The Scottish Government

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Ability of decentralised mechanical ventilation to act as 'whole-house' ventilation systems in new-build dwellings

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Executive Summary

As improvements to energy standards have led to greater levels of air tightness in buildings to reduce uncontrolled heat loss, a consequence is that the ventilation provision in modern homes now has to be designed. In current building regulations guidance, airtight buildings (between 3 and 5 $m^3/hr/m^2$ @50 Pa) require mechanical ventilation. One method for achieving this is through the use of dMEV systems. These are an increasingly popular strategy due to the relatively low cost and ease of integration.

However, some concerns have been expressed about the ability of these systems to provide whole house ventilation, particularly in the light of changes to the guidance for trickle vents. To investigate these issues the Scottish Government Building Standards Division (BSD) commissioned a study that would examine the real world performance of modern homes with dMEV systems. The study undertook a survey of 223 homes to ask occupants about their knowledge and operation of their ventilation system, and a subset of these homes were monitored to examine the actual ventilation performance and determine the factors that affect this. A further study was undertaken in a selected dwelling to experiment with different ventilation strategies using dMEV to identify key factors.

The survey found that although there was good awareness of the presence of ventilation provisions, there was a lack of knowledge regarding how these systems were controlled. Many households did not know how to boost the ventilation rate in the dMEV system (or didn't feel the need to do so), and a lack of engagement with trickle vents was clear.

The monitoring found that over 50% of homes appeared to have poor ventilation overnight (where carbon dioxide levels exceeded 1,000ppm for the majority of the time), and that bedrooms were a particular cause for concern. There were a number of variables that affected this. These included the nature of the trickle vents, the window coverings, the path between the room and the dMEV (including the door opening or undercut, and the arrangement of the home) and the installation and performance of the system. Essentially homes with shorter, more open paths for air movement performed better, but rooms which relied on more remote dMEV systems frequently had poor ventilation.

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

There were a number of homes (51%) where trickle vents were installed in wet rooms with dMEV systems. Whilst this may improve the efficacy of extract and moisture control in these rooms, this undermines the ability of the system to assist with ventilation in more remote rooms.

Whilst dMEV systems in ensuite bathrooms provided the best outcomes for adjacent bedrooms, problems with systems being disabled were encountered in 56% of homes and the predominate problem was one of noise. The physical monitoring found a much higher incidence of this than the overall survey.

In the test house a number of different ventilation scenarios were tested over a week. The bedroom with an ensuite performed reasonably well, but the bedroom which relied on a remote dMEV only achieved good ventilation when the windows were open at night. The next best scenario was when the occupants left the bedroom door open overnight. Subsequent modelling suggests that air flows from door undercuts are less effective.

The findings would suggest that whilst there are some situations where a dMEV system can assist with the ventilation provision of modern airtight homes, the ability to act as a whole house system is limited, particularly in larger more complex layouts, and where ventilation loads are high.

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

Issues to consider therefore include:

- Better design of ventilation strategies using dMEV as a component of the system and accounting for other key components
- A need for pass vents between rooms, fire protected where required, ideally at higher levels
- Better standards for commissioning and testing in use
- Improved standards for noise for as-installed systems
- Better design of occupant interfaces of mechanical systems, in particular boost modes and occupant control elements
- Better advice and information for occupants about the ventilation system, its optimal use, and requirements for maintenance
- Fall-back strategies for ventilation, where mechanical systems may fail or become sub-optimal over time
- Direct extract ventilation for non-flued gas appliances
- The development of performance standards for ventilation rates that can be compared with in-use data, and that provide an alternative means of compliance

1. Research Outline

Overview

The underlying context of this work is the increasing standards of airtightness in new construction as an industry response to the requirements of the Energy Standards in Scottish building regulations and the potential implications of this in terms of ventilation and air quality. In 2011 the Building Standards Division (BSD) commissioned research to identify the effect that increasing air-tightness may have on air quality within dwellings, which concluded that the Domestic Technical Handbook guidance on natural ventilation was fit for purpose down to an air-tightness level of 5 m^3/m^2.hr @50 Pa. However, the research assumed that trickle ventilators and internal doors remain open, but did not consider when and why occupants interact with trickle ventilators and windows in dwellings.

A subsequent workshop on ventilation was held at BSD offices in October 2013, which identified a number of research questions. These included how occupants use trickle ventilation, what effects this use may have on ventilation and indoor air quality (IAQ), and what measures may be undertaken to address this. As a result, the BSD commissioned a study to investigate occupier influence on IAQ in dwellings[1]. The findings of this evidenced a lack of trickle vent use in contemporary housing and poor ventilation in practice. These findings were supported by similar work commissioned by Department of Communities and Local Government (DCLG) on IAQ in naturally-ventilated homes built to 2006 standards[2], which concluded that to compensate for the fact that new homes are becoming more airtight, the size of the trickle vents provided in the most airtight homes (≤4 $m^3/hr/m^2$) should be increased.

Following the outcomes of the trickle vent study, proposals were made for revisions to the guidance supporting the standards, to increase occupant awareness of IAQ issues. In 2015, changes to the Domestic Technical Handbook introduced carbon dioxide (CO_2) monitors to principal bedrooms in new dwellings constructed to an airtightness of less than 15 $m^3/hr/m^2$ @50Pa, to help raise awareness of elevated CO_2 levels (and therefore poor ventilation) in the bedroom environment. Further changes in 2015 included the adoption of the European standard for sizing background ventilators using 'equivalent area', as opposed to geometric area. This was a subtle but important change that had significant implications, effectively increasing the requirements for trickle ventilation provision in Scottish housing.

At a workshop held at BSD offices in September 2014 to disseminate the findings of the study, concerns were raised regarding the ability of decentralised mechanical ventilation systems to act as 'whole house' ventilation systems in certain types of new-build housing with an air-tightness of between 3 and 5 $m^3/hr/m^2$ @50 Pa, coupled with reduced trickle ventilation (2,500mm^2) to habitable rooms, as has been accepted by some verifiers. The concern was that whilst this strategy can potentially achieve satisfactory results in factory conditions and in modelling, there are a number of real world situations arising which may compromise performance. These

[1] Sharpe et al. Research Project to Investigate Occupier Influence on Indoor Air Quality in Dwellings, http://www.gov.scot/Resource/0046/00460968.pdf
[2] DCLG, 2010, Ventilation and Indoor Air Quality in Part F 2006 Homes, BD 2702

include the effects of internal layouts, size and placement of trickle vents, doors and windows, building form and location, and occupant behaviour. Sub-optimal performance could result in inadequate ventilation and associated indoor air quality problems.

In 2015 MEARU were commissioned by Innovate UK to undertake a meta-study of homes within the IUK Building Performance Evaluation programme that utilised Mechanical Ventilation with Heat Recovery (MVHR). A dissemination event at BSD offices on this study also raised the issue of reliance on constantly running mechanical systems and possible effects of other interactions such as window opening and the efficacy of alternative mechanical strategies in airtight homes such as the use of dMEV.

The use of dMEV is gaining in popularity due to its relatively simple requirements in increasingly airtight homes. However, the question remains whether these systems are delivering sufficient ventilation rates, particularly in rooms that may be at risk of being bypassed and habitable rooms with limited cross ventilation, and this is the focus of this research.

Study aim and objectives

The main aim of this research is to establish if new-build dwellings fitted with dMEV systems in moisture producing rooms, coupled with a reduced area of trickle ventilation in habitable rooms of 2,500mm^2, can maintain satisfactory ventilation and IAQ in a real-life context.

The research objectives were to:

- Identify a sample of new-build (post 2012) housing developments in Scotland with a designed airtightness of between 3 and 5 m^3/hr/m^2 @50Pa that are ventilated using dMEV systems, with a reduced trickle ventilation provision of 2,500mm^2 in habitable rooms
- Understand the overall ventilation system design specifications, the as-designed individual ventilation component specifications, the as-built and as-operated ventilation systems and associated user guidance
- Investigate how occupants interact with dMEV systems, trickle ventilators and other components such as doors, door undercuts and windows in their home, their awareness of these systems and controls, their perception of IAQ, and their willingness to participate in the monitoring study, through a household survey
- Establish ventilation levels in selected homes with dMEV systems, and with reduced trickle ventilation of 2,500mm^2 during winter based on measured CO_2 levels in habitable rooms while gathering relevant contextual information
- Calculate ventilation rates and relate these to a range of standard occupancy patterns
- Identify the hygrothermal conditions in these homes based on measured temperature and humidity together with relevant contextual information
- Examine the airflows including potential for short-circuiting of fresh air from trickle ventilator(s) by the dMEV unit, through a review of the design, as-implemented and as-used systems coupled with analysis of airflow pathways using simulation tools

- Draw together data from the household survey, monitoring study, detailed measurements and modelling to examine and fully comprehend the nature of ventilation provision and use
- Compare ventilation rates and dwelling characteristics to identify patterns or explain variations, and
- Assess the implications for future design, legislation and advice, and identify any issues concerning current regulatory standards and/or practices and options for improvement.

Work Packages

WP1 *Project development*
Initial meetings were held with the Building Standards Division steering group and project team to outline and refine the methodology, responsibilities and timescales of the project and identify equipment requirements. Suitable new-build dwellings with dMEV systems (in central belt of Scotland) were identified. A review of current building standards was performed to provide a detailed understanding of the current context relative to national regulation and policies concerning the application of decentralised mechanical ventilation as whole house ventilation systems.

WP2 *Household survey*
This was a survey of 223 homes conducted between December 2017 and February 2018, to gather information on occupant use and awareness of ventilation within their home. The project identified household addresses for the survey from partner organisations, Building Standards departments and other contacts in the field. A professional survey company (Research Resource), conducted the doorstep survey, with the surveyors being briefed by the project team. The survey was also used to identify locations for follow-up sample monitoring.

WP3 *Monitoring study*
A sample of 41 dwellings with dMEV systems were selected for detailed monitoring. These were confined geographically for logistical reasons but included a range of house types that represent new-build stock, including differing building typologies (including flats and houses), tenures and varying aspects. The survey required access to the houses to undertake a building survey and measure ventilation performance in practice. Environmental monitors that record temperature, relative humidity and carbon dioxide were installed in living room, kitchen and bedrooms over a one-week period. This monitoring took place between December and March 2018.

WP4 *Analysis of ventilation effectiveness*
An overview analysis was undertaken to determine the nature and spread of occupancy, including more detailed analysis to examine the nature of ventilation provision and use. The CO_2 data obtained during the monitoring survey was analysed with reference to recommended guidelines (i.e. 1000ppm), to provide an indication of ventilation performance. Detailed analysis of air change rates (using the constant injection method) was also performed.

WP5 *Detailed monitoring study*
In this section of the project, more detailed testing was undertaken in a selected dwelling where a number of scenarios were tested using simulation software to examine the impact of air flow pathways.

WP6 *Analysis and dissemination*
On completion of field work, data from the household survey, monitoring study and detailed measurements were collated and analysed.

2. dMEV Guidance

Energy, airtightness and DMEV

The Scottish building regulations are supported by the Technical Handbooks, published by Building Standards Division. The Domestic Technical Handbook reiterates the mandatory standard from the regulations, while also providing guidance on how to comply with the standard. Verification of designs to the mandatory standards and guidance is undertaken by local authorities who have been appointed by Scottish Ministers.

The mandatory standard for ventilation is 3.14, which states:

"Every building must be designed and constructed in such a way that ventilation is provided so that the air quality inside the building is not a threat to the building or the health of the occupants." The Domestic Technical Handbook provides additional guidance information and in the absence of other metrics for compliance or performance, Local Authority verifiers generally accept designs following this guidance as a means to demonstrating compliance. As a result, the guidance is frequently viewed as the standard.

Ventilation levels are linked to airtightness, which is subsequently linked to energy performance. Increased levels of airtightness reduce unplanned air infiltration and therefore reduce heat demand. However this in turns places greater demand on the effective provision of planned ventilation. Section 3, clause 3.14.11 illustrates this fact and advises that higher levels of airtightness will result in ventilation design with mechanical assistance.

Section 7 in the Technical Handbook states the sustainability criteria which designs should meet. Bronze level is noted as the default, achieved with compliance of Section 6 Energy. There are also the optional levels of Silver, Gold and Platinum. These have more onerous energy performance criteria, which may result in higher levels of airtightness, should the person procuring the new building elect to achieve the upper aspects of Carbon Dioxide Emissions and Energy for Space Heating.

At present, a number of local authorities and social landlords are building new properties to achieve Silver level (Energy for Space Heating) in order to meet funding criteria. Others are considering further advancement to Gold standard. Currently, it is possible to achieve Silver level (Energy for Space Heating) using an air tightness of 4, which sits in the middle of the range of 3 to 5 $m^3/h/m^2$@ 50 Pa defined under 3.14.11. In this case specifying Decentralised Mechanical Extract Ventilation (dMEV) would meet the guidance.

Where dwellings are designed to an air infiltration rate of less than 3 $m^3/h/m^2$@ 50 Pa, whole house systems such as Mechanical Ventilation with Heat Recovery (MVHR) should be considered. For those building new homes, the cost increase between intermittent extract fans and dMEV is not significant; however the cost increase from dMEV to MVHR is considerable. Consequently, dMEV is a preferred route for many at present.

Trickle ventilation and DMEV

Although clause 3.14.6 of the technical handbook provides guidance on the use of dMEVs, this is based on a "single room" approach rather than as a "whole house" solution. The guidance within 3.14.3 on trickle ventilator sizing would still apply to dwellings with dMEV systems. This calls for trickle ventilators of 12,000mm^2 in apartments (habitable rooms) and 10,000mm^2 in kitchens, bathrooms, utilities, toilets and shower rooms. Although clause 3.14.6 clarifies that where dMEVs are used in wet rooms, the door to the adjoining room or area may be undercut rather than installing a trickle ventilator in the wet room, provided that the area has a trickle ventilator in accordance with clause 3.14.3.

In 2015, a change was introduced to the guidance regarding trickle ventilation sizing methodology. Clause 3.14.6 states:

"For the purpose of performance, the recommended areas in the table to clause 3.14.3 should be achieved by the use of ventilators that are sized by the equivalent area, as determined using BS EN 13141-1:2004."

The equivalent area is always less than the free area and is considered a better measure of airflow performance[3]. The difference between the equivalent area and free area depends upon the complexity of the airflow path through the ventilator. 3.14.6 states, *"When determining the equivalent area, the whole ventilator installation, including the external grille or canopy, should be considered as a single unit."*

Equivalent area is defined as, *'a measure of the aerodynamic performance of a ventilator. It is the area of a sharp-edged circular orifice which air would pass through at the same volume flow rate, under an identical applied pressure difference, as the opening under consideration'*[4].

On the other hand, free area is defined as, *'the geometric open area of a ventilator'*[3].

The move to equivalent area had significant implications on the measurement of trickle ventilation requirements in new homes. As such achieving 12,000mm^2 under 2015 standards is significantly more onerous than under 2014 standards. As such in 2014 where a single window in a bedroom could be provided with sufficient geometric area of integrated trickle ventilation, this may no longer be achievable under the guidance introduced in 2015. This issue is recognised within the Technical Handbook guidance and advice on locating trickle ventilators other than in window heads is provided. However, to address the need for additional trickle ventilators, manufacturers of dMEV units sought 'type approval' on their systems under the Scottish Type Approval Scheme (STAS).

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[3] Building Regulations 2009 Technical Guidance Document F Ventilation (Ireland)
[4] Approved Document Part F1, 2010, Ventilation, The Building Regulations (England and Wales)

The dMEV type approvals demonstrate that their systems can be used with a trickle vent equivalent area of 2,500mm^2 in apartments. This is a significant reduction from the measures within the Technical Handbooks, which does not include guidance on reducing the size of trickle ventilators when dMEVs are to be used. Guidance on the use of dMEVs as part of a "whole house" ventilation solution was deliberately omitted from the revised 2015 guidance as construction professionals and academics attending the 2014 BSD ventilation workshop advised caution about the ability of such installations.

Type Approval

The Scottish Type Approval Scheme (STAS) is governed by Local Authority Building Standards Scotland (LABSS). LABSS are an organisation representing all 32 local authority building standards verifiers. They describe the STAS as follows[5]:

"A customer focused national approval system for house builders and developers. STAS offers approvals of standard building designs prepared by designers and developers of domestic and non-domestic projects in support of building warrant applications in Scotland, and producing real savings in time in the approval process. All local authorities accept a STAS certificate as evidence of compliance of the building standards. No further checks, other than local site conditions, are made for a design which has been approved nationally. This results in faster responses and faster approvals of building projects." The process is voluntary and sits outwith the formal building standards process as laid out in legislation.

Two dMEV manufacturers currently hold STAS Registered Details which cover the use of their dMEV units as part of a whole house strategy in Scotland. In each case this allows a reduction in the provision of trickle ventilation to 2,500mm^2 per habitable room. The Registered Detail can be provided as part of a building warrant application to demonstrate compliance. Local Authorities will accept this as evidence of compliance with the mandatory standard.

Consequently, the change in technical guidance around energy parameters, trickle ventilation, the requirement for funders to achieve Silver Standard and the perceived cost burden associated with MVHR, has driven a significant number of dwellings constructed to 2015 regulations to utilise these type approvals.

Further Supporting Guidance - dMEV

Building Standards Division publish a library of technical guidance, which includes further advice on ventilation[6]. Building Standards Supporting Guidance Domestic

[5] For more information on STAS, see https://www.labss.org/partnership-schemes/scottish-type-approval-scheme/labss/1

[6] For more information, see http://www.gov.scot/Topics/Built-Environment/Building/Building-standards/techbooks/techhandbooks/domventguide

Ventilation was revised in 2015 to support the changes in the Technical Handbook. Part 7 of this guide provides guidance on dMEV.

The guidance reflects the information contained within Technical Handbooks and provides more detail in some aspects. Both documents confirm that doors to moisture producing rooms may be undercut as an alternative to installing a trickle ventilator in the moisture producing room:

Supporting Guidance 7.9, *"Trickle ventilators with an equivalent area of at least 10,000 mm^2 should be provided in an area fitted with a dMEV. These provide replacement air for the extract fan and should therefore be independent of the extract fan. As an alternative to a trickle ventilator to external air, the door to the wet room may be "undercut" to achieve an air space of at least 8,000 mm^2. This air space should be clear of the actual or notional floor covering. Ventilation via an undercut door can enhance background ventilation to the area that the wet room is accessed from, e.g. an en-suite off a bedroom. Doors that are required to have a period of fire resistance should not be subject to undercutting."*

Technical Handbook Clause 3.14.6 states, "*To assist air movement within dwellings with an air infiltration rate of less than 10m^3/hr/m^2@ 50 Pa, trickle ventilation to rooms with dMEVs could be formed by "undercutting" the room door to achieve an air space of at least 8,000mm^2. This air space should be clear of any actual or notional floor coverings."*

The trickle ventilation provision to a moisture producing room covered by a STAS approval differs from the guidance within the Technical Handbook with regard to the size of the undercut. The type approvals state:

"Where fresh air from the trickle ventilator(s) will be short-circuited by the dMEV unit, the wet area should not be fitted with trickle ventilators. Background ventilation should be made available by providing at least an 8mm undercut to the door that the wet area is accessed from, e.g. an en-suite off a bedroom. A door that is required to have a period of fire resistance should not be subject to undercutting, but a suitably dimensioned fire door may be installed to provide the 8mm clearance."

In order for dMEV to operate as a "whole house" system it is important to utilise the correct guidance. The Technical Handbook and Domestic Ventilation supporting guidance do not provide guidance on the use of dMEVs as a "whole house" ventilation solution and, as such, should not be used to design such a system. The STAS Registered Details covering dMEV "whole house" ventilation are based on guidance contained within the English building regulation guidance document Approved Document F, which was last revised in October 2010.

Further Supporting Guidance – Actions for Occupants

The 2015 changes to the ventilation section of the Technical Handbook also saw the introduction of carbon dioxide monitoring equipment in the main bedroom of a property. The installation of carbon dioxide monitoring equipment is required regardless of the chosen ventilation strategy. This action was taken to raise awareness of the risks of poor indoor air quality to the occupant. Clause 3.14.2 states:

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

The supporting guidance in the Domestic Ventilation Guide provides two appendices, Appendix A provides a blank pro-forma of information to be provided to the occupant and Appendix B provides a completed example. The following information is provided:

Table 1. Occupant guidance on carbon dioxide monitoring equipment (Source: Supporting Ventilation Domestic Ventilation 2nd Edition)

Action necessary to improve air quality	
Your home has openable windows and controllable trickle ventilators to allow you to adjust the fresh air entering each room. Trickle ventilators are adjustable and positioned to encourage ventilation through each of the rooms. In rooms with more than one trickle ventilator, all ventilators should be opened similar amounts to encourage through ventilation.	
CO2 level	**Action**
0 – 349 ppm	Check monitor is working correctly and recalibrate or replace sensor head if necessary
350 – 799 ppm	None
800 – 999 ppm	No immediate action but maintain daily monitoring
1,000 – 1,199 ppm	Partially open trickle ventilators or leave room door partially open
1,200 – 1,499 ppm	Fully open trickle ventilators or leave room door partially open
1,500 – 1,999 ppm	Partially open window
Over 2,000 ppm	Open window further and leave room door partially open
To achieve good air quality throughout your home, the actions identified above should be replicated in all occupied apartments in the dwelling.	

This should in theory improve occupant knowledge of their systems and provide them with options to achieve good levels of indoor quality that achieves the mandatory standard where the air quality inside the building is not a threat to the building or the health of the occupants.

English Approved Document

For continuous Mechanical Extract Ventilation systems, Approved Document Part F (2010) states the following:

*“For any design air permeability, controllable **background ventilators** having a minimum **equivalent area** of 2500 mm^2 should be fitted in each room, except **wet rooms**, from which air is extracted. As an alternative, where the designed air permeability is leakier than (>)5m^3/(h.m^2) at 50 Pa background ventilators are not necessary, but see the cautionary advice in paragraph 5.10. Where this approach causes difficulties (e.g. on a noisy site) seek expert advice.”*

The Approved Document also states that where background ventilators are fitted:

- *They should be located to avoid draughts, e.g. typically 1.7m above floor level*
- *Fans and background ventilators fitted in the same room should be a minimum of 0.5m apart*
- *Background ventilators may be either manually adjustable or automatically controlled (see paragraphs 4.18 to 4.20).*

Given the issues identified here and also raised in the workshops, this study was commissioned to develop an understanding of how well dMEV strategies work in practice. This included a general survey of properties with dMEV systems, the selection of a sample (41 houses) in which environmental monitoring was undertaken, more detailed monitoring and testing in some case study houses; and use of the data to undertake modelling of different scenarios.

3. Household Survey

Aims and objectives

The main aim was to obtain information on how occupants with dMEV systems were ventilating their homes and what issues they were experiencing. The door step survey was commissioned using a professional survey company, from a sample of approximately 1,000 addresses obtained from Local Authorities and existing clients and contacts. The study surveyed privately owned and rented homes within the central belt of Scotland, to evaluate occupant perception of IAQ, identify window and door opening behaviour, examine factors influencing ventilation behaviours and identify occupants understanding and awareness of dMEV systems and trickle ventilation in the home.

The objectives were to:

- Gather household demographic information
- Examine general occupant understanding and awareness of dMEV systems and trickle ventilation provision in the home and provision and use of user instructions
- Identify any issues or concerns with the dMEV systems that may result in occupant interference or deactivation, such as concerns with noise, cost of running etc.
- Examine occupants' perception of indoor air quality
- Establish whether households use 'high boost' mode regularly (where 'boost' is manually controlled), and to identify factors influencing this action
- Investigate how often occupants make adjustments to trickle vents (by opening/closing them)
- Identify door and window opening behaviours
- Identify households willingness to take part in the monitoring study

Sample size and addresses

The project aimed for 200 completed surveys. Addresses were obtained from two main sources:

- Midlothian Council (database of 839 dwellings with dMEV systems)
- Existing clients and contacts from the research team (>150 addresses)

Selection criteria

The sample included a mix of house types, sizes, and tenure; however, to be eligible for inclusion, homes had to be built since 2012, to a good design standard of airtightness (3-5$m^3/hr/m^2$) and fitted with a decentralised mechanical ventilation system in moisture producing rooms.

Questionnaire development
A questionnaire developed by MEARU for a previous BSD funded project on *Occupier Influence on Indoor Air Quality in Dwellings*[7] was adapted for this study. Show cards were used as a visual aid to help improve the reliability of responses to certain questions.

At the end of the household survey, respondents were asked if they would like to be considered to participate in a detailed monitoring study, which would involve physical monitoring of indoor environmental quality over a 1 week period. This helped the project team to identify suitable households for WP3. The household survey was initially piloted in a sample of >100 mid-market rent properties in Glasgow, which indicated a positive response to the questionnaire.

Where access was achieved through Housing Associations, authorisation was sought from each housing provider prior to issuing letters to households.

The Survey
The survey was conducted during the heating season from October 2017 – February 2018. Out of the initial 200 completed surveys, 36 households expressed interest in participating in the detailed monitoring. As this was lower than required, the survey company agreed to carry out additional fieldwork to try and identify more dwellings for the monitoring stage. In total, 223 households participated in the survey, the majority of which were located in the Midlothian area (see Figure 1).

Figure 1. Geographical spread of households surveyed

[7] Sharpe et al. 2014. Occupier influence on Indoor Air Quality in dwellings

Results

A complete set of responses is provided in Appendix A, and copies of the survey form are included in Appendix B.

Demographic information

The majority of households surveyed (68%) had been living at their current property for less than 2 years. The average household size was 2.6 persons, which is slightly higher than the average for Midlothian (2.3 persons) and South Lanarkshire (2.2 persons)[8]. The number of bedrooms varied considerably; with a higher percentage of homes with 4 or more bedrooms than the Scottish average (see Figure 2).[9]

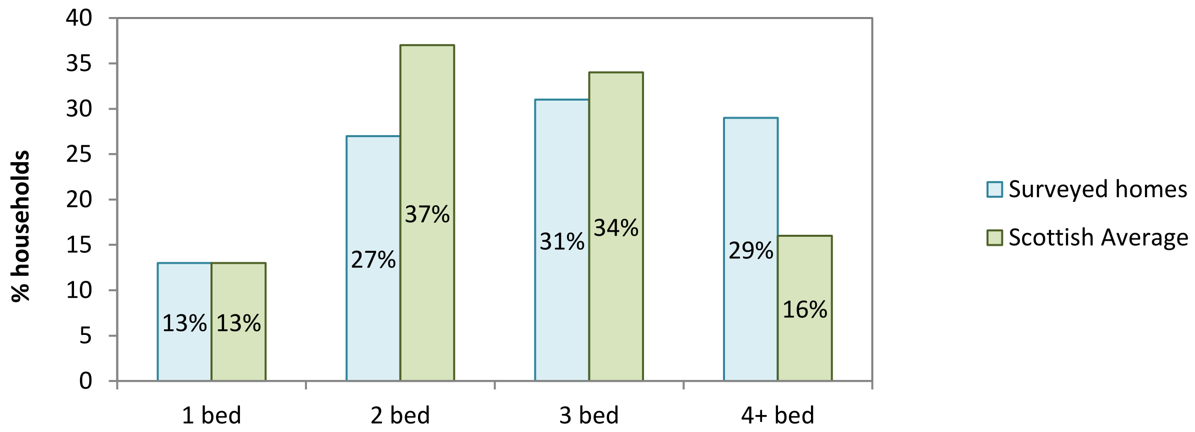

Figure 2. Average number of bedrooms in households surveyed

The surveyed developments were examined with reference to the Scottish Index of Multiple Deprivation map[10]. The map combines 38 indicators of deprivation into 7 domains (education, income, employment, health, crime, access to services and housing), which were used to rank each data zone in Scotland from most deprived to least deprived. Most developments surveyed fall within mid to least deprived areas.

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[8] Based on 2016 statistics - https://www.nrscotland.gov.uk/files//statistics/household-estimates/2016/house-est-16.pdf

[9] Scottish Government, 2015, Scotland's People Annual Report: Results from 2014 Scottish Household Survey. https://beta.gov.scot/publications/scotlands-people-results-2015-scottish-household-survey/pages/4/

[10] http://www.gov.scot/Topics/Statistics/SIMD/analysis

Window opening

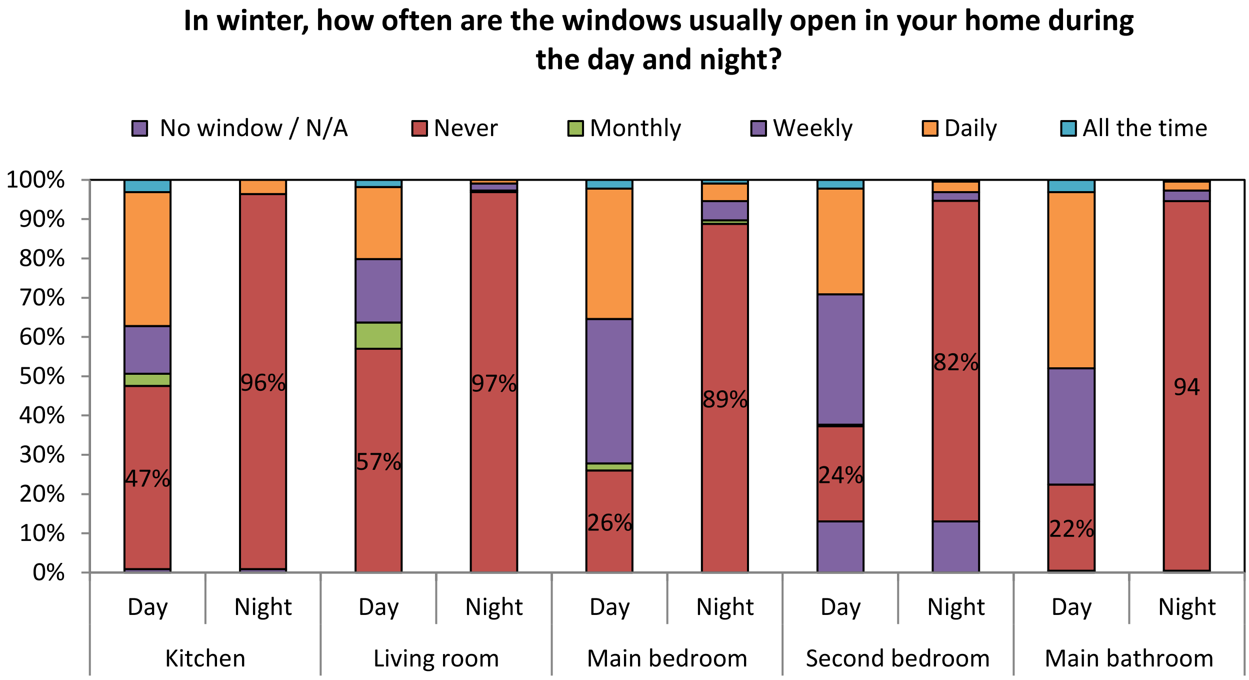


Figure 5: Reported frequency of window opening (winter)

The results from the household survey suggest a low frequency of window opening, particularly at night. Window opening was found to be more prevalent in the main bedroom and bathroom, in comparison to the living spaces.

Nevertheless, 11% of respondents reported opening the window in the main bedroom at night. This differs from the results of the previous survey[11], which found a higher proportion of window opening particularly in the bedroom, where 20% of respondents opened windows at night.

The diversity of the responses is of particular interest. For instance, in the kitchen during the day, 34% of households reported opening windows on a daily basis, while 47% reported never opening windows. This is similar for the living room and main bedroom, and supports the idea that window opening in dwellings may be largely habitual, influenced primarily by ingrained behaviours and values.

When asked what the main reasons for opening windows were in their home, the majority of households (85%) stated for fresh air / to air the room. Interestingly, this is in contrast to previous findings where temperature control was found to be the predominant factor. This could be due to a number of reasons. These include differences in weather conditions at the time of the survey, differences in tenure in which social rented homes may be more aware of heat loss, or it may be due to a

[11] Sharpe et al. 2014. Occupier influence on Indoor Air Quality in dwellings

greater general awareness of issues of air quality. It may be speculated that media reports on air pollution could indicate an increased awareness of the need for fresh air in the home.

A number of incident-related factors were reported, for example, to ‘get rid of smells’ (36%), to ‘dry clothes’ (28%), or ‘too warm’ (21%). It should be noted that 5% of respondents reported opening windows for a connection to outdoors, while 3% stated that it helps them to sleep better (see figure 6).

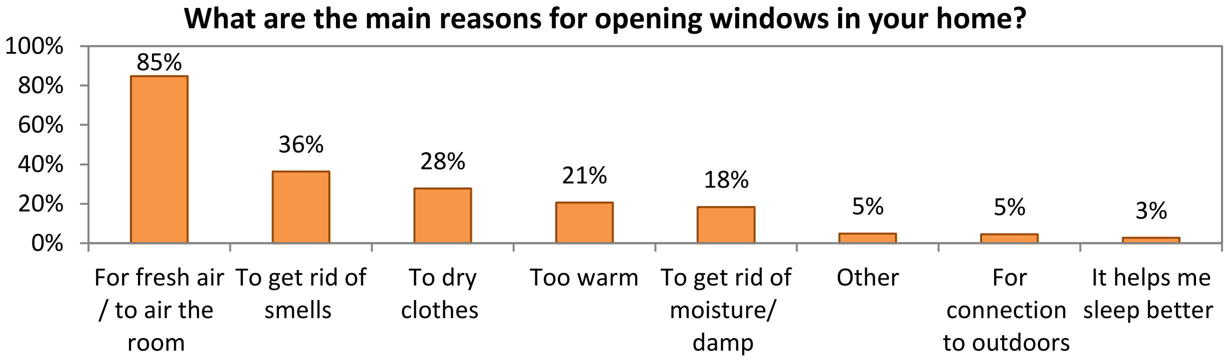


Figure 6: Reasons for window opening

The most common barrier identified for window opening was weather (61%), followed by security (34%). Heat loss was reported as a barrier to opening windows by 23% of respondents (see figure 7).

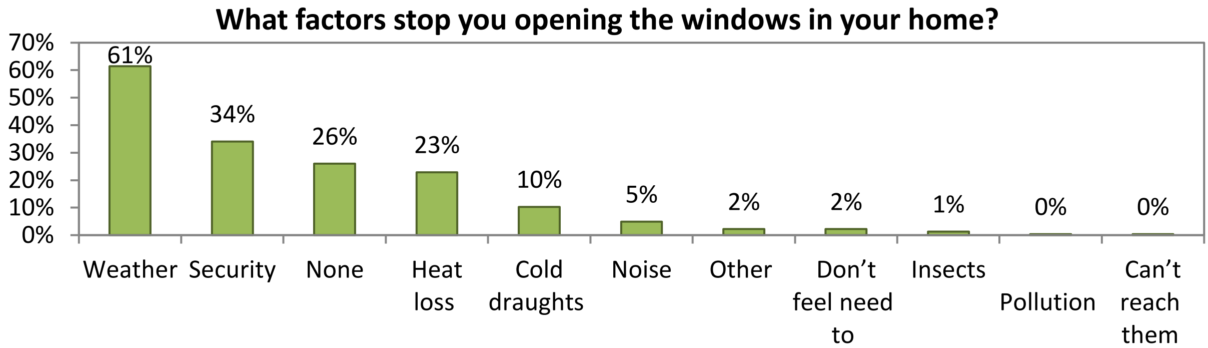


Figure 7: Barriers to window opening

Drying clothes indoors

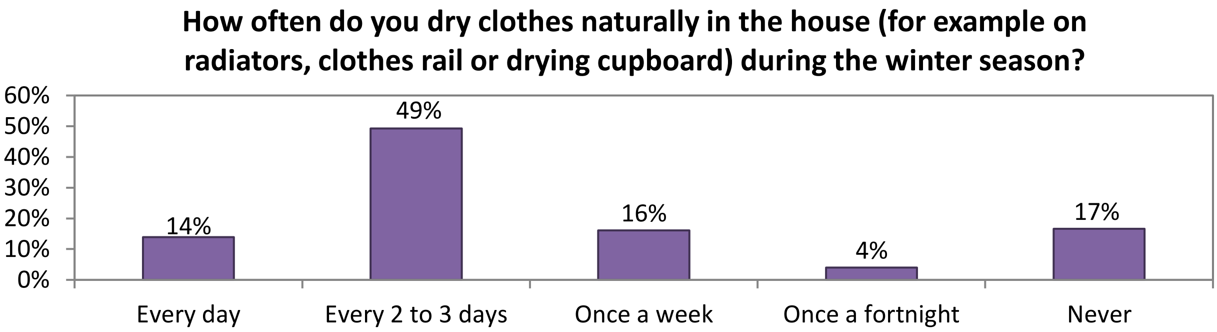


Figure 8: Frequency of drying clothes passively in the home

It is clear that drying clothes is a common moisture producing activity in rooms other than wet rooms, with 79% drying clothes weekly and 63% drying at least every few days. There was some evidence of ventilation behaviours in relation to this, with 28% of respondents reporting opening windows to dry clothes in the home. Clothes were most likely to be dried in the living room, followed by the hallway (see figure 9).

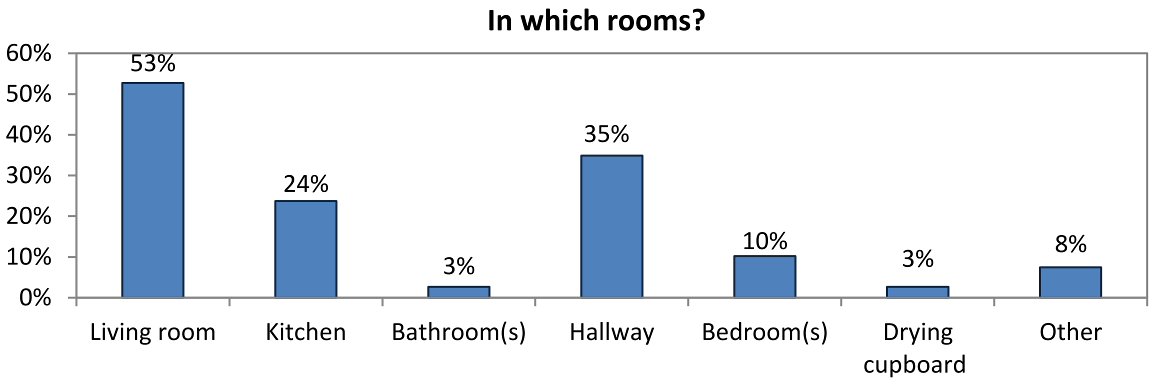
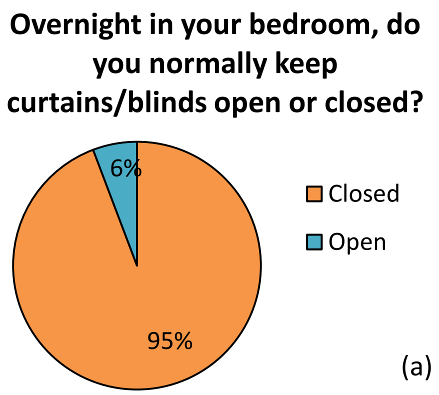


Figure 9: Rooms where clothes are dried passively

The effectiveness of a whole house ventilation system will be influenced by barriers affecting air movement between rooms. Night time presents a particular risk, where air movement may be impeded by occupants closing curtains or blinds, closing the bedroom door and lack of adaptive behaviour overnight. Overall, 71% of occupants reported closing the bedroom door at night. This is higher than previously reported[12] and signifies a particular challenge to providing a "whole house" ventilation system where dependence is placed on trickle vents and open doors to provide adequate air supply in bedrooms at night. In addition, 95% reported closing curtains/blinds (see figure 10) which will also reduce air movement.



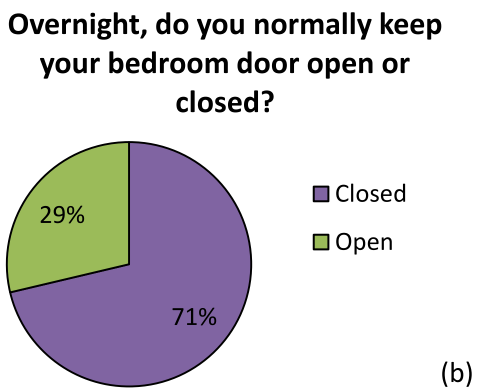


Figure 10a. Curtain/blind status in the bedroom at night, 10b. Bedroom door status at night.

Awareness and use of trickle vents

[12] Sharpe et al. Research Project to Investigate Occupier Influence on Indoor Air Quality in Dwellings http://www.gov.scot/Resource/0046/00460968.pdf

The survey results suggest good awareness of trickle vents, with 93% of respondents able to identify them from a show card and over 84% aware of their purpose. Only 8% of households surveyed did not know what they were (see Figure 11). Moreover, 91% of respondents were aware of the presence of trickle vents in their home, while only 9.4% were unsure if trickle vents were installed in their home.

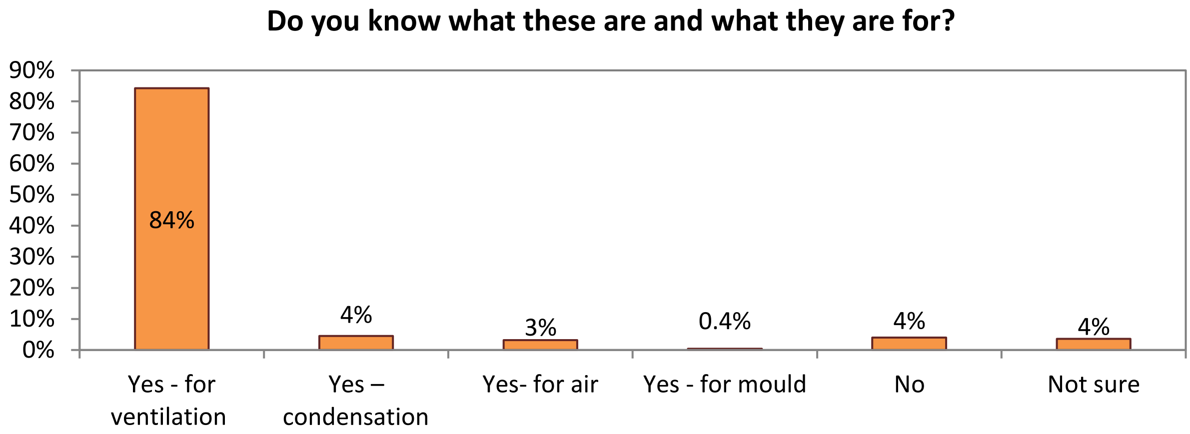
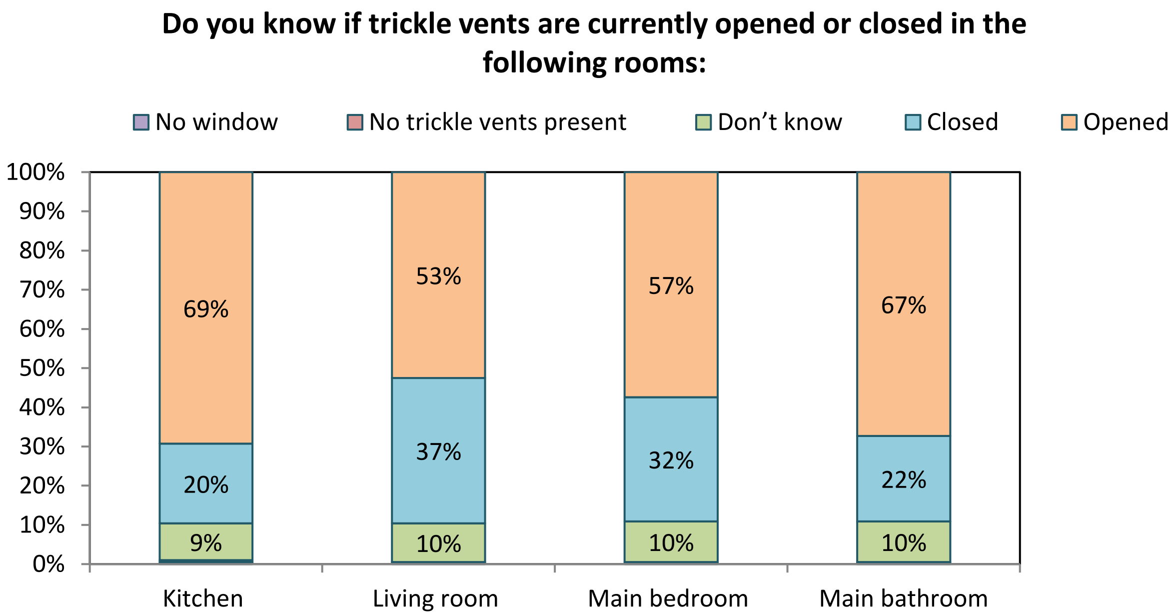


Figure 11. Awareness of trickle vents

Occupants were asked if trickle vents were currently opened or closed in various rooms in their home. While approximately 10% stated that they were not sure, the majority of respondents (53-69%) indicated that trickle vents were opened in the kitchen, living room, main bedroom and bathroom in their home.
Figure 12: Reported position of trickle vents (open / closed)



Based on the responses, trickle vents were more likely to be opened in the kitchen (69%), followed by the bathroom (67%).

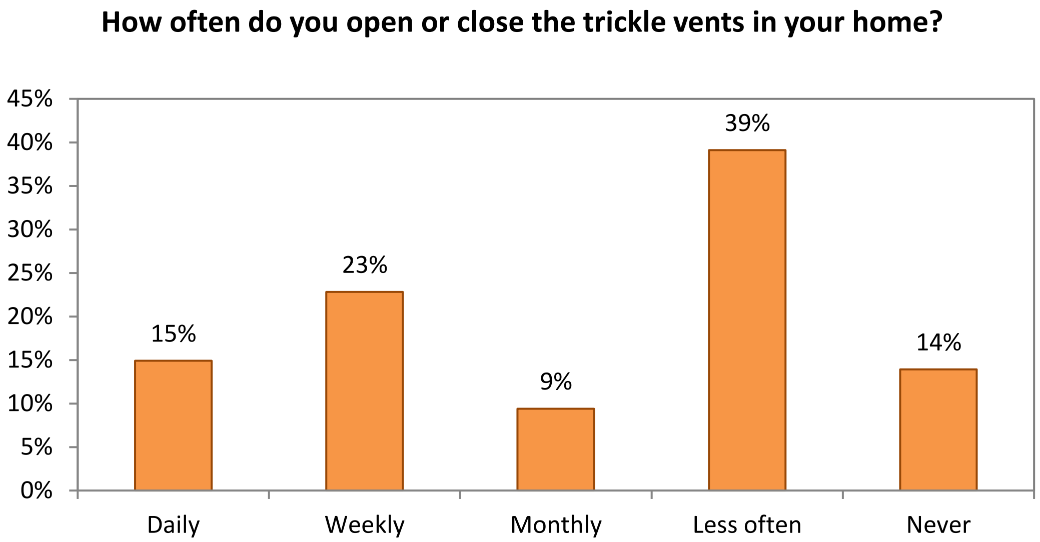


Figure 13. Frequency of adjusting trickle vents in the home

The majority of households reported adjusting trickle vents less than once a month (39%). 14% stated they never make any adjustments to trickle vents. Nevertheless, 15% reported opening or closing trickle vents on a daily basis. This is higher than in the previous study[13] in which trickle vent adjustments were less frequent (13% made adjustments in the living room and 9% in the bedroom).

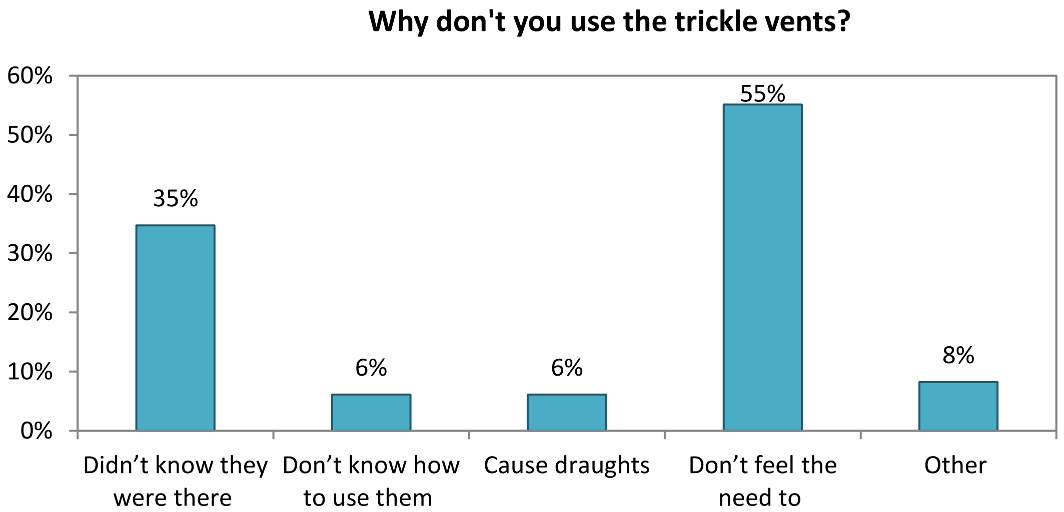


Figure 14. Reasons for not using trickle vents

Occupants who stated that they never used trickle vents (28 households) or were not sure if trickle vents were installed in their home (21 households), were asked why trickle vents were not used. The reasons varied, however the predominate factors were: i) they didn't feel the need to use them (55%, 12% of total), or ii) they didn't know they were there (35%, 7.6% of total) (see figure 14). Only a small proportion of

[13] Sharpe et al, 2014, Research project to investigate occupier influence on indoor air quality in dwellings, The Scottish Government, available here: http://radar.gsa.ac.uk/3554/1/00460968.pdf

households did not use trickle vents because of draughts. No households reported ‘noise’ or ‘heat loss’ as reasons why trickle vents were not used.

Awareness and perception of the dMEV system

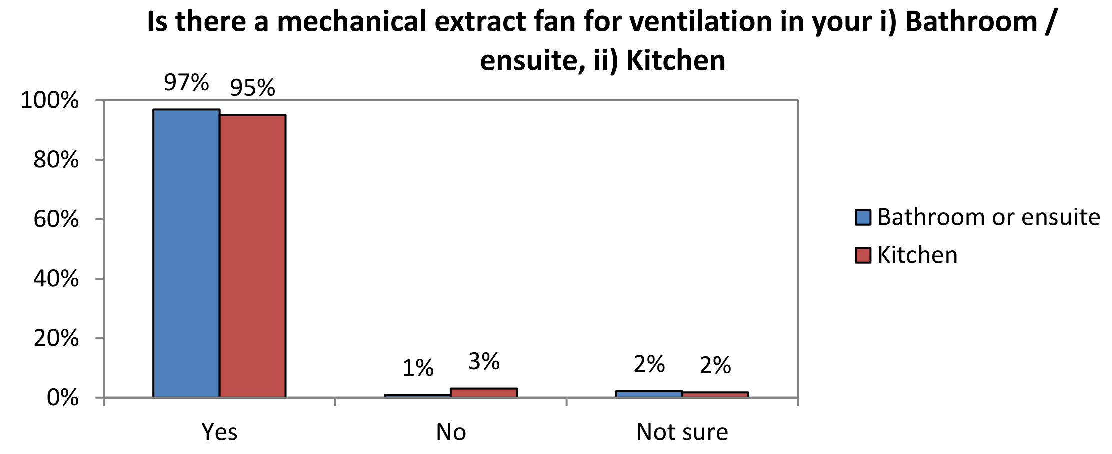


Figure 15. Awareness of the presence of mechanical extract fan

The majority of households were aware of the presence of a mechanical extract fan in the bathroom / ensuite (97%) and kitchen (95%); and 95% of households reported that the fans were operating.

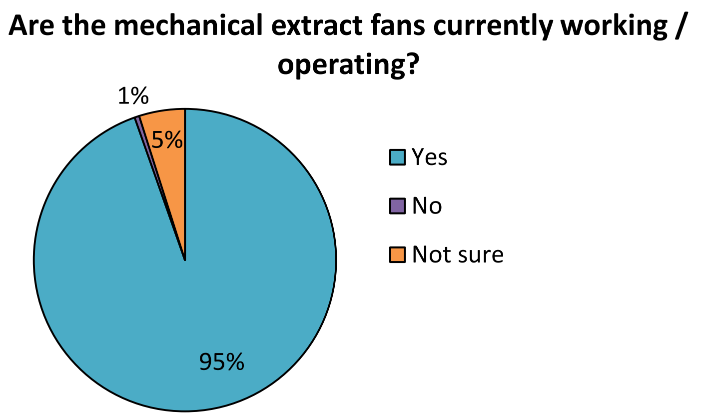


Figure 16. Operation of the dMEV systems

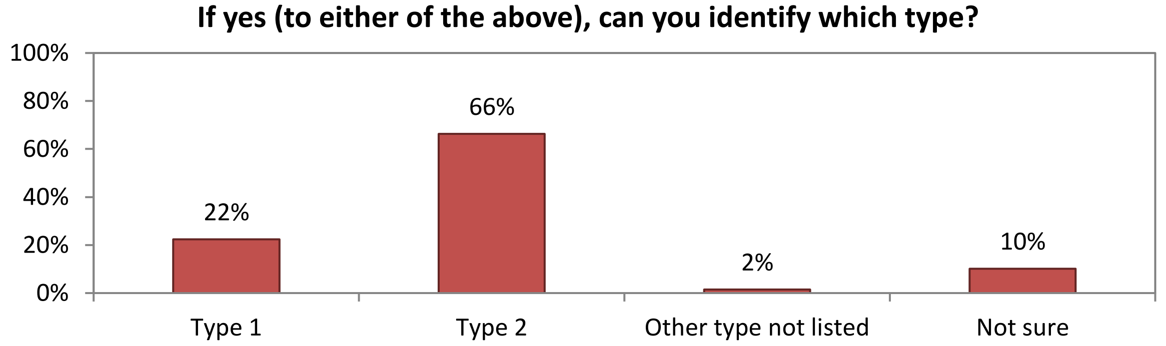


Figure 17. Type of ventilation system installed

Households were asked to identify the type of ventilation system installed in their home, with the help of show cards. The results are presented in Figure 17. The majority of households were able to identify their ventilation system from the show cards, with only 10% stating that they were not sure. According to the results, most homes (66%) had a ‘Type 2’ dMEV system installed. Key operational differences between Type 1 and Type 2 dMEV units are presented in Table 2.

Table 2. Key operational differences between Type 1 and Type 2 dMEV units

Operational characteristics		Type 1	Type 2
Power	Trickle	1 / 1.2 watts	Min 1.1 watts, Max 4.1 watts
	Boost	1.7 watts	
Noise	Trickle	12 / 17 dB(A)	10.1 dB(A)
	Boost	32.5 dB(A)	23.5 dB(A)
Occupancy control		Control panel not provided. Airflow settings can only be changed by unscrewing the protective covering to the unit.	Control panel provided. Settings can be changed by the user (including humidistat and timer options).
Sensor type		RH sensor	RH sensor
Delayed boost mode feature		Yes – delays boost operation for maximum of 20 minutes after light switch has been deactivated	Not available
Boost overrun time (after deactivation)		15 minutes (default)	5 minutes

Households were asked if they have ever had any problems or concerns with their ventilation system. In the survey, 6% of households reported problems; the most common issue reported being noise (5%), followed by draughts (1%) and performance (1%). Overall, the percentage of homes reporting problems was lower than expected.

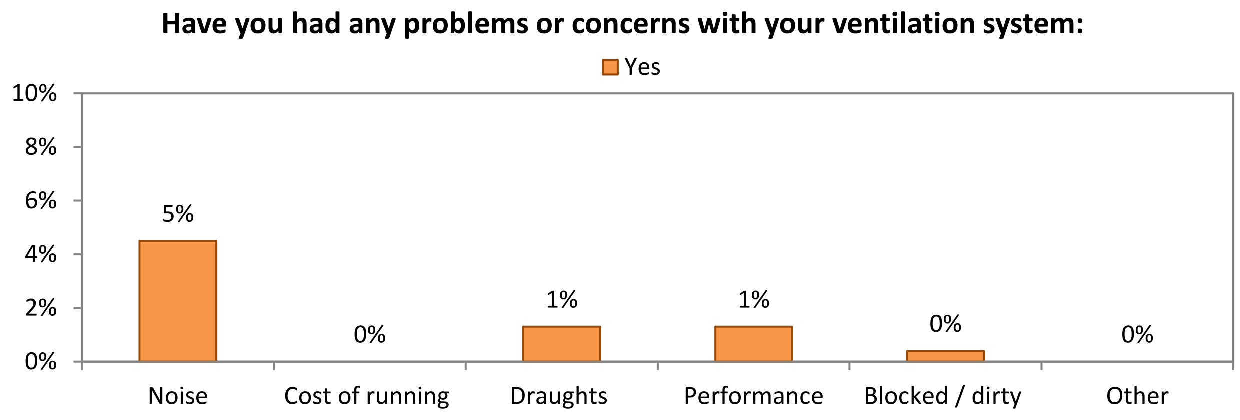


Figure 19. Problems reported with the dMEV system

Where problems were reported, occupants were asked to explain their response. The explanations are provided below:

- *Don't appear very effective.*
- *The noise is too loud, especially at night.*
- *Noisy in the bathroom, especially at night time.*
- *Sometimes noisy at night.*
- *It doesn't work properly.*
- *Water stuck in, they were faulty.*
- *Can be noisy and draughty.*
- *The fan can be quite loud.*
- *Night noise.*
- *Adjust the settings because it was too noisy at night.*
- *Not very strong.*
- *Draughty and noisy in certain parts of home.*
- *Noisy in the bathroom, especially at night time.*
- *Wind - the way the building faces.*

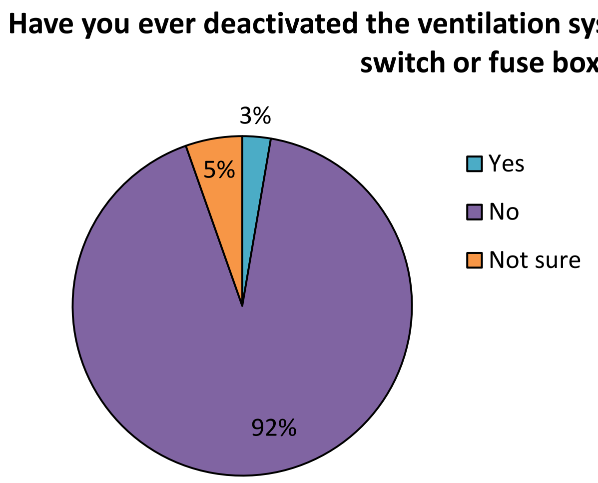


Figure 20. Percentage of respondents reporting deactivating dMEV system

Interestingly, only 3% of respondents reported ever deactivating the ventilation system using the local isolator switch or the fuse box. Households were asked to explain why they deactivated the dMEV system. The responses were mainly related to problems with noise, as summarised below:

- *Due to noise.*
- *It is noisy.*
- *Noises at night.*
- *If wife is in the bath and the kids are in bed because of the noise.*
- *Yes - trying to fix it.*
- *Because of noise.*

The Scottish Technical Handbook (2015) acknowledges concerns regarding noise of systems and provides the following guidance; *'Where dMEVs are located in rooms adjacent to bedrooms the noise generated by them on a continuous rate should not exceed 30 dBL $_{Aeq,T}$ calculated in accordance with BS 8233: 1999.'*

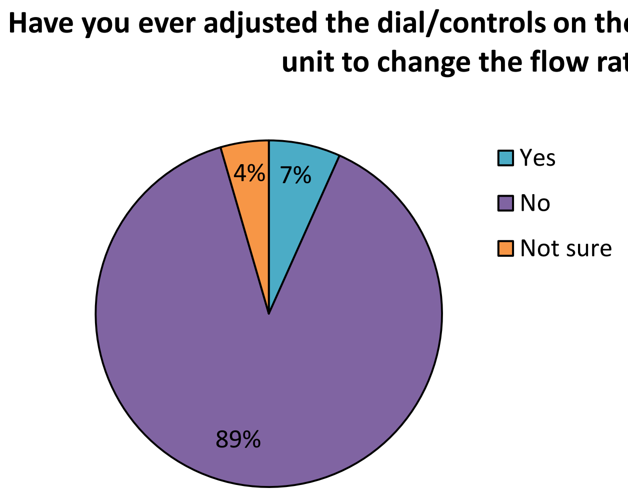


Figure 21. Percentage of respondents reporting adjusting the flow rate

A higher percentage of households (7%) however reported adjusting the dial/controls on the ventilation unit to change the flow rate (see figure 21), with an additional 4% stating 'not sure'. It is important to note that any households with Type 1 dMEV units installed would not have been able to adjust the flow rate without removing the protective covering to access the controls.

Operation of 'boost' mode

Households were asked if 'boost' switches were available to boost the ventilation rate in the mechanical ventilation system. The results suggest that there is some confusion regarding the control of the boost mode function. For instance, only 48% of households reported the presence of switches to boost the ventilation rate. Where boost switches were not reported, households were asked how the 'boost' mode was controlled; the majority of which stated they were not sure (85% - see figure 23).

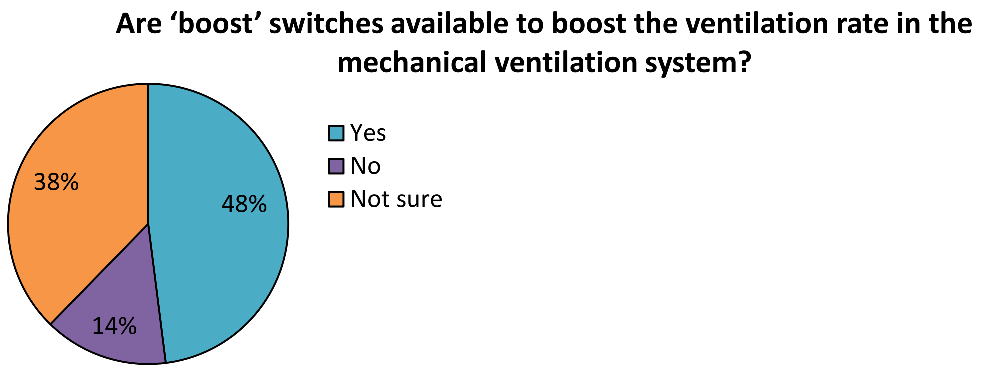


Figure 22. Reported presence of boost switches

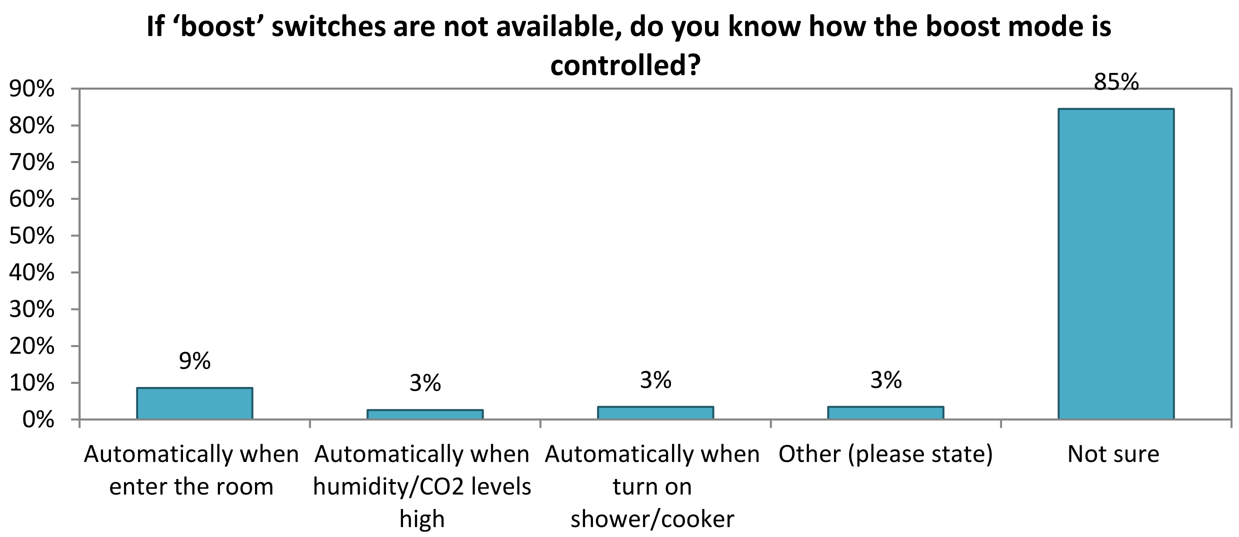


Figure 23. Awareness of control mechanisms (where boost switches not reported)

Where switches were available, households were asked how often they were used (figure 24). Of these, 50% stated they were never used. Only 15% of households with boost switches stated that they operated these on a daily basis.

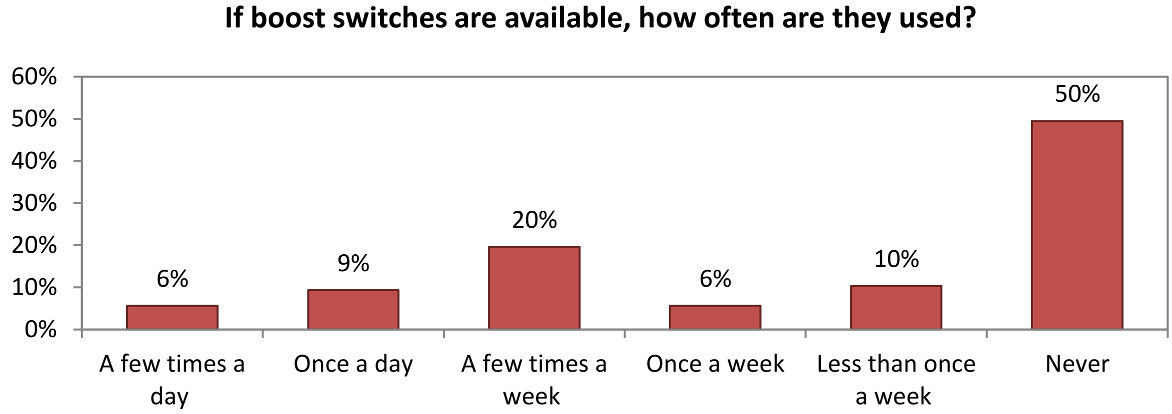


Figure 24. Reported frequency of using boost switches

Reasons for not using boost switches are presented in figure 25. As illustrated, most households (96%) stated that they 'don't feel the need to'. This suggests that either perceptions of air quality are not sufficiently noticeable to drive the need for additional ventilation, or that systems are maintaining adequate levels of ventilation. Thus, the provision of ventilation control alone may not be sufficient to ensure use, perhaps indicating a need for alternative control systems (for example, through the use of sensors and/or smart control systems).

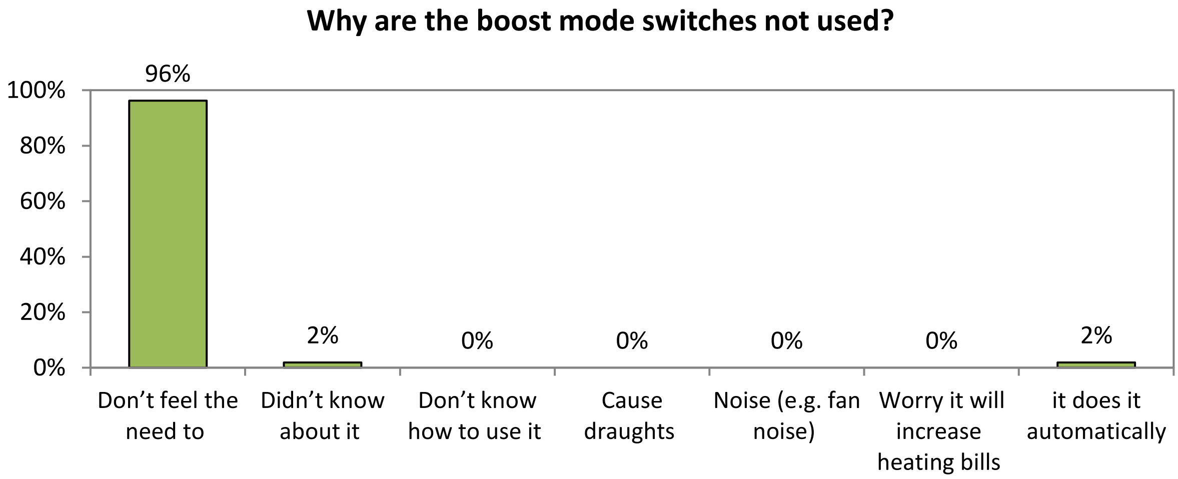


Figure 25. Reasons why the boost mode was not used

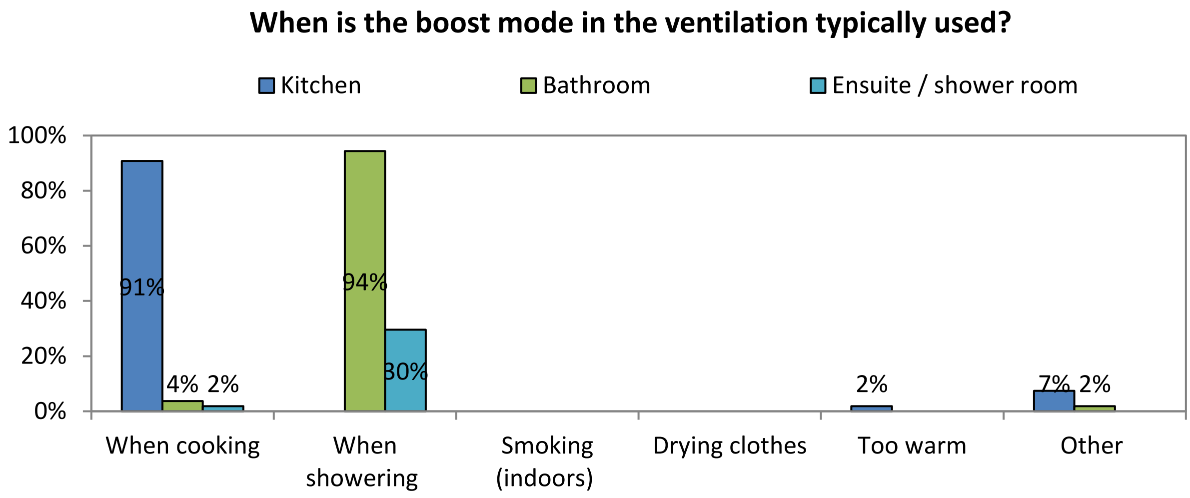


Figure 26. Typical activities where boost switch is used

Out of the 55 households that used boost switches, these were most likely to be used when showering / cooking, as illustrated in Figure 26.

Perception of the indoor environment

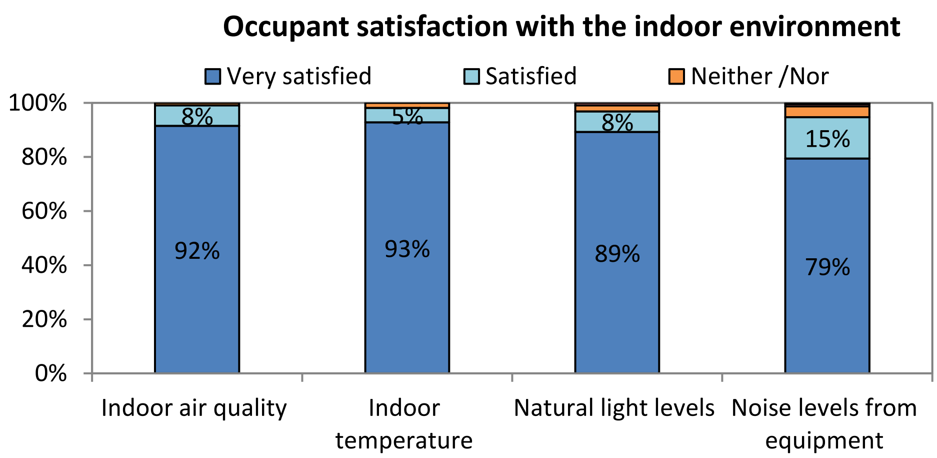


Figure 27. Reported satisfaction with the indoor environment

Overall, occupants were generally satisfied with the indoor environment, with 79-92% stating they were very satisfied with indoor air quality, indoor temperature, natural light levels and noise (from equipment) in their home (see figure 27).

Presence and understanding of carbon dioxide monitoring equipment in the home

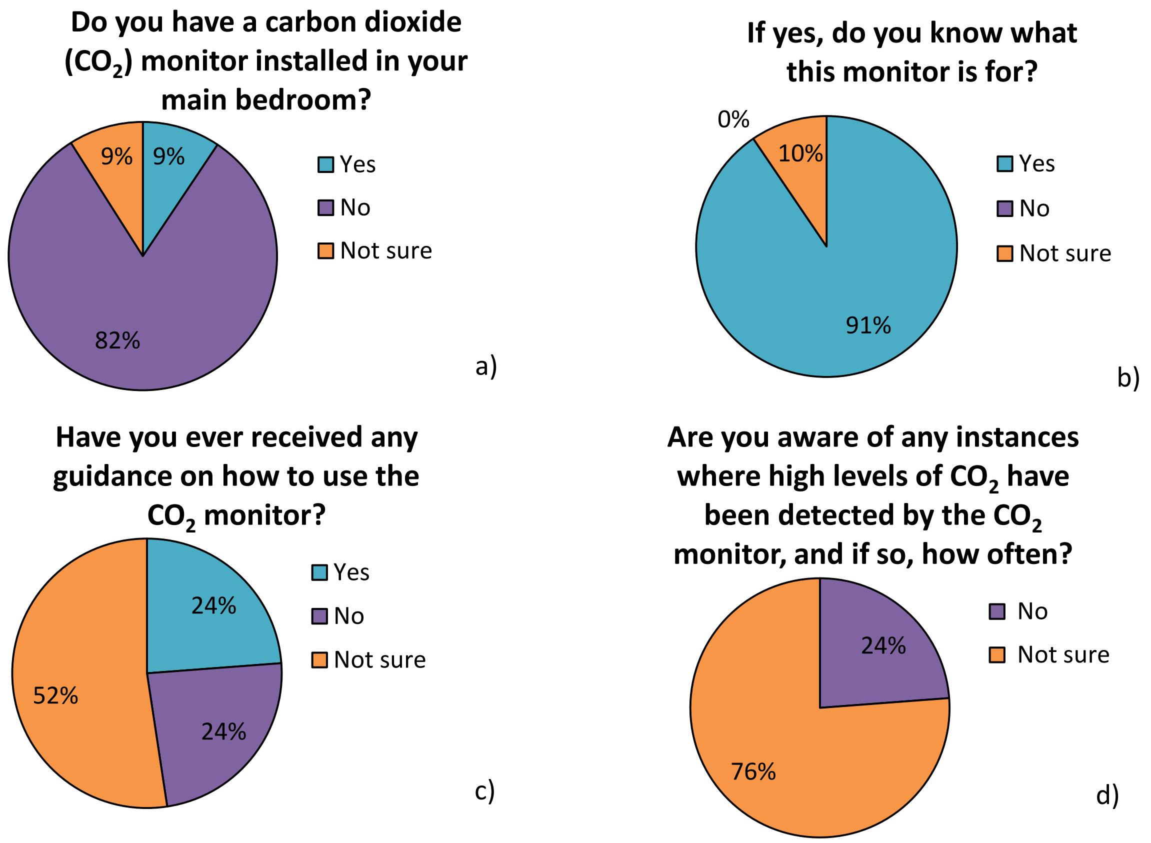


Figure 28. Presence and understanding of carbon dioxide monitoring equipment

Changes to the Scottish Technical Handbooks in 2015 saw the introduction of the requirement for carbon dioxide monitoring equipment to be installed in the main bedroom of all new dwellings constructed to an airtightness value not exceeding $15m^3/hr/m^2$, to help increase awareness of the risks of poor indoor air quality and ventilation in the home. Whilst only a small number of dwellings surveyed were constructed to 2015 standards, the study provided the opportunity to explore the impact of this change in regulations within a small sample of dwellings.

Overall, 9% of households' surveyed (21 homes) reported having a CO_2 monitor installed in their main bedroom. Of these, 91% (8.5% of total / 19 households) stated that they knew what the monitor was for. The responses varied from i) to measure / monitoring CO_2 (16 homes), ii) for health and safety (2 homes), or iii) gas poisoning (1 home). This suggests there may have been some confusion regarding the purpose of the monitor, with some possibly confusing these with carbon monoxide detectors in the home.

The majority of homes with carbon dioxide monitoring equipment stated that they were not sure if they received any guidance on how to use these (11 homes). Those that received guidance (5 homes) were asked to explain what this was. The responses were as follows:

- *Showed me how it works*
- *Full instructions from the building manager*
- *Can't remember*
- *Can't remember*
- *Got it from the building manager when moved in.*

Similarly, households with carbon dioxide monitoring equipment were asked if they were aware of any instances where high levels of CO_2 were detected and how often. All households stated either no (5 homes) or not sure (16 homes). The results suggest a lack of awareness and understanding of the carbon dioxide monitoring equipment in the investigated homes, however further work is required to explore this in more detail with a much larger sample.

4. Monitoring study

Aims and Objectives
The aim of the monitoring study was to obtain measured data on environmental conditions in homes with dMEV systems, to contextualise this in relation to occupancy factors and behaviour and to identify issues of performance. The locations for monitoring were identified from the general survey.

Challenges identified
The environmental monitoring encountered a number of challenges, which impeded the selection and recruitment of suitable households. These are summarised below.

- A predicted uptake of 4:1 was determined for the surveys, similar to the response rate acquired for previous studies. However, out of the initial 223 homes surveyed, only 36 households stated that they were interested in the environmental monitoring.

- Of the homes who expressed interest in the environmental monitoring, there were a large number of withdrawals or nonresponses when subsequently approached for setup of monitoring equipment in these homes.

To address this, the survey company was commissioned to approach additional households and survey only those interested in the detailed monitoring. This brought the sample number up to 44.

However, as there were still a high number of withdrawals, the survey company were commissioned to carry out additional surveying to identify 15 more homes specifically interested in the detailed monitoring. This time, they were asked to arrange a suitable date and time for equipment set up with the occupant, which helped to reduce the number of withdrawals / nonresponses.

Sample selection
The sample was confined geographically for logistical reasons but nevertheless included a range of house types that represent new-build stock, including differing building typologies (flats and houses) and varying aspects. Detailed monitoring was undertaken in the selected dwellings over a period of approximately one week during the winter season (2017/2018).

Initial walk through
An initial walk-through identified the following:

i) the positioning of trickle vents
ii) dMEV system and status
iii) confirmation of floor plan layout
iv) door undercut area
v) any occlusion of openings
vi) window conditions

A photographic survey was performed (with prior occupant consent) to record dwelling conditions. Dwellings were monitored concurrently where possible. Ambient conditions were monitored using local monitoring stations and Tinytag sensors.

Monitoring conditions
Where trickle vents were found to be in the closed position, this was noted before trickle vents were opened, to minimise confounding variables and ensure comparable conditions throughout the sample.

Where dMEV systems were found to be turned off when visiting the property, the researcher identified the reasons why the system had been deactivated and, if suitable, the systems were reactivated before monitoring. Similarly, if flow rates were found to be insufficient, these were noted before flow rates were readjusted, with prior occupant consent, to meet those detailed in the Technical Handbook (where possible).

Where dwellings recruited for monitoring were found to have a trickle vent area larger than 2,500 mm^2, these were included in the study and used as a comparative dataset to explore the impact of varying trickle ventilation provision on overall ventilation effectiveness.

Environmental monitoring
Environmental monitors were installed by a researcher in habitable rooms for a period of approximately one week. Temperature, relative humidity and carbon dioxide levels were monitored simultaneously at approximately 1m from finished floor level (where possible, depending on room use), following a methodology adopted by previous monitoring studies. Care was taken to ensure that the equipment was installed away from direct heat sources, inlets or extract vents, and in a way that did not affect the normal use of the room.

Occupant diaries were utilised to capture information on occupant behaviour during the measurement period, in particular, ventilation behaviour in the form of opening / closing windows and trickle vents and/or boosting the ventilation rate. Monitors were collected after the measurement period, along with the occupant diary.

dMEV air flow rates
Airflow measurements of mechanical ventilation systems were performed using a powered air volume flow meter (Observator) under trickle and 'high boost' conditions. These measurements were repeated three times for each system and recorded in a survey form.

Dwelling characteristics
Building information was acquired from Midlothian Council or the architectural practices involved in the design of the selected housing developments. Floor plans for each dwelling type are presented in Appendix D. Characteristics of the monitored dwellings are provided in Table 3. Airtightness data was ascertained by 'as-designed' figures where 'as-built' data was not available (17 out of 41 properties). Airtightness data in most cases represent average values for each development.

Table 3. Dwelling characteristics: monitored dwellings

	Code	Building warrant year	Description	SAP	DER	Airtightness
1	E01	2014	Erect 3 apt house	B84	16.46	4.0*
2	E02	2014	Erect 4 apt house	B84	16.24	4.0*
3	E03	2014	Erect 2 apt house	B84	15.93	4.0*
4	E04	2014	Erect 3 apt house	B83	18.06	4.0*
5	E05	2014	Erect 3 apt house	B83	16.89	4.0*
6	E06	2014	Erect 3 apt house	B83	16.80	4.0*
7	M01	2010	Erect 4 apt house	84B	16.29	4.84⁺
8	M02	2010	Erect 4 apt house	83B	17.72	4.84⁺
9	M03	2010	Erect 4 apt house	83B	17.72	4.84⁺
10	M04	2010	Erect 3 apt house	84B	16.55	4.58⁺
11	M05	2010	Erect 6 apt house	84B	15.56	4.58⁺
12	M06	2010	Erect 6 apt house	84B	15.46	4.84⁺
13	M07	2010	Erect 6 apt house	83B	16.57	4.58⁺
14	M08	2010	Erect 4apt house	84B	16.29	4.84⁺
15	M09	2010	Erect 6apt house	84B	15.63	4.84⁺
16	M10	2013	Erect 3 apt GF flat	n.a	n.a	4.59⁺
17	M11	2013	Erect 4 apt house	83B	17.48	4.17⁺
18	M12	2010	Erect 6 apt house	83B	17.07	4.58⁺
19	M13	2010	Erect 3 apt house	84B	16.55	4.84⁺
20	M14	2010	Erect 6 apt house	84B	15.63	4.84⁺
21	M15	2013	Erect 2 apt GF flat	n.a	n.a	4.59⁺
22	M16	2013	Erect 2 apt flat	n/a	18.36	4.69⁺
23	M17	2015	Erect 1 apt FF studio flat	81B	21.6	4.59⁺
24	M18	2015	Erect 2 apt TF flat	83B	17.48	4.59⁺
25	M19	2014	Erect 3 apt GF flat	82B	19.37	4.46⁺
26	M20	2010	Erect 6 apt house	84B	15.63	4.58⁺
27	M21	2014	Erect 3 apt FF flat	84B	16.35	4.46⁺
28	M22	2010	Erect 3 apt house	83B	18.09	5.00*
29	M23	2010	Erect 3 apt house	84B	16.55	5.00*
30	M24	2015	Erect 3 apt GF flat	82B	19.19	4.71⁺
31	M25	2010	Erect 6 apt house	84B	15.66	5.00*
32	M26	2010	Erect 4 apt house	83B	17.72	5.00*
33	M27	2010	Erect 5 apt house	84B	15.36	5.00*
34	M28	2010	Erect 5 apt house	83B	17.48	5.00*
35	M29	2010	Erect 6 apt house	83B	17.07	5.00*
36	M30	2010	Erect 3 apt house	83B	18.09	5.00*
37	M31	2013	Erect 4 apt house	83B	17.48	4.17⁺
38	M32	2010	Erect 6 apt house	84B	15.66	5.00*
39	M33	2010	Erect 6 apt house	83B	17.07	5.00*
40	B01	2015	Erect 5 apt house	85B	n.a	4.27
41	B02	2014	Erect 5 apt house	84B	16.0	n.a

*As designed airtightness
⁺Average airtightness for development as a whole
n.a Information not available

Results of environmental monitoring

Commissioning and operation in practice

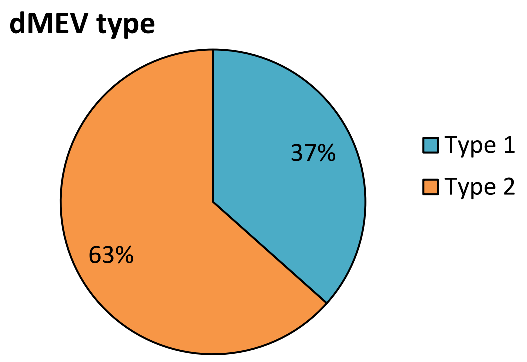


Figure 27. dMEV type (monitored dwellings)

An initial walk through of the properties identified the type of dMEV system installed and the status of the dMEV system. Out of the monitored dwellings, 37% had ‘Type 1’ systems and 63% had ‘Type 2’ systems (see figure 27).

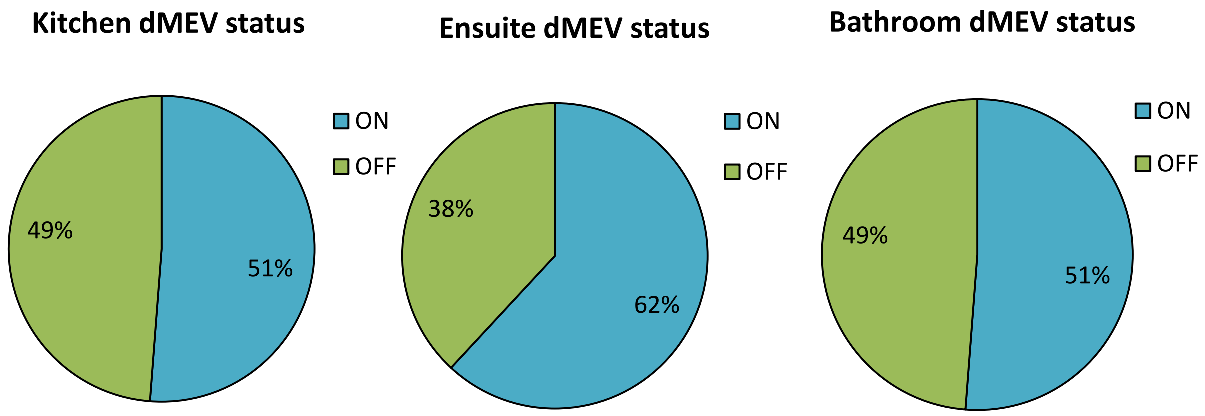


Figure 28. dMEV status (monitored homes)

The walk through revealed a significant proportion of the dMEV systems had been turned off by the building occupants (kitchen: 49%, bathroom: 49%, ensuite: 38% - see Figure 28). A pattern was evident; where households turned off dMEV systems in the kitchen, the majority also turned off the dMEV system in the main bathroom (90%). Similarly, where systems had been deactivated in the main bathroom, 73% of households had also turned off the dMEV unit in the ensuite (where present). Overall, 37% of households had deactivated all dMEV systems in their home.

Where systems were found to be turned off, the researcher(s) enquired as to why the systems had been deactivated and asked the occupants for permission to reactivate the systems for the purpose of the monitoring. As illustrated in Figure 29, 54% of homes monitored (22 dwellings) had deactivated dMEV units because of noise (7 homes with Type 1 systems and 15 homes with Type 2 systems). Noise measurements were not performed in all monitored dwellings, therefore it is not clear if these systems exceeded the maximum level of 30 $dBL_{Aeq,T}$ as set out in the Scottish Technical Handbook.

The percentage of households deactivating dMEV systems in practice was found to be much higher than reported during the household survey (56% compared to 3%). This is reflective of other studies which tend to find that deactivating mechanical systems, particularly due to noise, is common. It is possible that the use of the term ‘deactivating’ in the general survey may have been misleading, and that use of a provided switch was part of normal operation. It is also possible that occupants are aware that it is something that should be avoided, and under report accordingly.

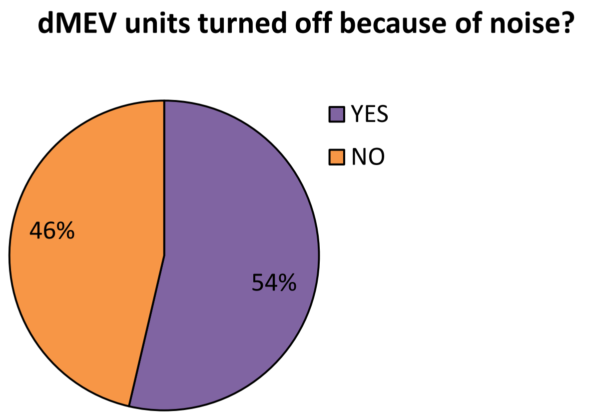


Figure 29. Percentage of homes that had turned off dMEV systems because of noise

Air flow rate measurements were taken before environmental monitors were installed, to ensure dMEV systems were performing as expected. Figure 30 presents the results. As illustrated, dMEV systems did not meet required airflow rates under trickle (normal) mode in 42% of kitchens, 48% of ensuites, 34% of bathrooms and 17% of WCs monitored. These values take into account the measurement accuracy (+/- 5%) required by the Building Standards Supporting Guidance for Domestic Ventilation (2017)[14]. The findings may be attributed to a number of factors, such as poor design, inadequate installation, poor commissioning, occupant interference (adjusting flow rates), and/or inadequate maintenance (dirty grilles, ducts etc.).

In the majority of dwellings monitored, measured airflow rates exceeded the minimum required airflow rates (under trickle mode) by more than 15%. Whilst this should help to improve ventilation levels, this may result in higher energy consumption and noise issues, particularly for systems installed in rooms adjacent to bedrooms.

[14] Building Standards Supporting Guidance for Domestic Ventilation (2017), 2nd Edition, The Scottish Government, available http://www.gov.scot/Resource/0052/00527695.pdf

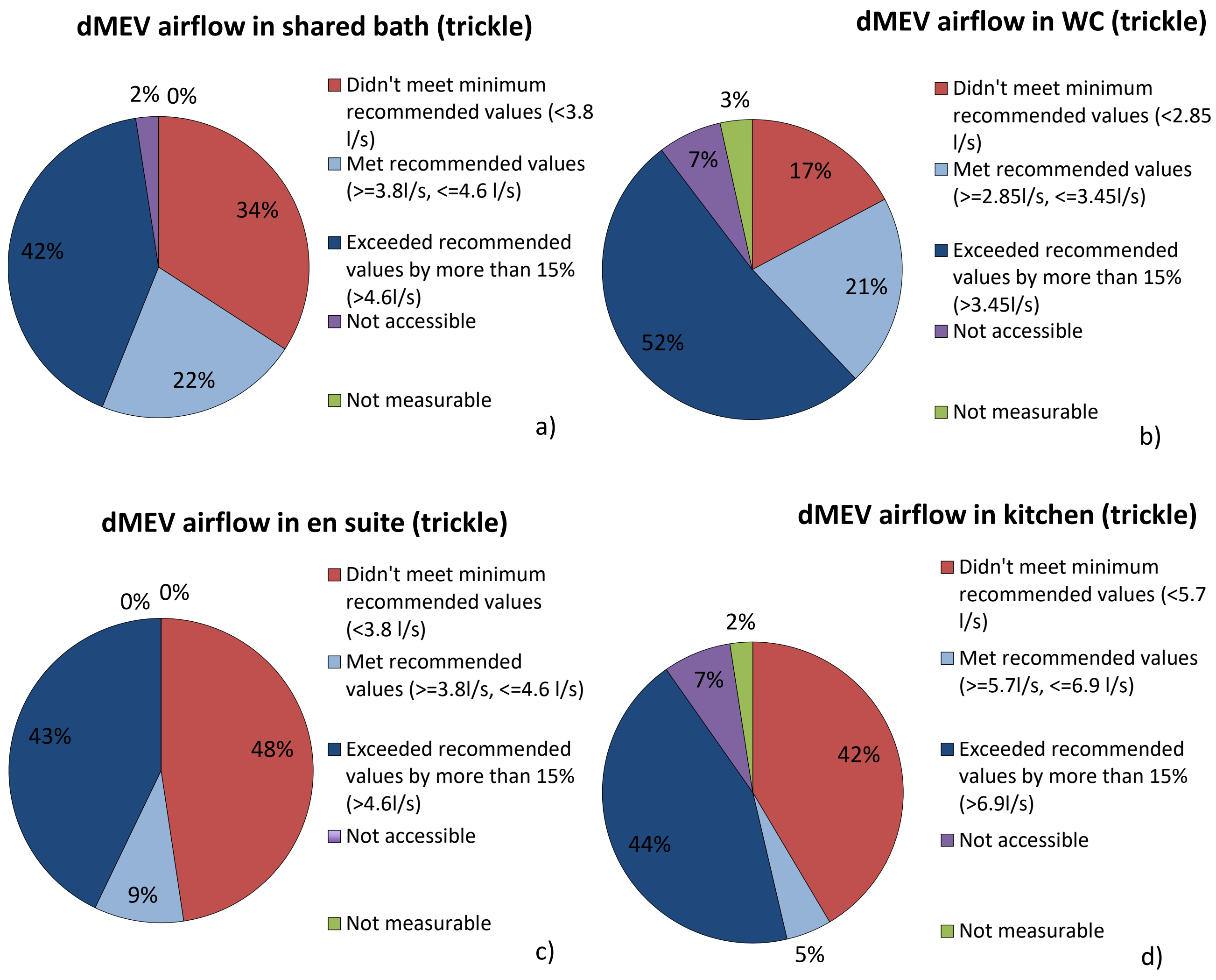


Figure 30. Measured airflow rates under normal (trickle) mode in a) shared bathroom, b) WC, c) ensuite and d) kitchen

Trickle ventilation provision

The Local Authority Building Standards Scotland (LABSS) type approval guidelines indicate that where dMEV units will be short-circuited by fresh air from trickle vents in moisture producing rooms, the wet area should not be fitted with a trickle ventilator and a door undercut of at least 8mm should be provided instead.

Trickle ventilators were provided in the bathroom / shower room in 7 homes (17%) and in the kitchen or kitchen-dining room in 15 homes (37%) monitored (see Figure 31). In homes with an open plan kitchen and living room (8 homes), all were found to be fitted with trickle ventilator(s).

It may be that this would improve the efficacy of removing moisture from these rooms, which may be beneficial to the household overall. Whilst not all of these homes had a reduced trickle ventilation provision of 2,500mm^2, the results nevertheless indicate that - where these trickle vents are open - the likelihood of short circuiting of ventilation provision (where make up air for the extract is drawn from the trickle vent in the room) would undermine the ability of these systems to provide a ‘whole house’ solution (see for example, figure 32).

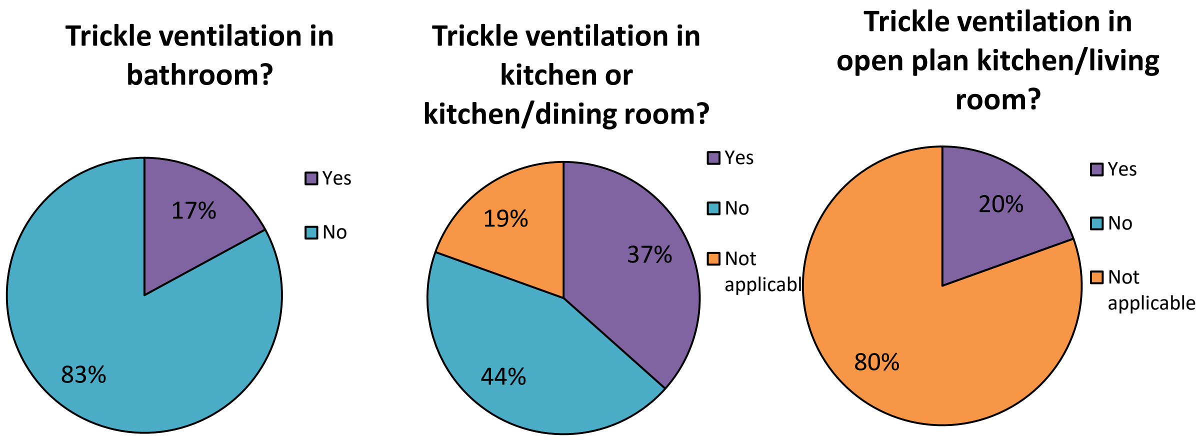


Figure 31. Trickle ventilation provision in moisture producing rooms

Figure 32. Examples of short circuiting, a) M21 Kitchen, b) M20 Kitchen c) M19 Bathroom d) M17 Bathroom e) M18 Bathroom

Main bedroom conditions

During the initial walk-through, trickle ventilator area and door undercut provision to each room was measured and recorded. The findings are presented below.

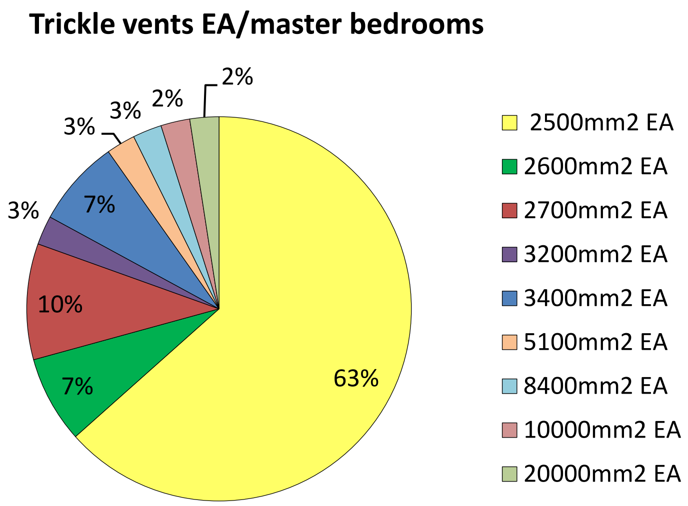


Figure 33. Equivalent area of trickle ventilators in main bedrooms

As illustrated in figure 33, 63% of dwellings monitored (26 homes) had a reduced trickle ventilation provision of 2,500mm^2 in the main bedroom. Ensuites were present in the main bedroom of 19 homes (46%). Trickle ventilators had not been fitted in any ensuites adjacent to the main bedrooms monitored.

The measured undercut of the main door to the bedroom was found to be less than the required 8mm / 8,000mm^2 clear area in 20% of households. Whilst in some cases this was due to thicker than expected floor coverings, it was also clear that many undercuts had not been adequately sized (i.e. ‘hard’ sizes too close), as illustrated in figure 35.

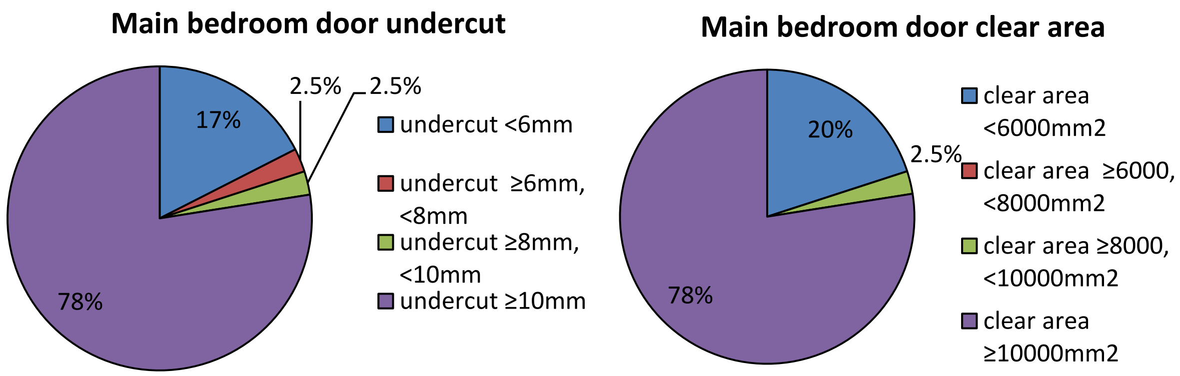


Figure 34. Main bedroom door undercut

Contextual information on main bedroom trickle ventilation provision, occupancy levels, room volume and door undercuts is provided for each home in Table 4. As illustrated, two main bedrooms were found to have reduced trickle ventilation provision (<2500mm^2) and door undercuts less than the required 8mm / 8,000mm^2 free area.

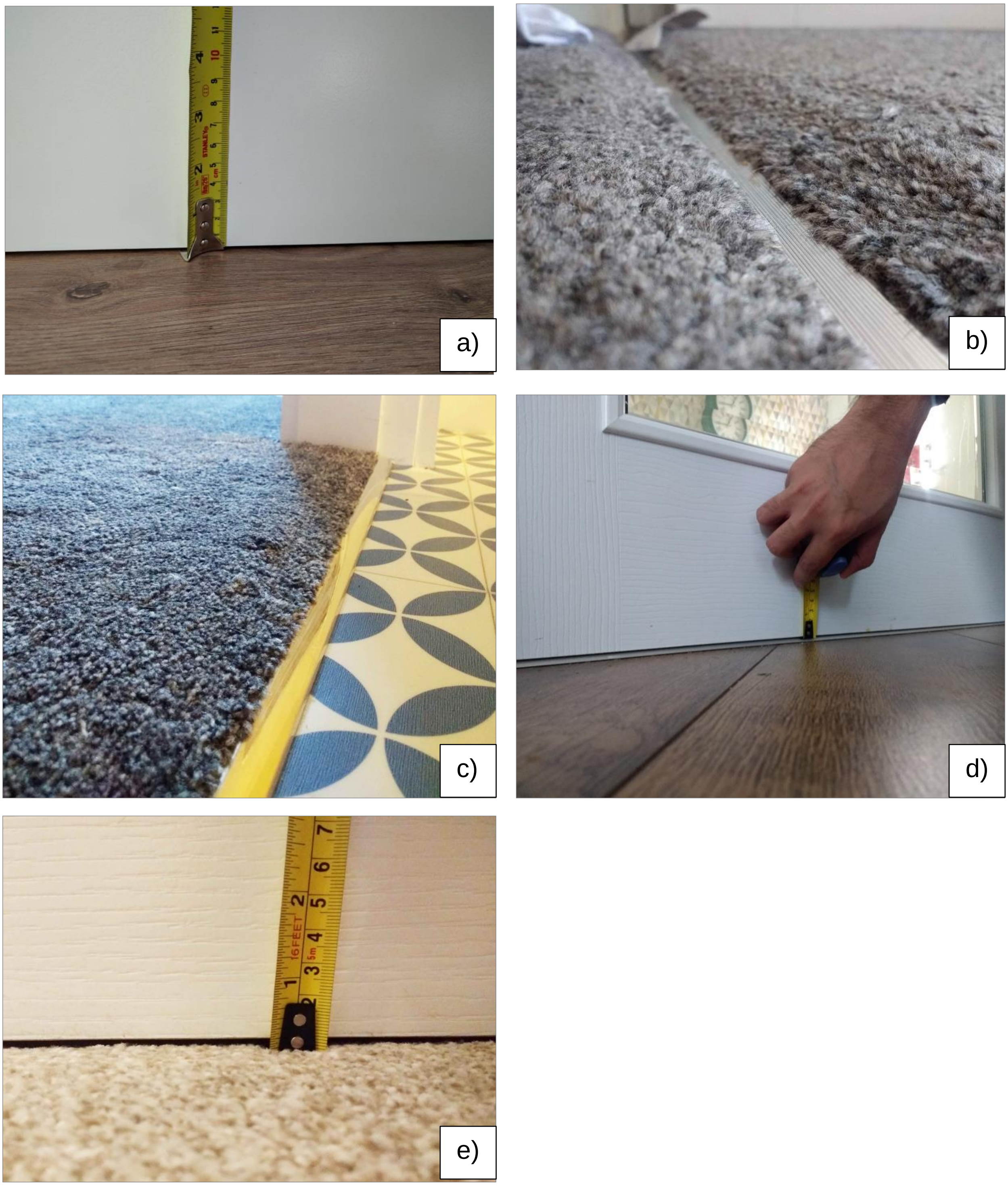


Figure 35. Examples of insufficient undercuts in a) B02, b) B02 (study room), c) B01 main bathroom, d)M01, and e) M21 main bedroom

Table 4. Main bedroom conditions during monitoring

Code	Main Bed Trickle vent EA	Main Bed Trickle Vent on collection	dMEV unit position (serving Main Bed)	Main Bed Window position night	Main Bed Door undercut	Main Bed night time Occupancy	Main Bed Volume (m3)	Distance from TV to dMEV in Main Bed (m)
E01	2700	Open	ON	Open	4 mm	2	29.18	6.7
E02	10000	Closed	ON	Closed	3 mm	2	25.53	7
E03	3400	Open	ON	Closed	3 mm	2	23.5	8.9
M01	2500	Closed	ON	Closed	15 mm	2 / 3	28.42	5
M02	2500	Closed	ON	Closed	16 mm	2	29.21	5.4
M03	2500	Closed	ON	Closed	16 mm	2 / 3	29.21	5.4
M04	2500	Closed	OFF	Closed	14 mm	2	33.08	6.4
M05	2500	Closed	OFF	Closed	16 mm	2	25.35	5.1
M06	2500	Closed	OFF	Closed	21 mm	2	21	6.3
M07	2500	Open	ON	Closed	16 mm	2	28.54	4.9
M08	2500	Open	ON	Closed	16 mm	2	29.85	5
M09	2500	Open	ON	Closed	20 mm	1 / 2	37.04	5.3
M10	2600	Open	OFF	Open	2 mm	2	25.3	8.2
M11	2500	Open	OFF	Closed	14 mm	2 / 3	30.42	6.15
M12	2500	Open	ON	Closed	17 mm	2	22.6	4.6
E04	2700	Open	OFF	Closed	9 mm	2	29.48	7.6
M13	2500	Open	OFF	Closed	15 mm	2	32.9	6.4
M14	2500	Closed	ON	Open	23 mm	2	36.43	5.3
M15	2600	Closed	OFF	Closed	17 mm	1	17.14	5.9
M16	2600	Open	ON	Varies	20 mm	2	26.18	6.7
M17	5100	Open	ON	Open	*Studio*	1 / 2	75.37	5.1
M18	3400	Open	ON	Varies	24 mm	1	26.42	7.3
M19	3200	Open	ON	Closed	19 mm	1	24.85	6.8
B01	20000	Varies	ON	Closed	16 mm	2 / 3	30.33	7.7
M20	2500	Open	OFF	Varies	18 mm	2	37.6	5.3
M21	3400	Open	ON	Varies	2 mm	1	30.42	10.7
B02	8400	Open	ON	Closed	14 mm	2 / 3	35.5	3.7
E05	2700	Closed	OFF	Closed	13 mm	1	28.42	8.7
M22	2500	Open	OFF	Closed	18 mm	1	32.9	6.4
M23	2500	Closed	OFF	Closed	19 mm	2 / 3	32.9	6.4
M24	2500	Open	OFF	Closed	0 mm	2 / 3	21.65	7.9
M25	2500	Open	OFF	Closed	14 mm	2	36.82	5.9
M26	2500	Open	ON	Closed	16 mm	2	29.48	5.4
M27	2500	Closed	OFF	Closed	19 mm	2	31.21	6.1
M28	2500	Closed	OFF	Closed	19 mm	1	31.21	6.1
M29	2500	Closed	OFF	Open	16 mm	2	22.6	4.6
M30	2500	Open	OFF	Closed	6 mm	1 / 2	32.9	6.4
M31	2500	Open	ON	Closed	19 mm	2	30.42	6.15
M32	2500	Open	ON	Closed	16 mm	2	36.82	5.9
M33	2500	Open	OFF	Closed	14 mm	2	22.6	4.6
E06	2700	Open	ON	Closed	5 mm	2 / 3	27.21	9

Main bedroom carbon dioxide levels

Figure 36. Night time carbon dioxide levels in the main bedroom. *RTV = Reduced Trickle Ventilation, ENS = With ensuite, U<8 = main bedroom door undercut less than 8 mm

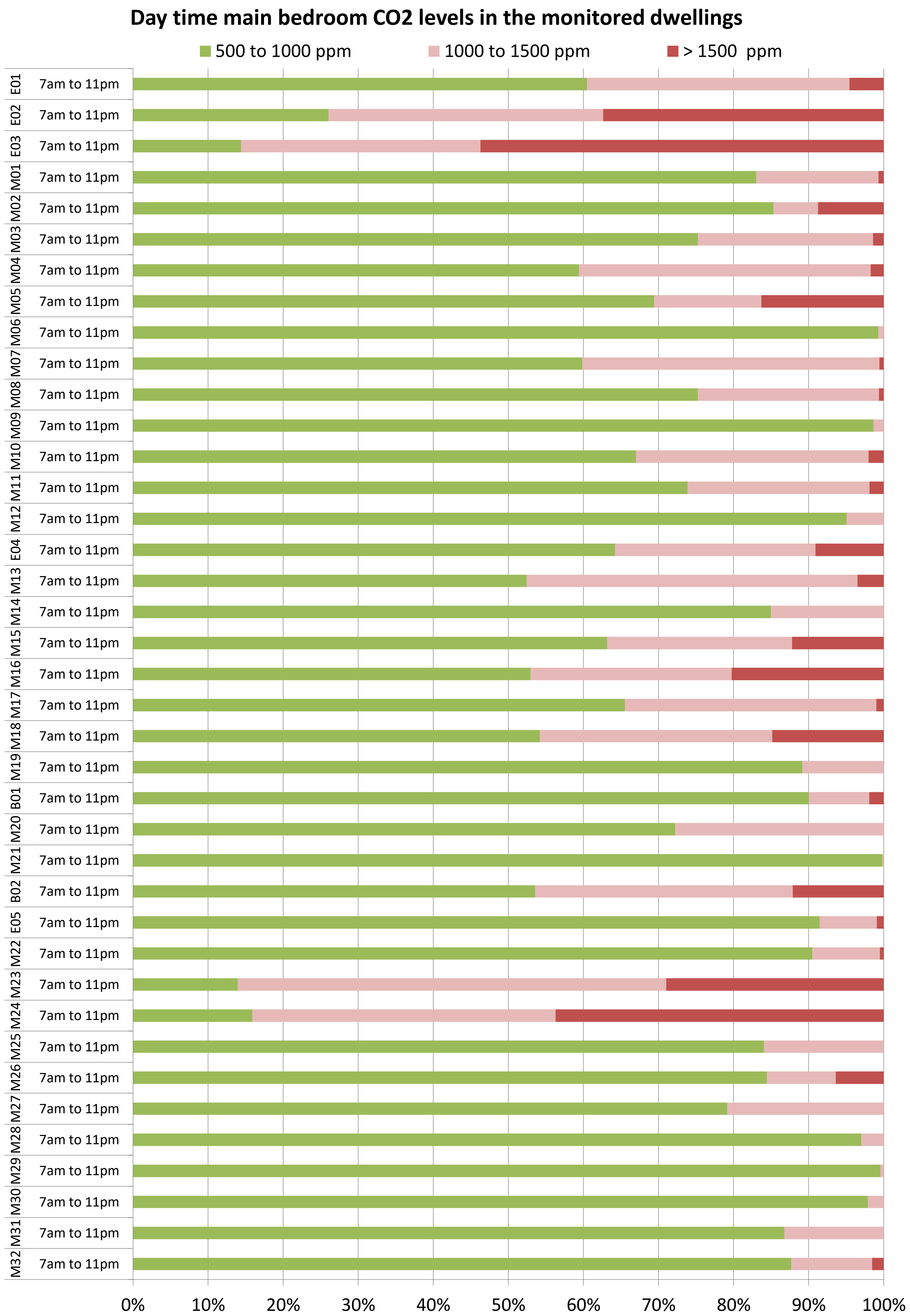
Figure 36 presents night time (11pm – 7am) carbon dioxide levels in 41 dwellings monitored. The red bars represent the percentage of time carbon dioxide levels exceeded 1,500ppm, the pink bars 1,000 – 1,500ppm and the green bars 500 – 1,000ppm.

As illustrated, high night-time (main) bedroom carbon dioxide levels were found in over half of the monitored dwellings, where levels exceeded 1,000ppm for more than 50% of the time. In comparison, daytime carbon dioxide levels in the main bedroom were much lower (see figure 37), yet these still indicated a cause for concern in four dwellings (EO2, EO3, M23, M24), but would suggest daytime occupancy of these rooms. Daytime living room carbon dioxide levels are presented in Figure 38. Overall, CO_2 levels were much lower in the living room compared to the main bedroom. It is unlikely that living rooms experience the same degree of uninterrupted occupancy as bedrooms, and factors such as door opening with people coming and going are likely to influence CO_2 levels.

It is important to note that flow rates of dMEV systems had been corrected (where possible) before environmental monitoring and all trickle vents had been opened. Therefore, conditions observed were assumed to be best-case scenarios, where ventilation systems were performing ‘as intended’. Nevertheless, some households were found to have made further adjustments to the systems / trickle vents over the monitoring period, given that some dMEV systems were found to be deactivated and/or trickle vents closed when revisiting properties to collect monitoring equipment (see Table 4), which may have affected the results.

Overall, main bedroom carbon dioxide levels peaked above 1,000 ppm in all 41 homes monitored. Mean levels (over the one week period) exceeded 1,000 ppm in 13 homes (32%). In the living room, carbon dioxide levels peaked above 1,000ppm in 40 homes (98%), with mean levels exceeding 1,000ppm in 5 homes (12%).

The concentration of carbon dioxide in a room will depend on a number of factors, including ventilation provision, occupancy levels, activity levels, room (air) volume and room conditions (e.g. door open, window open etc.). Carbon dioxide provides a good metric for exposure to occupant-related pollutants, such as bioeffluents. The provision of ventilation for dMEV systems does not take into account occupancy. Further analysis of ventilation effectiveness is provided in Section 5.



Day time main bedroom CO2 levels in the monitored dwellings
500 to 1000 ppm
1000 to 1500 ppm
> 1500 ppm
E01 7am to 11pm
E02 7am to 11pm
E03 7am to 11pm
M01 7am to 11pm
M02 7am to 11pm
M03 7am to 11pm
M04 7am to 11pm
M05 7am to 11pm
M06 7am to 11pm
M07 7am to 11pm
M08 7am to 11pm
M09 7am to 11pm
M10 7am to 11pm
M11 7am to 11pm
M12 7am to 11pm
E04 7am to 11pm
M13 7am to 11pm
M14 7am to 11pm
M15 7am to 11pm
M16 7am to 11pm
M17 7am to 11pm
M18 7am to 11pm
M19 7am to 11pm
B01 7am to 11pm
M20 7am to 11pm
M21 7am to 11pm
B02 7am to 11pm
E05 7am to 11pm
M22 7am to 11pm
M23 7am to 11pm
M24 7am to 11pm
M25 7am to 11pm
M26 7am to 11pm
M27 7am to 11pm
M28 7am to 11pm
M29 7am to 11pm
M30 7am to 11pm
M31 7am to 11pm
M32 7am to 11pm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

Figure 37. Day time carbon dioxide levels in the main bedroom

Figure 38. Day time carbon dioxide levels in the living room

Weekly carbon dioxide levels in selected homes

Analysis of weekly whole house carbon dioxide levels were performed, the results of which are presented below.

It is interesting to note the short peaks of CO_2 levels observed in the kitchen of some dwellings, which was most likely due to the use of a gas cooker, for example in M11 (figure 39).

Carbon dioxide levels - M11

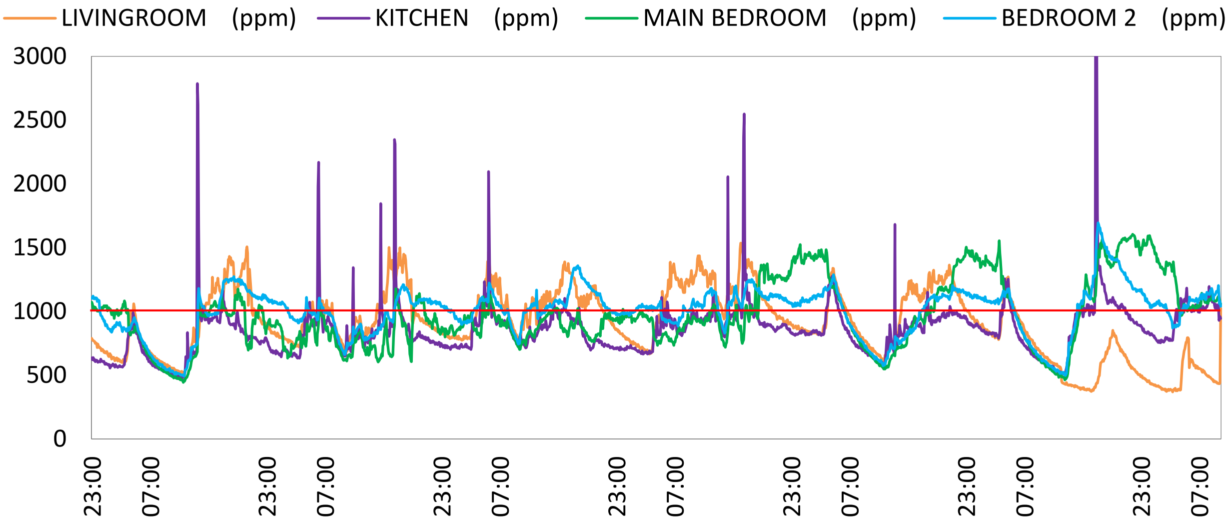


Figure 39*: (3 bedrooms/ terraced house), en-suite bathroom, dMEV units off. Door open, windows closed, trickle vents open, curtains closed in main bedroom.*

In most cases there is a clear distinction between CO_2 levels in the main bedroom and the rest of the home, with night time representing a particular problem. This is more pronounced in cases where the bedroom door was closed at night, for example in E01 or M03 (figure 40 – 41), however was also observed in homes where the bedroom door was open at night, such as the case in M18.

Carbon dioxide levels - E03

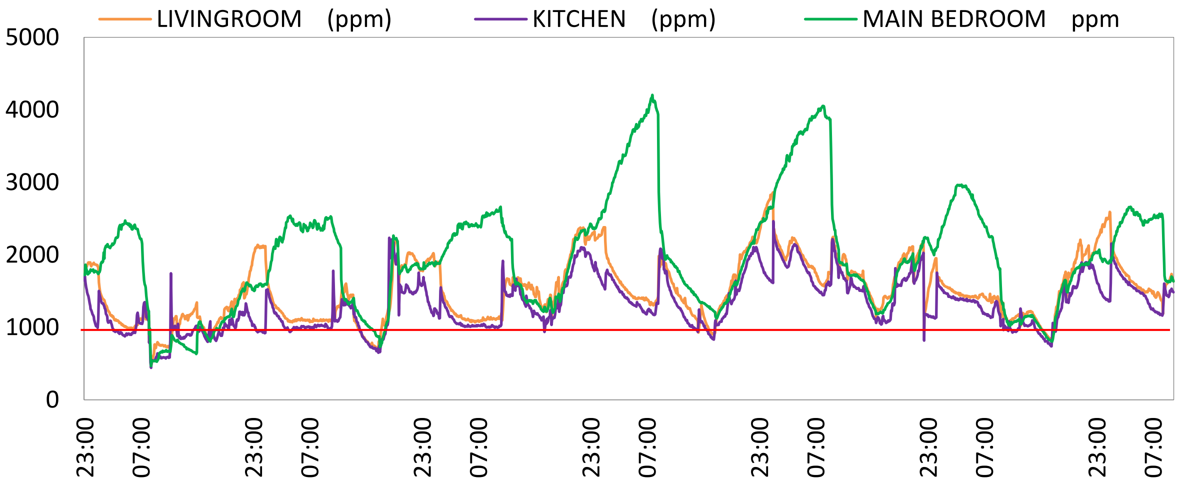


Figure 40. *E03: (ground floor/ 1 bed flat), no en-suite bathroom, dMEV unit on, door closed, windows closed, trickle vents open, curtains closed*

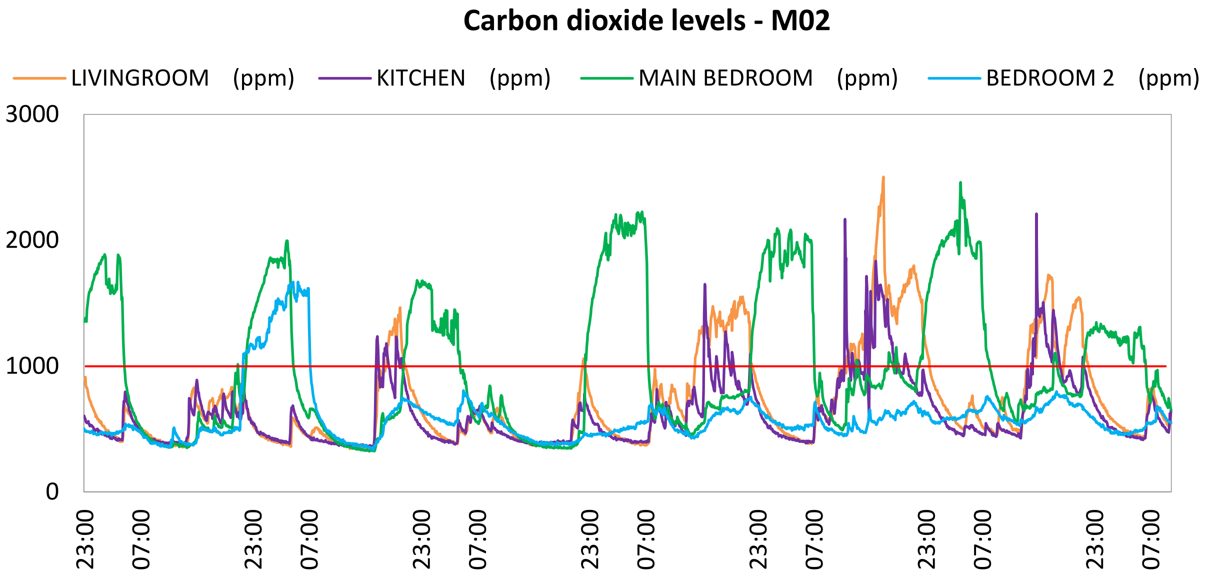


Figure 41. *M02: (3 bed, detached house), en-suite bathroom, dMEV unit on, door closed, windows closed, trickle vents closed, curtains closed*

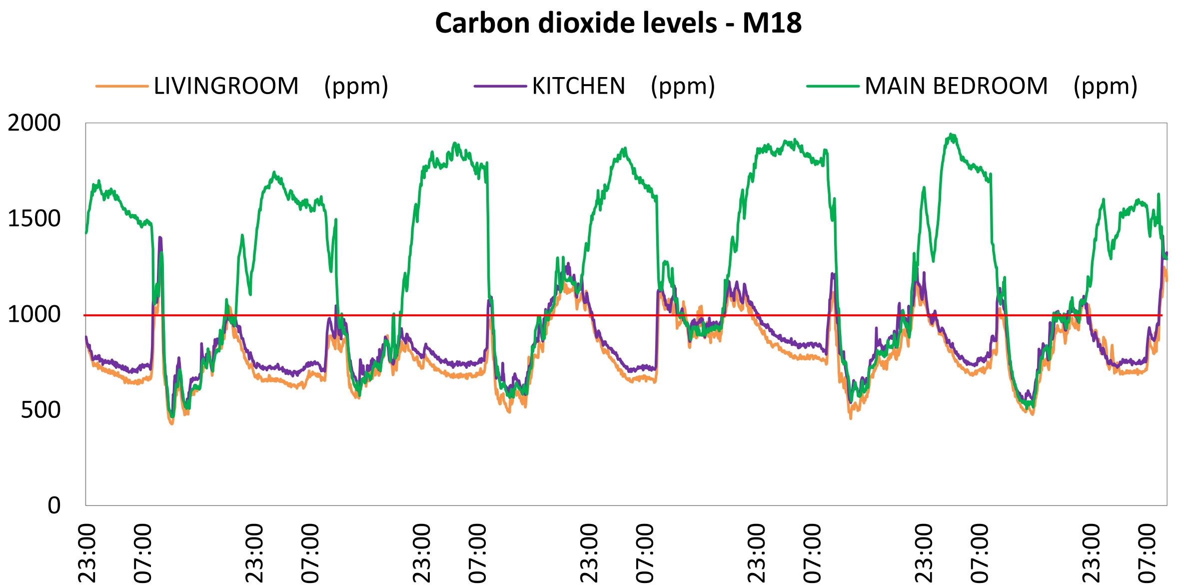


Figure 42. M18: (top floor flat/ 1 bed) no en-suite bathroom, dMEV unit on, bedroom door open, window sometimes open, trickle vents open, curtains closed

Nevertheless, more homogeneous conditions were observed in some homes, where CO_2 levels did not vary significantly between rooms (see for example in E01 and M08 – figures 43 and 44). This is most likely due to occupants opening doors during the monitoring period in these homes (as recorded by the occupant diary), highlighting the importance of overall patterns of use when analysing the results.

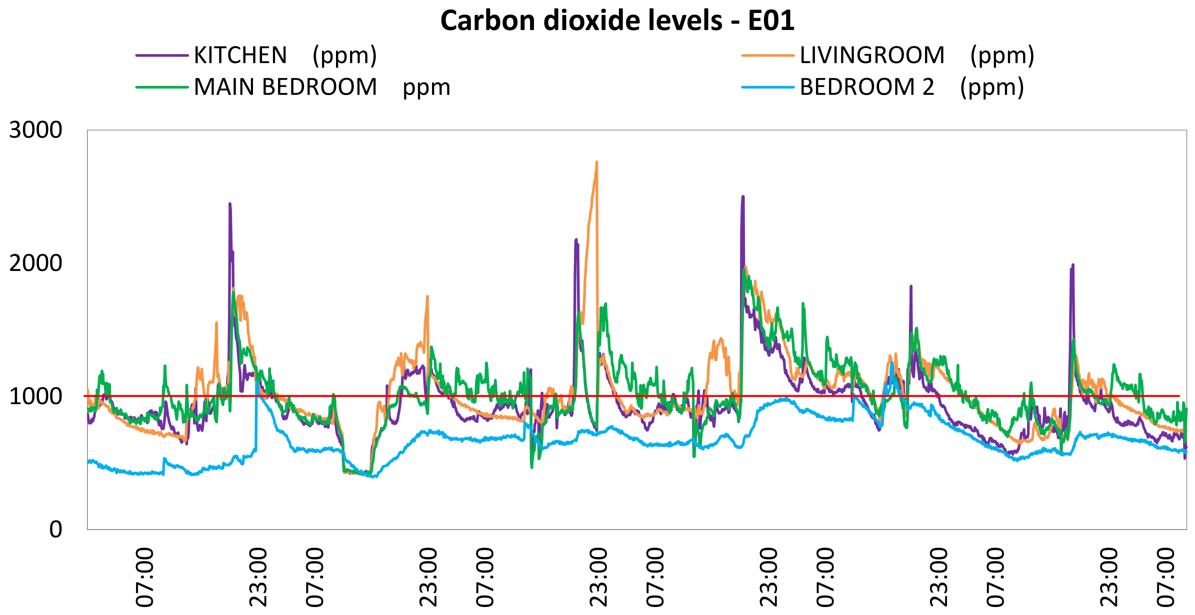


Figure 43. *E01: (ground floor, 2 bed flat), no en-suite bathroom, dMEV unit on, door open, windows closed, trickle vents open, curtains closed*

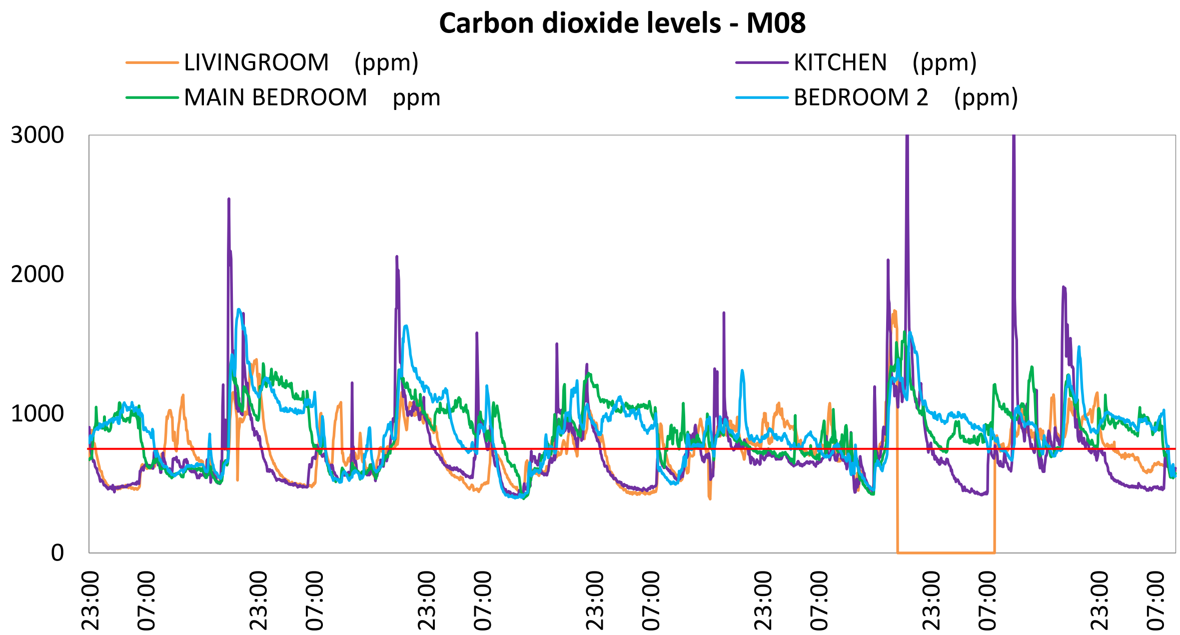


Figure 44. *M08: (3 bed, detached house) en-suite bathroom, dMEV unit off, door open, windows closed, trickle vents open, curtains closed *CO_2 sensor accidentally unplugged by occupants (night six)*

Indoor temperatures

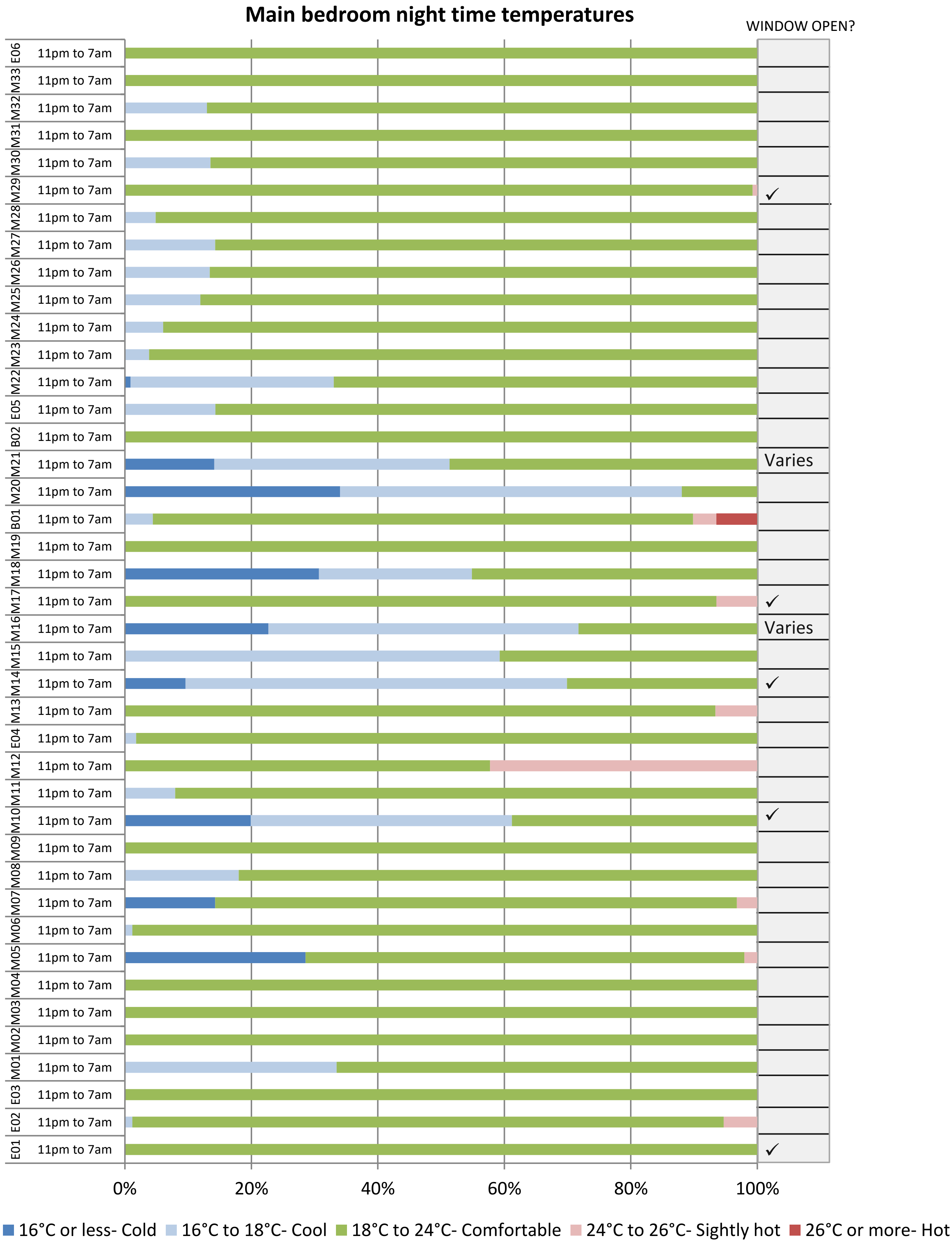


Figure 45. Main bedroom night time temperatures

CIBSE Environmental Design Guide A (2015)[16] recommend customary winter operative temperatures of 17-19°C for bedrooms and 22-23°C for living rooms. Average temperatures between 17-19°C were recorded in 31% of main bedrooms monitored. Nevertheless, average temperatures above 17°C were found in all main bedrooms, highlighting a potential shift in comfort expectations in modern housing.

Attention however should be given to the potential for overheating in bedrooms overnight. Research[17] suggests sleep quality and thermal comfort decrease at temperatures above 24°C, and CIBSE (2015) recommend a maximum night time bedroom temperature of 26°C, unless ceiling fans or means to create air movement are provided. As illustrated in Figure 45, night time temperatures exceeded 24°C in 20% (8 homes) of main bedrooms monitored, with temperatures exceeding 26°C in 1 home (2%).

Window opening – which generally improved ventilation in the main bedroom at night, (as recorded through the occupant diary), did not appear to have a significant effect on night time temperatures. Temperatures were slightly warmer overall in the main bedrooms during the day (mean 19.8°C) compared to at night (mean 19.6°C). The implication from this is that higher ventilation rates in bedrooms at night may not unduly affect comfort or energy consumption, but further investigation would be needed to verify this.

In the living room, average temperatures between 22-23°C (CIBSE recommended threshold) were recorded in 3 dwellings (7%). Recorded living room temperatures remained between 18 - 24°C in 2 homes, with peak temperatures exceeding 26°C in 7 homes (17%) – see Figure 46.

As illustrated in Table 5, there were minimal differences observed between temperature levels recorded in the living room and the main bedroom, suggesting homogeneous thermal conditions in the monitored homes.

Table 5. Average temperatures in monitored living rooms and bedrooms

	Living room (average)	Main bedroom (average)
Peak temperature	23.4	22.7
Minimum temperature	16.1	15.7
Mean temperature	20.0	19.8

[16] CIBSE 2015, Environmental Design: Guide A
[17] Humphreys (1979), 'The influence of season and ambient temperature on human clothing behaviour' in Fanger PO and Valbjorn O (eds.) Indoor Climate (Copenhagen: Danish Building Research)

Day time living room

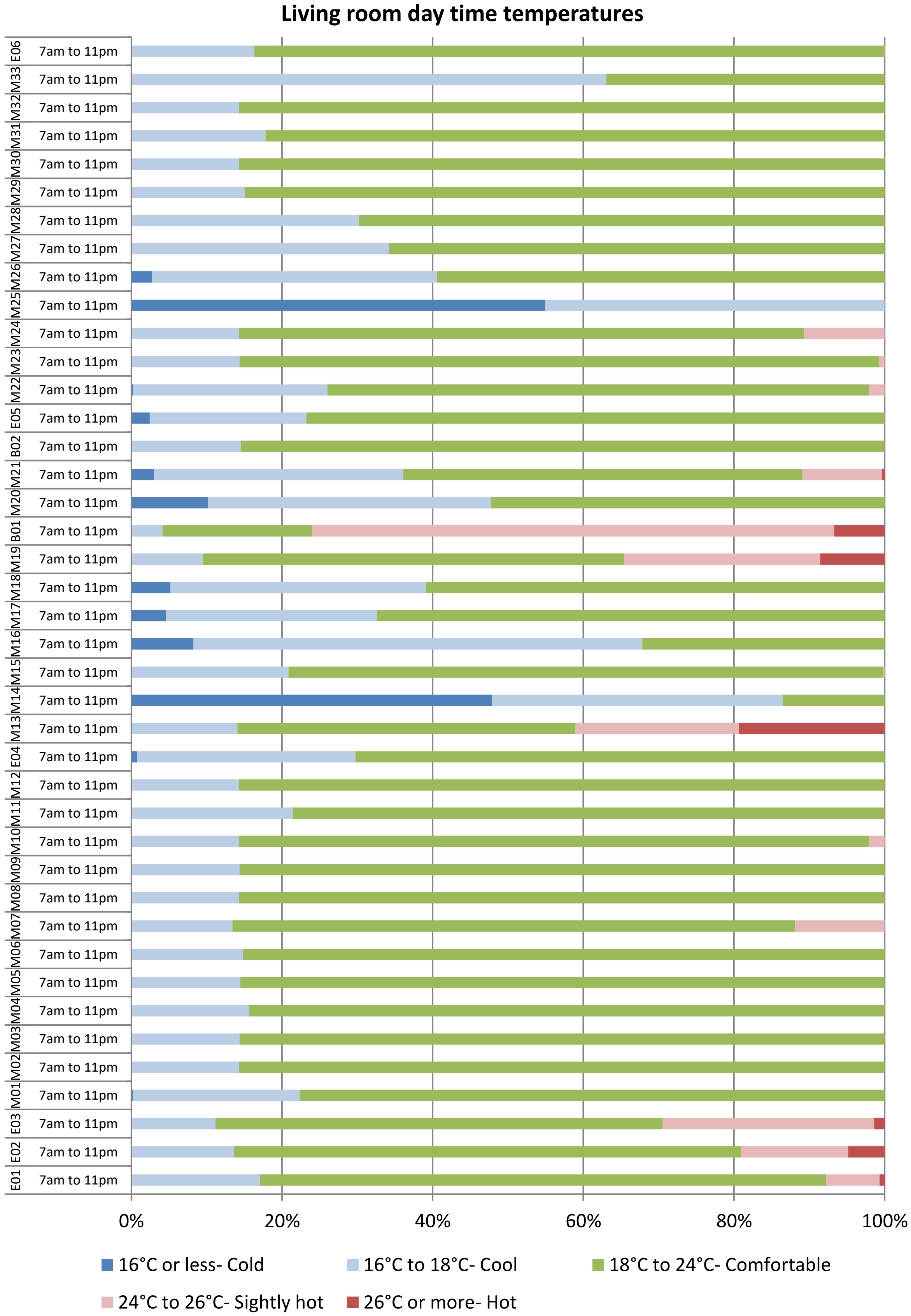


Figure 46. living room temperatures (day time)

Humidity levels indoors

While the results from the CO_2 measurements indicated poor levels of ventilation in the main bedroom, relative humidity levels generally remained within recommended levels, ranging between 30 and 60%RH in 39% of bedrooms. Relative humidity is ratio of the amount of water vapour present in air to the amount needed for saturation at the same temperature, usually expressed as a percentage[18]. Peak levels exceeded 70% RH in 8 main bedrooms monitored (19%), while mean levels exceeded 60% in 1 home (2.4%). Low humidity levels were observed, with average RH levels <40% recorded in 24% of main bedrooms.

In the living room, humidity levels exceeded 70% in 5 homes (12% of dwellings monitored). Humidity levels remained within recommended levels of 30 – 60% in 49% of living rooms monitored. Unlike carbon dioxide levels, humidity levels did not vary significantly between daytime and night. In one home (M24), living room humidity levels were found to be consistently below 30% RH, which may result in comfort concerns associated with dry air, such as dry skin, itchy eyes, irritated sinuses and/or congestion.

Relative humidity is dependent on temperature and high indoor temperatures may mask moisture problems indoors, particularly in warm thermally efficient housing. Higher temperature air can hold more moisture. As described in CIBSE Guide C, the moisture content at 70% RH (and the saturation moisture content) of the air at different temperatures are as follows: 18°C, 9g/kg (13g/kg); 21°C, 11g/kg (16g/kg); 24°C, 13g/kg (19g/kg); 27°C, 16g/kg (23g/kg).

Air at 70% RH and 27°C has almost twice as much moisture than air with 70% RH at 18°C. If 70% RH air at 27°C was cooled to 21°C, for example, it will have 100% RH; if air temperature drops below 21°C there will be condensation. This effect could have implications for the operation of extract ventilators with a humidistat controlled boost mode.

This variation between indoor relative humidity levels and moisture content is illustrated in Figure 47. In the main bedroom, moisture levels were generally higher at night (23:00 – 07:00) (with a few exceptions, as illustrated in Figure 48), most likely attributed to higher occupancy (increased moisture produced through respiration and transpiration) and lower ventilation.

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[18] CIBSE, Guide A: Environmental Design

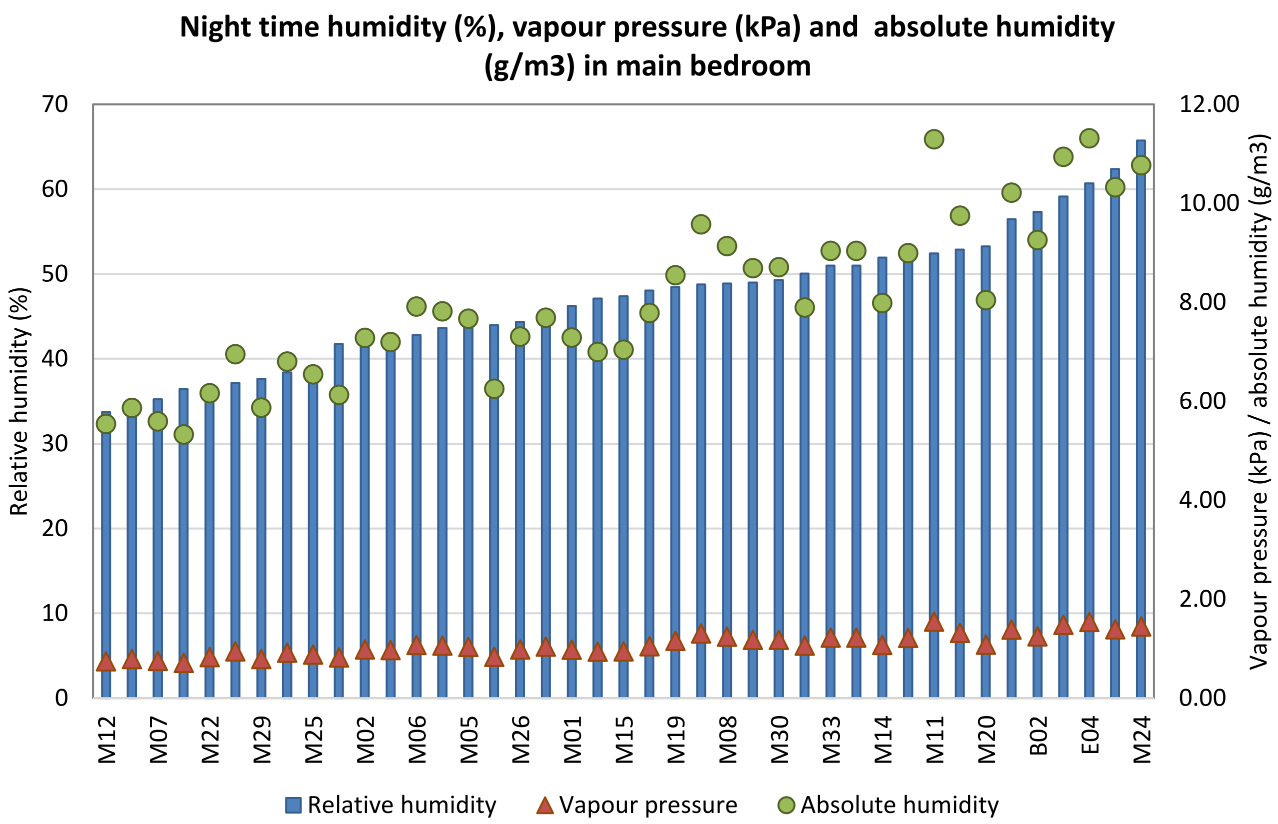


Figure 47. Night time main bedroom RH, vapour pressure and absolute humidity

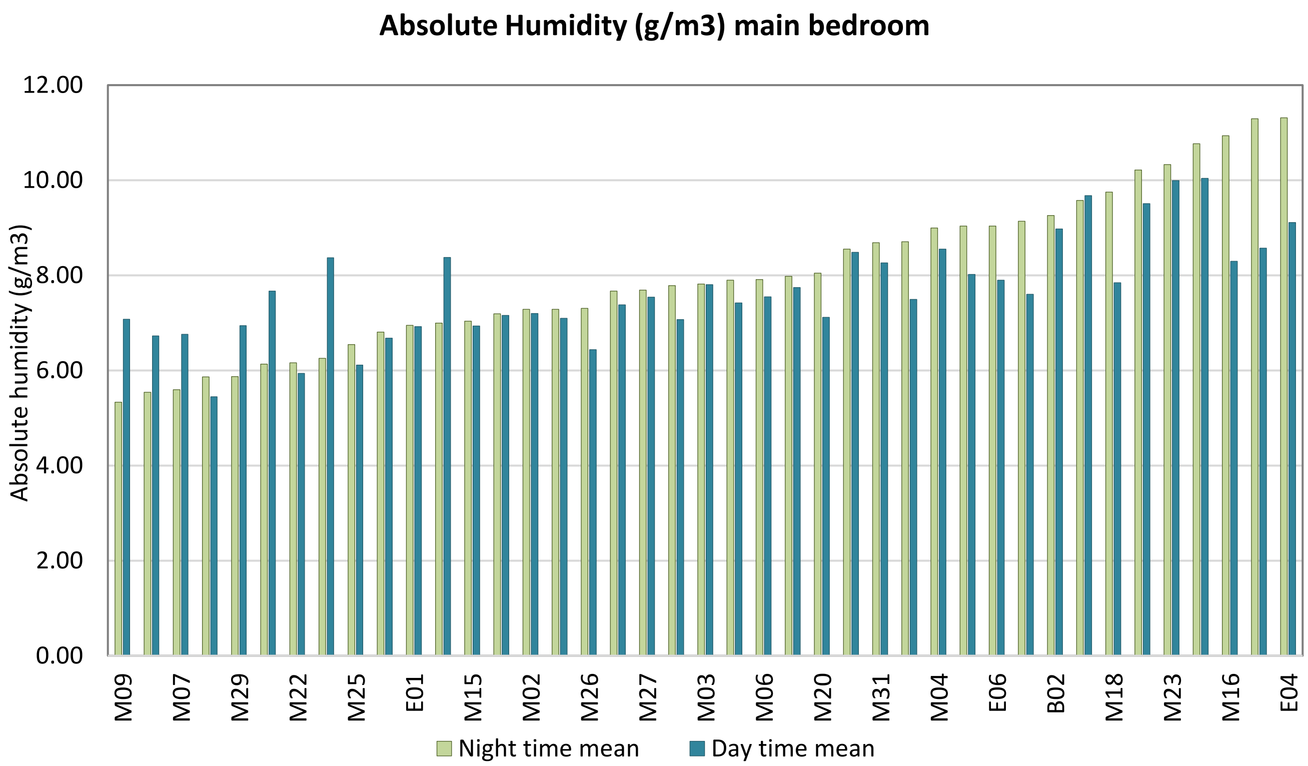


Figure 48. Comparison of average night time and day time absolute humidity (g/m^3)

5. Analysis of ventilation effectiveness

Calculated Ventilation rates for main bedrooms

Ventilation rates were calculated based on standard equations (CIBSE Knowledge Series) with assumed standard activity levels and body masses (CIBSE A). The table and figures below show the results. A wide variation in effective ventilation rates per person were observed ranging from 1.4 to 9.7 l/s/p across the surveyed properties. Room air change rates varied between 0.3 and 2.4 ac/h based on the same calculations (note these are room air change rates based on master bedroom volumes and not whole building air change rates). Ventilation performance is very variable; the following sections investigate the drivers for this variation.

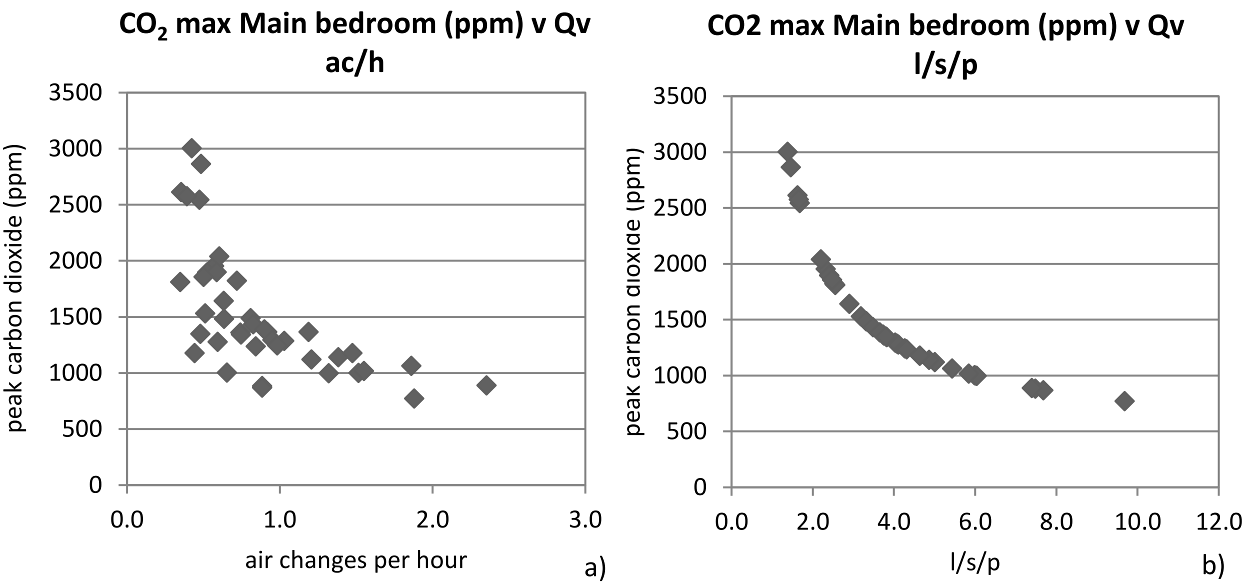


Figure 49. a) Average daily maximum CO_2 levels vs. air changes per hour in the main bedroom; b) Average daily maximum CO_2 levels vs. l/s/p in the main bedroom

Table 6. Calculated air change rates in main bedroom during the night

House	No. adults	Vol (m3)	CO_2/pers (l/s), M=50, Ab=1.8	CO_2 source (G) (l/s)	CO_2 ext (Co, ppm)	Mean daily CO_2 max (Ci, ppm)	Qv (l/s) = G*10^6/ (Ci-Co)	Qv (m3/h)	Qv (l/s/p)	Qv ac/h
M01	2	28.42	0.0036	0.0072	400	1285	8.1	29.3	4.1	1.0
M02	2	29.21	0.0036	0.0072	400	1953	4.6	16.7	2.3	0.6
M03	2	29.21	0.0036	0.0072	400	1366	7.5	26.8	3.7	0.9
M04	2	33.08	0.0036	0.0072	400	1895	4.8	17.3	2.4	0.5
M05	2	25.35	0.0036	0.0072	400	1821	5.1	18.2	2.5	0.7
M06	2	21	0.0036	0.0072	400	1063	10.9	39.1	5.4	1.9
M07	2	28.54	0.0036	0.0072	400	999	12.0	43.3	6.0	1.5
M08	2	29.85	0.0036	0.0072	400	1119	10.0	36.1	5.0	1.2
M09	2	37.04	0.0036	0.0072	400	772	19.4	69.7	9.7	1.9
M10	2	25.3	0.0036	0.0072	400	1140	9.7	35.0	4.9	1.4
M11	2	30.42	0.0036	0.0072	400	1294	8.1	29.0	4.0	1.0
M12	2	22.6	0.0036	0.0072	400	1177	9.3	33.4	4.6	1.5
M13	2	32.9	0.0036	0.0072	400	1641	5.8	20.9	2.9	0.6
M14	2	36.43	0.0036	0.0072	400	1359	7.5	27.0	3.8	0.7
M15	1	22.37	0.0036	0.0036	400	1529	3.2	11.5	3.2	0.5
M16	2	26.18	0.0036	0.0072	400	2039	4.4	15.8	2.2	0.6
M17	2	75.37	0.0036	0.0072	400	1177	9.3	33.4	4.6	0.4
M18	1	26.42	0.0036	0.0036	400	1810	2.6	9.2	2.6	0.3
M19	1	24.85	0.0036	0.0036	400	1277	4.1	14.8	4.1	0.6
M20	2	37.6	0.0036	0.0072	400	1483	6.6	23.9	3.3	0.6
M21	1	30.42	0.0036	0.0036	400	881	7.5	26.9	7.5	0.9
M22	1	32.9	0.0036	0.0036	400	1002	6.0	21.5	6.0	0.7
M23	2	32.9	0.0036	0.0072	400	2612	3.3	11.7	1.6	0.4
M24	2	21.65	0.0036	0.0072	400	2864	2.9	10.5	1.5	0.5
M25	2	36.82	0.0036	0.0072	400	1342	7.6	27.5	3.8	0.7
M26	2	29.48	0.0036	0.0072	400	1486	6.6	23.9	3.3	0.8
M27	2	31.21	0.0036	0.0072	400	1244	8.5	30.7	4.3	1.0
M28	1	31.21	0.0036	0.0036	400	869	7.7	27.6	7.7	0.9
M29	2	22.6	0.0036	0.0072	400	887	14.8	53.2	7.4	2.4
M30	2	32.9	0.0036	0.0072	400	996	12.1	43.5	6.0	1.3
M31	2	30.42	0.0036	0.0072	400	1432	7.0	25.1	3.5	0.8
M32	2	36.82	0.0036	0.0072	400	1235	8.6	31.0	4.3	0.8
M33	2	22.6	0.0036	0.0072	400	1364	7.5	26.9	3.7	1.2
E01	2	29.18	0.0036	0.0072	400	1387	7.3	26.3	3.6	0.9
E02	2	25.53	0.0036	0.0072	400	2543	3.4	12.1	1.7	0.5
E03	2	23.5	0.0036	0.0072	400	3003	2.8	10.0	1.4	0.4
E04	2	29.48	0.0036	0.0072	400	1897	4.8	17.3	2.4	0.6
E05	1	28.42	0.0036	0.0036	400	1348	3.8	13.7	3.8	0.5
E06	2	27.12	0.0036	0.0072	400	1016	11.7	42.1	5.8	1.6
B01	2	30.33	0.0036	0.0072	400	2575	3.3	11.9	1.7	0.4
B02	2	35.5	0.0036	0.0072	400	1856	4.9	17.8	2.5	0.5
					Averages	1513	7.2	25.9	4.0	0.9

Analysis of Variation in Performance within the monitoring dataset: Part 1 Overall Statistics

As is to be expected when monitoring real life data with the many uncertainties in human behaviour, the monitored dataset in this study does not by itself provide an experimental significance level giving a statistically high confidence. However, the data does provide interesting information which can be viewed together with more detailed analysis to support broad conclusions.

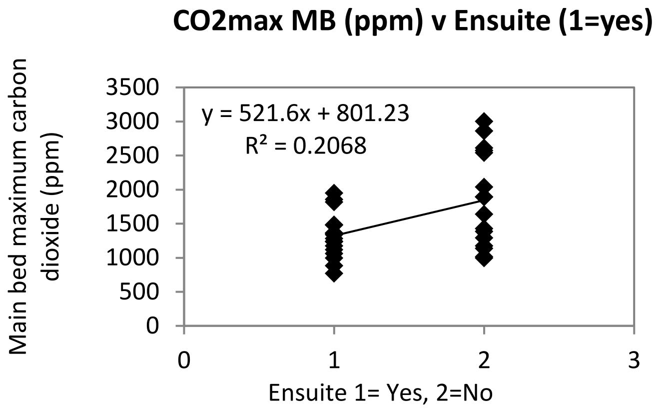
The graphs below in Figure 50 illustrate the output from statistical analysis of the CO_2 levels in the main bedrooms against likely performance influencing parameters. The dataset was reduced to only include bedrooms occupied by 2 persons, given the relatively few single person bedrooms included in the study. This consistency of occupancy enabled CO_2 to be used as a direct proxy for ventilation rates. The R^2 parameter displayed in the graphs indicates the fraction of the overall variation that may be explained by the parameter that is being analysed. Given the relatively small dataset and number of confounding variables, some caution is needed; however the analysis supports the following inferences:

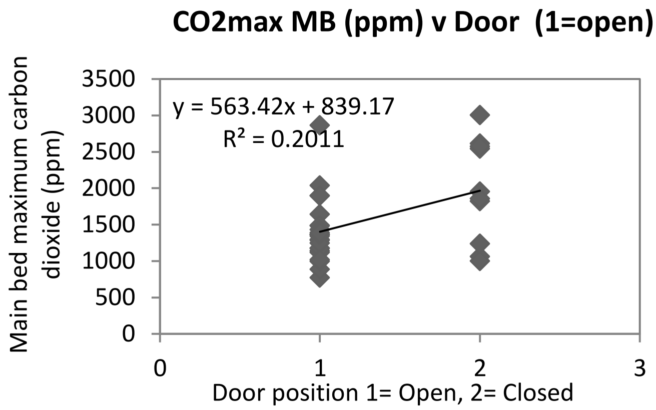
- Ensuite layout may be better than a separate bathroom
- Door open at night is better than door closed
- Larger door undercuts appear to be better
- Window open is better than window closed
- Larger properties may tend to be better
- Higher dwelling total dMEV flow rates appear to be better
- Higher dMEV ensuite extraction rates appear generally to be better

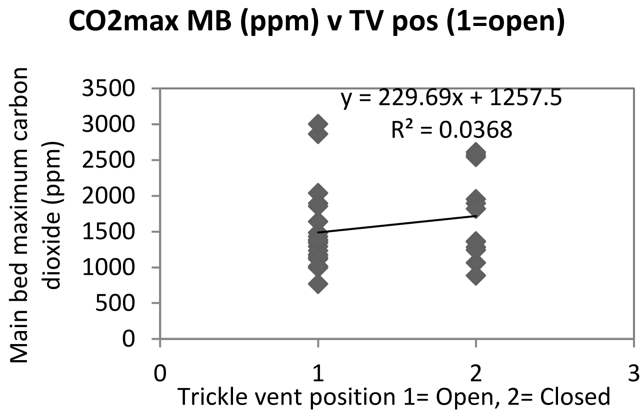
It was not possible to discern any trend in the data with reference to the size of the main bedroom trickle vents, possibly due to the majority of dwellings having trickle vents of very similar size.

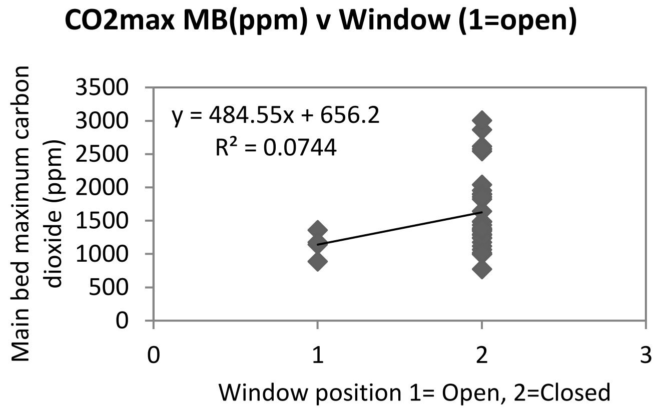
Further analysis was performed on homes with correctly implemented systems, by eliminating dwellings with: a) door undercuts less than 10mm, b) dMEV systems with less than 4 l/s in background mode, dwelling found with main bedroom Trickle Vents (TV) closed on collection of the monitors. This left a smaller dataset of 12 dwellings. This 'no defect' (nodef) case is shown in Figure 51.

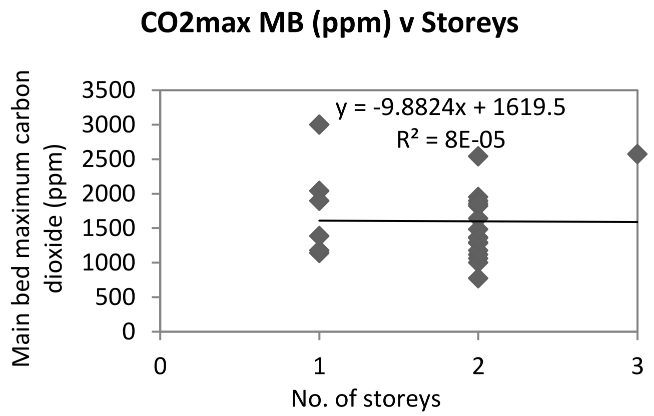
It would appear from this analysis that a 2-person bedroom with an adjacent ensuite (1 on the x-axis) is more capable of achieving peak CO_2 levels below 1,500ppm than a 2-person bedroom without an adjacent ensuite (see figure 51). No other trends were discernible from this reduced 'no defect' dataset.

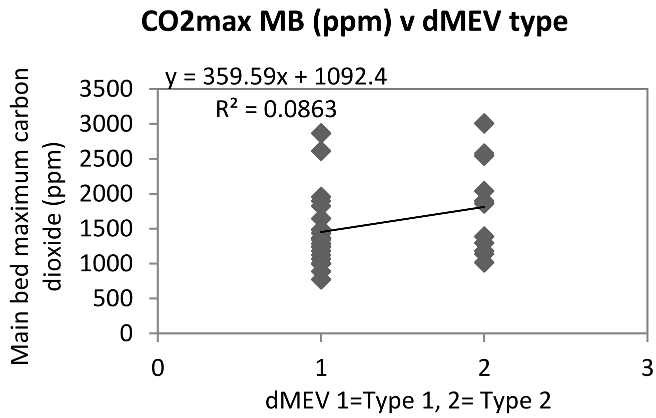

CO2max MB (ppm) v Ensuite (1=yes)
y = 521.6x + 801.23
R² = 0.2068
Main bed maximum carbon dioxide (ppm)
Ensuite 1= Yes, 2=No

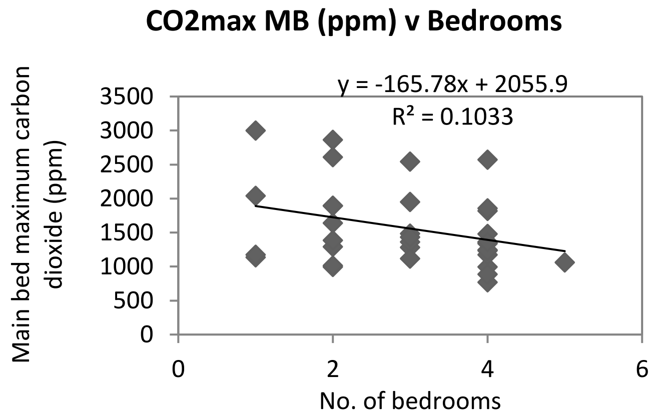

CO2max MB (ppm) v Door (1=open)
y = 563.42x + 839.17
R² = 0.2011
Main bed maximum carbon dioxide (ppm)
Door position 1= Open, 2= Closed


CO2max MB (ppm) v TV pos (1=open)
y = 229.69x + 1257.5
R² = 0.0368
Main bed maximum carbon dioxide (ppm)
Trickle vent position 1= Open, 2= Closed


CO2max MB(ppm) v Window (1=open)
y = 484.55x + 656.2
R² = 0.0744
Main bed maximum carbon dioxide (ppm)
Window position 1= Open, 2=Closed


CO2max MB (ppm) v Storeys
y = -9.8824x + 1619.5
R² = 8E-05
Main bed maximum carbon dioxide (ppm)
No. of storeys


CO2max MB (ppm) v dMEV type
y = 359.59x + 1092.4
R² = 0.0863
Main bed maximum carbon dioxide (ppm)
dMEV 1=Type 1, 2= Type 2


CO2max MB (ppm) v Bedrooms
y = -165.78x + 2055.9
R² = 0.1033
Main bed maximum carbon dioxide (ppm)
No. of bedrooms

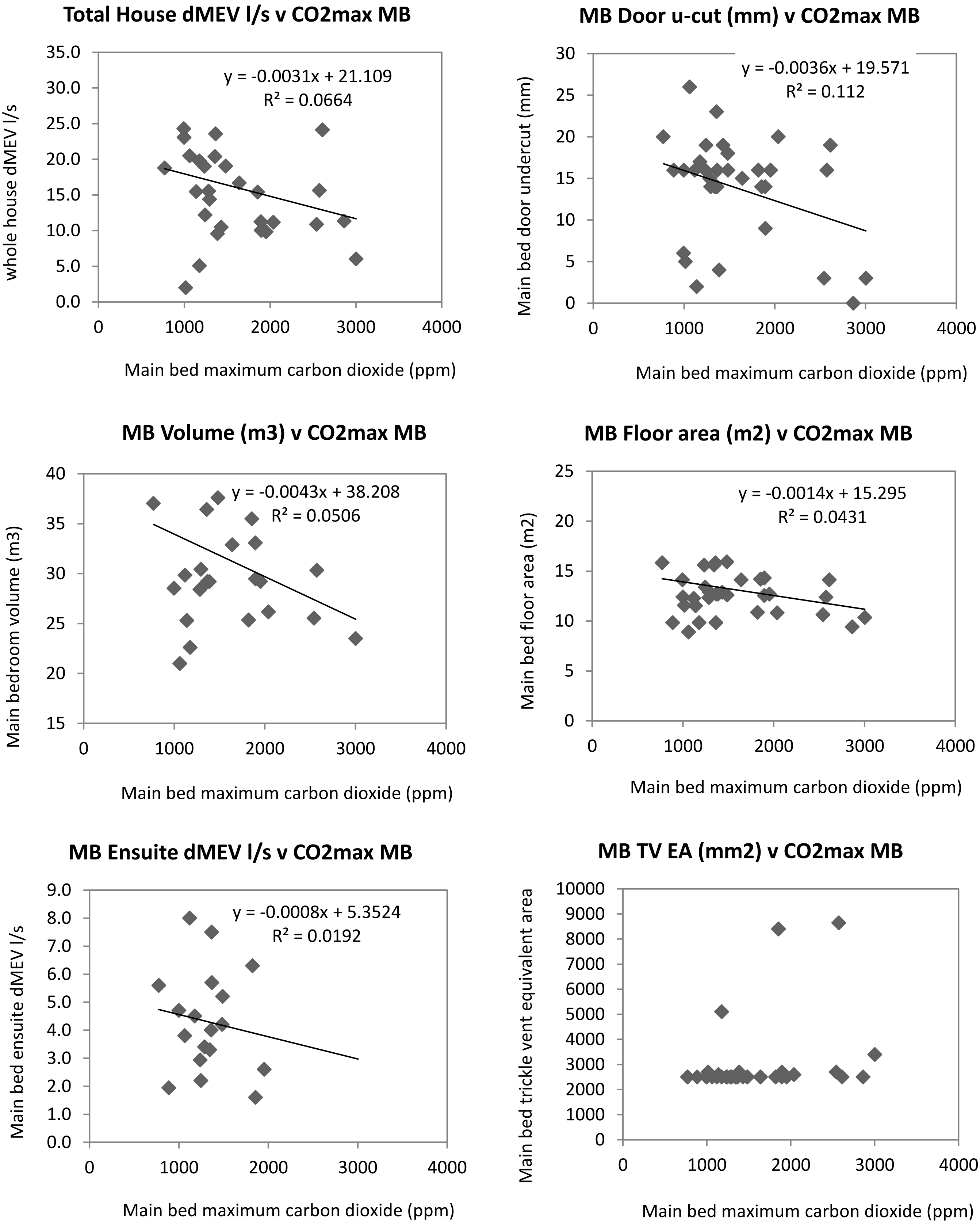


Figure 50. Statistical analysis of CO_2 levels in the main bedrooms. Various parameters v the average daily maximum CO_2 level in the main bedroom (CO_2max MB, ppm).

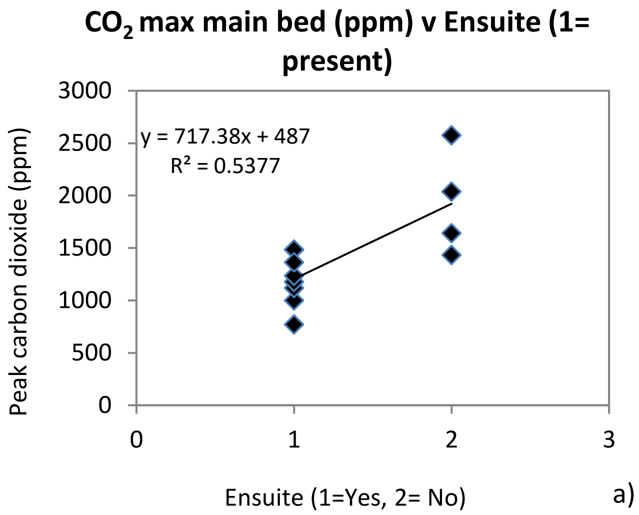


Figure 51. Main bedroom average daily maximum CO_2 levels (CO_2max MB) for Ensuite v Non-ensuite configurations for the subset of 12 homes without 'defects' ('nodef').

Variation in performance of the monitored dwellings (Part 2): Best and Worst-case Analysis

A separate analysis was done to investigate the characteristics of dwellings selected to represent the best and worst performing dwellings for main bedroom ventilation rates. Again, only double occupancy bedrooms were included, the results are given in table 7 below. The indications are:

- Ensuite may be better than separated bathroom layout
- Door open may be better than door closed
- Higher dMEV extraction rates may be better
- Larger door undercuts may be better
- Closed trickle vents may be problematic

Looking in more detail at the characteristic patterns for the representative best and worst-case dwellings for main bedroom performance, it appears that there is a marked difference with the worst-case dwellings showing a build-up of CO_2 throughout the occupied period, while the best-case dwellings generally showing a peak at the start of the night time period and a reduction overnight, presumably as activity levels decrease during sleep in comparison to the initial more active pre-sleep period.

Table 7. Best and worst-case scenarios

Home	Ave Peak CO_2	Occu-pancy	Ensuite	Door	Window	dMEV l/s	Under cut	TV Equiv area	dMEV system	Room Volume	TV at end
E02	**2543**	2	N	Varies	Closed	2.2	3	2700	2	25.5	Closed
E03	**3003**	2	N	Closed	Closed	3.14	3	3400	2	23.5	Open
B01	**2575**	2	N	Closed	Closed	3.97	16	8654	2	30.3	Varies
M06	**1063**	2	Y	Closed	Closed	3.8	26	2500	1	21	Open
M08	**1119**	2	Y	Open	Closed	8	16	2500	1	29.9	Open
M09	**772**	2	Y	Open	Closed	5.6	20	2500	1	37	Open

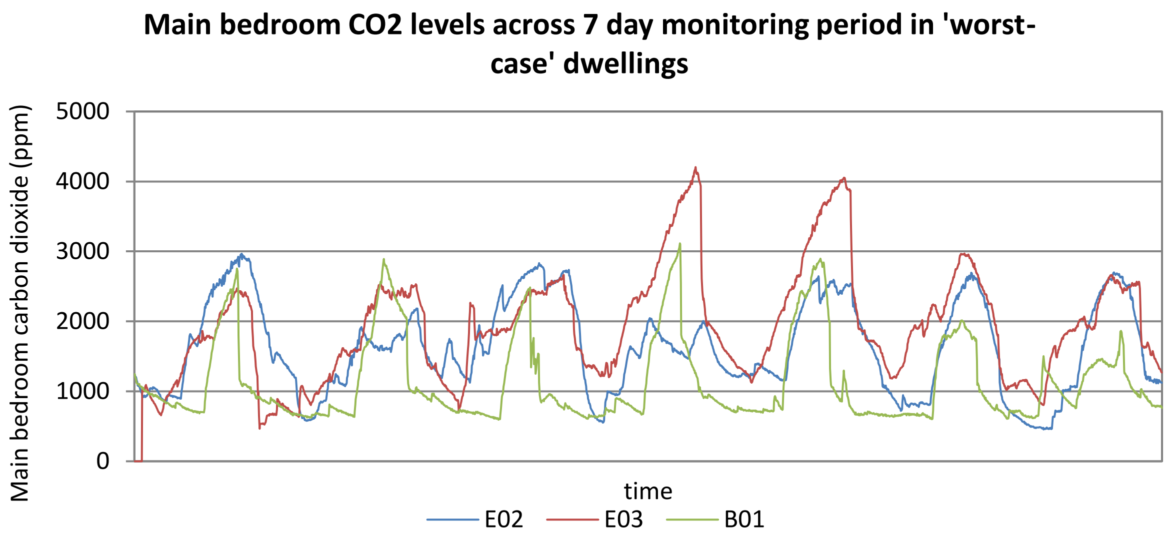


Figure 52. Three 'worst-case' dwellings: Measured main bedroom CO_2 ppm levels for the 7-day monitoring period showing nightly peaks in CO_2 concentrations.

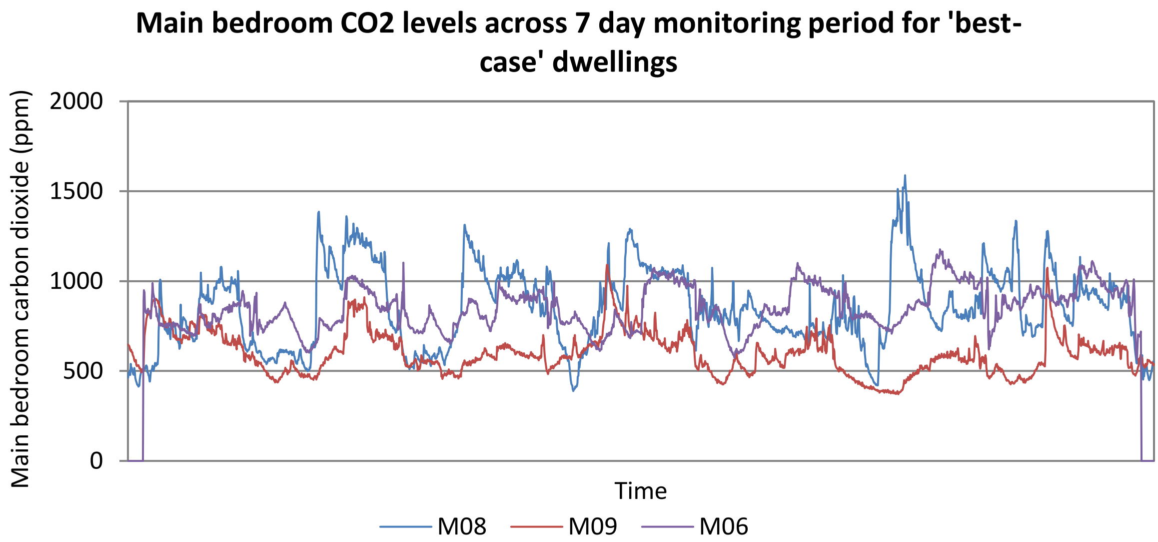


Figure 53.Three 'best-case' dwellings: Measured main bedroom CO_2 ppm levels for the 7-day monitoring period showing levels generally below 1500ppm with slight evening peaks in CO_2 concentrations.

6. Detailed monitoring

Detailed monitoring was undertaken in a test house to evaluate in more detail the impact of floor plan layout, trickle ventilator provision and door undercutting on the overall ventilation performance, and to evaluate a number of varying scenarios.

Based on this monitoring, integrated simulation models were built incorporating the zonal network method, to investigate and demonstrate the use of such models to provide insights and potentially help inform future guidance.

<u>Detailed Investigation of Ventilation Airflow Pathways</u>

Case Study: Selected dwelling (B01) based on monitoring in WP3

Dwelling B01 was identified in section 5 as being representative of worst-case main bedroom ventilation rates, based on CO_2 levels and chosen as a case study for more detailed investigation and modelling. This dwelling has 3 bedrooms: (i) the main bedroom used by 2 adults which is not ensuite, (ii) a large children's bedroom (bedroom 2) used by 3 children with an ensuite bathroom, (iii) a guest bedroom for a single adult, which is occasionally used by a senior family member who acts as a babysitter.

Dwelling B01 monitoring results are shown for the living room, main bedroom, kitchen and bedroom 2 in Figure 54. Daily peak CO_2 levels ranging between 2,500ppm and 3,150ppm were recorded in the main bedroom for the first 5 days of monitoring. For the final 2 days of the monitoring period, conditions were changed (the bedroom door was opened, as recorded by the occupant diary) leading to a reduction of CO_2 levels (below 2000ppm).

The large children's bedroom (Bedroom 2 with ensuite) was seen to have quite different CO_2 characteristics, similar in shape to the best-case ensuite dwellings but with a slightly higher peak in evening CO_2 levels. This bedroom was occupied by 3 children (8 - 12 years of age), who could be expected together to have similar CO_2 output to 2 adult occupants. Highest CO_2 levels were observed in the evening, with peaks between 1500 and 2000ppm generally followed by decreasing levels overnight.

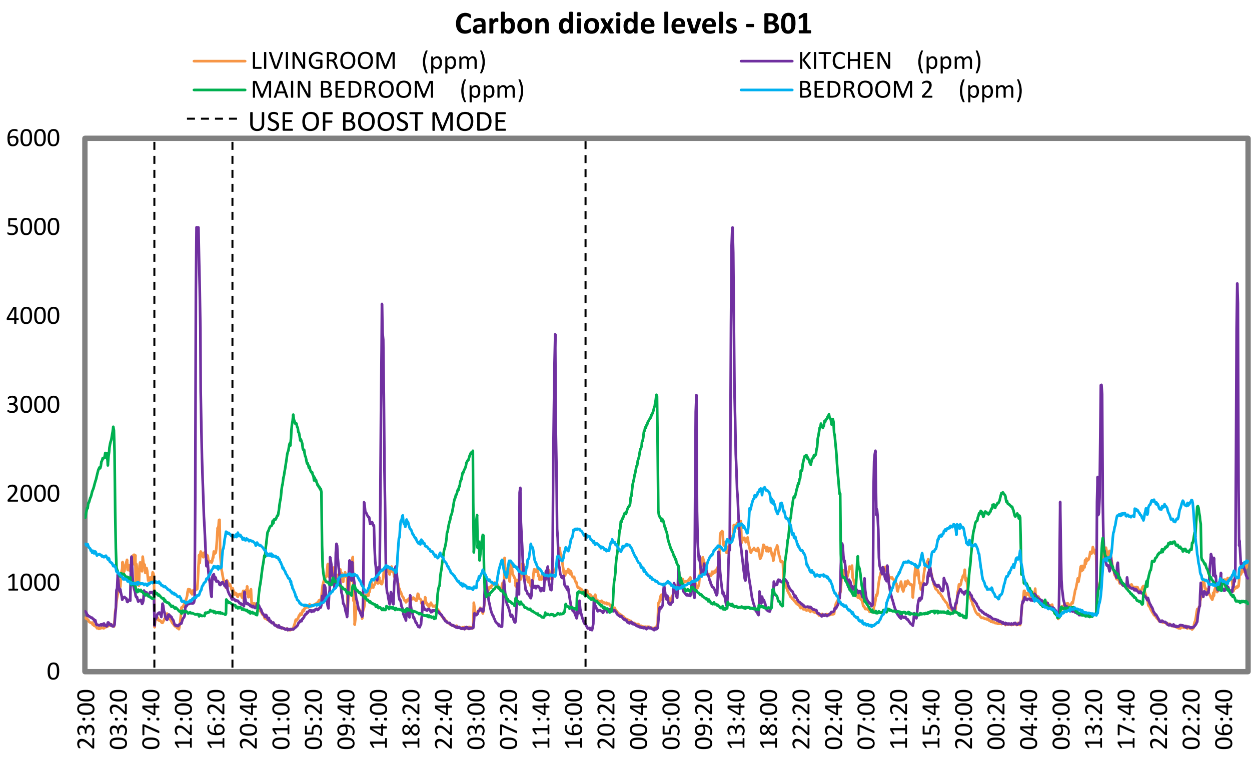


Figure 54. *BO1: (3 bed, terraced) no en-suite bathroom to main bedroom, dMEV unit on. Door closed, windows closed, trickle vents open, curtains closed (in main bed).*

The kitchen and living room CO_2 levels were also monitored. Kitchen combustion of gas for cooking was apparent. During these short 'episodes' of high CO_2, the boost mode function had reportedly not been operated, suggesting inadequate purge ventilation, which may help to explain the results.

Scenario testing in the main bedroom of dwelling B01

The dwelling was revisited and the main bedroom subjected to a range of imposed conditions over a further 7 day monitoring period.

- *Day 1 and 2:* Base-case days were imposed with the 'normal' conditions as recorded during the first 5 days of the earlier monitoring period
- *Day 3*: Main bedroom trickle vents were closed
- *Day 4:* Normal conditions were re-established where occupant opened the door by 10cm
- *Day 5:* A further base case 'normal' day was imposed
- *Day 6:* Window and the door opened by occupant by 1cm
- *Day 7:* Normal conditions, but with trickle vents partially closed to 25% of the total area

The settings and results from the experiment are captured in Table 8, and Figures 56 and 57.

Table 8. Summary of scenarios tested and resulting CO_2 levels

Scenario	Date	Trickle vents	Curtains/ blinds	Windows	Doors	Main bed CO_2 max	Bed 2 CO_2 max	Bed 3 CO_2 max
1 (Base)	13/02/18	Open	Closed	Closed	Closed	2600	1700	1200
2 (Base)	14/02/18	Open	Closed	Closed	Closed	2500	1500	1200
3	15/02/18	Closed	Closed	Closed	Closed	3700	1000	1200
4	16/02/18	Open	Closed	Closed	Open 10cm	1500	1200	900
5 (Base)	17/02/18	Open	Closed	Closed	Closed	3200	1700	1450
6	18/02/18	Open	Closed	Open 1cm	Open 1cm	700	1600	1200
7	19/02/18	Reduced (2500)	Closed	Closed	Closed	3300	1500	2400
Previous monitoring (WP3)	18/01/18 – 26/01/18	Open	Closed	Closed	Closed	2500 - 3150	1550 - 2100	Not measured

There is some uncertainty in occupant behaviour; in particular children occasionally wake in Bedroom 2 and join their parents in the main bedroom (possibly some evidence of this on day 3). Despite these uncertainties, the general indications are as follows:

- The ensuite Bedroom 2 provided better results than the non-ensuite main bedroom
- The door opening by 10cm greatly improved the situation in the main bedroom

- Opening the door and the windows 1cm greatly improved the main bedroom situation
- Closing the trickle vents had a detrimental effect

This indicates that in a best case scenario the main bedroom can have good levels of CO_2, but this relied on the occupant leaving doors and windows open.

This is not a good solution here as the dwelling is 3 storeys so the bedroom doors to the landings are fire doors and they should be kept closed. They do have undercuts as recorded in section 4.3. but this does not appear to provide sufficient air flow.

A general observation is that the ensuite situation appears to give a more direct pathway for airflow and more direct depressurisation of the adjacent bedroom than the situation where a bedroom is not directly coupled to the extracted room. If there is no direct coupling then the depressurisation of the master bedroom may be unlikely given the available range of flow paths with lower resistances. It would appear then that the efficacy of this ventilation strategy depends very much on providing effective paths for air movement between apartments and spaces with extract units.

Figure 55. WP5: Floor Plans B01 and Detailed Monitoring Equipment setup

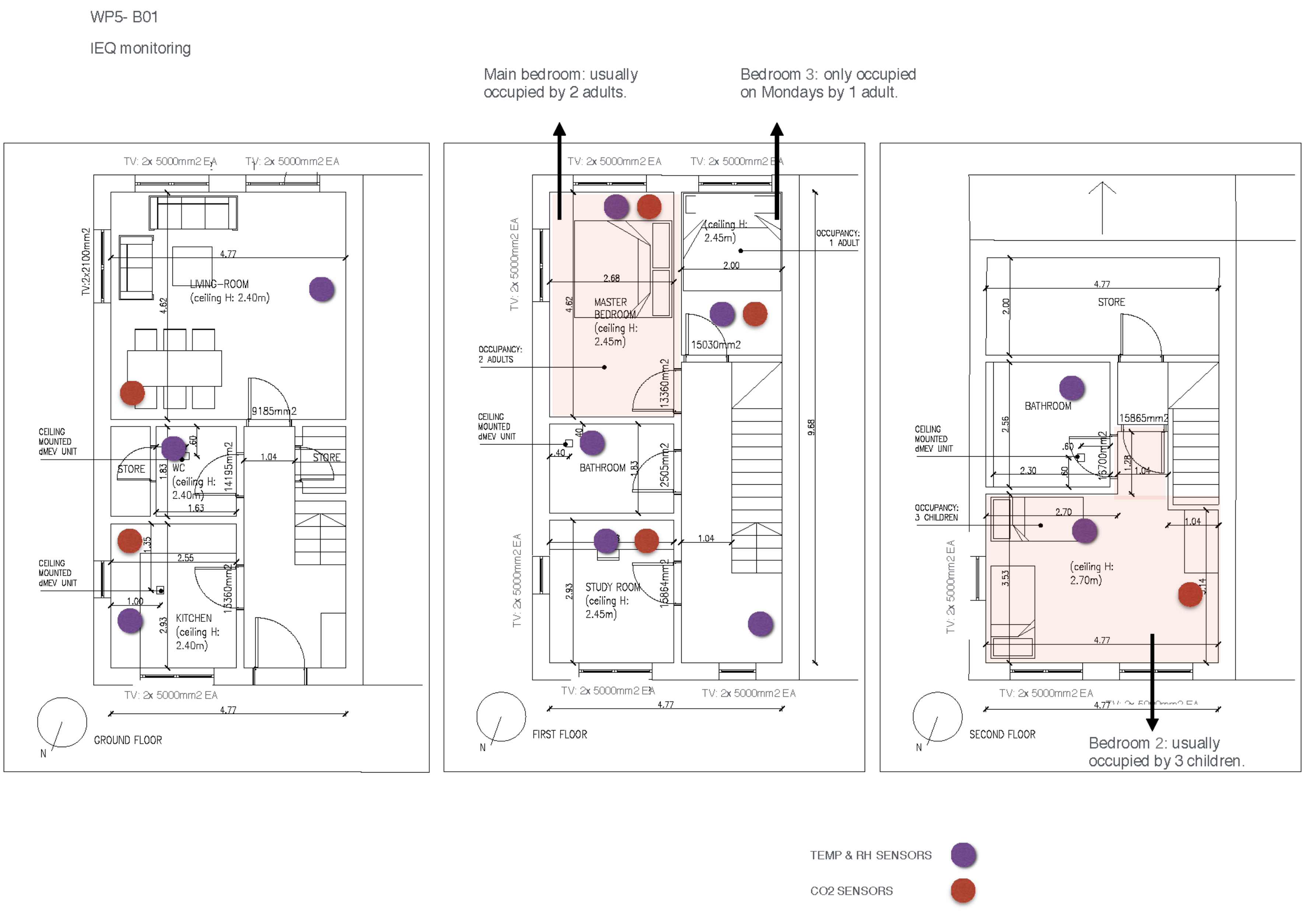
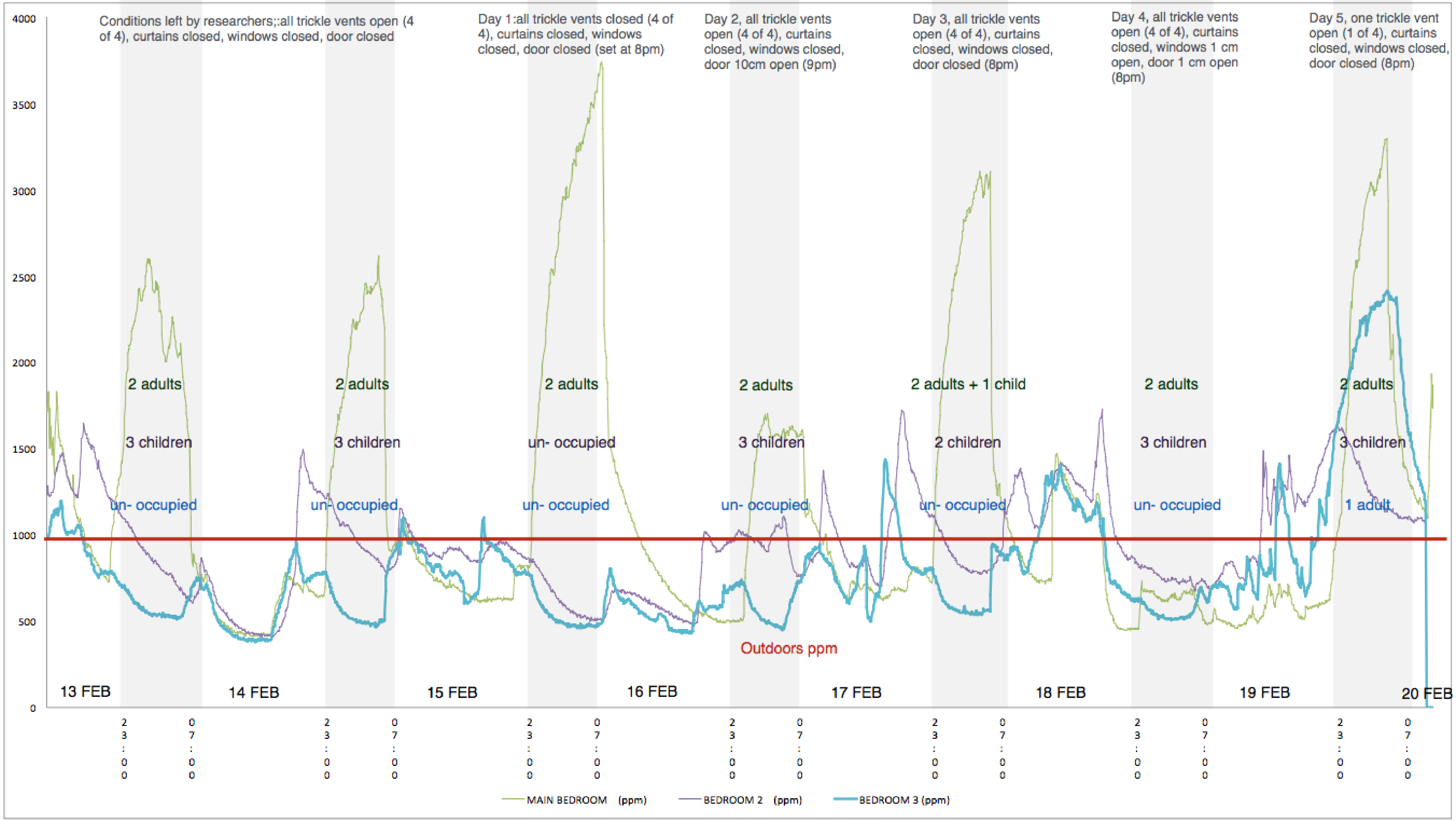


Figure 56. WP5: Scenarios for Flow Paths Investigation

Monitoring scenarios as agreed with ESRU set by the occupiers at 8pm every day, in the main bedroom (1F) and in Bedroom 1 (top floor):

Tuesday the 13th/ Wednesday the 14th of Feb	Thursday the 15th of Feb	Friday the 16th of Feb	Saturday the 17th of Feb	Sunday the 18th of Feb	Monday the 19th of Feb	Tuesday the 20th of Feb
Conditions left by researchers: all trickle vents open (4 of 4), curtains closed, windows closed, door closed	Day 1:all trickle vents closed (4 of 4), curtains closed, windows closed, door closed (set at 8pm)	Day 2, all trickle vents open (4 of 4), curtains closed, windows closed, door 10cm open.	Day 3, all trickle vents open (4 of 4), curtains closed, windows closed, door closed. Set at 8pm in the main bedroom (1F) and in Bedroom 2 (top floor).	Day 4, all trickle vents open (4 of 4), curtains closed, windows 1 cm open, door 1 cm open. Set at 8pm in the main bedroom (1F) and in Bedroom 2 (top floor).	Day 5, one trickle vent open (1 of 4), curtains closed, windows closed, door closed (8pm)	Collection at 11/12am

Figure 57. WP5: Changes to measured bedroom carbon dioxide levels (scenario testing)



Detailed investigation of dwelling B01 - Simple Modelling

The ventilation flow paths in dwelling B01 enabled investigation using simple modelling of both ensuite (Bedroom 2) and non-ensuite (main bedroom) layouts. Both of these rooms show typical characteristics in terms of CO_2 for each type (ensuite and non-ensuite) found in the wider monitoring study. These 2 rooms have been used to illustrate simple modelling of the flow paths for both the ensuite and non-ensuite situations.

Simple modelling of the non-ensuite main bedroom in dwelling B01

Figure 58 shows a simple flow path analysis for the main bedroom, considering only the floor on which the main bedroom is situated (a simplification). The components shown are:

- infiltration ('INF' components in the diagram with room location) which is assumed to be distributed around the dwelling
- door undercuts (Ucut)
- trickle ventilators (TV)
- curtains and blinds (CB)

The extract fan in the 2nd floor bathroom will potentially pull outside air through infiltration in the bathroom (path 1 on the diagram), an also via the hall (path 2), through the main bedroom (path 3), bedroom 3 (path 4) and study (path 5).

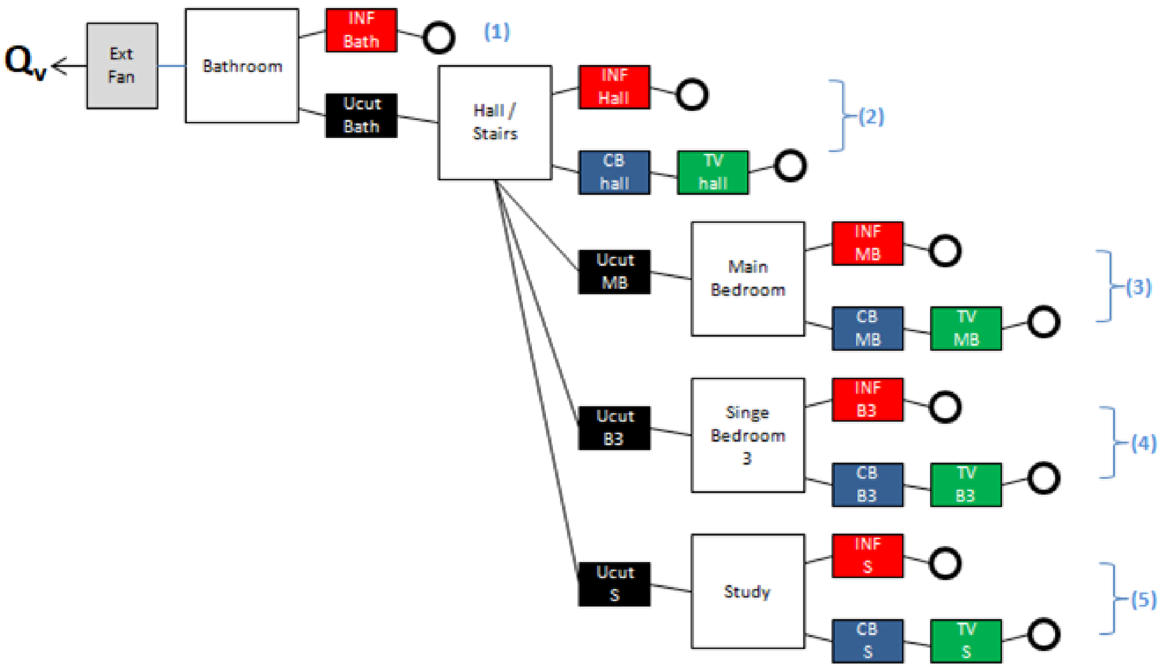


Figure 58. Simple flow path component analysis for B01 main bedroom and non-ensuite bathroom with extract fan.

A simple analysis can be done to illustrate the effect of the extract fan on air movement through the main bedroom. Assumptions have to be made due to lack of data. If we assume that 10% of the extracted air in each of the spaces is from infiltration within that space and that the more direct air path via the hall (path 2) has 2x the airflow via individual spaces separated by a door undercut (path 3, 4, and 5) then the analysis is as shown in figure 58a.

Path (B01)	Q	
Q_v	1	
Bathroom infiltration (1)	0.1	
Hall / Stairs Direct (2)	0.36	= 0.9x0.4*
Main Bedroom (3)	0.18	= 0.9x0.2*
Bedroom 2 (4)	0.18	= 0.9x0.2*
Study (5)	0.18	= 0.9x0.2*

* Path 2 flow = 2x paths 3,4,5 (resistance of undercut)

Figure 58a. Simple flow path calculation for B01 main bedroom extracted through the local non-ensuite bathroom.

The proportion of extracted air from the bathroom which would result in fresh air being drawn into the main bedroom is 0.18. It can be seen from this simple model that the fraction of extracted air which will result in fresh air input to the main bedroom is 0.18, i.e. if the bathroom extract is running at 4 l/s then the bedroom will receive 0.72 l/s (4 x 0.18).

Simple modelling of the ensuite bedroom 2 in dwelling B01

Figure 59a and 59b below show the same simple analysis but for the ensuite bedroom 2 of dwelling B01. The extract fan will pull from the infiltration in the ensuite bathroom (path 1) and then (via the ensuite door undercut) from the ensuite bedroom (path 2), then (via the further undercut to the hall) from the hall and stairs area (path 3) and via further undercuts to other rooms, in this case the store (path 4).

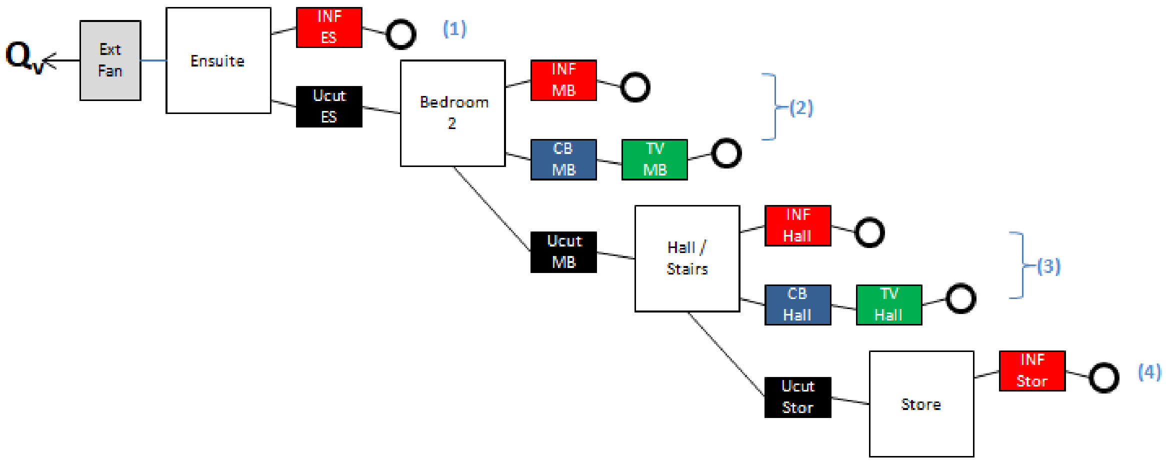


Figure 59a. Simple flow path component analysis for B01 bedroom 2 with ensuite bathroom with extract fan.

Path (B01)	Q	
Q_v	1	
Bathroom infiltration (1)	0.1	
Bedroom Ensuite (2)	0.6	= 0.9x0.67*
Hall / Stairs Direct (3)	0.22	= 0.9x0.33x0.75**
Store (4)	0.07	= 0.9x0.33x0.25**

* Path 2 flow = 2x path (3+4)
** Path 3 flow = 2x path 4

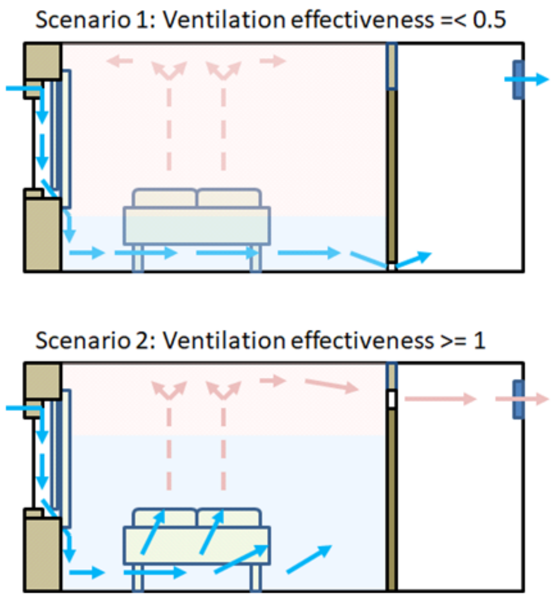
Figure 59b. Simple flow path calculation for B01 bedroom 2 extracted through the ensuite bathroom.

It can be seen from this simple model that the fraction of extracted air which will result in fresh air input to the bedroom 2 is 0.6, i.e. if the extract is running at 4 l/s then the bedroom will receive 2.4 l/s (4 x 0.6).

This indicates that the ensuite configuration will potentially lead to >3X higher ventilation rates of bedrooms than the non-ensuite case.

Further Observations based on Simple modelling (Ventilation Effectiveness)

A further factor that can be surmised from a simple analysis of the ventilation scheme is that the ventilation effectiveness of the bedrooms themselves will be less than 1 as it is unlikely the room air will be fully mixed and the tendency will be to extract air with lower contaminant concentration than the average for the room. The figure below illustrates that the current standard configuration will have an effectiveness of around 0.5, i.e. low level door undercuts as transfer openings (CIBSE). This effect will reduce further (by 50%) the effective fresh air ventilation rate to the breathing zone. An alternate configuration is also illustrated with high level transfer openings that would potentially have a much higher ventilation effectiveness.



Path (B01)	Q	Q_{eff} *	Q_{eff} **
Q_v	1		
Bathroom infiltration	0.1		
Bedroom Not Ensuite	0.18	0.09	0.18
Bedroom Ensuite	0.6	0.3	0.6

* Ventilation effectiveness = 0.5 (disp vent low extract)
** Ventilation effectiveness = 1 (disp vent high extract)

Figure 60. Illustration of ventilation effectiveness with cool incoming air from outside and a low level opening such as a door undercut (scenario 1) and an alternate configuration incorporating a high level opening (scenario 2).

It may also be worth considering the potential for natural ventilation without dMEV contributing to the ventilation of these spaces. If one was to design a natural ventilation scheme for these airtight dwellings it would be prudent to have both high and low openings as shown in figure 61 below. This would allow buoyancy effects to remove stale air from the upper portion of the room through the high level opening, while allowing ingress of cooler outdoor air through the lower level opening, effectively creating a displacement ventilation effect. An alternative to two openings would be a vertical trickle ventilator in the side of the window frame allowing egress of warm air at the top at the same time as ingress of cool outdoor air at the bottom.

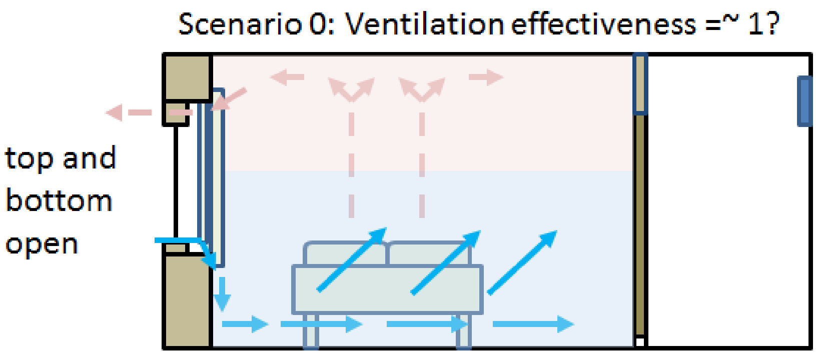


Figure 61. Improved natural ventilation scheme with high and low openings.

The simple modelling illustrates the roles of each of the components in the airflow networks. There are many uncertainties in the values for room by room infiltration rates, the resistances presented by undercuts, curtains and blinds, and trickle vents etc. but the simple model illustrates physical principles and potential effects consistent with the findings of the environmental monitoring, which can be useful to gain an understanding of the system.

The effectiveness of the system will also be affected by the placement of heaters below windows, which provide warming of incoming air and mixing of air within the room. These relationships between heating and ventilation systems are often not considered as part of design processes for dwellings.

This simple model analyses the flows attributed to the extract system in isolation. In reality, additional driving forces mainly relating to wind and buoyancy will act on the system, with the potential to dramatically change the real airflows. To comprehend these effects, a more detailed model is required.

Detailed Modelling and Ventilation Solution for Main Bedroom of B01

A simulation model was constructed in ESP-r software. This model was based on airflow network modelling (CIBSE AM10) and not CFD (which could be done in the future). A standard Edinburgh climate file was used. Averaged daily occupancy was estimated with a standard daily profile.

Two scenarios were evaluated: (i) the 2nd floor was modelled as it was found in the survey, (ii) a designed ventilation solution was evaluated.

The designed ventilation solution did not rely on door undercuts but implemented direct connection through high level ventilation ducts between each of the occupied rooms and the extract room. In addition the ventilation rate of the extract was increased to 16 l/s.

The existing ventilation networks is shown in figure 62a (left hand side) and utilises the components (INF = infiltration, TV = trickle vents, UC = undercuts, EXT = extract) as detailed in figure 58, but with curtains and blinds not shown. The extract rate was set to 4 l/s to mimic the extract continuously running in background mode.

The proposed solution is shown in figure 62b (right hand side) and includes duct components at high level to allow direct flow between each of the occupied rooms and the extract room. The extract rate was also increased to 16 l/s.

Figure 63 shows results of the airflow modelling for the 2 situations; the existing model gives a reasonable agreement with the measured data for the main bedroom of B01 while the proposed solution maintains the CO_2 levels in the main bedroom with 2 person occupancy below 1500ppm. This type of modelling is commonly applied in the non-domestic domain and is well documented in CIBSE guidance e.g. CIBSE AM10.

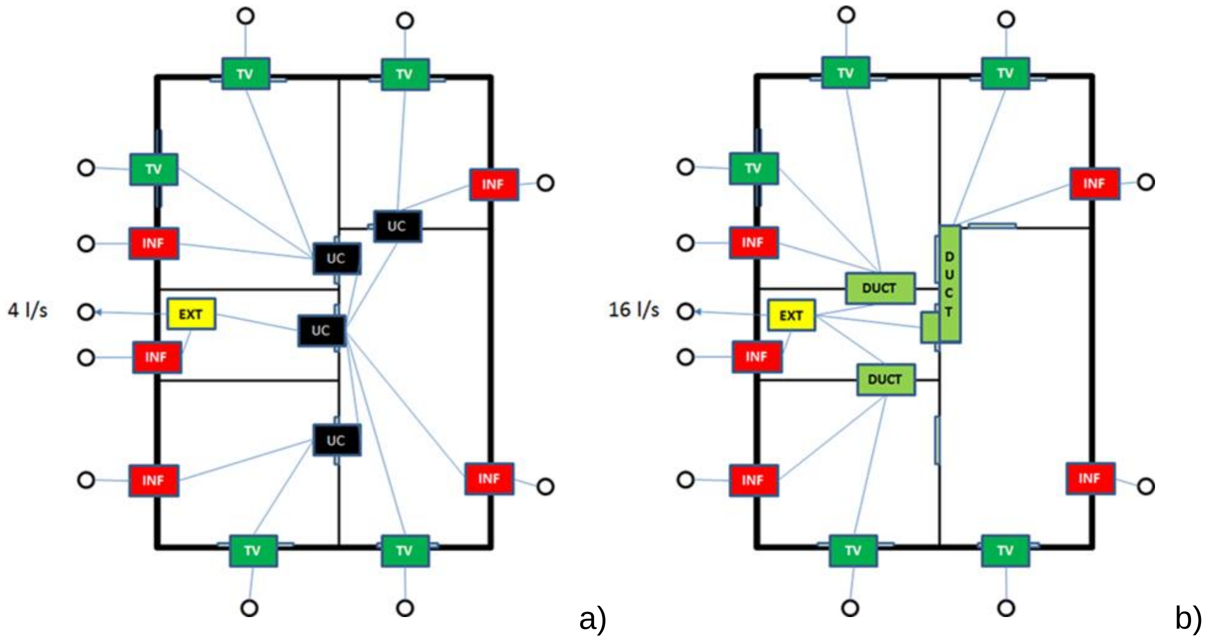


Figure 62. Ventilation network models for existing (a) and improved (b) ventilation schemes for the main bedroom of dwelling B01.

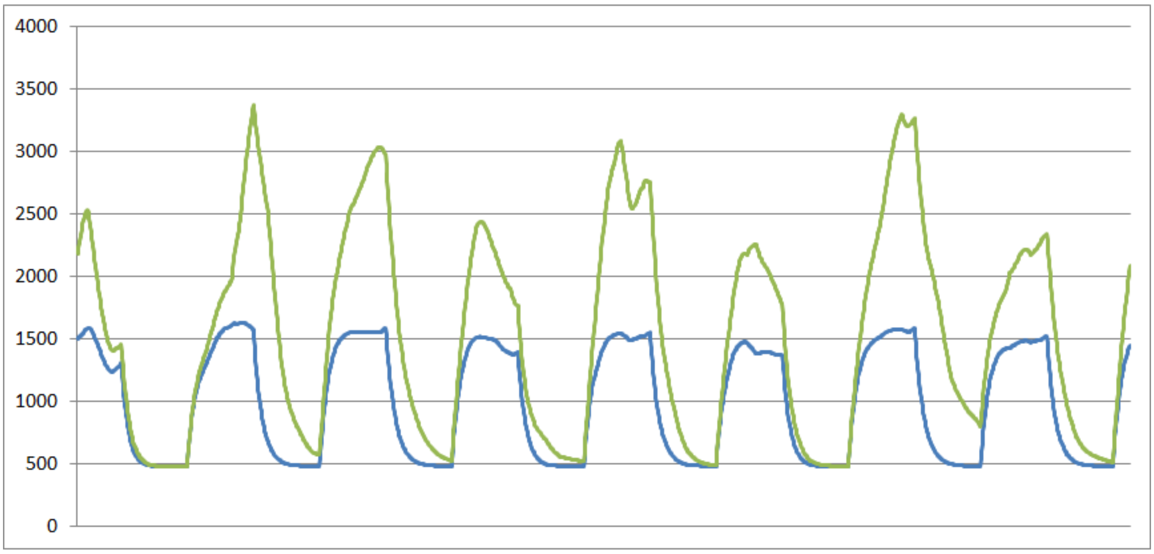


Figure 63. Modelling results for CO_2 levels in the main bedroom of dwelling B01 over an 8 day period with 2 person overnight occupancy for existing ventilation system and improved ventilation system. (y-axis = CO_2 ppm, x-axis = time).

7. Summary of findings

Window opening

- The results from the household survey suggest a low frequency of window opening, particularly at night.

- The primary driver for window opening was ‘for fresh air / to air the room’ (85%), followed by ‘to get rid of smells’ (36%) and ‘to dry clothes’ (28%). This is in contrast to previous findings where temperature control was found to be the predominant factor.

- The most common barrier identified for window opening was weather (61%), followed by security (34%). 23% reported ‘heat loss’ as a barrier to opening windows in their home.

Bedroom night time conditions

- Overall, 71% of households surveyed reported closing the bedroom door at night, while 95% reported closing curtains/blinds, which signifies a particular challenge to providing a whole house ventilation system (where dependence is placed on trickle vents and open doors at night).

- 63% of households monitored had a reduced trickle ventilation provision of 2,500mm^2 in the main bedroom. The measured undercut of the main door to the bedroom was found to be less than the specified 8mm in 20% of households.

- The results from the small sample of homes with carbon dioxide monitoring equipment suggest the presence of a CO_2 monitor in the main bedroom did not seem to have any impact of occupant awareness or behaviour relating to ventilation.

Awareness of trickle vents

- The results of the household survey suggested a good awareness of trickle vents, with 91% of respondents able to identify them from a show card and over 84% aware of their purpose.

- The majority of households surveyed reported adjusting trickle vents less than once a month (39%). 14% stated they never make any adjustments to trickle vents.

Awareness and use of dMEV systems

- During the household survey, the majority of respondents were aware of the presence of a mechanical extract fan in the bathroom / ensuite (97%) and kitchen (95%); and 95% of households reported that the fans were operating.

- 6% of households reported problems with the dMEV system; the most common issue reported being noise (5%). 3% stated that they had deactivated the ventilation system (2% due to concerns with noise). 7% reported adjusting the flow rate of the ventilation system. However, the percentage of households deactivating dMEV systems in practice was found to be much higher than reported during the household survey (56% compared to 3%). Similarly, a greater number of households reported deactivating dMEV systems due to problems with noise (54% compared to 2%).

Measured airflow rates and trickle ventilation provision

- dMEV systems did not meet required airflow rates under trickle (normal) mode in 42% of kitchens, 48% of ensuites, 34% of bathrooms and 17% of WCs monitored. In the majority of dMEV systems monitored (42-52% depending on location), measured airflow rates exceeded minimum required airflow rates (under trickle mode) by more than 15%, which could reduce energy performance and cause issues with noise.

- Trickle ventilators were found in moisture producing rooms (17% in bathrooms, 37% in kitchens), indicating that where these trickle vents are open, the likelihood of short circuiting of ventilation provision (where make up air for the extract is drawn from the trickle vent in the room) would undermine the ability of these systems to provide a ‘whole house’ solution.

Carbon dioxide levels

- High night-time (main) bedroom carbon dioxide levels were found in over half of monitored dwellings, where levels exceeded 1,000ppm for more than 50% of the time. Day-time carbon dioxide levels in the main bedroom were much lower.

- Door opening behaviour appears to have had a significant effect on improving CO_2 levels indoors.

- Short peaks of CO_2 levels were evident in the kitchen of some homes, most likely due to the use of a gas cooker. The concern is that the ‘bad company’ that CO_2 keeps there may be oxides of nitrogen (NOx) and there is increasing literature on pollutant risks for unvented gas appliances.

- It is important to note that flow rates of dMEV systems had been corrected (where possible) before environmental monitoring and all trickle vents had been opened. Therefore, conditions observed are likely to be best-case scenarios, where ventilation systems were performing ‘as intended’. Nevertheless, some occupants were found to have made further adjustments to the systems / trickle vents over the monitoring period, which may have affected the results, and this illustrates the potential weaknesses of such strategies.

8. Conclusions and issues to consider

General survey

The findings from the household survey generally confirmed the results from the previous studies, however key differences in tenure and socio-economic profile may have affected the responses.

Some evidence of increased awareness of issues of ventilation was observed (e.g. increased awareness of the need for fresh air), however the results from the small sample of homes with carbon dioxide monitoring equipment suggest the presence of a CO_2 monitor in the main bedroom did not seem to have any impact of occupant awareness or behaviour relating to ventilation.

Whilst there was good awareness of the presence of trickle vents and dMEV systems in the home, a lack of knowledge was evident regarding how these systems were controlled. Many households did not know how to boost the ventilation rate in the dMEV system (or didn't feel the need to do so), and a lack of engagement with trickle vents was clear.

Under reporting of disabling of dMEV systems was apparent, possibly due to confusion between 'disabling' of systems and 'controlling' through use of available switches.

Monitoring

It was clear that whilst levels of ventilation appeared to be adequate in living rooms and kitchens, poor levels of ventilation were evident in a high number of bedroom spaces.

There were a large number of identified factors which determined the ventilation effectiveness in dwellings with dMEV systems. These included the nature of the trickle vents and the extract system, but the key issue is thought to be the paths for air movement through the home. As bedroom doors are likely to be closed (and this may be required in some cases due to fire regulations), at present systems are reliant on the provision of undercuts, and this does not appear to provide a robust or effective solution. Further factors which may compromise the strategy include the overall layout of the home and alternative air paths for shortcuts which may bypass other rooms.

The current requirement for ventilation is based on the specification of trickle vents, undercuts and extract systems, but this does not vary depending on the layout of the building or the occupancy load. Buildings with complex paths are therefore at greater risk of having isolated rooms, as illustrated in Figures 64-66. Whilst provision of dMEV systems in en-suite bathrooms produced better results for the attached bedrooms, this does not appear to provide a whole-house solution.

It is very clear that there are significant performance gaps occurring between what is specified and what is being achieved on site in terms of installation and compliance. The use of dMEV requires a number of related components, installed by a range of different participants. There is very little evidence that this is checked or commissioned and the current guidance-based approach is not providing adequate standards of installation. A large number of properties had sub-optimal systems, and in some cases, systems that do not achieve the intent of the standard.

A large number of homes had disabled systems, primarily due to noise. Of relevance here were the significant number of dMEV systems with higher fan speeds (42-52%), which would have contributed to noise nuisances.

However, the use of dMEV as part of a planned ventilation strategy in energy efficient airtight homes does have value, particularly as an alternative to fully mechanical ventilation systems. These would need to be supported by modelling or other calculation methods.

Detailed monitoring

The detailed monitoring scenarios clearly illustrate the weaknesses of the system as installed. Whilst ventilation levels in the bedroom with ensuite were reasonable and consistent, in the main bedroom without an ensuite, the most effective measure was when occupants left the door open and good levels of ventilation were only experienced in the night when the bedroom window was open.

The issues with trickle vent sizing strongly suggest that the effectiveness of this provision is more influenced by the provision for air movement rather than the size of the opening. There was some evidence of this provided in the previous study that indicated an inverse relationship between CO_2 levels and external wind speeds. Thus, a system such as dMEV which incorporates a mechanical driver for air movement may have some advantage over entirely natural systems, as long as the air movement is available in all apartments, and the system is running.

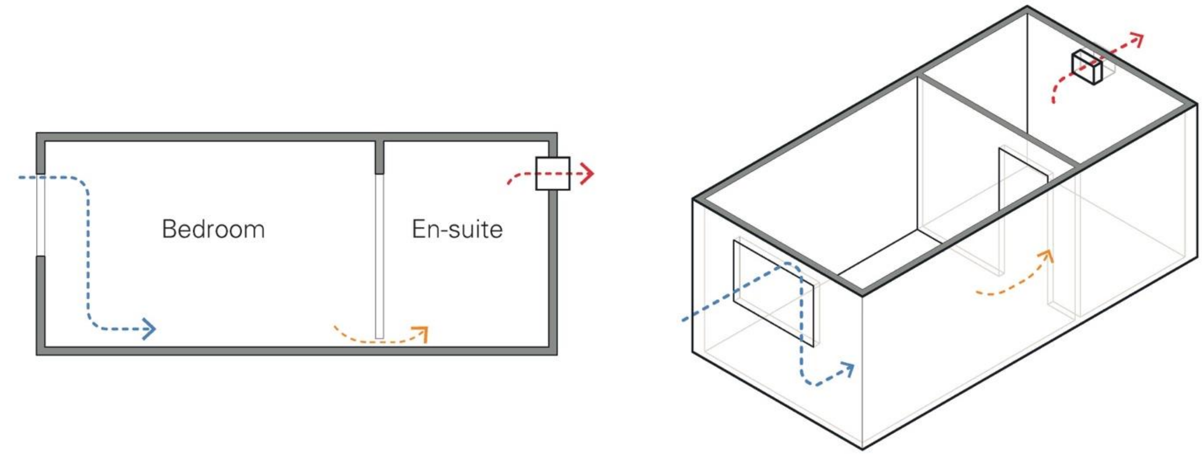


Figure 64. Ensuite condition (section and axonometric)

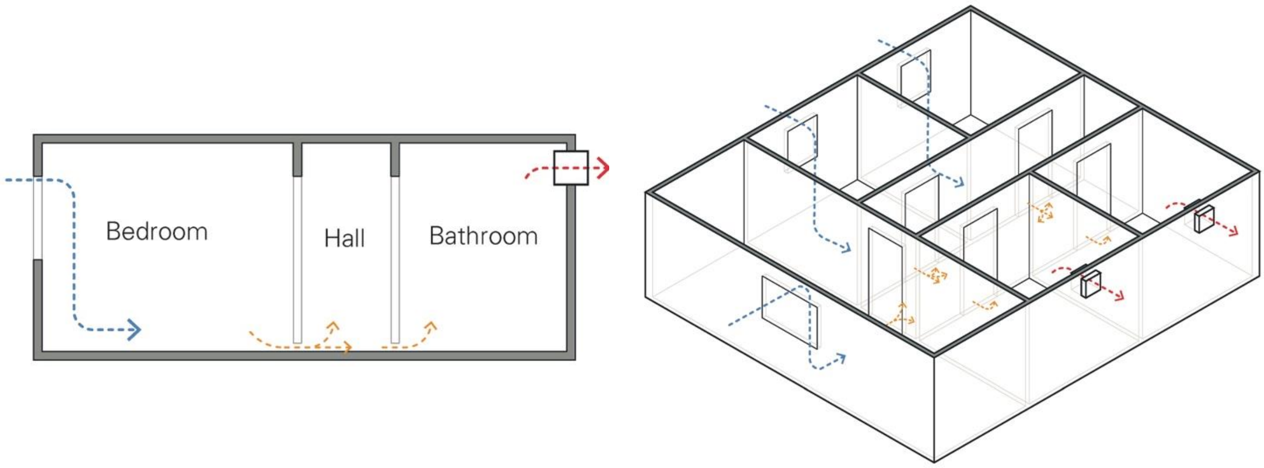


Figure 65. Single storey non-ensuite (section and axonometric)

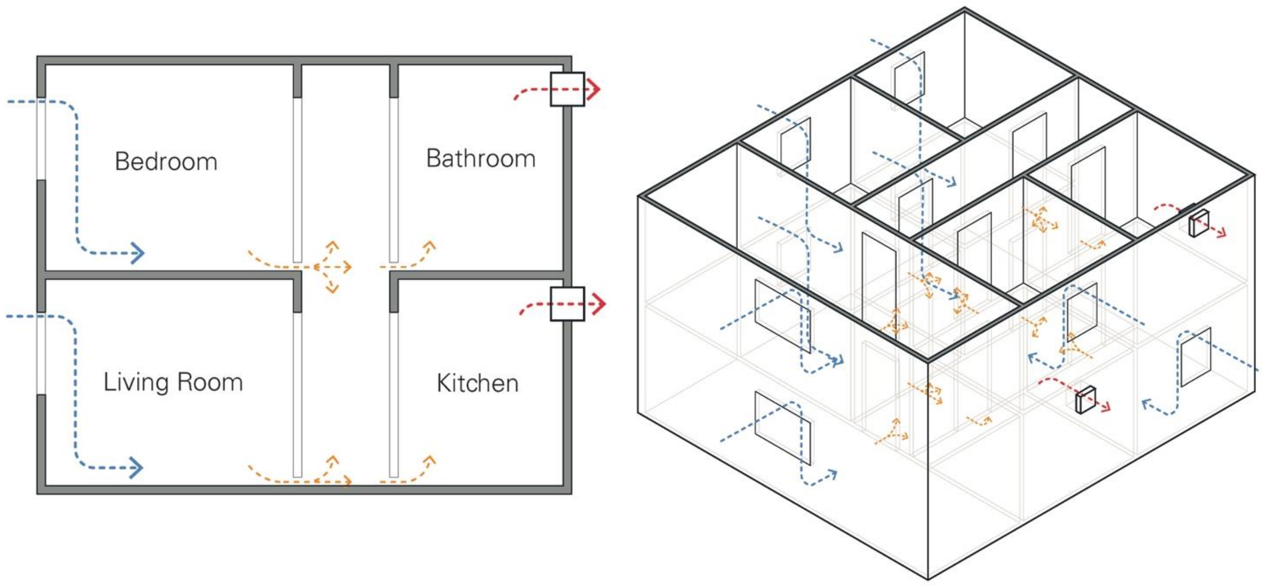


Figure 66. Multi-level condition (section and axonometric)

Issues to consider

The use of dMEV as a strategy to assist ventilation in low energy airtight homes can provide good levels of ventilation in certain circumstances. However, greater attention is needed to the design of the overall system, the interaction between elements of the system and the installation and maintenance of the system.

Whilst a well-designed, well-specified and well-installed dMEV system, coupled with reduced equivalent area trickle ventilators in habitable rooms, may be able to provide a whole house strategy in some circumstances, the design of this should take into account the complexity of the building, the likely ventilation loads within the building, and the likelihood of confounding factors. A ‘one size fits all’ approach is less likely to be effective. However, there are some key vulnerabilities in such a system, not least of which is the risk of the mechanical elements being disabled or failing. Strategies are required for spaces which may be isolated or easily bypassed, and mechanisms to ensure compliance with essential components, such as undercuts or pass vents are critical.

Greater attention is needed to the design and specification of paths for airflow between rooms and through the dwelling. Reliance on undercuts does not produce reliable results, due to variable practice in relation to provision of these, uncertainties and variabilities of floor finishes, and inadequate mixing of air. Therefore the design of the system should recognise the likely paths of air movement, and there is a need for the installation of pass vents between rooms and circulation spaces to facilitate air movement.

Nevertheless, situations can and will occur which will allow for shortcutting of air movement and a dMEV strategy should therefore have a fall-back position as a natural ventilation strategy.

Trickle vents in wet spaces with dMEV systems may assist with the efficacy of moisture removal in these rooms, but where these are provided, the extract should not be considered as part of the dMEV “whole house” ventilation system.

The usability of systems should be improved. More attention is needed to the design of control systems and information to occupants about the importance, use, control and maintenance of the system, in particular operation of boost modes, and the ability to disable the system.

Problems of noise nuisance, although not well evidenced in the survey, were commonplace in the monitoring. The problem here is not precisely one of noise levels, but more the noise nuisance. Whilst noise levels for fans in factory conditions can be (and are) established, the noise in use, taking into account fan speeds, the nature of the installation, and the location of the fan, should be assessed. The need to establish performance standards in-use is therefore critical.

As a building using a dMEV “whole house” ventilation strategy (with reduced trickle ventilation provision) will be reliant on it to produce minimum levels of ventilation, there is a need for certified commissioning for mechanical equipment to ensure that the installation meets specifications as-built and in-use.

Standards for in-use performance could also be developed as a potential alternative mechanism for compliance and to provide scope for designers to develop alternative ventilation strategies. However, if there is less on-site inspection and testing, and more design stage compliance, the need to develop robust regulatory and design processes is paramount.

The presence of carbon dioxide monitoring equipment in bedrooms now provides an evidential basis for in-use performance standards. Certainly, it may be helpful for standards to provide measures of success (akin to the CO_2 thresholds presented in current domestic ventilation supporting guidance).

Any ventilation system which relies on a constantly running piece of mechanical equipment needs to have strategies in place for the adequate maintenance and repair of systems. These should be identified at design stages and properly communicated to the owners, occupiers or landlords.

It appeared that there is still a shortfall in the information and advice given to occupants about ventilation provision and operation. There was limited knowledge about the nature and use of the installed carbon dioxide monitoring equipment and particularly the boost operation of the dMEV systems. At present operation of ventilation is significantly reliant on adaptive behaviour, but as occupants are less aware of, or sensitive to pollutants, this may not be an effective strategy. However, there was some emerging evidence of an awareness of the issues of IAQ. So improved advice, perhaps through the use of the mandatory occupant guides, may be beneficial.

Appendix A – Household survey results

Q1 How long have you been living at this property?

45 (20.2%)	Less than one year
148 (66.4%)	More than 1 to less than 3 years
30 (13.5%)	3 years or more

Q2 How many people normally live in this household?

Adults

57 (25.6%)	One
148 (66.4%)	Two
11 (4.9%)	Three
7 (3.1%)	Four

Children

111 (49.8%)	None
59 (26.5%)	One
46 (20.6%)	Two
6 (2.7%)	Three
1 (0.4%)	Four

Q3 On a typical weekday, how many people are normally in the home: during the day, during the evening and at night?

During the day (8am – 6pm)

66 (29.6%)	None
73 (32.7%)	One
71 (31.8%)	Two
9 (4.0%)	Three
3 (1.3%)	Four
1 (0.4%)	Eight

During the evening (6pm – 12am)

2 (0.9%)	None
35 (15.7%)	One
76 (34.1%)	Two
60 (26.9%)	Three
43 (19.3%)	Four
6 (2.7%)	Five
1 (0.4%)	Six

During the night (12am – 8am)

1 (0.4%)	None
33 (14.8%)	One
79 (35.4%)	Two
59 (26.5%)	Three
44 (19.7%)	Four
6 (2.7%)	Five
1 (0.4%)	Six

Q4 At the weekend, how many people are normally in the home: during the day, during the evening and at night?

During the day (8am – 6pm)

8(3.6%)	None
36 (16.1%)	One
80 (35.9%)	Two
55 (24.7%)	Three
38 (17.0%)	Four
5 (2.2%)	Five
1 (0.4%)	Six

During the evening (6pm – 12am)

33 (14.8%)	One
86 (38.6%)	Two
56 (25.1%)	Three
41 (18.4%)	Four
6 (2.7%)	Five
1 (0.4%)	Six

During the night (12am – 8am)

34 (15.2%)	One
83 (37.2%)	Two
57 (25.6%)	Three
42 (18.8%)	Four
6 (2.7%)	Five
1 (0.4%)	Six

Q5 How many bedrooms are there in your home?

28 (12.6%)	One
60 (26.9%)	Two
69 (30.9%)	Three
39 (17.5%)	Four
27 (12.1%)	Five or more

Q6a How many people sleep in each of the bedrooms? [WRITE IN NUMBER OF ADULTS AND CHILDREN (UNDER 16). IF NONE WRITE IN ‘0’] Bedroom 1

No. of adults

1 (0.4%)	None
64 (28.7%)	One
158 (70.9%)	Two

No. of children

219 (98.2%)	None
4 (1.8%)	One

Q6b How many people sleep in each of the bedrooms? [WRITE IN NUMBER OF ADULTS AND CHILDREN (UNDER 16). IF NONE WRITE IN ‘0’] Bedroom 2

No. of adults

28 (12.6%)	NULL
164 (73.5%)	None
31 (13.9%)	One

No. of children

28 (12.6%)	NULL
95 (42.6%)	None
90 (40.4%)	One
10 (4.5%)	Two

Q6c How many people sleep in each of the bedrooms? [WRITE IN NUMBER OF ADULTS AND CHILDREN (UNDER 16). IF NONE WRITE IN ‘0’] Bedroom 3

No. of adults

88 (39.5%)	NULL
123 (55.2%)	None
12 (5.4%)	One

No. of children

88 (39.5%)	NULL
89 (39.9%)	None
43(19.3%)	One
3 (1.3%)	Two

Q6d How many people sleep in each of the bedrooms? [WRITE IN NUMBER OF ADULTS AND CHILDREN (UNDER 16). IF NONE WRITE IN ‘0’] Bedroom 4

No. of adults

157 (70.4%)	NULL
64 (28.7%)	None
2 (0.9 %)	One

No. of children

157 (70.4%)	NULL
63 (28.3%)	None
3(1.3%)	One

Q7 How many bathrooms are there in the home (including en-suites)?

57 (25.6%)	One
85 (38.1%)	Two
64 (28.7%)	Three
17 (7.6%)	Four or more

Q8 Do you have an en-suite/ shower room?

60 (26.9%)	Yes
163 (73.1%)	No

Q9 How many occupants smoke in the home?

15 (6.7%)	One
2 (0.9%)	Two
2 (0.9%)	Three
1 (0.4%)	Four or more
203 (91.0%)	None

Q10 How often do you dry clothes naturally in the house (for example on radiators, clothes rail or drying cupboard) during the winter season?

31 (13.9%)	Every day
110 (49.3%)	Every 2 to 3 days
36 (16.1%)	Once a week
9 (4.0%)	Once a fortnight
37 (16.6%)	Never

Q11 In which rooms?

98 (52.7%)	Living room
44 (23.7%)	Kitchen
5 (2.7%)	Bathroom(s)
65 (34.9%)	Hallway
19 (10.2%)	Bedroom(s)
5 (2.7%)	Drying cupboard
14 (7.5%)	Other

Q12 Do you know what these are and what they are for?

188 (84.3%) Yes - for ventilation
18 (8.1%) Yes – other
9 (4.0%) No
8 (3.6%) Not sure

Q12other Yes – other (specify)

10 (4.5%) Condensation
9 (4.0%) Air/ Air flow/ Air vent
1 (0.4%) Stop mould

Q13a Are trickle vents installed in your home?

202 (90.6%) Yes (WHICH TYPE)
0 (0.0%) No
21 (9.4%) Not sure

Q13b If yes, which type?

201 (90.1%) uPVC
1 (0.4%) Not sure which type
21 (9.4%) Not sure

Q14 If yes, can these be manually opened and closed?

193 (95.5%) Yes
1 (0.5%) No
8 (4.0%) Not sure

Q15 Do you know if the trickle ventilators are currently opened or closed in the following rooms:

	No window	No trickle vents present	Opened	Closed	Don't know	
Q15a Kitchen	2 (1.0%)	1 (0.5%)	139 (68.8%)	41 (20.3%)	19 (9.4%)	
Q15b Living room	0 (0.0%)	1 (0.5%)	106 (52.5%)	75 (37.1%)	20 (9.9%)	
Q15c Main bedroom	0 (0.0%)	1 (0.5%)	116 (57.4%)	64 (31.7%)	21 (10.4%)	
Q15d Second bedroom*	0 (0.0%)	1 (0.6%)	103 (58.5%)	52 (29.5%)	20 (11.4%)	
Q15e Third bedroom*	0 (0.0%)	0 (0.0%)	83 (68.6%)	28 (23.1%)	10 (8.3%)	
Q15f Fourth bedroom*	0 (0.0%)	0 (0.0%)	45 (72.6%)	14 (22.6%)	3 (4.8%)	
Q15g Main bathroom	0 (0.0%)	0 (0.0%)	137 (67.8%)	44 (21.8%)	21 (10.4%)	
Q15h Shower room/en-suite*	0 (0.0%)	0 (0.0%)	34 (16.8%)	11 (5.4%)	5 (2.5%)	152 (75.2%)NA

Q16 How often do you open or close the trickle vents in your home?

30 (14.9%) Daily
46 (22.8%) Weekly
19 (9.4%) Monthly
79 (39.1%) Less often
28 (13.9%) Never

Q17 Why don't you use the trickle vents?

17 (34.7%) Didn't know they were there
3 (6.1%) Don't know how to use them
0 (0.0%) Can't get to them
3 (6.1%) Cause draughts
0 (0.0%) Noise (e.g. blinds rattling or noise from outside)
0 (0.0%) Worry it will increase heating bills
27 (55.1%) Don't feel the need to
4 (8.2%) Other

Q17Other (please specify)

- *Always open.*
- *Was not aware of them.*
- *Open windows.*
- *Prefer to use windows.*

Q18 In winter, how often are the windows usually open in your home during the day?

	No window	Never	Monthly	Weekly	Daily	All the time	
Q18a Kitchen	2 (0.9%)	104 (46.6%)	7 (3.1%)	27 (12.1%)	76 (34.1%)	7 (3.1%)	
Q18b Living room	0 (0.0%)	127 (57.0%)	15 (6.7%)	36 (16.1%)	41 (18.4%)	4 (1.8%)	
Q18c Main bedroom	0 (0.0%)	58 (26.0%)	4 (1.8%)	82 (36.8%)	74 (33.2%)	5 (2.2%)	
Q18d Second bedroom*	0 (0.0%)	54 (27.7%)	1 (0.5%)	75 (38.5%)	60 (30.8%)	5 (2.6%)	
Q18e Third bedroom*	0 (0.0%)	37 (27.4%)	1 (0.7%)	57 (42.2%)	36 (26.7%)	4 (3.0%)	
Q18f Fourth bedroom*	0 (0.0%)	17 (25.8%)	1 (1.5%)	27 (40.9%)	19 (28.8%)	2 (3.0%)	
Q18g Main bathroom	0 (0.0%)	49 (22.0%)	0 (0.0%)	66 (29.6%)	101 (45.3%)	7 (3.1%)	
Q18h Shower room/en-suite*	0 (0.0%)	20 (9.0%)	1 (0.4%)	12 (5.4%)	24 (10.8%)	3 (1.3%)	163 (73.1%)NA

Q19 In winter, how often are the windows usually open in your home during the night?

	No window	Never	Monthly	Weekly	Daily	All the time	
Q19a Kitchen	2 (0.9%)	213 (95.5%)	0 (0.0%)	0 (0.0%)	8 (3.6%)	0 (0.0%)	
Q19b Living room	0 (0.0%)	216 (96.9%)	1 (0.4%)	4 (1.8%)	2 (0.9%)	0 (0.0%)	
Q19c Main bedroom	0 (0.0%)	198 (88.8%)	2 (0.9%)	11 (4.9%)	10 (4.5%)	2 (0.9%)	
Q19d Second bedroom*	0 (0.0%)	183 (93.8%)	0 (0.0%)	5 (2.6%)	6 (3.1%)	1 (0.5%)	
Q19e Third bedroom*	0 (0.0%)	127 (94.1%)	0 (0.0%)	3 (2.2%)	4 (3.0%)	1 (0.7%)	
Q19f Fourth bedroom*	0 (0.0%)	64 (97.0%)	0 (0.0%)	0 (0.0%)	1 (1.5%)	1 (1.5%)	
Q19g Main bathroom	0 (0.0%)	211 (94.6%)	0 (0.0%)	6 (2.7%)	5 (2.2%)	1 (0.4%)	
Q19h Shower room/en-suite*	0 (0.0%)	56 (93.3%)	0 (0.0%)	3 (5.0%)	1 (1.7%)	0 (0.0%)	0 (0.0%)NA

Q20 What are the main reasons for opening windows in your home?

46 (20.6%)	Too warm
41 (18.4%)	To get rid of moisture/ damp
81 (36.3%)	To get rid of smells
62 (27.8%)	To dry clothes
189 (84.8%)	For fresh air / to air the room
6 (2.7%)	It helps me sleep better
10 (4.5%)	For connection to outdoors
11 (4.9%)	Other (please specify)

Q20Other (please specify)

- *No reason.*
- *Dog - patio doors in living room.*
- *Summer weather.*
- *Smells.*
- *Ventilation.*
- *Summer weather.*
- *No reason.*
- *Nothing.*
- *Shower.*
- *Dry kitchen floors.*
- *Dust.*

Q21 What factors stop you opening the windows in your home?

5 (2.2%)	Don't feel the need to
1 (0.4%)	Pollution
11 (4.9%)	Noise
76 (34.1%)	Security
51 (22.9%)	Heat loss
3 (1.3%)	Insects
23 (10.3%)	Cold draughts
137 (61.4%)	Weather
1 (0.4%)	Can't reach / get to them
0 (0.0%)	Difficult handle/ control
0 (0.0%)	Locked
5 (2.2%)	Other (please specify)
58 (26.0%)	None

Q21Other - please specify

- Health reasons.
- Temperature outside.
- Winter.
- At work at different times.
- Spiders.

Q22 Overnight, do you normally keep your bedroom door:

159 (71.3%)	Closed
64 (28.7%)	Open

Q23 Overnight in your bedroom, do you normally keep curtains/blinds:

210 (94.2%)	Closed
13 (5.8%)	Open

Q24 Is there a mechanical extract fan for ventilation in your bathroom(s) or en-suite(s)?

216 (96.9%)	Yes
2 (0.9%)	No
5 (2.2%)	Not sure

Q25 Is there a mechanical extract fan for ventilation in your kitchen?

212 (95.1%)	Yes
7 (3.1%)	No
4 (1.8%)	Not sure

Q26 If yes (to either of the above), can you identify which type? [ALL THAT APPLY]

46 (21.0%)	Option 1 (Vent Axia)
136 (62.1%)	Option 2 (Zehnder/Greenwood)
3 (1.4%)	Other type not listed
35 (16.0%)	Not sure

Q27 Do the mechanical extract fans run continuously?

152 (69.4%)	Yes
35 (16.0%)	No
32 (14.6%)	Not sure

Q28 Are the mechanical extract fans currently working / operating?

207 (94.5%)	Yes
1 (0.5%)	No
11 (5.0%)	Not sure

Q28No - please explain

- *Think bathroom one isn't working.*

Q29 Have you had any problems or concerns with your ventilation system:

	Yes	No
Q29a Noise	10 (4.5%)	213 (95.5%)
Q29b Cost of running	0 (0.0%)	223 (100.0%)
Q29c Draughts	3 (1.3%)	220 (98.7%)
Q29d Performance (stopped working / ineffective)	3 (1.3%)	220 (98.7%)
Q29e Blocked / dirty	1 (0.4%)	222 (99.6%)
Q29f Other (please state)	0 (0.0%)	223 (100.0%)

Q29 Have you had any problems or concerns with your ventilation system:
0 (0.0%)

Q30 If yes [FOR ANY OF THE ABOVE], please explain

- *Don't appear very effective.*
- *The noise is too loud, especially at night.*
- *Noisy in the bathroom, especially at night time.*
- *Noisy in the bathroom, especially at night time.*
- *Sometimes noisy at night.*
- *It doesn't work properly.*
- *Water stuck in, they were faulty.*
- *Can be noisy and draughty.*
- *The fan can be quite loud.*
- *Night noise.*
- *Adjust the settings because it was too noisy at night.*
- *Not very strong.*
- *Draughty and noisy in certain parts of home.*
- *Wind - the way the building faces*

Q31 Are ‘boost’ switches available to boost the ventilation rate in the mechanical ventilation system?
107 (48.0%) Yes
32 (14.3%) No
84 (37.7%) Not sure

Q32 If ‘boost’ switches are not available, do you know how the boost mode is controlled?
10 (8.6%) Operates automatically when enter the room (PIR/ occupancy sensor)
3 (2.6%) Operates automatically when humidity/CO2 levels high (RH/CO2 sensor)
4 (3.4%) Operates automatically when turn on shower/cooker
4 (3.4%) Other (please state)
98 (84.5%) Not sure

Q32Other - please state
- *Push it to increase.*
- *Not aware of them.*
- *Automatically come on in kitchen and bathroom.*
- *Kitchen is manual.*

Q33 If ‘boost’ switches are available, how often are they used?
6 (5.6%) A few times a day
10 (9.3%) Once a day
21 (19.6%) A few times a week
6 (5.6%) Once a week
11 (10.3%) Less than once a week
53 (49.5%) Never

Q34 Why are the ‘boost’ mode switches not used?
51 (96.2%) Don’t feel the need to
0 (0.0%) Don’t know how to use it
0 (0.0%) Can’t reach the switch
0 (0.0%) Cause draughts
0 (0.0%) Noise (e.g. fan noise)
0 (0.0%) Worry it will increase heating bills
0 (0.0%) Worry about energy use of the fan
1 (1.9%) Didn’t know about it
1 (1.9%) Other (please specify)

Q34Other (please specify)
- It does it automatically.

Q35 When is the ‘boost’ mode in the ventilation system typically used in

	When cooking	When showering	Smoking (indoors)	Drying clothes	Too warm	Other (please state)	
Q35a Kitchen	49 (90.7%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (1.9%)	4 (7.4%)	
Q35b Bathroom	2 (3.7%)	51 (94.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (1.9%)	
Q35c En-suite	1 (1.9%)	16 (29.6%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	37 (68.5%)NA
Q35d Shower room	1 (1.9%)	16 (29.6%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	37 (68.5%)NA

Q35a Other (please state)
- *Not used.*
- *Not used.*
- *Not used.*
- *Comes on automatically.*

Q35b Other (please state)

- *Comes on automatically.*

Q36 Have you ever deactivated the ventilation system using the local isolator switch or fuse box?

6 (2.7%)	Yes
205 (91.9%)	No
12 (5.4%)	Not sure

Q37 If yes, why did you do this? (Was it because of any of the problems identified in Q28/Q29?)

- *Due to noise.*
- *It is noisy.*
- *Noises at night*
- *If wife is in the bath and the kids are in bed because of the noise.*
- *Yes - trying to fix it.*
- *Because of noise.*

Q38 Have you ever adjusted the dial/controls on the side of the ventilation unit to change the flow rate?

15 (6.7%)	Yes
198 (88.8%)	No
10 (4.5%)	Not sure

Q39 Have you ever received advice on how best to ventilate the house?

84 (37.7%)	Yes
85 (38.1%)	No
54 (24.2%)	Can't remember

Q40 What was this advice?

1 (1.2%)	Can’t remember
48 (57.1%)	Keep vents open
8 (9.5%)	Open windows regularly / air house
6 (7.1%)	Given handbook
4 (4.8%)	Don’t know
15 (17.9%)	Keep fans running at all times
2 (2.4%)	Building manager gave advice

Q41 Is there anything that could improve the ventilation in your house?

128 (56.5%)	Nothing
68 (30.5%)	None
9 (4.0%)	Not sure
6 (2.7%)	Don’t know
1 (0.4%)	Yes I had to get a humidifier because of dampness
	Nothing, there's plenty of ventilation
1 (0.4%)	Always leave trickle vents open because we had condensation on windows. Condensation on windows still an issue
1 (0.4%)	Nothing, it's well ventilated
1 (0.4%)	No problems
1 (0.4%)	More windows
1 (0.4%)	No quite happy, not any problems
1 (0.4%)	Nothing, ventilation isn't a problem
1 (0.4%)	The vents are missing from all the toilets
1 (0.4%)	Nothing, no problems
1 (0.4%)	Nothing, plenty ventilation
1 (0.4%)	Better explanation of how to make best use of extraction fans

1 (0.4%) I feel isolator is pointless
1 (0.4%) I don't know but there is green mould in my bedroom

Q42 Do you have a carbon dioxide (CO_2) monitor installed in your main bedroom?
21 (9.4%) Yes
182 (81.6%) No
20 (9.0%) Not sure

Q43 If yes, do you know what this monitor is for?
19 (90.5%) Yes
0 (0.0%) No
2 (9.5%) Not sure

Q43Yes (please explain)
2 (9.5%) Health and safety
16 (76.2%) Carbon Dioxide/ Co2 monitoring
1 (4.8%) Gas poisoning

Q44 Have you ever received any guidance on how to use the CO2 monitor?
5 (23.8%) Yes
5 (23.8%) No
11 (52.4%) Not sure

Q45 What was this advice?

- *Showed me how it works.*
- *Full instructions from building manager.*
- *Can't remember.*
- *Can't remember.*
- *Got it from the building manager when moved in.*

Q46 Are you aware of any instances where high levels of CO2 have been detected by the CO2 monitor, and if so, how often?
0 (0.0%) Yes- Daily
0 (0.0%) Yes- Weekly
0 (0.0%) Yes- Monthly
0 (0.0%) Yes- less than once a month
5 (23.8%) No
16 (76.2%) Not sure

Q47 If yes, what action did you take?
0 (0.0%)

Q48 Would you say that the presence of a CO2 meter has had any influence on the way you ventilate your home?
3 (1.3%) Yes
113 (50.7%) No
107 (48.0%) Not sure

Q49 Please explain
69 (30.9%) Don’t know
1 (0.4%) Never think about it
1 (0.4%) Ventilate regardless
1 (0.4%) Not sure
3 (1.3%) Nothing
1 (0.4%) Just acted on the advice given
1 (0.4%) No reason
1 (0.4%) Never thought about it

144 (64.6%)	None
1 (0.4%)	I just do what I always did

Q50 Overall, how satisfied are you with the following in your home?

	Very satisfied	Satisfied	Neither/Nor	Dissatisfied	Very dissatisfied
Q50a Indoor air quality	204 (91.5%)	17 (7.6%)	2 (0.9%)	0 (0.0%)	0 (0.0%)
Q50b Indoor temperature	207 (92.8%)	12 (5.4%)	4 (1.8%)	0 (0.0%)	0 (0.0%)
Q50c Natural light levels	199 (89.2%)	17 (7.6%)	5 (2.2%)	2 (0.9%)	0 (0.0%)
Q50d Noise levels from equipment	177 (79.4%)	34 (15.2%)	9 (4.0%)	2 (0.9%)	1 (0.4%)

Q51 Would you like to be considered to participate in a detailed monitoring study?

59 (26.5%)	Yes
164 (73.5%)	No

Appendix B – Household questionnaire

YOUR HOUSEHOLD

1. How long have you been living at this property? [*IF DO NOT LIVE HERE – THANK AND CLOSE]

Number of years		Go to Q2

2. How many people normally live in this household? [WRITE IN NUMBER OF ADULTS AND CHILDREN (UNDER 16). IF NONE WRITE IN '0']

Number of Adults		Go to Q3
Number of Children		

3. On a typical weekday, how many people are normally in the home: during the day, during the evening and at night?

During the day (8am - 6pm)	Evening (6pm- 12am)	Night (12am- 8am)	Go to Q4

4. At the weekend, how many people are normally in the home: during the day, during the evening and at night?

During the day (8am - 6pm)	Evening (6pm- 12am)	Night (12am- 8am)	Go to Q5

5. How many bedrooms are there in your home? [WRITE IN NUMBER]

One	1	Go to Q6
Two	2	
Three	3	
Four	4	
Five or more	5	

6. How many people sleep in each of the bedrooms? [WRITE IN NUMBER OF ADULTS AND CHILDREN (UNDER 16). IF NONE WRITE IN '0']

	No. of adults	No. of children	Go to Q7
Bedroom 1 (main)			
Bedroom 2			
Bedroom 3			
Bedroom 4			

7. How many bathrooms are there in the home (including en-suites and shower rooms)?

One	1	Go to Q8
Two	2	
Three	3	
Four or more	4	

8. Do You have an ensuite / shower room?

Yes	1	Go to Q9
No	2	
Not sure	3	

9. How many occupants smoke in the home? [ONE ONLY]

One	1	Go to Q10
Two	2	
Three	3	
Four or more	4	
None	5	

10. How often do you dry clothes naturally in the house (for example on radiators, clothes rail or drying cupboard) during the winter season? [ONE ONLY]

Every day	1	Go to Q11
Every 2 to 3 days	2	
Once a week	3	
Once a fortnight	4	
Never	5	Go to Q12

11. In which rooms? [ALL THAT APPLY]

Living room	1	Go to Q12
Kitchen	2	
Bathroom(s)	3	
Hallway	4	
Bedroom(s)	5	
Drying cupboard	6	
Other	7	

12. [SHOWCARD 01] Do you know what these are and what they are for? [ONE ONLY]

Yes - for ventilation	1	Go to Q13
Yes – other (please specify)	2	
No	3	
Not sure	4	

TRICKLE VENTS

13. LOOKING AT THE SHOWCARD Are trickle vents installed in your home?

Yes	1	Go to Q18
No	2	
Not sure	3	

14. If yes, can these be manually opened and closed?

Yes	1	Go to Q15
No	2	
Not sure	3	

15. **Do you know if the trickle ventilators are currently opened/closed in the following rooms: (*if applicable)**

	No window	No trickle vents	Opened	Closed	Don't know	
Kitchen	1	2	3	4	5	Go to Q16
Living room	1	2	3	4	5	
Main bedroom	1	2	3	4	5	
Second bedroom*	1	2	3	4	5	
Third bedroom*	1	2	3	4	5	
Fourth bedroom*	1	2	3	4	5	
Main bathroom	1	2	3	4	5	
Shower room/en-suite*	1	2	3	4	5	

16. **How often do you open or close the trickle vents in your home? [ONE ONLY]**

Daily	1	Go to Q18
Weekly	2	
Monthly	3	
Less often	4	
Never	5	Go to Q17

17. **[IF NEVER] Why don't you use the trickle vents? [ALL THAT APPLY]**

Didn't know they were there	1	Go to Q18
Don't know how to use them	2	
Can't get to them	3	
Cause draughts	4	
Noise (e.g. blinds rattling or noise from outside)	5	
Worry it will increase heating bills	6	
Don't feel the need to	7	
Other (please specify)	8	

WINDOW AND DOOR OPENING

18. **In winter, how often are the windows usually open in the following rooms in your home during the day? (*if applicable)**

	No window	Never	Monthly	Weekly	Daily	All the time	
Kitchen	1	2	3	4	5	6	Go to Q19
Living room	1	2	3	4	5	6	
Main bedroom	1	2	3	4	5	6	
Second bedroom*	1	2	3	4	5	6	
Third bedroom*	1	2	3	4	5	6	
Fourth bedroom*	1	2	3	4	5	6	
Main bathroom	1	2	3	4	5	6	
Shower room/en-suite*	1	2	3	4	5	6	

19. In winter, how often are the windows usually open in the following rooms in your home during the night? (*if applicable)

	No window	Never	Monthly	Weekly	Daily	All the time	
Kitchen	1	2	3	4	5	6	Go to Q20
Living room	1	2	3	4	5	6	
Main bedroom	1	2	3	4	5	6	
Second bedroom*	1	2	3	4	5	6	
Third bedroom*	1	2	3	4	5	6	
Fourth bedroom*	1	2	3	4	5	6	
Main bathroom	1	2	3	4	5	6	
Shower room/en-suite*	1	2	3	4	5	6	

20. What are the main reasons for opening windows in your home? [ALL THAT APPLY]

Too warm	1	Go to Q21
To get rid of moisture/ damp	2	
To get rid of smells	3	
To dry clothes	4	
For fresh air / to air the room	5	
It helps me sleep better	6	
For connection to outdoors	7	
Other (please specify)	8	

21. What factors stop you opening the windows in your home? [ALL THAT APPLY]

Don’t feel the need to	1	Go to Q22
Pollution	2	
Noise	3	
Security	4	
Heat loss	5	
Insects	6	
Cold draughts	7	
Weather	8	
Can’t reach / get to them	9	
Difficult handle/ control	10	
Locked	11	
Other (please specify)	12	

22. Overnight, do you normally keep your bedroom door:

Closed	1	Go to Q23
Open	2	

23. Overnight in your bedroom, do you normally keep curtains/blinds:

Closed	1	Go to Q24
Open	2	

MECHANICAL VENTILATION

24.[INTERVIEWER- SHOWCARD 02- DMEV FANS] Is there a mechanical extract fan for ventilation in your bathroom, en-suite or shower room?

Yes	1	Go to Q25
No	2	
Not sure	3	

25.[INTERVIEWER- SHOWCARD 02- DMEV FANS] Is there a mechanical extract fan for ventilation in your kitchen?

Yes	1	Go to Q26
No	2	
Not sure	3	

26.[INTERVIEWER- SHOWCARD 02- DMEV FANS] If yes (to either of the above), can you identify which type? [ALL THAT APPLY]

Option 1 (Vent Axia)	1	Go to Q27
Option 2 (Zehnder/Greenwood)	2	
Other type not listed	3	
Not sure	4	

27. Do the mechanical extract fans run continuously?

Yes	1	Go to Q28
No	2	
Not sure	3	

28. Are the mechanical extract fans currently working / operating?

Yes	1	Go to Q29
No (please explain)	2	
Not sure	3	

29. Have you had any problems or concerns with your ventilation system:

	Yes	No	
Noise	1	2	IF YES [FOR ANY], Go to Q30 IF NO, Go to Q31
Cost of running	1	2	
Draughts	1	2	
Performance (stopped working / ineffective)	1	2	
Blocked / dirty	1	2	
Other (please state)	1	2	

30.If yes [FOR ANY OF THE ABOVE], please explain

31. Are 'boost' switches available to boost the ventilation rate in the mechanical ventilation system?

Yes	1	Go to Q33
No	2	Go to Q32
Not sure	3	

32. If 'boost' switches are not available, do you know how the boost mode is controlled?

Operates automatically when enter the room (PIR/ occupancy sensor)	1	Go to Q36
Operates automatically when humidity/CO_2 levels high (RH/CO_2 sensor)	2	
Operates automatically when turn on shower/cooker	3	
Other (please state)	4	
Not sure	5	

33. If 'boost' switches are available, how often are they used?

A few times a day	1	Go to Q35
Once a day	2	
A few times a week	3	
Once a week	4	
Less than once a week	5	
Never	6	Go to Q34

34. Why are the 'boost' mode switches not used?

Don't feel the need to	1	Go to Q36
Don't know how to use it	2	
Can't reach the switch	3	
Cause draughts	4	
Noise (e.g. fan noise)	5	
Worry it will increase heating bills	6	
Worry about energy use of the fan	7	
Didn't know about it	8	
Other (please specify)	9	

35. When is the 'boost' mode in the ventilation system typically used in a) the Kitchen, b) the bathroom, c) en-suite* and d) shower room* (*if applicable) (ALL THAT APPLY]

	Kitchen	Bathroom	En-suite	Shower room	
When cooking	1	1	1	1	Go to Q36
When showering	2	2	2	2	
Smoking (indoors)	3	3	3	3	
Drying clothes	4	4	4	4	
Too warm	5	5	5	5	
Other (please state)	6	6	6	6	

36. Have you ever deactivated the ventilation system using the local isolator switch or fuse box?

Yes	1	Go to Q37
No	2	Go to Q38
Not sure	3	

37. If yes, why did you do this? (Was it because of any of the problems identified in Q28/Q29?)

	Go to Q38

38. Have you ever adjusted the dial/controls on the side of the ventilation unit to change the flow rate?

Yes	1	Go to Q39
No	2	
Not sure	3	

ADVICE

39. Have you ever received advice on how best to ventilate the house?

Yes	1	Go to Q40
No	2	Go to Q41
Can't remember	3	

40. What was this advice? [PROBE FULLY]

	Go to Q41

41. Is there anything that could improve the ventilation in your house? [PROBE FULLY]

	Go to Q42

CO2 meter

42. [INTERVIEWER SHOWCARD 03- CARBON DIOXIDE MONITOR] Do you have a carbon dioxide (CO_2) monitor installed in your main bedroom?

Yes	1	Go to Q43
No	2	Go to Q48
Not sure	3	

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

Yes (please explain)	1	Go to Q44
No	2	
Not sure	3	

44. Have you ever received any guidance on how to use the CO_2 monitor?

Yes	1	Go to Q45
No	2	Go to Q46
Not sure	3	

45. What was this advice? [PROBE FULLY]

	Go to Q46

46. Are you aware of any instances where high levels of CO2 have been detected by the CO2 monitor, and if so, how often?

Yes- Daily	1	Go to Q47
Yes- Weekly	2	
Yes- Monthly	3	
Yes- less than once a month	4	
No	5	Go to Q48
Not sure	6	

47. If yes, what action did you take?

	Go to Q48

48. Would you say that the presence of a CO_2 meter has had any influence on the way you ventilate your home?

Yes	1	Go to Q49
No	2	
Not sure	3	

49. Please explain

	Go to Q50

Perception of the indoor environment

50. Overall, how satisfied are you with the following in your home?

	Very satisfied	Satisfied	Neither/ Nor	Dissatisfied	Very dissatisfied	
Indoor air quality	1	2	3	4	5	Go to Q51
Indoor temperature	1	2	3	4	5	
Natural light levels	1	2	3	4	5	
Noise levels from equipment	1	2	3	4	5	

51. Would you like to be considered to participate in a detailed monitoring study?

This study will involve physical monitoring of indoor environmental quality over a 1 week period, during the winter season and a walk-through building survey. Monitoring equipment will be left within your home, and collected at the end of the monitoring period. You will also be asked to complete a short occupant diary during the monitoring period. More information on the study is provided in the information sheet.

If you agree to take part in the detailed monitoring study and are selected, you will receive a shopping voucher worth £20 after successful completion, to thank you for your participation. **[IF YES, COLLECT INFORMATION ON SEPARATE SHEET]**

Yes	1	COLLECT INFO
No	2	FINISH

Appendix C – Show cards

Showcard 01 - Identifying a Trickle Vent - Typical Examples

Timber Window

uPVC Window

Showcard 02 - DMEV Fans

Constantly running fans in "wet rooms" which run faster when either the light is turned on or there is steam in the air.

Option 1

Option 2

Showcard 03 - Carbon Dioxide Monitor

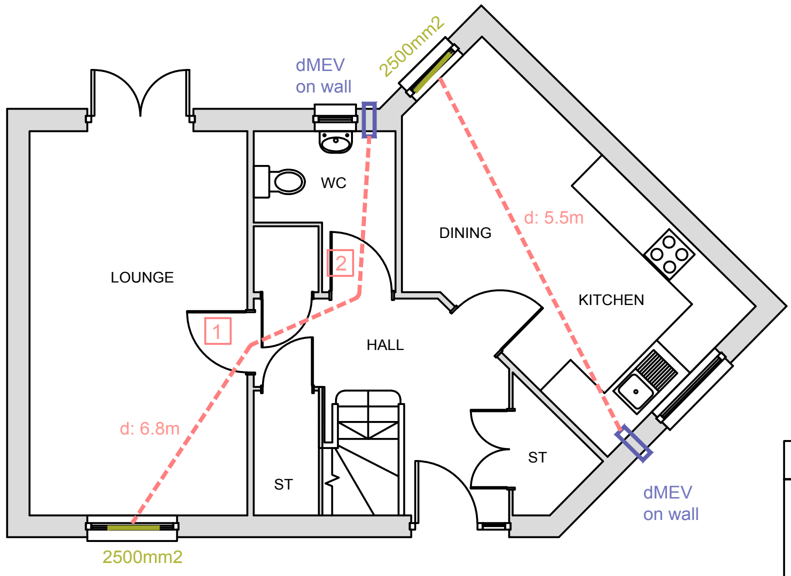
Located in the master bedroom on the wall.

Version with coloured display

Alternatives

Appendix D – Floor plans

M01-M08
Ground Floor Plan



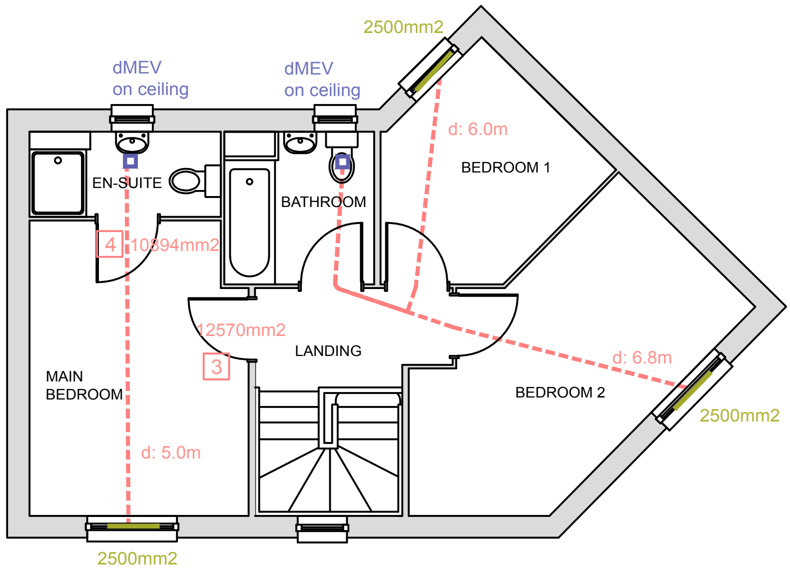
KEY REFERENCES

- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:
Door 1:
M01: 6704mm2
M08: 11732mm2
Door 2:
M01: 7542mm2
M08: 12570mm2
Door 3:
M01: 12570mm2
M08: 13408mm2
Door 4:
M01: 10894mm2
M08: N/A

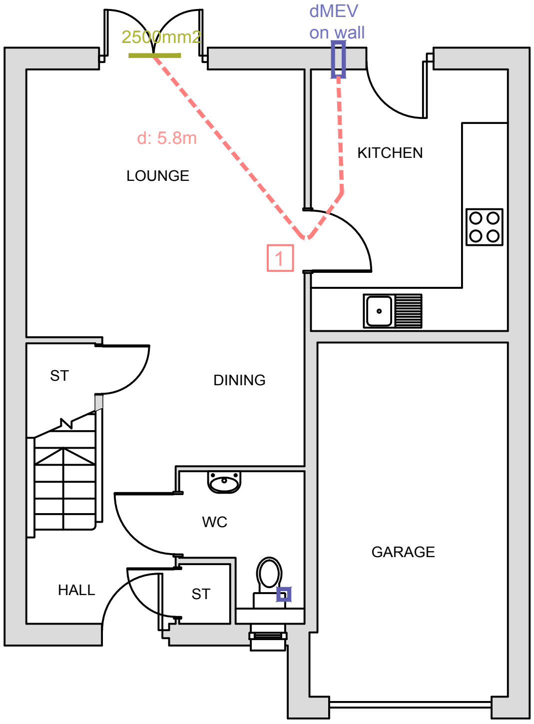
M01-M08
First Floor Plan



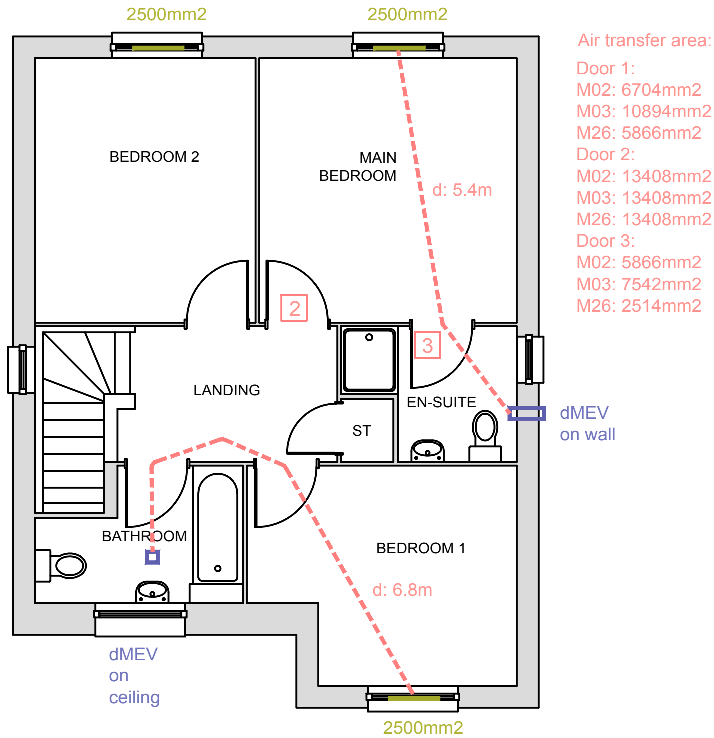
WP3

All drawings are not for dimensional use
and for information only.

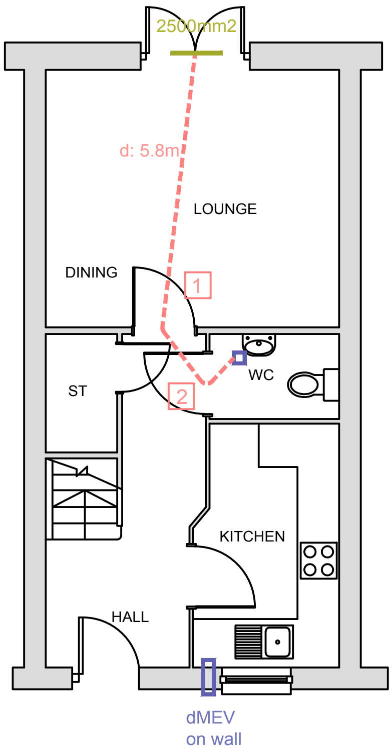
M02-M03-M26
Ground Floor Plan



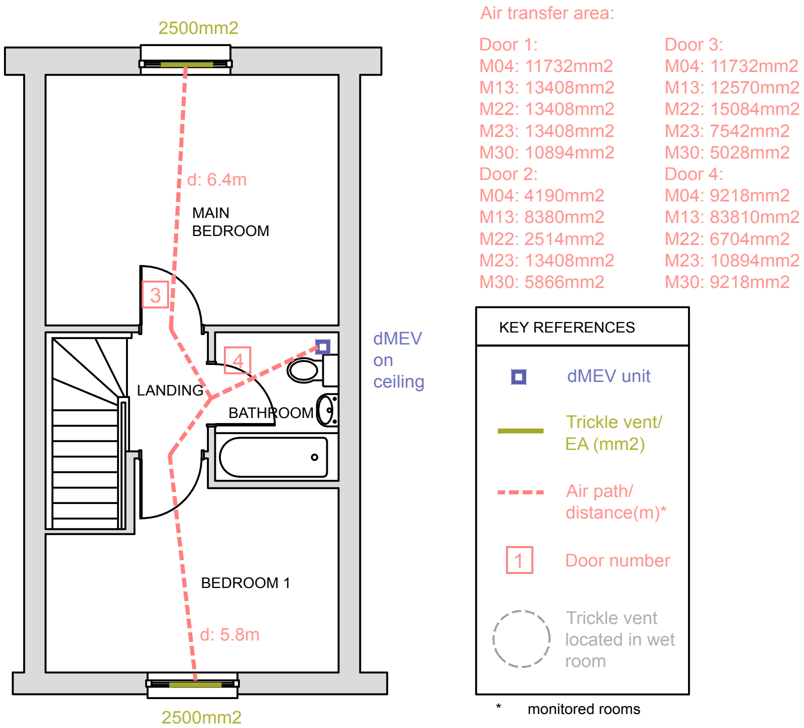
M02-M03-M26
First Floor Plan



M04-M13-M22-M23-M30
Ground Floor Plan



M04-M13-M22-M23-M30
First Floor Plan



WP3

All drawings are not for dimensional use
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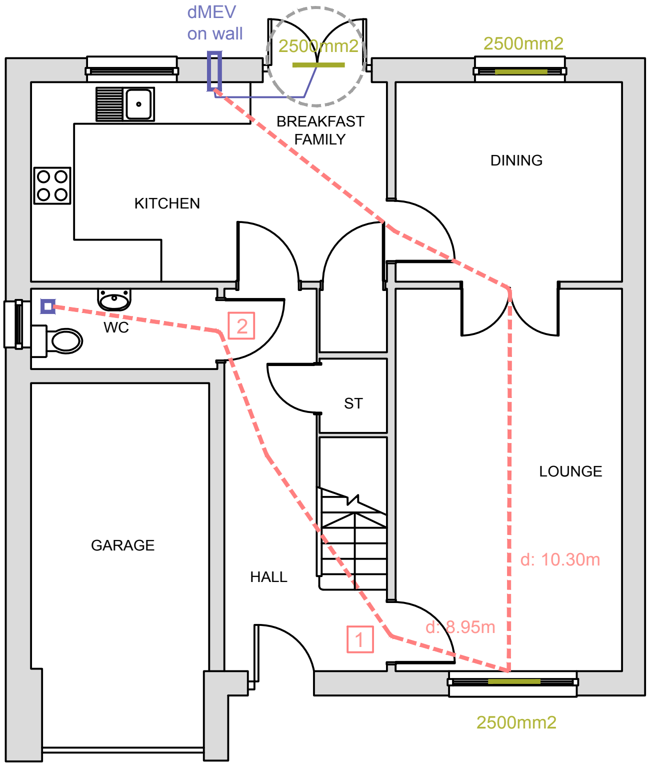
M05
Ground Floor Plan



KEY REFERENCES

dMEV unit

Trickle vent/ EA (mm2)

Air path/ distance(m)*

Door number

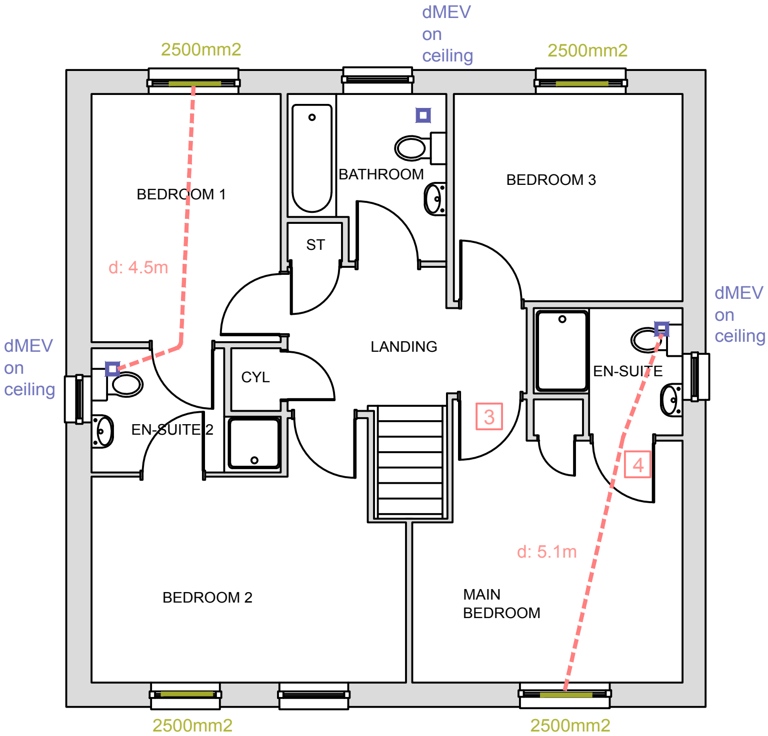
Trickle vent located in wet room

* monitored rooms

Air transfer area:

Door 1: 5866mm2
Door 2: 9218mm2
Door 3: 5866mm2
Door 4: 11732mm2

M05
First Floor Plan



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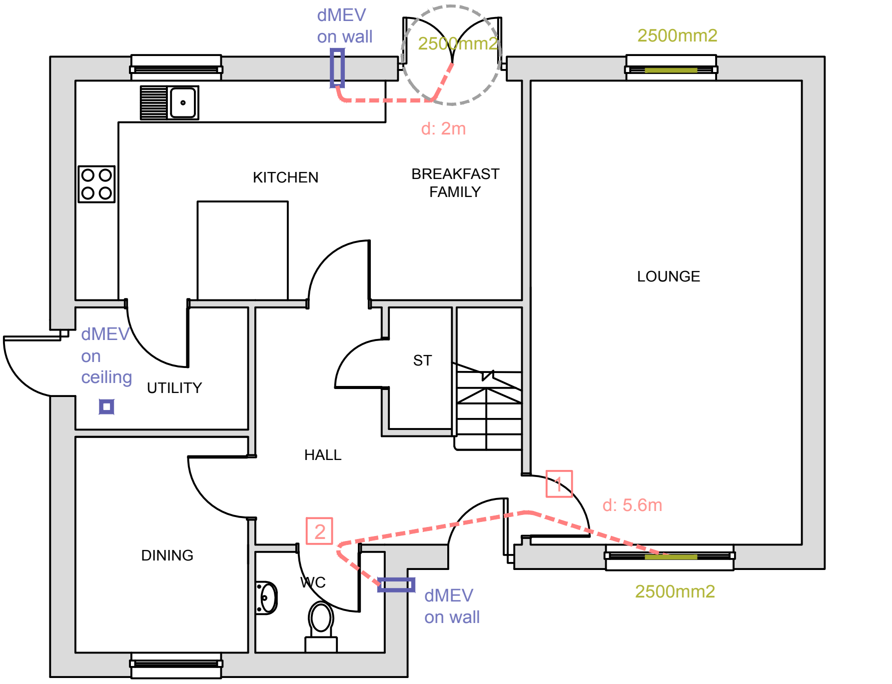
M06
Ground Floor Plan



KEY REFERENCES

dMEV unit

Trickle vent/ EA (mm2)

Air path/ distance(m)*

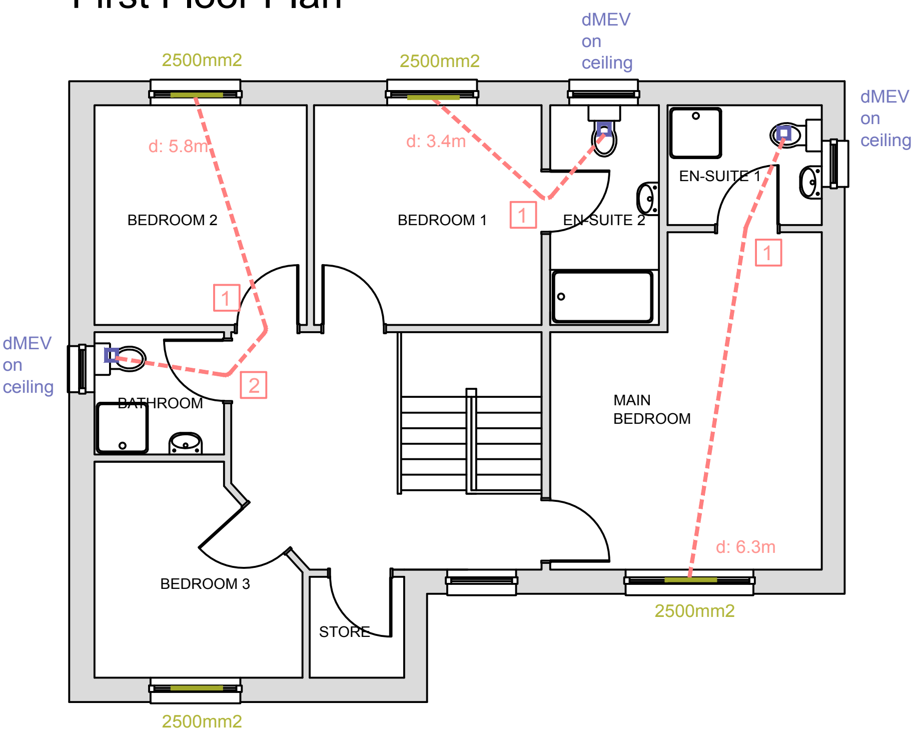
Door number

Trickle vent located in wet room

* monitored rooms

Air transfer area:
Door 1: 14246mm2
Door 2: 4190mm2
Door 3: 17598mm2
Door 4: 6704mm2

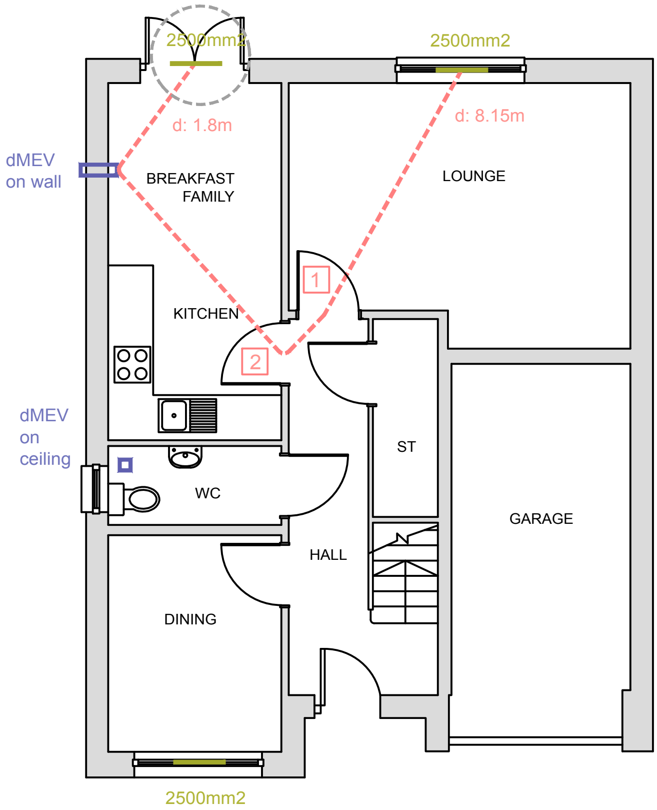
M06
First Floor Plan



WP3

All drawings are not for dimensional use and for information only.

M07
Ground Floor Plan



KEY REFERENCES

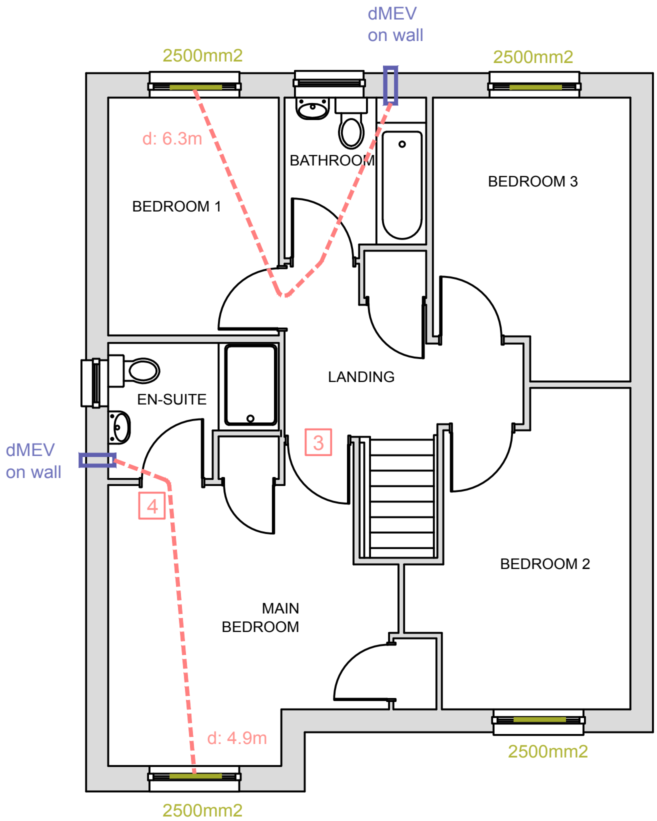
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

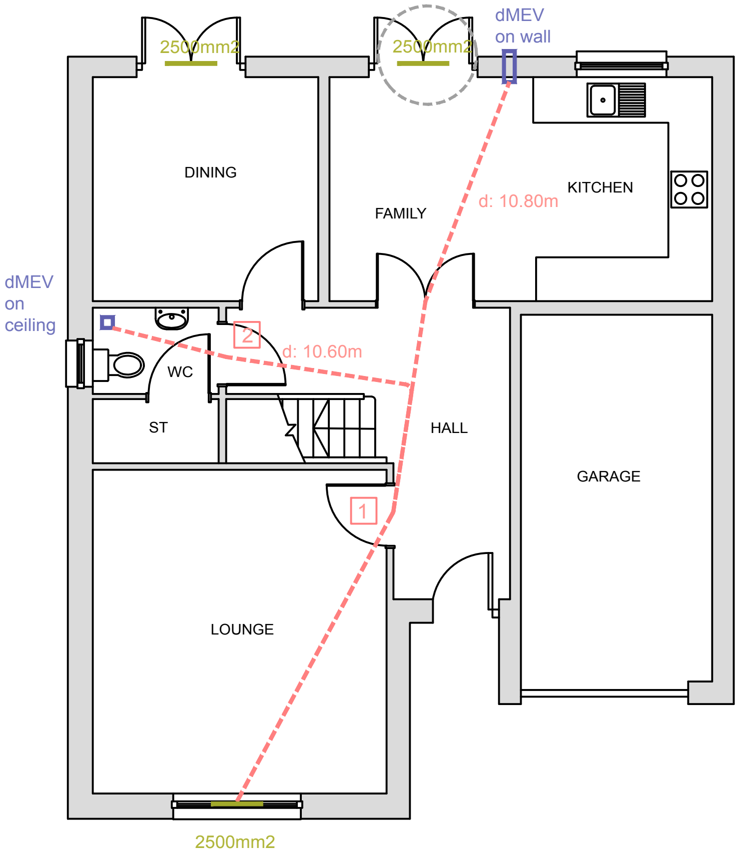
Air transfer area:

Door 1: 9218mm2
Door 2: 5028mm2
Door 3: 13408mm2
Door 4: 3352mm2

M07
First Floor Plan



M09-M14-M20
Ground Floor Plan



KEY REFERENCES

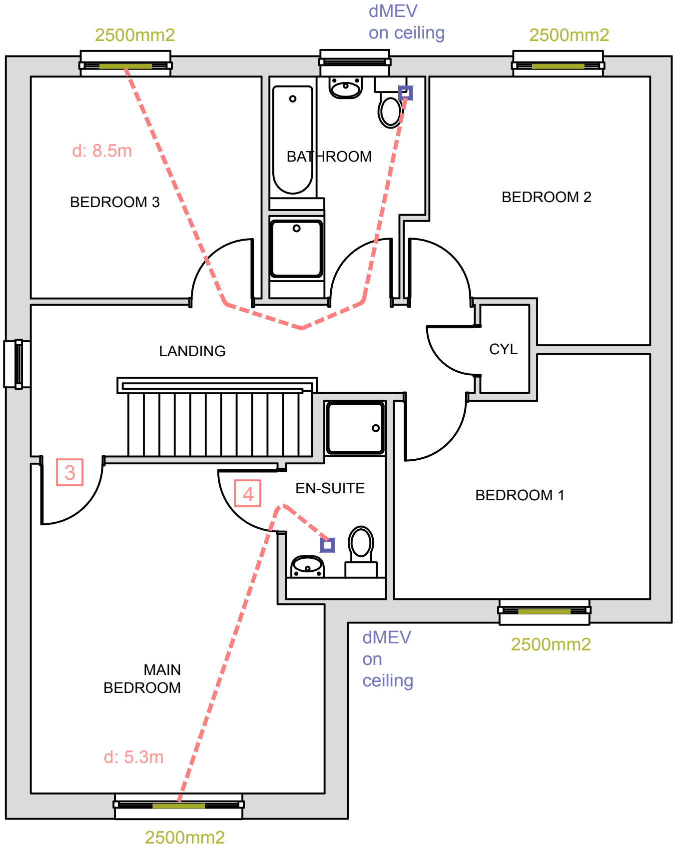
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:

Door 1:
M09: 13408mm2
M14: 3352mm2
M20: 7542mm2
Door 2:
M09: 14246mm2
M14: 3352mm2
M20: 2514mm2
Door 3:
M09: 16760mm2
M14: 19274mm2
M20: 15084mm2
Door 4:
M09: 15084mm2
M14: 13408mm2
M20: 10056mm2

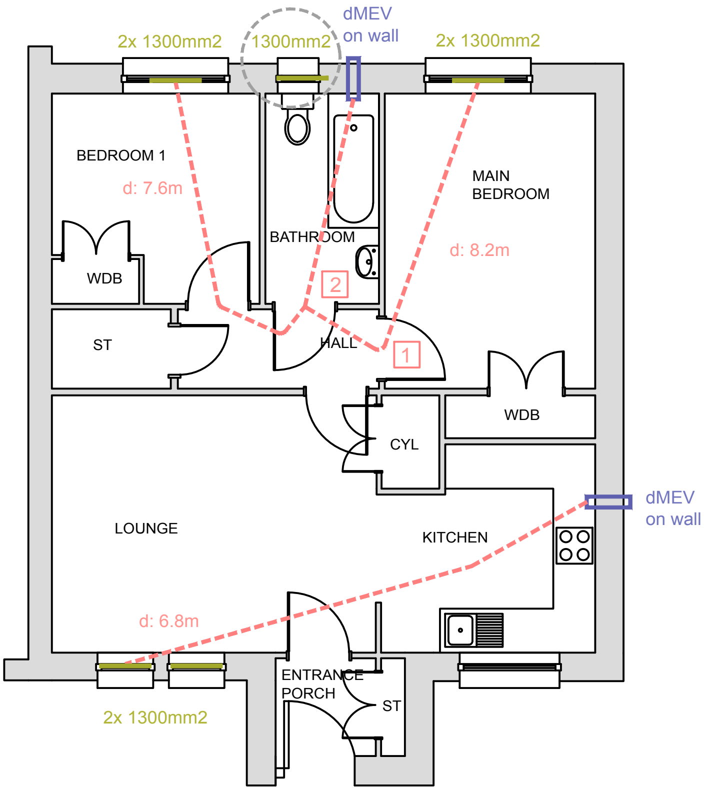
M09-M14-M20
First Floor Plan



WP3

All drawings are not for dimensional use
and for information only.

M10
Floor Plan

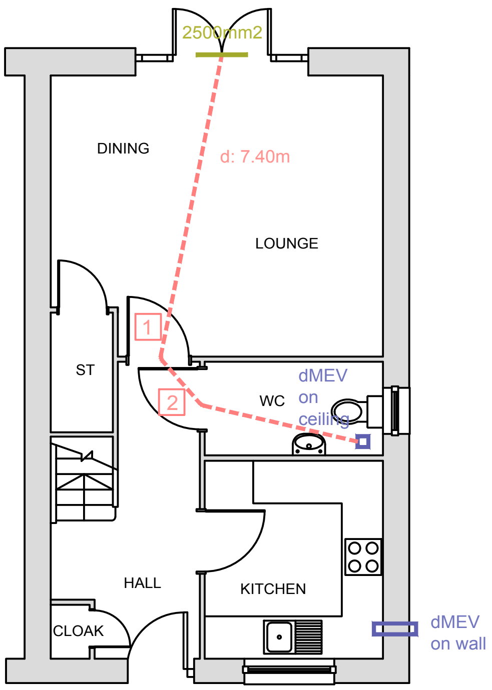


KEY REFERENCES	
▪	dMEV unit
—	Trickle vent/ EA (mm2)
- - -	Air path/ distance(m)*
1	Door number
◌	Trickle vent located in wet room

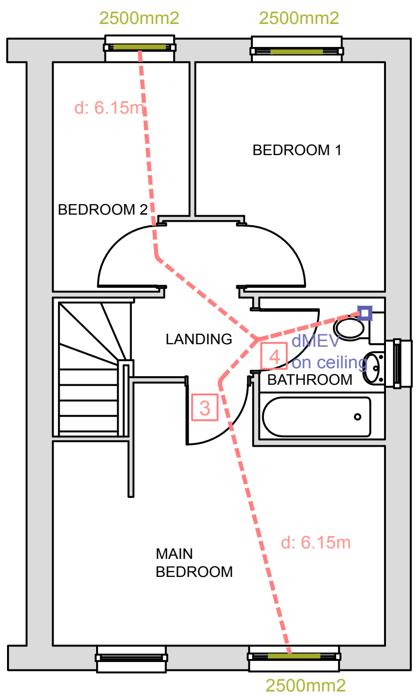
* monitored rooms

Air transfer area:
Door 1: 1676mm2
Door 2: 5866mm2

M11-M31
Ground Floor Plan



M11- M31
First Floor Plan

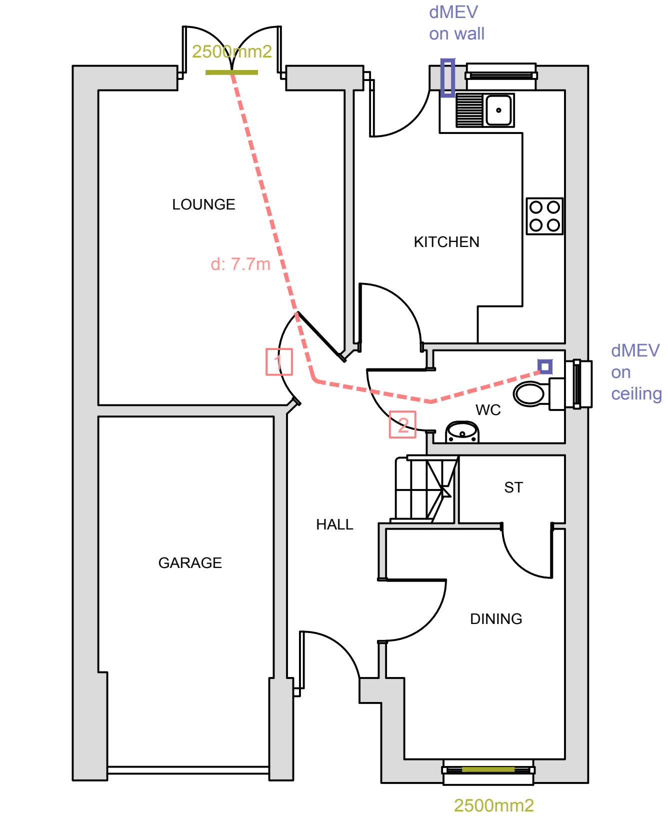


Air transfer area:
Door 1:
M11: 3352mm2
M31: 10056mm2
Door 2:
M11: 14246mm2
M31: 8380mm2
Door 3:
M11: 11732mm2
M31: 15922mm2
Door 4:
M11: 11732mm2
M31: 12570mm2

WP3

All drawings are not for dimensional use
and for information only.

M12-M29-M33
Ground Floor Plan



KEY REFERENCES

- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- 1 Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:

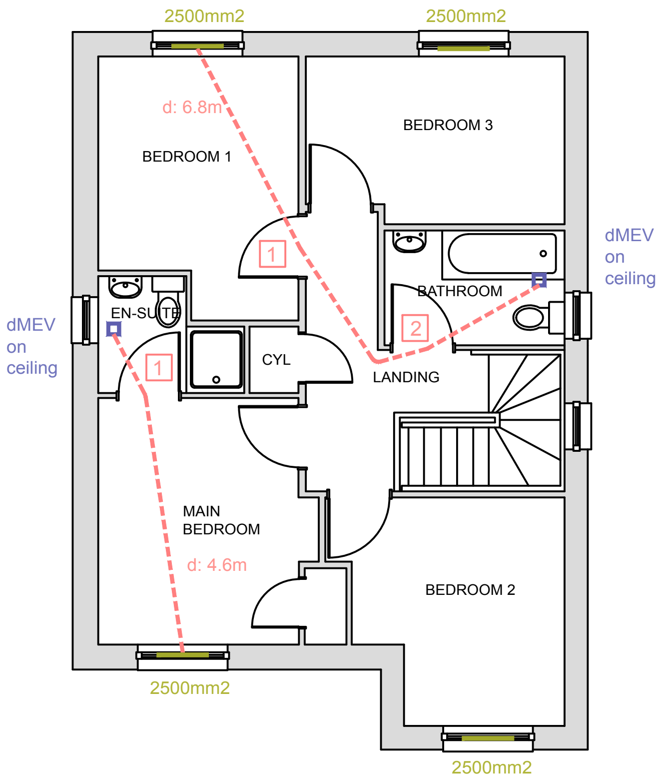
Door 1:
M12:12570mm2
M29:12570mm2
M33:5028mm2

Door 2:
M12:14246mm2
M29: 7542mm2
M33: 6704mm2

Door 3:
M12:14246mm2
M29: 13408mm2
M33: 11732mm2

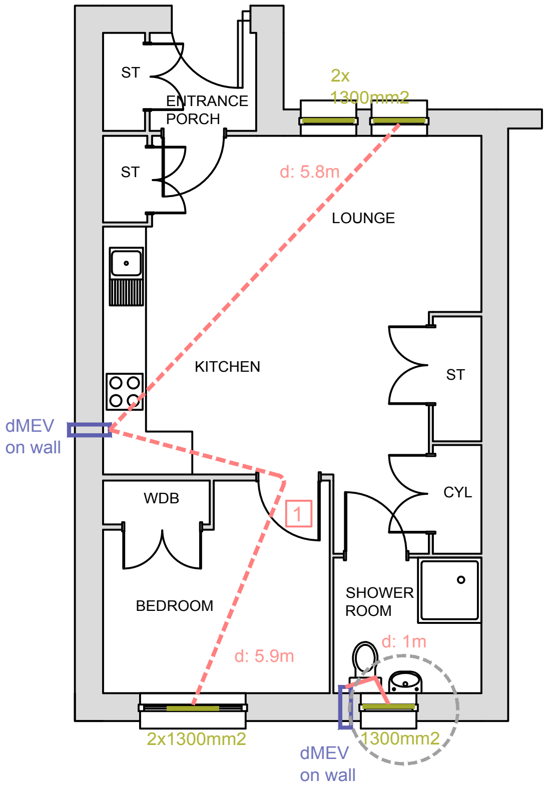
Door 4:
M12: 5028mm2
M29:5866mm2
M33:N/A

M12-M29-M33
First Floor Plan



All drawings are not for dimensional use and for information only.

M15
Floor Plan



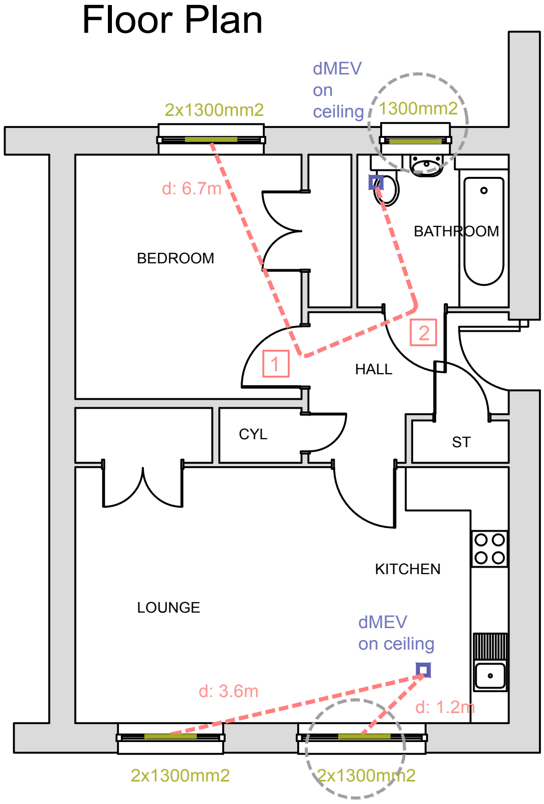
KEY REFERENCES

- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- 1 Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:
Door 1: 14246mm2

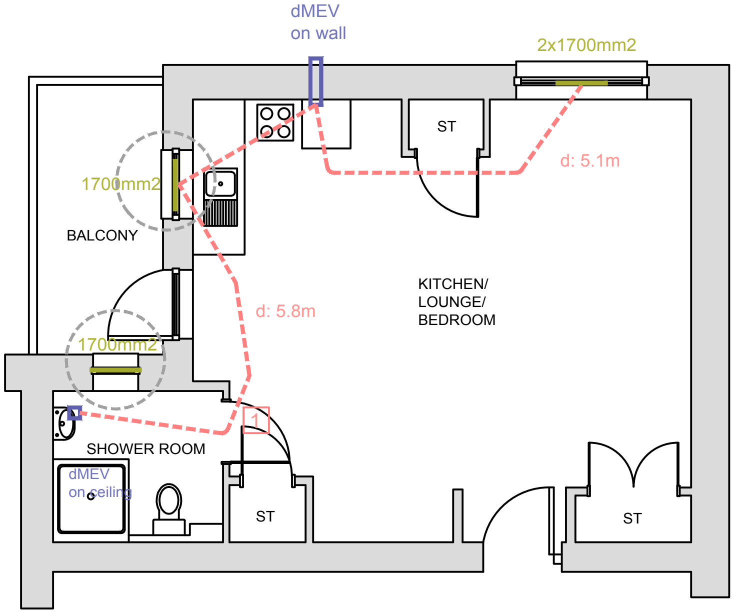
M16
Floor Plan

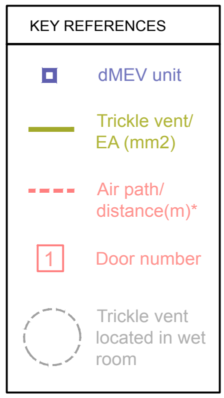


Air transfer area:
Door 1: 16760mm2
Door 2: 16760mm2

All drawings are not for dimensional use and for information only.

M17
Floor Plan

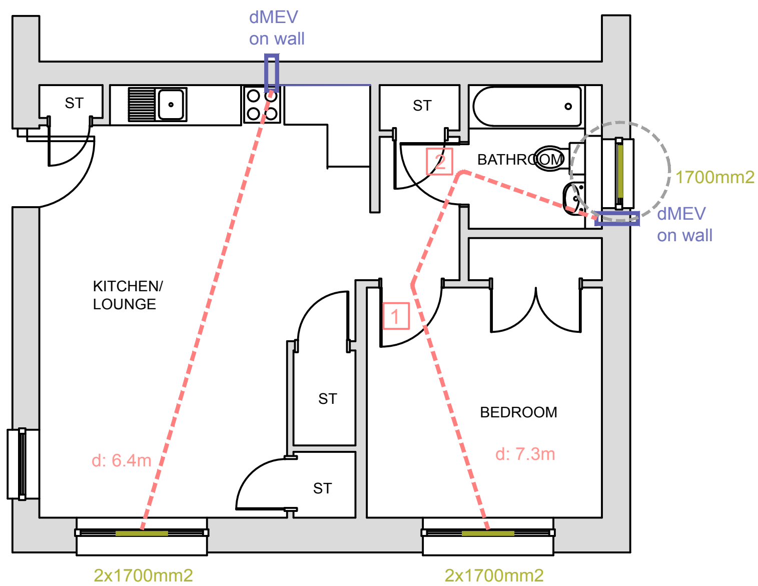




* monitored rooms

Air transfer area:
Door 1: 13408mm2

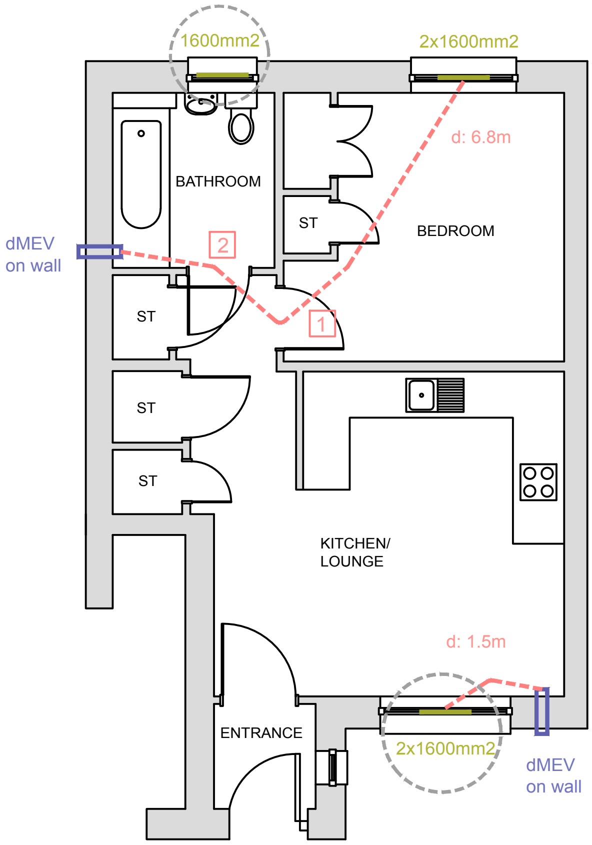
M18
Floor Plan



Air transfer area:
Door 1: 20112mm2
Door 2: 15084mm2

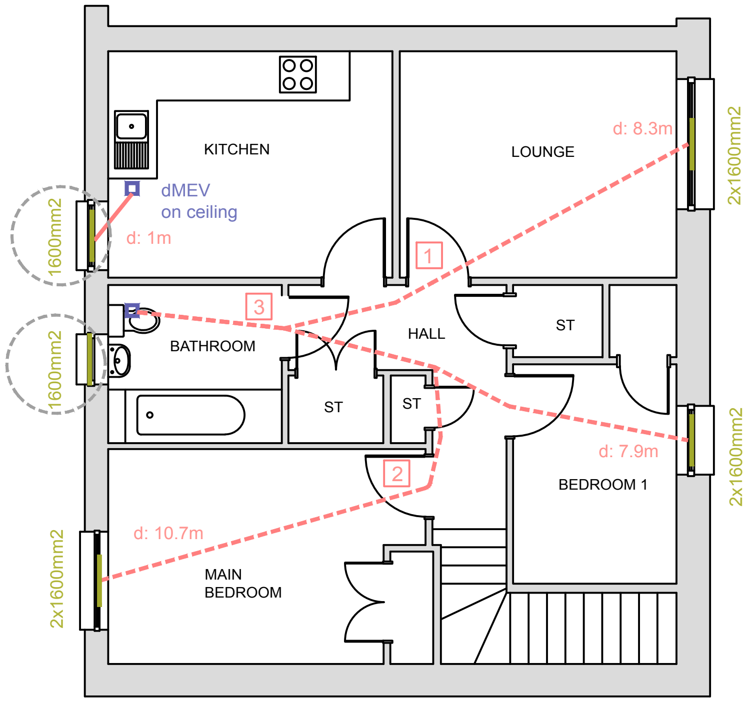
M19
Floor Plan

Air transfer area:
Door 1: 15922mm2
Door 2: 5866mm2

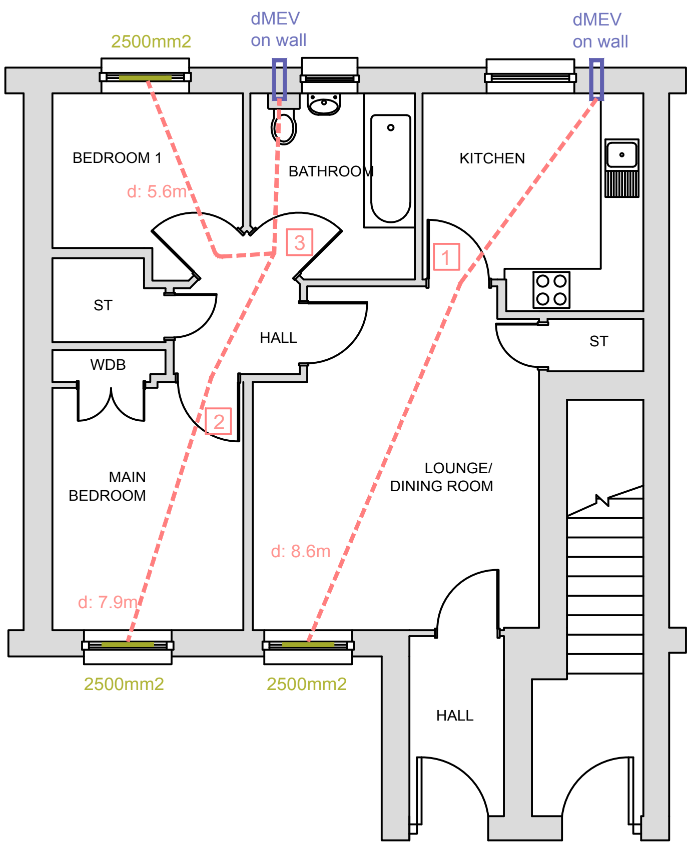


M21
Floor Plan

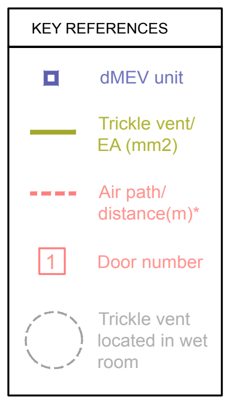
Air transfer area:
Door 1: 2514mm2
Door 2: 0mm2
Door 3: 0mm2



M24
Floor Plan



Air transfer area:
Door 1: 6704mm2
Door 2: 0mm2
Door 3: 8380mm2

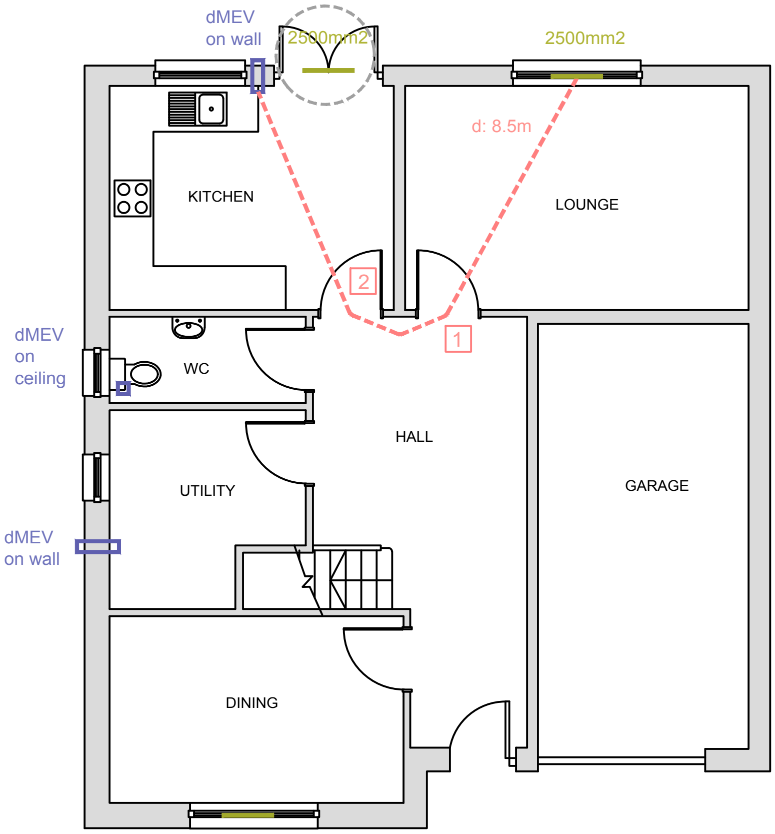


* monitored rooms

WP3

All drawings are not for dimensional use
and for information only.

M25-M32
Ground Floor Plan



KEY REFERENCES

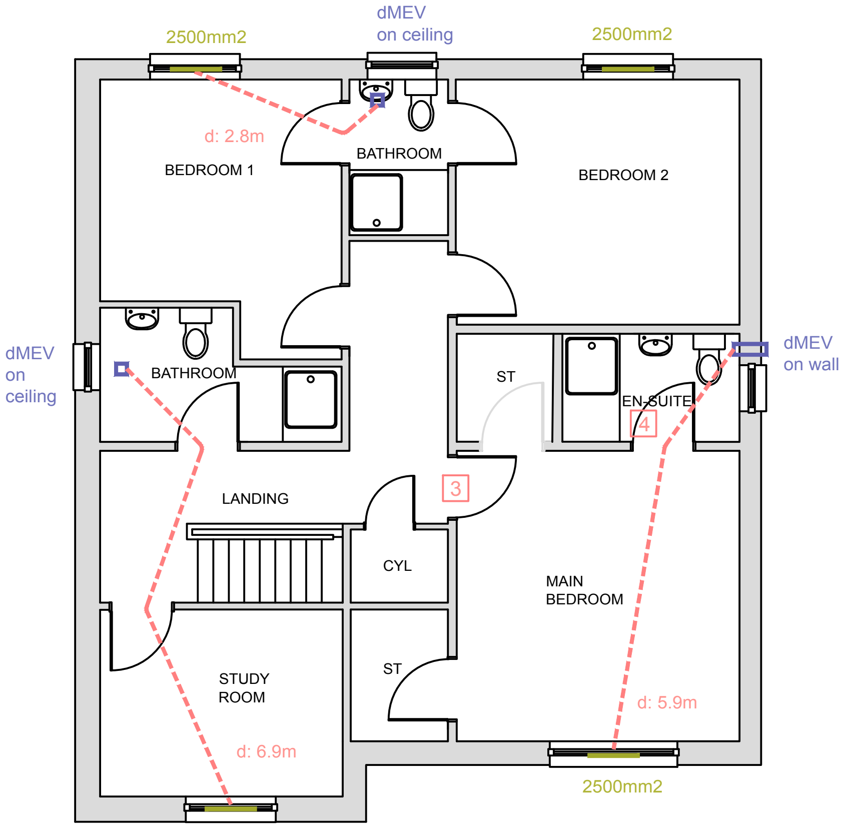
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:

Door 1:
M25:6704mm2
M32:10894mm2
Door 2:
M25:6704mm2
M32: 2514mm2
Door 3:
M25:11732mm2
M32: 13408mm2
Door 4:
M25: 4190mm2
M32: 3352mm2

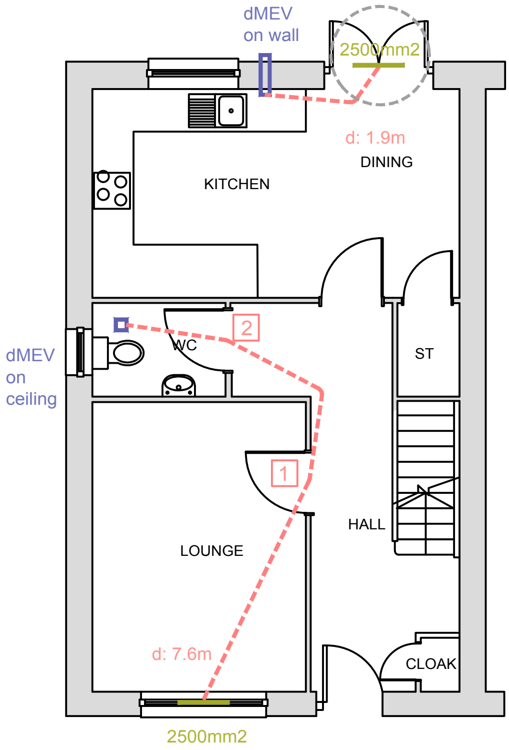
M25- M32
First Floor Plan



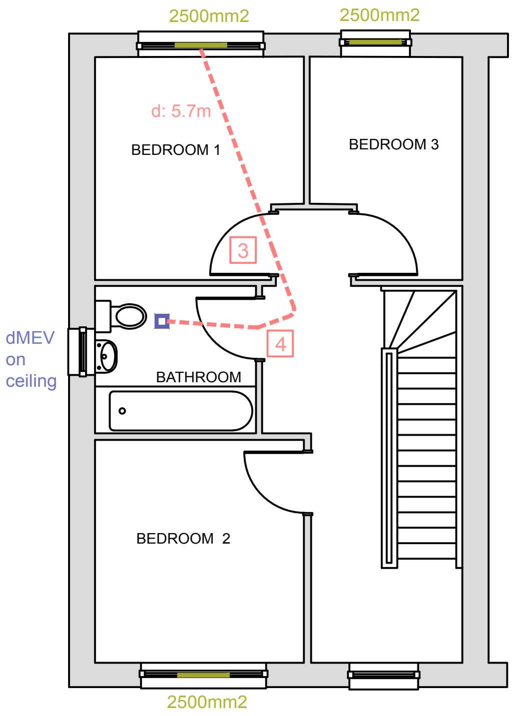
WP3

All drawings are not for dimensional use
and for information only.

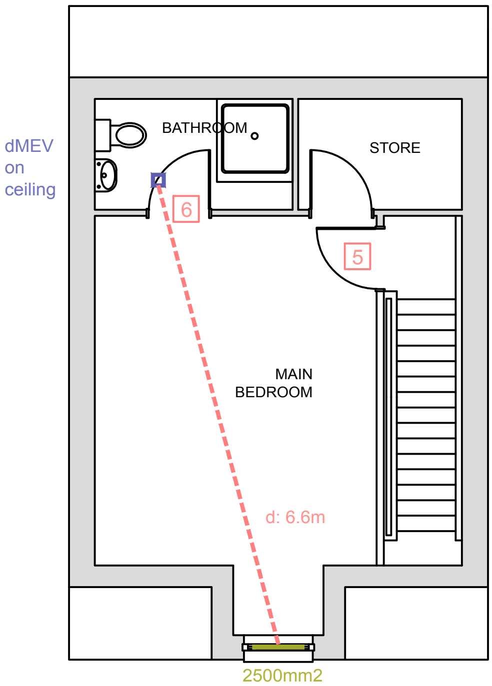
M27
Ground Floor Plan



M27
First Floor Plan



M27
Second Floor Plan



Air transfer area:

Door 1: 8380mm2
Door 2: 8380mm2
Door 3: 12570mm2
Door 4: 14246mm2
Door 5: 15084mm2
Door 6: 7542mm2

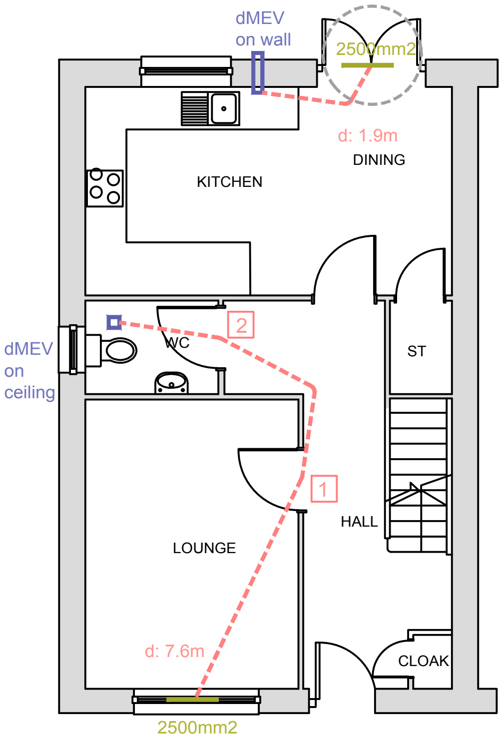
KEY REFERENCES	
▣	dMEV unit
▬	Trickle vent/ EA (mm2)
----	Air path/ distance(m)*
1	Door number
◌	Trickle vent located in wet room

* monitored rooms

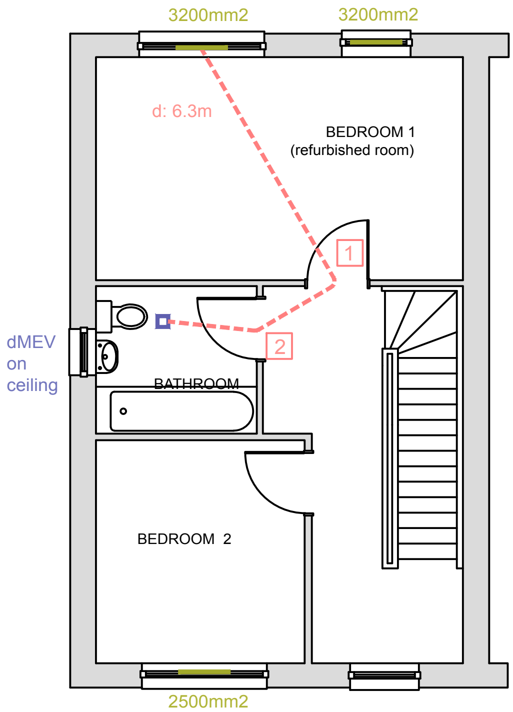
WP3

All drawings are not for dimensional use and for information only.

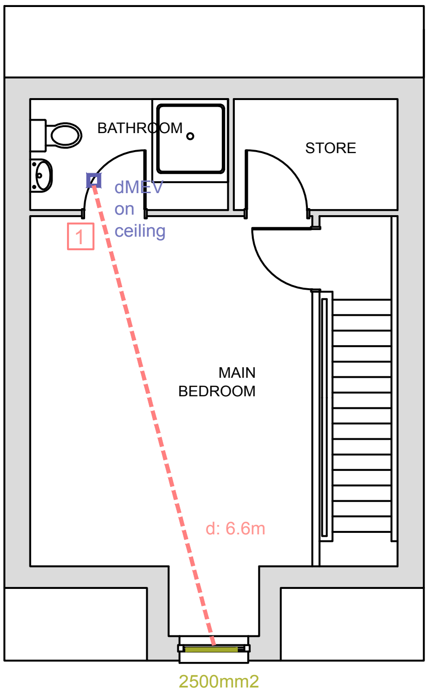
M28
Ground Floor Plan



M28
First Floor Plan



M28
Second Floor Plan



Air transfer area:

Door 1: 8380mm2
Door 2: 9218mm2
Door 3: 10894mm2
Door 4: 9218mm2
Door 5: 15922mm2
Door 6: 5028mm2

KEY REFERENCES

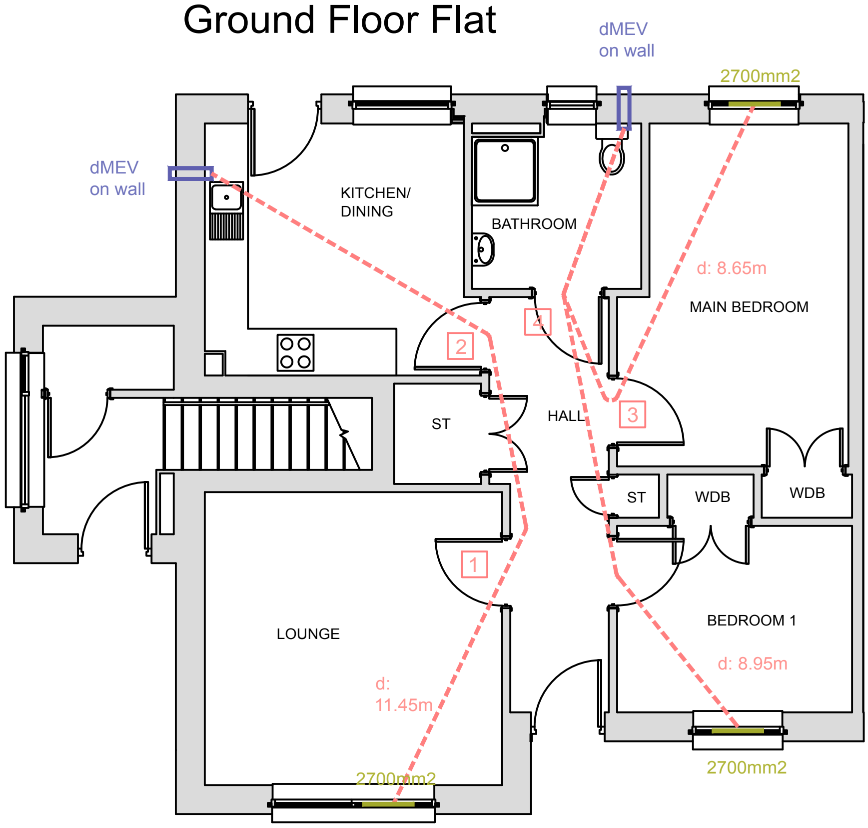
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

WP3

All drawings are not for dimensional use and for information only.

E01
Ground Floor Flat



KEY REFERENCES

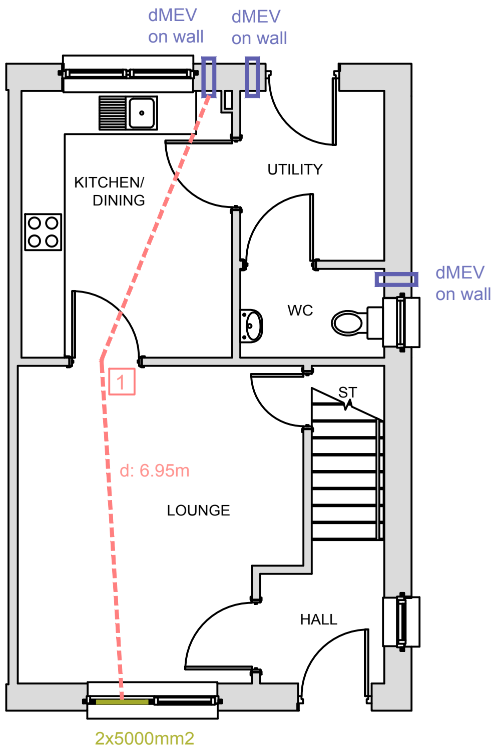
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

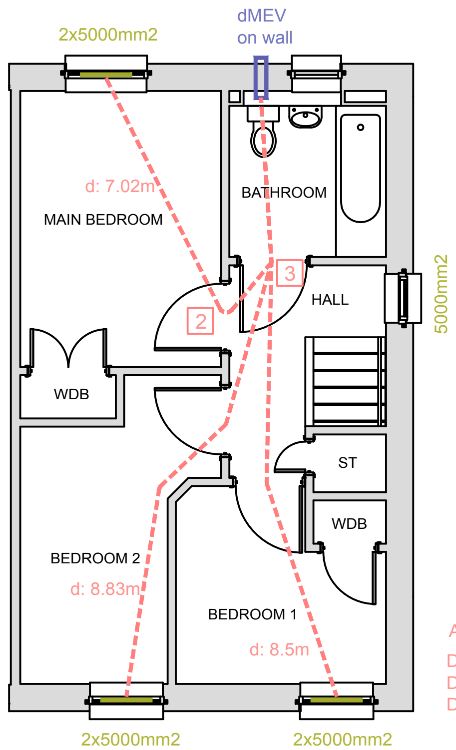
Air transfer area:

Door 1: 2775mm2
Door 2: 2775mm2
Door 3: 3700mm2
Door 4: 6475mm2

E02
Ground Floor-plan



E02
First Floor-plan



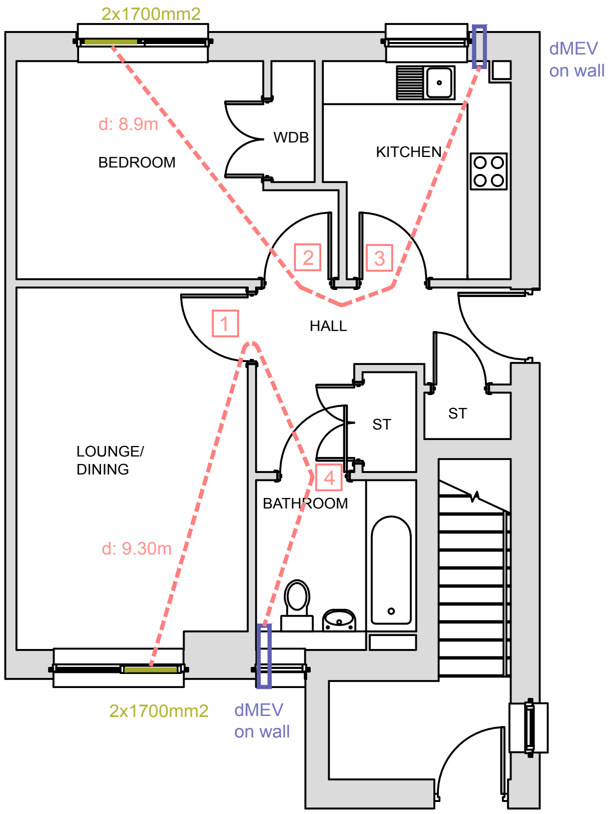
Air transfer area:

Door 1: 1850mm2
Door 2: 2775mm2
Door 3: 2775mm2

WP3

All drawings are not for dimensional use
and for information only.

E03 Floor-plan



KEY REFERENCES

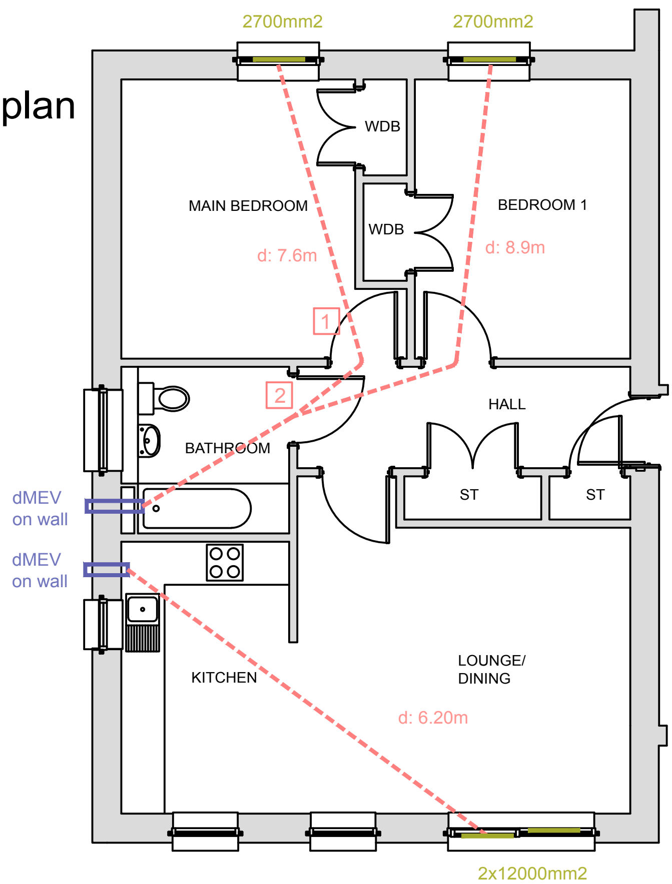
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- 1 Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:

Door 1: 2775mm2
Door 2: 2775mm2
Door 3: 2775mm2
Door 4: 1850mm2

E04 Floor-plan



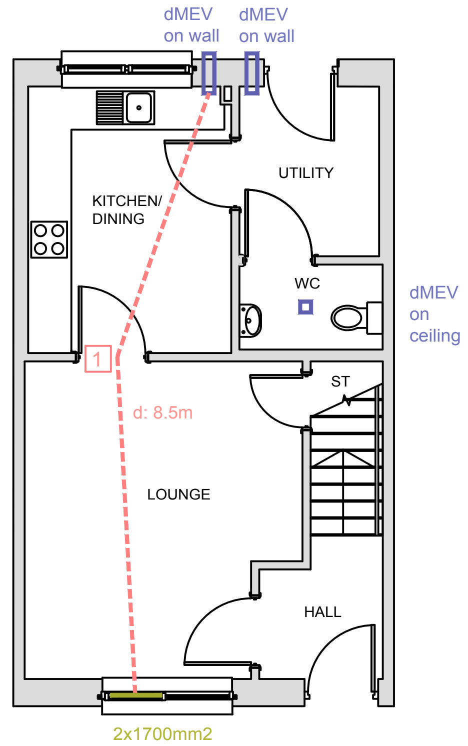
Air transfer area:

Door 1: 8325mm2
Door 2: 5550mm2

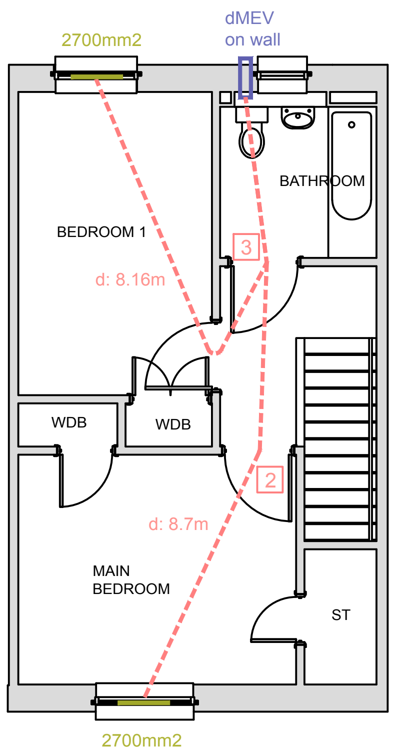
WP3

All drawings are not for dimensional use and for information only.

E05
Ground Floor-plan

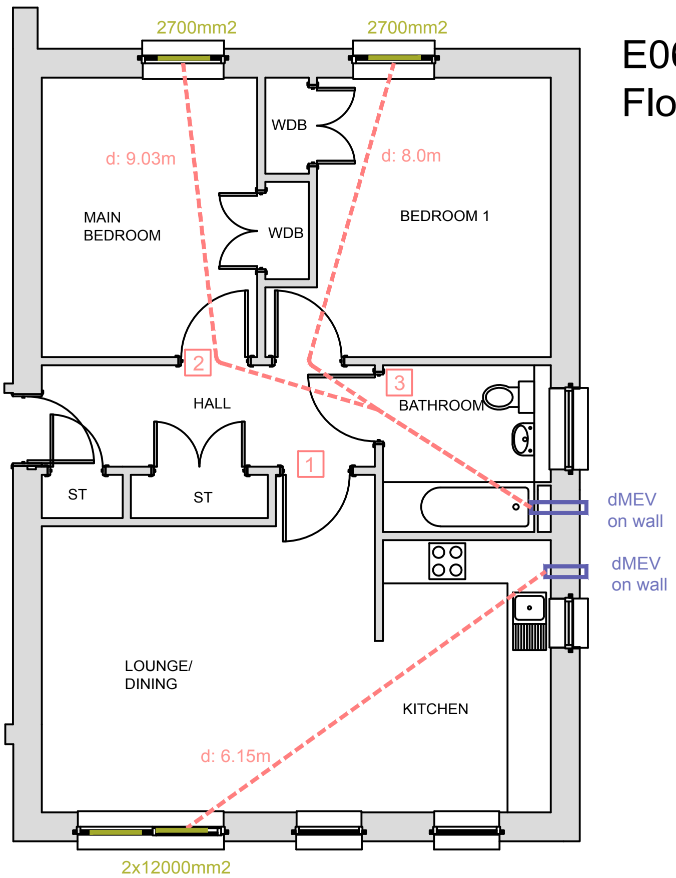


E05
First Floor-plan



Air transfer area:

Door 1: 4625mm2
Door 2: 12025mm2
Door 3: 2775mm2



E06
Floor plan

Air transfer area:

Door 1: 6475mm2
Door 2: 4625mm2
Door 3: 7400mm2

KEY REFERENCES

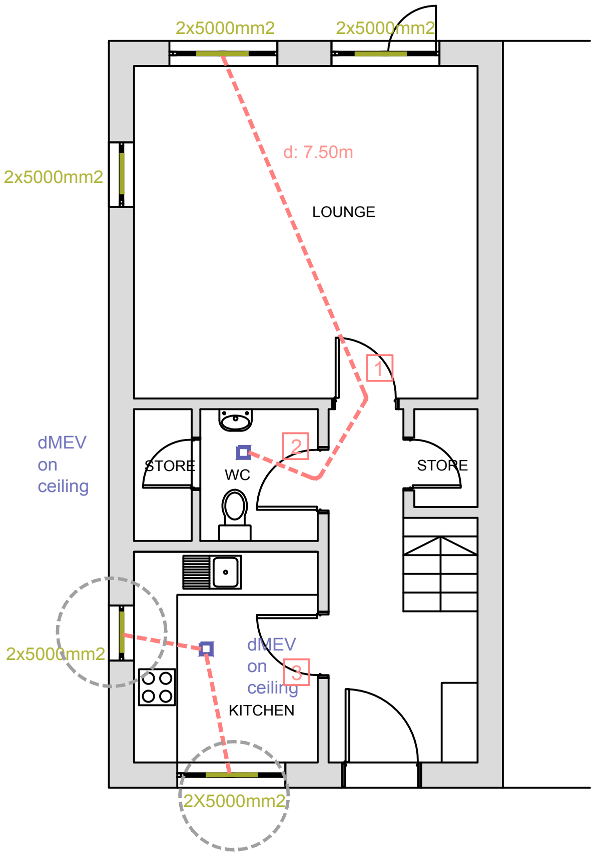
- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

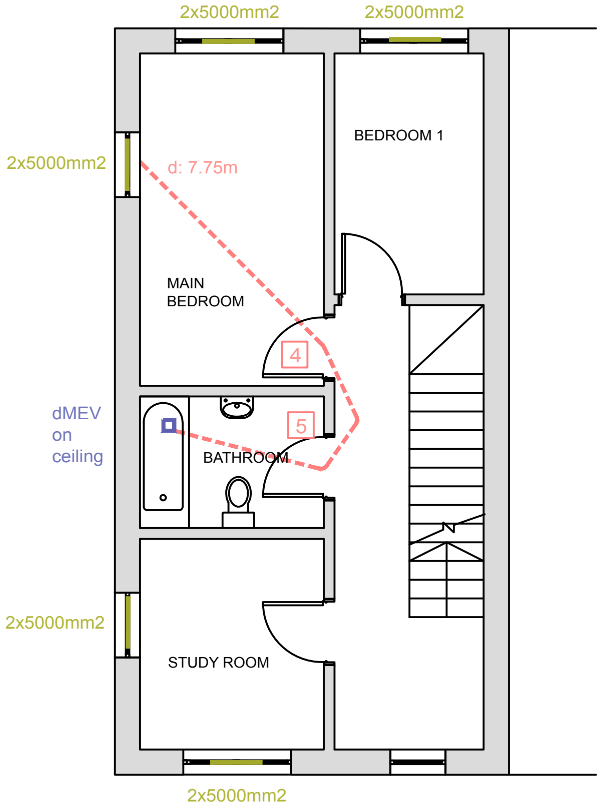
WP3

All drawings are not for dimensional use and for information only.

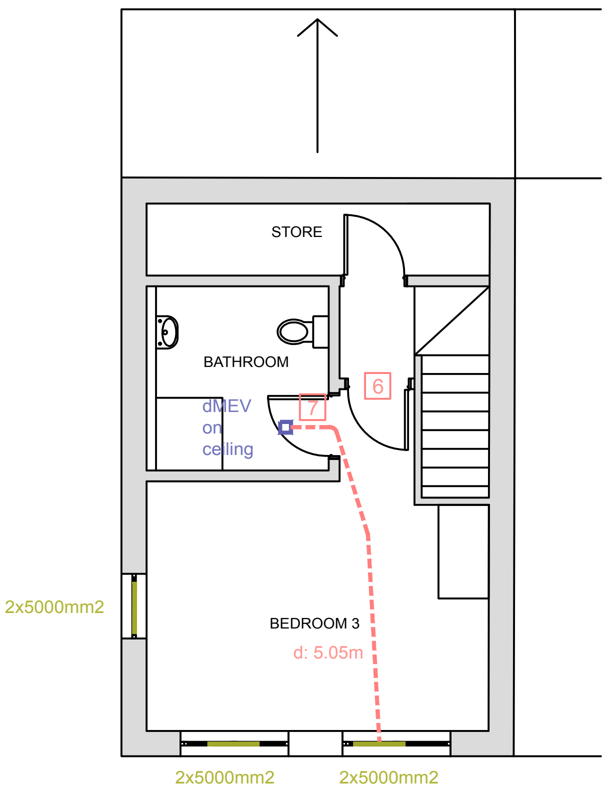
B01
Ground Floor Plan



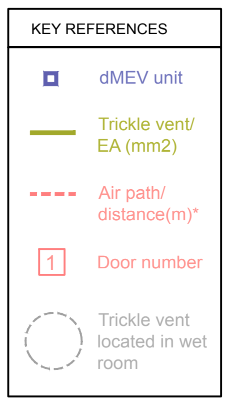
B01
First Floor Plan



B01
Second Floor Plan



Air transfer area:
Door 1: 9185mm2
Door 2: 14195mm2
Door 3: 13360mm2
Door 4: 13360mm2
Door 5: 2505mm2
Door 6: 15865mm2
Door 7: 16700mm2

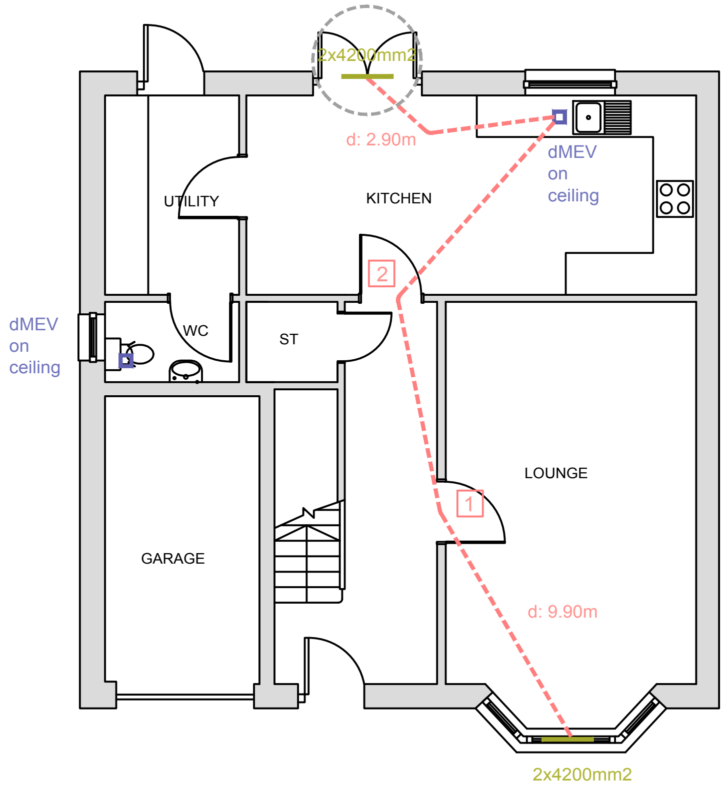


* monitored rooms

WP3

All drawings are not for dimensional use
and for information only.

B02
Ground Floor Plan



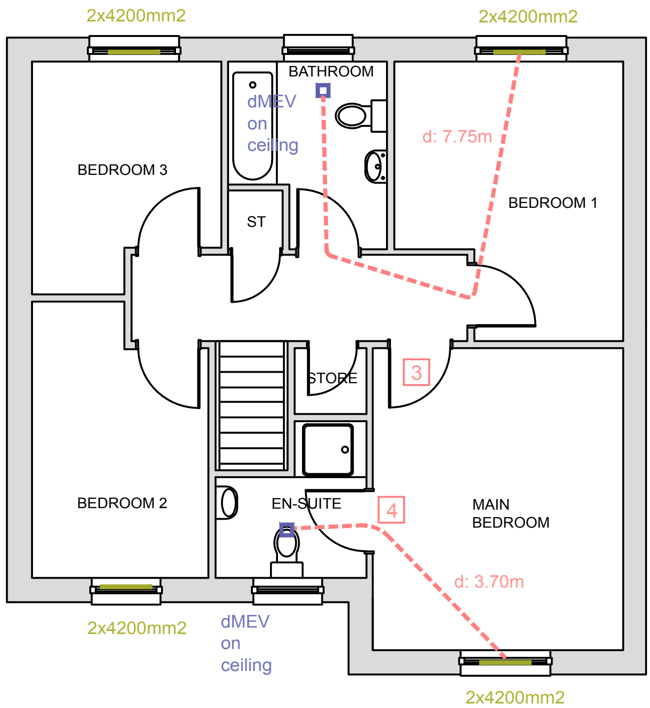
KEY REFERENCES

- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- Door number
- Trickle vent located in wet room

* monitored rooms

Air transfer area:
Door 1: 5866mm2
Door 2: 1676mm2
Door 3: 11732mm2
Door 4: 3352mm2

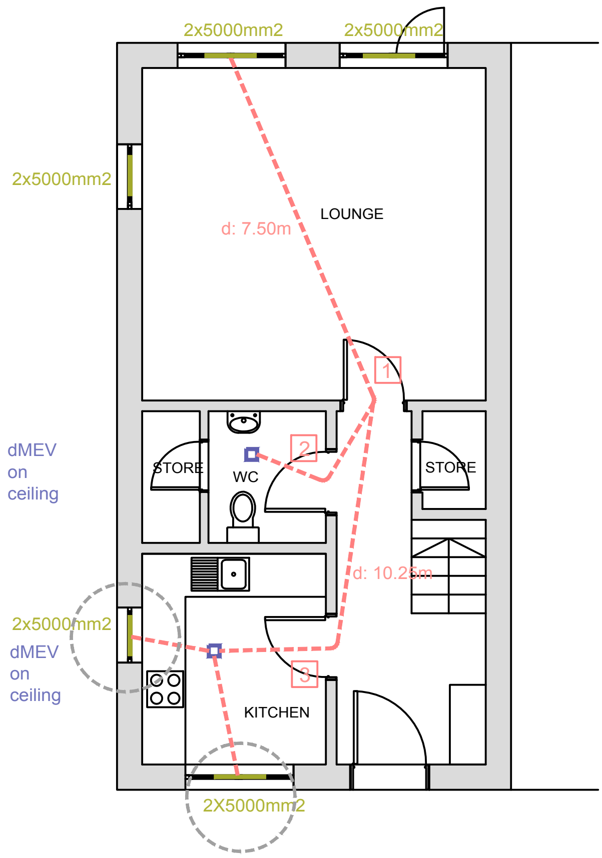
B02
First Floor Plan



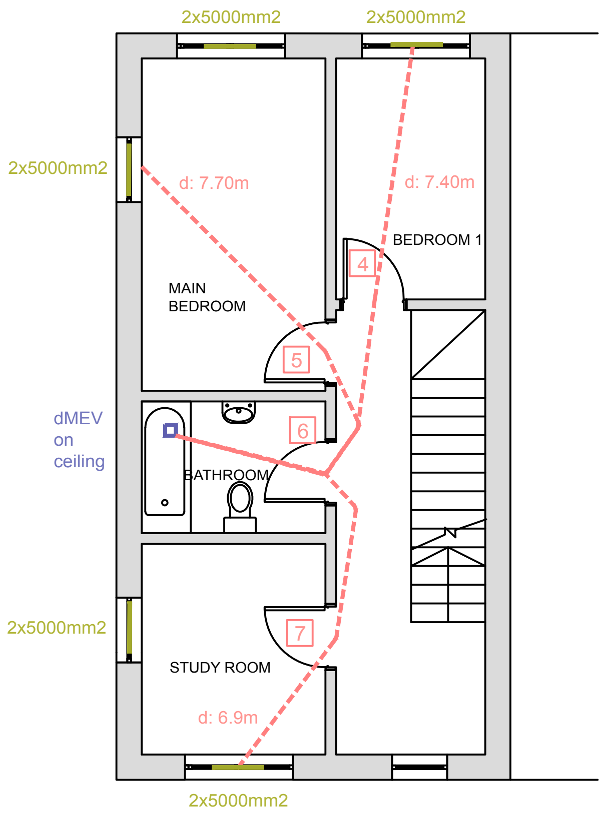
WP3

All drawings are not for dimensional use and for information only.

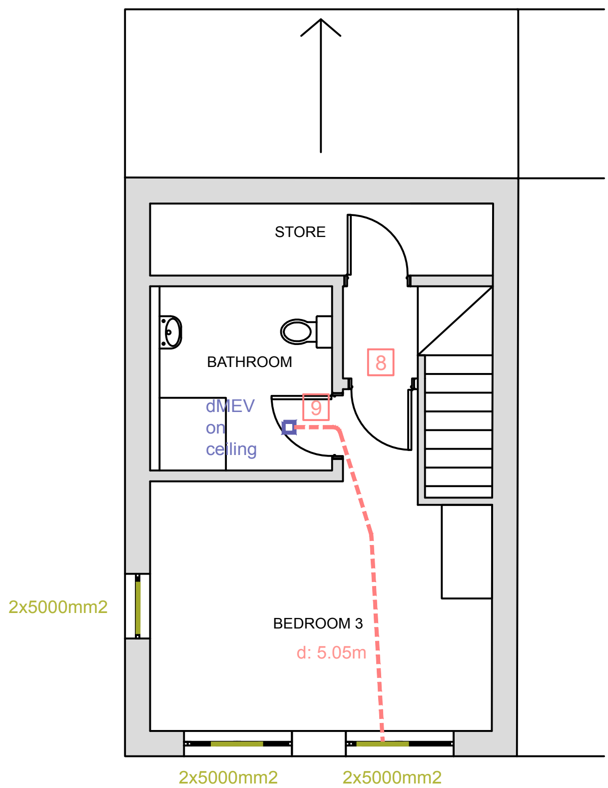
B01
Ground Floor Plan



B01
First Floor Plan



B01
Second Floor Plan



Air transfer area:
Door 1: 9185mm2
Door 2: 14195mm2
Door 3: 13360mm2
Door 4: 15030mm2
Door 5: 13360mm2
Door 6: 2505mm2
Door 7: 15865mm2
Door 8: 15865mm2
Door 9: 16700mm2

KEY REFERENCES

- dMEV unit
- Trickle vent/ EA (mm2)
- Air path/ distance(m)*
- 1 Door number
- Trickle vent located in wet room

* monitored rooms

WP5

All drawings are not for dimensional use
and for information only.