Building Performance Evaluation Programme

Characteristics and performance of MVHR systems

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Note to students and researchers This document is a meta-study of MVHR systems used in buildings studied under the Building Performance Evaluation Programme (BPE) which ran between 2011 - 2015.

The individual projects covered in the report are available in the non-domestic and domestic sections of the Usable Buildings website. Note that while the website is hosting all non-domestic BPE studies, some domestic studies are not yet available.

The Usable Buildings website is not able to respond to enquiries about the missing domestic studies. However, efforts are being made to source them. Researchers are recommended to check the website periodically for updates.

Citations The Usable Buildings website can be cited as the source of this document as InnovateUK no longer hosts BPE reports. Students should also check on-line academic libraries for papers published by the authors of this report.

Characteristics and performance of MVHR systems

A meta study of MVHR systems used in the Innovate UK Building Performance Evaluation Programme

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Introduction

This meta-study was commissioned by Innovate UK as part of the Building Performance Evaluation (BPE) Programme to provide an overview of the performance and use of whole-house heat recovery ventilation (MVHR) systems in domestic projects. With increasing requirements for energy reduction, the impact of ventilation strategies has increased in importance, both in terms of energy reduction and indoor air quality (IAQ).

The primary aims of this meta-study are to:

1. Review the characteristics of installed systems in relation to air flow, system balance and compare to existing published guidelines, particularly those contained in the relevant Building Regulations documents;
2. Investigate, via surveys and interviews, the reasons for selecting MVHR as a ventilation strategy on a development and experience of MVHR systems in practice;
3. Review available monitored data to investigate the performance of houses with MVHR systems;
4. Determine the key features of MVHR systems with respect to the quality of their design and installation and commissioning procedures.

Across the BPE domestic programme, a total of 85 study dwellings from 29 projects with MVHR systems were investigated. Development sizes range from single homes to major developments of 700+ dwellings, thus the total number of homes that the study dwellings potentially represent is in excess of 3300. Characteristics data was available for 51 dwellings, while consistent monitored CO_2 data was available for 21 dwellings. The data used has been taken from three main sources:

1. Final versions of reports, submitted to Innovate UK, which include mandatory elements, e.g. ventilation measurement data, installation and commissioning reviews, contextual data in final reports, etc.;
2. Surveys and/or interviews with a selection of participating project teams across fifteen projects;
3. The online data repository for the BPE (and other) programmes, known as Embed (www.getembed.com). This Platform is owned and operated by the Energy Saving Trust, whereas the BPE data within it is owned by Innovate UK.

The dataset contains a number of limitations which are described in the report, particularly with regard to the monitored data.

Characteristics

The review of the air flow designs showed that the majority of systems met the minimum requirements of the building regulations. However, significant problems were found with the commissioning, with only 16% of systems being found to have been commissioned correctly with respect to air flow and balancing. Consequently, the performance of the systems investigated in the BPE programme varies significantly, with only 56% of installations meeting the design air flow value. Similarly, 52% of systems were found to have a measured imbalance between supply and extract airflow of >15%. Extracts in 'boost' setting from wet rooms, such as kitchens and bathrooms were found to have a significant range, with only 44% of kitchens meeting the minimum requirement of 13 litres per second.

A review of ductwork types revealed that the measured air flow in 88% of systems utilising rigid ducting were equal to or greater than their design air flow values, whereas between only 40 and 44% of systems utilising flexible ducting met their respective design values.

Design

Due to the nature of the BPE programme, only projects with high sustainability standards (Code for Sustainable Homes level 4, 5, Passivhaus) were funded. This meant that the dwellings were designed to have good levels of airtightness. This is why provision of acceptable indoor air quality was an important consideration for installation of MVHR systems across the majority of the projects studied. In a few cases, MVHR systems were selected to achieve Code compliance without much understanding of required air-tightness of the building envelope or the maintenance requirements of these systems.

Performance

Overall comparison of CO_2 levels in houses with non-MVHR ventilation indicates that average and peak CO_2 levels are lower in MVHR houses, but this should be contextualised with emerging evidence of poor performance (particularly in bedroom spaces) of natural ventilation in airtight homes. However, peak CO_2 levels were consistently lower suggesting that, when working, mechanical systems may improve ventilation rates.

However, a number of the MVHR houses demonstrated sub-optimal performance and indicate that there are risks when systems do not work correctly or are not being used. This would lead to houses being naturally ventilated, but relying entirely on opening windows where there is no provision for background ventilation. In some spaces where this is not possible (for example due to external factors such as noise or security), or where there is less adaptive behaviour (for example bedrooms overnight), very poor levels of ventilation are experienced.

The impact of MVHR on internal conditions such as relative humidity was not clear. Within the available sample there was no obvious association with low RH, however, this may be masked by the tendency for MVHR houses to be heated closer to optimum temperatures. Looking at the absolute moisture content of the air also revealed no clear trends, but some MVHR houses had high levels of moisture. What was clear is that houses with MVHR systems tended to have more stable environmental conditions – differences between peak and low levels of both RH and temperature were consistently lower in the MVHR houses.

In general the energy consumption in houses with MVHR systems was lower, but again this needs to be contextualised – 77% of the MVHR dwellings with energy data were of Passivhaus construction, which in general have lower consumption within the domestic sample (albeit with MVHR as a key component).

Overall the study indicates that the rationale behind the use of MVHR systems is borne out – the rates of ventilation as evidenced very generally by CO_2 levels are better, and the energy use overall is lower. However, the study highlights the prevalence of sub-optimal systems and the possible implications on both energy efficiency and indoor air quality.

Summary

Well designed, installed, maintained and used MVHR systems are able to make useful contributions to energy reduction and good ventilation. However, in practice achieving all these conditions is a challenge for the industry and many of the projects in the studies had a number of problems that would undermine these benefits.

Common problems included: insufficient system air flow and system imbalance; lack of appropriate airtightness; poorly designed and installed ductwork; lack of occupant handover and understanding; inadequate maintenance, in particular filter cleaning or replacement.

In airtight homes, the importance of maintaining the ventilation provision is imperative and the consequences of failure may be more significant, and may have detrimental health implications for the occupants.

Key stages are improving design to avoid problems. This includes:

- Ensure that the performance requirements in terms of energy and ventilation are clear;
- Consider design issues to ensure good airflow and to anticipate and avoid installation problems associated with ductwork;
- Consider and design in maintenance requirements including unit location, filter cleaning and replacement;
- Good communication of the design details with installers and commissioners in conjunction with better quality control onsite to avoid installation defects;
- Improved handover processes and occupant guidance.

The most common problems at the installation or commissioning stages include imbalance between supply and extract airflows (half of the projects), poor installation, and inadequate commissioning (likely as a result of the former problems), with systems requiring recommissioning in one-third of the projects. Other problems which occurred include blockages or no airflow, systems difficult to commission, and fan speeds that were too high.

In terms of operation, most interviewee dissatisfaction was with the inadequate level of user understanding of how to operate and control the system, which suggests insufficient training or handover. The most common operational issue was found to be system maintenance. Without appropriate handover and training (including easy-to-follow documentation and follow-ups), it is difficult to make occupant or housing association-led maintenance regimes work.

Half of the projects sampled had occupants that disabled the system; the most common reason was out of concern for the operating cost of the MVHR. Though potentially tenuous, high cost of running the system was a common perception among occupants.

1. Introduction

1.1. Study context

There is growing evidence that decarbonisation strategies aimed at the housing sector do not always achieve intended results. This performance gap between 'as designed' and 'as built' is increasingly well evidenced[1]. To address this, Innovate UK (formerly the Technology Strategy Board) commenced the *Building Performance Evaluation* programme in 2010. This was a 4-year programme to support a range of BPE studies across the UK in both domestic and non-domestic buildings. They include Phase 1 studies looking at post-construction and early occupation, and Phase 2 studies, which undertook Phase 1 evaluation but also in-use and post-occupancy monitoring and evaluation over a 2-year period.

A key aim of the programme was to identify the causes and scope of performance gaps across a wide range of buildings. In the Domestic programme there were 53 projects supported (representing 350 homes), with 23 Phase 1 early occupation studies and 30 Phase 2 detailed monitoring projects.

1.1.1. Building performance evaluation

The requirements of the programme were identified in the 'Guide for Project Execution' which set out the mandatory testing and evaluation requirements. For Phase 1 projects, this included:

- Design & construction audit, photographic survey, drawings and SAP calculation review, qualitative semi-structured interviews and walkthroughs with occupants and separately, the design team, to explore design intentions compared with final performance;
- Whole house heat loss testing, including air permeability test, infra-red thermography, in-situ U-value measurements and smoke based air leakage test;
- Review of systems design and implementation, including installation and commissioning checks of all services and systems provided to the dwelling, including measurement of performance and energy use of any MV or MVHR systems;
- Occupant survey using standardised housing questionnaire; analysis of which is covered centrally by the Technology Strategy Board;
- Evaluation of hand-over process and any guidance provided to the occupants;
- Comparison of predicted performance with actual performance and interpretation of findings.

For Phase 2 projects monitoring was undertaken for a 2-year period and mandatory elements included:

- Design & construction audit, photographic surveys, drawings and SAP calculation review, qualitative semi-structured interviews, walkthroughs with occupants, and separately, the design team to explore design intentions compared with final

[1] Zero Carbon Hub (2014) *Closing the Gap between Design & as-Built performance–End of Term Report.* Milton Keynes: Zero Carbon Hub

performance. This element was only necessary if not already undertaken as part of a post-construction and early occupation study;

- Metered gas, electricity, water and if appropriate heat, into (and out of) the dwelling;
- Sub metering according to use e.g. space heating, water heating, cooker, lights and appliances;
- Measurement of the performance of microgeneration technologies generating electrical energy and heating/cooling, including separate measurement of the energy consumption and generation;
- Measurement of the performance and energy use of MVHR systems if not already carried out as part of a post-completion and initial occupation study;
- An air permeability test towards the end of the monitoring period and also at the beginning of monitoring period, if not already undertaken as part of a post-completion and early occupation study;
- In-situ U-value measurement, if not already carried out as part of post-construction and early occupation study;
- Monitoring of internal environmental conditions (temperature, relative humidity and CO_2);
- Monitoring of external temperature and relative humidity on site;
- External climatic conditions – obtained from an appropriate local weather station;
- Energy audit, including Appliance audit with equipment load and usage profiles using DomEARM - domestic version of TM22;
- Occupant survey using standardised housing questionnaire – analysis of which was covered centrally by the Technology Strategy Board;
- Comparison of predicted performance with actual performance and interpretation of findings.

In practice not all projects were able to undertake all of these tests, or conduct them to the same standard. Some reporting requirements and deliverables varied over the 4 year period and projects were undertaken at different times, consequently the dataset is quite diverse. Nevertheless it represents a substantial body of information from which important insights can be gathered on a range of issues.

More information on the Building Performance Evaluation programme is available from the Knowledge Transfer Network [connect.innovateuk.org/web/building-performance-evaluation] and outputs from individual BPE projects are available from the Digital Catapult: Building Data Exchange [www.buildingdataexchange.org.uk]

1.2. Ventilation and MVHR

It was apparent from the start of the BPE programme that a significant number of dwellings were using MVHR systems. The requirements for building airtightness have increased and building regulations require all new dwellings to achieve an air permeability level of less than $10m^3/(h.m^2)$ @50 Pa. With improved fabric thermal performance, ventilation losses become more significant and strategies that can reduce these may carry considerable weight when evaluating proposed performance. As a result, MVHR is an attractive option when undertaking SAP calculations and for improved performance standards in place during the studies, such as Code for Sustainable Homes and Passivhaus. Consequently, the uptake of MVHR systems is on the rise, with these systems expected to become a common form of ventilation in the coming years [2].

The ability to provide requisite levels of ventilation, whilst maintaining energy efficiency is a highly desirable goal, but a move away from traditional and familiar forms of ventilation is a step-change in UK housing design. These systems have been found to provide considerable reductions in space heating demand, and improvements of indoor air quality (IAQ) and thermal comfort[3,4]. However, with increasingly mainstream use, a series of studies have also highlighted significant concerns regarding the specification, installation, commissioning, performance, operation and maintenance of MVHR systems in a domestic context (Appendix A).

Links between ventilation and health are well established; however there is growing concern that the modern building practice of reducing natural infiltration, increasing insulation and limiting ventilation to reduce heat loss could cause a significant detrimental impact on indoor air quality. A UK study carried out by the Ventilation and Indoor Air Quality (VIAQ) Task Group on MVHR systems in new homes[5] has found significant concerns regarding the delivery and performance of these systems, and provides recommendations for good practice and highlights the need for more information.

1.3. Study aims and objectives

This meta study was therefore commissioned to undertake a broad assessment of domestic projects that utilised MVHR systems in the BPE programme. Whilst projects have undertaken individual assessments of performance, this study provided an opportunity to make a broad comparison across a range of projects, to identify common issues and to make a comparative analysis of the use of these systems.

The initial research questions included:

- Are MVHR systems in low energy homes delivering acceptable levels of indoor air quality on a long term basis and to what extent? If not, why not?
- What was the design intention and expectation of these?
- What is their mode of operation in relation to the houses in which they are installed?
- What is their operating efficiency in respect of heat recovery?
- Are they providing sufficient ventilation to maintain IAQ?
- What is their contribution to the overall energy efficiency of the homes?
- Are there problems in terms of specification, maintenance or operation that can be identified?
- How are occupants interacting with this equipment and how does this impact on their performance?

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[2] Sullivan L, Smith N, Adams D, Andrews I, Aston W, Bromley K, et al. (2012) *Mechanical Ventilation with Heat Recovery in New Homes.* London: NHBC, Zero Carbon Hub

[3] Schnieders J and Hermelink A (2006) CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy* 34(2): 151-171

[4] Derbez M, Berthineau B, Cochet V, Lethrosne M, Pignon C, Riberon J, et al. (2014) Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment* 72(0): 173-187.

[5] Sullivan L, Smith N, Adams D, Andrews I, Aston W, Bromley K, et al. (2013) *Mechanical Ventilation with Heat Recovery in New Homes.* London: NHBC, Zero Carbon Hub

The aims of the study were to identify the nature of MVHR systems, to analyse the available performance data, to gather information and insights from projects about the issues affecting the use and performance of these systems, and to share this information, experience and knowledge both within projects and to the wider construction industry.

2. Methods and data sources

2.1. Dwelling selection and sample size

From the funded projects within the Innovate UK BPE portfolio, there were a total of 237 MVHR ventilated dwellings. The dwellings represented come from a range of development sizes, one-off through to major developments (largest ~790 dwellings), thus the total number of homes represented is in excess of 3300.

The map below shows the geographical spread of MVHR ventilated dwellings that are included within this study. Subsequently, no one particular developer or installer features more than once across the projects.

Figure 2.1a Geographical spread of MVHR dwellings

Owing to the tiered study nature of the BPE programme, not all of the 237 MVHR ventilated dwellings were studied in detail. However, at least one dwelling from each project site had been subject to detailed investigation by the project teams. The systems subject to this level of review totalled 54 out of the 237 dwellings, covering 29 domestic BPE projects.

Considerable challenges were experienced accessing data for the study due to the timescale of varying and progressive project completion dates and collation and curation of the data that continued post-project completion. Assessments made in this meta-study is based upon data that has been made available through mandatory reporting templates and the web-based data repository known as Embed. Detailed assessment of all the final reports was not practical, however, anonymised case studies illustrating specific issues are included throughout this study.

The data from these 54 systems has been analysed in this meta-study with respect to air flow characteristics. A selection of these have been assessed for their contribution toward maintaining comfort conditions within the dwellings.

To give context to the physical data, responses from BUS Methodology© (covering resident satisfaction, comfort, control) were reanalysed for 27 projects. Further information was obtained through surveys and interviews with 15 BPE projects based on the willingness of the design team to get involved with qualitative review. Care was taken to ensure that both mainstream low energy housing and Passivhaus projects were represented in the sample (see section 2.2).

2.2. Dwelling types and systems

2.2.1. Dwelling types and data availability

A range of meta-reviews across different dwellings within the BPE portfolio have been applied to projects where usable data has been available. Out of the 237 MVHR-ventilated dwellings in the programme, 54 were studied in sufficient detail by the project teams and this data has been used to assess performance characteristics. 33 MVHR-ventilated dwellings had consistent data available for assessing indoor hygrothermal conditions, and this data has been used to assess comfort criteria. Carbon dioxide data was available for 21 MVHR dwellings, which was used as an indicator of ventilation performance. Out of all the dwellings assessed in this meta-study, 20 are certified Passivhaus properties. To enrich the study, a further 15 non-MVHR (MEV or naturally ventilated) dwellings have been assessed for environmental performance, and this has been used to benchmark performance against these two principle ventilation strategies. A summary of systems reviewed is provided in Table 2.2a.

Table 2.2a. Summary of properties reviewed

Dwelling types	Performance characteristics	Design team interviews	Temp / RH data	BUS survey	CO_2 data	Energy
MVHR	54 homes	15 projects (163 homes)	33-34 homes	27 projects (211 homes)	21 homes	39 homes
Non-MVHR	n/a	n/a	15 homes	15 homes	15 homes	20 homes

2.2.2. Overview of key building characteristics

A range of construction types were included within the portfolio of dwellings: traditional masonry; timber-frame; pre-fabricated timber-panel; etc. The main dwelling characteristic assessed in relation to ventilation characteristics is the airtightness standard, both design target and tested.

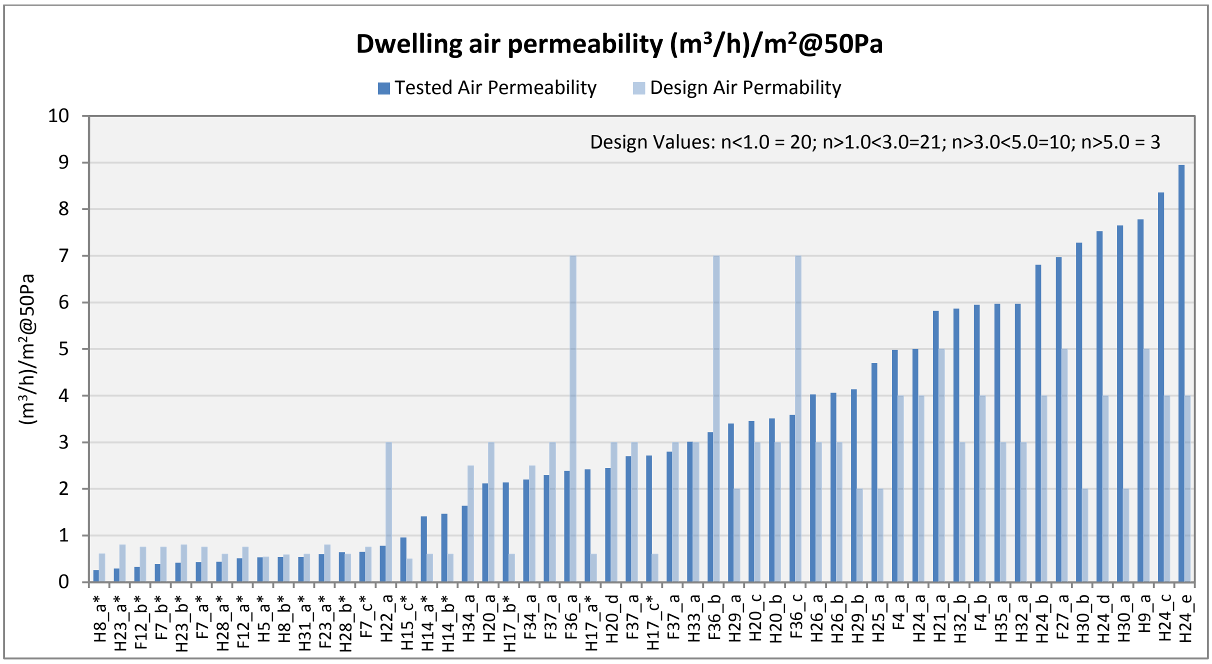

Figure 2.2a. Dwelling air permeability characteristics – design and tested
* against dwelling reference denotes Passivhaus

The design air permeability target is important in the context of MVHR installations as any leakage through the dwelling envelope will have an impact on the efficiency of the heat recovery component. Figure 2.2a illustrates the design and tested air permeability across 54 dwellings.

The design air permeability targets shown in light blue have a range from as low as 0.5 $(m^3/h)/m^2$ @50Pa to as much as 7.0 $(m^3/h)/m^2$ @50Pa. In total 20 dwellings (37%) had a design air permeability of <1.0 $(m^3/h)/m^2$ @50Pa; 21 dwellings (39%) between >1.0 and <3.0 $(m^3/h)/m^2$ @50Pa, and 13 dwellings (24%) were >3.0 $(m^3/h)/m^2$ @50Pa. There are differences of opinion about the appropriate air permeability threshold suitable for MVHR strategies. Passivhaus advocates suggest <1.0 $(m^3/h)/m^2$ @50Pa, whereas other suggested target thresholds are for 3.0 $(m^3/h)/m^2$ @50Pa to an upper limit of 5.0 $(m^3/h)/m^2$ @50Pa. Out of these 54 dwellings, 3 (6%) had a design air permeability of >5.0 $(m^3/h)/m^2$ @50Pa.

The measured air permeability values for each dwelling are also shown in the chart, coloured in dark blue against their design values (the chart is ranked in this order). There is significant variance, even for some dwellings with <1.0 $(m^3/h)/m^2$ @50Pa target, between the intended air permeability and the tested value. The tested values in the chart are for those conducted as part of the BPE projects, and not the test result obtained at dwelling completion.

The measured air permeability test results range from 0.26 $(m^3/h)/m^2$ @50Pa to 8.95 $(m^3/h)/m^2$ @50Pa. In total, 16 out of the 54 dwellings (30%) achieve a tested air permeability of <1.0 $(m^3/h)/m^2$ @50Pa, with 15 of these being Passivhaus dwellings. A further 13 dwellings (24%) achieve an air permeability between >1.0 and <3.0 $(m^3/h)/m^2$ @50Pa, and an additional 11 dwellings (20%) are between >3.0 and <5.0 $(m^3/h)/m^2$ @50Pa. This leaves 14 dwellings (26%) with a tested air permeability of >5.0 $(m^3/h)/m^2$ @50Pa, with 6 of these being >7.0 $(m^3/h)/m^2$ @50Pa. The mean air permeability test value in the dataset is 3.2 $(m^3/h)/m^2$ @50Pa. In total, 25 dwelling air permeability tests (46%) meet their design target value.

2.3. Data collection methods

2.3.1. Assessing performance characteristics

Through the mandatory deliverables from each project, various data relating to the characteristics of the dwelling and their ventilation systems was available. Final reports were also reviewed in order to obtain the required information. This data trawl resulted in standardised characteristics forms being created for each MVHR system to allow characterisation of the systems and dwellings: air permeability; air flow performance; system balance, etc. This process would also identify any emerging trends, e.g. ducting types; relationship to original commissioning values, etc., which may also have a bearing on in-use performance.

The first review for the performance characterisation was to understand the range of air permeabilities within the MVHR ventilated dwellings. All projects, whether Phase 1 or Phase 2, undertook air permeability testing on their subject dwellings. These tests were additional to any testing carried out for regulatory compliance purposes.

The programme requirement for air permeability testing was to test in Phase 1 (or at the start of Phase 2 if no Phase 1 study), and to conduct a further test at the end of Phase 2. For the purpose of this meta-study, the first test result has been used.

All tests performed followed the guidance within *Technical Standard 1 – Measuring air permeability of building envelopes, Issue 2*, (ATTMA 2007) and BS EN 13829: 2001 *Thermal performance of buildings - Determination of air permeability of buildings – Fan pressurization method*; with the additional requirement that the derived permeability was the mean of the resulting pressure and de-pressure tests.

For assessing the air flow characteristics, the volume flow rates associated with each system were re-measured by the project teams as part of the BPE study, irrespective of any original commissioning that had previously taken place. This task usually took place during Phase 1, with the intention being to understand the systems' performance and make any necessary adjustments prior to taking the dwelling forward to long-term monitoring. Measurements were made using UKAS calibrated volume flow equipment, and followed specific requirements in the project execution guide, which references the procedure in the published *Domestic Ventilation Compliance Guide*[6].

For the purpose of this meta-study, Phase 1 measurement data has been used, as this, theoretically, should closely represent the air flow performance of the systems post-commissioning, but pre-occupation (i.e. condition at hand-over). The Phase 1 data was considered to be the most reliable of that available, and has been used as a benchmark to compare against both the design and commissioning data, where this was made available. However, in some cases, Phase 2 measurement data has been used, but only where a project did not participate in Phase 1, or where full re-commissioning of the system was necessary as a result of poor results from Phase 1 measurements. This is to discount potential system adjustments by residents (Phase 2 studies were undertaken in occupied dwellings), which may skew comparisons with design and commissioning data.

Assessments have been made for each system to determine their success for meeting both their original design air flow values, and for meeting the design specification published in Approved Document F – Ventilation (AD F: Part F of the Building Regulations for England and Wales). Where design information was not available, the meta-study team have derived the minimum design air flow values in accordance with the values published either in Approved Document F 2006 or 2010 editions (whichever revision was in force at the time for that particular dwelling).

[6] Department for Communities and Local Government (July 2011) *Domestic Ventilation Compliance Guide*

Some dwellings within the portfolio are located in Scotland and Northern Ireland, where different regulations are used. However, for the purpose of this meta-study, comparisons have been made with the design guidance published in AD F, irrespective of dwelling location. AD F, which carries the same specification as Technical Booklet K (Building Regulations (Northern Ireland)), and Building (Scotland) Regulations (Technical Handbook - Domestic Section 3 Environment), does not contain any performance specification for dwelling air flow rates.

2.3.2. In-use performance

Phase 2 projects generally spanned a two year period, during which time monitoring equipment was installed in the dwellings to collect data in accordance with the BPE programme protocol. The data recorded by the numerous sensors and meters in each house has been uploaded onto the Embed data repository. Being a new system, created during the same period as the BPE programme, there were significant delays with uploading, configuring, and ultimately accessing the data from individual projects. Access by the meta-study team was given in July 2015.

Included within this data is information applicable to understanding MVHR performance. This included the following:

- Internal temperature (°C), typically living room and bedroom(s);
- Internal %RH, typically living room and bedroom(s);
- Internal CO_2 concentration (ppm), typically living room and bedroom(s);
- Energy used by MVHR (kWh) installation.

Following a review of the data available on Embed, a decision was made to use the statistics (max, min, mean and range) generated within the Embed platform to form the basis of the analysis. Whilst this may have limited the results, it did eliminate the need for analysis of the raw data files (which is beyond the scope of a meta-study), and therefore significantly reduced the time required for data collection.

Monitoring sites were limited to living rooms and bedrooms, as these tend to have the greatest levels of occupancy. Bedrooms are spaces where occupants spend the most uninterrupted time. Children may also use their bedrooms for socialising and schoolwork, in which case they could spend a significant amount of time in the bedroom. Bedrooms over-night present consistent conditions with occupants asleep, with little or no adaptive behaviour, which minimises confounding variables in respect of ventilation. Accordingly, environmental conditions and ventilation rates in bedrooms and living rooms are of particular interest as these spaces provide the greatest exposure to occupants.

Analysis of environmental data (temperature, relative humidity and CO_2) was limited to three months (February, April and August), representative of winter, spring and summer conditions. This provided the opportunity to explore seasonal variations. The analysis was further limited to the year 2013, to reduce the impact of yearly climate variations. Only complete datasets for each month were included in the analysis.

Although energy data was available on the Embed platform, this was significantly limited and there were a number of caveats pertaining to the validity of the available information. Specifically, there was concern regarding the correct use of units (W, kW, kWh) and the format (cumulative or differential) in which the data was available. Furthermore, aggregated data for total electrical, non-electrical and space heating consumption was not available at the time for all projects, therefore manual calculations were required. For these reasons, a decision was made to extract energy data (annual space heating, electricity consumption and non-electricity consumption) from the available DomEARM spreadsheets. Unfortunately, it was not possible to accurately evaluate the energy performance (electrical consumption or heat recovery efficiency) across the range of MVHR systems in practice due to a lack of viable data.

2.3.3. Surveys and interviews

As well as dwelling characteristic information and monitored data, additional data were gathered from the BUS surveys which were undertaken by all projects. To give context to the physical data, responses from BUS Methodology© (covering resident satisfaction, comfort, control) were reanalysed for 27 projects. Further information was obtained through surveys and interviews with 15 BPE projects based on the willingness of the design team to get involved with qualitative review.

The purpose of the reanalysis of BUS surveys, surveys and interviews by the BPE project teams was to:

- Understand the design intention and expectation of the MVHR systems;
- Identify problems and good practices in terms of specification, maintenance or operation;
- Evaluate how occupants interact with MVHR systems and how this may impact on their performance.

Feedback from occupants was assessed by undertaking a re-analysis of BUS survey results (n: 27 projects covering 211 dwellings) along with primary data collection using online survey questionnaire and/or telephone interviews with design teams (n: 15 projects covering 163 dwellings). Table 2.3a lists the projects for which primary data collection was undertaken.

Table 2.3a BPE projects represented by design team interviews (and/or questionnaire)

Project Code	Feedback from design teams
H17	Questionnaire & Interview
F4	Questionnaire & Interview
H20	Questionnaire & Interview
H23/F23	Questionnaire & Interview
F1	Questionnaire & Interview
H14	Questionnaire only
H25	Interview
H8	Interview
H5	Interview
H15	Interview
H26	Interview
F27	Interview
H10	Interview
H9	Interview
H35	Interview

2.4. Limitations of the study

The study relies both on the quality and availability of project data that has been collected by other parties. There will likely be some variances with data collection techniques between 3rd party project teams and the completeness of their respective project data. This study has made reasonable attempts to ensure that any data used for the purpose of meta-analysis is of sufficient quality to ensure that the findings herein are satisfactorily robust.

The findings have some caveats. Importantly:

- Dwellings were not randomly selected for inclusion in the Building Performance Evaluation programme, therefore may not be representative of all UK new build dwellings with MVHR systems;
- Measurements were undertaken independently for each housing project, therefore sampling equipment and methodology may have varied;
- Exact occupancy levels during the monitoring period were not known;
- Occupant behaviour and use were not objectively measured and are likely to have had a significant effect on the results. In particular, it is not clear if all MVHR systems were in operation during the environmental monitoring;
- The frequency of window opening was not monitored in the majority of homes;
- The volume of monitored living room and bedroom spaces were unknown;
- Data was extracted from the Embed platform manually, therefore may be subject to human error;
- Variations of localised climatic conditions, airtightness levels, construction type and space heating strategies were not taken into account;
- Start and end date for the annual energy monitoring data were not consistent across all projects;
- Uneven sample sizes for MVHR and Non-MVHR data.

Despite these limitations, the results provide an important insight into the performance of MVHR systems in practice. Furthermore, since the limitations were the same for all monitored dwellings, they are not expected to have had a significant impact on the results.

3. Characteristics of MVHR systems

3.1. Compliance: design stage

Figures 3.1a and 3.1b show data from a selection of 43 properties where the original design data had been submitted. As the guidance for minimum air flow rates changed between AD F 2006 and 2010, the charts have been separated to reflect the whole dwelling ventilation rate according to the revision of the Approved Document that was in force for that particular property.

Figure 3.1a shows the properties that were completed under the 2006 revision of AD F. The minimum whole-house ventilation rate required, shown by the green line, is based upon the requirement of 0.3 l/s per m^2 of internal floor area with an allowance for infiltration by subtracting 3% (single-storey) or 4% (multi-storey) internal volume of air from the whole dwelling ventilation rate, according to dwelling type.

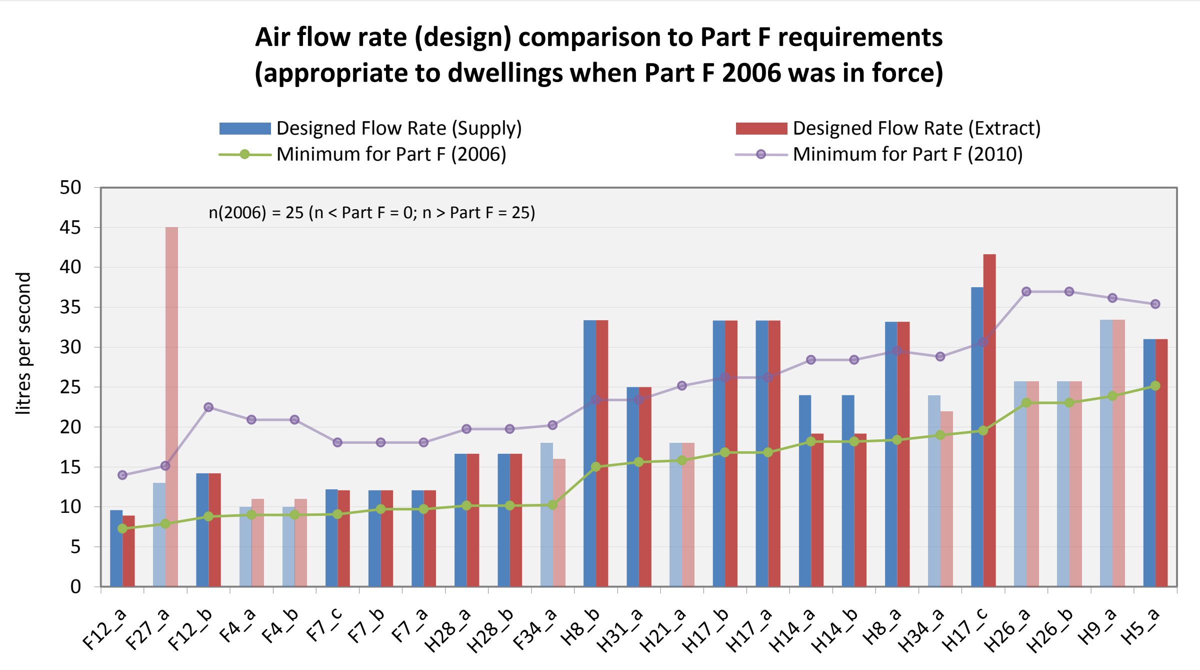

Figure 3.1a. Design stage air flow rates compared to AD F (2006)
Bold bars denote Passivhaus dwellings

The chart (Figure 3.1a) shows that, in all 25 submitted cases, the ventilation designs meet the minimum air flow specification given AD F (2006). However, the guidance published in this revision of AD F was designed to cope with air permeability levels down to around 3-4 (m^3/h)/m^2 @50Pa, and it suggested that additional ventilation provisions (air flow) should be considered for more airtight properties. It would be reasonable to consider that the allowance for additional provision would be to remove the infiltration allowance, thereby the provision of all air flow is via the ventilation system (i.e. not relying upon infiltration to account for a proportion of the total ventilation). The purple line shows the 0.3 l/s per m^2 (without infiltration allowance), and this is the revised specification for minimum ventilation rates as required by AD F (2010).

Of the 25 properties represented in Figure 3.1a, 18 of the properties have a tested air permeability of <3.0 (m^3/h)/m^2 @50Pa, and therefore the design air flow rate should accord with the requirements of AD F (2010). As the chart shows, only 6 of the designs (all <3.0) meet the required air flow criteria. Thus, it could be considered that only 13, or 52% of the design ventilation rates meet the AD F (2006) specification.

Figure 3.1b shows a further 18 properties that were completed to meet AD F (2010) revision. The purple line in the chart shows the minimum design flow rate for each property to meet the AD F (2010) specification. In the majority of cases (72%), the original design values are equal, or greater than the minimum value. However, the design for 5 properties do not meet the minimum specification. Given the period during which the BPE programme spanned, it is probable that these properties fell during the transition between 2006 and 2010 revision of AD F coming into force.

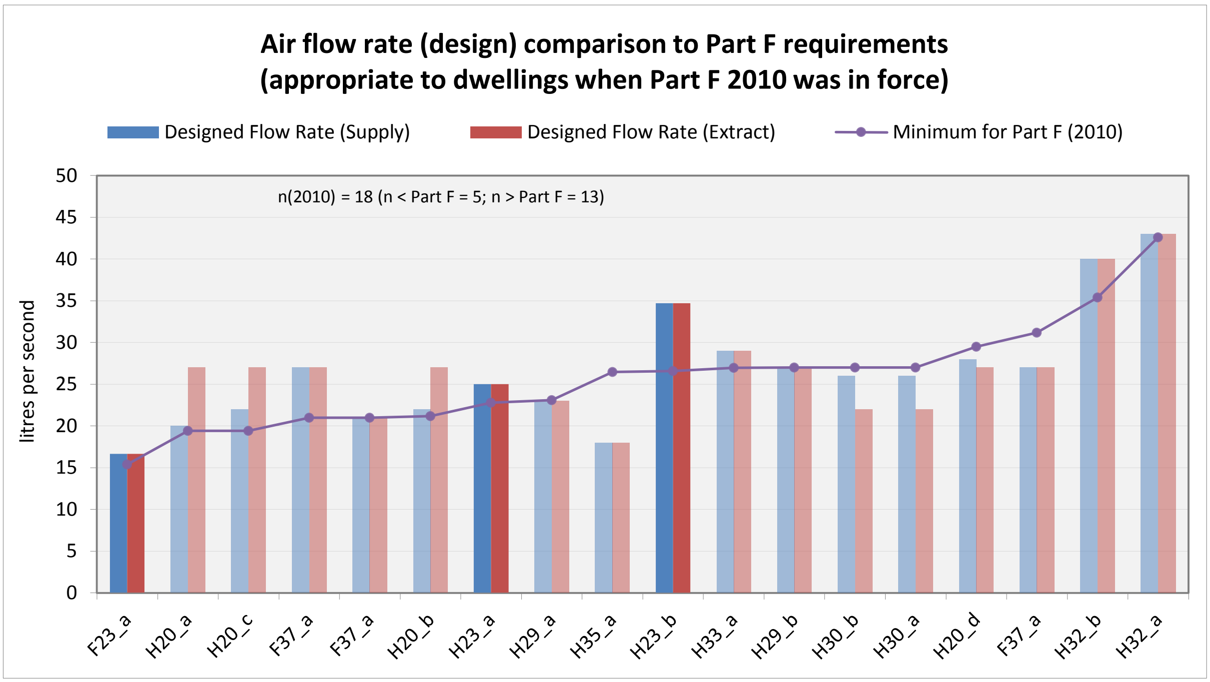

Figure 3.1b. Design stage air flow rates compared to AD F (2010)
Bold bars denote Passivhaus dwellings

The origin of the designs are not known, whether they had been undertaken by the manufacturers (or their agents), or by a member of the project design team (e.g. M+E engineer). Out of these 43 properties it is noted that the submitted design values for the whole-dwelling supply and ventilation rates, are out of balance for 17 (39%) of systems, the most striking being property F27_a in Figure 3.1a. In 16 out of 17 cases (all except ref F27_a) it was found that the design flow rates followed the guidance in the relevant revision of AD F, e.g. supply air rates determined by 0.3 l/s per m^2, and extract rates determined from minimum high rate published for each room. AD F does not require system air flows to balance, although it is necessary to obtain optimum thermal efficiency and minimise risks relating to condensation. Imbalance findings are discussed later in this section. It is believed that the design for property F27_a used higher design extract rates, which are applicable to intermittent, as opposed to continuously running mechanical extract fans.

3.2. Commissioning

The original commissioning data was available for 38 out of the 54 systems reviewed. In most cases, this data has been transcribed by the project teams, thus the original commissioning sheets have not been reviewed as part of this study. Table 3.2a shows that, out of the 38 systems with commissioning data, it would seem that only 19 have been commissioned at both speeds (normal and boost speeds are necessary for demonstrating AD F minimum values have been met). It is acknowledged that some MVHR systems have more than two speed settings, but this review is limited to the published guidance values for minimum low and minimum high rates in AD F.

Table 3.2a: Summary of commissioning data available

Number of systems reviewed	Both speeds	Normal speed only	Boost Speed only	No data
54	19	28	27	16

Thus, 50% of the systems can be judged to be only partially commissioned with respect to air flow. Of those that had partial commissioning data, a small number gave only the supply air values in normal speed and extract values in boost speed. These are the key values for demonstrating that the minimum requirement for 0.3 l/s per m^2 for supply, and individual room boost extract rates had been met.

Irrespective of completeness of commissioning, of greater concern is the reliability of the commissioning values recorded. Out of the 38 systems reviewed, 25 (66%) had either identical values to their design values, and/or the individual room extract rate values were identical to those published in AD F. Whilst it is accepted that there may be a degree of ‘rounding’ of recorded values during commissioning, the similarities between commissioned and design values are unlikely. There is a strong possibility that some systems have been provided with air flow commissioning values, even though the systems themselves have not been commissioned.

Out of the 38 sets of commissioning data reviewed, only 6 (16%) systems have provided sufficient evidence to demonstrate that they have been satisfactorily commissioned with respect to minimum air flow rates and balancing.

3.3. Air flow rates

Measured air flow rates were available for 52 properties. The air flow measurements used for this assessment were those taken during the BPE study, and not the original commissioned air flow values. 34 of the systems are represented in figure 3.3a, and are judged against AD F (2006), which was in force at the time.

Out of the 34 systems, the minimum air flow requirement is met in 23 systems (68%), with two systems (H24_c and H24_d) failing significantly. A number of systems were commissioned to have higher air flow rates, meeting or exceeding the AD F (2010) air flow rates. In most cases, these are the more airtight dwellings (<3.0 $(m^3/h)/m^2$), as summarised later.

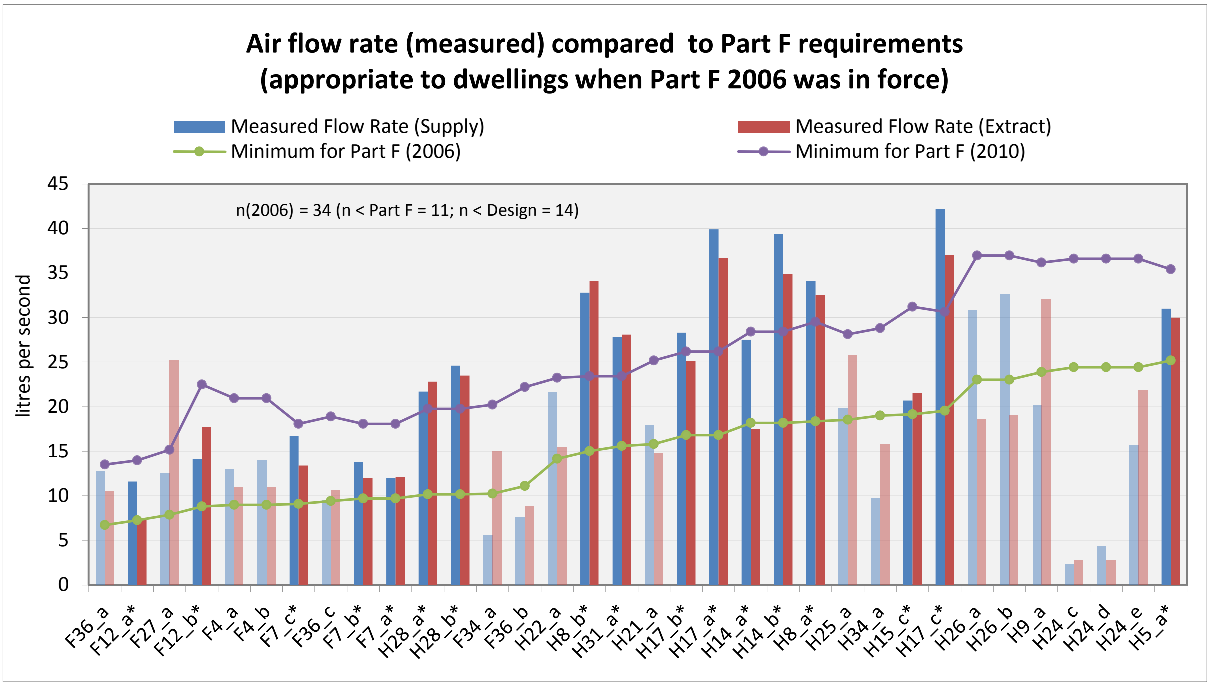

Figure 3.3a. Measured air flow rates compared to AD F (2006)

Bold bars denote Passivhaus dwellings.

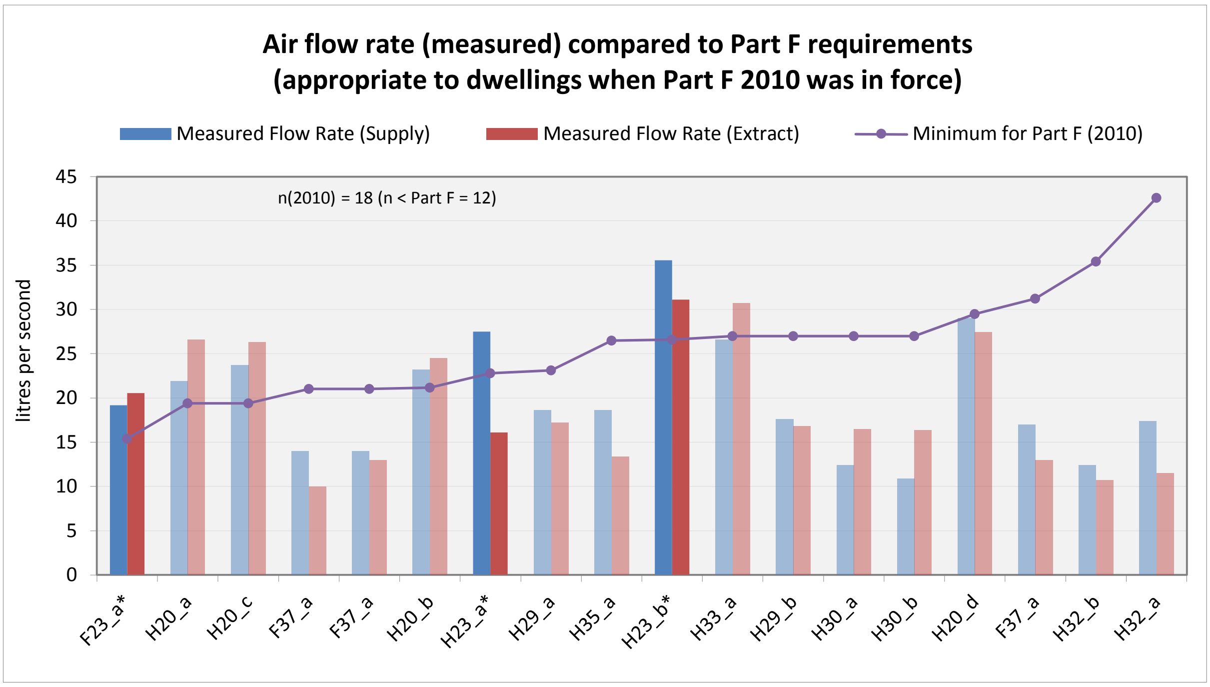

Figure 3.3b. Measured air flow rates compared to AD F (2010)

Bold bars denote Passivhaus dwellings

Chart 3.3b displays systems where AD F (2010) was in force. Out of the 18 systems represented, only 6 (33%) meet the minimum air flow rate required.

Across the 52 systems assessed, 27 were for dwellings with a tested air permeability of <3.0 $(m^3/h)/m^2$. Using AD F (2010) minimum dwelling ventilation rate for these, more airtight homes (irrespective if AD F (2010) was in force), only 33% met the minimum criteria.

Specific extract air high rates (or boost speed) for wet rooms are published in AD F for the removal of excess moisture production during cooking and bathing times.

These extract rate values between the 2006 and 2010 revisions are the same and set the minimum value for these rooms, as illustrated in table 3.3a.

Table 3.3a. Extract air: minimum high rate values AD F

Room	Minimum High Rate (l/s)
Kitchen	13
Bathroom	8
Utility room	8
Sanitary (e.g. W.C. no bath/shower)	6

Figure 3.3c quantifies the individual room extract air high flow rates across the 48 systems assessed. The boxes show the upper and lower quartiles, and the median value. The whiskers show the minimum and maximum values from the dataset. The red dot highlights the minimum value required to satisfy AD F.

Overall, the measured boost extract air flow rates meet the 13 l/s minimum for kitchens (AD F) in 44% of systems. 71% of bathrooms meet the 8 l/s requirement, whereas only 30% of en-suites and 38% of utility rooms meet the 8 l/s criteria. In W.C.'s, which have a lower extract flow rate requirement of 6 l/s, the flow rates were met in 77% of systems.

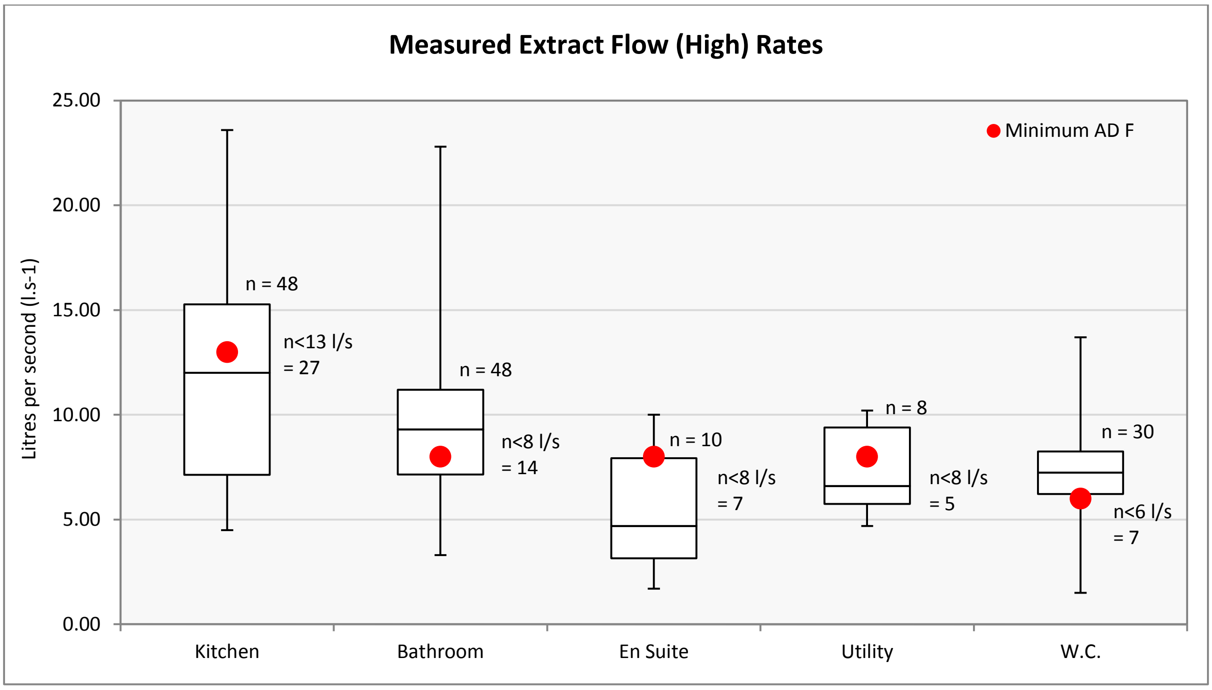

Figure 3.3c Measured individual room extract flow rates in boost

3.4. System balance

Achieving a reasonable balance between supply/intake air streams and extract/exhaust air streams is important for heat recovery with an MVHR system. By achieving a reasonable system balance it can be assumed that all ventilation air entering and leaving the property passes via the heat exchanger, thus maximising the available heat recovery potential. An imbalance between these air streams can put the dwelling under a slight pressure differential, which in turn will allow ventilation air to find alternative air paths via the building envelope. This will likely have a bearing on the system heat recovery efficiency, although it has not been possible to explore this aspect in this meta-study.

In practice, achieving a perfect balance, that is a balance of 0%, is usually impracticable to achieve. Some of this is due to the accuracy limitations of measurement devices used during commissioning and influences during commissioning (e.g. wind), and some is to do with the variability of some manufactured systems to allow such a degree of fine-tuning. In order to achieve a reasonable balance it is often necessary to set an imbalance between supply and extract fans. The amount of imbalance will depend upon the difference in resistances present in these two air streams, dictated by variables such as: the length of ducting; number of junctions, and bends; number of room outlets.

AD F (2010) does not set imbalance criteria, and the only known specification for system balance is that set within the protocols for commissioning Passivhaus certified installations. The maximum allowable imbalance between intake and exhaust air flow for these systems is 10%. A slightly more relaxed allowance of 15% is taken as current accepted practice, although there is no known publication of this value.

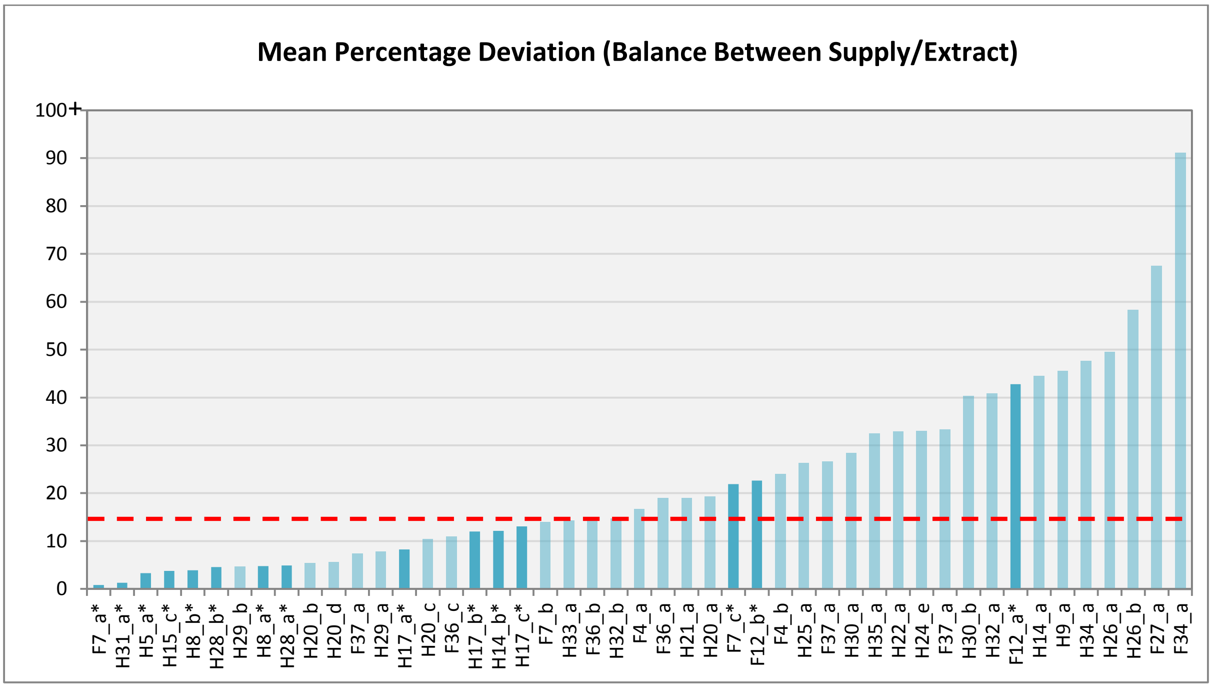

Figure 3.4a. Symmetrical mean percentage deviation between supply and extract rates
** against dwelling reference denotes Passivhaus.*

Figure 3.4a shows the balance observed in 52 MVHR systems set at 'normal' speed. These values are taken from the sum of the individual room supply and extract rates, and not the intake and exhaust measurements, as these were not available in most cases. The red dotted line shows the 15% allowance. Out of the 52 systems, 25 (48%) have an imbalance of <15%, the remainder being above this, with 14 (27%) being significantly out of balance (deemed as >30%). Of the 15 Passivhaus systems, 6 show an imbalance of >10%.

3.5. Influence of duct type

The type of ducting across 48 systems has been reviewed. The systems selected are those where data about the ducting type has been reported by the projects. This has been categorised into three broad types:

1. Flexible: this is where 100% of the installed ducting for the system is flexible, irrespective of material or quality.
2. Hybrid: this is where the large majority of ducting is rigid, but some flexible elements have been used, particularly for final connections to room terminals and the MVHR fan unit. Some installations may have had flexible components for bends, offsets, or other awkward elements.
3. Rigid: this is where it is known that 100% of the installed ducting is rigid (an exception being final connections to the MVHR unit which is often a recommendation of some manufacturers), irrespective of material, e.g. plastic or metal.

This review, limited by the data available, compared the measured air flow performance against the original design air flow. Although a fairly simple assessment, it is useful to determine any emerging trend for ducting types where system air flow performance is better than or equal to the design air flow. The design data used for this assessment is the original submitted design.

The results from this review are presented in figure 3.5a. The upper segment of the chart (green background) represents systems where the measured air flow rates are equal to or greater than the design. The lower segment represents system air flow rates that do not meet the design air flow. The air flows for the supply (S) and extract (E) for each duct type are plotted.

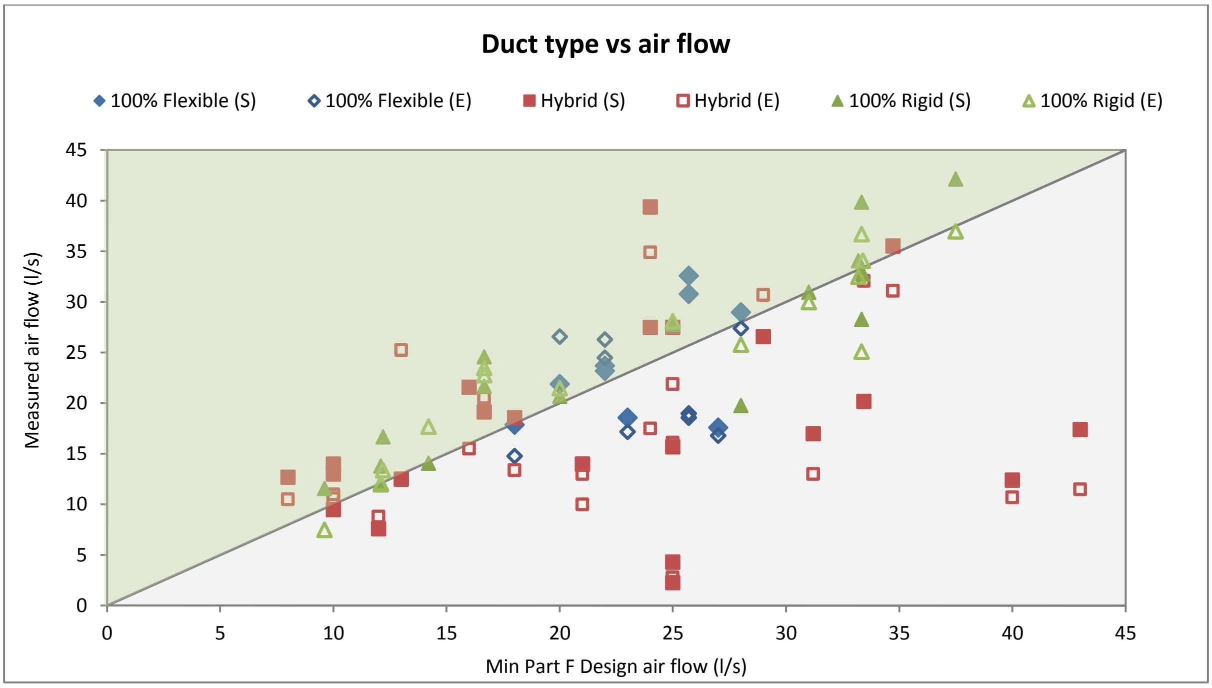

Figure 3.5a Duct types: measured airflow comparison with design air flow.

Overall, 40% of hybrid ducted systems and 44% of flexible ducted systems meet their design air flow criteria. By comparison, the measured air flow in 88% of rigid-duct systems meet the design air flow criteria. This assessment is limited and some caveats need to be considered. For example, duct pressure drop is not known for any system in the data set, air leakage through ducting is not known, the fan system employed by the MVHR may either be constant power or constant velocity types, quality of installation and commissioning is not known, etc. The results do however indicate a trend toward improved performance with rigid ducting systems.

4. In-use performance

4.1. Ventilation performance

Levels of carbon dioxide indoors correlate well with human occupancy and human-generated pollutants. There is a general acceptance that carbon dioxide keeps 'bad company' and that levels above 1000 ppm are indicative of poor ventilation rates. The derivation of this is well evidenced[7] and corresponds well with a ventilation rate of 8 l/s per person identified in CIBSE Guide A[8], which also sets down classifications for IAQ and CO_2 concentrations associated with these.

Health effects of ventilation are also well evidenced and whilst there is less literature available as to these effects in housing, a recent paper by Wargocki[9] identifying associations between carbon dioxide levels and health concluded, *"The ventilation rates above 0.4 h^{-1} or CO_2 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".*

There are however some limitations to the use of CO_2 as an indicator. The rise in levels is relative to external levels, which may vary by location and time; different projects may be using different types of equipment, placement and methodology; the degree of range and accuracy is not known; and periods of occupancy are likely to vary over time and between projects. Levels of CO_2 may also be unconnected to pollutants unrelated to occupancy, such as off-gassing from building materials, carpets and furniture.

Nevertheless, in the context of concern over ventilation rates, CO_2 levels provide a useful indicator of relative levels of ventilation and the BPE projects have used CO_2 measurements as a low cost means of examining ventilation. Projects also recorded temperature and relative humidity levels, and in a limited number of projects, occupancy (through passive infrared (PIR) sensors) and window opening (through contact sensors) were recorded. This data has been examined to evaluate the comparative performance across a range of projects.

Available data (maximum, minimum, range and average values) for each parameter was extracted manually from the BPE section in Embed and transferred to Excel for analysis. Cleaning of the data was performed within the Embed platform, where data greater than two standard deviations from the median was classified as 'in error' and was not used in the calculations. Monthly data was constructed from average daily rollups for instant readings.

After initial observation, it was evident that the available dataset for MVHR dwellings was relatively limited and there was not a complete overlap with the dataset on system characteristics (only 21 dwellings with both environmental and system characteristics data). Properties were selected based on the availability of data and the completeness of the datasets. A decision therefore was made to include data pertaining to non-MVHR dwellings (also collected as part of the BPE programme) in the analysis to provide a basis for comparison.

4.1.1. Comparative ventilation performance

The internal CO_2 levels were initially compared to available data of non-MVHR dwellings (dwellings that were ventilated naturally or with Mechanical Extract

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[7] Porteous, Colin (2011) Sensing a historic low-CO2 future. *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality, Rijeka, Croatia: Intech*.

[8] CIBSE. Guide A: Environmental design. 7th Edition, London: CIBSE, 2006

[9] Wargocki P (2013) The effects of ventilation in homes on health. *International Journal of Ventilation* 12(2): 101-118.

Ventilation). Data is shown for living rooms (MVHR n=18-22, non-MVHR n=15) and bedrooms (MVHR n=20-23, non-MVHR n=20) in three sample months (February, April and August 2013). Comparison graphs show mean and peak levels of CO_2 during February (figure 4.1a and 4.1b) and are ranked in order of magnitude. The full range of graphs is shown in Appendix B and the data is summarised in Tables 4.1a and 4.1b.

Table 4.1a. Average living room CO_2 levels (ppm) in MVHR and Non-MVHR homes

	MVHR (n=18-22)			Non-MVHR (n=15)		
	Peak CO_2	Mean CO_2	Range of CO_2	Peak CO_2	Mean CO_2	Range of CO_2
Feb (mean)	1046	754	492	2013	867	1588
Apr (mean)	1206	754	669	1768	783	1388
Aug (mean)	966	631	471	1675	726	1262

Table 4.1b. Bedroom CO_2 levels (ppm)

	MVHR (n=20-23)			Non-MVHR (n=20)		
	Peak CO_2	Mean CO_2	Range of CO_2	Peak CO_2	Mean CO_2	Range of CO_2
Feb (mean)	1122	762	614	2514	1118	2040
Apr (mean)	1275	749	779	2638	1103	2121
Aug (mean)	1120	644	674	2623	966	2189

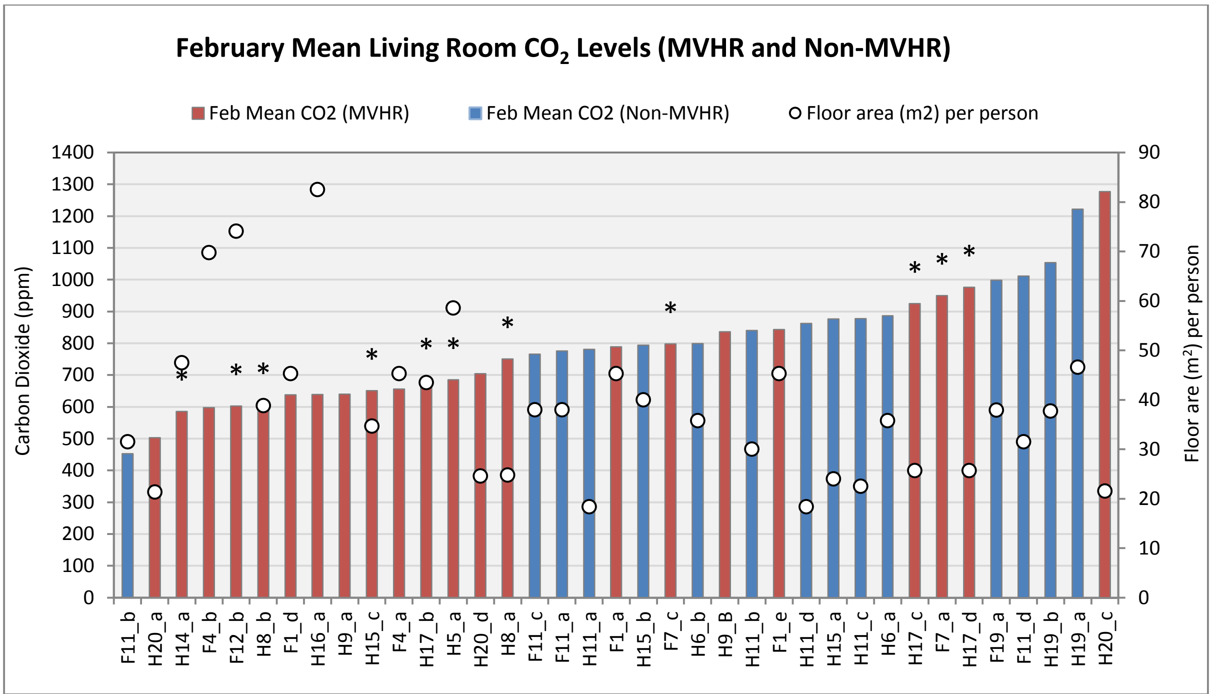


Figure 4.1a. February average (mean) living room CO_2 levels in MVHR and Non-MVHR homes
** Passivhaus dwellings*

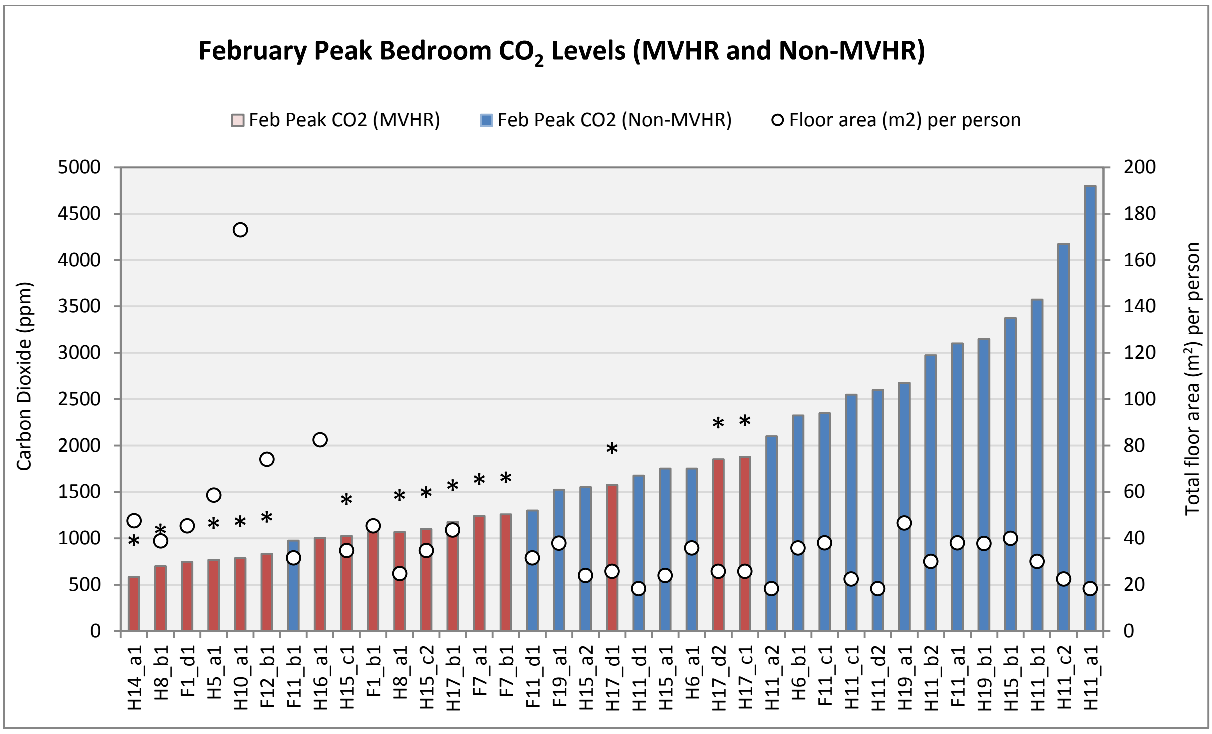


Figure 4.1b. February Peak Bedroom CO_2 levels in MVHR and Non-MVHR homes
** Passivhaus dwellings*

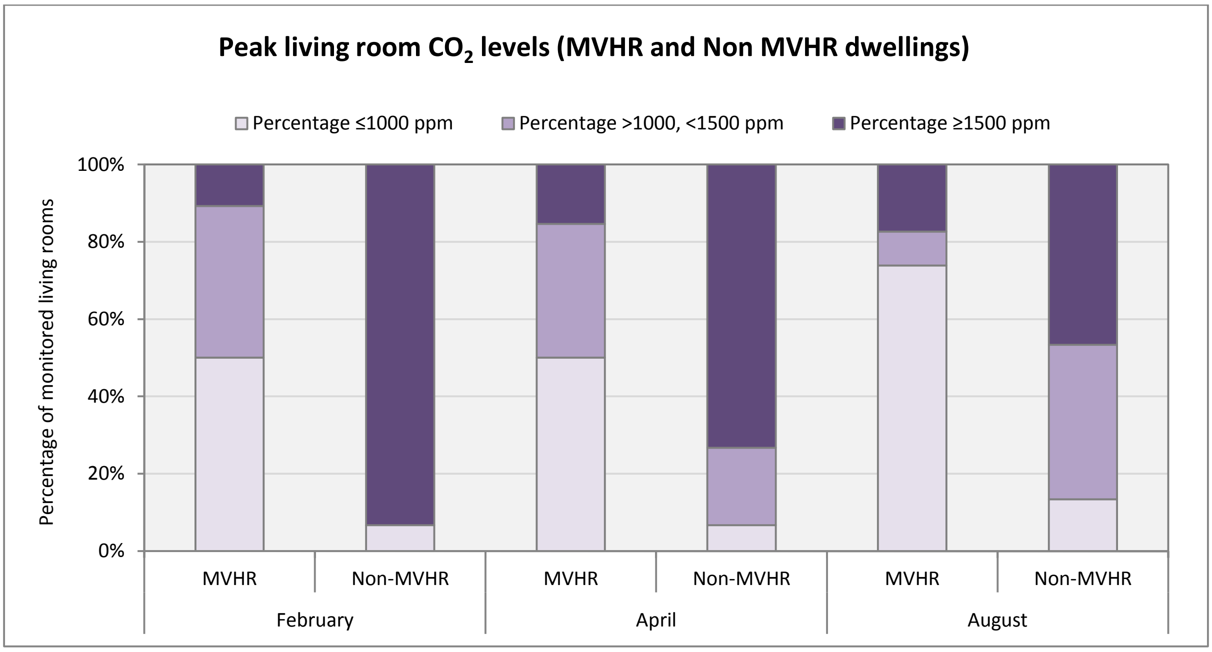


Figure 4.1c. Peak Living room CO_2 levels in MVHR and Non-MVHR homes

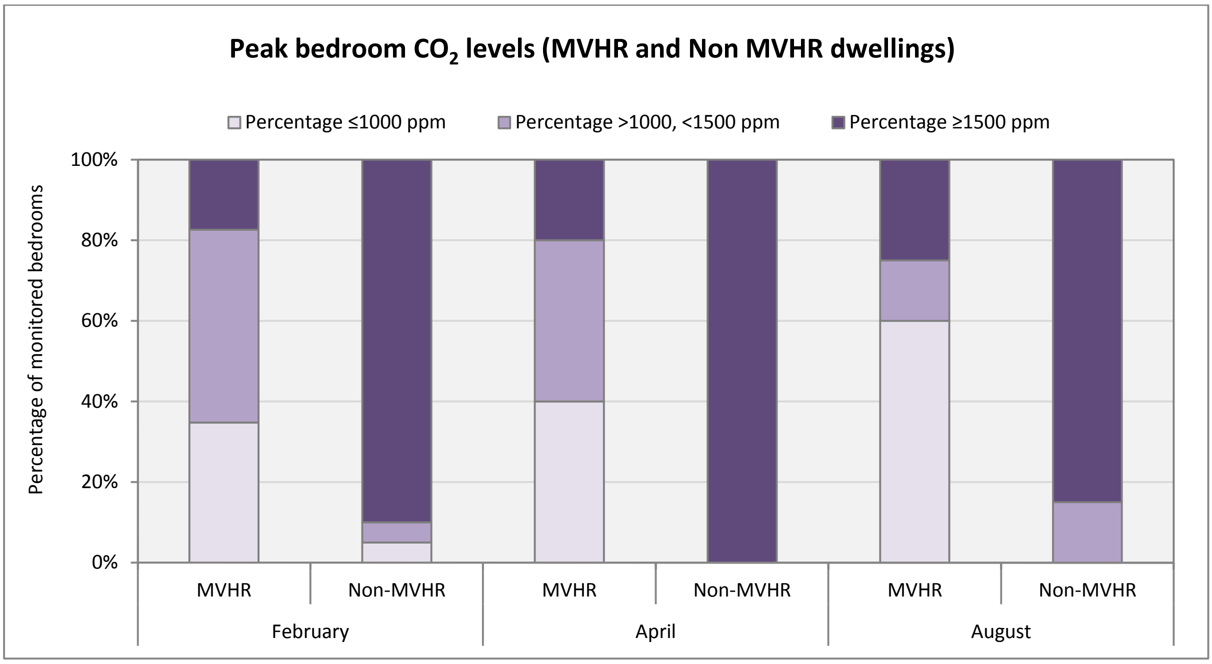


Figure 4.1d. Peak Bedroom CO_2 levels in MVHR and Non-MVHR homes

It is important to note that the limitations of data access means that average levels are not time weighted and are therefore averaged across the entire month, regardless of times or intensity of occupation. Furthermore, although data in Embed has been checked to omit spurious results, individual peaks may be isolated events.

Nevertheless, there is a clear differentiation between the dwellings with and without MVHR systems, with MVHR systems in general having lower levels of CO_2. The difference is more marked when comparing peak CO_2 levels in living rooms and bedrooms, which were noticeably higher in the non-MVHR dwellings (see Figures 4.1c and 4.1d). Both peak and average levels were higher in the bedrooms and in these spaces the difference was much greater in non-MVHR houses.

The impact of ventilation provision on indoor CO_2 levels was most evident during February, which is likely due to a lower prevalence of window opening during the winter season. However higher CO_2 levels were also found in general in non-MVHR compared to MVHR dwellings during both April and August months, but in the summer the picture is more mixed, with more MVHR houses with higher CO_2 levels. This may be due to a shift toward natural ventilation strategies in summer with greater window opening, but may also be due in some cases to MVHR systems being turned off in summer.

This comparison may indicate that the homes with MVHR systems achieved a better ventilation outcome compared to non-MVHR homes and, specifically, that the use of an MVHR system may have attributed to improvements of ventilation levels in these homes. There are some exceptions to this, which are evident through the outliers identified in the graphs. In the case of dwellings with MVHR systems, the disabling of the system may mean that the dwelling has effectively become non-MVHR. Reporting of the projects suggest that in a number of cases systems may be disabled due to issues of noise and understanding, and that dwellings then revert to a window opening strategy (in the absence of any means of background ventilation); examples of these are described in later case studies.

These findings may however be flattering to MVHR dwellings and should be considered in light of previous studies that have demonstrated significant issues with ventilation effectiveness in naturally ventilated dwellings with low air permeability, particularly the performance of trickle vents in practice[10]. Furthermore, analysis of the occupancy levels and floor area data indicates that many of the homes with MVHR systems had lower occupancy densities than non-MVHR dwellings, which is likely to have significantly influenced the results. The total floor area per person (m^2) was determined by dividing the footprint of each home by the stated number of occupants (extracted from the DomEARM spreadsheets). Since occupancy levels were not objectively measured during the Building Performance Evaluation process, these figures represent estimated occupancy densities only, and therefore do not take into consideration, for example, changes of household occupancy over the measurement period, employment status (working at home or away), or occupancy levels in specific rooms.

Nevertheless, the prospect that a dwelling which has a constantly running mechanical system supplying air to these rooms would result in an improved ventilation provision is not unreasonable. Of remaining concern however is what the effects are when such a system is not in operation or operating correctly.

4.1.2. Ventilation performance in dwellings with MVHR systems

Focusing particularly on the dwellings with MVHR systems, an analysis of the limited available monitoring data did not produce any significant differentiation between dwellings. Figure 4.1e presents average bedroom levels of CO_2 for February, April and August. CO_2 levels were generally lowest during the summer season, attributed most likely to a greater prevalence of window opening. Of interest is that peak levels were rarely above 1000ppm in all seasons in the majority of dwellings, but those that were high were significantly higher. Whilst the majority are Passivhaus, there was no clear association between these and lower CO_2 (see Table 4.1c and Figure 4.1e), or between houses with higher flow rates. However given the relatively small sample size, there will be other confounding variables, for example room occupancy and flow rate to the room being monitored.

Table 4.1c. Average living room CO_2 levels (ppm) in Passivhaus and Non-Passivhaus homes

	Passivhaus (n=12-15)			Non-Passivhaus (n=11-12)		
	Peak CO_2	Mean CO_2	Range of CO_2	Peak CO_2	Mean CO_2	Range of CO_2
Feb (mean)	1134	757	599	946	748	372
Apr (mean)	1265	691	795	1138	829	522
Aug (mean)	1157	628	706	758	633	215

[10] Sharpe T, Porteous C, Foster J and Shearer D (2014) An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland. *Indoor and Built Environment* 23 (3): 393-416.

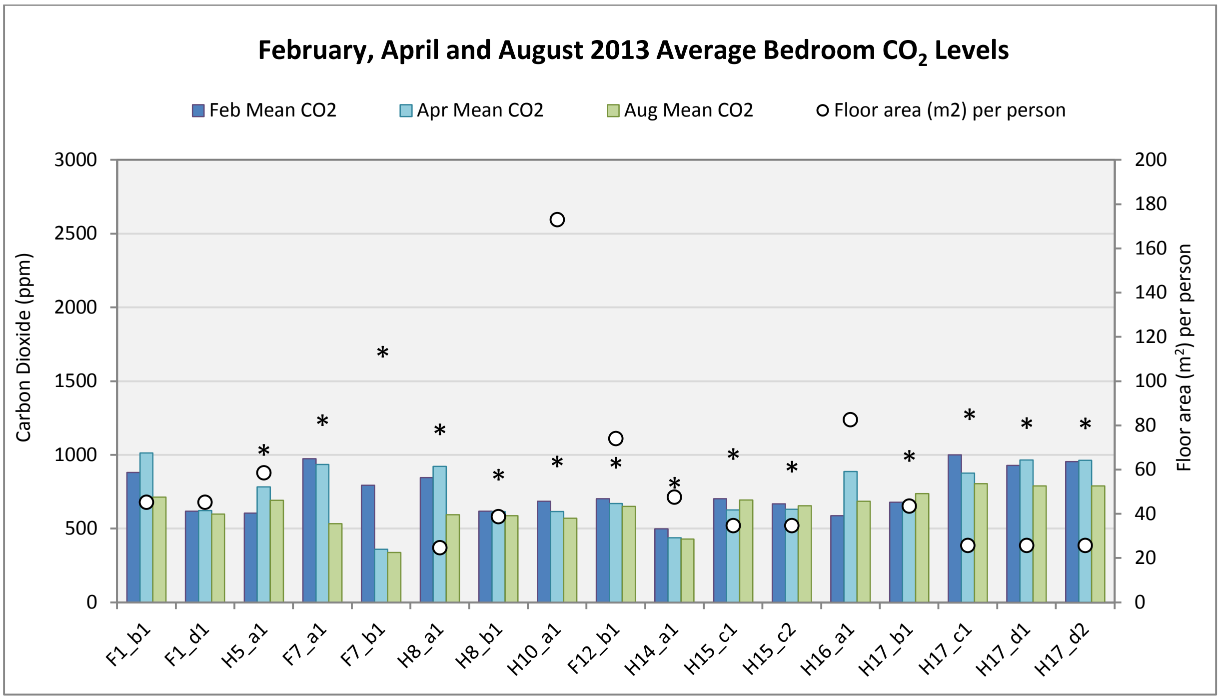


Figure 4.1e. Average bedroom CO_2 levels in dwellings with MVHR
** Passivhaus dwellings*

Whilst these averages were generally lower than 1000ppm the limitations of the data are such that these figures represent average bedroom levels for the whole month and therefore will include significant periods of time when the bedrooms were most likely unoccupied, particularly during the day time; occupied periods may have higher CO_2 averages.

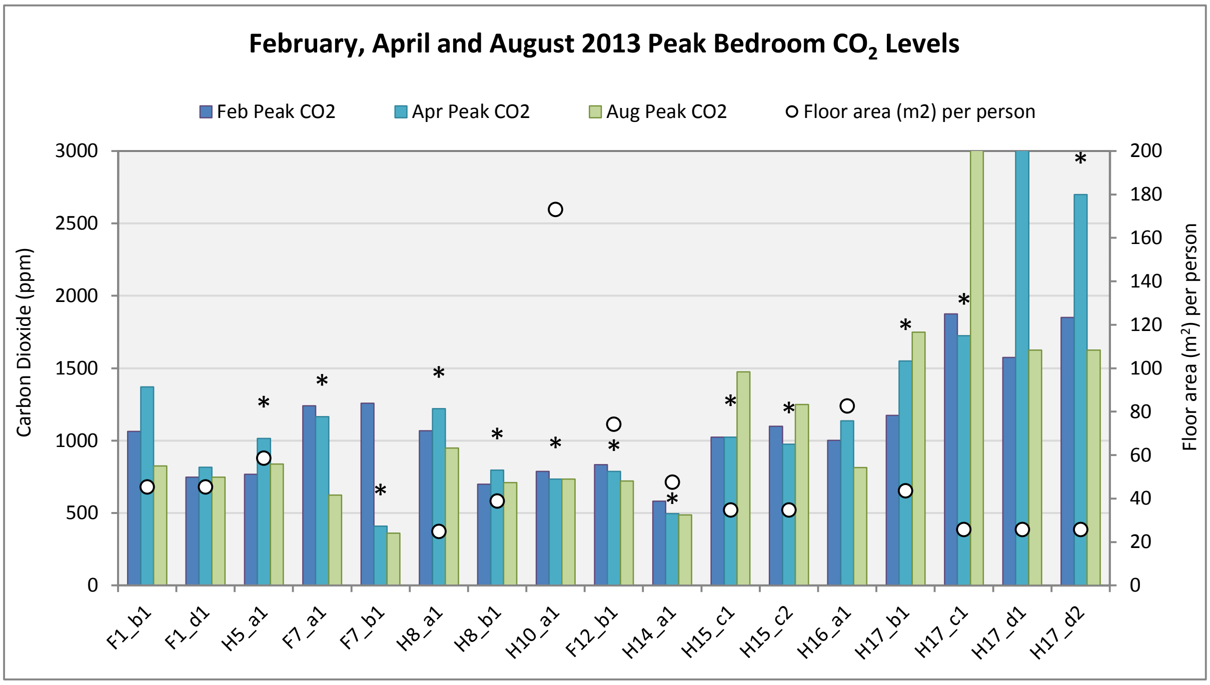


Figure 4.1f. Peak bedroom CO_2 levels in dwellings with MVHR
** Passivhaus dwellings*

Peak CO_2 levels therefore may be considered a better indicator of bedroom ventilation rates, (see Figure 4.1f). This graph demonstrates that whilst in most bedrooms peak CO_2 levels remained relatively low (<1,500 ppm), in a few cases this value was significantly exceeded. Peak CO_2 levels exceeded 1,000 ppm in 65% of monitored bedrooms during February, 59% during April and 35% during August.

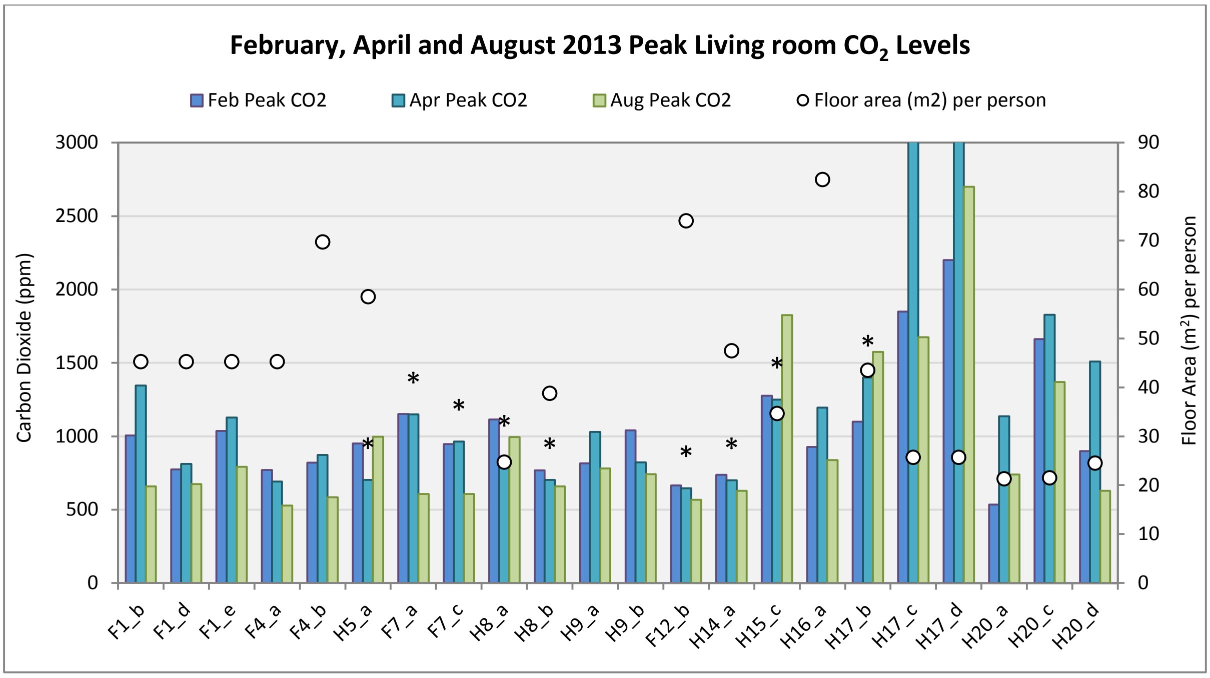


Figure 4.1g. Peak living room CO2 levels in dwellings with MVHR
** Passivhaus dwellings*

In the monitored MVHR living rooms, levels peaked above 1000ppm in 45% of homes during February, 55% of homes during April and 23% of homes during August, as illustrated in Figure 4.1g. In the majority of cases (73%) however, peak levels did not exceed 1500ppm. Similar to the bedroom results, living room peak CO_2 levels were highest in H17_c1 and H17_d1, suggesting particular problems with ventilation rates in these homes.

4.2. Comparative relative humidity levels

One of the potential consequences of ventilation performance is the impact on moisture in the buildings. Ventilation rates set in regulations are primarily designed to control moisture (rather than a more general requirement of IAQ) so a comparison may be made of relative humidity (RH) levels in MVHR and Non-MVHR dwellings. It should be noted that the RH sample size was not identical to the CO_2 data since a larger dataset was available for MVHR dwellings compared to Non-MVHR dwellings. The results are summarised in Tables 4.2a and 4.2b.

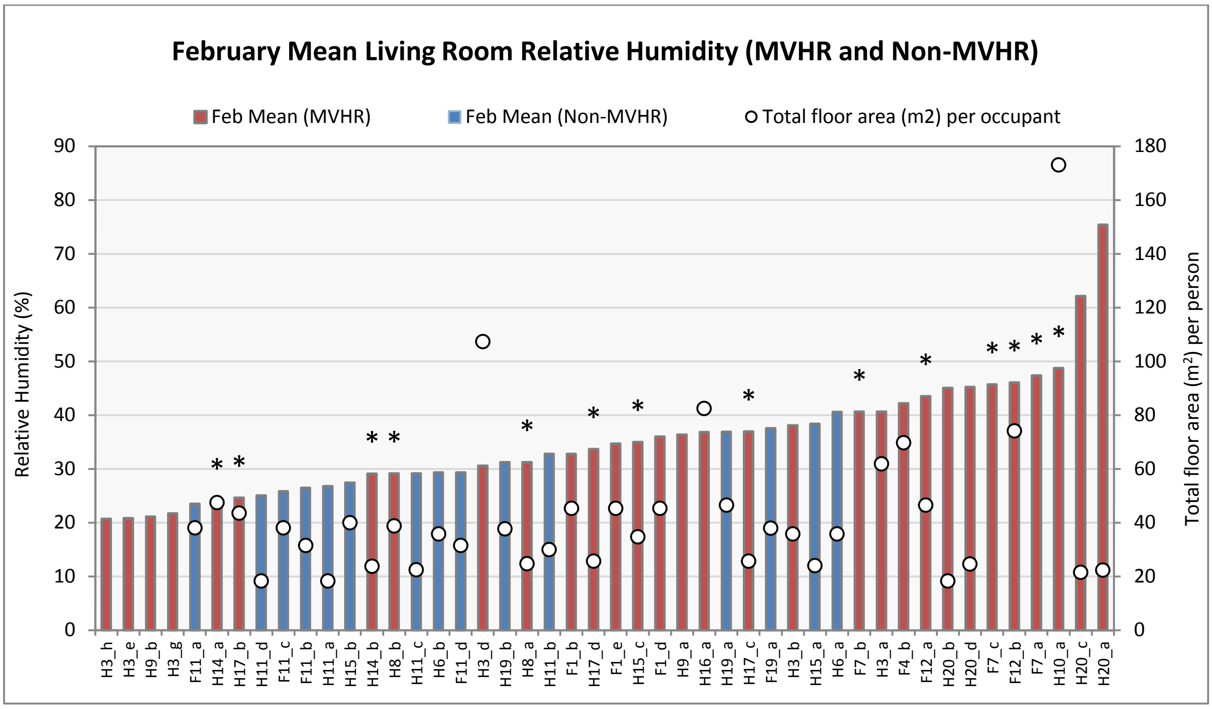
Table 4.2a. Living room relative humidity levels (%)

	MVHR (n=34-36)				Non-MVHR (n=15-17)			
	Minimum RH	Peak RH	Mean RH	Range of RH	Min RH	Peak RH	Mean RH	Range of RH
Feb (mean)	30.9	44.7	37.3	13.8	22.0	48.3	31.7	26.3
Apr (mean)	29.1	47.4	37.9	18.3	20.6	47.6	31.2	26.9
Aug (mean)	42.0	56.8	49.5	14.8	33.8	57.3	44.5	23.5

Table 4.2b. Bedroom relative humidity levels (%)

	MVHR (n=37-39)				Non-MVHR (n=20-24)			
	Min RH	Peak RH	Mean RH	Range of RH	Min RH	Peak RH	Mean RH	Range of RH
Feb (mean)	30.9	45.5	37.2	14.6	26.8	48.5	36.7	21.7
Apr (mean)	29.1	48.7	38.2	19.6	24.2	49.2	35.0	25.0
Aug (mean)	41.9	57.5	49.1	15.6	38.1	58.5	47.6	20.4

In general RH levels were within reasonable ranges, tending toward the lower end. The average and minimum living room and bedroom RH levels (during February, April and August) were generally higher in dwellings with MVHR systems but were not at unduly extreme levels. However, these relationships are inverted when considering temperature (Figure 4.2a), in general, dwellings with MVHR systems had lower and more stable temperatures, which suggests that the RH is more a function of temperature than ventilation in this data.



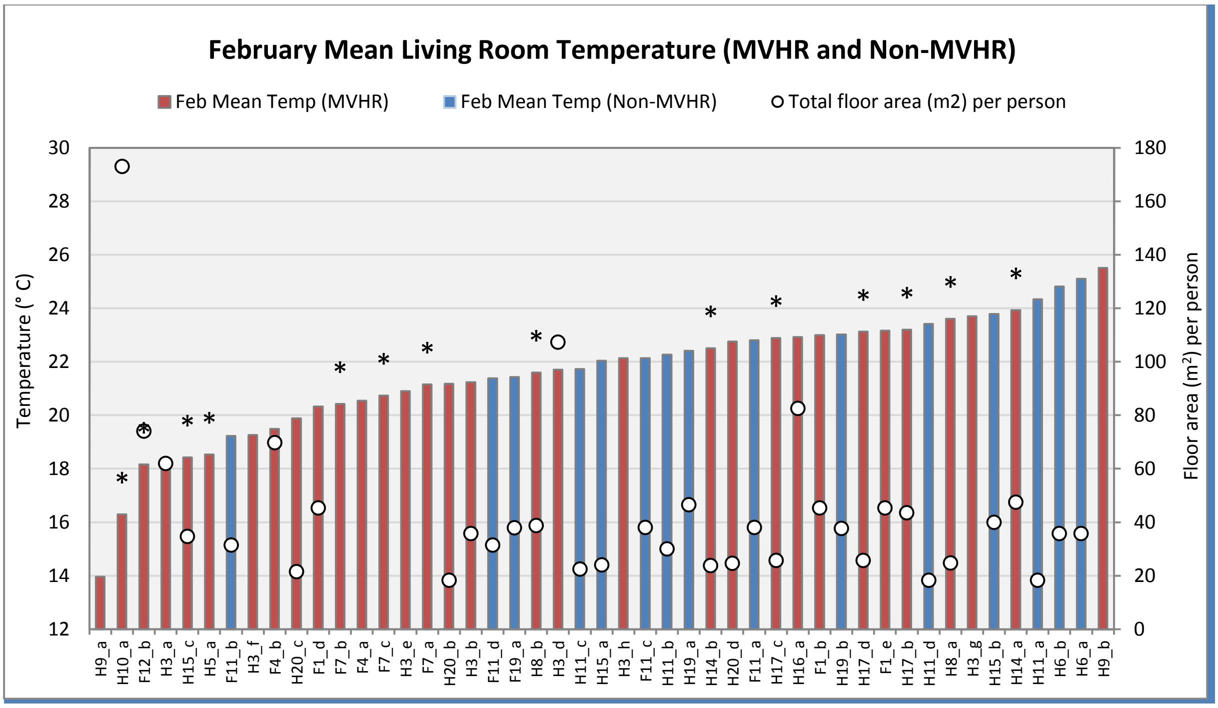


Figure 4.2a. February mean living room temperature and RH% (MVHR and Non MVHR)
** Passivhaus dwellings*

However, a clear difference was in the range of relative humidity levels between MVHR and Non-MVHR dwellings. In general RH levels were more stable during all monitored seasons (see Table 4.2a and 4.2b) in the MVHR houses and this trend was particularly evident during winter (Figures 4.2b and 4.2c).

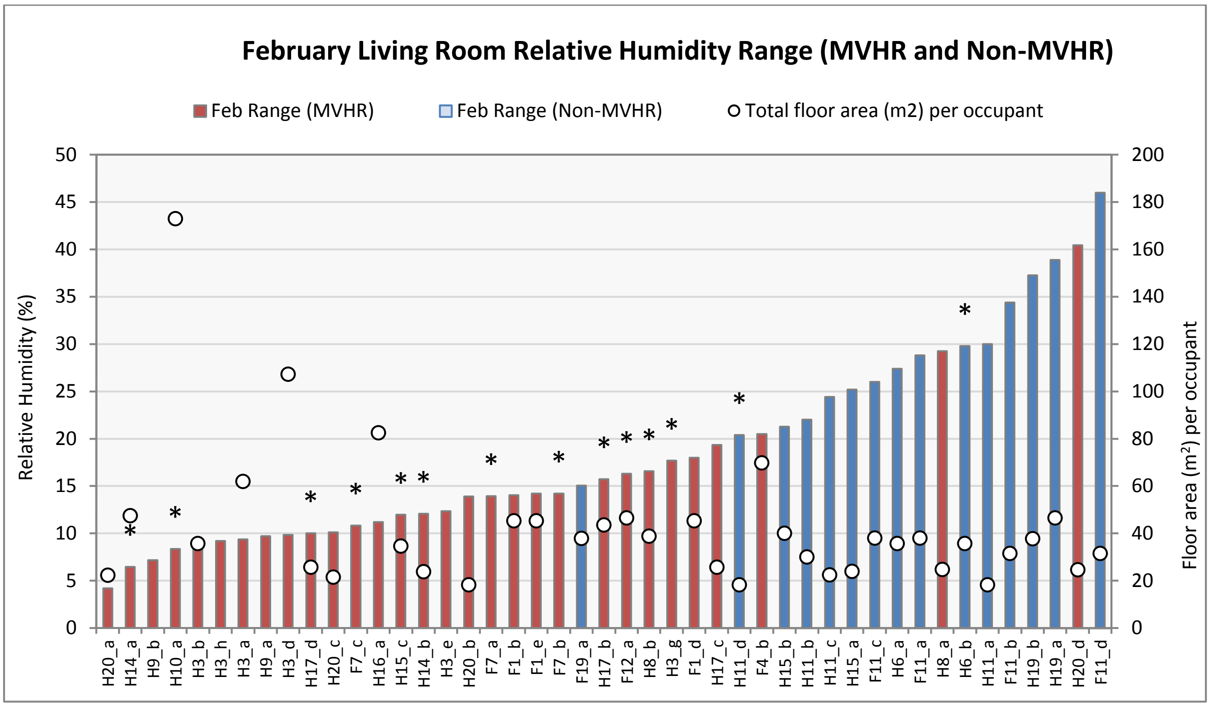


Figure 4.2b. Range of February living room relative humidity levels
** Passivhaus dwellings*

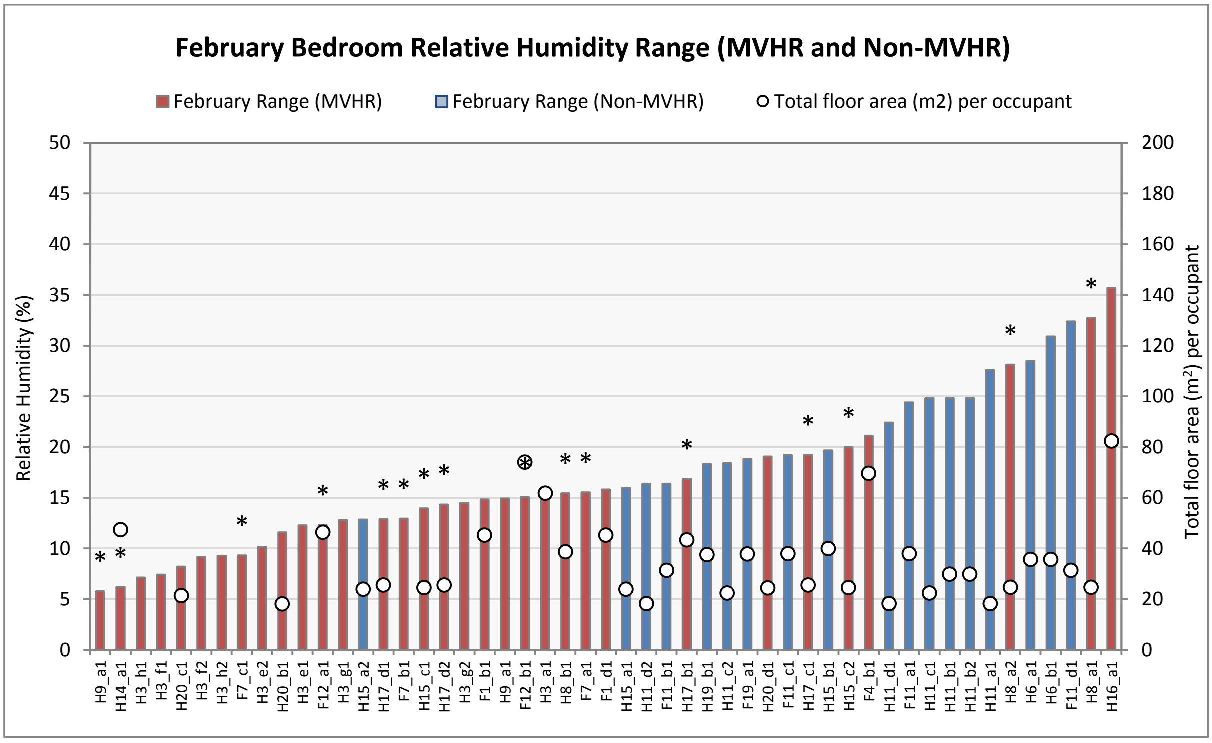


Figure 4.2c. Range of February bedroom relative humidity levels
** Passivhaus dwellings*

4.2.1. Relative humidity in dwellings with MVHR

A more detailed analysis of the dwellings with MVHR systems found average and peak living room levels were generally low (<70%) during February, April and August months, as illustrated in Figure 4.2.d. Living room relative humidity levels were highest during August, with the exception of H20_a, H20_b, H20_c. There does not appear to be any association between Passivhaus and non-Passivhaus certified dwellings, or between systems that were out of balance. Highest RH levels were seen in August with 35% of MVHR dwellings recording peaks > 60% RH. As indicated by the CO_2 data this suggests high rates of window opening.

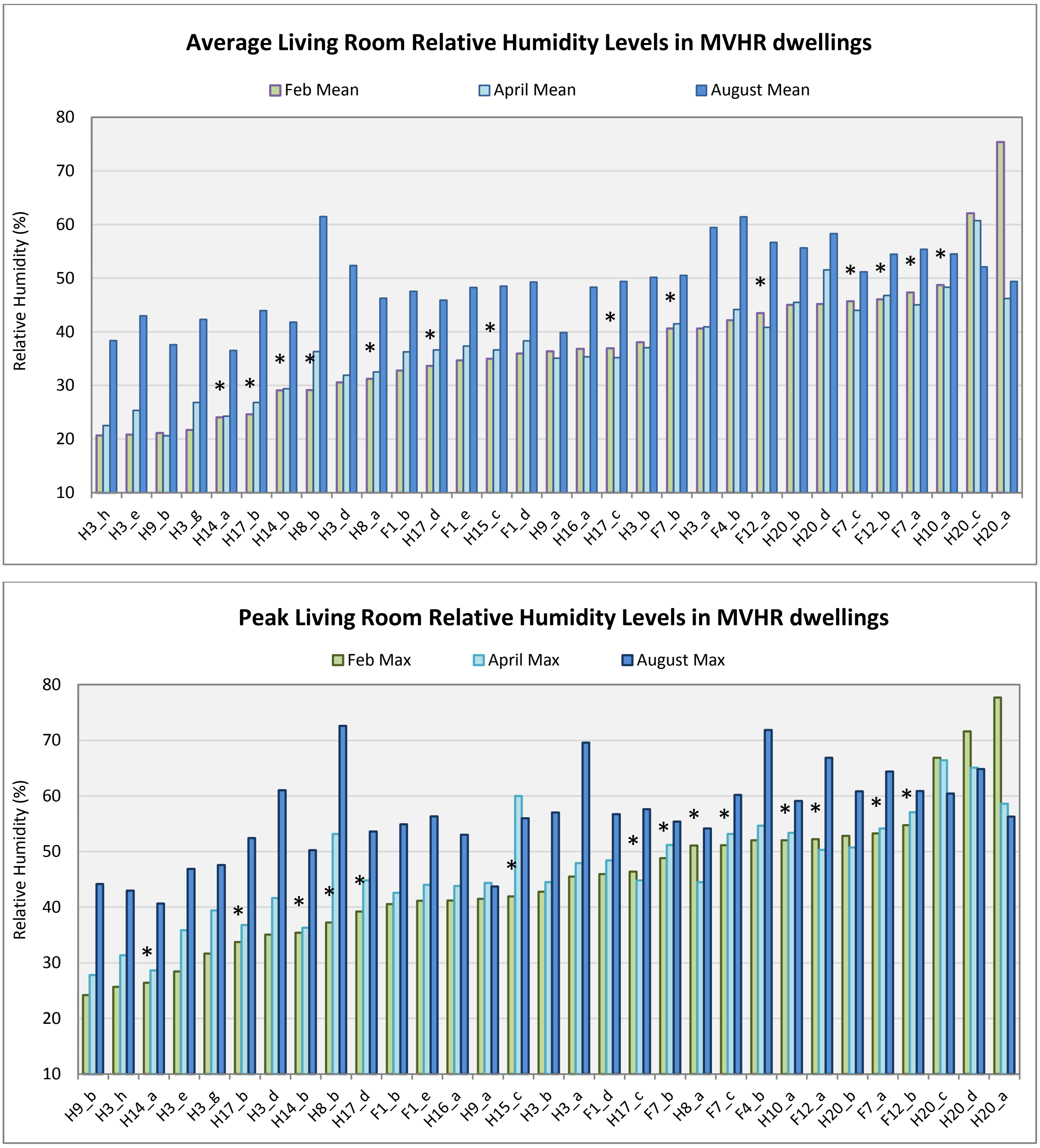


Figure 4.2.d. Average and peak living room relative humidity levels in MVHR dwellings

** Passivhaus dwellings*

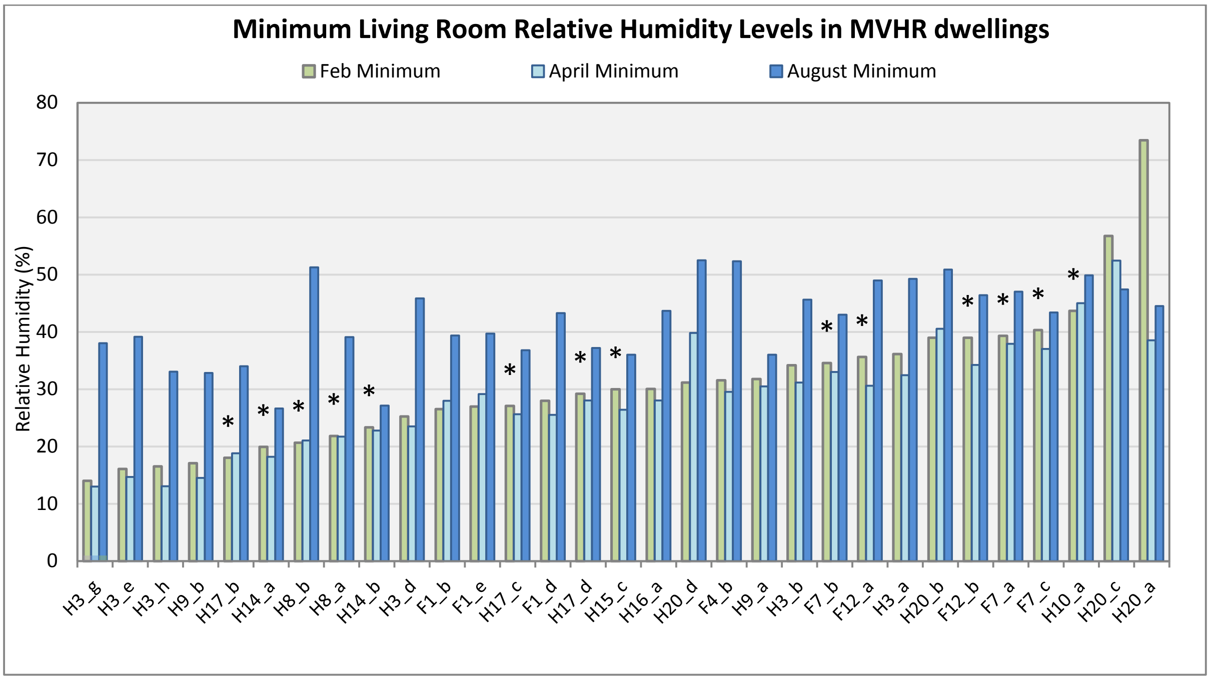


Figure 4.2e. Minimum living room relative humidity levels in dwellings with MVHR
** Passivhaus dwellings*

Monitored relative humidity levels fell below 30%RH in 48% of living rooms during February and 58% of living rooms during April (see Figure 4.2e). Average humidity levels were below 30% in roughly a quarter of monitored living rooms during February (26%) and April (23%) months.

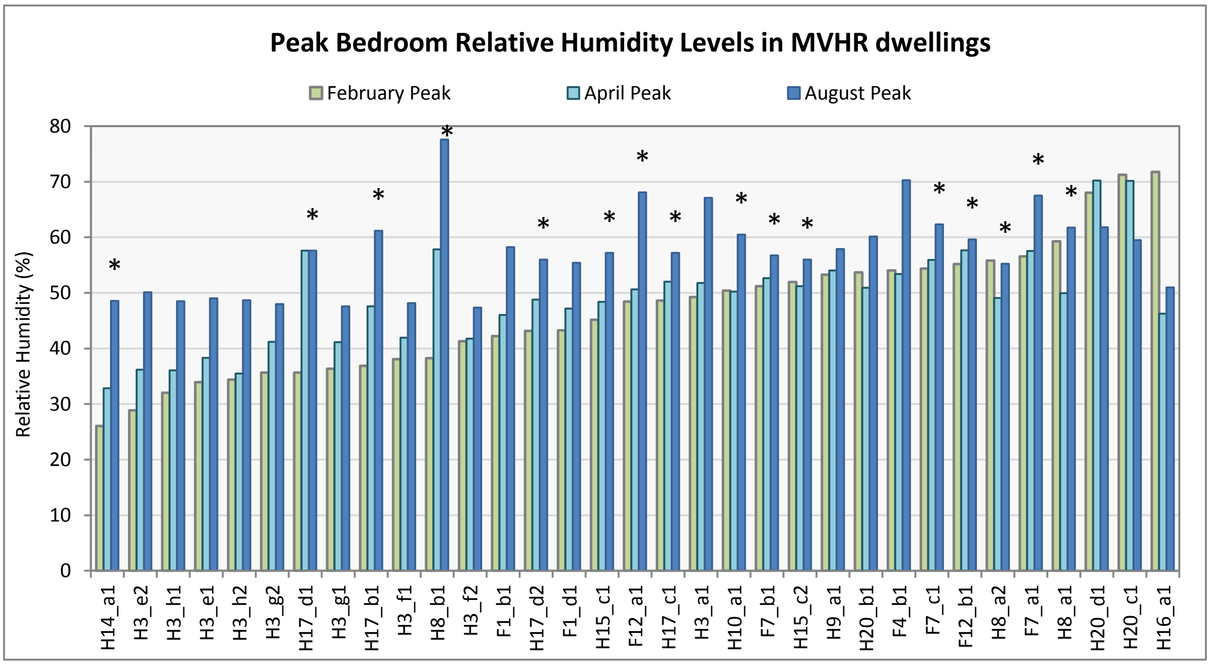


Figure 4.2f. Peak bedroom relative humidity levels in dwellings with MVHR
** Passivhaus dwellings*

In the bedrooms, average humidity levels remained below 70%, with levels peaking above this in 15% of cases (Figure 4.2f). Figure 4.2g shows the percentage of rooms that had average relative humidity levels between 40 and 60%. It is apparent that low RH is common in MVHR dwellings during the heating season.

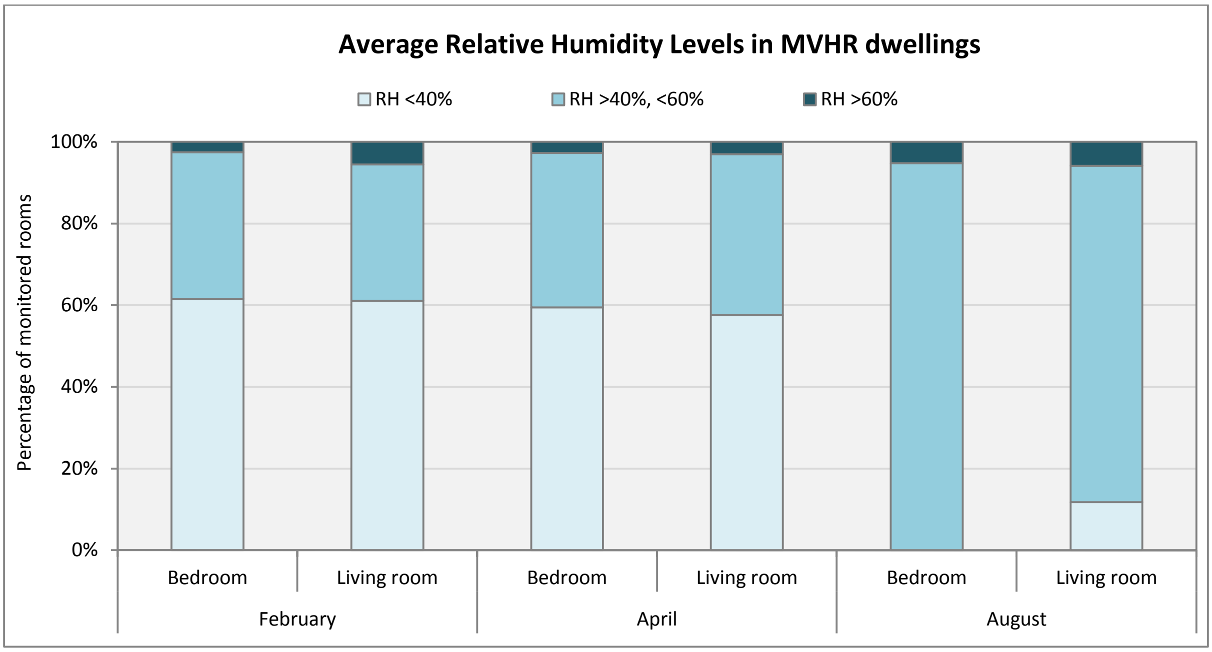


Figure 4.2g. Average relative humidity levels in dwellings with MVHR

4.3. Comparative indoor temperatures

Data on temperature is summarised in Tables 4.3a and 4.3b. An observation of this data is that in general average temperatures were higher in Non-MVHR dwellings during February and April, but higher in MVHR dwellings during summer. These findings may help to explain the higher relative humidity levels observed in MVHR dwellings (compared to Non-MVHR dwellings) during February and April.

Table 4.3a. Living room temperature levels (°C)

	MVHR (n=34-35)				Non-MVHR (n=15-17)			
	Min temp	Peak temp	Mean temp	Range of temp	Min temp	Peak temp	Mean temp	Range of temp
Feb (mean)	18.7	23.3	21.1	4.6	18.2	27.3	22.8	9.1
Apr (mean)	18.7	23.5	21.3	4.8	17.9	28.4	23.0	10.4
Aug (mean)	22.5	26.2	24.2	3.7	20.5	27.7	23.5	7.2

Table 4.3b. Bedroom temperature levels (°C)

	MVHR (n=42-45)				Non-MVHR (n=21-24)			
	Min temp	Peak temp	Mean temp	Range of temp	Min temp	Peak temp	Mean temp	Range of temp
Feb (mean)	18.0	22.5	20.3	4.4	17.9	24.8	21.6	6.9
Apr (mean)	18.2	22.8	20.7	4.7	18.3	25.7	22.3	7.4
Aug (mean)	22.3	26.1	24.1	3.9	20.2	26.2	23.2	6.0

Correspondingly, an analysis of peak temperatures found higher levels in Non-MVHR dwellings when compared to MVHR dwellings. This trend was most evident in the monitored living rooms during February, (Figure 4.3a). Higher average and peak temperatures during February in Non-MVHR dwellings may be attributed to a number of factors, including oversizing of heating systems in Non-MVHR homes or a lack of awareness of the post heater (where available) in the dwellings with MVHR systems. Average temperatures in MVHR dwellings were closed to the expected norms, so this suggests a tendency for overheating in non-MVHR dwellings. Nevertheless, incidences of high temperatures were also observed in MVHR dwellings.

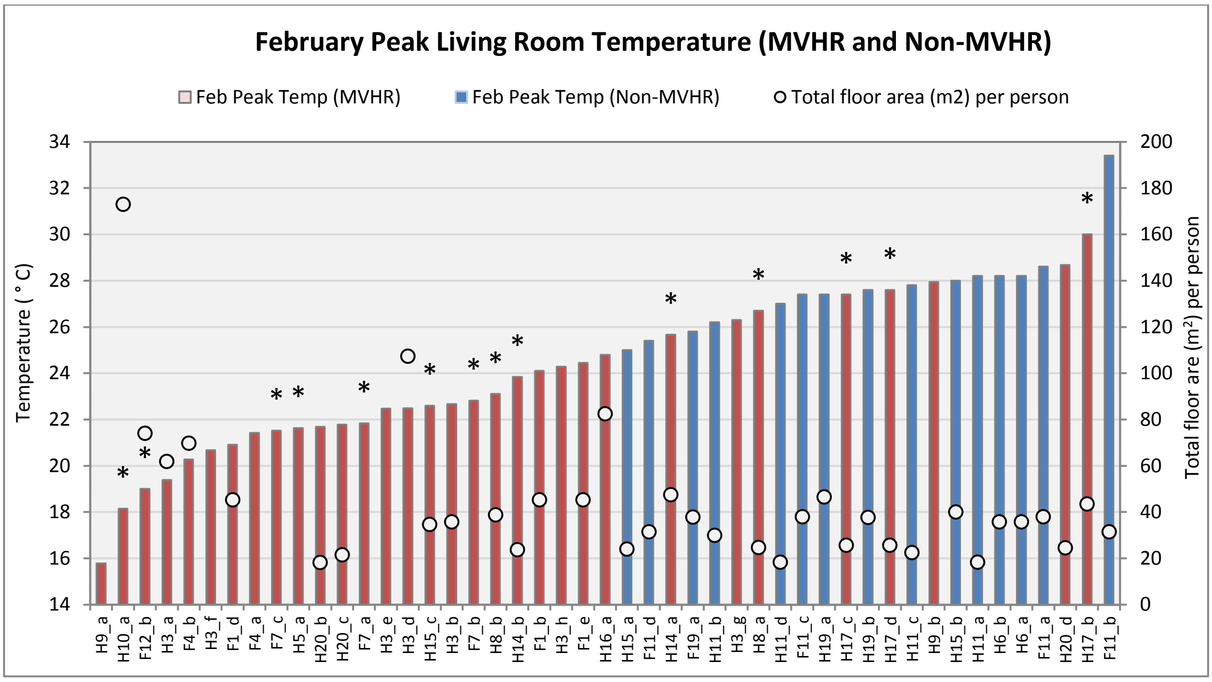


Figure 4.3a. Peak February living room temperatures in MVHR and Non MVHR homes
** Passivhaus dwellings*

As with the data on relative humidity, an apparent trend is for houses with MVHR systems to have greater temperature stability, with a greater dispersion of indoor hygrothermal conditions found in dwellings without MVHR systems. For example, Figures 4.3b and 4.3c present the range of living room temperatures during April and August months. Despite the small sample size and uneven sample numbers, the tendency towards lower temperature ranges in MVHR dwellings is clear.

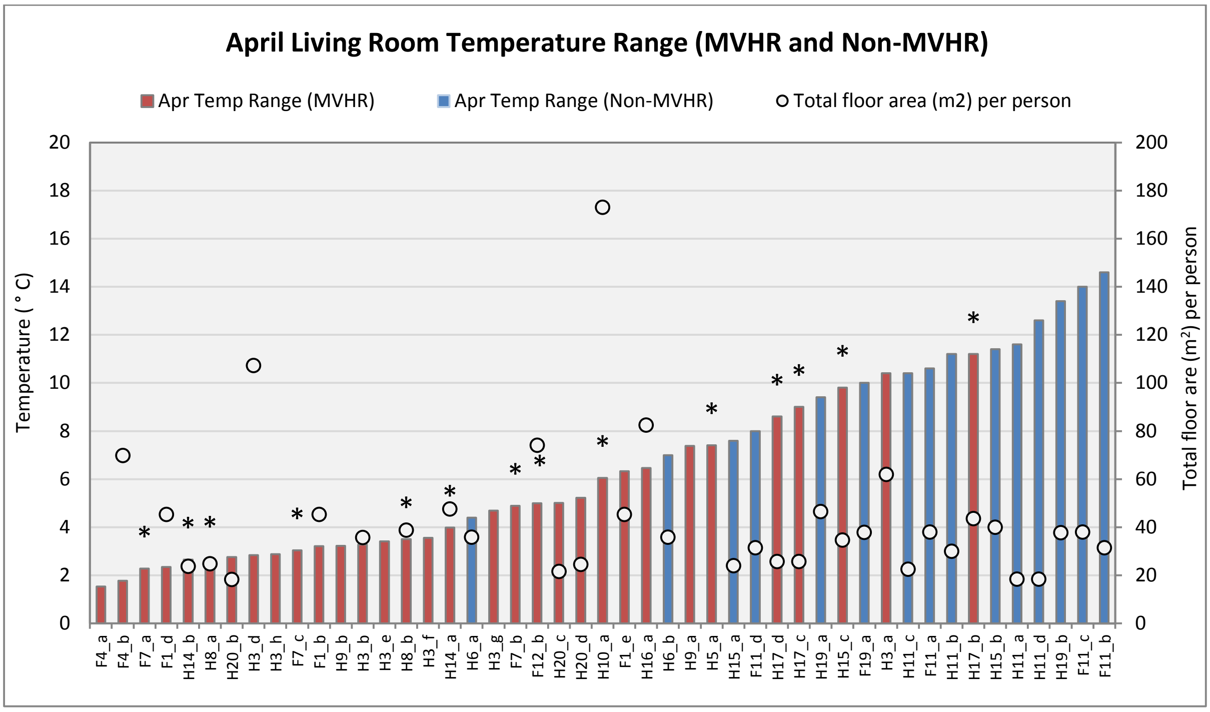


Figure 4.3b. Range of April living room temperatures in MVHR and Non MVHR homes
** Passivhaus dwellings*

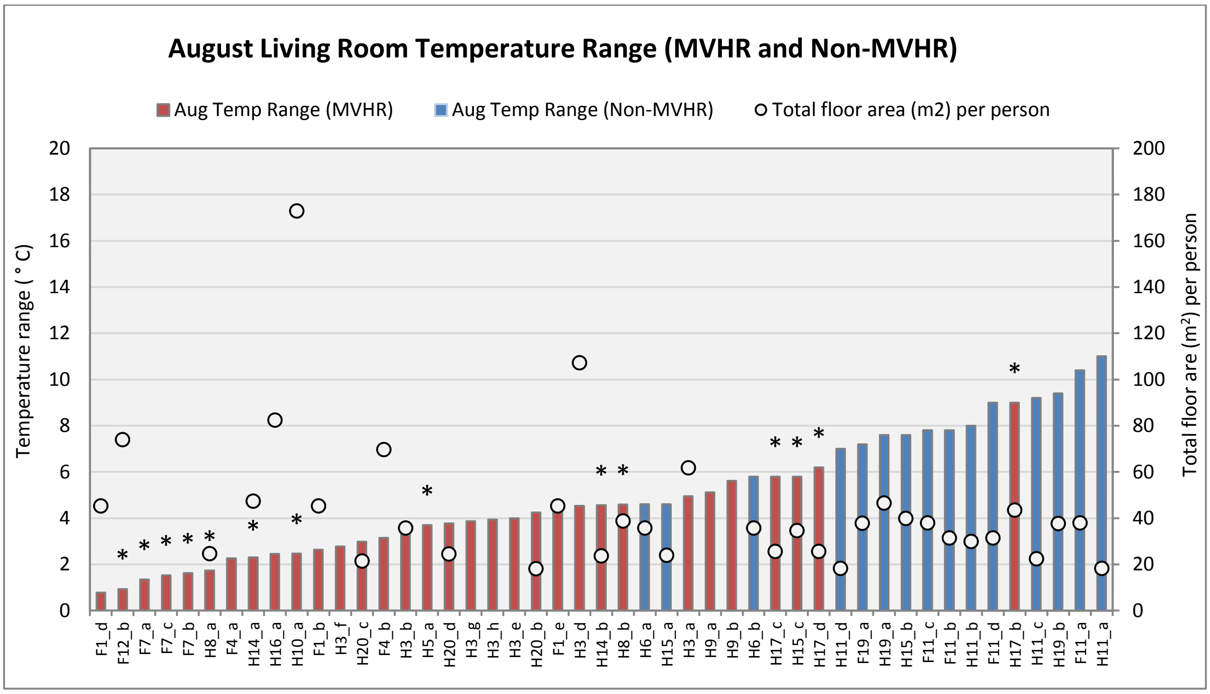


Figure 4.3c. Range of August living room temperatures in MVHR and Non MVHR homes
** Passivhaus dwellings*

The temperatures observed in the MVHR dwellings were closer to optimal conditions. This may be affected by the prevalence of Passivhaus dwellings in this cohort, but may also be due to poor performance in non-MVHR houses which may have oversized and poorly controlled heating systems.

Whilst it may be considered that having stable temperatures close to optimum conditions is beneficial in terms of energy consumption and indoor comfort, a growing body of research suggests that temperature fluctuations may in fact be beneficial for health[11] and that lack of temperature stimulation indoors may result in thermal monotony[12]. This may be particularly problematic during the summer season if occupants are exposed to repeatedly high temperatures indoors.

In summer a differentiation between MVHR and non-MVHR was less clear (see appendix B), with some MVHR houses having very high peak temperatures. Whilst the overall trend for MVHR houses is positive, there are outliers where conditions are poorer.

4.3.1. Indoor temperatures in dwellings with MVHR

Looking at the MVHR houses only, no obvious trends were apparent in terms of Passivhaus or system balance. Figures 4.3d and 4.3e present average and peak bedroom temperatures in dwellings with MVHR systems. It should be acknowledged that these values are for the whole month, therefore are likely to include significant periods of time where the rooms were unoccupied.

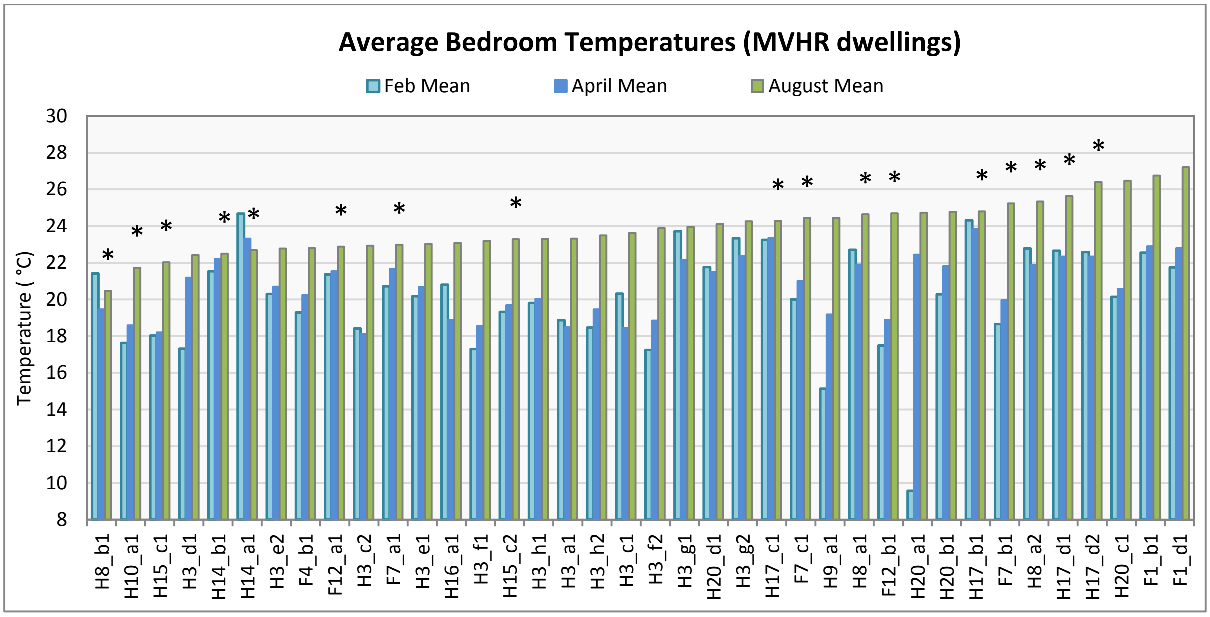


Figure 4.3d. Average bedroom temperatures in dwellings with MVHR
** Passivhaus dwellings*

Without detailed occupancy data and external weather data, it may not be applicable to compare measured indoor temperatures with comfort criteria. Nevertheless, it is important to highlight that average temperatures exceeded 25°C (Passivhaus overheating criteria) during August in 18% of MVHR bedrooms, with peak levels exceeding 28°C in 11% (Figure 4.3e).

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11 van Marken Lichtenbelt, Wouter D (2015) *To Comfort Or Not to Comfort, Keynote Presentation at Healthy Buildings Conference, Eindhoven, 18-20th may, 2015.*

12 de Dear, RJ and Brager, GS (2002) Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings* 34(6): 549-561.

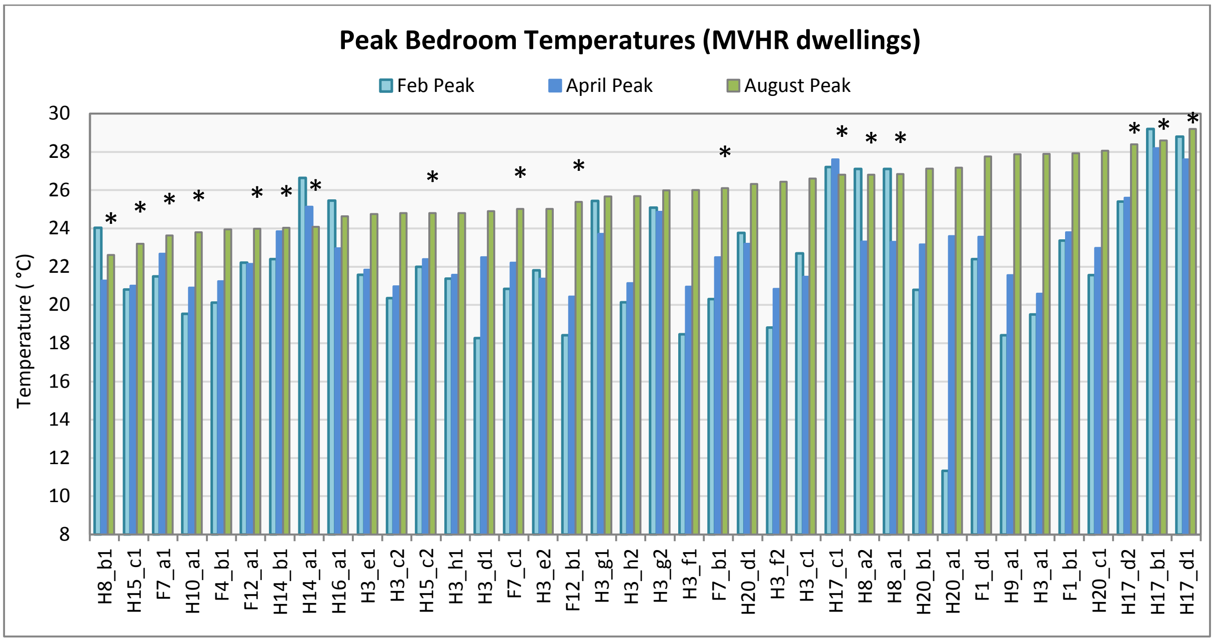

Figure 4.3e. Peak bedroom temperatures in dwellings with MVHR
** Passivhaus dwellings*

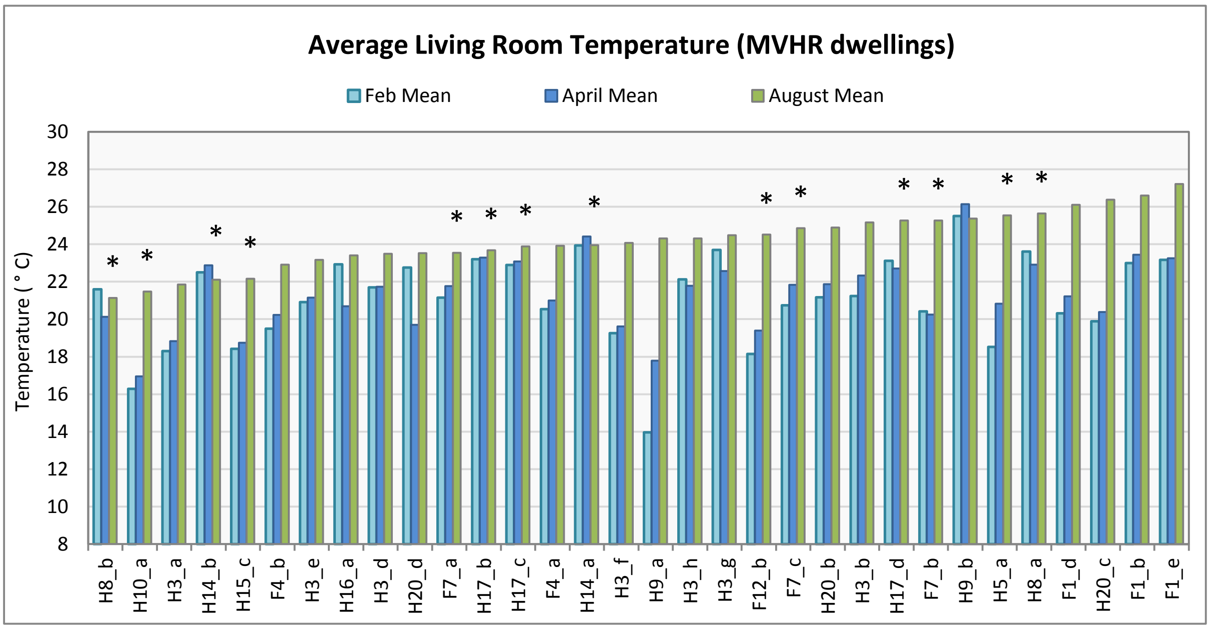

Figure 4.3f. Average living room temperatures in MVHR dwellings
** Passivhaus dwellings*

Correspondingly, in the monitored living rooms (Figures 4.3f and 4.3g), average temperatures exceeded 25°C in 31% of MVHR dwellings during August, with levels peaking above 28°C in 16%. These results suggest issues with summertime overheating in a number of the MVHR dwellings. This may be attributed to a lack of summer by-pass capabilities in some homes, or systems being disabled in the summer, which is also suggested by the CO_2 and RH data. Whilst this may be expected, or indeed planned, it raises questions about the effectiveness of this in certain rooms which may be less tolerant of window opening due to issues of noise or security. It is interesting to note that despite the majority of dwellings demonstrating temperature distinctions between seasons, some dwellings appear to maintain constant temperatures year round, with average February or April temperatures exceeding August temperatures in some cases.

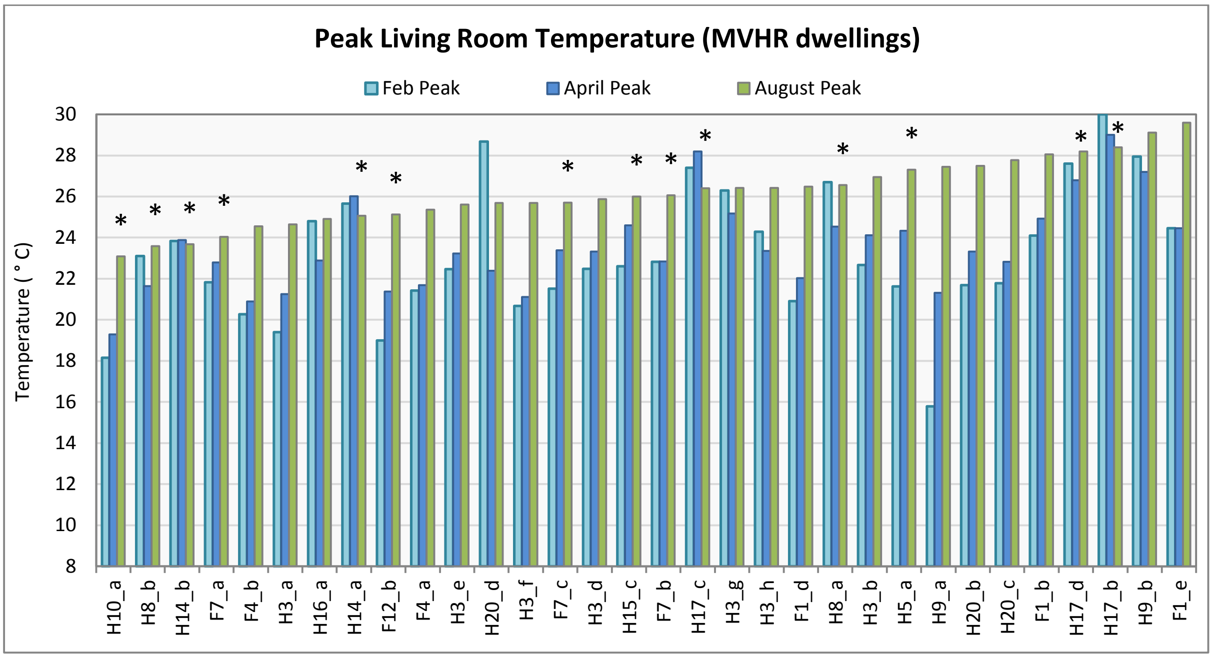

Figure 4.3g. Peak living room temperatures in MVHR dwellings
** Passivhaus dwellings*

4.4. Comparative vapour pressure levels

Given the anomalies with regard to RH and temperature data, this data was used to calculate vapour pressure levels in the dwelling as a means to identify possible risks associated with moisture. Vapour Pressure (VP) levels in the monitored dwellings were calculated using the following equation:

$$e^o = 0.6108\ exp\ ((17.27 \ \times T)/(T + 273.15))$$

$$e^a = \ (RH/100) \ \times e^o$$

Where:

e^o = Saturation Vapour Pressure (kPa)
T = Temperature (° C)
e^a = Actual Vapour Pressure (kPa)
RH = Relative Humidity (%)

Summary data is shown in Tables 4.4a and 4.4b. There is a noticeable difference between average, peak and range of VP in MVHR and Non-MVHR dwellings (see for example Figure 4.4a), which corresponds to the findings from the temperature and relative humidity analysis. Figure 4.4b illustrates the average VP across MVHR and non-MVHR houses during August. Mean August vapour pressure levels were significantly lower in MVHR dwellings, with some notable exceptions, and the range in VP is also generally smaller in houses with MVHR. This supports the premise that use of an MVHR system may help to provide greater level of stability of hygrothermal conditions indoors, when compared to natural or Mechanical Extract Ventilation strategies.

Table 4.4a. Living room vapour pressure (kPa)

	MVHR (n=31-34)				Non-MVHR (n=15-17)			
	Min VP	Peak VP	Mean VP	Range of VP	Min VP	Peak VP	Mean VP	Range of VP
Feb (mean)	0.64	1.25	0.90	0.61	0.47	1.76	0.88	1.29
Apr (mean)	0.61	1.36	0.95	0.74	0.43	1.82	0.88	1.39
Aug (mean)	1.15	1.92	1.49	0.78	0.82	2.12	1.29	1.30

Table 4.4b. Bedroom vapour pressure (kPa)

	MVHR (n=33-37)				Non-MVHR (n=19-22)			
	Min VP	Peak VP	Mean VP	Range of VP	Min VP	Peak VP	Mean VP	Range of VP
Feb (mean)	0.65	1.29	0.90	0.63	0.52	1.54	0.93	1.02
Apr (mean)	0.61	1.37	0.94	0.76	0.51	1.61	0.94	1.10
Aug (mean)	1.15	1.98	1.49	0.83	0.90	1.98	1.34	1.08

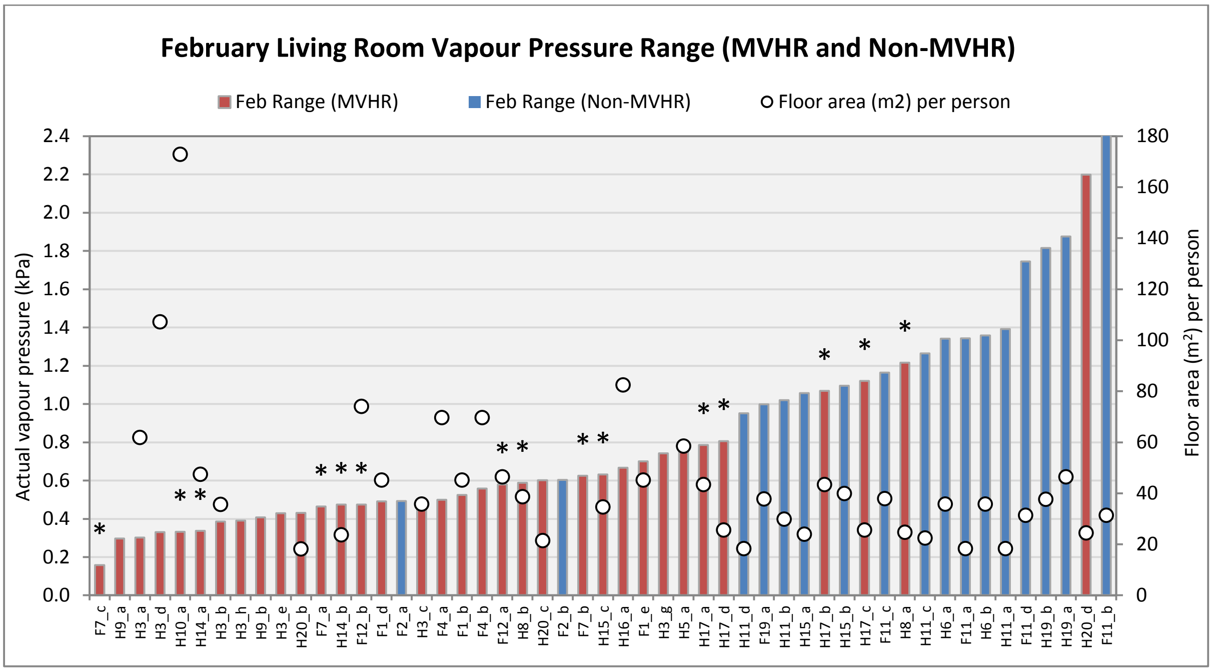

Figure 4.4a. February living room vapour pressure ranges in MVHR and Non-MVHR homes
** Passivhaus dwellings*

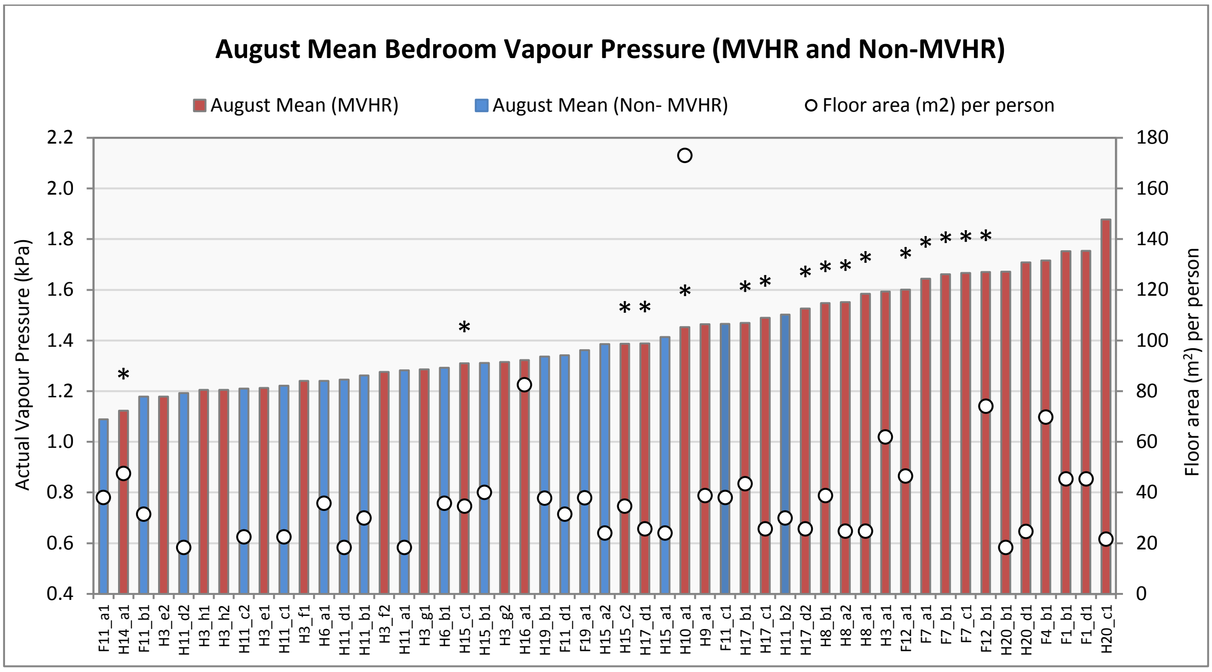

Figure 4.4b. August mean bedroom vapour pressure in MVHR and Non-MVHR homes
** Passivhaus dwellings*

Vapour pressure levels followed the same trends as temperature and RH data generally – non MVHR houses had lower range of VP levels, but some outliers were observed. Whilst the observation of the RH levels did not indicate conditions that would lead to problems of dampness in general, there is a concern that higher temperatures in thermally efficient dwellings may be masking an underlying moisture problem, particularly in relation to proliferation of dust mite populations. To test this, data was plotted against the Critical Equilibrium Humidity (CEH) levels for *Dermatophagoides pteronyssinus* and *Dermatophagoides farina,* common dust mite species of the UK and USA[13]. PEH refers to Population Equilibrium Humidity, which is the percentage relative humidity at a given temperature at which house dust mite populations neither propagate nor decline[14] .

[13] Arlian LG (1992) Water balance and humidity requirements of house dust mites. *Experimental & Applied Acarology* 16(1-2): 15-35.

[14] Crowther D, Wilkinson T, Biddulph P, Oreszczyn T, Pretlove S and Ridley I (2006) A simple model for predicting the effect of hygrothermal conditions on populations of house dust mite Dermatophagoides pteronyssinus (Acari: Pyroglyphidae). *Experimental & Applied Acarology* 39(2): 127-148

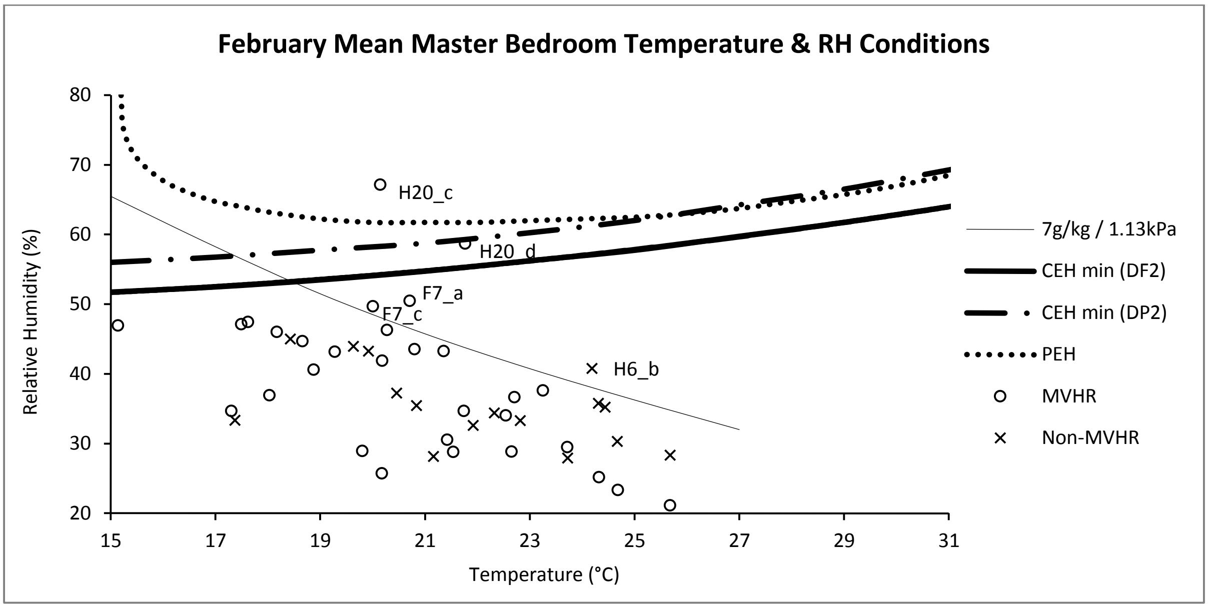

Figure 4.4c. February master bedroom mean temperature and relative humidity levels

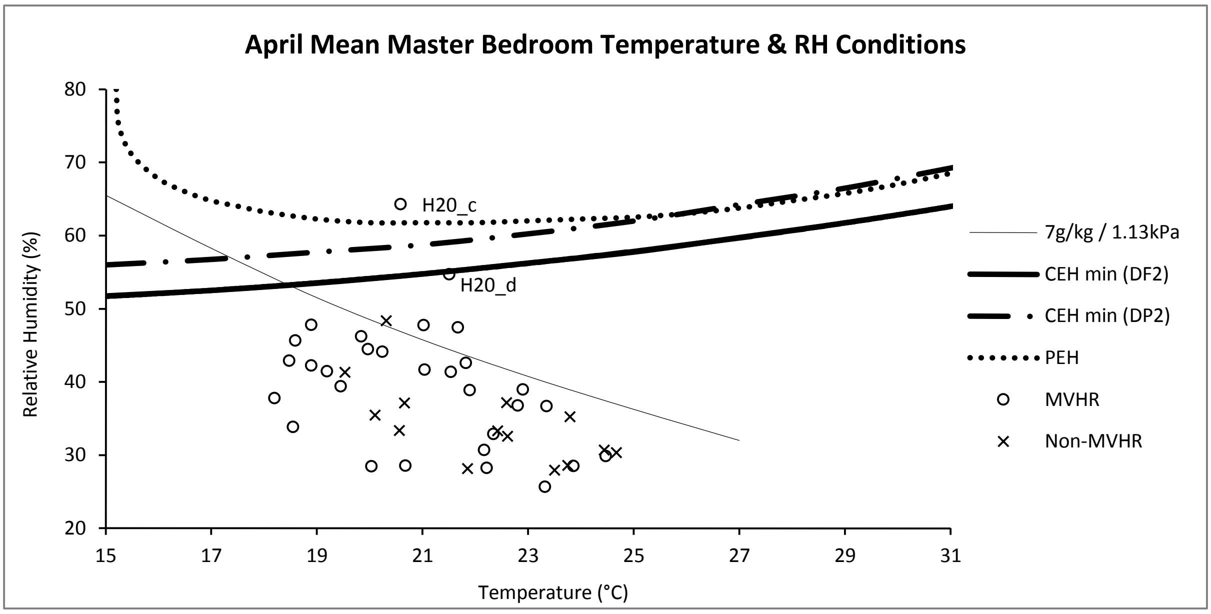

Figure 4.4d. April master bedroom mean temperature and relative humidity levels

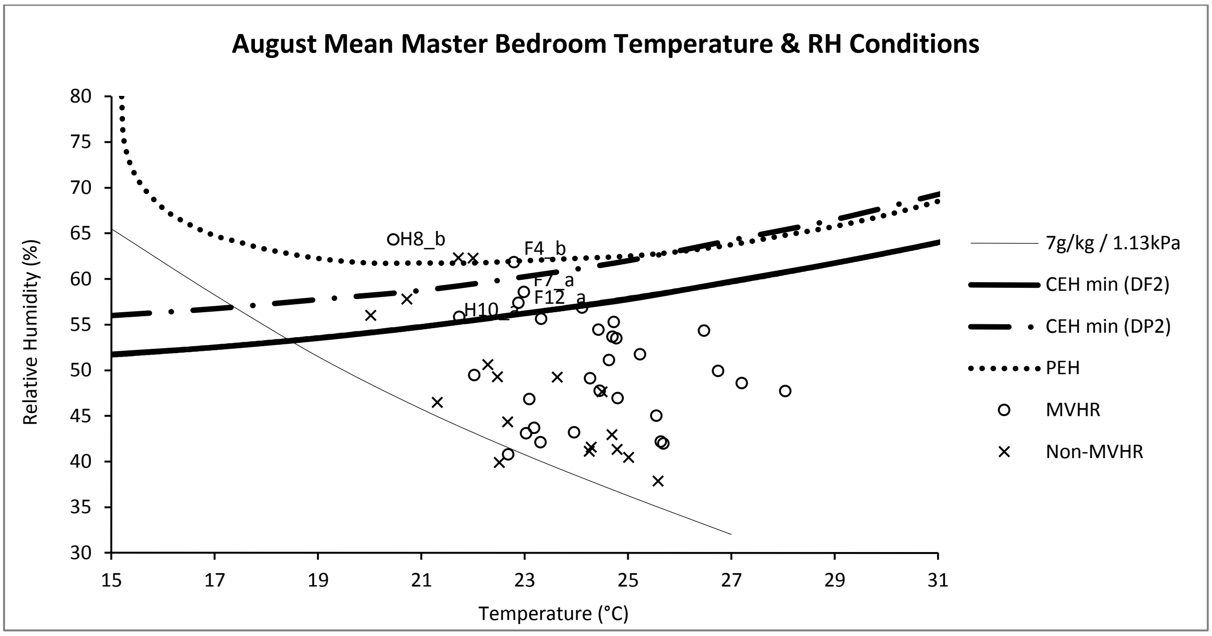

Figure 4.4e. August master bedroom mean temperature and relative humidity levels

It is apparent from this that thresholds were exceeded in one MVHR master bedroom (H20_c) during both February and April months (see Figures 4.4c and 4.4d). However, during August vapour pressure levels exceeded 7g/kg in almost all master bedrooms monitored, with levels at or exceeding the CEH levels in six MVHR dwellings. The exact circumstances leading to these conditions is not known but a possible scenario is that with more frequent window opening, MVHR may be turned off, resulting in insufficient levels of background ventilation.

4.4.1. Vapour pressure levels in MVHR dwellings

Looking at the MVHR data (only as illustrated in Tables 4.4a and 4.4b), vapour pressure levels in the monitored living rooms and bedrooms of dwellings with MVHR systems appeared to be generally undifferentiated. This is true also for the results of the relative humidity and temperature measurements (see Table 4.2a and 4.2b, Table 4.3a and 4.3b), and suggests homogeneous hygrothermal conditions throughout.

However, some elements of concern are noted. In MVHR dwellings, calculated average vapour pressure levels exceeded 1.13kPa (approximately 7g of water vapour per kg of dry air) in 93% of living rooms during August, 17% during April and 14% during February months (Figure 4.4f). This recommended maximum vapour pressure level corresponds to a threshold limit value for house dust mite exposure of 100 mites/g of dust [15,16]. Maintaining indoor humidity below 7g/kg should help to reduce the risk of excess mite growth[17].

Correspondingly, peak living room vapour pressure levels exceeded 1.13kPa in all MVHR homes during August, 79% during April and 62% during February (see Figure 4.4g). In the monitored bedrooms, average vapour pressure levels greater than

15 Harving H, Korsgaard J and Dahl R (1993) House-dust mites and associated environmental conditions in Danish homes. *Allergy* 48(2): 106-109

16 Korsgaard J (1998) Epidemiology of house-dust mites. *Allergy* 53(48): 36-40.

17 Platts-Mills TA, de Weck AL, Aalberse R, Bessot J, Bjorksten B, Bischoff E, et al. (1989) Dust mite allergens and asthma—a worldwide problem. *Journal of Allergy and Clinical Immunology* 83(2): 416-427.

1.13kPa were identified in 97% of dwellings during August and 12% of dwellings during April and February, with levels peaking above 1.13kPa in all dwellings during August, 78% during April and 70% during February.

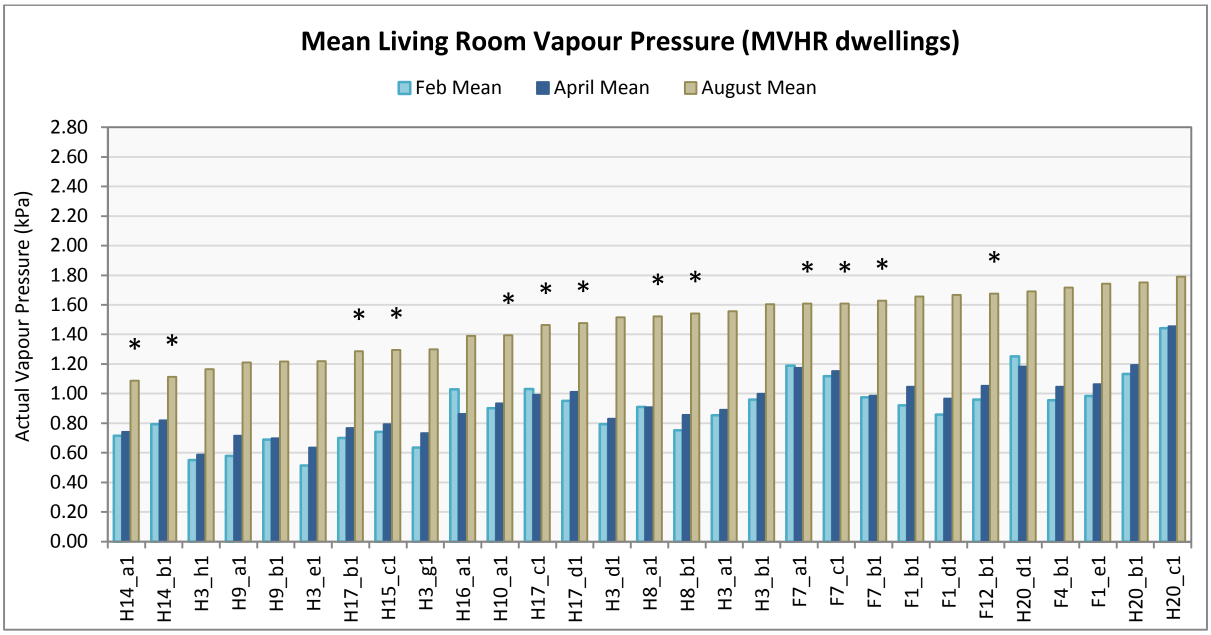

Figure 4.4f. Average living room vapour pressure levels in MVHR dwellings
** Passivhaus dwellings*

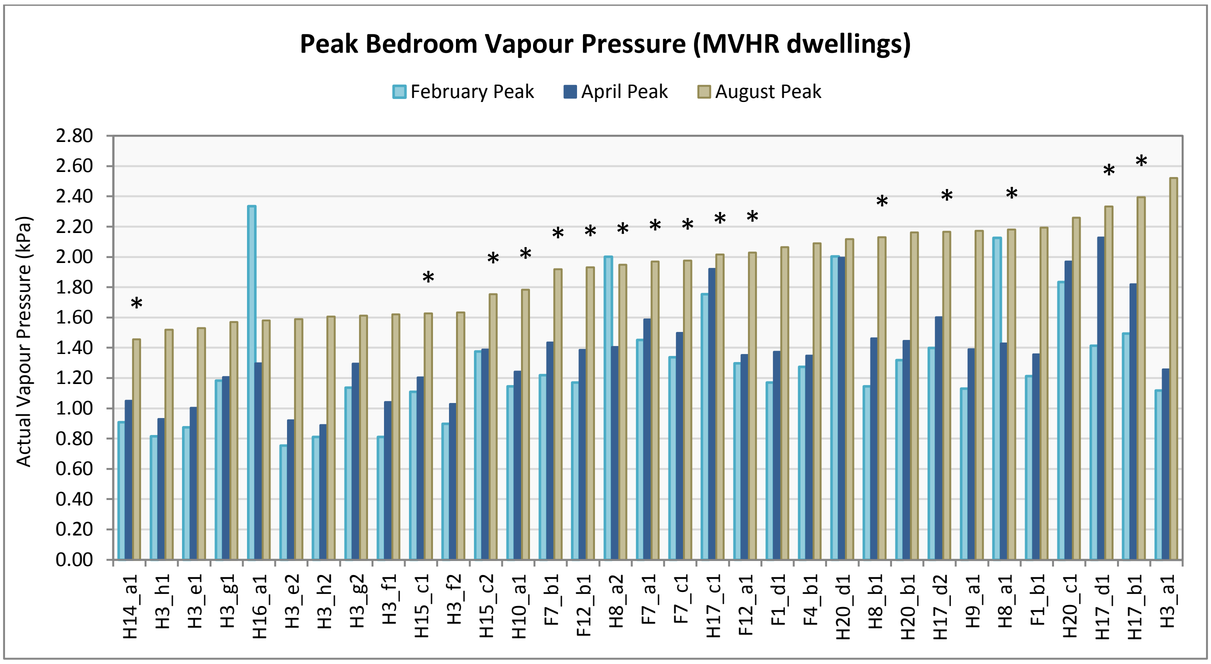

Figure 4.4g. Peak bedroom vapour pressure levels in MVHR dwellings
** Passivhaus dwellings*

4.5. Energy use comparative analysis

A comparison of the annual space heating demand for MVHR and Non-MVHR dwellings is presented in Table 4.5b. Correspondingly, the metered data indicates that the space heating demand was generally lower in dwellings with MVHR systems.

There are a few exceptions to this, most notably house H14_b, where the highest space heating demand was recorded. It is important to note that airtightness levels, construction type and space heating strategies are likely to have significantly influenced these results. Statistical analysis of the annual energy consumption and space heating consumption of MVHR and Non-MVHR dwellings are presented in Table 4.5a and b.

Table 4.5a. Annual energy consumption (MVHR vs Non-MVHR)

	Electricity (kWh/a)	Electricity (kWh/m^2/a)	Non-Electricity (kWh/a)	Non-Electricity (kWh/m^2/a)	Total Consumption (kWh/a)	Total Consumption (kWh/m^2/a)
MVHR (n=39-40)	3320.6	40.3	3689.8	46.5	6918.2	85.6
Non-MVHR (n=20-24)	3025.0	38.2	8611.2	113.3	10201.0	132.6

Table 4.5b. Annual space heating consumption (MVHR vs Non-MVHR)

	Space heating (kWh/m^2/a)
MVHR (n=33)	39.95
Non MVHR (n=20)	91.06

A comparison of the total electrical consumption in the monitored MVHR and Non-MVHR dwellings revealed that homes with MVHR systems generally consumed less energy than homes without MVHR systems (see Figure 4.5a). However, it is important to emphasise that the majority of monitored MVHR dwellings were Passivhaus certified and given the stringent energy requirements of the Passivhaus certification method, this is likely to have had a significant impact on the results.

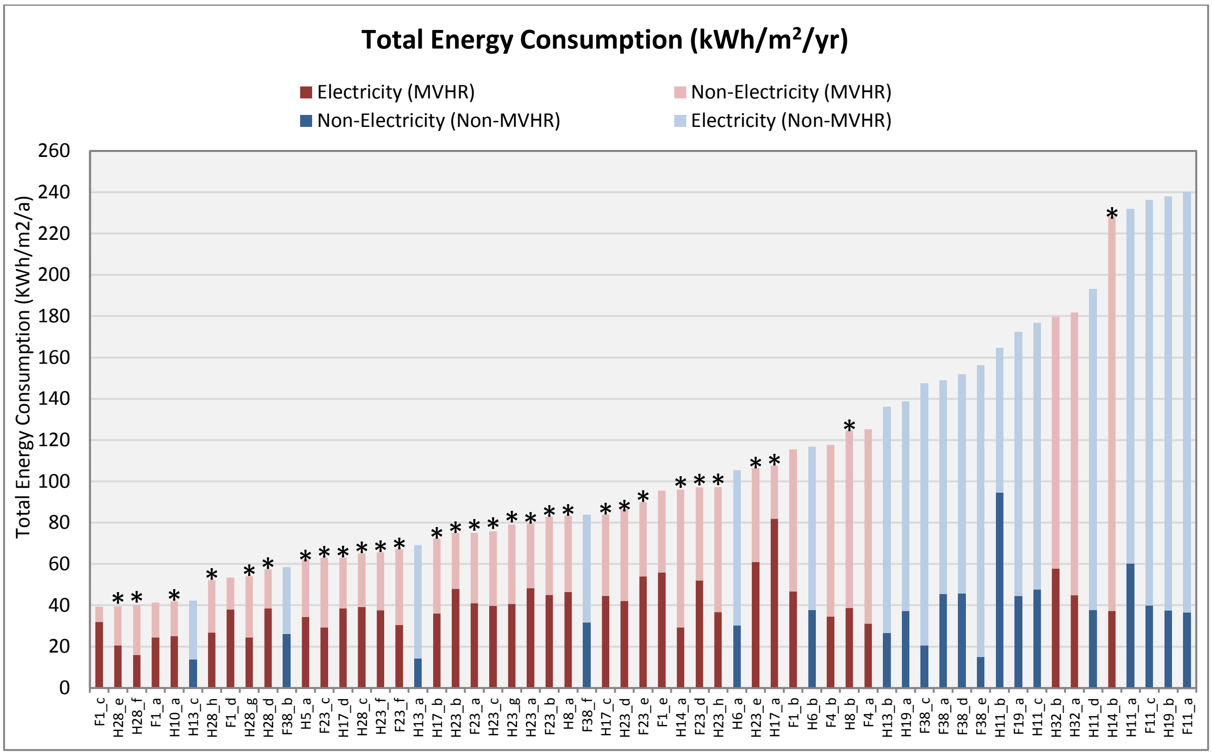

Figure 4.5a. Total Energy consumption (kWh/m^2/yr) in MVHR and Non-MVHR dwellings

* Passivhaus dwellings

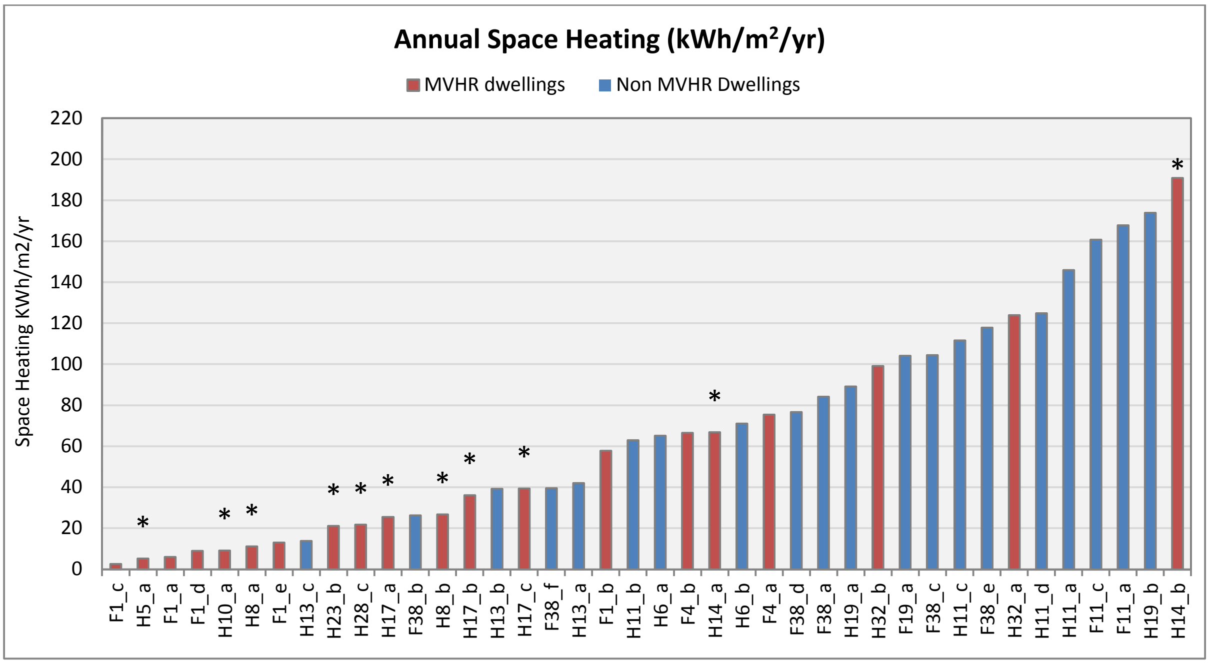

Figure 4.5b. Annual space heating (kWh/m²/yr) in MVHR and Non-MVHR dwellings
** Passivhaus dwellings*

5. Feedback from design team and residents

5.1. Introduction

The analysis of the characteristic and monitoring data was supported by a qualitative review to:

- Understand the design intention and expectation of the MVHR systems.
- Identify problems and good practices in terms of specification, maintenance or operation.
- Evaluate how occupants interact with MVHR systems and how does this impact on their performance

This section assesses the feedback from design teams and residents for a number of BPE projects with MVHR installed. A semi-structured interview and online questionnaire survey were used to gather insights from the design, development or BPE team related to:

- Design and procurement
- Construction and installation
- Handover, use and maintenance

Semi-structured interviews were completed for nine projects (covering 107 dwellings), while both semi-structured interviews and online questionnaires were completed for five projects (covering 51 dwellings), and one online questionnaire was completed by the BPE team member of one project (five dwellings) for which an interview was not completed. In total 15 projects (163 dwellings) were represented by interviews and or online questionnaires. Of these, seven projects involved Passivhaus dwellings.

In addition, to assess feedback from residents, cross-project analysis of BUS survey results was conducted to evaluate occupant satisfaction with environmental conditions. BUS results were evaluated for 27 projects (211 dwellings) in which MVHR was installed.

5.2. Design and procurement

Figure 5.2a lists the varying design standards cited by the respondents. The design intent for nearly half of the projects was the Passivhaus standard (more than one standard could have been selected by respondents, e.g. one projects design intentions could have focussed on Passivhaus but also achieved Scottish or Northern Ireland building regulations).

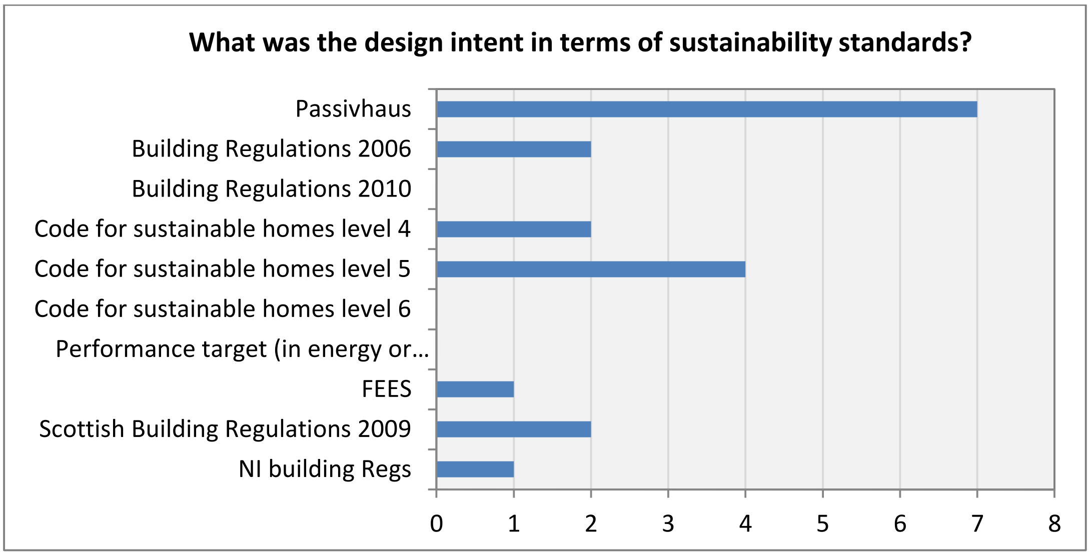

Figure 5.2a. Design intent (Based on responses from 15 projects)

According to responses from the 15 projects, compliance with energy requirements was the primary motive for the selection of MVHR in the majority of cases. However, provision of acceptable IAQ was an important consideration for the installation of MVHR 40% of projects (Figure 5.2b).

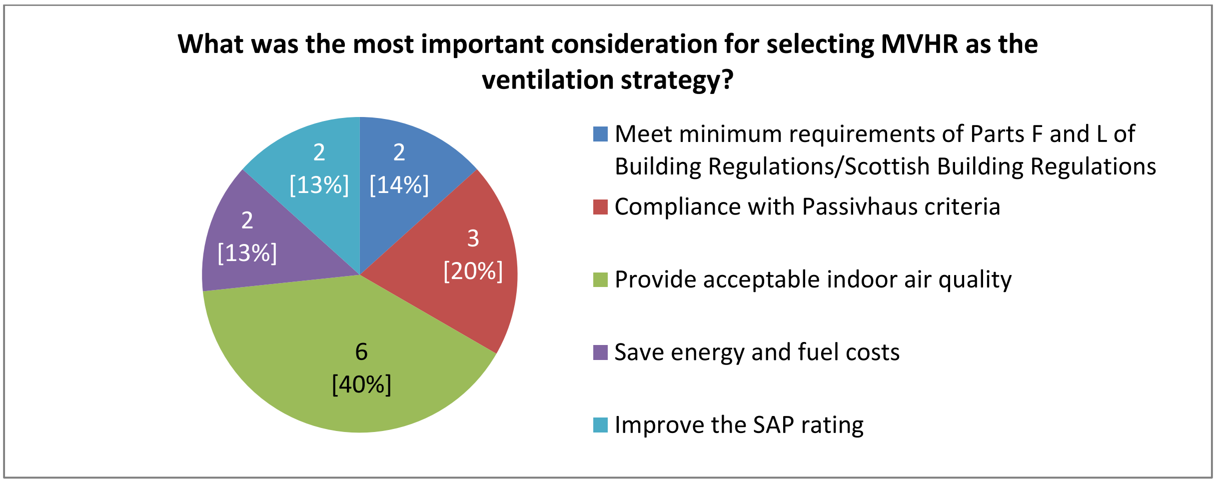

Figure 5.2b. Responses from the design teams as to the reason for MVHR selection (n:15 projects)

Teams were also asked about which key aspects were considered at design stages. In order to achieve the design intentions, the following aspects were most successfully considered at the design stage (figure 5.2c): location of the MVHR unit; and usability of the system and controls. The most poorly considered aspect was the maintenance regime of the system. However it is clear that there are a number of design issues that are not well considered across the projects.

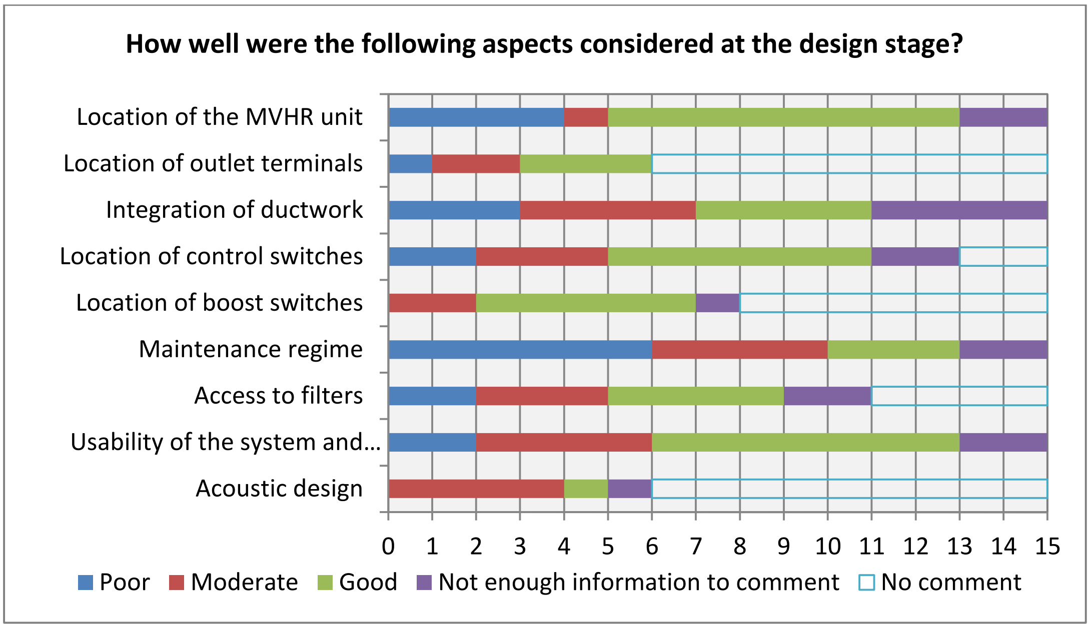

Figure 5.2c. Design stage considerations (based on responses from 15 projects)
Note: 'Location of outlet terminals,' 'Location of boost switches' and 'Acoustic design' were only specifically queried in the questionnaires (hence the high occurrence of 'no comment').

5.3. Construction and installation

Three of the projects (20%) had MVHR systems installed that were not the same as-designed (figure 5.3a). There was clear dissatisfaction with the installer's procedures, competence and the quality of the ductwork installed. Most satisfaction with as-installed systems was with the location of the outlet terminals and the accommodation of the system within the structure of the dwellings, but all the aspects, with the exception of coordination of trades, had some dissatisfaction and indicates a need for improved installation processes.

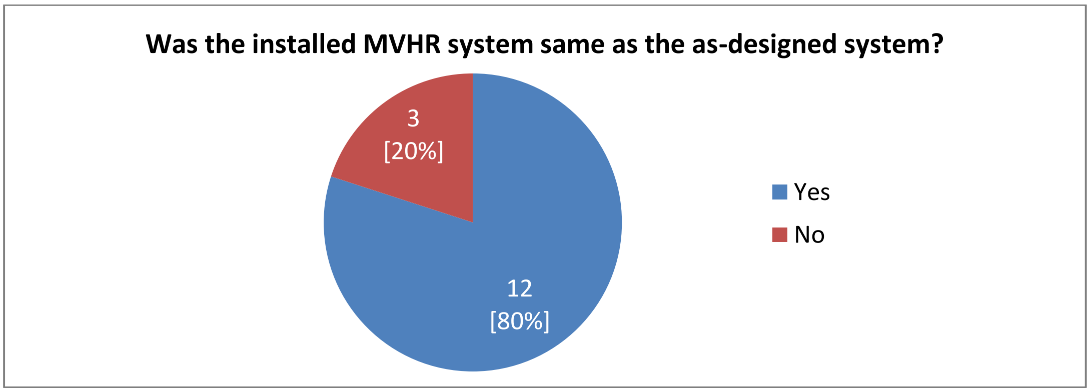

Figure 5.3a. Was the system installed as-designed?

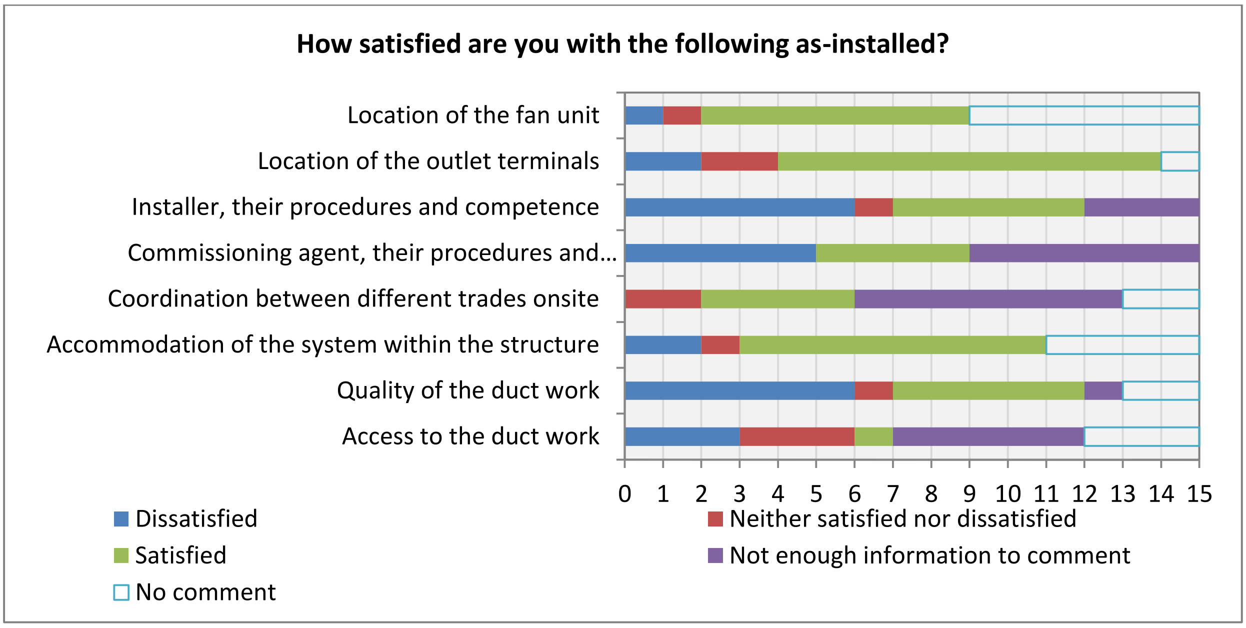

Figure 5.3b. Satisfaction with as-installed system

Note: 'Accommodation of the system within the structure' was only specifically queried in the questionnaires.

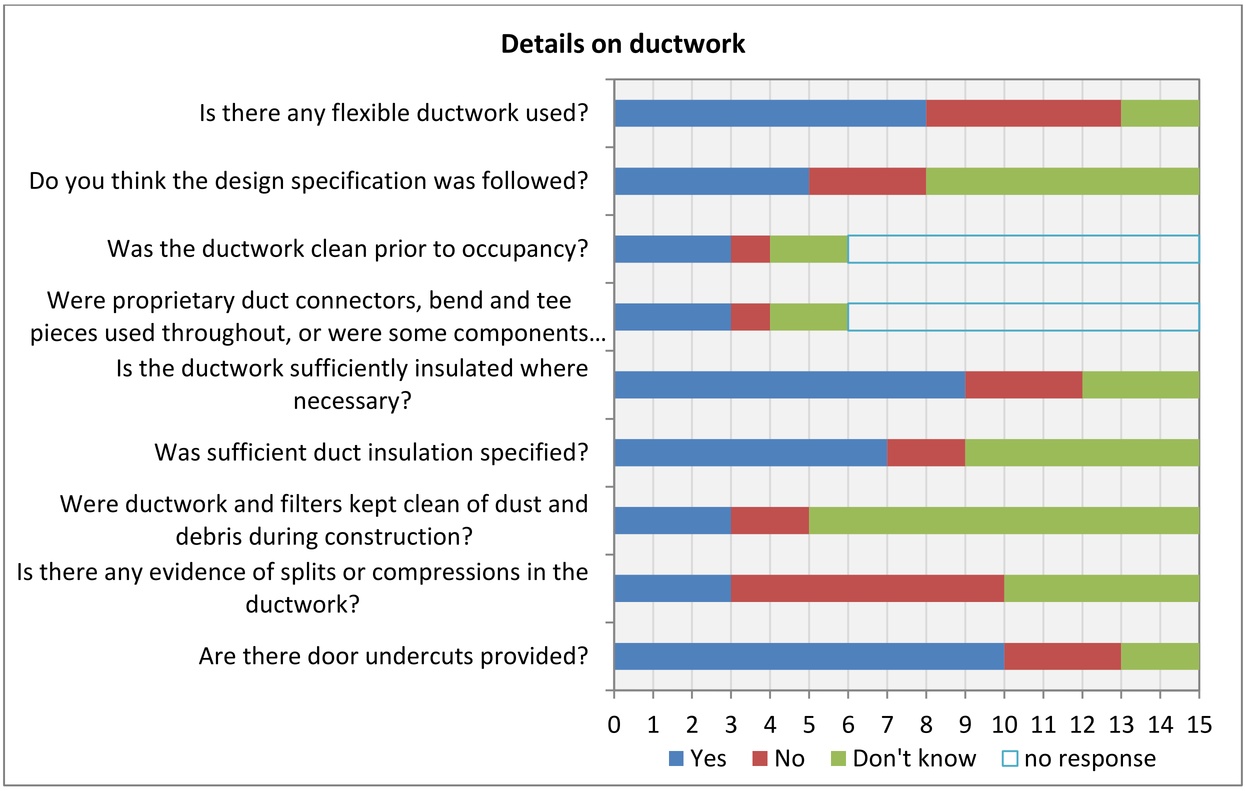

Figure 5.3c. Details of ductwork

Note: 'Was the ductwork clean prior to occupancy?' and 'Were proprietary duct connectors, bend and tee pieces used throughout, or were some components adapted on site?' were only specifically queried in the questionnaires (hence the high occurrence of 'no comment').

With regards to the ductwork (Figure 5.3c), the majority of projects found the ductwork to be sufficiently insulated and door undercuts to be provided where necessary. However a large number of projects reported issues with defects in the ductwork, possibly due to flexible ductwork.

According to the responses (5.3d), the most common problems at the installation or commissioning stages include imbalance between supply and extract airflows, poor installation and (likely as a result of the former problems) the system had to be recommissioned in one-third of the projects.

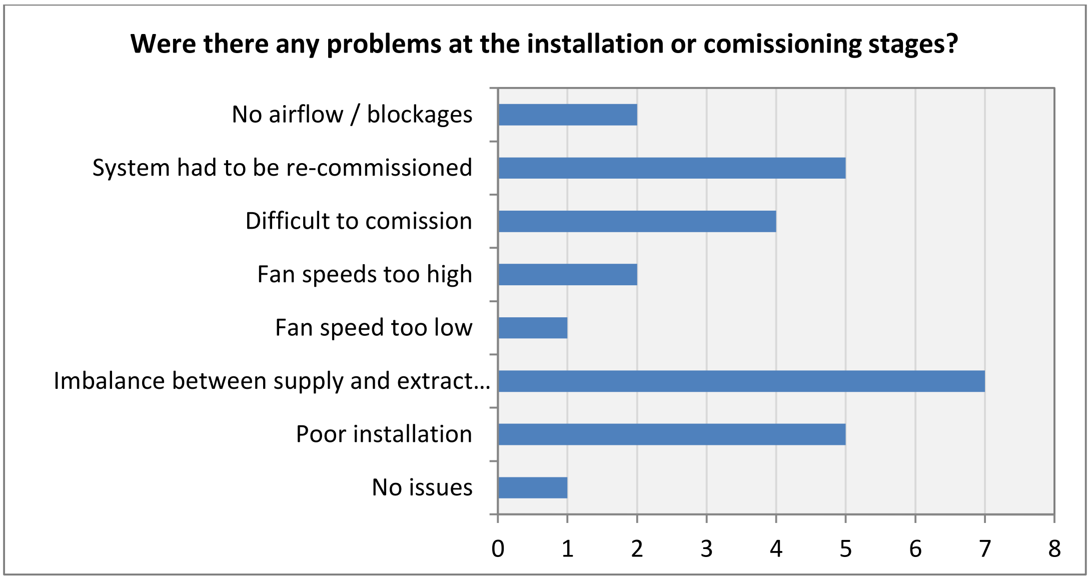

Figure 5.3d. Problems at the installation or commissioning stages

Examples of installation and commissioning issues:

Six months after installation, people were complaining about the high bills and after a few months of investigation we were able to get NIBE representatives to the site to inspect. The exhaust and supply air were set too high, no airflow on some of the supplies, blockage, restricted ducts, some ducts could not be checked, had to re-pressurise the system. Installation and commissioning was not correctly completed. I would like to believe that the issues were resolved by the NIBE representative(s). We were given certificates saying so but we were also give certificates saying that installation and commissioning was completed and it wasn't so you do begin to question…

One tenant complained of smelling smoke coming into the house. The reason was that the supply air was taking in a neighbour's smoking (outside their back door). Because the houses are terraced the closeness can be an issue.

Some ducts were crushed, not insulated…lack of understand and attention to detail were issues [with the installer, procedures and competence]. **– H25**

…there was a marked difference between the two dwellings when tested after commissioning. Big imbalance and pressure difference [issue] *that lead to the fan cutting out. This unit was using half the energy as the other unit but because the fan was constantly cutting out.*

The biggest issue was a gradual drop in flow rates due to long duct runs and kinks and crushed areas.

Approved installer – hoped correct delivery. Problems reported – were related to issues out of their control as in crushed or damaged ducts due to other building *works. With this said the amount of flexi-duct and way it was installed was at a poor standard.* **– H26**

… we got the system commissioned two months before handover the units were finished they were complete then and they were commissioned by the installers but as part of the TSB funding we got the systems re-commissioned…they found that two of the systems weren't performing at all near where they should be. They found a lot of problems with the commissioning certificate from the original commissioning and ***there was no real logic to how these systems were performing****…So when we got it re-commissioned they actually came back with the original installers and met them on site so they rectified the system, rebalanced it, locked off the vents because the vents hadn't been locked off either and they re-commissioned the system with the original installers so they did it together as a re-commissioning as sort of the learning process as well for them.* **– H20**

… one of the things that they tried to achieve throughout [the project] *was consistency so in order to make things easier for the contractor the wall structure design was the same in the flats and the houses for example it was the same boiler, it was the same solar panels on the roof, all of the things were consistent, doesn't mean that the M&E guys connected them all up the same which is a bit worrying but the idea was that everything would be standardised and consistency* ***so it was the same MVHR unit for a fifty metre squared one-bed flat as it was for an eighty metre squared three-bed house.*** *Which mean that in the flats it was ticking over whereas in the houses it was working you know there was less headroom on the fan speeds so in the flats I think it was sixty metres a second and in the houses it was running at a hundred and twenty metres a second but he did find that he had to set the fan speeds higher and in one or two of the rooms the extract was not at the levels expected so the airflow extracts in a couple of the places you know one where they should have been which I think you know he was saying that'll be down to ductwork and not testing it and probably the mastic on one of the connections had come apart or something, the taping had gone loose and so yes I think there was some issues there, not huge ones but in a couple of the properties it's not quite where it should have been.* **– F23/ H23**

5.4. Handover and use

According to the design teams, the dissatisfaction of occupants with the MVHR system is mainly due to inadequate understanding of how to use, operate and control the system, indicating inadequate handover, training and/or guidance (figure 5.4a).

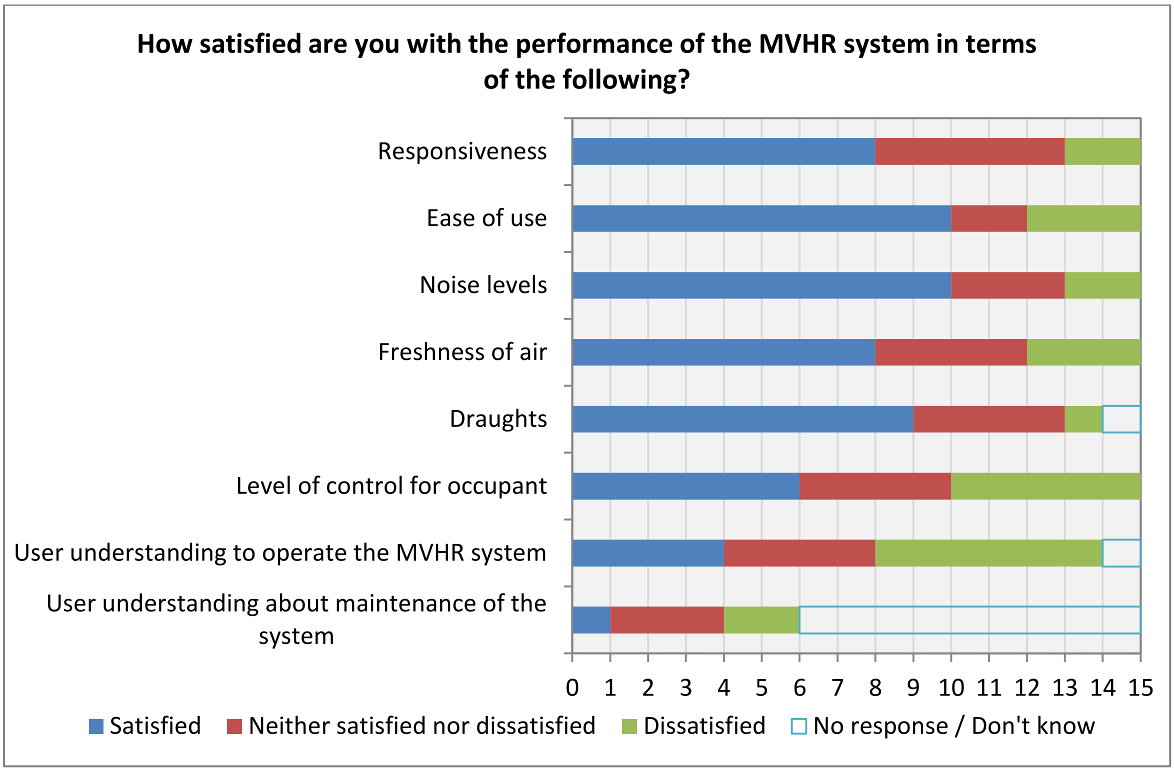

Figure 5.4a Satisfaction with performance

Note: 'User understanding about maintenance of the MVHR system' was only specifically queried in the questionnaires (hence the high occurrence of 'no comment').

Aligned with the IAQ findings above, respondents of 12 projects consider their dwellings to achieve good IAQ. Interestingly, although the majority of systems have humidity/CO_2 sensors that control moisture level and ventilation rates, only in a minority are the sensors presumed to be effective (figure 5.4b). This again implies the gap between intended and actual performance of these systems.

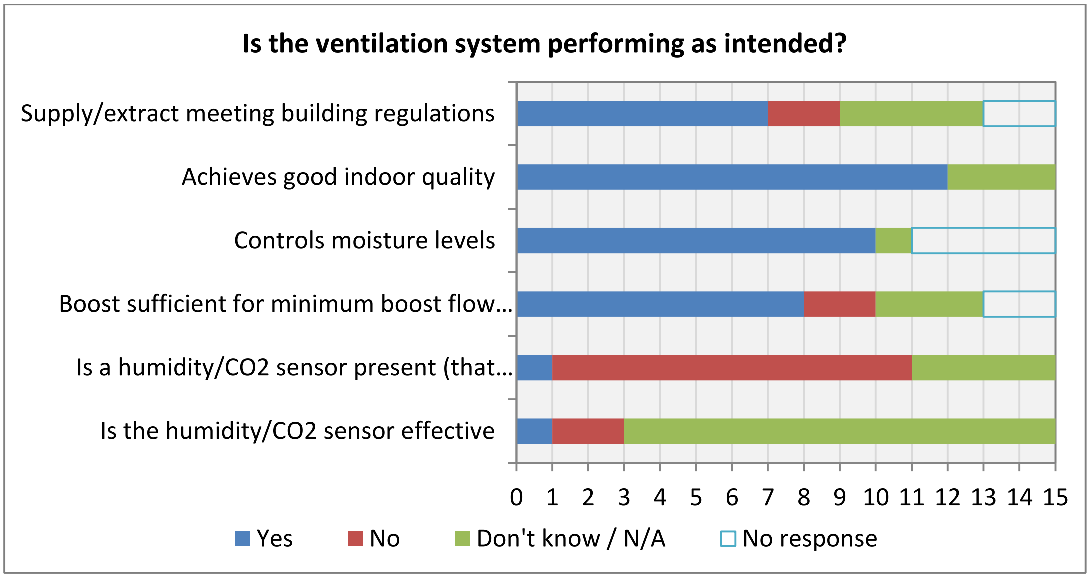

Figure 5.4b. Is the ventilation systems performing as intended?

According to the mean BUS results from 10 projects (those in which design teams were interviewed, Figure 5.2c below), satisfactory levels of indoor air quality was achieved both in summer and winter. (Note: not all projects for which interviews and questionnaires were completed had completed BUS surveys; 10 of 15.) For comparison, figure 5.2d (below) shows the mean available BUS results for all 27 BPE projects that had MVHR installed. As satisfaction is higher in figure 5.2c, this may indicate the self-selection bias of the interview/questionnaire process.

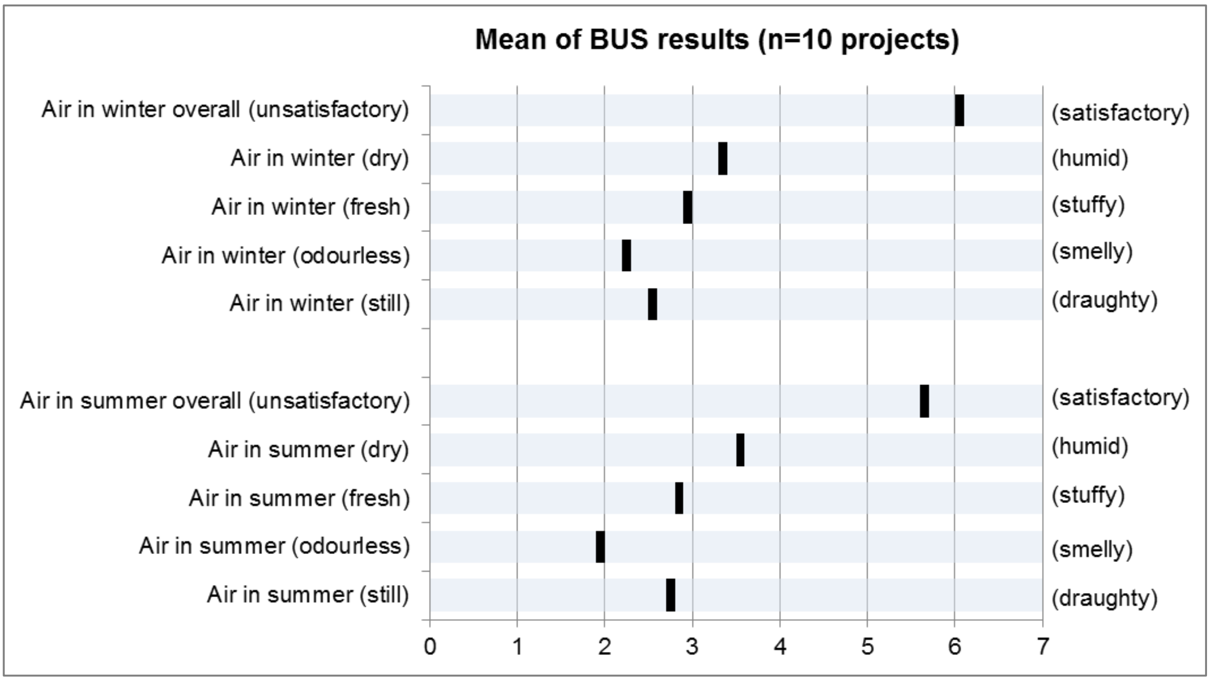

Figure 5.2c. Mean BUS results total 10 projects interviewed, 43 dwellings (96 respondents)

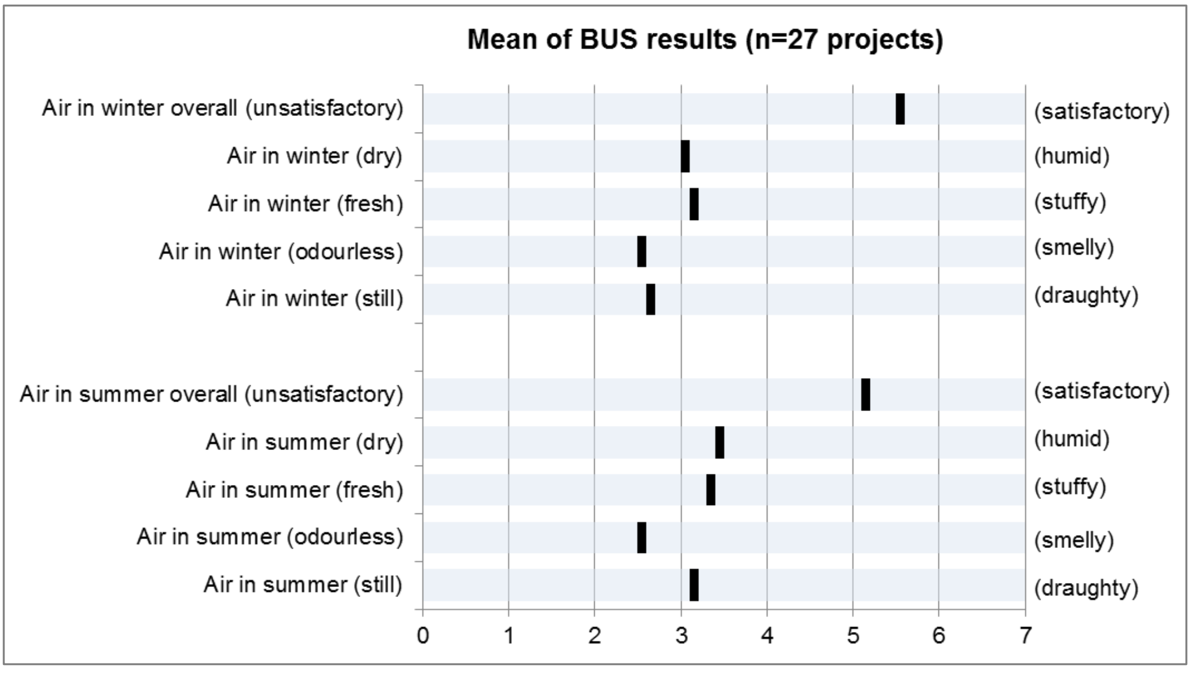

Figure 5.4c. Mean BUS results for 27 surveys, 211 dwellings (304 respondents) with MVHR systems

Satisfactory perception of indoor air quality in summer and winter as indicated by the BUS supports the fact that occupants in only four projects have reported IAQ problems, as stated by the design teams interviewed (figure 5.2e).

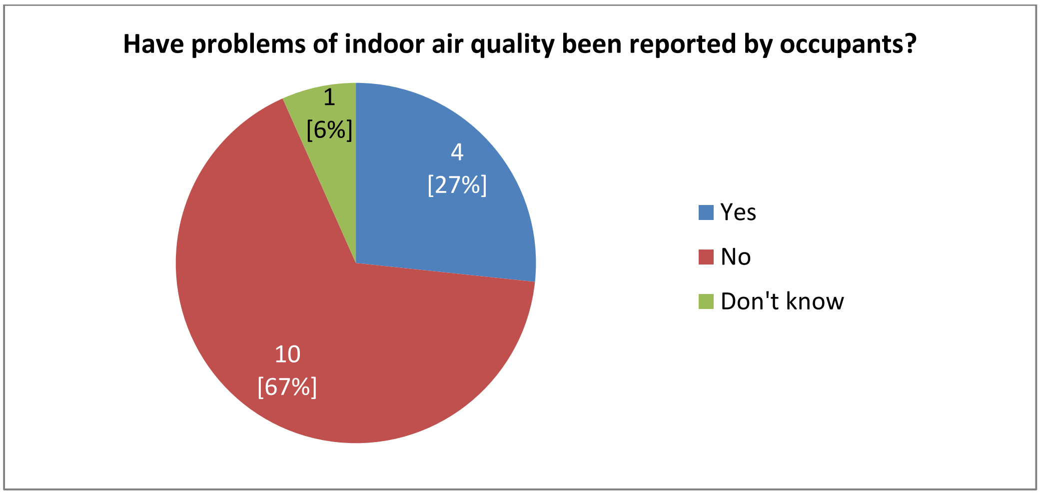

Figure 5.4d Reports of IAQ problems

Although the respondents felt that although the majority of the occupants were aware of the purpose of the MVHR and where the essential controls and displays of these systems were located, there was a lack of understanding of what these controls and displays are meant for and actually do (figure 5.4e).

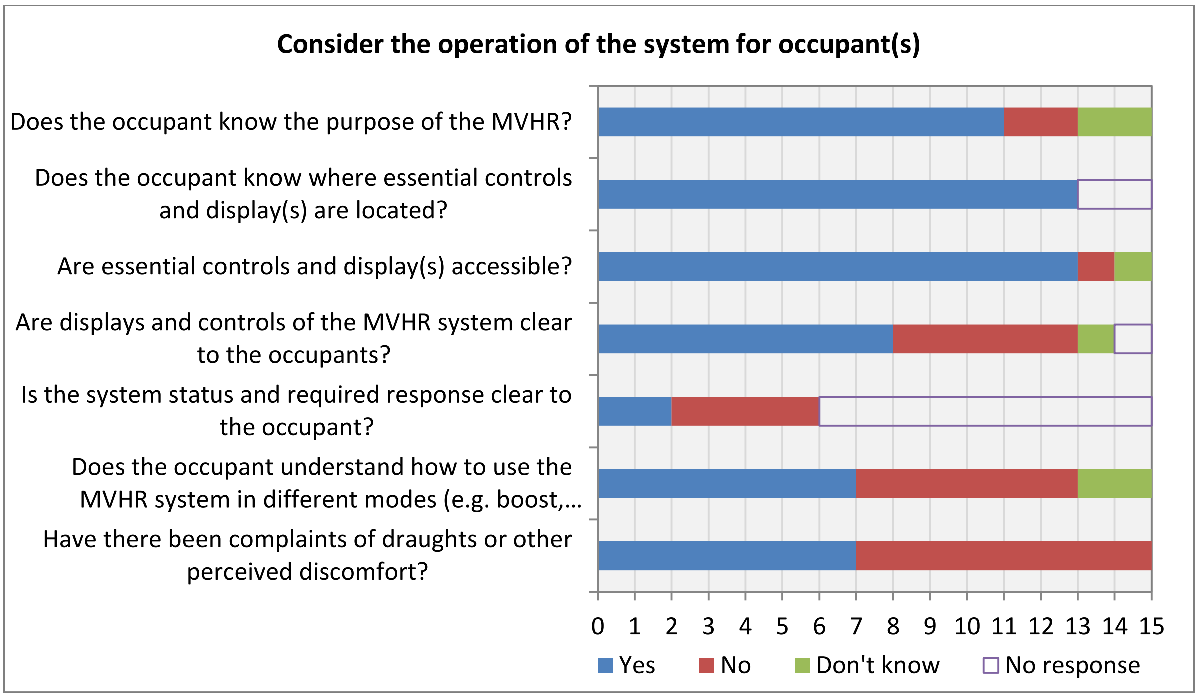

Figure 5.4e. Operational aspects of the MVHR system for the occupants as perceived by the design team respondents.

With respect to the occupant's knowledge regarding the use of the MVHR in different modes, one interview/questionnaire respondent stated:

… their information pack advised the occupants of the two bed houses to switch off the units in summer but I think they don't actually, I think one occupant does, one lady does switch it off in the summer and just has her windows open but the rest just leave it on, I think it doesn't cost them much and I think they've all just decided it's easier to leave it and keep a bit of ventilation going. – **H17**

In contrast, according to the BUS results, the occupants felt that they had a higher level of control over ventilation than the design team perceived them to have. The BUS response can however, include the ability to open windows and from the point of view of the respondent they may not consider the MVHR system alone as a source for ventilation control. Actual user controls in the interviewed projects are shown in figure 5.4f.

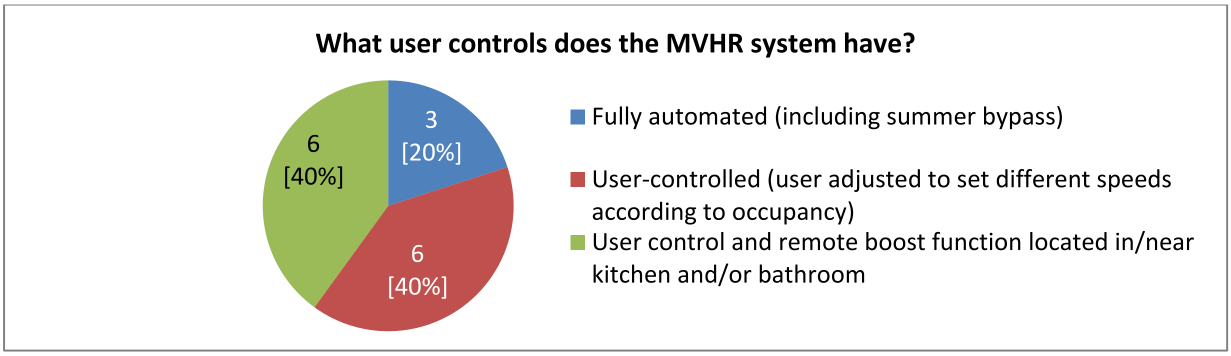

Figure 5.4f. User controls

The interview/questionnaire respondents felt that the most common operational issue with the MVHR systems for occupants was maintenance of the system (figure 5.4g). As an example, in case study 1 in Section 6, the MVHR system is not easily accessible for occupants, precluding occupant led maintenance in most cases.

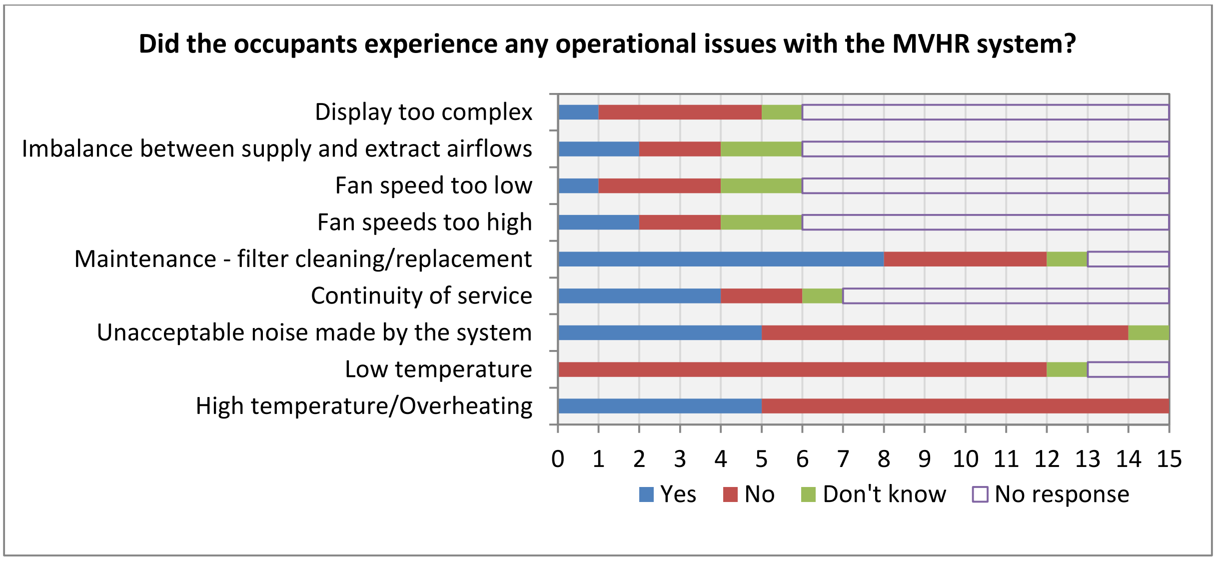

Figure 5.4g. Operational issues

Note: 'Display too complex,' 'Imbalance between supply and extract airflows,' 'Fan speed too low,' 'Fan speeds too high,' 'Continuity of service' were only specifically queried in the questionnaires (hence the high occurrence of 'no comment').

Half of the responded reported evidence of the system being disabled, the most common reason was out of concern for the operating cost of the MVHR. The widespread disabling of systems is a cause for concern in respect of both energy use – MVHR being a critical element of the energy strategy and code compliance - but also the potential effects on ventilation provision and consequent air quality.

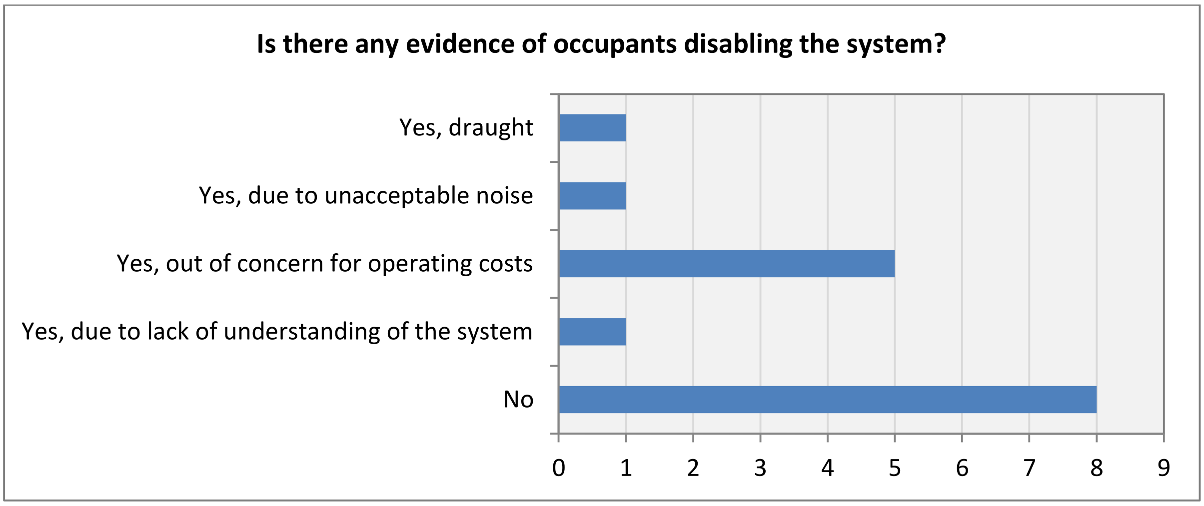

Figure 5.4h. Evidence of occupants disabling the system

The interviews highlighted a number of issues related to occupants understanding of the system that could lead to it being disabled and this was a common concern:

The only time they would have disabled it which was intermittent was when they thought it was the one consuming a lot of energy. And that was disproved by our service. ***It was actually the towel rail.*** **– H15**

I think some of them disabled it because they said that it gave them a ***draught*** *in the wrong place. Some of them disabled it because I think they thought that it was costing them money...* – **H35**

There was one property, one flat that they took out the fuse and had switched it off. He mentioned it because he noticed it used up too much electricity which it was minor compared to other appliances and he just didn't understand it and I remember him saying that ***he just didn't see the need for it.*** – **F27**

Specifically this one tenant felt the system was ***too noisy,*** *didn't particularly like it and* ***didn't particularly trust it.*** *So they turned it off and they prefer to live with the windows open, they sleep with the windows open all year round and they know that they need to do something if they turn the system off they need to keep windows open or have some other form of air coming into the property and they're happy that that's what they prefer to do.* – **H20**

There was one gentleman in one of the flats who I think he's unemployed and from the outset he has tried to run everything absolute minimum cost and ***his attitude was the MVHR is an unnecessary cost*** *I'm going to switch it off, I'll have the windows open so he has not used his MVHR in his flat.* – **F23/ H23**

It was apparent from the interviews that the Passivhaus projects investigated had fewer performance issues than the non-Passivhaus dwellings, particularly with regards to draughts or other discomfort and high temperatures (figure 5.4i) and this is generally supported in the analysis of the data in the preceding section. This difference in performance between the Passivhaus and non-Passivhaus dwellings may be in part to the level of detail and planning required for a Passivhaus as a whole system.

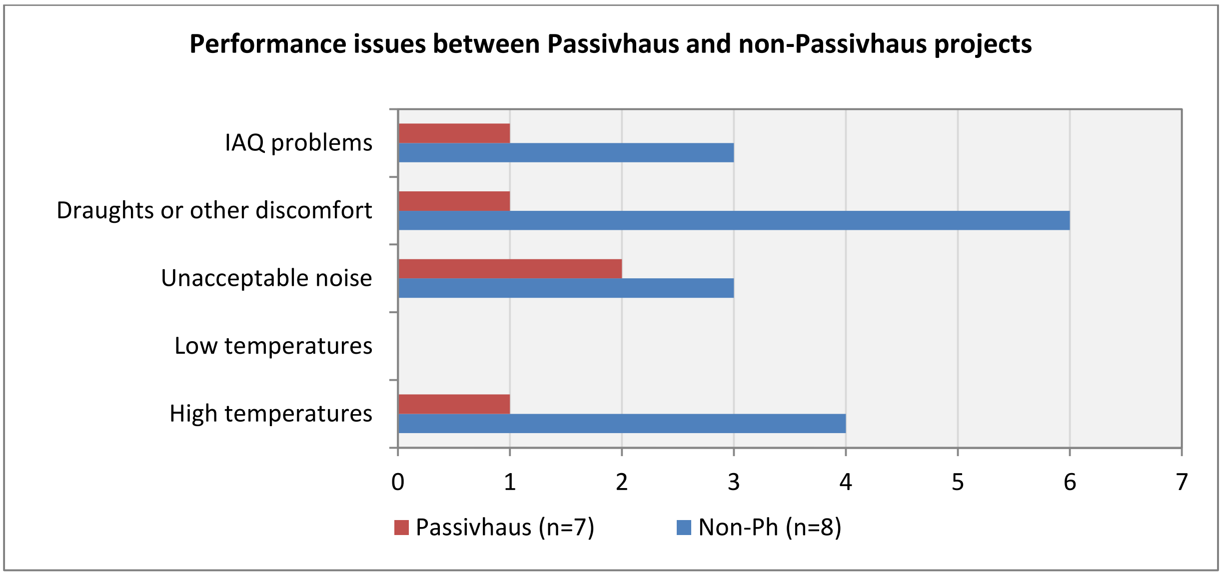

Figure 5.4i. Performance issues

Most overheating or high temperatures reported were not linked specifically to the MVHR:

…there is a general trend for overheating in the homes. Not a result of the MVHR operation though. – **H2**

Not complaints but there was certainly evidence of high temperatures in the Code 5 properties. The tenants seemed to view it was a reasonable compromise considering that the properties are warm in winter but the temperatures in summer did get certainly above what you would expect as normal in an average residential property and tenants lack of understanding of the MVHR systems in the evidence of imbalance and flow rates and suchlike could well be a factor in the tenants inability to do anything about that, to alter that temperature. – **H9**

… she would complain about overheating and the reason was because she would rely on the system without opening windows in summer so in summer actually the apartment was extremely hot and she wasn't happy opening the windows because for all the reasons, she has a pet so she was scared that the pet is going to leave the home so the way in which she ventilated the apartment was through the system so this one is saying that actually the system they believe that the system was a cooling system so this is why they complained that actually the system wasn't good enough. – **F1**

… they've never been cold in these properties so I don't think that we've ever recorded temperatures below about eighteen degrees in any of these properties over the three years but you know they do get a bit warm in the summer but it's a very complex issue as to why that is. – **H23/ F23**

…as a cost saving choice they decided that they would step down a model which meant that they lost the things like having a summer bypass there wasn't one and it was decided that it wasn't necessary to have a summer bypass… - **H23/ F23**

As was shown earlier (figure 5.2f), the most poorly considered aspect was the maintenance regime of the system. Without appropriate handover and training (including easy-to-follow documentation and follow-up), occupant-led maintenance regimes cannot work. This was the intended maintenance regime in a third of the interviewed projects (figure 5.4j).

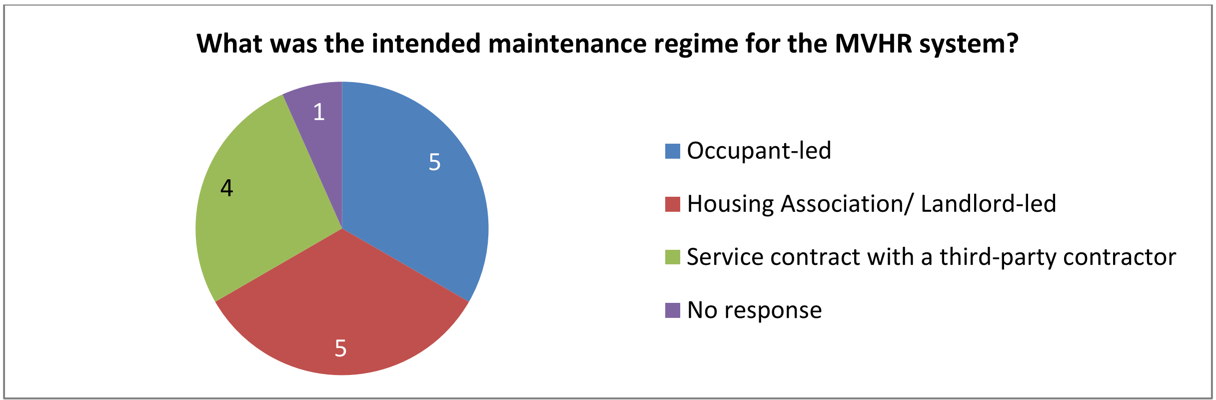

Figure 5.4j. Intended maintenance regime

5.5. Summary

For the majority of the projects in which design or BPE teams were interviewed or questioned, the design intention for including an MVHR system was some element of code compliance. However, the need to provide acceptable indoor air quality in the homes was also seen as a driver for installing MVHR systems.

Only three of the interviewed projects had MVHR systems installed that were not the same as-designed. However, almost half of the interviewees were dissatisfied with the installer's procedures and competence and the quality of the ductwork installed. In addition, a little over one-third of the project's interviewees were dissatisfied with the procedures and competence of the commissioning agent (unfortunately, about the same number of respondents could not respond to this question due to lack of information). The most common problems at the installation or commissioning stages include imbalance between supply and extract airflows (half of the projects), poor installation and (likely as a result of the former problems) the system had to be recommissioned in one-third of the projects. Other problems which occurred in more than one project include blockages or no airflow, systems difficult to commission, and fan speeds that were too high.

The overall picture shows a mixed experience with construction and installation, suggesting that this is an area that needs further development. It also provides some context for the findings in Section 3 on numbers of systems that have installation issues.

In terms of operation, most interviewee dissatisfaction was from the user's level of control and understanding of how to operate and controls the system. These issues suggest insufficient training or handover on how to use the system and system design for use. Essentially, though many occupants may have a basic knowledge of the purpose of the system there is little comprehension on how to use the system. The most common (50%) operational issue with the MVHR systems (and most poorly considered aspect in integration) for the occupants was with maintenance of the system. Without appropriate handover and training (including easy-to-follow documentation and follow-up), occupant or housing association/landlord maintenance regimes cannot work. This happened to be the intended maintenance regime of two-thirds of the interviewed projects.

Half of the projects sampled had occupants that disabled the system; the most common reason was out of concern for the operating cost of the MVHR. Though potentially tenuous, high cost of running the system was a common perception among occupants. Other issues experienced by occupants in more than one project include system service discontinuity and unacceptable system noise. High temperatures and overheating was also experienced in a number of projects. Although some occupants may incorrectly expect the system to cool the space, it is difficult to establish the impact that a MVHR system may have on high temperatures or overheating. Finally Passivhaus projects were found to have less performance issues particularly with regard to draughts or other discomfort and high temperatures. Notably, the source of 'performance issues' such as draughts and high temperature can be poorly understood.

These finding underpin the data from the system characteristics and monitored data. Whilst it is evident that some systems have clear design intentions that consider both energy and ventilation; are well installed and correctly commissioned; and are understood and properly operated and maintained, many projects do not meet some or all of these criteria and will therefore underperform. The critical issue emerging is the need for these systems to be sufficiently well-designed, installed, handed over and maintained so that they do not become disabled in-use.

6. Learning from representative case studies

6.1. Case Study 1: Typical 'fit and forget' example

Development: Thames Valley Houses in Feltham (10 council houses built to CSH 4).

Owner: Thames Valley Housing Association (TVHA)

Location: London

Innovate UK BPE ref no: 450096

Figure 6.1a. Front façade of Dwelling 1

6.1.1. Design

For this development, MVHR systems were used to achieve code (CSH4) compliance and were regarded as a 'low maintenance' system by the designer and the developer. This has not been the case in reality given issues with commissioning, operation and maintenance. The developer in hindsight would have reconsidered the use of MVHR systems; and have avoided MVHR if the design target could be achieved without it. The developer also believes that the tenants' familiarisation with the technologies would have to be improved and is looking for ways to improve handover and occupant training in future projects.

The design and delivery team was not familiar with achieving low air-tightness targets and was not experienced in the implementation of MVHR systems, both of which proved to be more complicated than expected as revealed through the evaluation of fabric performance and usability of controls. Lack of familiarity with the MVHR system in particular had resulted in a series of commissioning and operation issues that undermined the reliability of the system.

The MVHR system was considered to be a ‘fit and forget’ system. However, given the high measured air-permeability rates of the case study dwelling (around $6m^3/m^2h$), the use of the electricity-driven MVHR system is questionable.

Table 6.1a. Case study details of Dwelling 1

Case study specifics	As-designed	As-built
Area	128 m²	
Typology	Four bed Mid-terrace	
Floors	3	
Orientation	South	
Occupancy patterns	N/A	Weekdays: 13:00-8:00 Weekend: 24h
Occupants	N/A	2 adults, 3 children
Target design rating	CSH Level 4	
SAP Rating	90 (B)	86 (B)
Main construction elements U-values W/m2K	**Walls:** Timber frame and brick, U-value: 0.21 **Roof:** Slate roofing, U-value: 0.13 **Ground floor:** Precast concrete with insulation, U-value: 0.25 **Windows:** Aluminium frame, double glazing, U-value 1.3	**North facing wall**, measured U-value: 0.18
Space heating and hot water system	Gas condensing boilers and radiators	
Target air tightness	3 m³/hm² @50Pa	5.87 m³/hm² @ 50Pa
Mechanical Ventilation	MVHR with summer bypass mode and thermal sensors.	

6.1.2. Construction and installation

The MVHR units are located in the loft space, which is accessible through the loft hatch. The units are not easily accessible by the occupants. This suggests that there is not sufficient access for routine maintenance repair and replacement of components.

The air tightness tests performed showed that the houses did not meet the design air permeability target. In the case study dwelling and a similarly designed dwelling in the development, the measured air-permeability values were around double the design target, indicating heat losses due to air leakage paths and also questioning the need for having always-on MVHR systems, which are usually installed in houses with air permeability rates less than $3\ m^3/h.m^2$.

Due to lack of familiarity of the contractor with installation and commissioning of MVHR systems, they were not commissioned properly, and had unbalanced air flow between supply and extract, leading to occupant discomfort. The commissioning review revealed that the system was not installed in accordance with the manufacturer’s requirements, e.g.:

- The ductwork was not properly insulated even though it is located in an unheated space.
- Controls were not set in accordance with the manufacturer's recommendations. The review showed that the correct number of grills had been installed; however, none of the extract and supply grills were locked in a fixed position, thus allowing the occupants to open or close them at will, inevitably unbalancing the system.

  However, all internal doors had sufficient undercut to allow air transfer between rooms and all protection/packaging had been removed and the system was fully functional.

MVHR test 1 conducted during the commissioning review indicated that there was a discrepancy between design and measured extract rates and that the system needed to be re-commissioned, as some supply vents were closed (Table 6.1b). Following the 1st test, the system was re-commissioned by the BPE team and a second MVHR test was performed:

- total extract after the second test was 10.7 l/s
- total supply was 12.4 l/s
- discrepancy between supply and extract is 13%
- Monitoring data has shown that the re-commissioning has had a great impact on the total monthly electricity consumption of the MVHR.
- During the test the filters were found to be dirty. Additionally, the boost switch did not appear to be operational.

Table 6.1b. Air flow measurements taken during commissioning review - Test 1 & Test 2

Location of terminals		Air flow high rate (l/s)	Air flow low rate (l/s)	Air flow high rate (l/s)	Air flow low rate (l/s)	Air flow high rate (l/s)
		Design	Test 1 - measured		Test 2 - measured	
Extract	Kitchen	13	8.9	Not functioning	4.5	4.5
	Bathroom	8	12.3	Not functioning	4.6	4.5
	WC	6	8.5	Not functioning	1.6	1.7
Supply	Living room	13	6.5	Not functioning	2.4	2.4
	Bedroom 1	6	6.1	Not functioning	1.9	1.9
	Bedroom 2	13	0 (valve closed)	Not functioning	1.6	1.7
	Bedroom 3	5	7.4	Not functioning	2.4	2.3
	Bedroom 4	5	5.2	Not functioning	2.1	2.1
	Kitchen Diner	13	5.9	Not functioning	2.0	1.9

As a result of the system imbalance, noise and draughts have been reported. Occupants have actively tried to stop the 'annoying' cold draughts by shutting the supply terminals thus further creating imbalance in the system and potentially undermining IAQ.

6.1.3. Handover and use

Occupants of dwelling 1 were satisfied with the induction process and find the home user guide easy to use. However, when asked about the purpose and operation of the MVHR system both occupants appeared to be unfamiliar with it. For the handover a demonstration on technologies was provided by a specialist explaining controls, the operation of the boiler and the benefits of the MVHR units and PV panels. The demonstration took place in the houses and the benefits of low carbon technologies and building services available in the properties were presented to the occupants. However, very limited time was allocated to the presentation of the systems and controls, some of which, like the MVHR, were completely new and unfamiliar to the occupants. Inadequate installation and commissioning of the MVHR system has further undermined occupant understanding of systems and has resulted in confusion regarding the use and operation of the MVHR system. The evaluation of the handover showed that little of the information provided to the residents during that day was retained by them. Moreover, the MVHR system has proven to be the system creating most confusion for the occupants. The occupant in dwelling 1also pointed out that they do not remember all the information provided during the induction tour and has expressed the need for a follow-up presentation of systems.

Occupant interviews revealed that the occupants are unfamiliar with the purpose and use of the MVHR system. Further comments received mention unpleasant draughts and noise from the MVHR system. In winter, air is perceived as satisfactory by the majority of the respondents. Air quality in winter scored higher than the benchmark. These findings, however, cannot be directly related to the performance of the MVHR system as occupants tend to open the windows to ventilate the houses even during winter. From the development-wide BUS, six respondents feel they have good control of ventilation; however, interviews with occupants from the case study dwelling indicated that the occupants do not fully understand the purpose of the MVHR system and normally open the windows to ventilate the houses. Walkthroughs also revealed that the occupants do not make good use of the heating system, setting the thermostat at 30ºC and leaving the windows open when the heating is on. This combined with the fact that high measured air permeability of the houses suggest that the MVHR systems are essentially redundant.

Following the re-commissioning, energy consumption of the MVHR unit was measured as 11.8 W. One year of energy use was monitored at 190 kWh. In addition, mean and maximum CO_2 levels increased since the MVHR system was re-balanced. Overall, occupant habits of keeping the thermostats high and opening the windows while the heating is on has resulted in increased heating loads, thereby widening the discrepancy between the design targets and actual energy use.

6.1.4. Maintenance

The MVHR unit is located in the loft space that is accessible through the loft hatch. Although adequate space is provided for operation and maintenance of the MVHR panel and switches in the loft, the space is hardly accessible to the occupants; a portable ladder is essential to access the space. This suggests that there is not sufficient access for routine maintenance repair and replacement of components. Furthermore, the MVHR system purpose is not clear and there is no indication of system response or whether any fault is occurring. There is no indication of when filters need to be changed and users and the developer have not been informed about the importance of changing filters and maintaining the unit regularly. Occupants would need more training on how to use the MVHR system (especially to check MVHR filters in case they need changing before the scheduled date of maintenance by the developer) and controls that would include information about the benefits of the correct operation of the ventilation system. The system in the case study house was found to be unbalanced because supply vents had been closed by occupants due to cold draughts or the central MVHR unit was completely shut.

Several breakdowns of the MVHR system in dwelling 1have undermined its reliability and have confused the occupant, who in turn has become accustomed to operating the house without it.

During one system malfunction, the supply terminals on the top floor supplied cold air whereas both the supply and extract terminals in the ground and middle floors stopped working. The breakdown was due to a manufacturing fault.

6.1.5. Recommendations

- Design teams should debate and discuss the need for MVHR systems at the design stage within a broader discussion on airtightness targets and ventilation;
- MVHR should be introduced only if necessary as there are alternative solutions available such as natural ventilation, passive stack ventilation or even demand controlled ventilation;
- If MVHR units are installed, they should be located within the insulated envelope and in a more easily accessible space to allow enough space for maintenance and filter change;
- Since the MVHR installation and commissioning was not up to standard and even after re-commissioning of the systems, the systems were still not operating to expected levels, this raises an important question for the industry - how can commissioning quality be improved? Installation and commissioning procedures need to be robust and be carried out by qualified technicians/engineers using calibrated equipment for system balancing;
- Training and guidance for occupants should include operation of the MVHR systems and controls, as well as maintenance requirements. Customer care should be improved for rapid trouble-shooting;
- The Home User Guide should be concise and visual and provide accurate and useful information to occupants on how and when to change the settings of the heating and ventilation system seasonally;
- Extract and supply grilles should be locked in fixed positions and occupants re-trained regarding the purpose and seasonal operation of the system, as well as reporting of breakdowns;
- In the case study example, the occupant is used to keeping the windows open at all times when in the house. Such habits are hard to shake and occupants need to be trained well to gain a good understanding of how the house operates as a whole and how to use the house in different seasons.

6.2. Case Study 2: Consequences of system failure

Development: The 'Glasgow House'.

Owner: Glasgow Housing Association (GHA)

Innovate UK BPE ref no: 450055

It was apparent during the study that there were a number of instances where MVHR systems had failed or been disabled in some way. Common causes of this were drafts, noise, running costs and general lack of understanding. In addition, lack of maintenance of filters was also reported, as was systems being turned off in the summer. There may be other situations where the system may fail, for example power cuts or use of power cards, technical failures. It is likely that some of the poor performance data is due to these types of occurrences, but isolating particular incidences is difficult. However the consequences of system failure were examined in some detail in the Glasgow House project.

Table 6.2a. Case study details

Case study specifics	As-designed	As-built
Area	Scotland	
Typology	Four bed end terrace town-house	
Floors	3	
Orientation	West	
Occupancy patterns	SC2, SC5	Weekdays: 17:00 – 09:00 Weekend: 24h
Occupants	4 adults	
Target design rating	CSH Level 4	
SAP Rating	Plot 1: 85 (B) Plot 3: 85	Plot 1: 83 (B) Plot 3: 84
Main construction elements U-values W/m2K	*Walls:* Clay block, external insulation and render: Timber frame and brick, U-value: 0.15 Timber frame, external brick U-value: 0.15 *Roof:* Slate roofing, U-value: 0.13 *Windows:* Timber frame, double glazing, U-value: 1.2	U-value: 0.27 U-value: 0.18 U-value 1.22
Space heating and hot water system	Gas boilers and radiators, thermal store, 2.33m2 Solar thermal panels on east and west facing roofs.	
Target air tightness	4 m^3/hm^2 @50Pa	4.05 m^3/hm^2 @ 50Pa
Mechanical Ventilation	MVHR with summer bypass mode, unit located in the loft, 100mm flexible ducting.	

The Glasgow House is a prototype dwelling constructed by building apprentices on the site of the Glasgow City Building Skills Academy, on behalf of the Glasgow Housing Association (GHA), one of the largest landlords in Scotland. It was based on a design for a low energy house for both sale and rent. Originally entitled the £100 house it aimed to have very low running costs for occupants. The original design included a high thermal mass clay block system, but GHA were concerned that this construction system differed significantly from the predominant construction used in

Scotland which is timber frame, so they commissioned City Building to construct 2 versions of the house, one using the clay block system (Plot 1) and one using a timber frame (Plot 3) to the same thermal specification. As well as low fabric u-values, energy reduction measures included sun-spaces, solar hot water collectors, low energy lighting and MVHR systems.

As the dwellings were built as test houses they were not occupied. However, the BPE project team were asked to undertake an assessment of their performance, first as a pilot study and later as a BPE Phase 1 study. The methodology that was developed to test performance is that both houses would be occupied by volunteer student inhabitants for a series of two-week periods, which would test different occupancy scenarios, with both houses being used in identical ways to compare performance.

A particular area of interest was the MVHR system. The initial pilot study had found the system to be quite badly installed, with crushed ducting, ducts fixed to incorrect spigots and the system generally out of balance. The unit is located in the loft and although the filters can be removed for cleaning, access is very difficult. Some remedial works were undertaken to improve the system, but as some parts of the ducting was inaccessible not all of the necessary remedial measures could be undertaken. The table below shows the flow rates at the start of the testing.

Table 6.2b. Flow rates at start of testing

Extract Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Utility/ WC	7.23	5.49
Kitchen	9.81	6.81
Bathroom	9.3	6.3
Total	26.34	18.6
Supply Positions	High Rate Volume Flow (l/s)	Low Rate Volume Flow (l/s)
Living Room	5.64	4.51
Bedroom 1	9.31	7.45
Bedroom 2	8.13	6.23
Bedroom 3	7.8	5.96
Attic Room	8.42	6.69
Total	39.3	30.84

At a high flow rate the system is 33% out of balance, rising to 38% at low flow rates. Flow rates to some rooms are also very low. There were concerns about the efficacy and viability of this type of system in social housing and so two of the test scenarios looked at issues related to the performance of the MVHR system.

In the pilot study the filters had been cleaned prior to the first occupied scenario and then inspected at the end. This revealed that the filters had become very dirty in a short space of time and there were concerns that occlusion of the filter might affect its ventilation.

Figure 6.2a. Filter condition

To examine this the first test scenario compared the base performance with one week in which the filter was occluded to simulate it being blocked and in the second week the system was disabled. During this period the students were asked not to open windows.

It was very clear that levels of ventilation decline comparing 'normal' with 'occluded' and then 'disabled'. The mean and peak levels are shown in Table 6.2c. In the normal mode the CO_2 levels increased overnight but remained at reasonable levels. In the 'occluded' scenario the CO_2 levels increased noticeably. In the third week the CO_2 was at very high levels. Conditions were worse in the bedrooms and this was a common finding across the project.

Table 6.2c. Carbon dioxide levels (ppm) with filter occluded and MVHR system disabled

Plot 1	Living		Bedroom	
	Mean	Max	Mean	Max
Normal	591	1262	619	1300
Occluded	680	1800	847	1530
Disabled	726	2306	1067	2850

A further scenario was undertaken to compare the MVHR and natural ventilation. In this case the MVHR system was used as normal in the first week and then the system was disabled in the second week and occupants were allowed to open windows as they required.

There is an interesting comparison between the week using MVHR, and the natural ventilation week. Looking firstly at the living room across the 2-week period there is relatively little apparent differences in CO_2 levels (Figure 6.2b). Some additional peaks of CO_2 and consequent RH are apparent but overall conditions are unchanged. Here adaptive behaviour was observed with occupants opening windows in response to changing conditions.

However in the bedroom the difference was quite clear (Figure 6.2c), with much higher CO_2 levels recorded during the second week when the MVHR system was disabled. In this scenario occupants would go to bed when conditions were reasonable, but these would decline overnight, only improving when the occupants left the room in the morning. As the occupants were asleep there was no adaptive behaviour.

Interestingly comfort polling found that the occupants had marginally higher satisfaction in the second week, despite conditions being demonstrably poorer. Also of interest is the difference in running costs. The external temperatures were broadly similar across the two weeks, but in the second week energy consumption was higher in both houses, but by a much higher margin in the timber frame house.

These tests indicate that whilst a well maintained MVHR system is able to deliver reasonable ventilation rates, the failure or disablement of the system can result in very poor conditions. Whist it may be argued that windows can always be opened by occupants and there is a suggestion that this may lead to improved perception of comfort, this does however lead to greater heat loss and consequent energy consumption.

Table 6.2d. Internal air quality perception for week 1 and week 2

	Mean Internal Air Quality Perception (std. dev)	
Testing Period	Plot 1	Plot 3
Week 1 (19.11.12 to 24.10.12)	4.38 (0.14)	4.75 (0.32)
Week 2 (25.10.12 to 30.10.12)	3.78 (0.22)	4.79 (0.33)

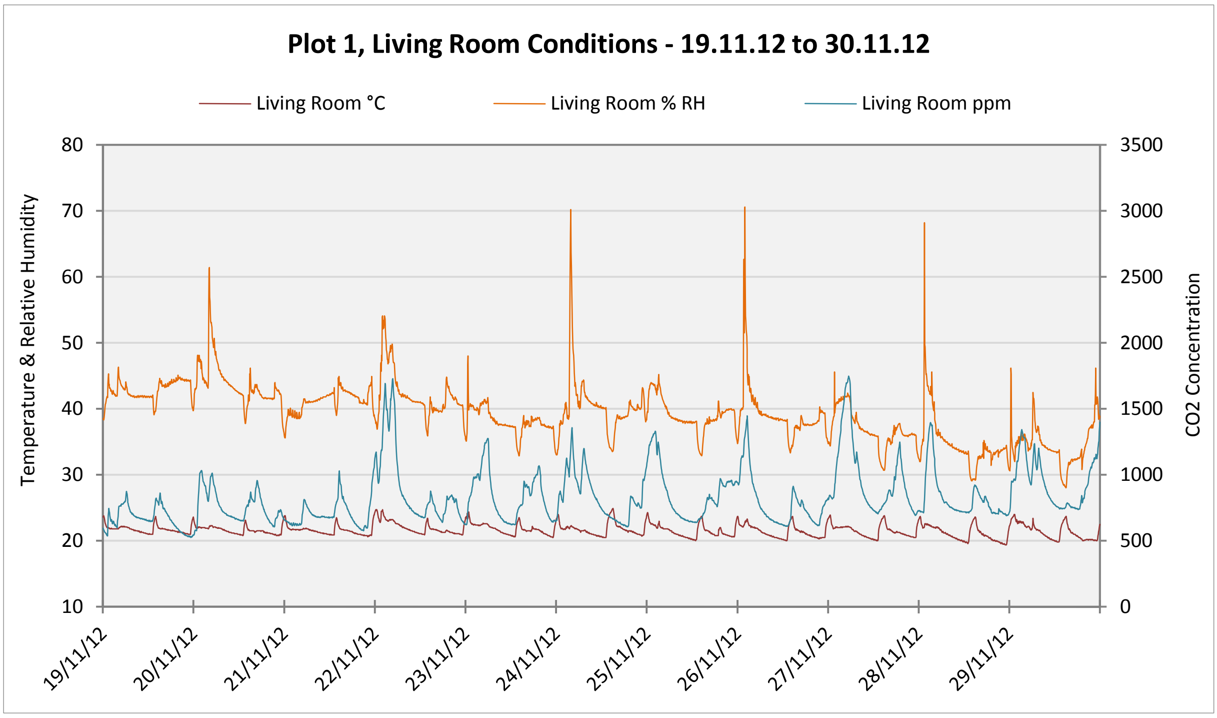

Figure 6.2b. Living room environmental conditions

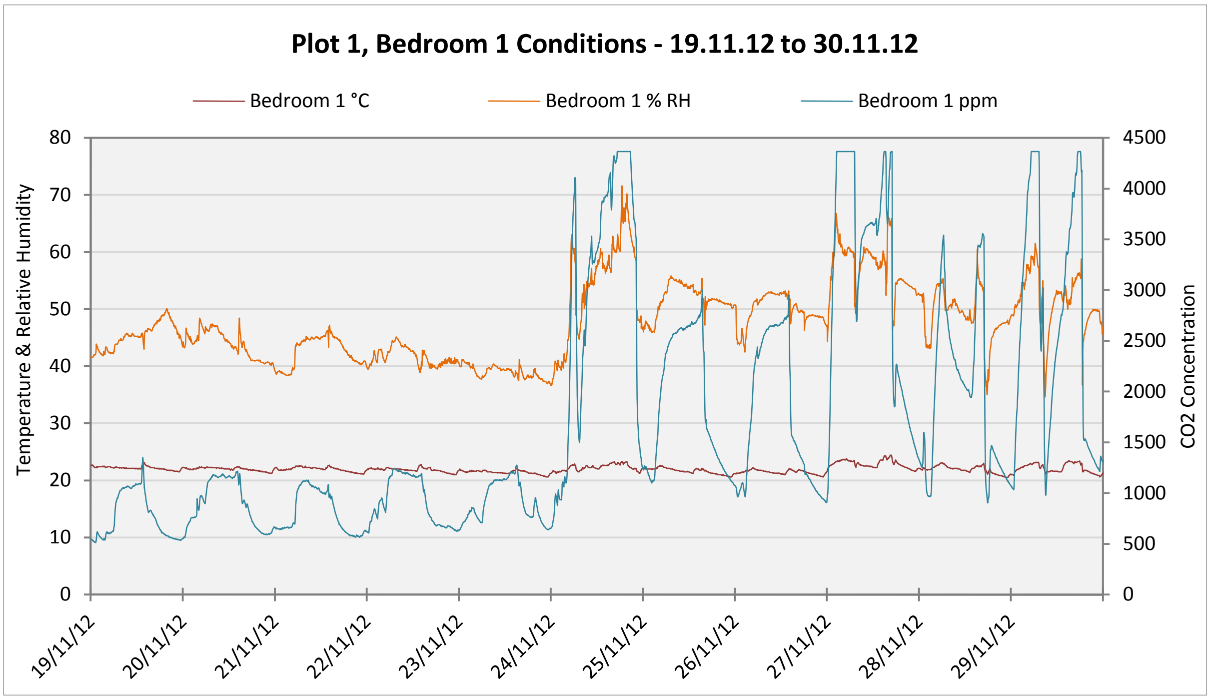

Figure 6.2c. Bedroom environmental conditions

6.3. Case Study 3: Impact of inadequate maintenance

Development: Wimbish Passivhaus

Owner: Hastoe Housing Association

Location: East Anglia

Innovate UK BPE ref no: 450038

6.3.1. Design

This project is a development of 14 social rent/ co-ownership dwellings constructed and certified to the Passivhaus standard. The development comprises of a block of 6 one-bedroom flats, and two rows of 4 houses, comprising 3 three-bedroom and 5 two-bedroom dwellings. The construction is 190mm of thin joint blockwork on a reinforced concrete slab over 400mm of insulation. The walls are clad externally with 285mm insulation, with a 16mm render. Roofs are pitched roof trusses with a dropped chord and 500mm mineral wool insulation laid flat at ceiling joist level. Air tightness is generally provided by a wet plaster system and specialist tapes at junctions; windows and doors are triple glazed. The dwellings generally meet the Passivhaus requirements of 0.6 ach@50 Pa, although one dwelling was 1.2 ach@50 Pa on retest.

A key technology is the use of an MVHR system. The chosen unit is a Paul Focus 200 system, which supplies air via rectangular ducts. The MVHR supplier recommended Lindab push-fit galvanised steel spiral wound ducting to make installation simple, avoiding the need for mastic and taping, and to minimise leakage, however the M&E Sub-contractor chose a less expensive plastic system, employing a mix of 204x60mm low profile rectangular and 125mm ⌀ circular rigid ducts. Duct joints were sealed with mastic and where necessary tape – access was often difficult, making the task time-consuming, and with high risk of a leak. Flexible ductwork was introduced wherever direct alignment was not possible. The flexible duct was not extended, and thus would introduce significant pressure losses. In particular, flexible ductwork was used in connecting to the MVHR unit, and through walls to the supply and extract terminals.

Figure 6.3a. Typical dwellings at Wimbish

Figure 6.3b. Rigid rectangular ducting and flexible ducting to MVHR unit. Panflex acoustic attenuators employed.

6.3.2. Performance

The system was balanced and the room air flows adjusted to the designed levels. This was undertaken at and shortly after handover to the residents, and was repeated on several occasions before acceptable results were obtained. However, in a couple of properties there was a significant disparity between the amount of air exhausted, and the amount extracted from the rooms; this implies a high level of leakage from the ducts. It would seem from the commissioning that the pressure loss in the ducting is very high. This means that the fans, which are constant flow, needed to be set higher to provide the necessary supply and extract air flows; the actual level varying from dwelling to dwelling.

Table 6.3a. Flat flow rates

Flats			Measurements (m^3/hr)											
	Design		Flat 1		Flat 2		Flat 3		Flat 4		Flat 5		Flat 6	
	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}
Living room	35		32		39		37		40		38		30	
Kitchen		40		41		36		34		34		39		51
Bedroom	25		37		25		41		21		33		34	
Shower		20		33		20		30		27		27		25
Sum	**60**	**60**	**69**	**74**	**64**	**56**	**78**	**64**	**61**	**61**	**71**	**66**	**64**	**76**
			V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}
Inlet			71		70		75		69		70		70	
Exhaust				73		71		73		69		66		71

Table 6.3b. Two-bed houses flow rates

Flats			Measurements (m^3/hr)									
	Design		House 8		House 9		House 10		House 12		House 13	
	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}
Diner	10		10		9		15		15		15	
Kitchen		40		44		25		42		42		34
Living room	30		37		31		29		28		34	
WC		20		17		15		20		15		17
Bedroom 1	30		33		38		32		31		25	
Bedroom 2	20		18		21		28		20		25	
Bathroom		30		27		18		30		28		33
Sum	**90**	**90**	**98**	**88**	**99**	**58**	**104**	**92**	**94**	**85**	**99**	**84**
			V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}
Inlet			90		90		101		94		89	
Exhaust				93		90		92		88		91

Table 6.3c. Three-bed houses flow rates

Flats			Measurements (m^3/hr)					
	Design		House 7		House 11		House 14	
	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}	V_{su}	V_{ex}
Diner	15		20		18		13	
Kitchen		65		46		50		58
Living room	40		28		29		39	
WC		25		19		22		22
Bedroom 1	30		35		35		37	
Bedroom 2	20		21		23		20	
Bedroom 3	20		18		23		18	
Bathroom		35		38		40		40
Sum	**125**	**125**	**122**	**103**	**128**	**112**	**127**	**120**
			V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}	V_{AUL}	V_{FOL}
Inlet			120		122		116	
Exhaust				125		119		120

In general, the building performs well, with low running costs and measured performance of the ventilation. For instance, measured CO_2 levels indicated that levels remained below 1,000 ppm for 90% of the time.

A particular area of interest was the performance of the system as judged by three measures:

- The heat recovery effectiveness – what percentage of the heat from the outgoing air is transferred to the incoming air;
- Energy use for the fans and the frost protection heater;
- Effects of filters on air quality and efficiency.

Measurement of the heat recovery system suggested that overall efficiency was generally good, in most months over 80% (It should be noted that the location of the sensors only enabled analysis by the supply air method employed by SAP, and not by the slightly more onerous method specified by the Passivhaus Institute). Figure 6.3d charts the heat recovery percentage month by month for each of the three monitored properties. Note that the Paul Focus 200 unit used has been certified by the Passivhaus Institute at 91% efficient; it seems unlikely that in the real world it would exceed this.

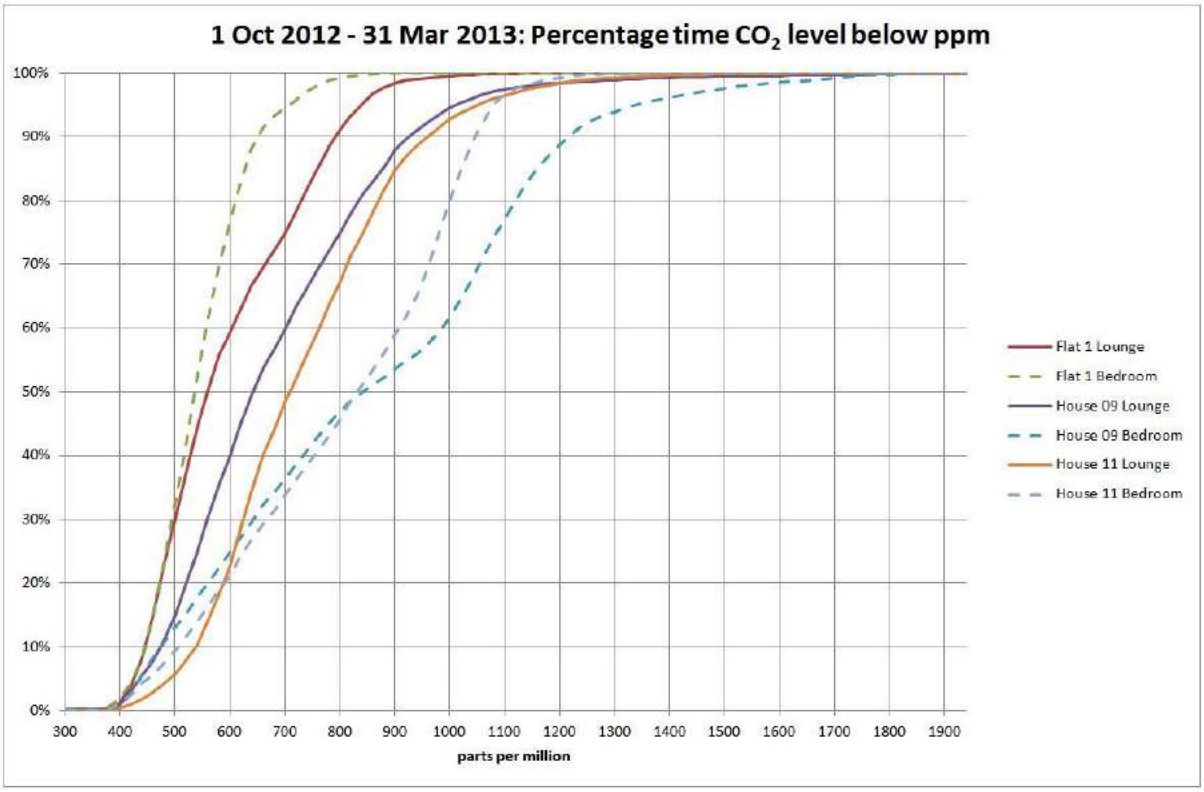

Figure 6.3c. Percentage of time distribution of CO_2 below 1,000 ppm

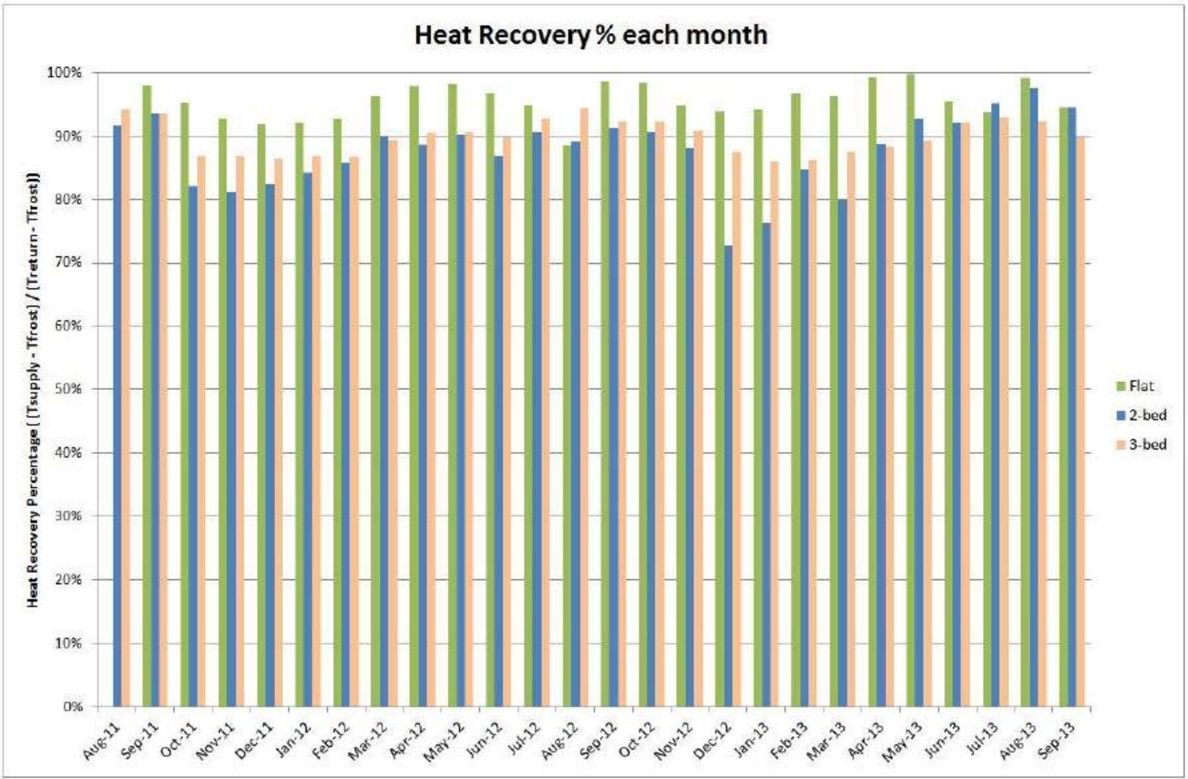

Figure 6.3d Monthly heat recovery efficiency

The other significant issue is the effectiveness of the system is the fan power consumption. The electricity used by the pair of fans in the heat exchange units is a function of the efficiency of the fans, the pressure they are working against, and the volume of the air flow.

The Paul Focus 200 unit employed has a PHI certificate showing a rating of 0.31 $W/m^3/h$, against an allowable Passivhaus limit of 0.4543 $W/m^3/h$. The power consumed in use each day has been monitored in three dwellings. By inspection of these logs a 'normal' low consumption, and a peak consumption, have been established (see Table 6.3c. Fan energy consumption).

The low consumption is the period immediately following a filter change. A typical period was from January to March 2013. Consumption then rises as the filters become blocked – the peak period for the houses was April to May 2012. Note that varying the fan speed from the nominal level 2 (either up to boost or down to absent setting) more than occasionally, would affect the analysis – however, it is understood from interviews (and the data) that these households very rarely change the setting.

Table 6.3c. Fan energy consumption

Property	Commissioned air flow (m^3/hr)	Low consumption		Peak consumption	
		Watts	SFP $W/m^3/h$	Watts	SFP $W/m^3/h$
Flat 1	73	25	0.34	30	0.41
House 9	90	29	0.32	67	0.74
House 11	122	54	0.44	108	0.88

A particular observation from the project was that the fan power consumption varied over time – as the filters became more blocked, energy consumption increased as shown in Figure 6.3f.

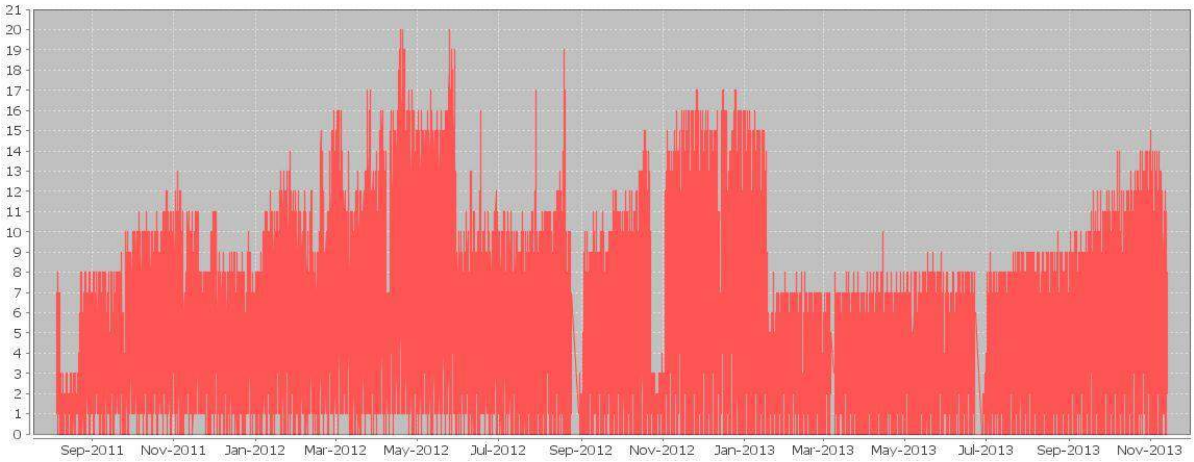

Figure 6.3f. Fan power consumption over time (in pulses).

As the filters become more clogged-up, the fans in a Paul Focus 200 MVHR work harder in an attempt to maintain the required levels of air flow; this consumes more electricity as can be seen in Figure 6.3f. They will become increasingly noisy and ultimately there is a risk of damaging the motors. If the filters are not changed, the fans will eventually reach their limits and be unable to maintain the air flow. A reduced air flow is likely to mean that air quality will deteriorate.

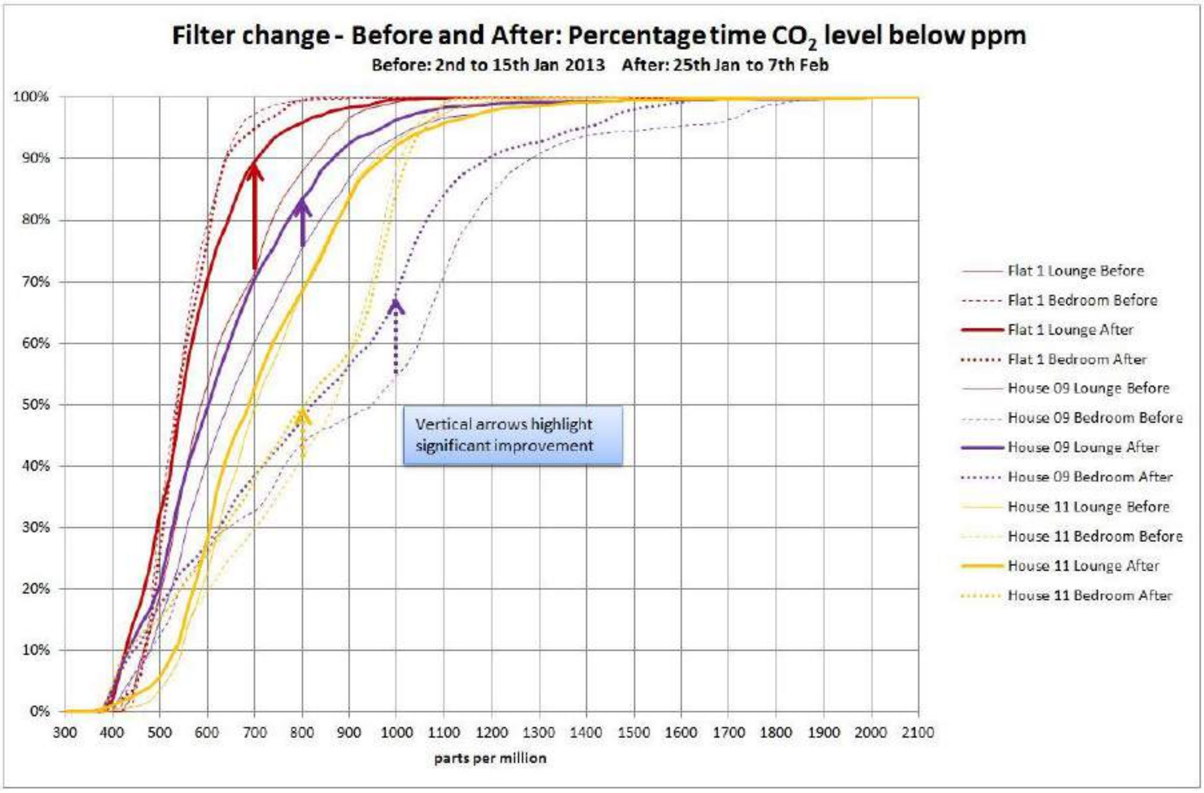

Figure 6.3g. CO_2 levels before and after filter changes

Figure 6.3g shows air quality distribution curves from a fortnight just before the filters were changed (thin line), and a second set from a fortnight after the changes (heavy line). In several rooms, the air quality did seem to have improved, implying that air flows had been reduced by the blocked filters. As the fans are constant flow devices this should not happen until the fans reach their limit. Furthermore, the system will probably become increasingly out of balance, reducing the heat recovery effectiveness and more heat is likely to be lost. In winter the post heater cannot provide as much heat to the dwelling as is needed and the dwelling may cool (especially if the heater is on a timer). These issues are most likely in the three-bed houses where the MVHR, as commissioned, is closer to its peak air flows.

At Wimbish, the MVHR units are located in small ‘plant’ rooms, making access to the filters to change them relatively straightforward. For the tenanted properties, Hastoe provide the service, for the shared owners it is their responsibility.

The study also examined the cost-benefits of filter changes. In the example shown in Figure 6.3h, a normal level of electricity consumption for the unit is 0.8kWh, or about 11p a day or about £40 pa. As can be seen this can double when the filters block.

The air flow is set to 90 m^3/hr. Since the heat capacity of air is 1.2kJ/m^3/K this gives us 0.72 kWh/K of heat lost a day, if there was no heat recovery. Replacing this heat uses gas at about 5p/kWh, and allowing for the efficiency of the boiler means heat costs about 6p/kWh. Thus the cost of replacing the heat lost would be 4.3p per degree per day. But with 85% efficiency the cost of the heat is only 0.65p per degree per day. When the temperature difference is 3 degrees, the saving by having heat recovery is roughly the same as the cost of running the MVHR, and with colder weather, the saving becomes greater.

For those households responsible for replacing the filters themselves the set of 3 plus post and packing costs about £50, and if done twice a year (as seems highly desirable), this adds 27p a day to the running costs. The cost of filters is an impediment to shared owners, as is inertia and simply ‘not getting round to it’.

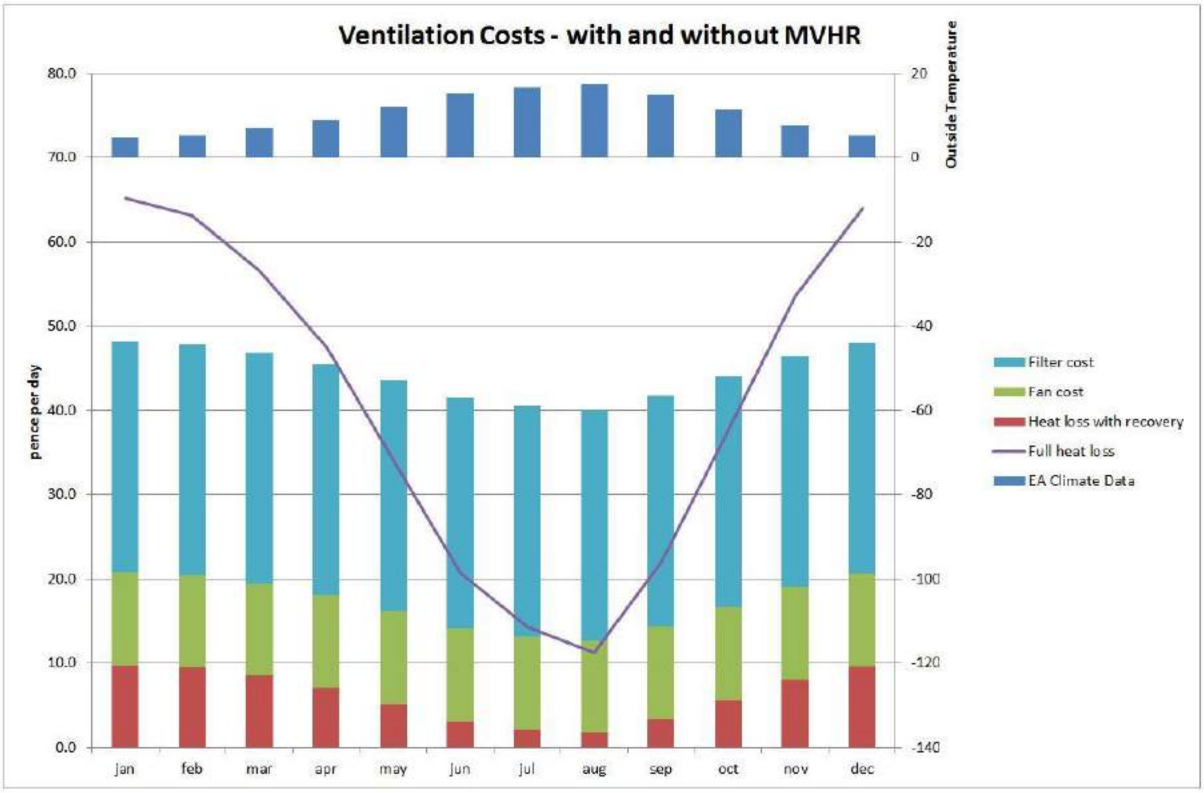

Figure 6.3h. MVHR ventilation costs

A comparison of the cost of replacing lost heat simply by ventilating the house with no heat recovery ('full heat loss') against the costs of employing mechanical ventilation with heat recovery is shown in Figure 6.3h. Ignoring the filter costs, the MVHR is cheaper every month but August; however when the filter cost is added, the MVHR is only cheaper half the year, and, considering the year as a whole, is slightly more expensive. It should be noted that this analysis ignores the personnel costs of the filter replacement (or cleaning) if undertaken by the Housing Association.

Ventilation without heat recovery can be achieved naturally by opening windows. This, however, runs the risk of either under-ventilating, resulting in poor air quality that can lead to health concerns, or of over-ventilating where extra heat will be lost and need to be replaced. Achieving the desirable ventilation balance (when not employing heat recovery) would probably be best achieved by use of a continuous mechanical extract ventilation system. Employing MEV would add to the costs, both in terms of the electricity required, and need for some maintenance.

It would clearly be more cost effective to have a cheaper filter system, either for the replacement filters, or for cleaning the filters, so long as the air quality was not reduced – for example washable filters may be worse at removing particulates from the air and thus the building would not deliver some of the health benefits (for example to asthma or hayfever sufferers).The analysis suggests that for this system it would be more cost effective to either turn down the MVHR to level 1 in the summer, or even to turn it off, to reduce the rate at which the filters clogged – and then to ensure windows are opened to provide fresh air.

Along with this, it is desirable that the system alert the householder when the filters need replacing, so that they are not changed too late, or too early. Preferably, the alert would be built into the unit; it could be triggered by a change in fan energy use, or change in pressure.

6.3.3. Summary

The heat recovery performance is in the range of 85-90% most of the time, close to expected levels. There is the suggestion that the recovery might be a little less (about 5%) in cold weather. It can fall even further, 15% or so, when the filters need replacing. With fresh filters, the smaller properties operate at an SFP (specific fan power) close to specification. The 3-bed property was not as efficient, because the fan was operating at a higher load. As the filters block, the fans work harder to maintain the air flow, becoming less efficient.

The filters do an important job, but once they reach a certain level of blockage there are a number of consequences including increased energy use, greater heat loss, reduced air quality and impaired ability to deliver heat. The cost of replacement filters each year is about double the cost of electricity used. Over a year, the costs are roughly in balance with the value of the heat recovered, only during the winter months is the system ‘in profit’. Of course, we must bear in mind that the quantity of heat required has been hugely reduced by the Passivhaus, for which we need ventilation. Having saved several hundred pounds a year on heating, we should not quibble over spending a small portion of this on providing fresh, healthy air.

Heat recovery performance is impacted by the insulation of the intake and exhaust ducts; these must be as well insulated as the walls of the building. The frequency of filter change, and triggers for doing so, should consider the risk of reduced heat recovery performance. The cost of running the fans must also be considered when accounting for the saving from recovering heat which otherwise would be lost. Selection of efficient fans is important - consumption at Wimbish has cost from £30 pa in the flats and up to £90 pa in a 3-bed house.

Design to minimise pressure losses in the systems is important to enable fans to work at the lowest possible load. It is believed that those at Wimbish have higher losses than they ought. It is vital that the filters do an efficient job without imposing excess load on the system. They must be easy to replace, and at the same time only require changing infrequently and at relatively low cost. There should be a means for the householder to be made aware that a change is needed. Meeting all these conflicting requirements is not easy.

Perhaps the ideal would be to size filters such that they could be used for 12 months, with a ‘service’ of the MVHR being conducted at the same time as another annual service, for example of the boiler.

7. Conclusions

7.1. Observations from the study elements

With 29 out of 53 domestic projects using MVHR it is clear that this is an increasingly widespread system in new energy efficient homes. For some construction approaches, particularly Passivhaus, it is standard practice. For houses built to the Code for Sustainable Homes (CSH) standard, MVHR was also frequently used. Given the existing drivers for reducing energy and increasing airtightness, and emerging issues such as indoor (and to some extent external) air quality, it would seem likely that a solution that can provide good levels of ventilation, whilst providing heat recovery will continue to be an important component in contemporary low energy homes.

Within the construction industry emerging issues around the use of MVHR have raised concerns about its viability, particularly in certain tenure types. For example, the possible costs and overheads of on-going maintenance have been identified by some housing associations as barriers to widespread use. The discontinuation of CSH and delay of Zero Carbon standards may also affect its more mainstream adoption.

Within this study a number of problems and issues were also encountered and this is evidenced both from the characteristic data, and also the feedback from designers and occupants. These included lack of appropriate airtightness, lack of complete commissioning, poor air flow and extract rates (and associated lack of compliance with regulatory standards), lack of balance and inappropriate duct types.

There was a lack of consideration of key issues at design and construction stages, including the function of the system, integration into the design, quality of installation and commissioning, control systems, and occupant guidance and understanding.

Despite these issues, the performance data suggests that overall the use of MVHR systems can result in better levels of ventilation in comparison to naturally ventilated houses. The average CO_2 levels were reasonable; both average and peak levels were lower; and the environmental data suggests that more consistent temperature and relative humidity was achieved in dwellings with MVHR systems.

There are a number of important caveats to these observations. Firstly, there is evidence to suggest that natural ventilation strategies and lack of occupant engagement with these may lead to unsatisfactory levels of ventilation. Secondly the comparison ignores a number of important factors such as construction, occupied volume and intensity. A significant proportion of the MVHR houses were built to Passivhaus standard, although it is noted that comparison of these and non-Passivhaus projects did not reveal any significant difference in environmental conditions.

Whilst it may be a reasonable expectation that a house with a constantly running mechanical ventilation system can deliver better air change rates - and the performance data suggests that this stabilises internal environmental conditions - a significant question remains as to what conditions occur when the system has sub-optimal air flow or is not in use. It is apparent that within the general trends there are some outliers in which environmental conditions in houses with MVHR are very poor – this may be due to a poorly performing system, but the likelihood is that the system is disabled.

Indeed the feedback from design teams and occupants indicated a number of instances where systems were turned off. In some cases this was unplanned, for example due to lack of knowledge, or concerns about noise or running costs, but in other cases it was expected behaviour, for example systems being turned off in summer and/or frequent window opening. Whilst it may be argued that use of window opening and natural ventilation can and should be used in certain situations, the means to provide background levels of ventilation in locations where window opening may be less prevalent or desirable – for example urban locations where noise, security or pollution may be problematic - is generally not considered.

This also raises questions about the optimal way to use such systems. Evidently with reasonable flow rates and correct balance leading to high heat recovery efficiencies, good energy savings may be made. However it is not clear what effects sub-optimal performance and the exact energy benefits (and costs) of the MVHR have been hard to identify. Whilst there may be good coefficients of performance in cold weather, these will diminish as temperature differences reduce, and there will be a net cost for running an MVHR system in the summer. The airtightness of a house with some windows open is much lower, decreasing the efficiency. Overall costs also need to factor in filter changes and maintenance. The energy penalties of systems being out of balance needs to be further examined. It may be that the impacts are relatively small, particularly in situations where less heat may be recovered, and justifiable in the context for better ventilation.

In spite of these uncertainties, the comparison of energy use between MVHR and non-MVHR houses is very clear. In general, houses with MVHR systems had lower energy consumption. Again, it is important to acknowledge the caveats here and in this case the predominance of Passivhaus dwellings is likely to have a bigger impact on energy consumption. Whilst a comparison of the average energy consumption of Passivhaus/non-Passivhaus suggests that the former has lower energy use, the sample size is small and there are significant outliers.

Primary consideration of energy benefits at design stages tends to ignore the principal purpose of an MVHR system, which is to provide good ventilation to homes. This omission seems to be commonplace where systems are selected to assist with energy compliance, as a result of which the importance of ventilation can be forgotten. Flow rates for houses and in particular individual rooms need to be considered. It is apparent that some individual rooms have very low flow rates – whilst overall rates from the unit may be appropriate for the house size, in many cases air is being oversupplied to empty rooms and undersupplied to well used rooms, and extract rates from some wet rooms insufficient to control moisture.

It is clear that MVHR are not fit-and-forget systems. A constantly running mechanical system will require regular maintenance, and the requirement for filter cleaning or replacement is a significant issue and requires consideration of the location of the unit, the type of filters, who will maintain them, and the frequency. A particular issue is that the consequences of underperformance are not immediately obvious to users. A comparison may be made between a central heating system where any type of failure is immediately obvious and will lead to repair. The failure modes of MVHR systems are less apparent – occupants are generally unaware of perceptions of poor indoor air quality, and this was borne out in the examination of the BUS studies.

For any domestic system, the proper understanding and interaction of occupants is critical. Lack of knowledge about the nature and control of MVHR systems is likely to lead to poorly used or disabled systems. Whilst there are examples of good handover processes, this is not yet commonplace, in part at least because the understanding of the nature and performance of the system is not clear amongst designers, landlords and contractors. The system also needs to not cause nuisance to occupants in the form of noise or draughts.

The overall picture that emerges from this study is that whilst there are some demonstrable benefits of MVHR systems, both in terms of ventilation and energy use, there are a number of significant risks. The tendency is for the construction industry is to take a low risk approach and to avoid, rather than to solve problems. In the context of the removal of CSH and Zero Carbon targets, it would be tempting to conclude that the risks outweigh the benefits. However the ability to provide good ventilation without consequential heat loss is an important goal in modern housing, and its use in high performing standards such as Passivhaus require continual development and improvement. There are emerging issues, for example urban locations where pollution or noise may mitigate against window opening, where MVHR systems could have important benefits for health and well-being. It is therefore important that the insights gained from this study are used to improve standards and practice.

7.2. Implications for practice and policy

Whilst there has been some useful practice guidance[18] on how to improve standards for the design and installation of MVHR systems, further mechanisms are needed to improve the implementation of MVHR systems in housing. Areas for improvement include design, installation, usability and maintenance.

7.2.1. Design

Design requirements for MVHR are key. Poorly conceived and designed systems are difficult to install, difficult to maintain and difficult to use. The need for systems to be correctly selected, specified and designed could reduce many subsequent issues.

Particular considerations include:

- The selection of the ventilation strategy at early design stages and where MVHR is used, consideration of the impacts this has on layouts. Selection should not be for energy considerations alone. There may be other important reasons why and MVHR system could be beneficial, for example in urban areas with higher levels of pollution;
- The required in-use performance of the unit in terms of both energy and ventilation, taking into account the location of the project and the nature of the occupancy and tenure;
- The unit location in terms of ease of installation, and subsequent maintenance regime. For example likely frequency of filter changes in areas of higher pollution;
- The layout position and type of ductwork and inlets to provide good flow rates, ease of installation, minimal noise, maintenance and repair, and placement and types of outlets;
- Consideration of modes of use and how it is intended to be used by occupants, particularly under varying patterns of occupancy, season and external conditions, including how the system will be controlled;
- Consideration of the interaction with other factors, such as windows, other mechanical systems, and heating provision.

7.2.2. Installation

Problems of installation and commissioning are common and need to improve. The study found a lack of Building Regulation compliance to be commonplace, and this is a cause for concern, particularly given the potential health impacts of under-ventilation. It is clear that a more rigorous commissioning and compliance checking

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[18] Zero Carbon Hub (2013) *Mechanical Ventilation with Heat Recovery in New Homes - Final Report* [http://www.zerocarbonhub.org/sites/default/files/resources/reports/Mechanical_Ventilation_with_Heat_Recovery_in_New_Homes_Final%20Report.pdf]

regime is needed which may lead to increased onsite inspections by building control, but also warranty providers.

There is a need for improved skills in the construction industry. One of the observations is the different trades that might be involved in the installation of a system, including plumbers, joiners and electricians, and there is a lack of oversight at installation stages. Although some improved guidance is available (for example NHBC Standards Chapter 3.2 'Mechanical ventilation with heat recovery', further improvement is needed, for example protection of ductwork during construction and on-site inspection to ensure compliance with these standards.

The study found some issue with commissioning tests, and more rigour is required to ensure that such tests are undertaken to required standards. An issue arising with commissioning is subsequent interference with room supply air terminals, for example to reduce air movement. This may be addressed by having vents which can be locked or marked in place; better occupant guidance about the nature of the vents; or alternative (or variable) flow regulation systems. This may be important when considering variable flows such as demand led systems relying on CO_2 or RH sensors.

Ultimately however, building producers are responsible for ensuring that buildings comply with regulations and standards, and that there is a liability if these are not met. Given the potential health effects of environmental conditions, greater awareness is needed of the effects of poor performance and a greater understanding of the risks.

7.2.3. Usability

A critical element is ensuring firstly that there is clear understanding of the nature of the system and how it is supposed to be used by the procurement team, and secondly that robust mechanisms are in place for ensuring that occupants are given clear guidance in how to operate the system. Processes need to be available not just at early occupancy, but during changes in ownership or tenancy.

7.2.4. Maintenance

Finally, a planned, legible maintenance regime will be needed for any house that has an MVHR system. For home owners this is an important aspect of the handover process. For tenanted properties, the landlord will need to evaluate who will be undertaking this maintenance, how frequent it will be, what access requirements are, and what the costs of this will be.

7.3. Future work

Whilst the study has been able to make a number of useful observations and comparisons of MVHR systems, a great deal remains unknown. Key areas for further work include:

Effects on health – whilst relationships between health and ventilation are well-established, robust data on actual effects on health of varying ventilation strategies are limited. Further study is needed on effects on occupant health, comparison of indoor and external pollutants, off gassing from ducts, effects of leaks within systems and pollutant source control.

Long term viability, reliability and performance – there has been very little work that has looked at the longitudinal performance of systems. Do they change or decline over time, are they reliable, what levels of maintenance are undertaken and what are the costs and effects of these?

Energy balance and coefficients of performance, including filter occlusion – further work is needed to quantify the energy benefits of MVHR systems under a range of varying conditions, in practice. These may include different seasonal and climatic scenarios, sub-optimal performance, energy and ventilation effects of filter occlusion, and window opening.

Flow rates – examination of desirable flow rates for rooms to achieve moisture control, good indoor air quality, removal of pollutants, variable flow and demand control systems.

Duct and delivery systems – whilst there have been advances in duct system, further work to improve duct performance in relation to better installation, integration, insulation, sealing, noise reduction; and also mechanisms to deliver air into rooms that maximise comfort and reduce noise and unwanted air movement.

Filter standards - effects of different filter types on: filter life; energy consumption; and pollutant screening.

Alternative systems – are there alternative systems than can maintain ventilation rates and reduced ventilation energy losses. This might include localised MVHR, overflow systems, hybrid and mixed mode systems, demand control and flow control.

8. Appendices

8.1. Appendix A: Common shortcomings of MVHR systems[19]

Common MVHR Shortcomings	Reference(s)
Specification	
Wrong type of fan installed	(DCLG, 2008; Dorer and Breer, 1998)
Poor manufacturing of components	(Dorer and Breer, 1998)
Lack of summer by-pass function	(Balvers et al., 2012)
Poor control interface/ occupant inadequate control	(Aizlewood and Dimitroulopoulou, 2006; Mlecnik et al., 2012; Schnieders and Hermelink, 2006)
Installation	
Inadequate adjustment of control settings	(Balvers et al., 2012)
Failure to insulate ductwork	(DCLG, 2008)
Failure to securely affix fan	(DCLG, 2008)
Deviations from design	(Sullivan et al., 2012; Turner et al., 2013)
Failure to connect ductwork to outside terminal	(DCLG, 2008)
Supply/extract ducts installed wrong way around	(Lowe and Johnston, 1997; Taylor and Morgan, 2011)
Supply/extract vents too close (short circuiting)	(Balvers et al., 2012)
Outside supply/extract vents too close together- recirculation of exhausted air	(Balvers et al., 2011; Mlecnik et al., 2012)
Pollutant sources within 2m of supply grill	(Hill, 1999)
Poor sound installation/ silencers not installed properly	(Balvers et al., 2012)
Over-use of flexible ducting (bends in ductwork)	(Balvers et al., 2012; Sullivan et al., 2012)
Contamination of ductwork during construction	(Balvers et al., 2012)
Leaky joints	(Balvers et al., 2012)
Air supply and/or extract vents not locked in place/ marked; wrong vents used	(Balvers et al., 2012)
Insufficient gradient on condensate drains	(Lowe and Johnston, 1997)
Lack of traps (condensate tubes)	(Hill, 1999)
Commissioning	
Insufficient and/or inaccurate commissioning	(Dorer and Breer, 1998; Lowe and Johnston, 1997; Sullivan et al., 2012)
Maintenance	
Inadequate access for cleaning	(Dorer and Breer, 1998; Sullivan et al., 2012)
Insufficient changing of filters	(Dorer and Breer, 1998; Hill, 1999)
Lack of dedicated trade body/ accredited training for servicing/installation	(Bone et al., 2010; Schnieders and Hermelink, 2006)
Occupant Knowledge/Use	
Inadequate occupant knowledge of ventilation system	(Aizlewood and Dimitroulopoulou, 2006; Hill, 1999; Leech et al., 2004)
Occupant(s) turning system off altogether or at certain times of the year	(Aizlewood and Dimitroulopoulou, 2006; Leech et al., 2004; Offermann, 2009)
Tightening/blocking of supply/extract vents	(Leech et al., 2004)
Inadequate use of 'boost' mode	(Schnieders and Hermelink, 2006)
MVHR system operated in lowest setting	(Schnieders and Hermelink, 2006)
Performance	
Problems with noise, particularly in bedrooms	(Bone et al., 2010; van der Pluijm and Jeffry, 2010)
Thermal comfort, perceived draughts, overheating	(Balvers et al., 2012; Offermann, 2009)

[19] McGill et al., 2015, *Indoor air quality investigation in Code for Sustainable Homes and Passivhaus dwellings, World Journal of Science, Technology and Sustainable Development*, 12(1):39-60

8.2. Appendix B: Carbon dioxide

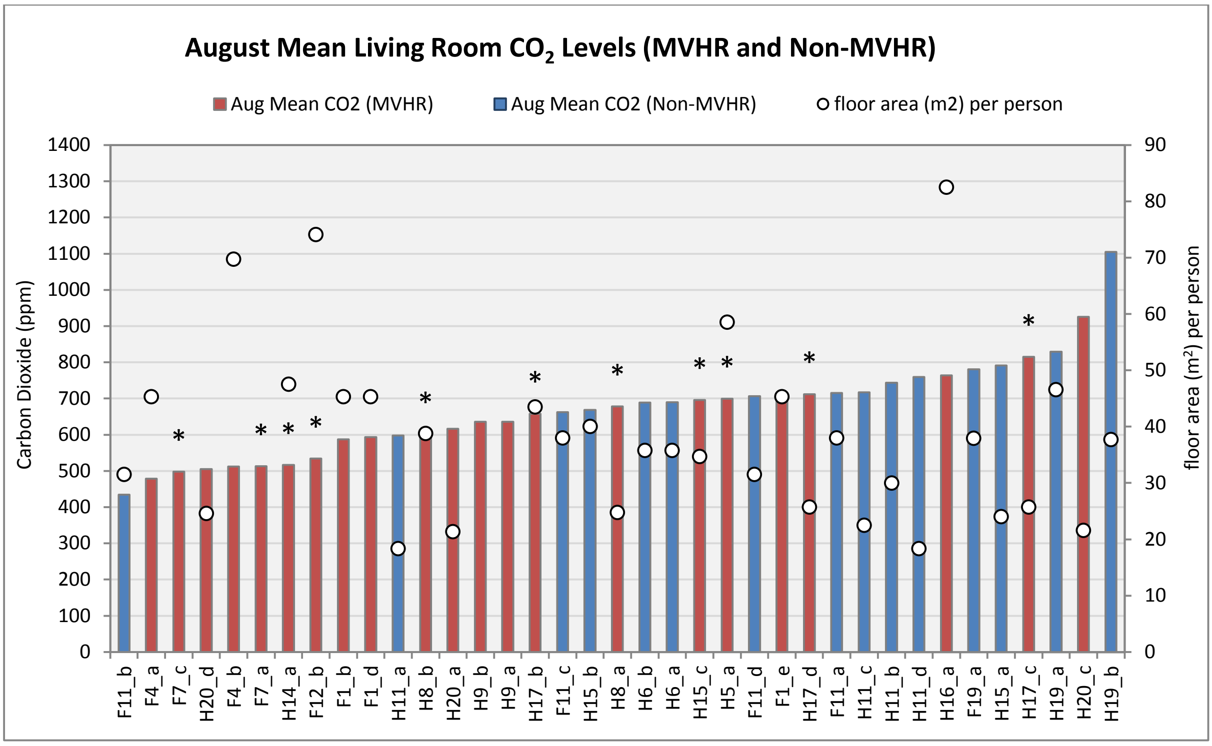

Figure 8.2a. August average living room CO_2 levels in MVHR and Non-MVHR homes

** Passivhaus dwellings*

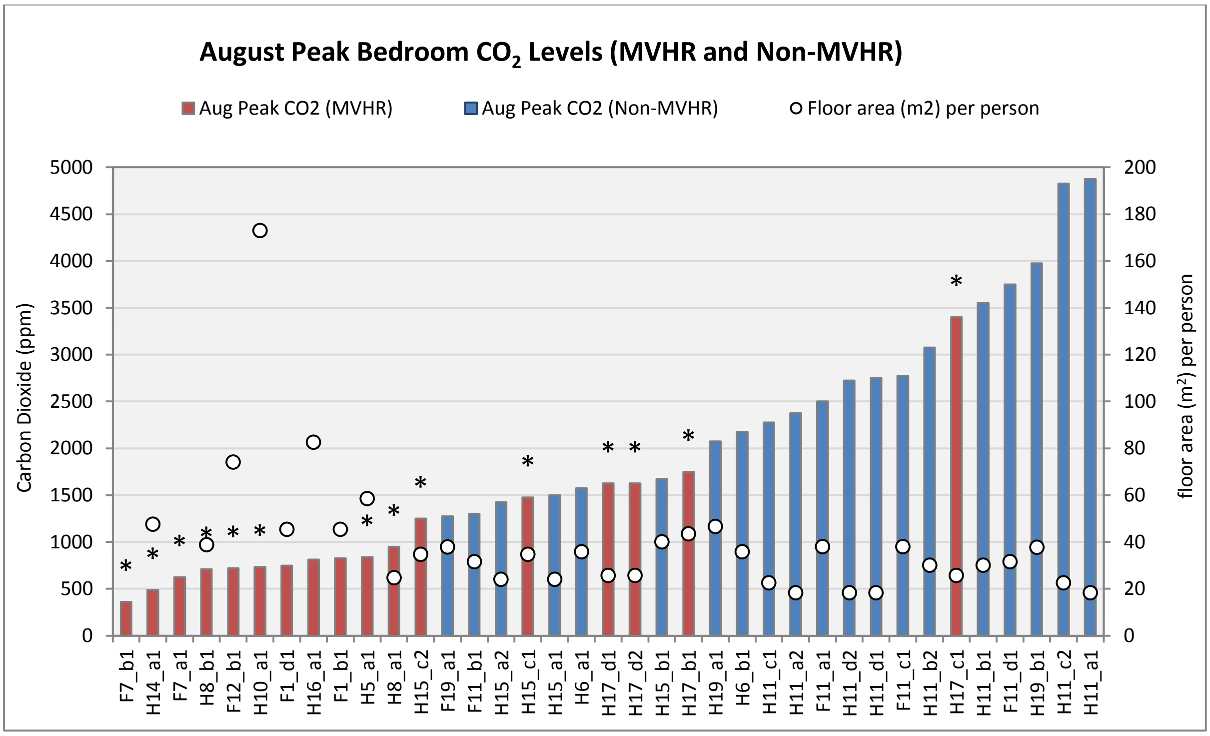

Figure 8.2b. August Peak Bedroom CO_2 levels in MVHR and Non-MVHR homes

** Passivhaus dwellings*

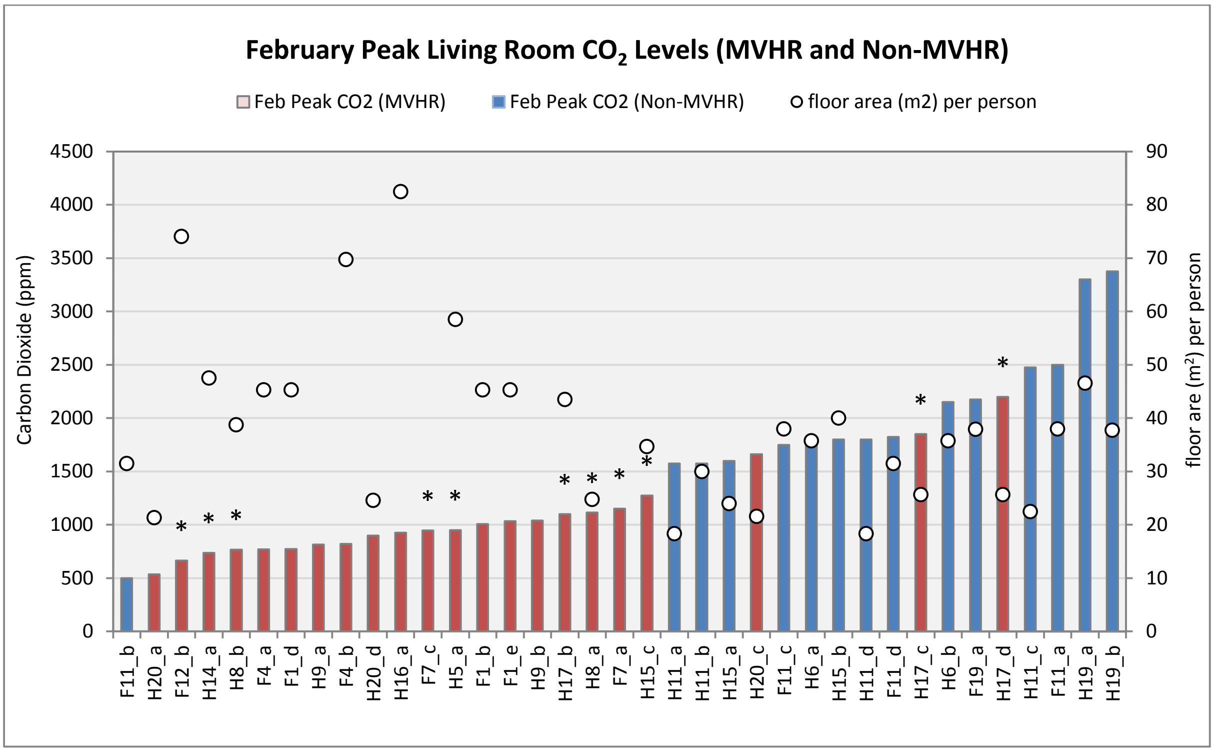

Figure 8.2c. February peak living room CO_2 levels in MVHR and Non-MVHR homes
** Passivhaus dwellings*

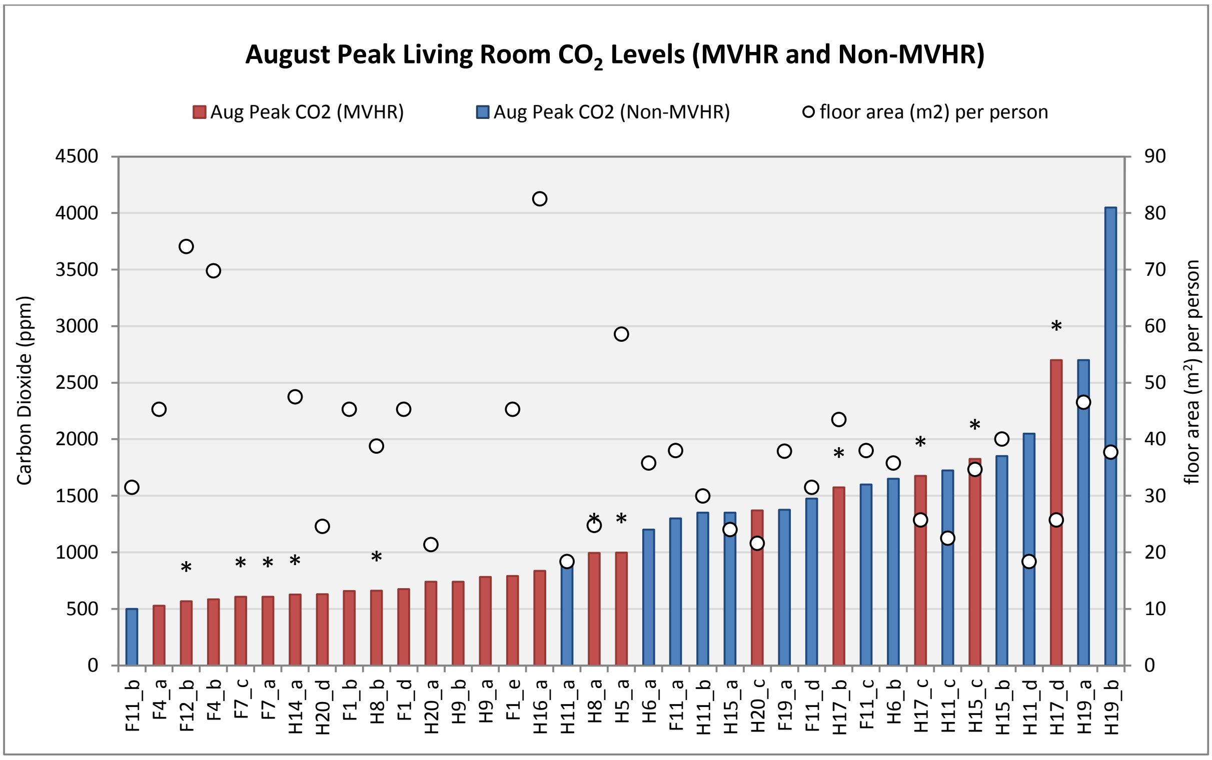

Figure 8.2d. August peak living room CO_2 levels in MVHR and Non-MVHR homes
** Passivhaus dwellings*

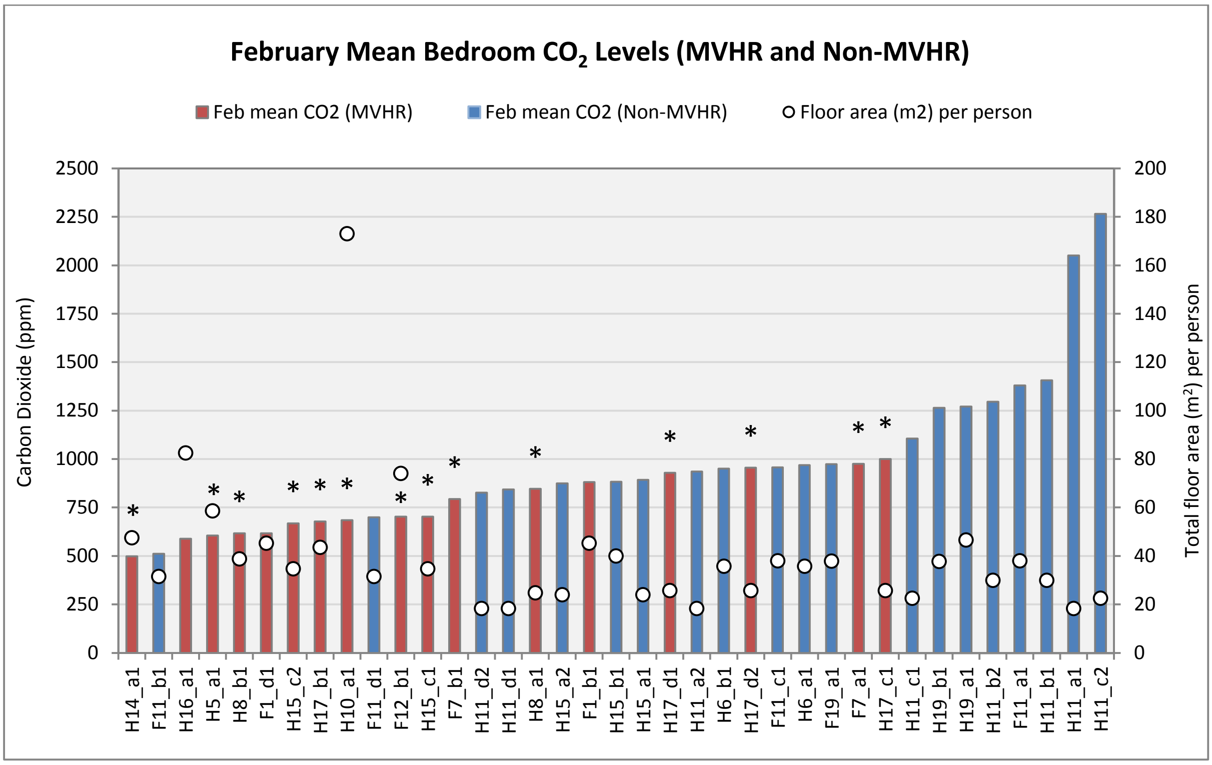

Figure 8.2e. February mean bedroom CO_2 levels in MVHR and Non-MVHR homes
** Passivhaus dwellings*

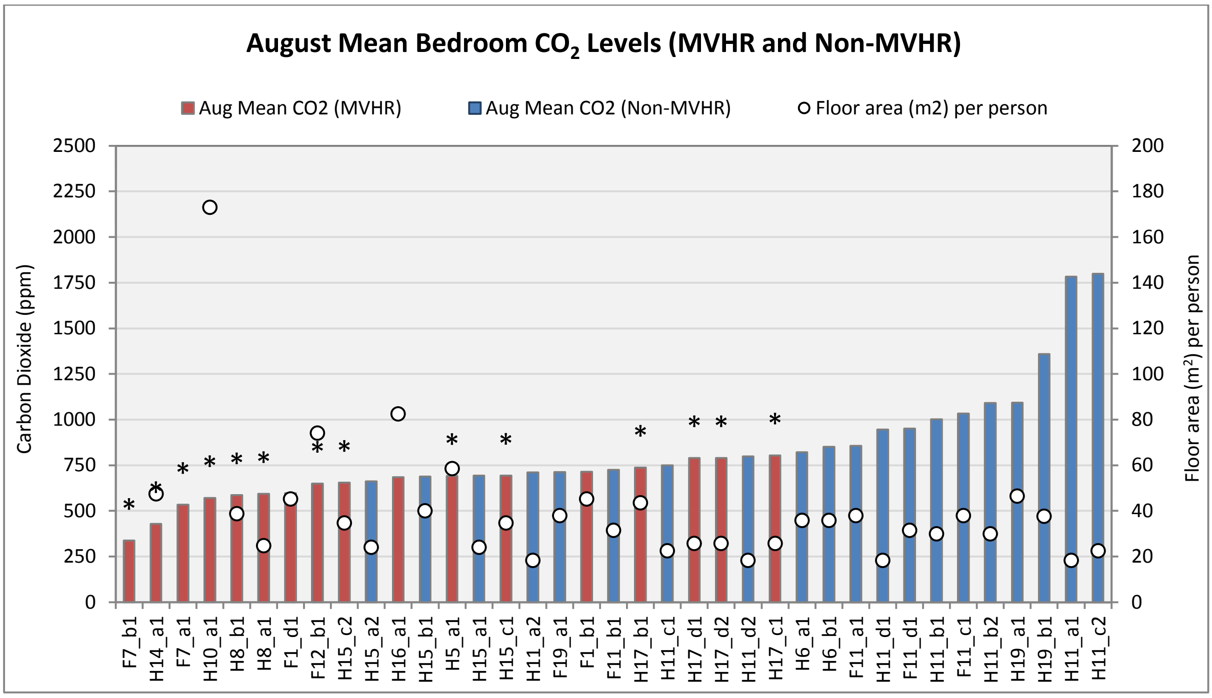

Figure 8.2f. August mean bedroom CO_2 levels in MVHR and Non-MVHR homes
** Passivhaus dwellings*

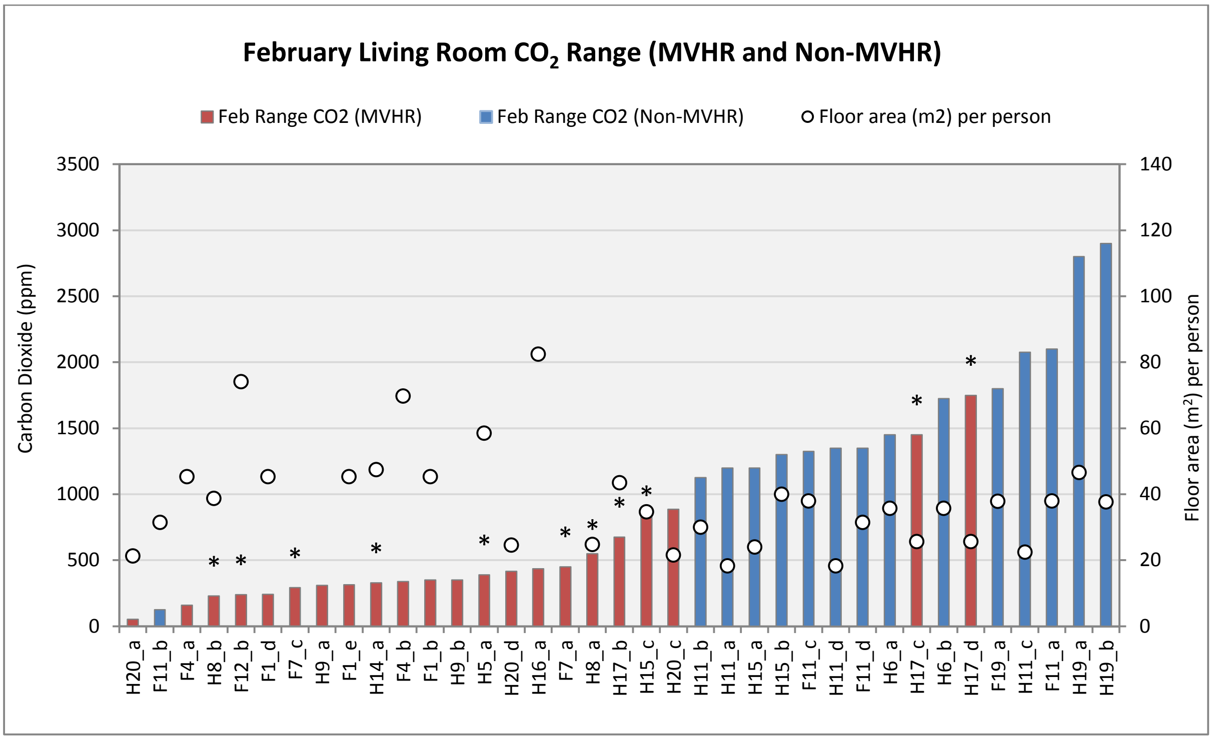

Figure 8.2g. Range of living room CO_2 levels in February in MVHR and Non-MVHR homes
** Passivhaus dwellings*

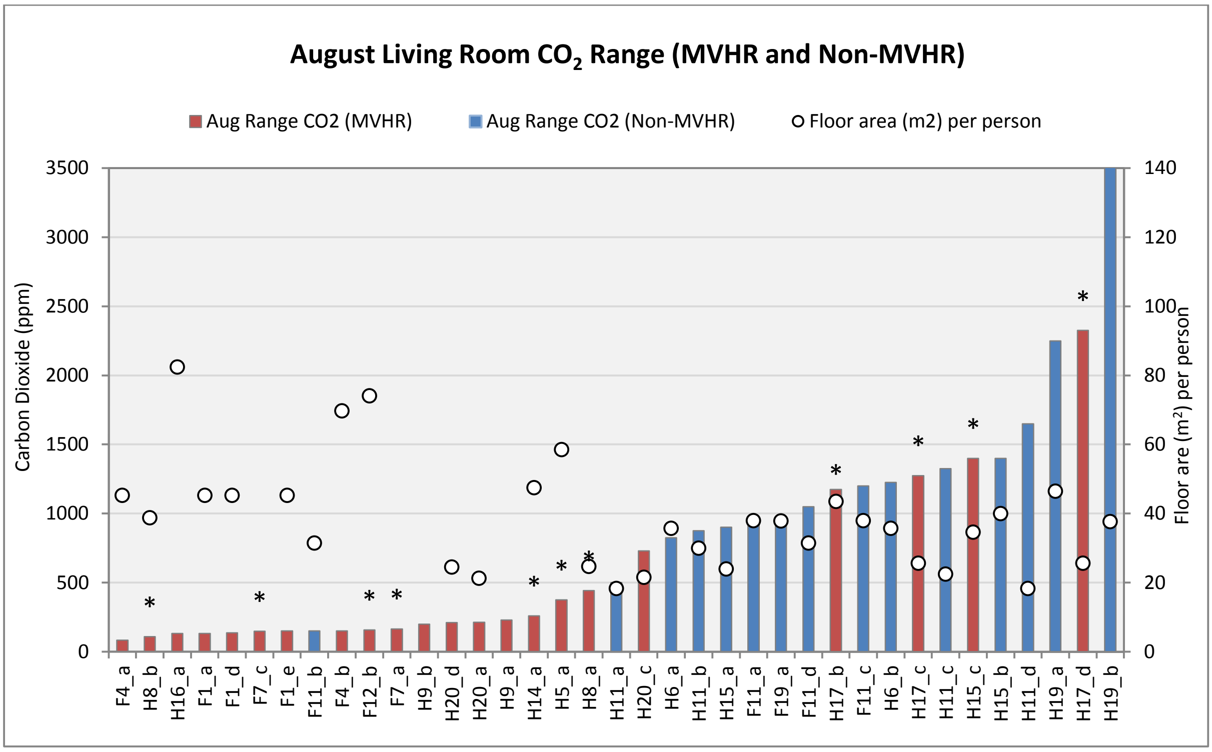

Figure 8.2h. Range of living room CO_2 levels in August in MVHR and Non-MVHR homes
** Passivhaus dwellings*

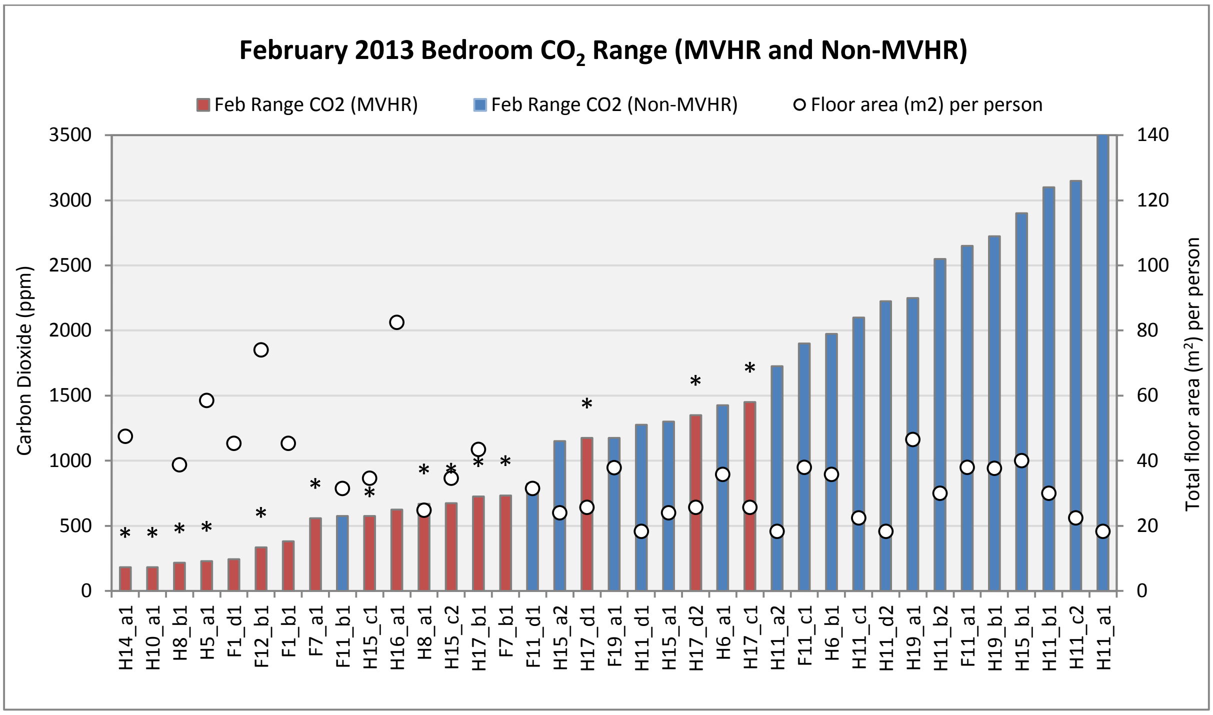

Figure 8.2i. Range of bedroom CO_2 levels during February in MVHR and Non-MVHR homes
** Passivhaus dwellings*

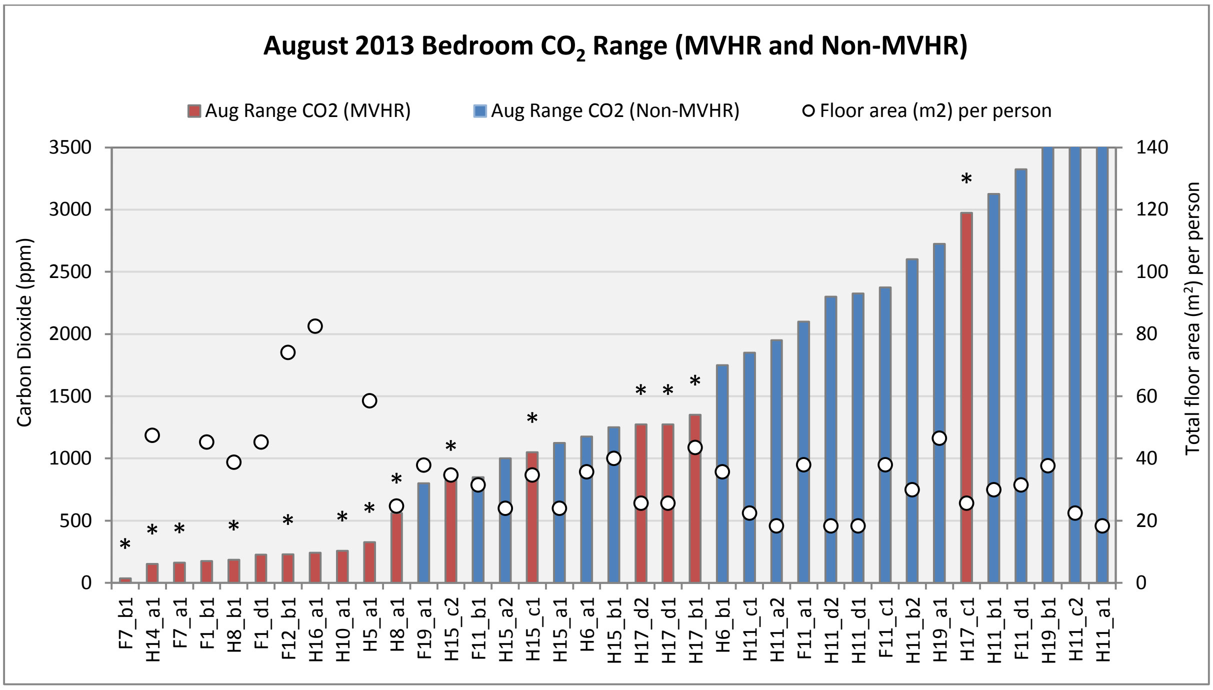

Figure 8.2j. Range of bedroom CO_2 levels during August in MVHR and Non-MVHR homes
** Passivhaus dwellings*

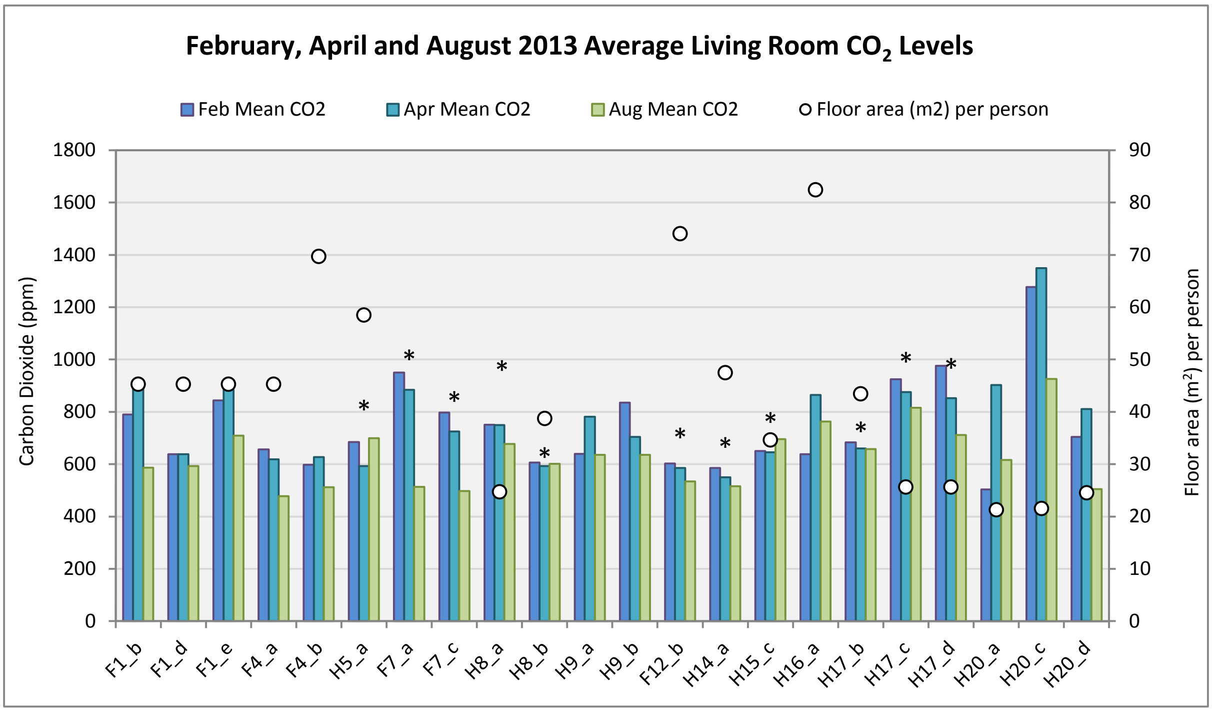

Figure 8.2k. Average living room CO_2 levels in MVHR homes

** Passivhaus dwellings*

8.3. Appendix C: Relative Humidity

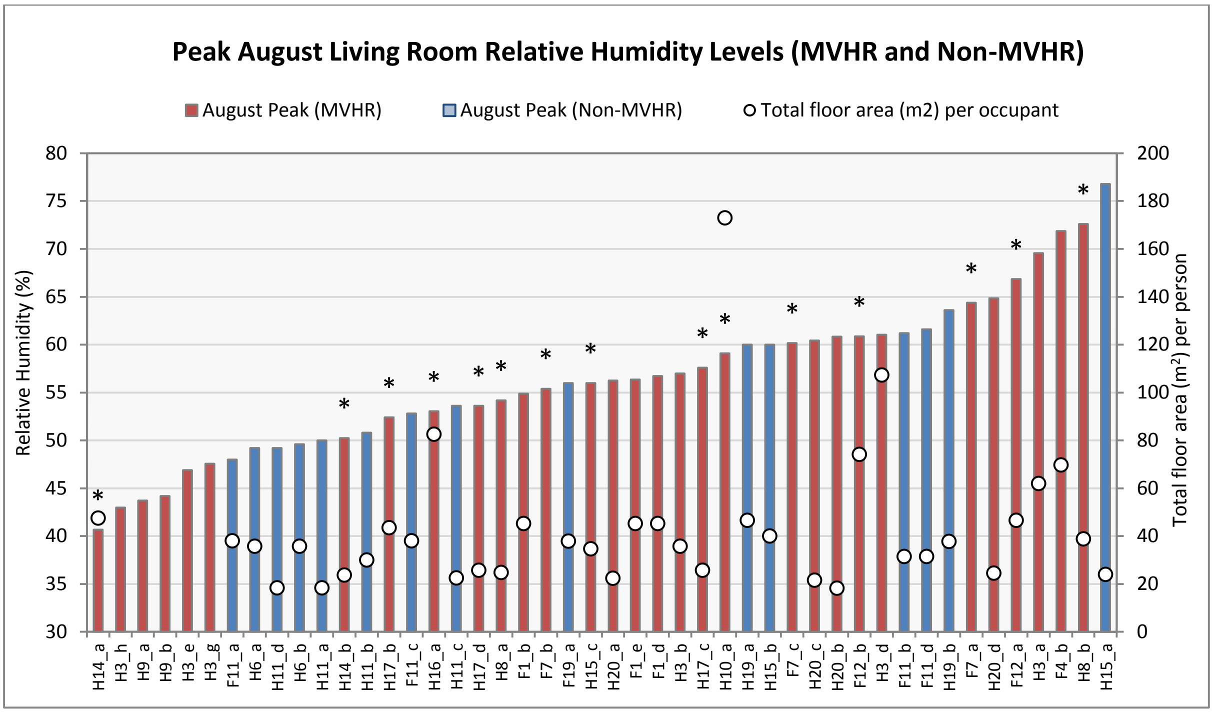

Figure 8.3a. Peak August bedroom relative humidity levels
** Passivhaus dwellings*

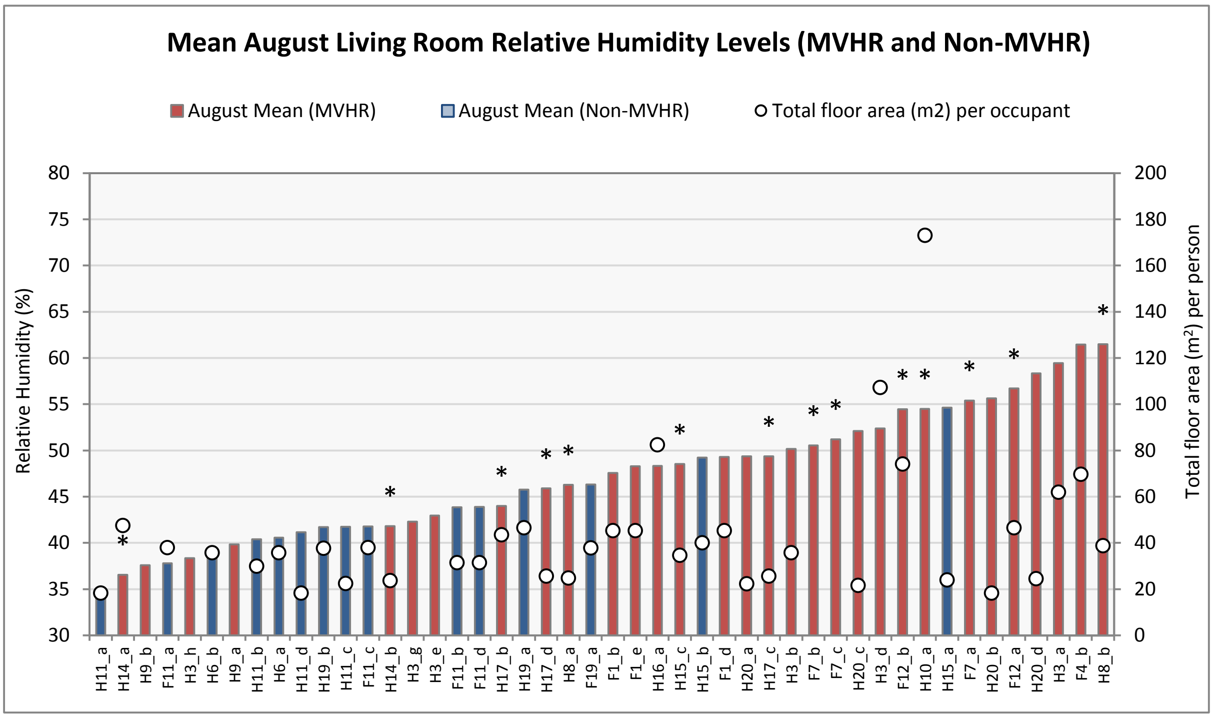

Figure 8.3b. Mean August living room relative humidity levels
** Passivhaus dwellings*

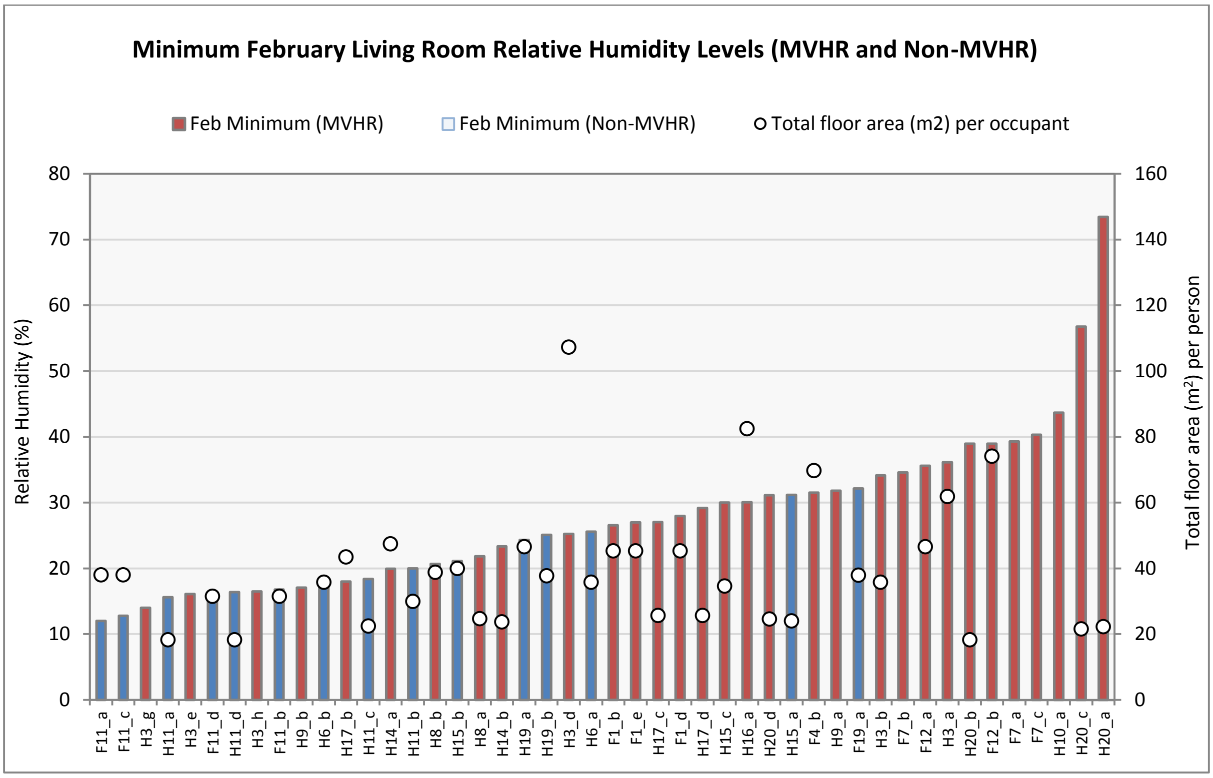

Figure 8.3c. February Minimum living room relative humidity levels

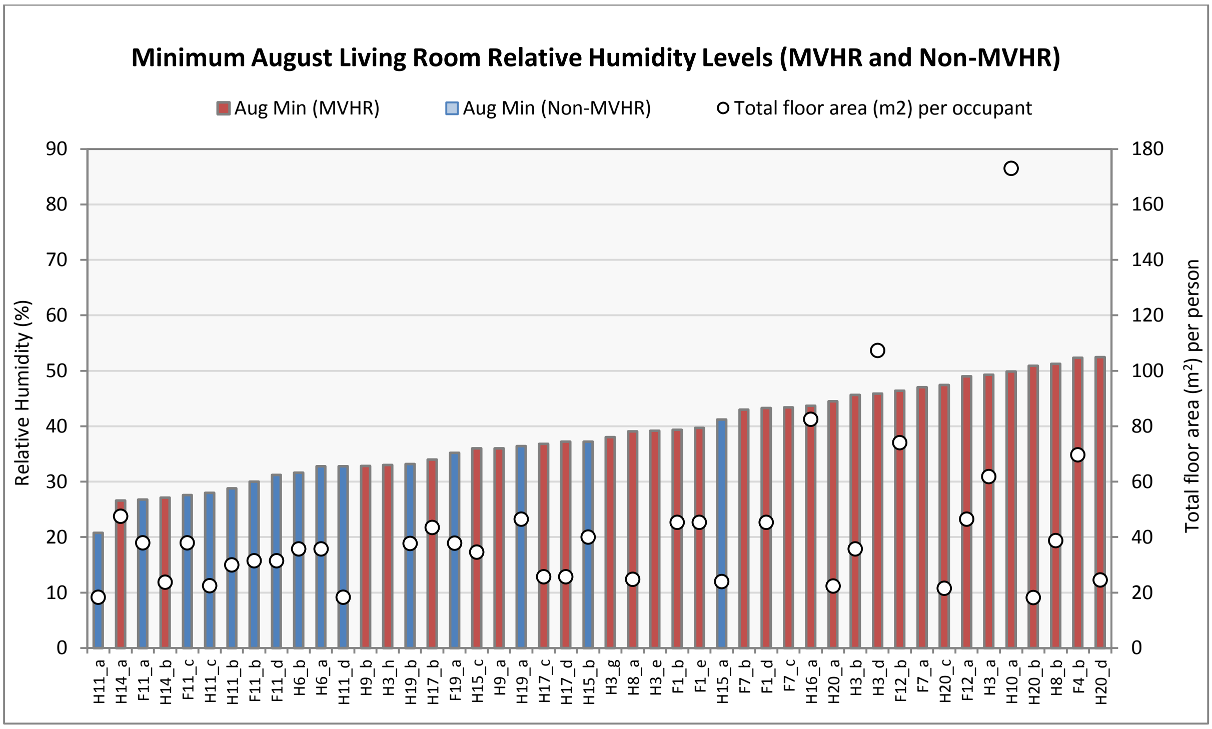

Figure 8.3d. August Minimum living room relative humidity levels

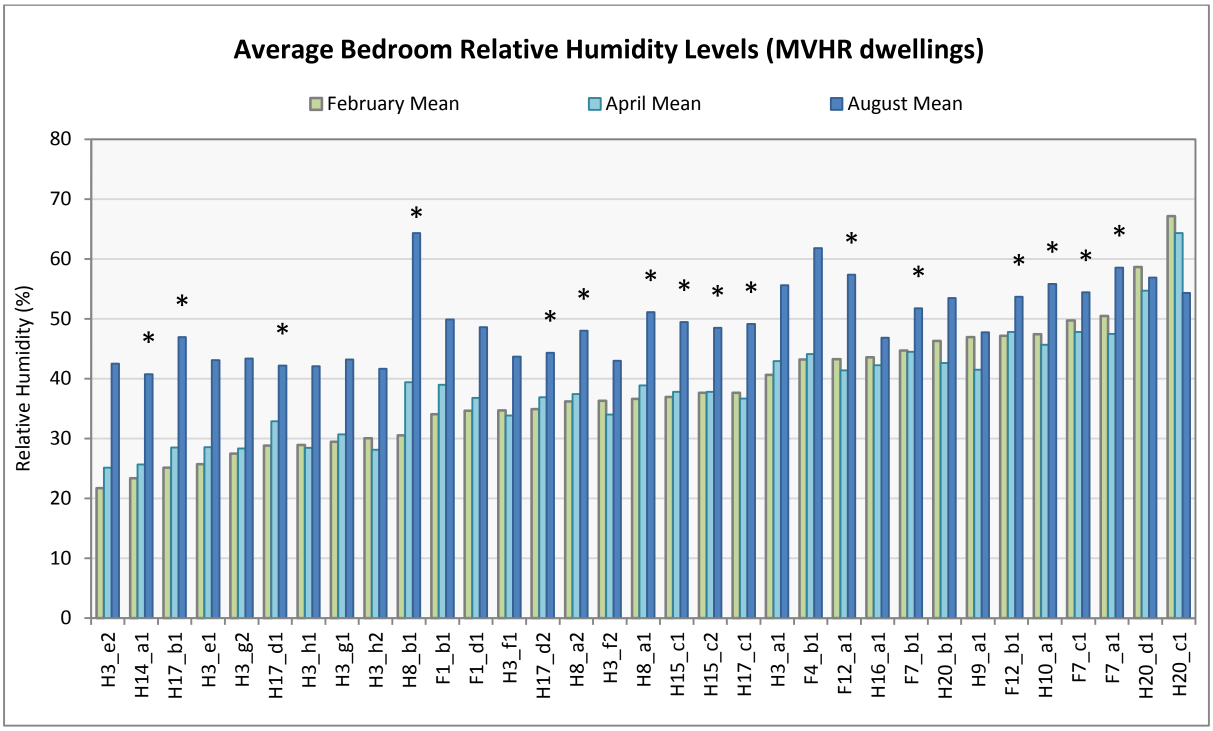

Figure 8.3e. Mean bedroom relative humidity levels in dwellings with MVHR

** Passivhaus dwellings*

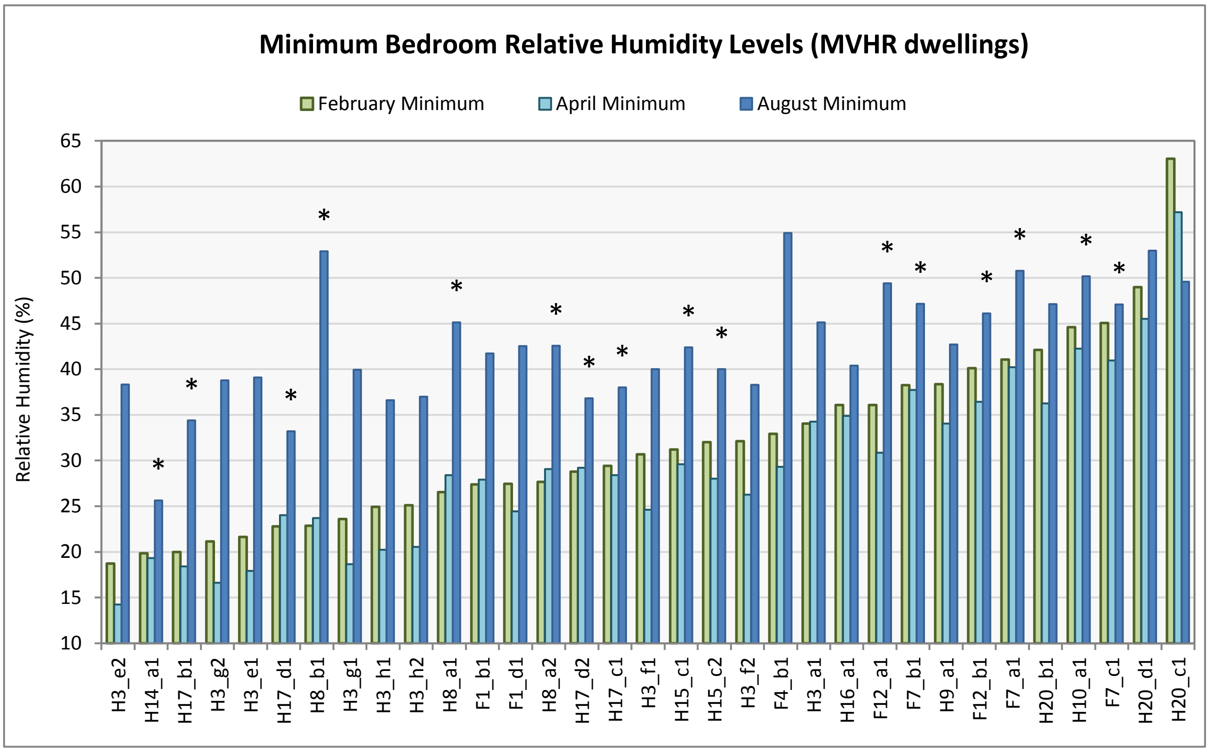

Figure 8.3f. Minimum bedroom relative humidity levels in dwellings with MVHR

** Passivhaus dwellings*

8.4. Appendix D: Temperature

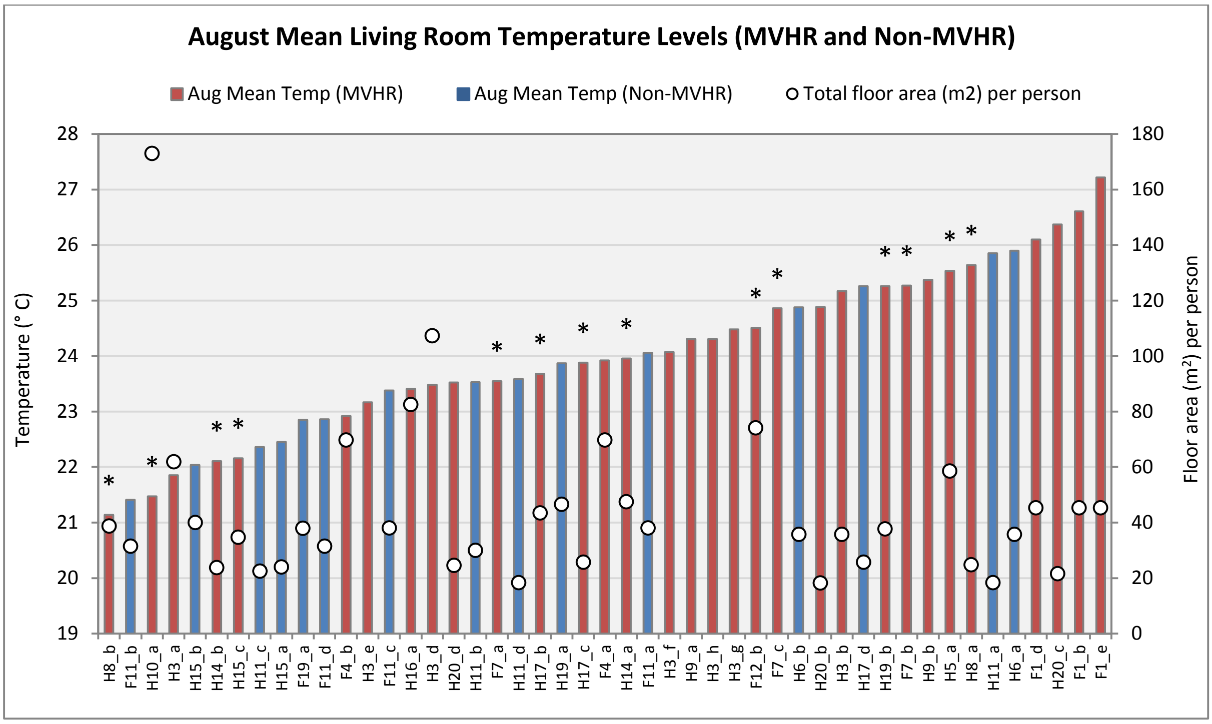

Figure 8.4a. Average August living room temperatures in MVHR and Non MVHR homes
** Passivhaus dwellings*

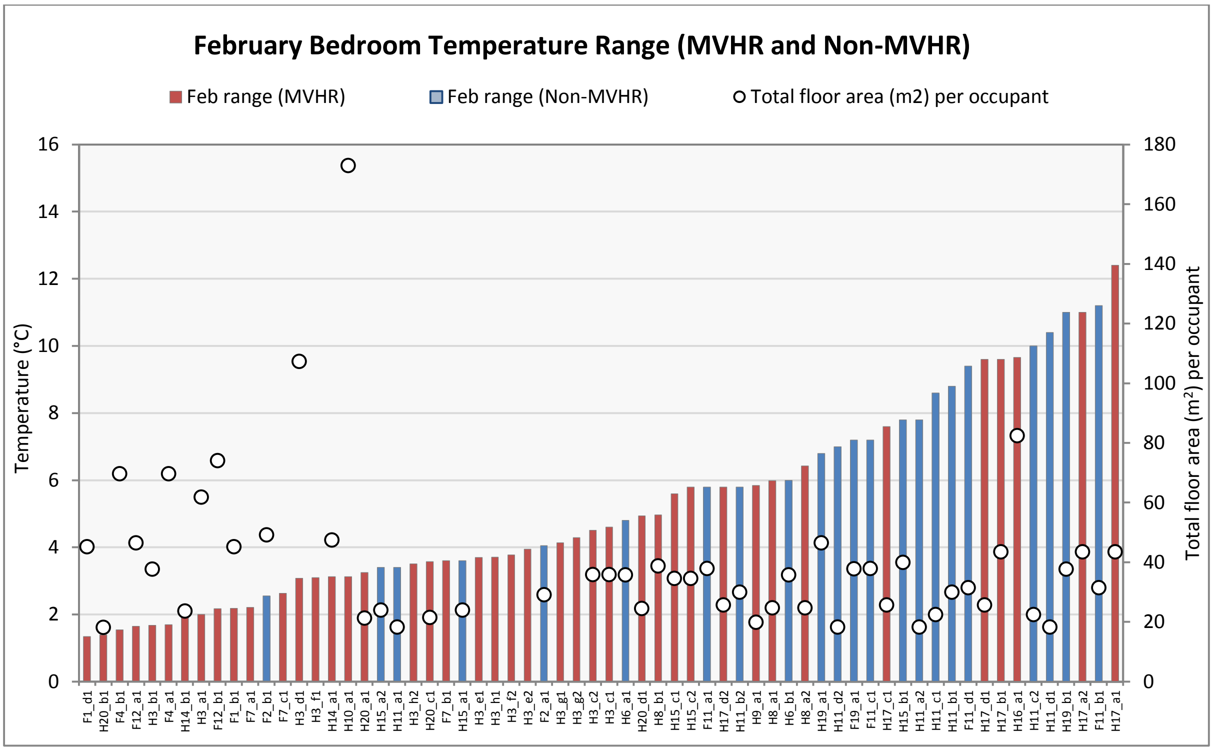

Figure 8.4b. Range of February bedroom temperatures in MVHR and Non-MVHR homes

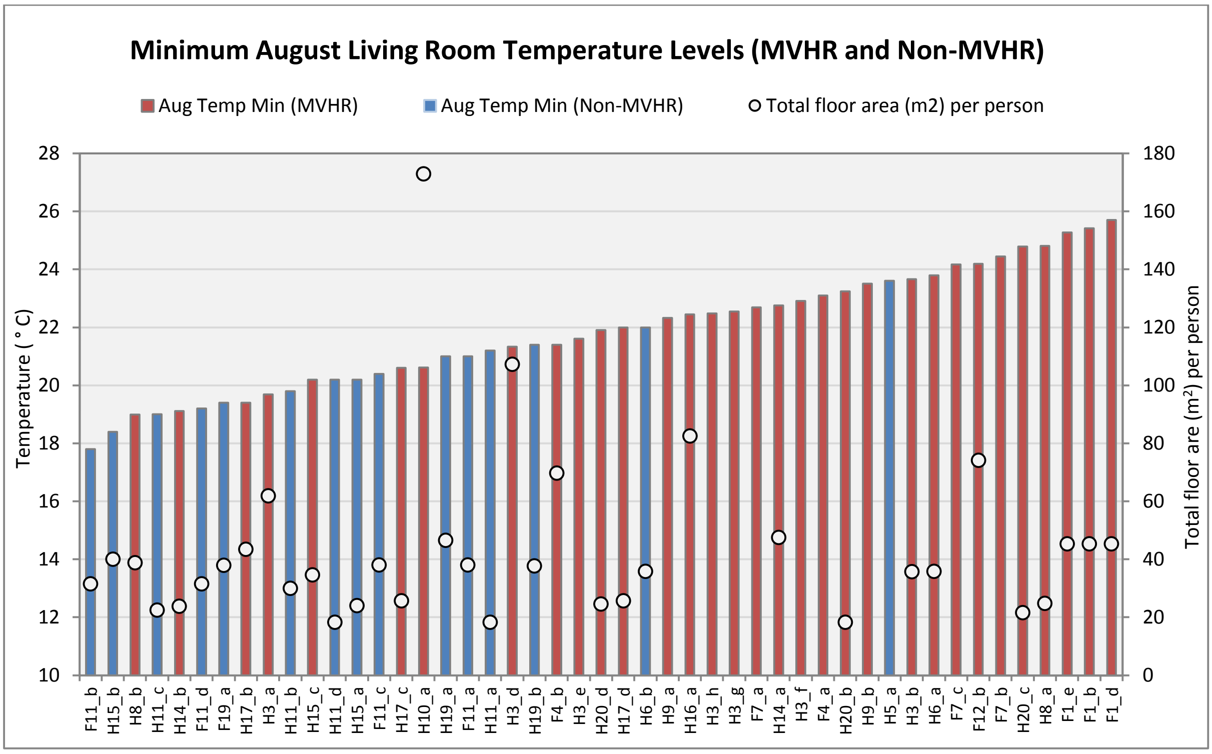

Figure 8.4c. August living room minimum temperatures in MVHR and Non-MVHR dwellings

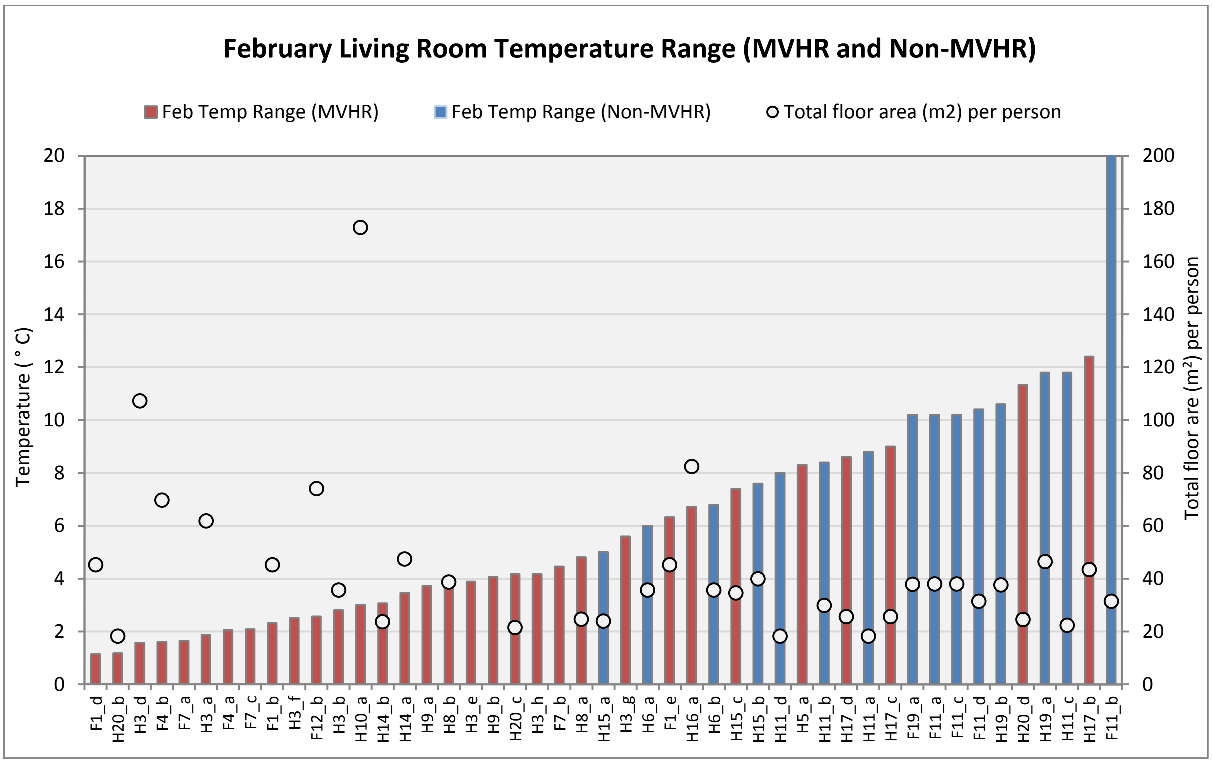

Figure 8.4d. February living room range of temperatures in MVHR and Non-MVHR homes

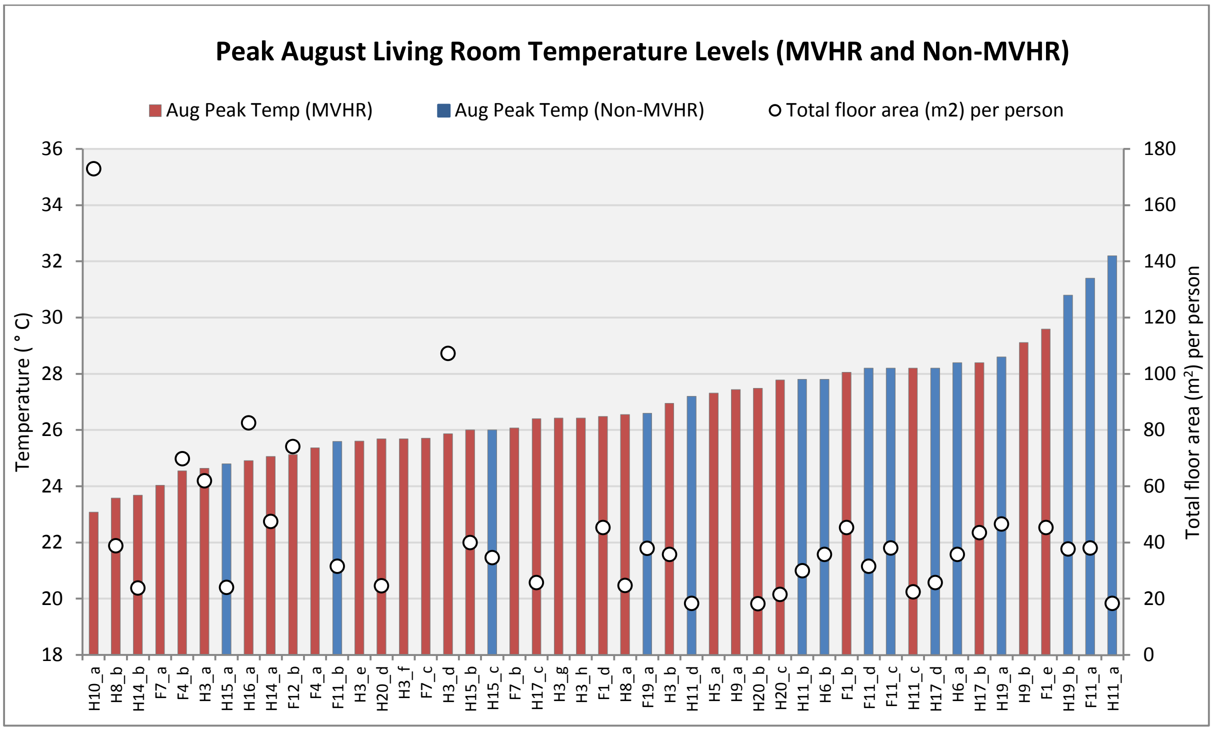

Figure 8.4e. Peak August living room temperatures in MVHR and Non MVHR homes

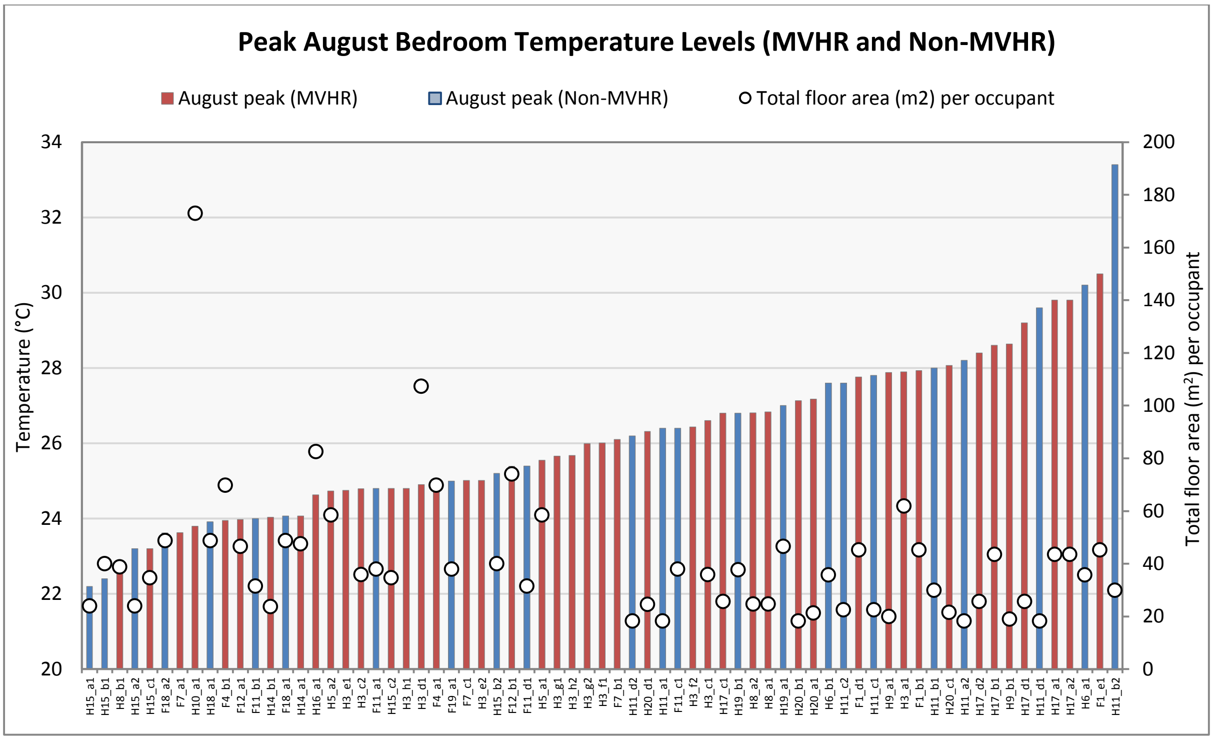

Figure 8.4f. Peak August bedroom temperatures in MVHR and Non MVHR homes

8.5. Appendix E: Vapour pressure

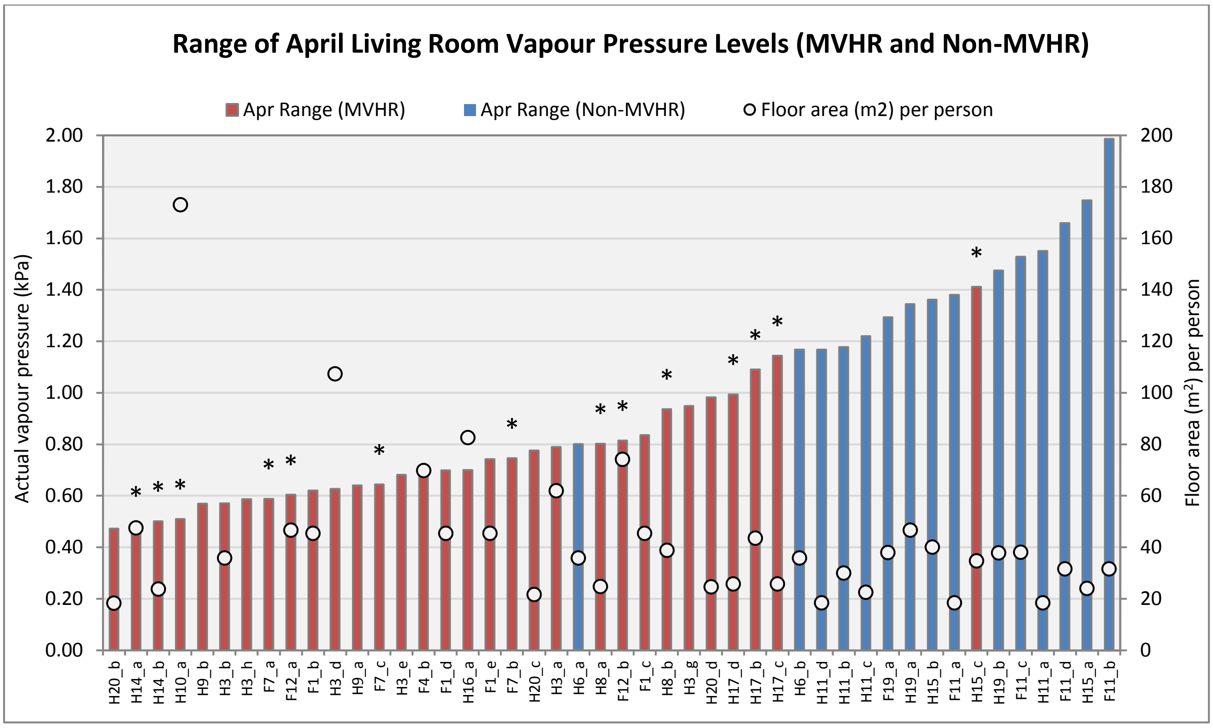

Figure 8.5a. April living room vapour pressure ranges in MVHR and Non-MVHR homes
** Passivhaus dwellings*

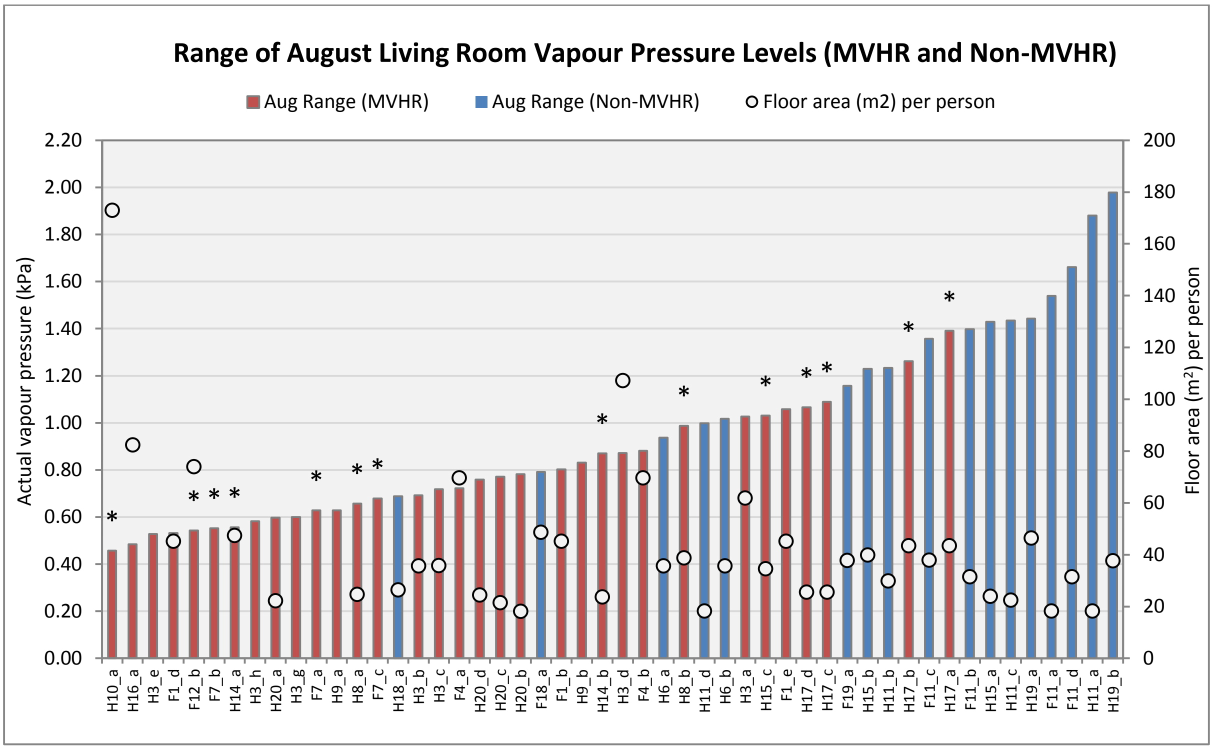

Figure 8.5b. August living room vapour pressure ranges in MVHR and Non-MVHR homes
** Passivhaus dwellings*

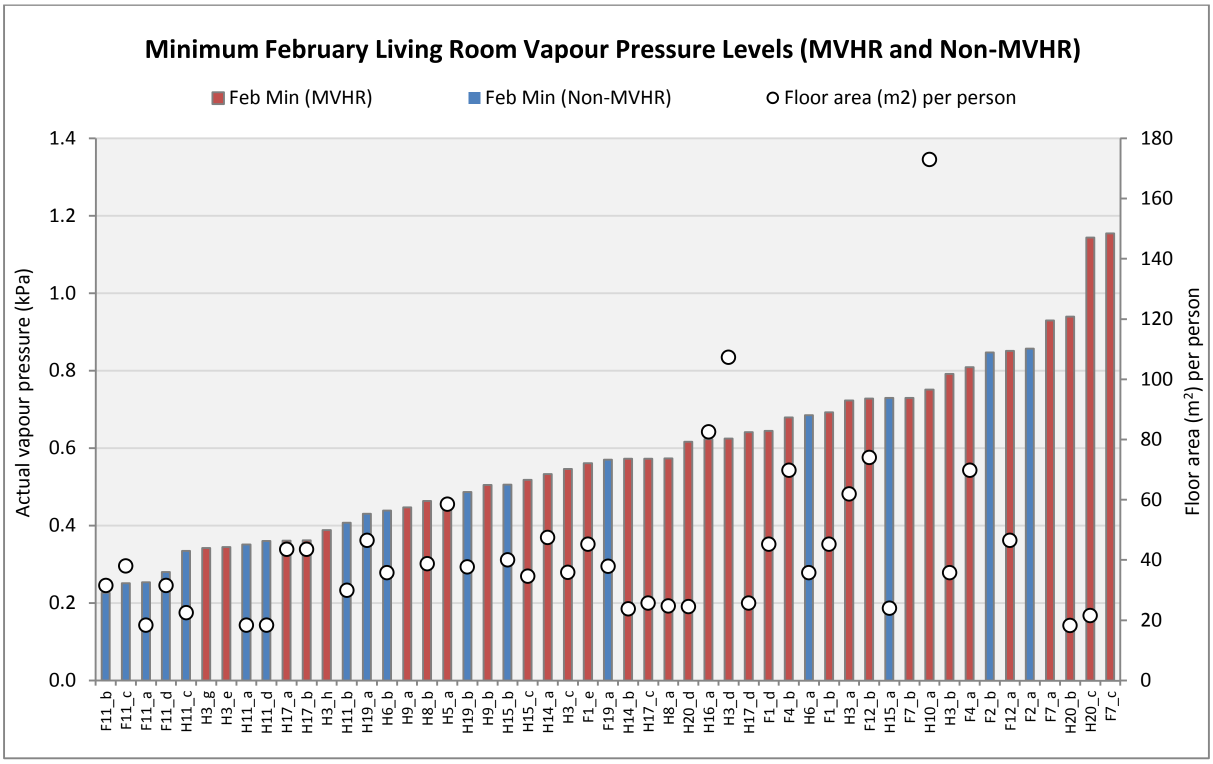

Figure 8.5c. Minimum February living room vapour pressure levels in MVHR and Non MVHR homes

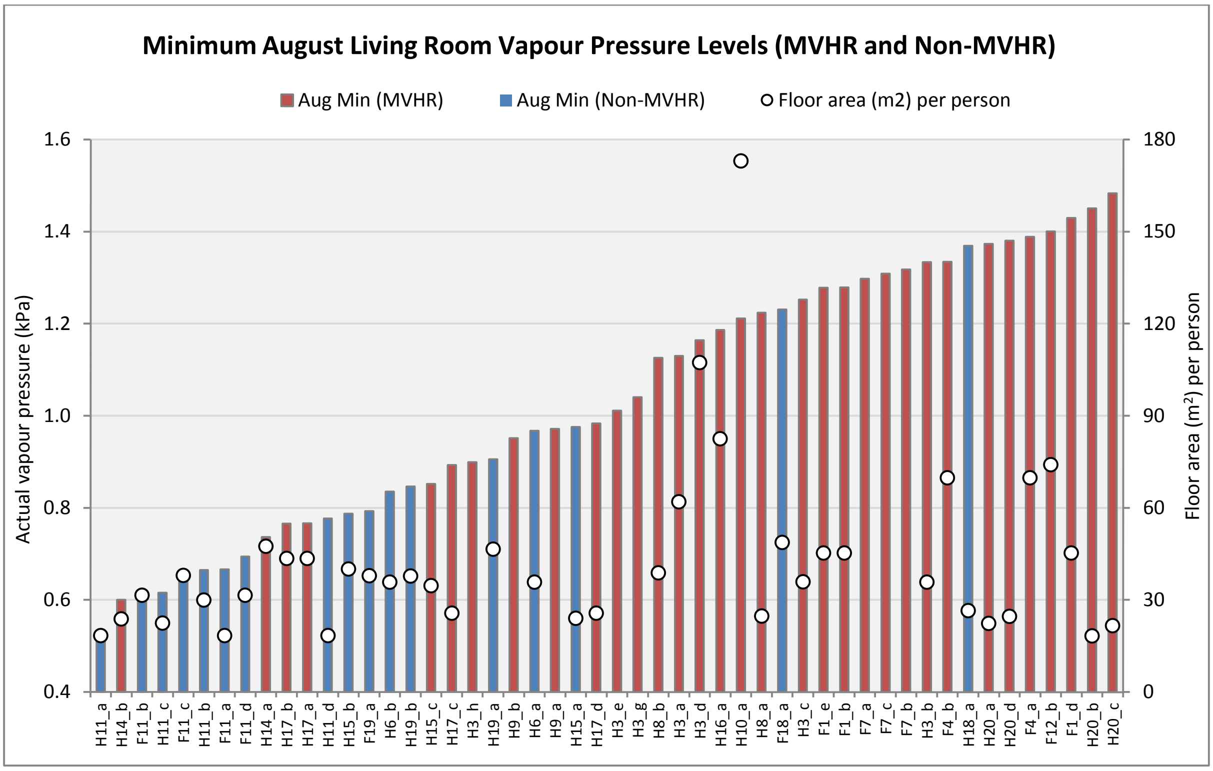

Figure 8.5d. Minimum August living room vapour pressure levels in MVHR and Non MVHR homes