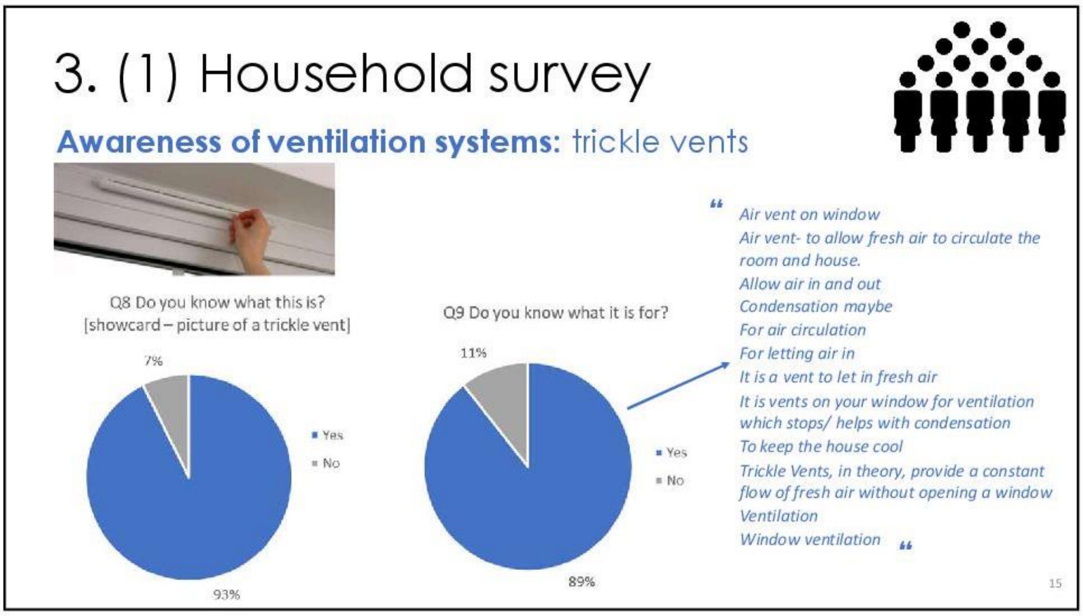


3. (1) Household survey

Households characteristics

Q7 Does anyone in your household have a health condition that affects the way you ventilate your home?

“
Asthma
Asthma, keep windows open for fresh air
Hay fever
High blood pressure
I have asthma and i also have heart problem
I have chronic sinusitis and rhinitis
Lots of health condition
My kids have asthma. One is in the hospital just now
My son is asthmatic
C.O.P.D.
Son is prone to chest infections. He uses an inhaler
“



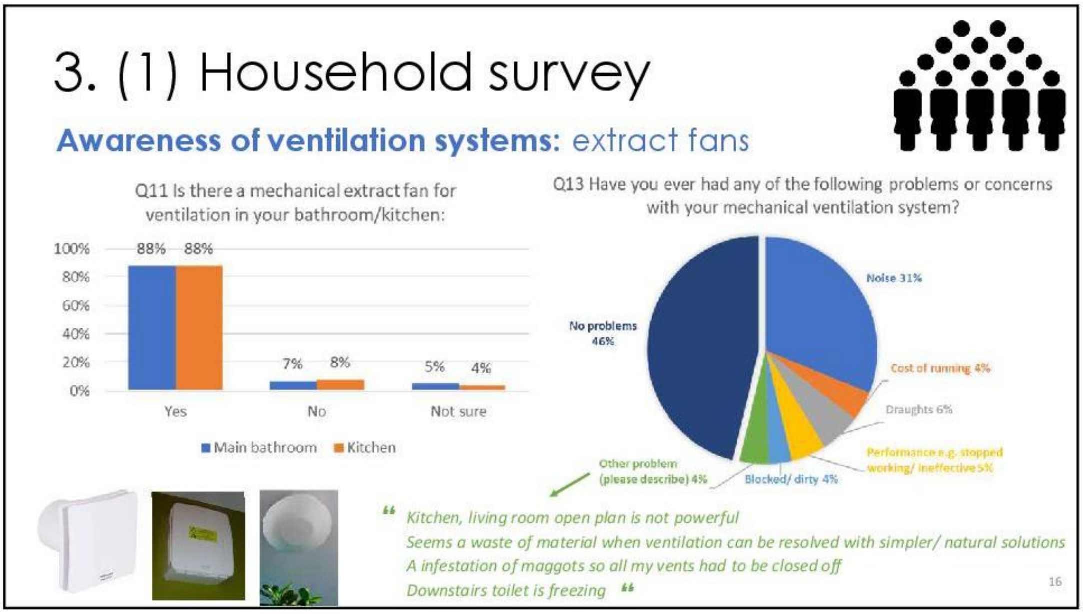
3. (1) Household survey

Awareness of ventilation systems: trickle vents

Q8 Do you know what this is?
[showcard – picture of a trickle vent]

Q9 Do you know what it is for?

“ Air vent on window
Air vent- to allow fresh air to circulate the room and house.
Allow air in and out
Condensation maybe
For air circulation
For letting air in
It is a vent to let in fresh air
It is vents on your window for ventilation which stops/ helps with condensation
To keep the house cool
Trickle Vents, in theory, provide a constant flow of fresh air without opening a window
Ventilation
Window ventilation “



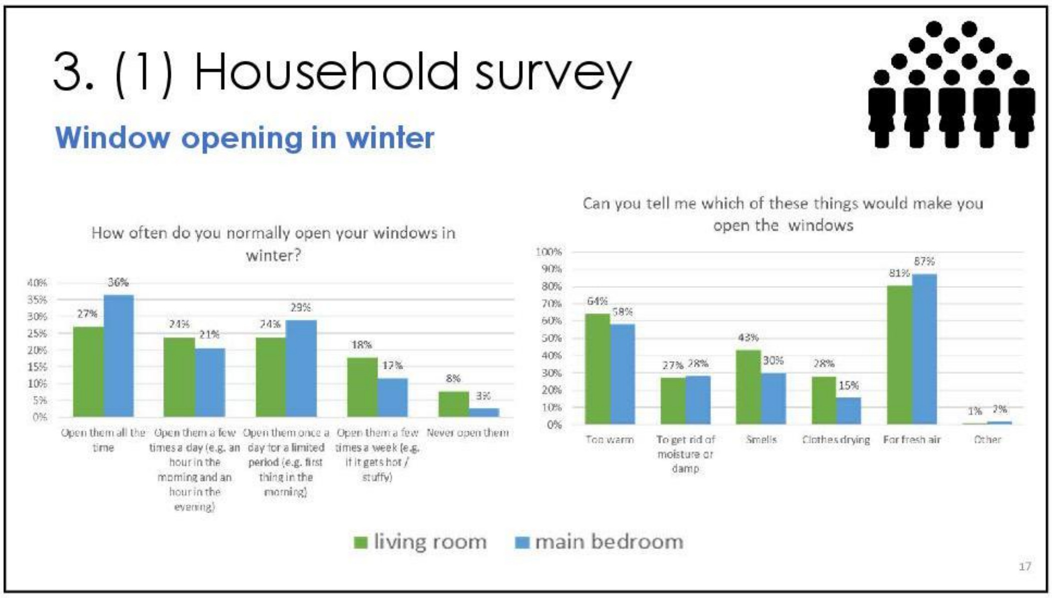
3. (1) Household survey

Awareness of ventilation systems: extract fans

Q11 Is there a mechanical extract fan for ventilation in your bathroom/kitchen:

Q13 Have you ever had any of the following problems or concerns with your mechanical ventilation system?

“ Kitchen, living room open plan is not powerful
Seems a waste of material when ventilation can be resolved with simpler/ natural solutions
A infestation of maggots so all my vents had to be closed off
Downstairs toilet is freezing “

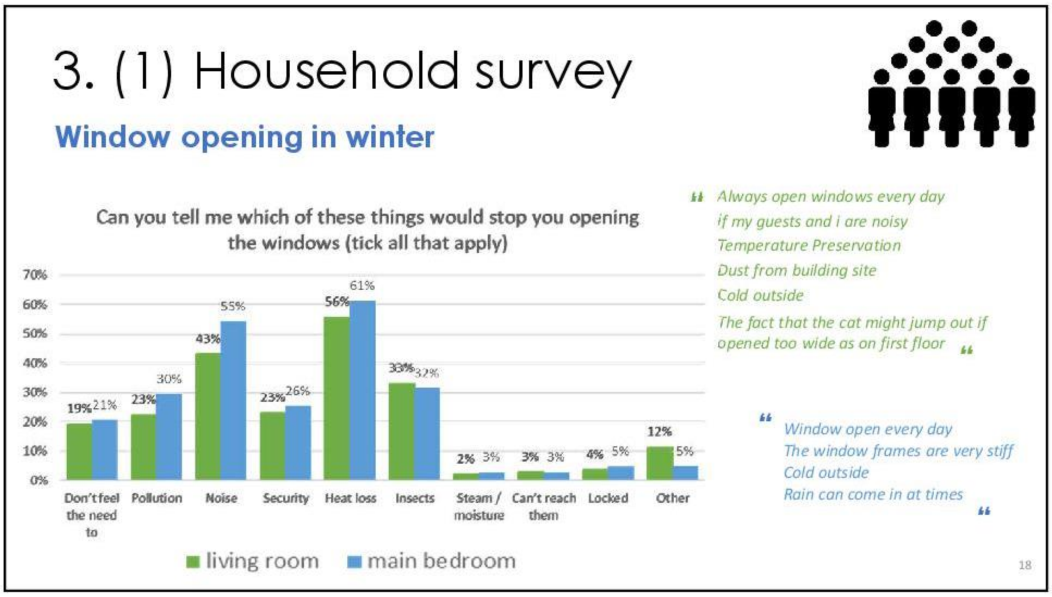


3. (1) Household survey

Window opening in winter

How often do you normally open your windows in winter?

Can you tell me which of these things would make you open the windows



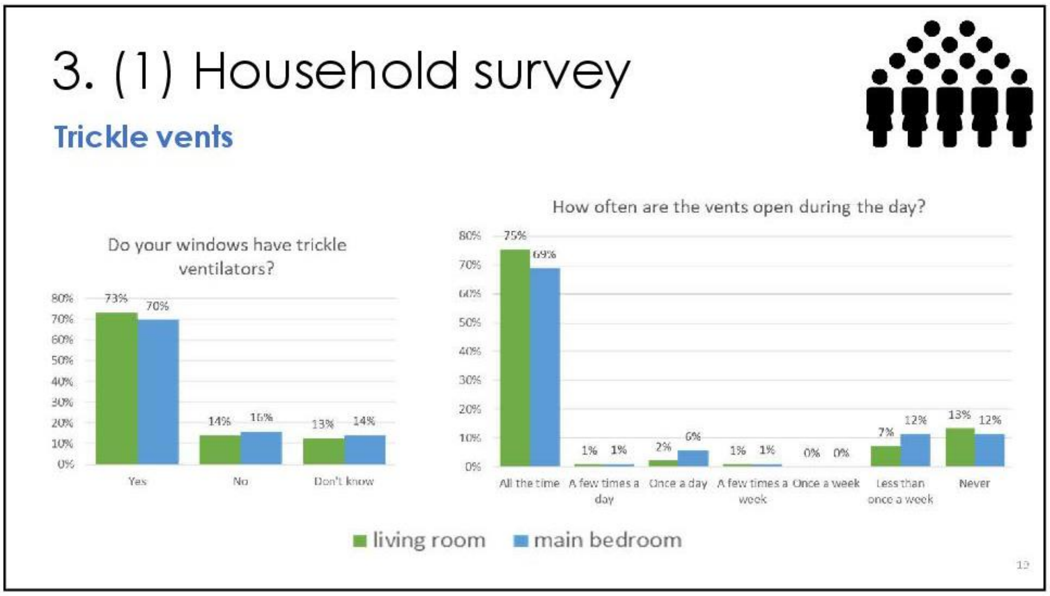
3. (1) Household survey

Window opening in winter

Can you tell me which of these things would stop you opening the windows (tick all that apply)

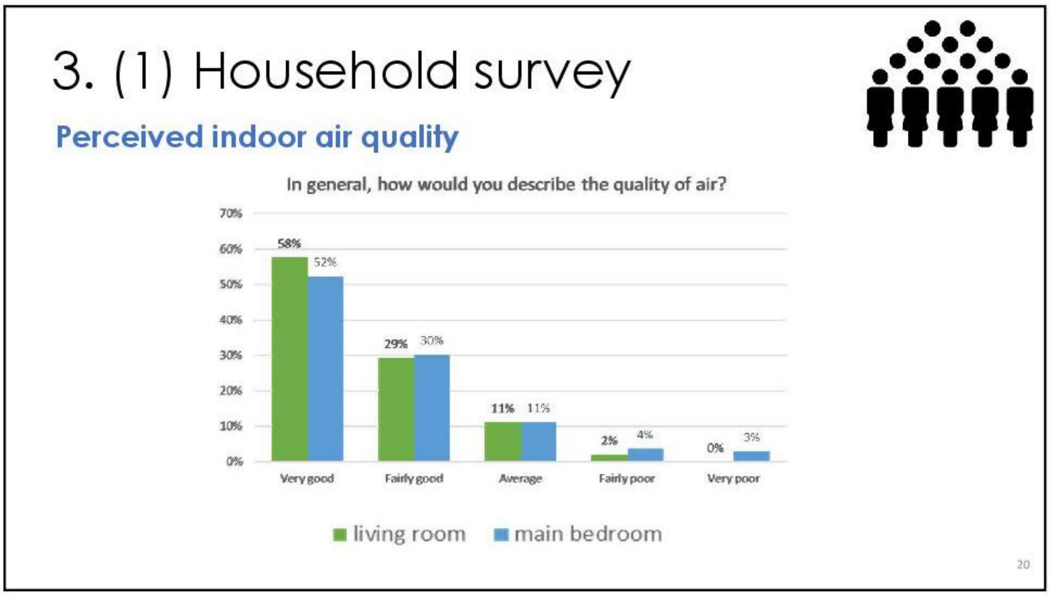
“ Always open windows every day
if my guests and i are noisy
Temperature Preservation
Dust from building site
Cold outside
The fact that the cat might jump out if opened too wide as on first floor ”

“ Window open every day
The window frames are very stiff
Cold outside
Rain can come in at times ”



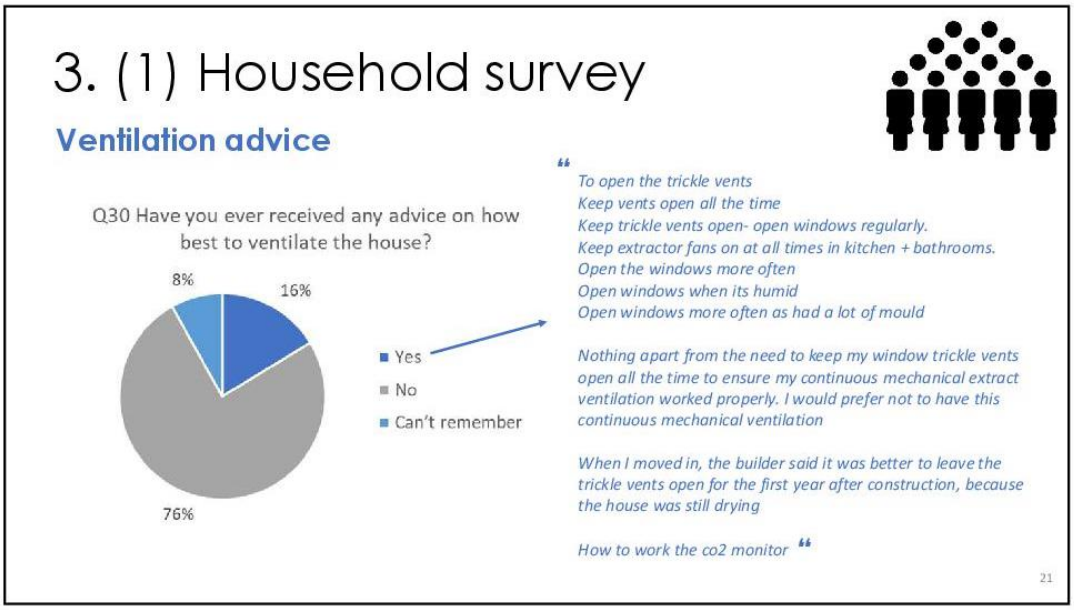
3. (1) Household survey

Trickle vents



3. (1) Household survey

Perceived indoor air quality

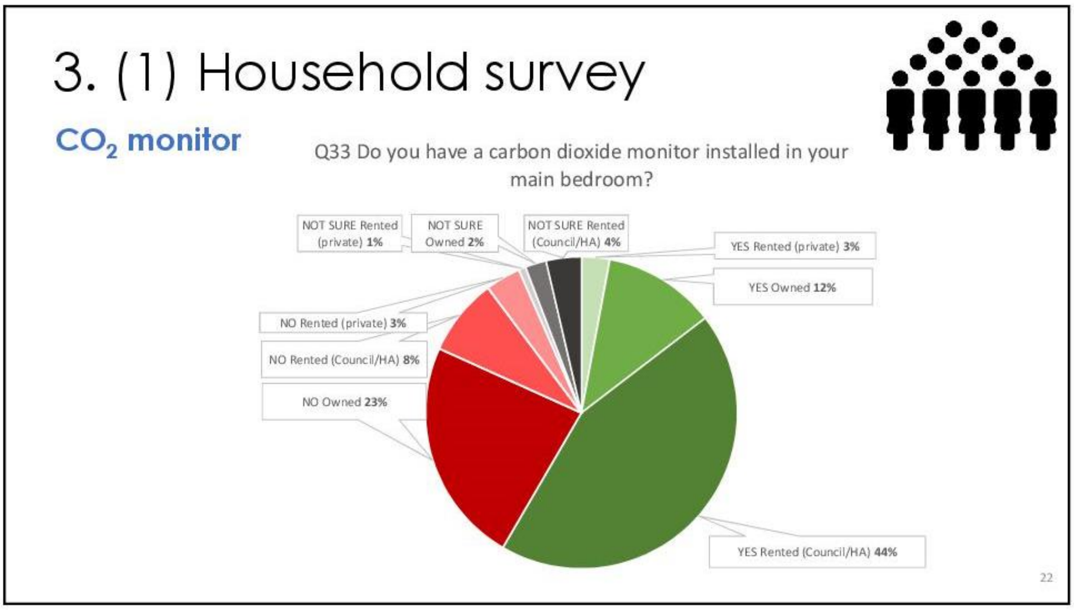


3. (1) Household survey

Ventilation advice

Q30 Have you ever received any advice on how best to ventilate the house?

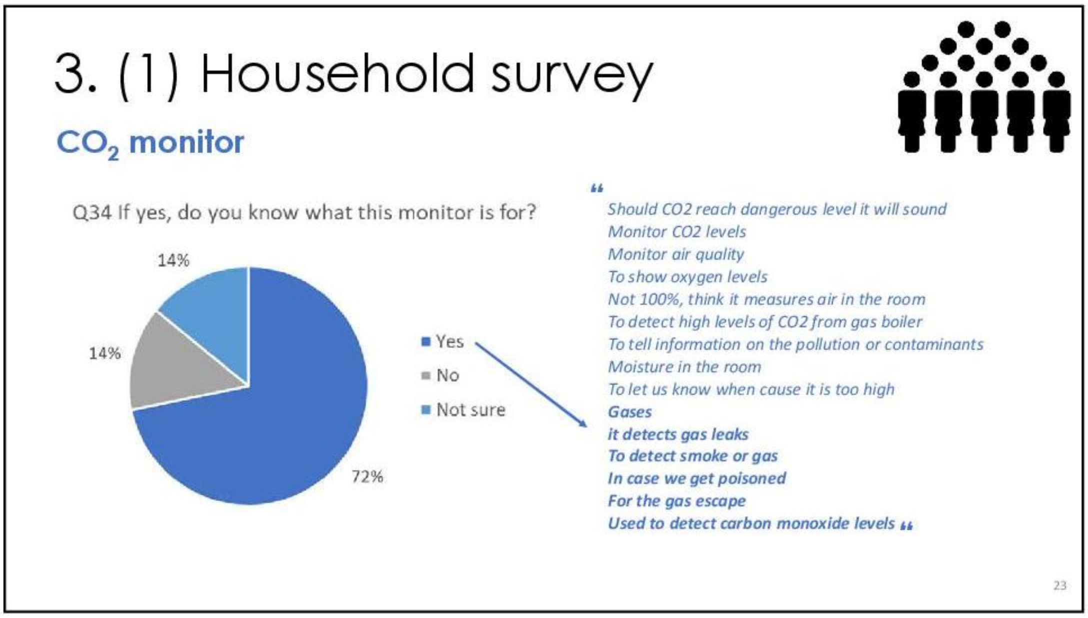
> *To open the trickle vents*
> *Keep vents open all the time*
> *Keep trickle vents open- open windows regularly.*
> *Keep extractor fans on at all times in kitchen + bathrooms.*
> *Open the windows more often*
> *Open windows when its humid*
> *Open windows more often as had a lot of mould*
>
> *Nothing apart from the need to keep my window trickle vents open all the time to ensure my continuous mechanical extract ventilation worked properly. I would prefer not to have this continuous mechanical ventilation*
>
> *When I moved in, the builder said it was better to leave the trickle vents open for the first year after construction, because the house was still drying*
>
> *How to work the co2 monitor*



3. (1) Household survey

CO_2 monitor

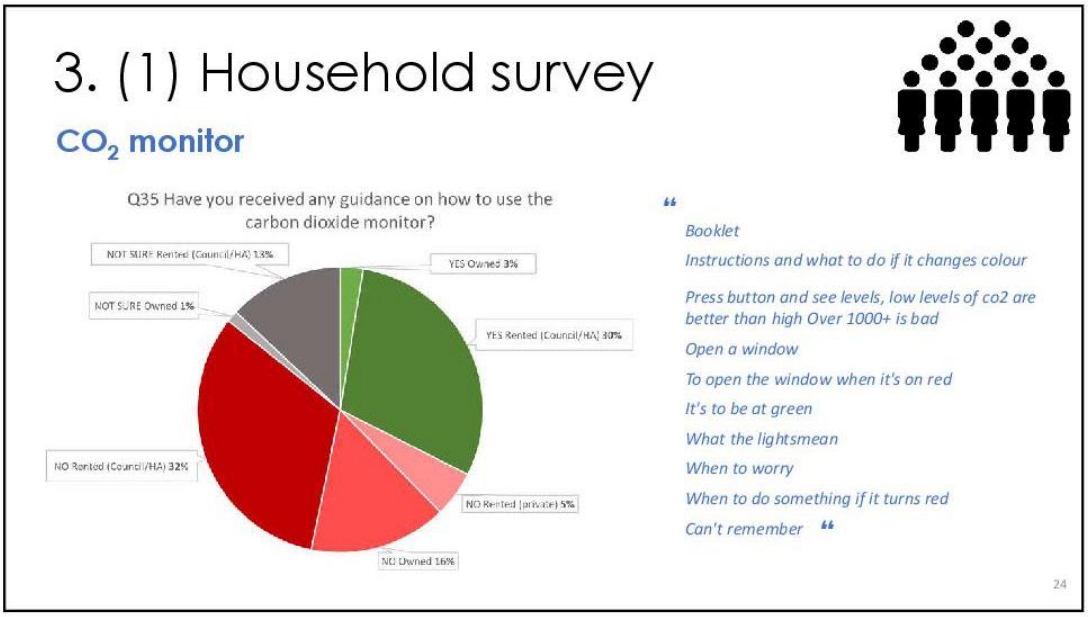
Q33 Do you have a carbon dioxide monitor installed in your main bedroom?



3. (1) Household survey

CO$_2$ monitor

“
Should CO2 reach dangerous level it will sound
Monitor CO2 levels
Monitor air quality
To show oxygen levels
Not 100%, think it measures air in the room
To detect high levels of CO2 from gas boiler
To tell information on the pollution or contaminants
Moisture in the room
To let us know when cause it is too high
Gases
it detects gas leaks
To detect smoke or gas
In case we get poisoned
For the gas escape
Used to detect carbon monoxide levels “



3. (1) Household survey

CO$_2$ monitor

“
Booklet

Instructions and what to do if it changes colour

Press button and see levels, low levels of co2 are better than high Over 1000+ is bad

Open a window

To open the window when it's on red

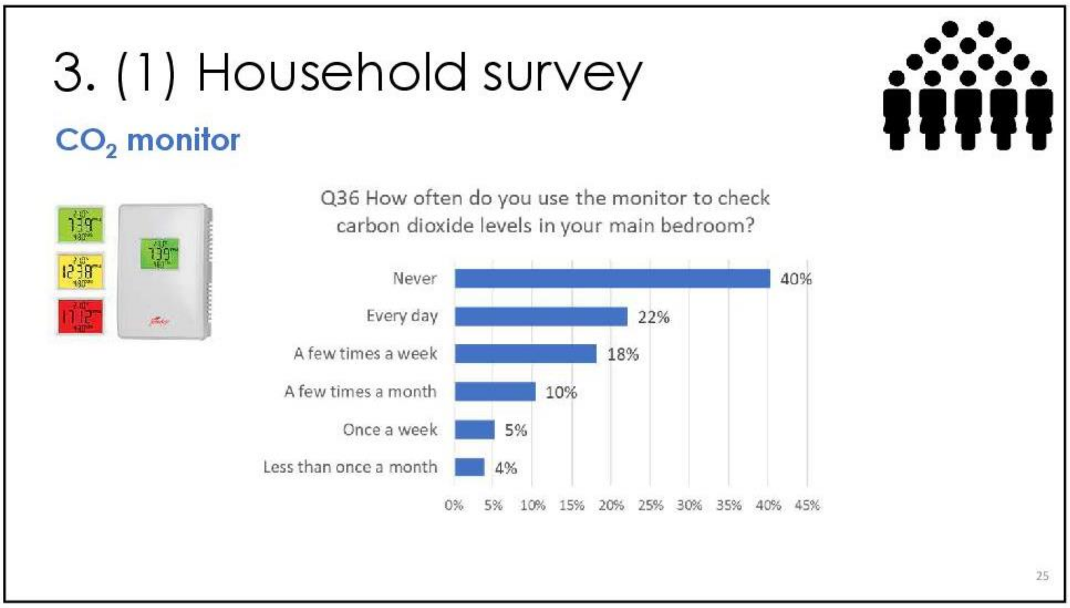
It's to be at green

What the lightsmean

When to worry

When to do something if it turns red

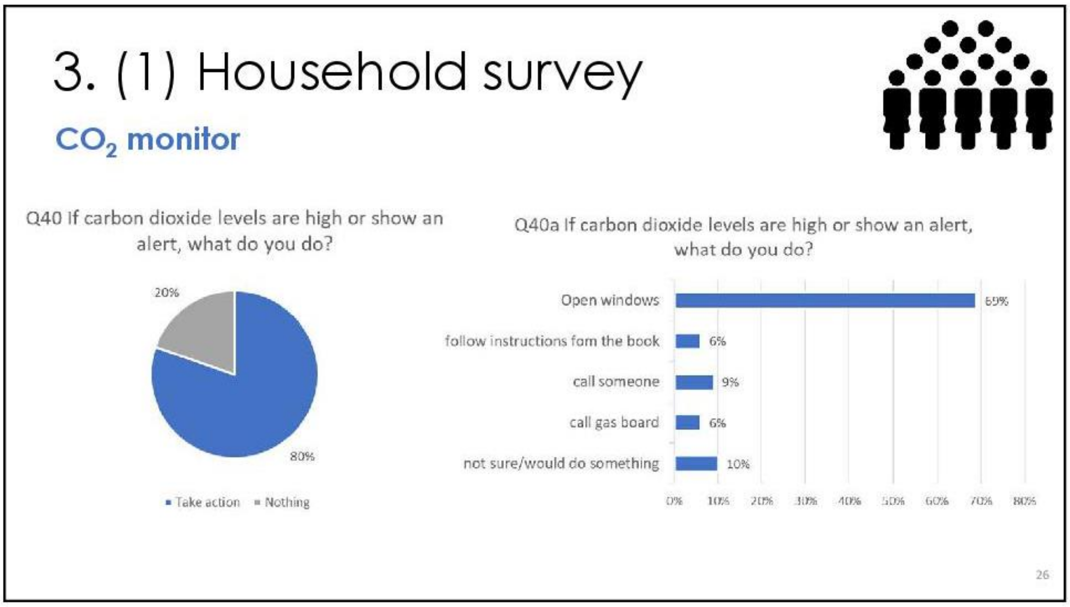
Can't remember “



3. (1) Household survey

CO_2 monitor

Q36 How often do you use the monitor to check carbon dioxide levels in your main bedroom?



3. (1) Household survey

CO_2 monitor

Q40 If carbon dioxide levels are high or show an alert, what do you do?

Q40a If carbon dioxide levels are high or show an alert, what do you do?

3. (1) Household survey

Summary

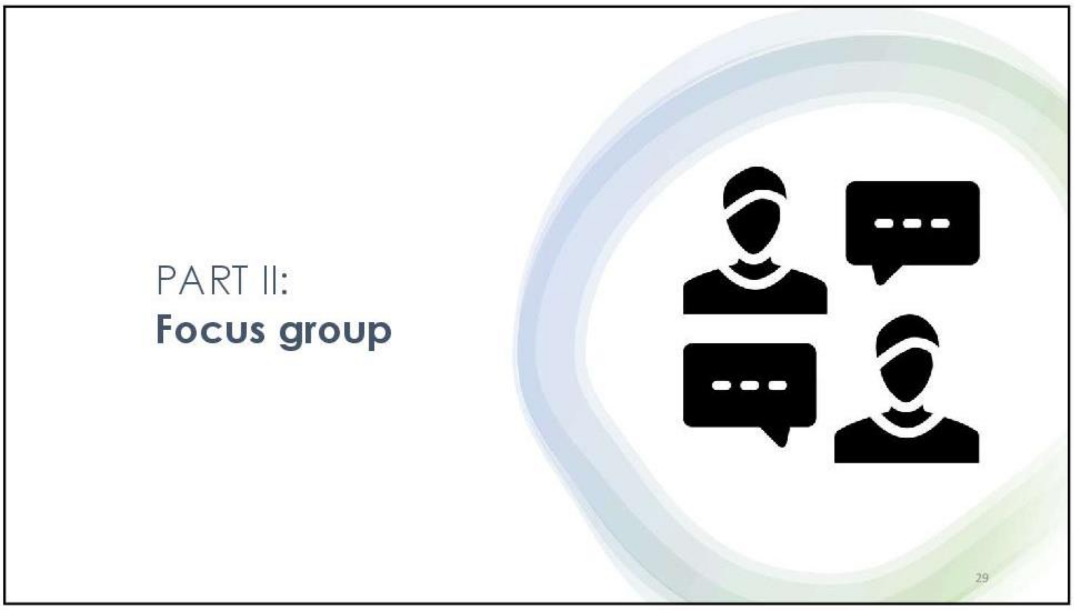
- People do interact with the ventilation systems (drivers are thermal comfort and energy consumption)
- A large portion of households don't have CO_2 sensors
- From those who have it (58%), very few have received advice or guidance on how to use the CO_2 monitor

3. (2) POE and ventilation survey

16 homes monitored in the Central Belt: 11 homes in Glasgow area and 5 homes in Edinburgh.

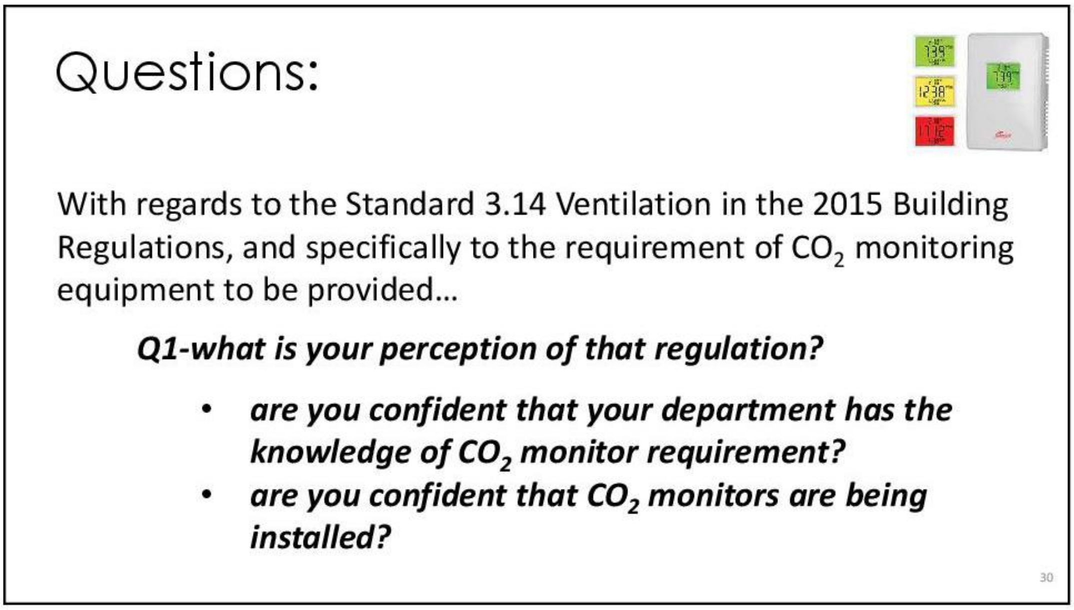
Home ID	Carbon dioxide (CO_2) monitor	Postcode	Dwelling Type	Total floor area (m²)	Air Tightness (design)	Air Tightness (tested)	Mechanical Ventilation	long term monitoring (WP3)	short term monitoring (WP4)
1 (ex RR983)	No	G32 7BS	Mid-floor flat	76		0.4	MVHR	✓	✓
2 (ex RR1211)	yes	G43 1FF	Ground-floor flat	69	4		dMEV	✓	✓
3 (ex RR991)	No	G32 7BS	Mid-floor flat	55	4		dMEV	✓	✓
4 (ex RR1628)	No	G78 2BF	End-terrace house	74	4.5		dMEV	✓	✓
5 (ex RR25)	Yes	EH11 4FF	Mid-terrace house	76		2.5	dMEV	✓	
6 (ex RR575)	Yes	EH42 1ZT	Ground-floor flat	71	4		dMEV	✓	
7 (ex RR619)	Yes	EH5 1RW	Ground-floor flat	74	5		dMEV	✓	
8 (ex RR846)	No	EH7 5FQ	Mid-floor flat	64	5		dMEV	✓	
9 (ex RR12)	Yes	EH11 3US	Mid-floor flat	72		4.5	dMEV	✓	✓
10 (ex RR914)	Yes	G31 1AR	Ground-floor flat	65	4		dMEV	✓	
11 (ex RR1560)	Yes	G73 2DS	Mid-floor flat	51	4		dMEV	✓	✓
12 (ex RR1386)	Yes	G53 6ER	Semi-detached house	95	4		dMEV	✓	✓
13 (ex RR1351)	Yes	G53 6EH	Semi-detached house	95	4		dMEV	✓	✓
14	Yes	G46 8AZ	Semi-detached house	96	4.5		dMEV	✓	✓
15	Yes	ML5 3AY	Mid-floor flat	52	5		dMEV	✓	
16	Yes	G46 8AZ	Ground-floor flat	81	4.5		dMEV	✓	

Overview of monitoring locations & characteristics



PART II:

Focus group



Questions:

With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided…

Q1-what is your perception of that regulation?

- ***are you confident that your department has the knowledge of CO_2 monitor requirement?***
- ***are you confident that CO_2 monitors are being installed?***

Questions:

With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided…

Q2-Have you encountered resistance from occupants to install CO2 monitors?

- ***has the installation of CO_2 monitors resulted in complaints from occupants?***
- ***Or has it helped to identify any problems?***

Questions:

With regards to the Standard 3.14 Ventilation in the 2015 Building Regulations, and specifically to the requirement of CO_2 monitoring equipment to be provided…

Q3-What is been done to explain the CO_2 monitor to occupants?

- ***what instructions are provided to occupants?***

Scottish Government
Riaghaltas na h-Alba

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