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Abstract

This paper describes the monitored environmental conditions in the bedrooms of 26 low energy houses in Scotland, include both naturally ventilation and houses with mechanical ventilation with heat recovery systems (MVHR). The context of the paper is the performance gap that is emerging between design predictions and actual performance of housing, and this paper focuses on the environmental performance of bedrooms. Bedrooms are of particular interest as they are the spaces in which occupants have the greatest exposure to the indoor environment, and in which conditions are relatively constant. The study indicates that ventilation is generally poor in these spaces and that both temperature and humidity frequently exceed accepted parameters for comfort and health. Increased window opening is a mitigating factor, but effects are limited by overall ventilation strategies.

Keywords

Ventilation, IAQ, energy, MVHR, performance, bedrooms, temperature, CO_2

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Introduction

The increasing body of evidence on the causes and possible effects of climate change[1] has led some governments to establish targets for carbon reduction. In the UK this includes the Climate Change Act[2] and in Scotland (the location for this research) more ambitious timescales have been set with a requirement to achieve a 42% reduction by 2020.[3]

Buildings make a significant contribution to energy use and consequent carbon emissions, particularly housing, which accounts for over 27% of CO_2 emissions in the UK.[4] The primary mechanism for achieving the aforementioned targets has been increasingly stringent requirements for buildings' energy performance, partly as a result of European legislation, enforced through building regulations.[5,6] The main focus of primary legislation is on energy and carbon reduction and this in turn has led to the adoption of new designs, materials and technologies for buildings that seek to reduce energy consumption and carbon emissions.

Compliance with these regulations in housing occurs primarily at design stages through tools such as the Standard Assessment Procedure (SAP).[7] However, these tools do not provide evidence to either the regulator or client of what level of performance has actually been achieved in reality and there are no requirements for proof that new build homes have achieved their planned energy performance in use.[8] It is becoming apparent that there can be significant performance gaps between design intentions at compliance stages and the actual performance of buildings and this is now increasingly well evidenced.[9–11] As well as

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performance gaps in energy use, there is also a growing concern about other areas of environmental performance, particularly indoor air quality (IAQ).[12,13] Previous research has made associations between increasing air-tightness and health issues in non-domestic buildings[14,15] and concerns have been raised about the effects this will have in domestic environments.[16] Relationships with several health effects such as allergies have been evidenced in several studies.[17–19] Problems with IAQ have been identified in new homes[20] and a recent study has identified research that shows associations between low ventilation rates and health effects including asthma, allergy, airway obstruction and sick building syndrome symptoms.[21]

As well as being a cause for concern in its own right,[22] poor IAQ problems can undermine energy strategies, for example overheating being controlled by liberal window opening, leading to increased energy consumption. Not only is there a lack of integration between requirements for ventilation and energy use in regulation, but tools such as SAP energy do not take into account requirements for IAQ[23] and methods for assessing IAQ are not well defined.[24]

A key challenge is that different sections of legislation have particular targets and this can lead to competing agendas and a lack of holistic thinking at design stages. An example of this is the debate about building air-tightness. As fabric performance improves, the importance of ventilation losses increases. Increasingly stringent regulations – underpinned by one of the few post completion testing requirements, an air-tightness test – is leading to increasing levels of air-tightness. Unfortunately regulatory requirements for ventilation have been slow to address changes required by energy targets. For example, requirements for background ventilation strategies have not followed suit, relying primarily on trickle vents, which have been shown to be inadequate.[25,26] So whilst on the one hand evidence on air quality leads to the need for higher air changes rates, the focus on energy losses requires its reduction.

Under Scottish regulations a mechanical ventilation system is required when the air-tightness of houses is below $5\,m^3/h\,m^2$. The measure being widely adopted is the use of mechanical ventilation with heat recovery (MVHR),[27] primarily as these systems contribute to meeting energy targets at design stages.[28] There is evidence that mechanical ventilation can result in better ventilation rates,[29] with some indication of improved health effects.[30] However, there is a developing body of knowledge that, with more widespread implementation, some systems are frequently poorly specified, installed and used[31,32] leading to poor ventilation rates and increased energy use, and such problems require re-commissioning.[33] A lack of adequate maintenance also presents a risk to their effective performance[34] and incidences of health complaints.[35] In some circumstances occupants may disable systems. Common reasons include poor user understanding of the purpose and control of such systems, concerns about their energy consumption[36,37] and noise.[38] Such occurrences, along with technical risks of failure such as loss of power, would lead to significant deterioration in ventilation rates.[39]

At the same time as ventilation rates are being reduced, there are also increasing concerns about indoor pollutants. At the outset of the 20th century there were approximately 50 materials used to construct buildings, but by the end of the century this number has been estimated to be 55,000, with half of them being synthetic.[40] Compounds found in indoor air are implicated in IAQ toxicity and may have off-gassed from the building materials, furnishings and fittings, internal processes, cleaning products and even air fresheners. The most common gases found in the indoor environment are carbon dioxide/monoxide, nitrogen and sulphur dioxide, volatile organic compounds, radon, formaldehyde and ozone. Suspended particulate matter includes asbestos fibres, fibrous particulates, bacteria and fungi, tobacco smoke, house dust mite (HDM) allergens, pollen and dust.[41,42] Changes in lifestyle, such as indoor clothes drying, are in part driven by changes in design, and high levels of indoor humidity can have a major impact in terms of bacteria, fungi and HDM proliferation.[43] As well as the pollutants themselves, there are unknown effects due to interactions between compounds and their environments,[44] a case in point being the effects of higher temperature and humidity increasing emissions of volatile organic compounds such as formaldehyde.[45]

A particular challenge is that as increasingly stringent energy requirements have been written into legislation, the low energy measures which, until a few years ago were confined to small numbers of exemplar houses, are now becoming mainstream in new housing. This raises a number of important questions: Are these measures leading to the reduction in energy use required to meet the targets? Are they resulting in any unintended negative consequences, for example reduced IAQ? The context for these questions is that at present there is very little mandatory testing of buildings in use and consequent information about their energy use and environmental performance. Building performance evaluation (BPE) has been identified as a key strategy in this regard.[46] BPE has previously been defined as 'the act of evaluating buildings in a systemic and rigorous manner after they have been built and occupied for some time'.[47] Early BPE methods include the gathering of both quantitative data through monitoring and qualitative data through surveys,[48] but more recently the methodology for this has been developed through studies such as the Post-occupancy Review Of Buildings and their Engineering studies.[49] In housing, several methods and parameters have been developed to capture data.[50] BPE is the one process that can generate the intelligence needed to learn lessons from buildings in order to make the required changes to improve future design. With rapidly changing standards, leading to innovations in materials, technologies and construction, it seems reasonable to say that all new buildings are some form of experiment. If we do not evaluate the results of these experiments, how can we ever learn from them?

To address these questions the UK Technology Strategy Board (TSB) has funded an £8m 4-year programme of support for BPE studies that aims to undertake studies and develop capacity for BPE for both domestic and non-domestic buildings across the UK. Studies include phase 1 projects, which undertake post-construction testing and early occupancy, and phase 2 studies, which additionally undertake monitoring of energy and environmental conditions for a 24-month period. The programme includes 32 domestic phase 2 projects across the UK. There are seven domestic phase 2 studies in Scotland and this paper presents data from six multi-dwelling sites (the seventh being a single privately owned house) being evaluated by the Mackintosh Environmental Architecture Research Unit (MEARU), and includes 26 houses in total.

A comprehensive set of criteria for BPE has been set out by the TSB for projects funded by the BPE programme.[51] These include a series of physical tests including air permeability testing at the both the start and the end of the project, U-value testing and thermographic surveys. Information is gathered on the construction, design intention and occupant experiences through a design and construction audit; drawings and SAP calculation review; qualitative semi-structured interviews and walkthroughs with occupants and, separately, the design team; photographic survey and an occupant survey using a domestic version of the Building Use Survey.

There is also a review of systems design and implementation, including installation and commissioning checks of all services and systems. Energy and environmental monitoring includes metered gas, electricity, water and, if appropriate, heat into (and out of) dwelling; sub-metering according to use, e.g. space heating, water heating, cooker, lights and appliances. Monitoring of internal environmental conditions includes temperature humidity and CO_2, external temperature and relative humidity (RH) on site and external climate conditions. Monitoring is undertaken at 5-min intervals over a 24-month period.

For the projects being evaluated by the MEARU that are the subjects of this paper, some additional data are being collected. The TSB requirement only specifies CO_2 in one room, but this is being monitored in three rooms, including at least one, but in some cases, two bedrooms. Additionally, contact sensors have been placed on the principal opening to these rooms, which detect opening incidences (but not degree). The occupant surveys and interviews have been extended to gather specific data on patterns of occupancy and behaviour, with occupant diaries being used to gather detailed information.

In these studies CO_2 is being used as an indicator of ventilation rates and IAQ. Levels of CO_2 correlate well with human occupancy and human-generated pollutants, but may be unconnected from pollutants not related to occupancy, such as off-gassing from building materials, carpets and furniture. Nevertheless, in the context of concern over ventilation rates they provide a useful indicator of relative levels of ventilation, and their use in this study allows a comparative analysis across a number of projects. There is a general acceptance that CO_2 keeps ‘bad company’ and that levels above 1000 ppm are indicative of poor ventilation rate. The provenance of this is well evidenced,[52] and corresponds to a ventilation rate of 8 l/s per person.[53] This figure is also relevant in comparison with the findings of a review of the literature looking at the associations between ventilation rates and CO_2 levels with health outcomes which concluded ‘Almost all studies found that ventilation rates below $10\,\mathrm{Ls}^{-1}$ per person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes’.[54] Associations between health and CO_2 levels have been found in office buildings[55] and a study by Batterman and Peng[56] identified associations between CO_2 levels and TVOCs. A recent paper by Wargoki identified associations between CO_2 levels and health and concluded ‘The ventilation rates above $0.4\,\mathrm{h}^{-1}$ or CO_2 below 900 ppm in homes seem to be the minimum level protect against health risks based on the studies reported in the scientific literature’.[57]

This study is examining the overall energy and environmental performance of the buildings, but the particular focus of this paper is the performance of bedrooms. These are the spaces in which occupants spend the most uninterrupted time, typically 7–8 h, and children may also use bedrooms for socialising and schoolwork in which case they could spend almost all their home time in the bedroom. Furthermore, bedrooms overnight present steady-state conditions with occupants asleep, with little or no adaptive behaviour – ventilation regimes established at the time of going to bed remain in force overnight. Curtains and blinds tend to occlude background ventilation strategies such as trickle vents, and doors are more likely to be kept closed. Accordingly, environmental conditions in bedroom spaces are of interest, both in terms of occupant exposure to ventilation effects, but as steady-state conditions, which can be used to identify effects of ventilation.

Project information

Construction

There are six sites included in this study. These are in a diverse number of geographical locations across Scotland: Inverness in the north of Scotland, Lockerbie in the south, Livingston in the east, Dunoon in the Barrhead and Glasgow.

Inverness (Latitude 57.4; Longitude –4.2). This rural site has 52 properties in total and was constructed as a Housing Expo, which opened in 2010, showcasing designs of contemporary low energy architecture. Evaluation is being undertaken on n = 8 houses (2 × 4 different house types). Occupants include social rented and owner-occupiers.

Lockerbie (Latitude 55.2, Longitude –3.3). This is also a rural development of 8 × 2 storey houses built to Passivhaus standards, of which n = 4 are included in this study. These are privately rented, but subsidised for affordable rents.

Livingstone (Latitude 55.9, Longitude –3.5). This is a development of eight 2 storey terraced houses of which n = 2, an end and a mid-terraced, are being monitored. These are social rented for tenants with special needs.

Barrhead (Latitude 55.1, Longitude –4.4). This is a development of 16 amenity cottages, houses and flats for older people. There are n = 3 houses being monitored, 1 cottage flat, 1 two-storey mid-terrace house and one upper floor flat.

Queens Cross (Latitude 55.8, Longitude 4.2). The development is on two neighbouring inner city sites, providing 117 flats and houses. The flats include 34 supported one and two-bedroom flats for the elderly in one block and 54 one and two-bed mainstream flats block; of which n = 3 sheltered flats and n = 3 conventional flats are being monitored.

Dunoon (Latitude 55.9, Longitude –4.9). The development consists of 14 semi-detached affordable sector houses. One is a fully accredited Passivhaus Standard dwelling and the adjacent 13 dwellings meet the code level 4 low-energy standard, but not the Passivhaus standard. The Passivhaus dwelling $m^3/h\,m^2$ (n = 1) and n = 2 low-energy houses are being monitored. The houses have shared equity between the housing association and part owner occupiers.

A summary of the construction types is provided in Table 1.

The predominant form of construction is timber frame (84%). This is broadly representative of the construction industry in Scotland in which 75% of new-build construction is timber, up from 50% in 2009.[58] Four of the houses (15%) use a vapour permeable timber construction; however, in two of these the bedrooms are in roof spaces and thus the enclosing structure is traditional timber frame. Only four of the dwellings (15%) use masonry construction, primarily for reasons of fire separation, being flats.

The most common form of heating in the dwellings is some form of wet central heating, used in 17 houses (65%). Of these, in eight houses (30% of the total) this is from some form of communal boiler (six are gas and two are biomass). The remaining nine (35%) use gas central heating. All the wet systems use traditional programmers, thermostats and thermostatic radiator valves (TRVs) on radiators.

In the remaining houses two dwellings use electric storage heaters, supplemented by log stoves. In four of the Passivhaus dwellings (15%), heating provision is provided by a post-heater supplied from the hot water cylinder and one Passivhaus project uses an air source heat pump.

All the houses have openable windows, and all have trickle vents, with the exception of the Passivhaus projects. In all but two of the bedrooms there is a single window, the others (9BB1 and 11BB1) have two windows on adjacent walls.

Air-tightness

All the dwellings have had the first of two air permeability tests undertaken and the results of these are presented in Table 1. Air permeability figures are within design expectations, but results range from 0.955 $m^3/m^2\,h$ (in P15) to 10.39 $m^3/h\,m^2$ (in S17). This latter figure is the only one that fails to meet the Building Standard recommendation, in force at the time of construction (2010 Scottish Building Standards), of 10 $m^3/h\,m^2$. All but five meet the current requirement of 7 $m^3/m^2\,h$ and the average is 4.59 $m^3/h\,m^2$. The Passivhaus projects (P15, CC, OC, BC and HC) are the best performers and average at 2.45 $m^3/h\,m^2$ but it is noted that the levels are all above the Passivhaus requirement of 0.6 $m^3/h\,m^2$. They remain within the recommended figure of 3–5 $m^3/h\,m^2$ for MVHR systems.[59] Outwith these projects there is no obvious pattern associated

Table 1. Construction, ventilation and heating provision for the case study dwellings.

Location	Ref	Construction	Type	No. Bedrooms	Floor area (m^2)	Space heating	Control	Hot Water heating	Permeability $m^3/h\,m^2$	Vent type	No. Adults (A) Children (C)
BA	*27MP*	*TF, VP*	*2H MT*	*2*	*93.9*	*R GB*	*P T, TRVs*	*GB, ST*	*4.25*	*Trickle*	*2A*
BA	*29MP*	*TF, VP*	*1F GF*	*2*	*75.8*	*R GB*	*P T, TRVs*	*GB, ST*	*2.88*	*Trickle*	*2A*
BA	*37MP*	*TF, VP*	*2H ET*	*2*	*75.4*	*R GB*	*P T, TRVs*	*GB, ST*	*4.98*	*Trickle*	*2A*
LI	*25BC*	*TF, VP*	*2H MT*	*3*	*106*	*R GB*	*P T, TRVs*	*GCB*	*3.71*	*Trickle*	*3A*
LI	*26BC*	*TF, VP*	*2H ET*	*3*	*105.9*	*R GB*	*P T, TRVs*	*GCB*	*3.73*	*Trickle*	*3A*
LO	BC	TF	2H SD	2	87.3	MVHR HW	T	LBS/ST	2.42	MVHR	1A1C
LO	CC	TF	2H SD	2	87.3	MVHR HW	T	LBS/ST	2.14	MVHR	1A
LO	HC	TF	2H SD	3	102.8	MVHR HW	T	LBS/ST	2.72	MVHR	3A2C
LO	OC	TF	2H SD	3	102.8	MVHR HW	T	LBS/ST	2.41	MVHR	2A2C
DU	P5	CPTF	2H SD	3	113.6	EC	T	EB, ST	4.04	Trickle	2A3C
DU	P14	CPTF	2H SD	3	113.6	EC	T	EB, ST	4.29	Trickle	2A2C
DU	P15	CPTF	2H SD	2	103.4	MVHR, ASHP	T	ASHP, ST	0.96	MVHR	2A2C
IN	3BS	TF	2H ET	3	109	R/UF GCB	P T, TRVs	GCB	3.82	Trickle	2A4C
IN	4BS	TF	2H MT	3	109	R/UF GCB	P T, TRVs	GCB	4.21	Trickle	1A5C
IN	6BS	TF	1F GF	2	76	R CBB	P T, TRVs	CBB	5.71	Trickle	2A
IN	7BS	TF	1F GF	2	76	R CBB	P T, TRVs	CBB	4.53	Trickle	2A
IN	4BG	TF	2H SD	3	90	R GB	P T, TRVs	GCB	5.82	Trickle	2A2C
IN	5BG	TF	2H SD	3	90	R GB	P T, TRVs	GCB	6.07	Trickle	2A1C
IN	9BB	TC	1F GF	1	52	EC, LBS	P, T	IH	5.93	Trickle	1A
IN	11BB	TC	1F TF	1	52	EC, LBS	P, T	IH	6	Trickle	2A
GL	MF02	M	1F GF	2	67.57	R, CB CHP	P T, TRVs	CBCHP	3.61	Trickle	2A1C
GL	MF03	M	1F GF	1	72.15	R, CB CHP	P T, TRVs	CBCHP	7.91	Trickle	1A
GL	MF22	TF	1F MF	1	67.57	R, CB CHP	P T, TRVs	CBCHP	4.59	Trickle	1A
GL	*SF02*	*TF*	*1F TF*	*1*	*49.53*	*R, CB CHP*	*P T, TRVs*	*CBCHP*	*7.91*	*Trickle*	*1A*
GL	*SF17*	*M*	*1F GF*	*2*	*49.53*	*R, CB CHP*	*P T, TRVs*	*CBCHP*	*10.39*	*Trickle*	*1A*
GL	*SF32*	*TF*	*1F TF*	*2*	*75.5*	*R, CB CHP*	*P T, TRVs*	*CBCHP*	*7.59*	*Trickle*	*2A*

CB: communal boiler; CGB: gas combi boiler; CHP: combined heat and power; CPTF: closed panel timber frame; EI: electric immersion; ET: end terrace; F: flat; GB: gas boiler; GF: ground floor; H: house; M: masonry; MF: mid floor; MT: mid terrace; R: radiators; SD: semi-detached; ST: solar thermal; TC; timber cassette; TF: timber frame; TF: top floor; UF: underfloor; VP: vapour permeable.

Italics indicates elderly/disabled occupants, Bold indicates Passivhaus.

with construction, for example flats in Glasgow having figures at opposite ends of the spectrum.

Nevertheless high levels of air-tightness are present across the sample, which suggests that standards in general are improving. Of significance however is the fact that, excluding the Passivhaus projects, 12 out of 21 dwellings (57%) have ‘overshot’ the building standards requirement (for mechanical ventilation) of $5\,m^3/h\,m^2$, but do not have the required mechanical ventilation provision. This is a cause for concern on two levels: firstly, that these high levels of air-tightness exist without the necessary planned ventilation strategy; and secondly, it reveals a lack of compliance and verification of regulatory standards.

A further observation is that in the air permeability tests common causes of air leakage could be identified, including external doors, but also service penetrations in bathrooms from water and waste pipes. A reasonable assumption leading from this is that, given the test figure applied to the whole house, some areas may experience much lower rates of air permeability. Since bedrooms may (especially with closed doors) be considered as discrete spaces and rates of air permeability in these spaces may be much lower than the whole house value.

Monitoring method

A very large dataset is being generated by these projects and some simplification is required for reporting. This paper uses data collected between February and September 2013. Data are collected from Wireless Sensor Technology (WIST) sensors which monitor temperature (0°C to +51°C ± 0.5°C over full range 0.2°C), RH (0–100% rh ± 1.5 rh over full range) and CO_2 (0–5000 ppm ± 50 ppm over full range 10 ppm). These are connected wirelessly to a Wist Gateway and this data, along with sub-metered energy data is streamed remotely over Global System for Mobile communications (GSM) mobile phone networks. Some additional data are collected using Gemini Tinytag Ultra 2 temperature (25–85°C) and RH (0–95% RH) sensors.

For the purposes of this analysis, data from three sample months in winter (February), spring (April) and summer (August) are used.

Results

This paper focuses specifically on the environmental conditions of the bedroom spaces; accordingly, the data presented are for the period between 11 pm to 7 am overnight, to reflect the conditions experienced by occupants.

Ventilation

Figure 1 shows the mean CO_2 levels in the bedrooms overnight for the three sample months, ranked by the winter mean CO_2 level. The immediate picture being presented is that CO_2 levels in bedrooms are consistently >1000 in 20 bedrooms (57%) in February, but when excluding the houses with MVHR, the figure

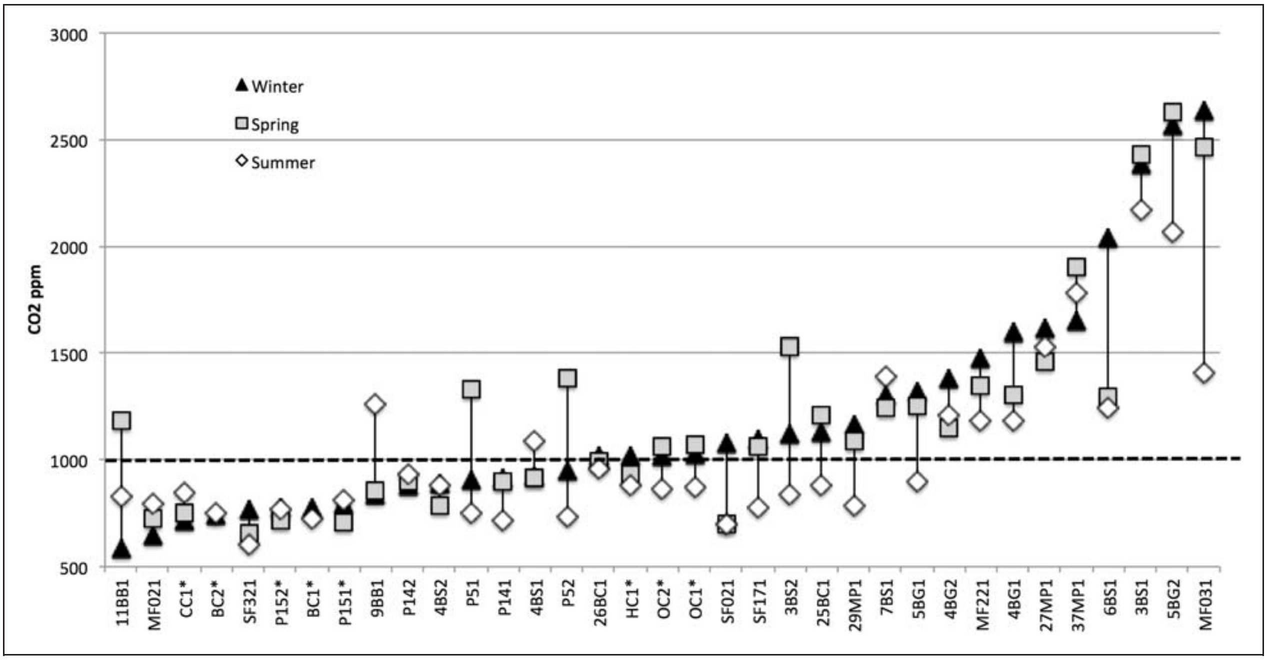

Figure 1. Seasonal mean CO_2 levels in each case study bedrooms (considering data between 11 pm and 7 am) CO_2 ppm.

rises to 62%. In general the houses with MVHR perform better but there are exceptions, for example HC1, OC1 and OC2, where there is a higher occupancy load. The number of bedrooms where CO_2 levels are > 1000 ppm is similar in the spring, but in the summer the figure reduces to 12 (34%).

To provide a more accurate picture of general performance, the percentage of time that the rooms remain above the 1000 ppm threshold (CO_2 exposure, here called CO_2E) has been calculated, as has the recorded window opening activity values for the three seasons are shown in Figures 2 to 4. It should be noted that the window data apply to the principal window in a yes/no condition only, and other window opening may occur.

All but three of the bedrooms have some periods above 1000 ppm, and 71% of bedrooms have CO_2 E

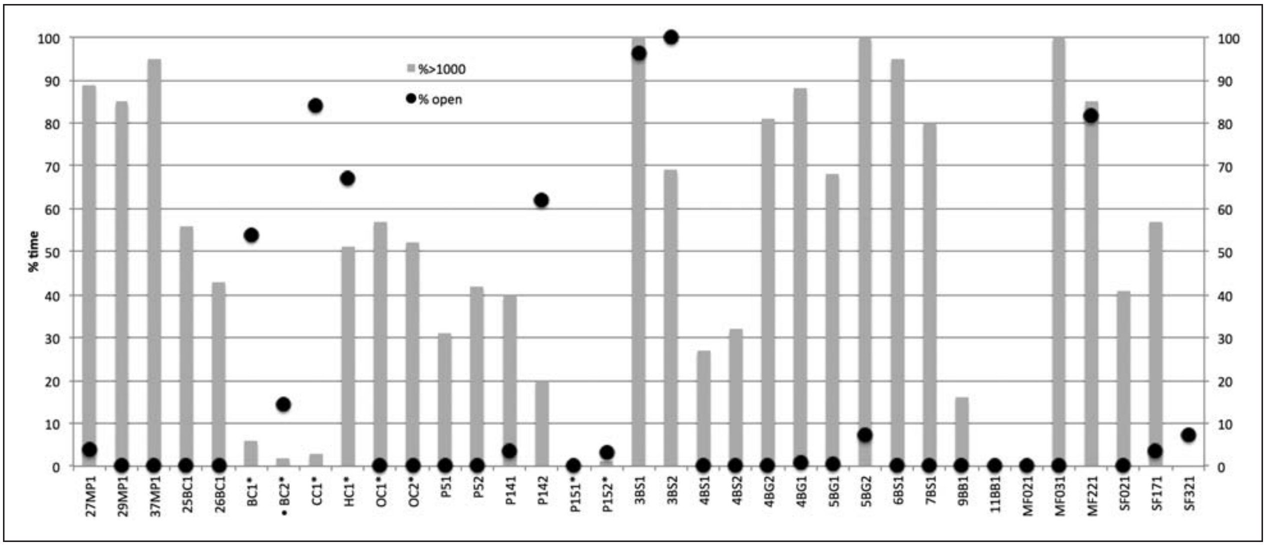

Figure 2. February: Overnight CO_2 E (grey bars = % of time CO_2 levels are > 1000 ppm) and % window opening (black dots = % time windows are open).

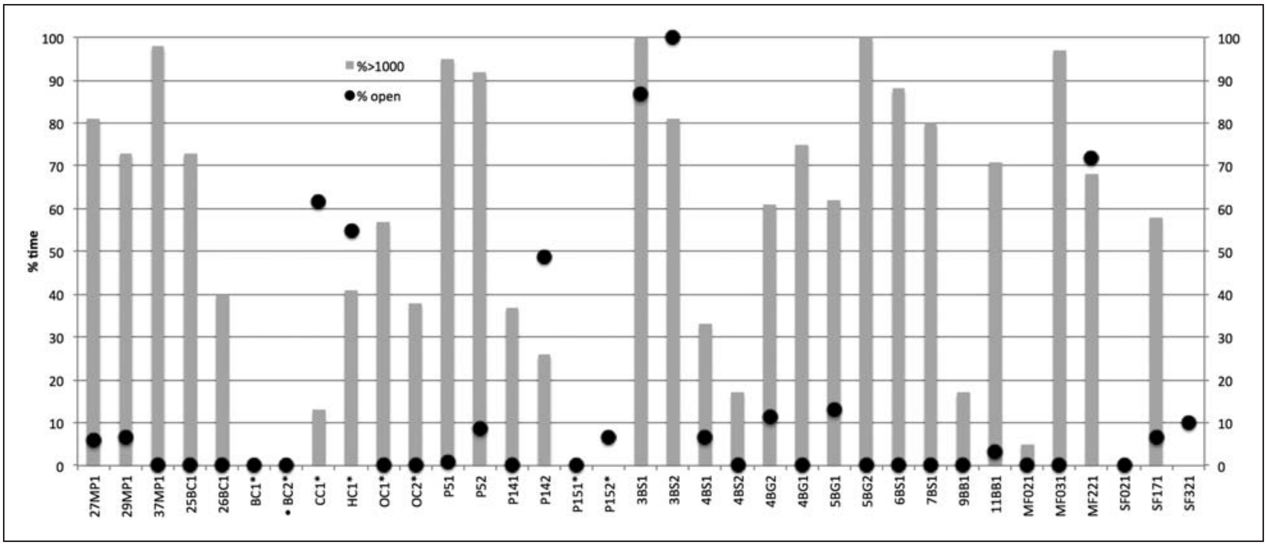

Figure 3. April: Overnight CO_2 E (grey bars = % of time CO_2 levels are > 1000 ppm) and % window opening (black dots = % time windows are open).

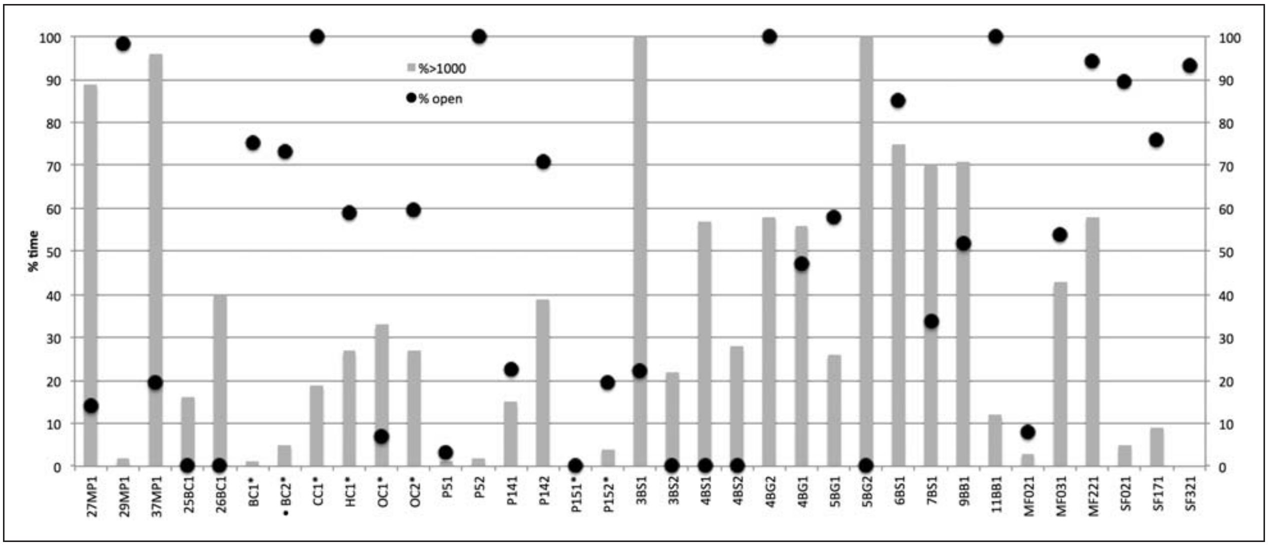

Figure 4. August: Overnight CO_2 E (grey bars = % of time CO_2 levels are > 1000 ppm) and % window opening (black dots = % time windows are open).

>25% (2 h). This decreases to 34% in the summer. It is clear that window opening is more prevalent in the summer, but the effect on overall CO_2 levels is mixed across the sample. A positive effect can be observed by comparing 27MP1 with 29MP1 – in the latter CO_2 E changes from 73% to 2% as window opening increases from 6% to 98% in the summer. In other dwellings, for example SF171, there is a clear difference – the small rise in window opening between winter and spring (4–7%) has little effect on CO_2 E which remains constant at about 57%, but when window opening rises to 75% in the summer the CO_2 E drops to 9%. In other cases the data appear anomalous, such as 11BB where the summer conditions appear worse, despite greater window opening, however in this case this may be due to changes in occupancy due to shift work.

The performance of the houses with MVHR systems is generally better – average winter CO_2 is 858 ppm for the MVHR houses, compared with 1292 ppm for the naturally ventilated houses. There are some exceptions, for example OC2 that has CO_2 E over 50% (4 h a night) in winter. In these houses there appears to be a relationship between poorer CO_2 levels and family size. It is also apparent that in some of the MVHR houses, for example HC1, windows are being opened during the heating season. Such instances may have implications for energy consumption, but the likely causes for this may be overheating, which is discussed in the next section.

There are a number of factors that will determine ventilation performance. These include room volume, number of occupants, ventilation provision, use and occlusion, door opening, other house openings and external weather conditions. Detailed information is not yet gathered on trickle vents and the overall pattern of trickle vent opening or closing is not clear. However, it seems reasonable to conclude that the trickle ventilation provision as required by the building regulations is not providing sufficient ventilation for two reasons – either the vents do not contribute to the ventilation or they are closed. The fact that the vents can be closed undermines this as a fail-safe strategy in a reasonably airtight building, and especially in one that may be more airtight than intended. Even when they are open, observations during the walkthroughs indicated they would be largely occluded in the dwellings by curtains and blinds in the bedrooms at night. In many cases they cannot be easily accessed physically due to their height, especially in dwellings occupied by older or disabled people (n = 8) and in the majority of cases occupants do not change them.

Houses with larger families tend towards poorer results. For example, 3BS and 4BS have six occupants and both 4BG and 5BG have families including teenage children, in which bedroom occupancy is more intensive. Some anomalies due to patterns of occupancy are noted. For example, changes in shift working patterns of the two occupants in 11BB mean that in some seasons there is one occupant and in others there are two. In MF011 a grandchild frequently sleeps in the same room as the two occupants leading to high CO_2 levels.

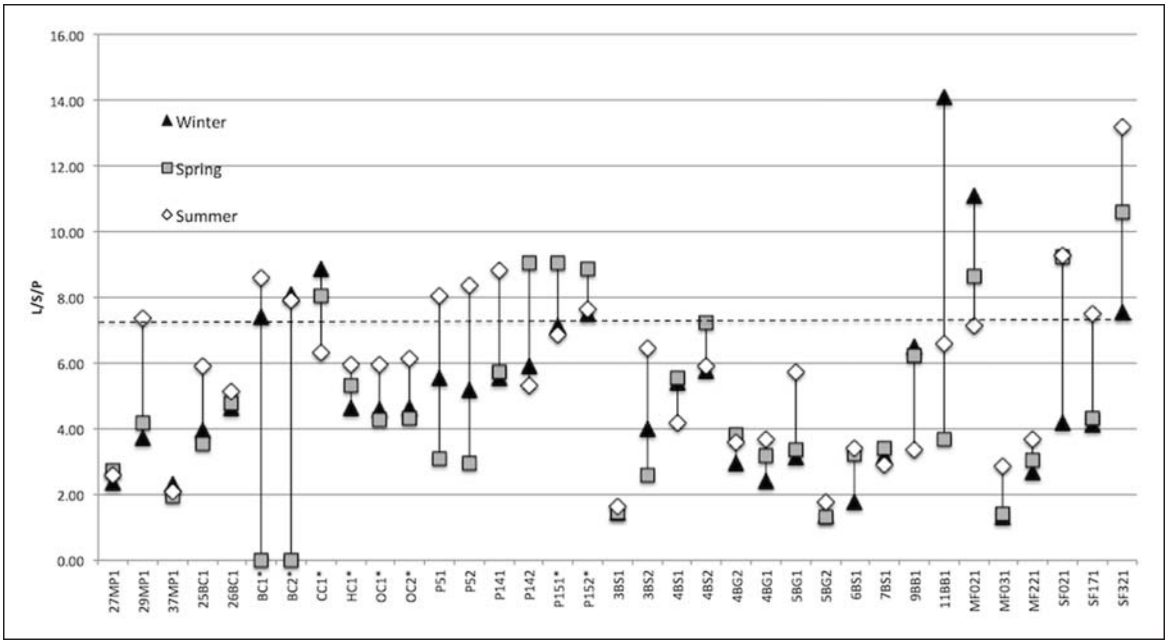

Figure 5. Calculated seasonal ventilation rates for the case study bedrooms (l/s/p).

The measured CO_2 levels have been used to estimate actual ventilation rates. This calculation (equation (1)) is based on the constant injection tracer gas technique described by Persily.[60] Thus

$$Q_o = \frac{10^6 \times G_p}{(C_{in.eq} - C_{out})} \tag{1}$$

where

Q_o	outdoor airflow rate into the space, l/s;
G_p	carbon dioxide generation rate per person in the space, l/s;
$C_{in,eq}$	equilibrium carbon dioxide concentration in the space, ppm; and
C_{out}	outdoor carbon dioxide concentration, ppm.

Carbon dioxide generation rate is a function of the occupant activity (metabolic rate) and occupant size. CO_2 production rate is described in Table 1 in BS 5925:1991,[61] thus the following formula was derived

$$CO_2 P_p = 0.00004\,\mathrm{M} \tag{2}$$

where

$CO_2\ P_p$	CO_2 production rate per person, l/s; and
M	Metabolic Rate, W.

The following assumptions were made for the calculation of ventilation rate:

Infiltration was excluded from the calculation.

41 W/m^2 metabolic rate (occupant activity of sleeping) (Chartered Institution of Building Services Engineers (CIBS) Guide A).[62]

Occupant size 1.8 m^2 (CIBSE Guide A).

No other carbon dioxide generation sources are in the spaces other than occupants.

Outdoor carbon dioxide concentrations remain constant at 380 ppm.

Ventilation rate is expressed in litres/second per person (l/s/p), taking account the occupancy of each room. Calculated values can be compared with the accepted rates of 8 l/s/p and this also takes into account the levels of occupancy. These values for the respective seasons are shown in Figure 5. It should be recognised that these calculations make certain assumptions and simplifications; however, it provides a useful measure for comparison. These values can be compared with the accepted rates of 8 l/s/p referenced previously and this takes into account the levels of occupancy. Figure 5 shows that in winter, 31 bedrooms (88%) do not have sufficient ventilation. Of the four bedrooms that do meet this standard, two are houses with MVHR systems. Whilst houses with MVHR systems fare better, having an average rate of 6.61 l/s/p compared with 4.53 l/s/p for naturally ventilated bedrooms, they are not immune – for example in OC2, the ventilation rate is 4.62 l/s/p. Of the two naturally ventilated houses, one has access to cross ventilation.

The picture improves marginally in the spring with seven bedrooms having average rates above 8 l/s/p. As with the CO_2 levels, the overall effect of window

Table 2. Seasonal temperatures and relative humidity (24-h conditions).

	Int temperature (°C)			Ext temperature (°C)		
Bedrooms	M Min	Mean	M Max	M Min	Mean	M Max
Winter	18.34	21.99	25.29	3.5	6.8	0.2
Spring	18.88	22.17	25.38	6.5	10.3	2.7
Summer	21.11	24.34	27.07	15.2	19.1	11.3
	Internal RH			External Rh		
Bedrooms	M Min	Mean	M Max	M Min	Mean	M Max
Winter	33.47	46.72	58.13	82.0	94.0	67.0
Spring	28.99	37.00	46.15	74.0	55.0	91.0
Summer	34.77	42.88	50.75	81.0	64.0	95.0

opening is not as evident as expected, with average values for all rooms rising from 4.58 l/s/p in spring to 5.77 l/s/p in summer. However, some bedrooms do demonstrate a clear ventilation benefit associated with window opening, for example 29MP1 where the rate increases from the winter figure of 3.74 l/s/p (with 0% window opening) to 7.36 l/s/p (with 98% window opening) in the summer.

In the MVHR houses, the effectiveness of this system remains important throughout the period. For example, in CC1 the ventilation rate deteriorates in the summer, despite more frequent window opening. In this case this is due to the system being turned off in the summer (being conceived as a heating system). Conversely only BC1, BC2 and CC1 have rates >8 l/s/p in winter, and these have winter window opening rates of 54%, 14% and 84%, respectively. Of relevance here are the measured flow rates for these systems. Tested air delivery rates to bedrooms vary from 12.58 l/s (BC1) to 6.61 l/s (HC1) with an average of 9.76 l/s, which would be insufficient for bedrooms with double occupancy.

Hygrothermal conditions

Mean seasonal environmental conditions, in the bedrooms and externally, are summarised in Table 2.

To examine the overall environmental conditions in bedrooms overnight, average temperature and RH is plotted for sample months in Figure 6 (winter), Figure 7 (spring) and Figure 8 (summer) in the period 11 pm – 7 am. However, absolute moisture is also an important consideration, particularly in relation to problems of dust mite population. Four curves are therefore plotted for vapour pressure (VP). Literature has identified a number of threshold levels of significance in control of dust mite populations. These are Plats-Mills and De Weck which cite a figure of 1.13 kPa[63,64] (significant at lower temperature ranges between 15–18°C, expected in bedrooms); the 'critical equilibrium humidity' (CEH)[65–67] for *Dermatophagoides farinae* (DF) a common dust mite species in USA; the CEH for *Dermatophagoides pteronyssinus* (DP),[68] common in UK and 'population equilibrium humidity' (PEH).[69] The graphs also indicate the CIBSE recommended comfort levels for temperature and humidity in the respective seasons in the shaded area,[70] an important consideration with regard to indirect effects of RH on health.[71] The plots show the average overnight conditions for the various houses. Only those dwelling referred to in the text are labelled for clarity.

Looking at temperature to begin with, it is apparent that the bedrooms are very warm even during the heating seasons. In the winter 25 bedrooms (71%) have average temperatures > 21°C, and 13 bedrooms (37%) have average temperatures > 23°C. In the spring, over 36% have averages > 23°C. In the summer, all but two bedrooms (94%) have overnight average temperatures >21°C and 68% are >23°C. There are 10 bedrooms (28%), which exceed 25°C overnight. It is apparent that there is a seasonal shift occurring due to changes in ambient weather conditions, but in general these temperatures exceed the recommended comfort levels.

These temperatures are impacting on internal RH levels, which in general are low; with nearly half (48%) having average RH levels < 40% in the winter. Only one dwelling had values > 60%. In the spring- > 77% have RH levels below 40%. Only five bedrooms (14%) have average values in the intended comfort band in winter or spring.

In the summer a noticeable shift can be observed with both moisture levels and temperature increasing. There are nine dwellings (25%) that now have environmental conditions within accepted parameters (accounting for an increased temperature range), and the increased

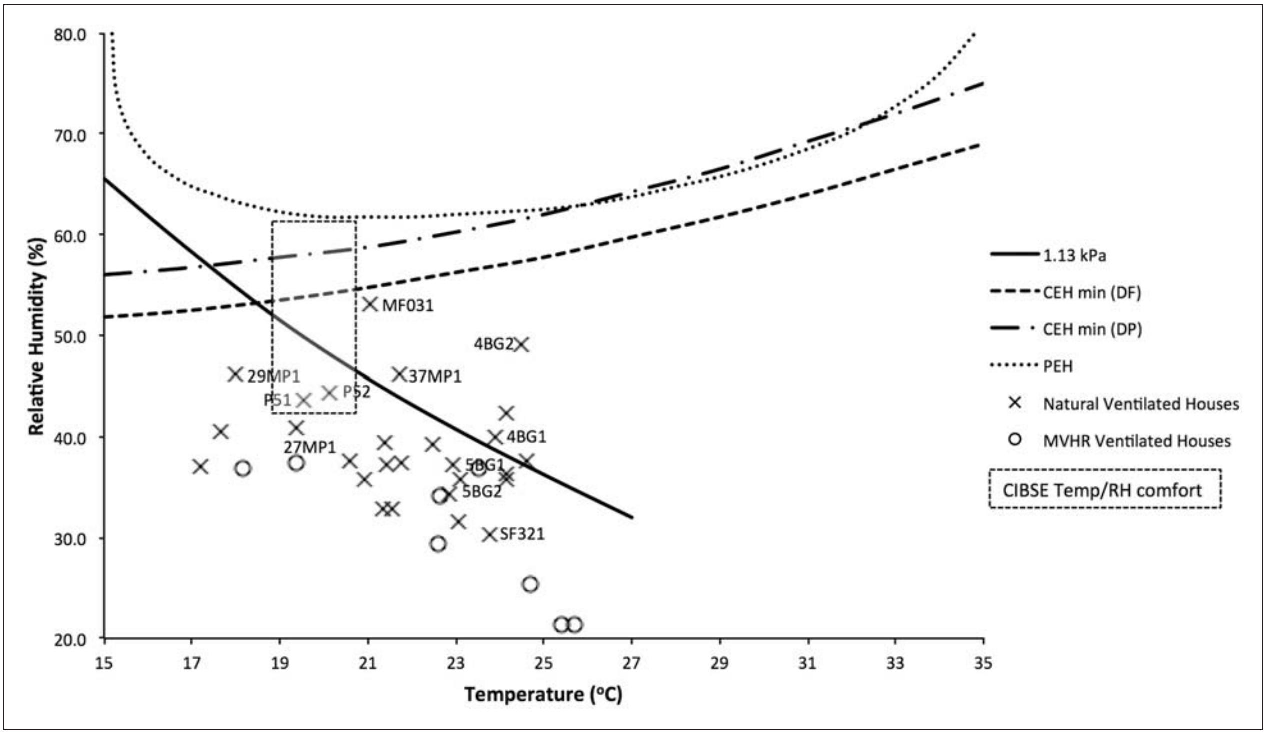

Figure 6. February – average bedroom temperature and RH condition overnight.

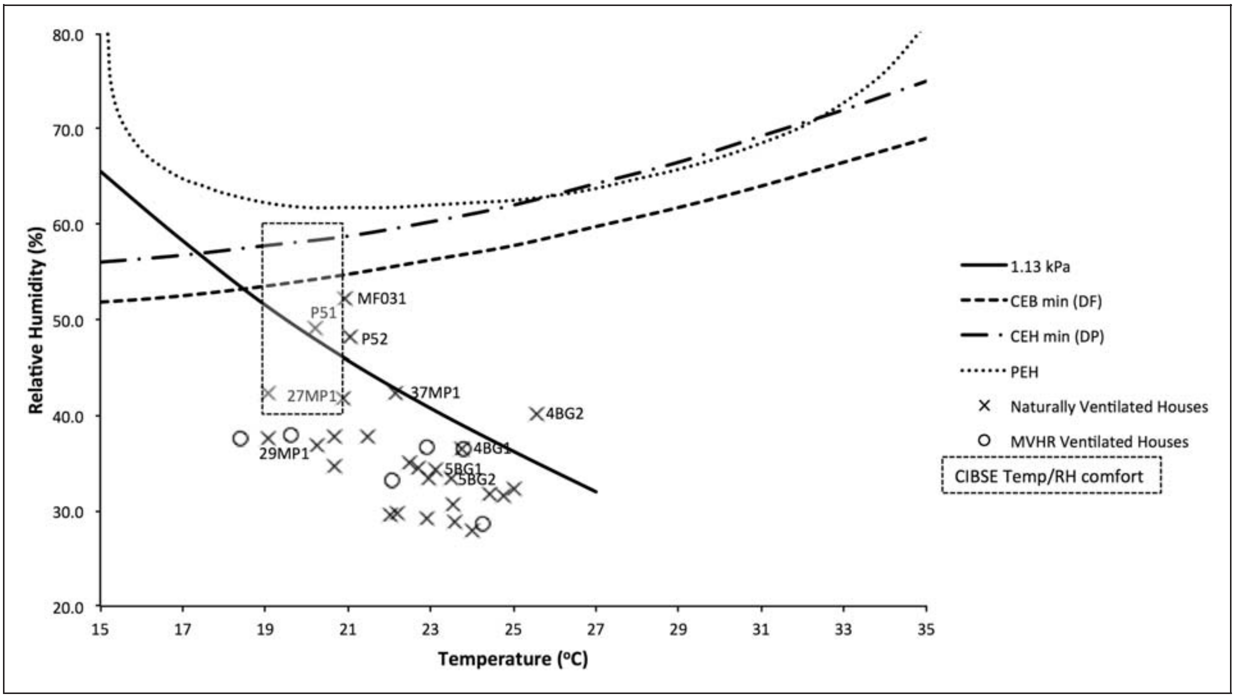

Figure 7. April – average bedroom temperature and RH condition overnight.

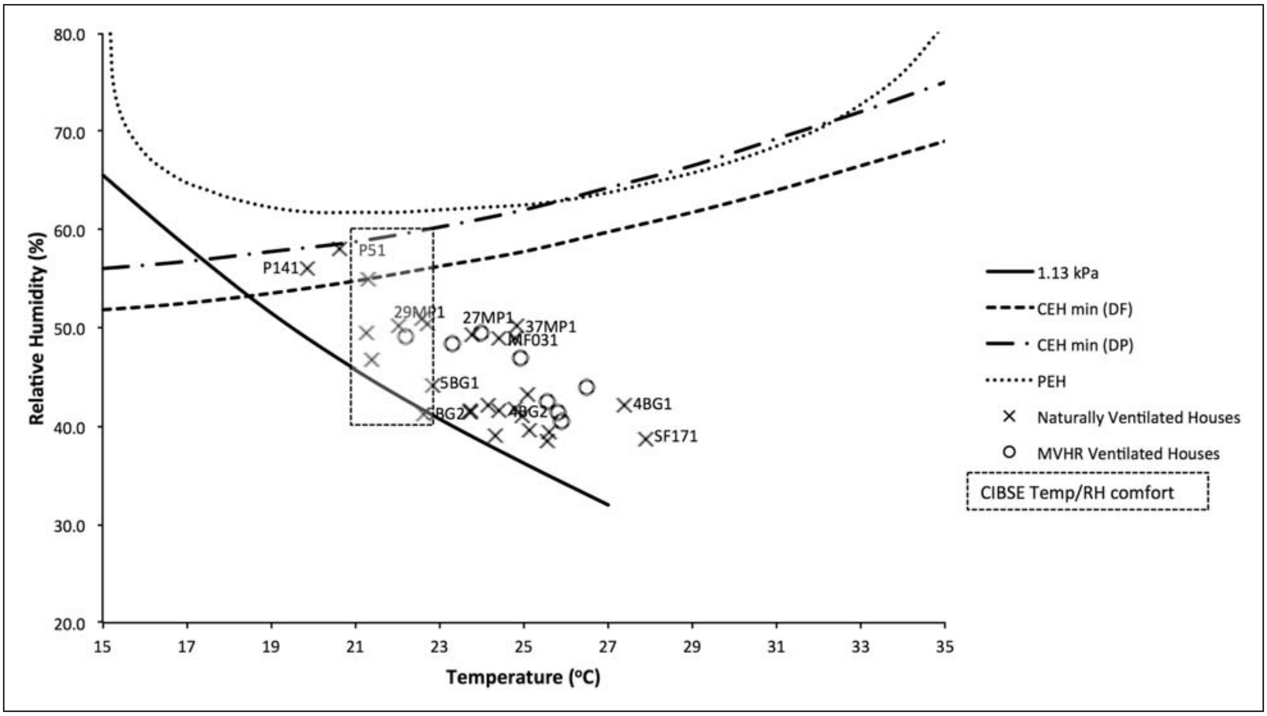

Figure 8. August – average bedroom temperature and RH condition overnight.

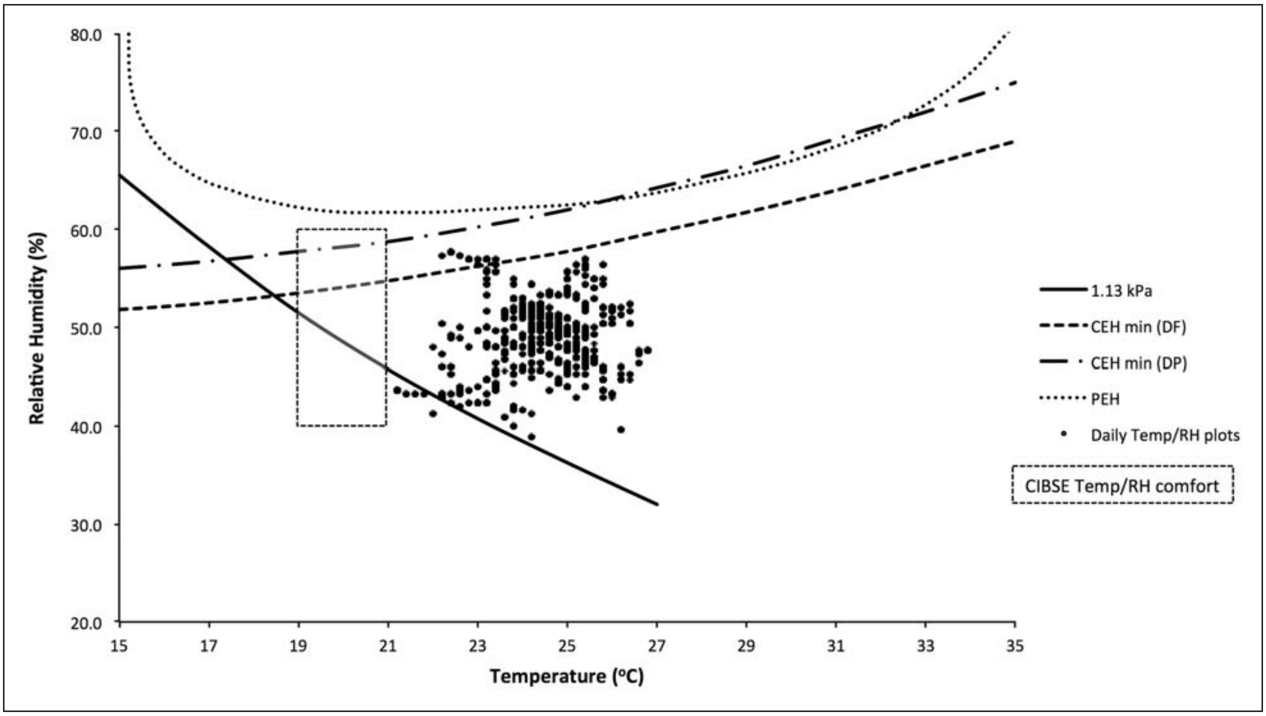

Figure 9. February – 4BG2 Daily (overnight) plots of mean temperature and relative humidity (RH).

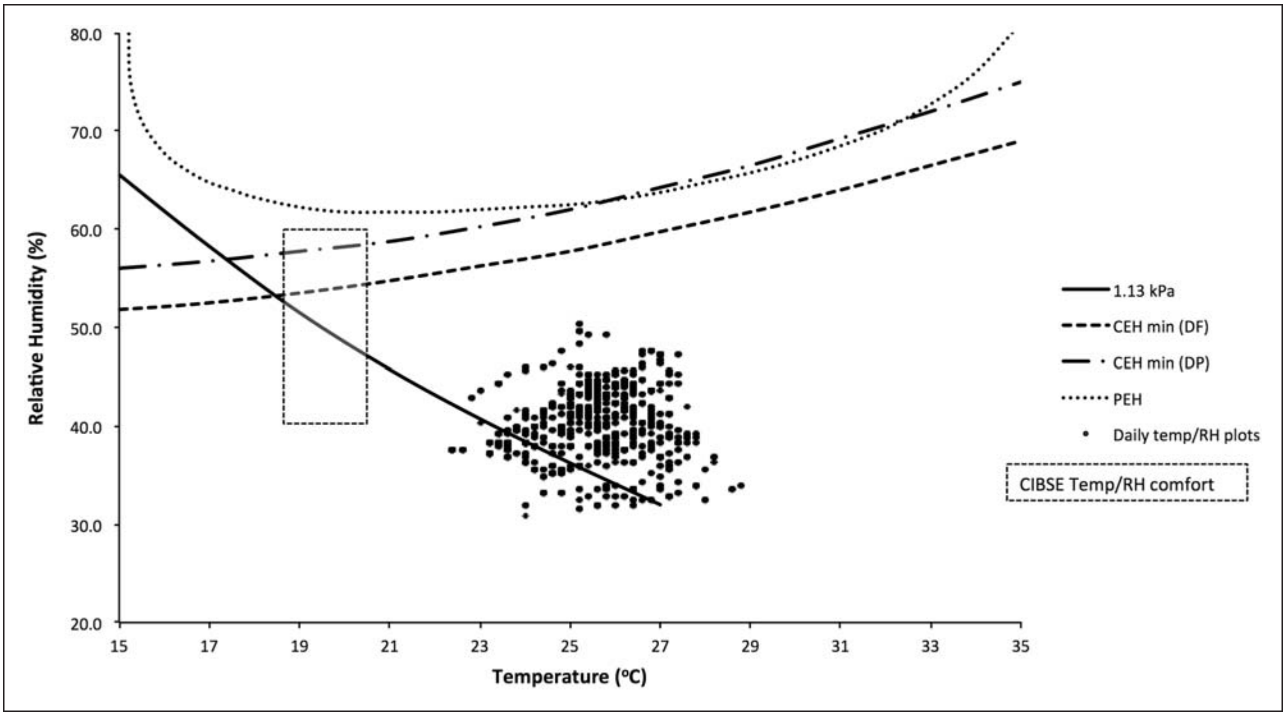

Figure 10. April – 4BG2 Daily (overnight) mean temperature and RH.

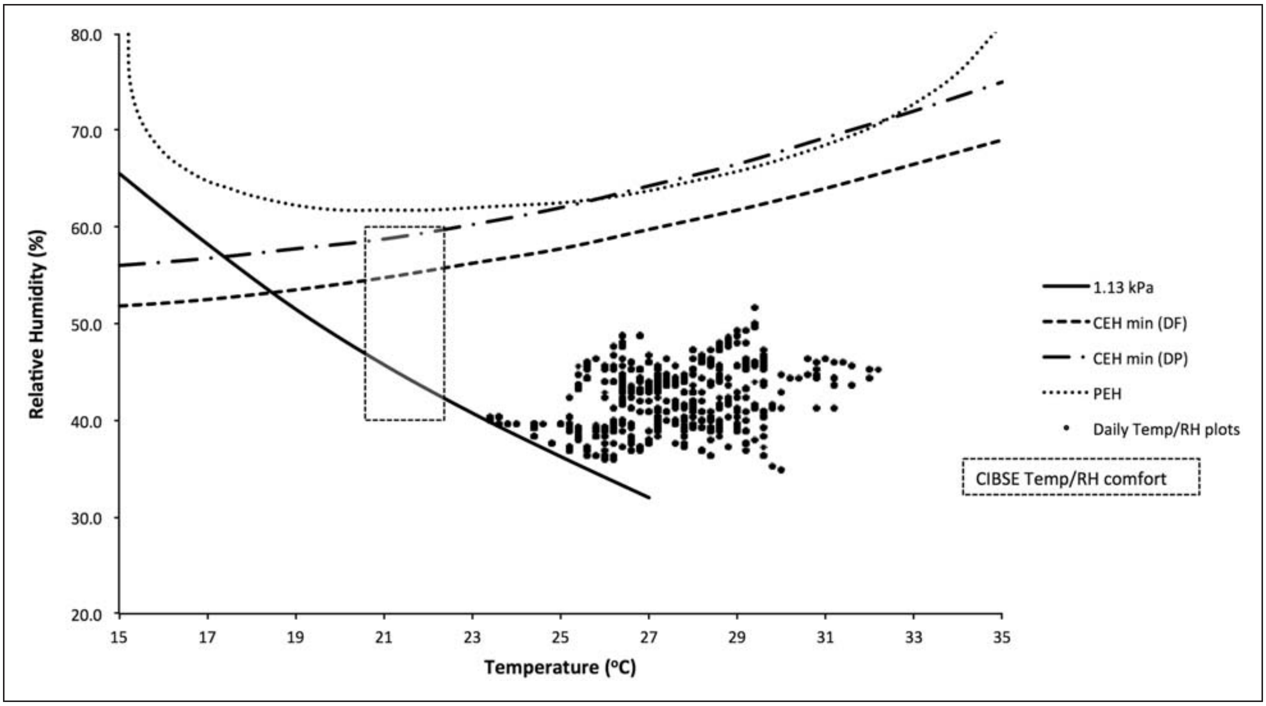

Figure 11. August – 4BG2 Daily (overnight) mean temperature and RH.

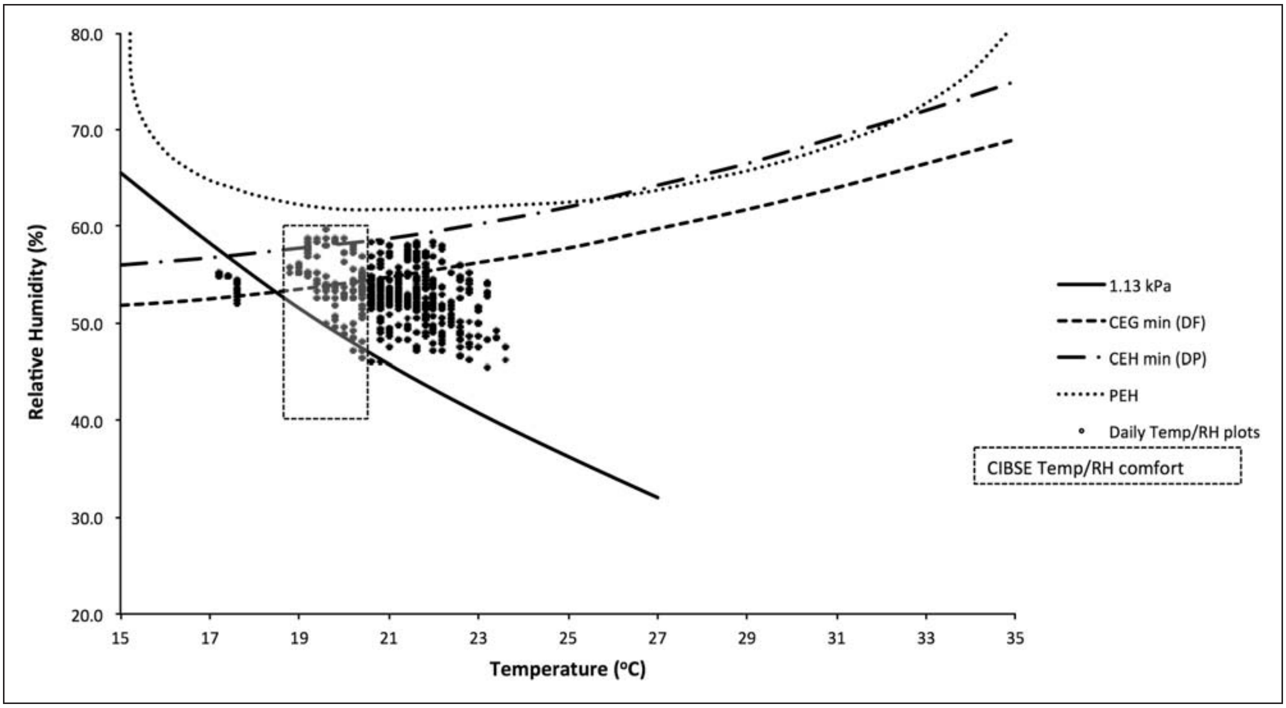

Figure 12. February – MF031 Daily (overnight) mean temperature and RH.

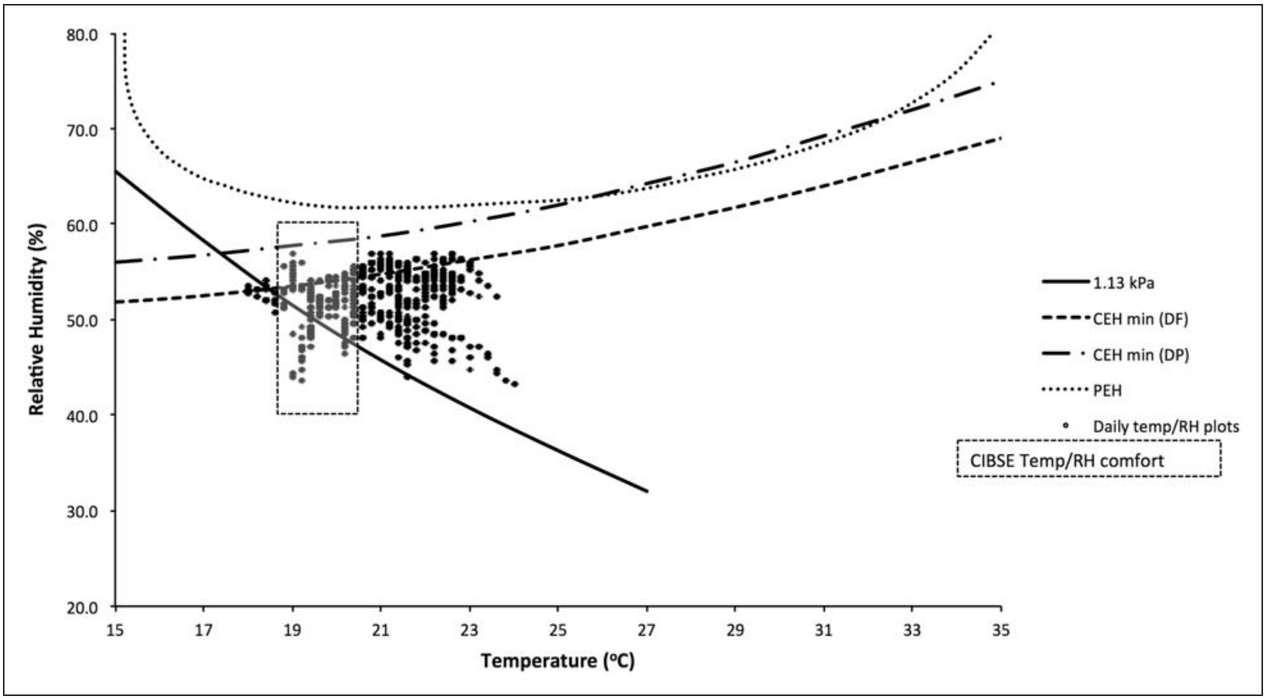

Figure 13. April – MF031 Daily (overnight) mean temperature and RH.

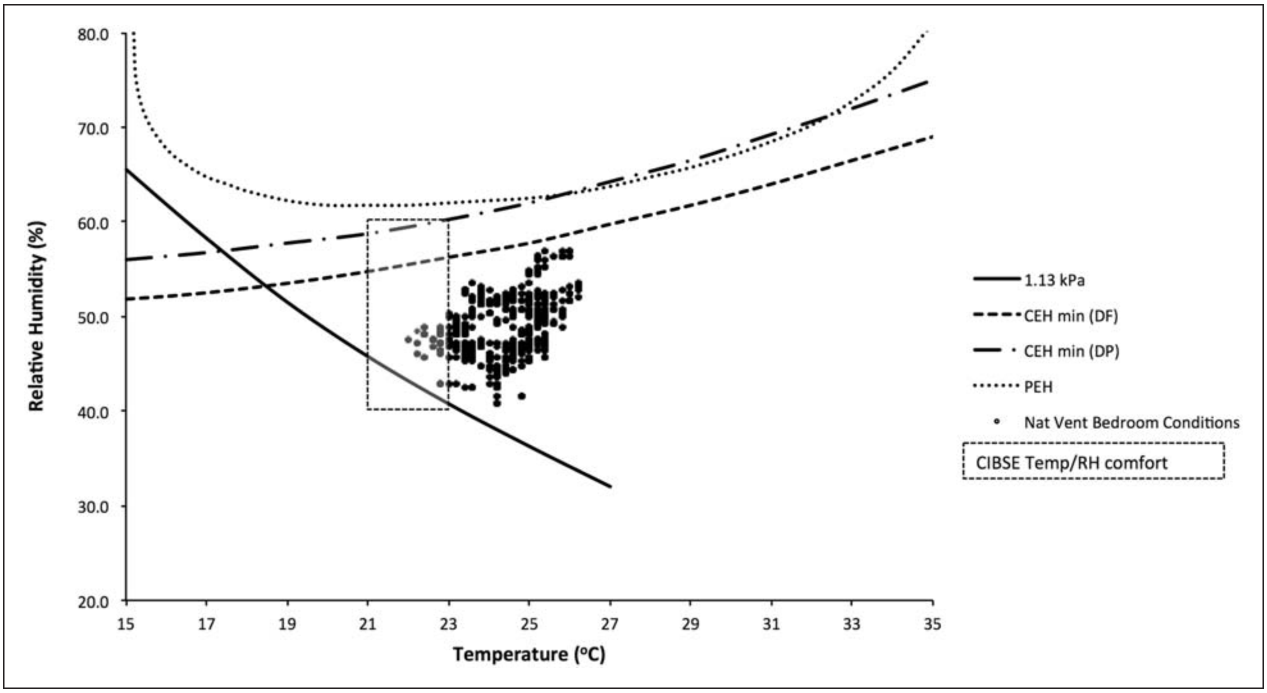

Figure 14. August – MF031 Daily (overnight) mean temperature and RH.

frequency of window opening is clearly affecting internal conditions. However, the temperatures remain high, above ambient external conditions at night.

Few of the buildings have thermal mass, which may help to control temperature. The beneficial effects of this can be observed when comparing 29MP (blockwork) and 27MP (timber frame), both of which have similar occupancy. In August, 29MP has an average temperature of 22.04°C with a standard deviation of 0.67°C whereas 27MP1 has an average of 23.76°C with a standard deviation of 1.04°C. However, the majority of the dwellings (which are typical of contemporary construction in Scotland) are thermally lightweight.

VP

In assessing the internal conditions it is important to consider the absolute moisture content. Occupants and domestic activities such as washing and clothes drying will still generate moisture and these data indicate the relative levels of moisture across the seasons. In relation to IAQ, VP is an important marker in identifying the prevalence of conditions that can encourage dust mite populations. Whilst some studies in the UK have not found the 1.13 kPa threshold significant for controlling HDM,[72] it is nevertheless a useful indicator of absolute humidity and useful in identifying moisture loads which could contribute to rising RH, for example passive indoor drying (PID).

In the winter, 14 bedrooms (40%) have VP levels above 1.13 kPa, albeit not at temperatures that would cause concern, and seven bedrooms (20%) exceed the CEH threshold. It is interesting to note that these are all on one site in Dunoon, which is located directly on the coast and may therefore be strong effect of external climatic conditions. In the spring only a small number (11%) exceed 1.13 kPa and none exceed the CEH, but this situation is reversed in the summer with 94% having average VP levels over the 1.13 kPa threshold, although none exceed the CEH limits. This would appear to be an effect of greater window opening in summer, with moisture from ambient conditions entering the rooms, but peaks being mitigated by improved ventilation. As temperatures reduce in Autumn, RH levels will rise above CEH threshold levels for dust mite populations. It is predicted that this will occur in the autumn. Previous work examining houses in Scotland[73] has identified a seasonal adaptive lag, wherein heating and ventilation regimes set for one season remain in force as ambient condition change. So winter regimes persist into spring, and summer regimes persist into autumn. In the latter situation summer levels of ventilation, in combination with reducing temperatures and lack of heating could lead to high RH levels.

Whilst these results indicate that VP levels do not regularly exceed threshold levels for dust mite populations, looking in more detail at the daily (overnight) mean values for the sample months for specific houses

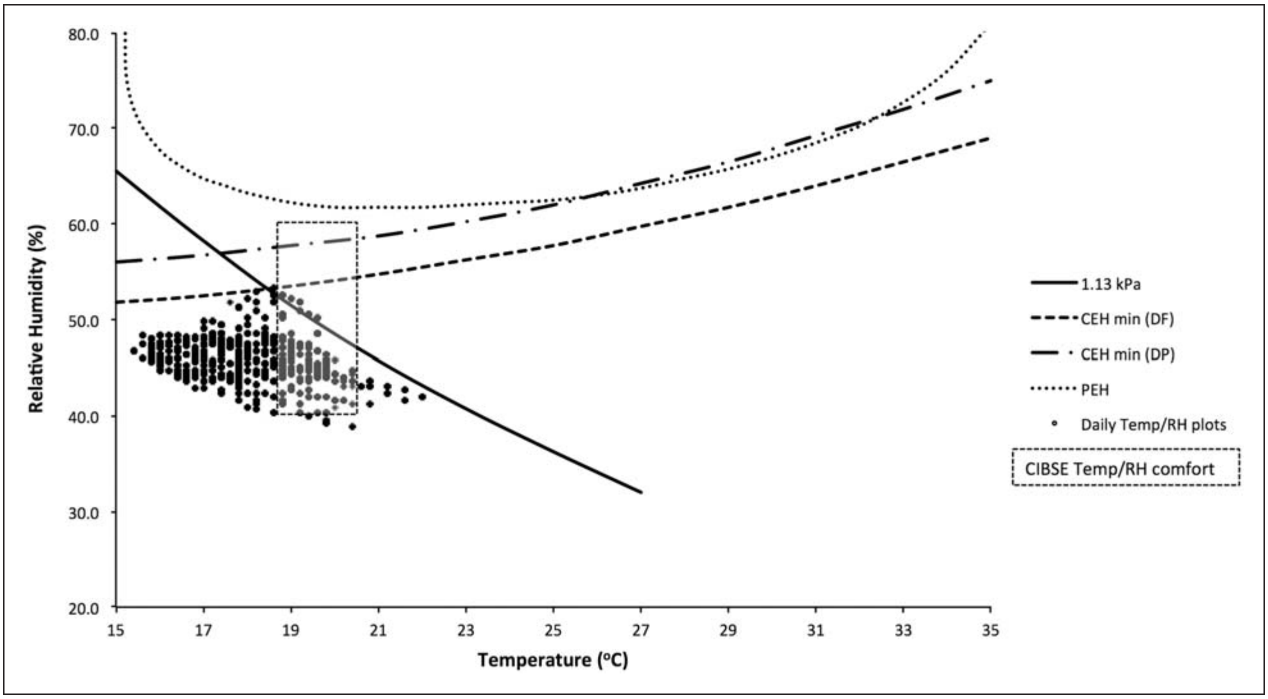

Figure 15. February – 29MP1 Daily (overnight) mean temperature and RH.

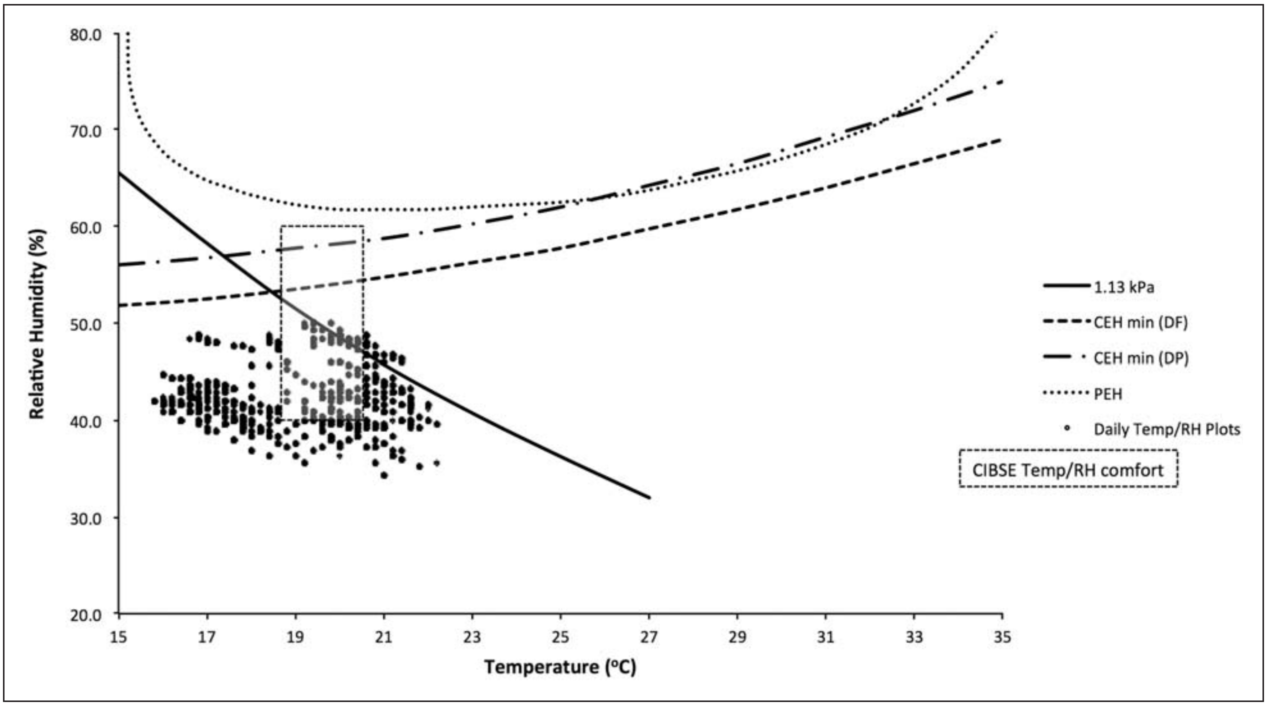

Figure 16. April – 29MP1 Daily (overnight) mean temperature and RH.

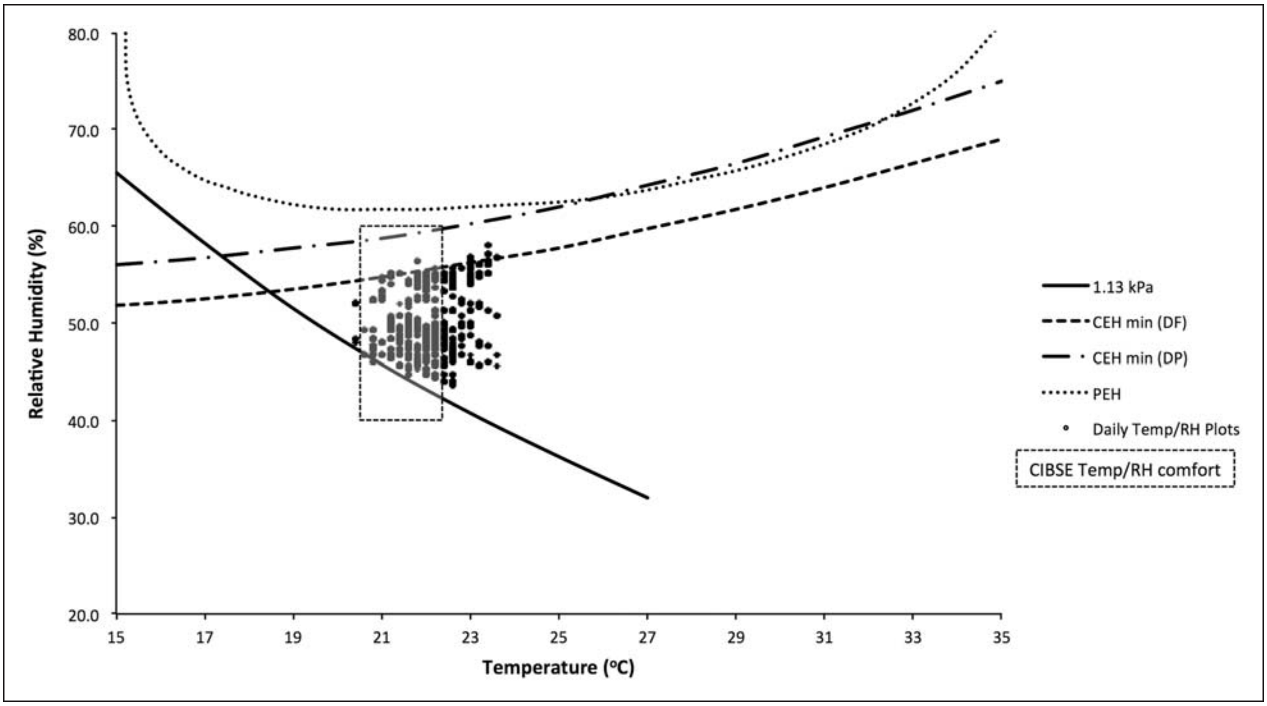

Figure 17. August – 29MP1 Daily (overnight) mean temperature and RH.

illustrates variations in internal conditions that may give rise to problems. It illustrates that, even though mean values are reasonable, there are incidences where VP rises over the threshold levels. For example, examining 4BG2 in winter (Figure 9) shows a cluster of days that exceed not only the CEH DF and CEH DP curves, but also the PEH levels.

In the spring and summer (Figures 10 and 11), the temperatures remain high, but VP levels are reduced. This house contains a large family, including a new born baby and undertakes large amounts of indoor clothes drying, particularly on a generous upper landing (the design intent of which was a workspace) and the inference is that frequency of this may be reduced through spring into summer as the house does have access to external drying. This house also has a direct gain sun space with little thermal mass, which is open to the landing space which may also be contributing to the temperatures here. Also window opening is increased in the spring and is constant in the summer. Greater numbers of occupants will increase moisture, CO_2 and incidental temperature gains, and although this may not directly affect the room being studied, high moisture and CO_2 in other parts of the dwelling will reduce the decay rates through diffusion into the remainder of the house. The concern here is that attempts to reduce temperature to reduce energy consumption could have a consequent effect on moisture levels and consequent HDM proliferation.

A similar situation is also seen in MF031, which also contains a family. Whilst monthly average values are within accepted parameters, daily means exceed CEH DF and CEH DP levels in both winter and spring (Figures 12 and 13). In the summer (Figure 14), with more liberal window opening, the conditions are more acceptable.

A further comparison may be made with 29MP1 (Figures 15, 16 and 17) which has a much more consistent cluster of conditions over the season. In this flat, which contains an older couple, the dwelling is not heated as intensively, conditions are much closer to the accepted levels and vary less. Again, with more liberal window ventilation in the summer, conditions become closer to ambient.

Some context for the variation in VP levels can be seen when comparing CO_2 levels. For example, when comparing the diurnal CO_2 levels for both 29MP and 37MP, shown in Figure 18, it is evident that 37MP1 is being ventilated less and this trend can be seen by comparing the CO_2 levels of both dwellings over the spring and summer seasons (Figures 19 and 20). These graphs also illustrate the diurnal pattern of CO_2 typical of bedrooms in which there is a rapid rise in CO_2 levels overnight. This trend is evident in all properties.

In the winter, MP291 is closer to an optimum temperature and humidity, and remains below the CEH curves, whereas MP371 is hotter and drier. What is interesting about MP37B1 is that although the CO_2

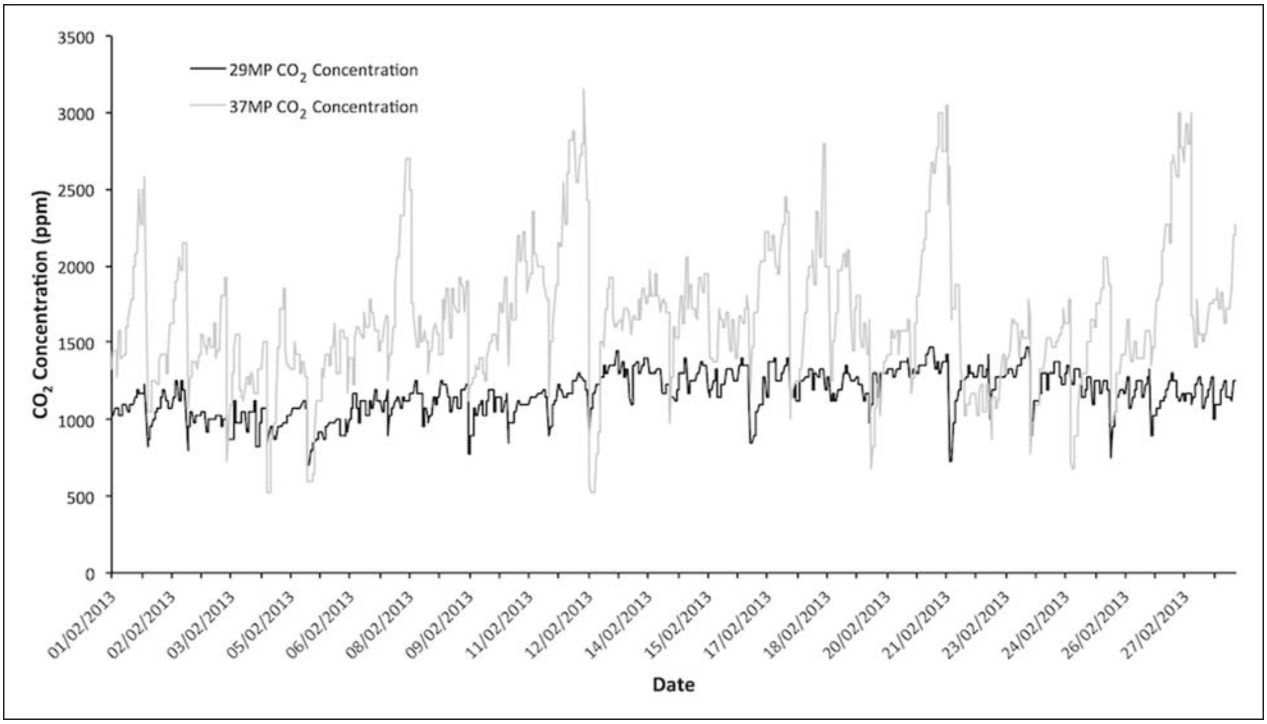

Figure 18. February – Comparison of CO_2 levels 29MP vs. 37MP.

levels indicate that the ventilation is poor, the moisture levels never become excessive. This is an indication that the vapour permeable construction may be having a beneficial effect under these conditions.

Discussion

The starting premise of the paper is that increasing air-tightness is leading to reduced ventilation rates. It is evident from these data from dwellings with low air-tightness that in general ventilation rates in bedrooms overnight, when occupied, are poor. This is a consistent and widespread observation across a range of construction types, in varying climatic conditions and locations across Scotland. Conditions are influenced by the intensity of occupation and the principal mitigating factor is window opening, but when detached from heating this is an uncontrolled strategy. Given that the default background ventilation is trickle vents (excepting the MVHR houses), it seems reasonable to conclude that this is not a sufficiently robust strategy.

However, poor ventilation rates are seen in bedrooms with more frequent window opening – which compromises the air-tightness – and previous research has identified similar conditions in dwellings that are not particularly airtight.[74] The focus then shifts towards the nature of the ventilation strategies.

Whilst the effects of window opening were apparent, they were not as marked as might be anticipated. For example in 29MP1 with windows open 98% of the time overnight only provides 7.36 l/s/p. The limitations of the window sensors should also be noted, and there are simplifications in the calculation of ventilation rates.

Nevertheless, there are several reasons for why the opening effects may be diminished: (i) as discussed under air-tightness, background permeability of bedroom spaces is likely to be lower; (ii) bedroom spaces are more likely (especially in family houses) to have the doors closed for reasons of privacy and noise, thus reducing opportunities for cross ventilation; (iii) the windows (and therefore trickle vents or openings) are commonly occluded by curtains and/or blinds at night reducing air flow into or out of the room; (iv) openings in the remainder of the house will be closed at night, which, in conjunction with the preceding factors leads to reduced opportunities for cross-ventilation; (v) the design and placement of the windows does not facilitate air movement – the window is commonly in the centre of the wall, and ‘tilt and turn’ windows (the most common opening type) do not facilitate high and low level openings in the wall. Only two rooms have more than one opening, which would enable cross ventilation in the space.

In these circumstances opportunities for effective ventilation are limited. Paths for air movement are restricted, especially when relying on a stack effect. The movement of air into or out of a room would be

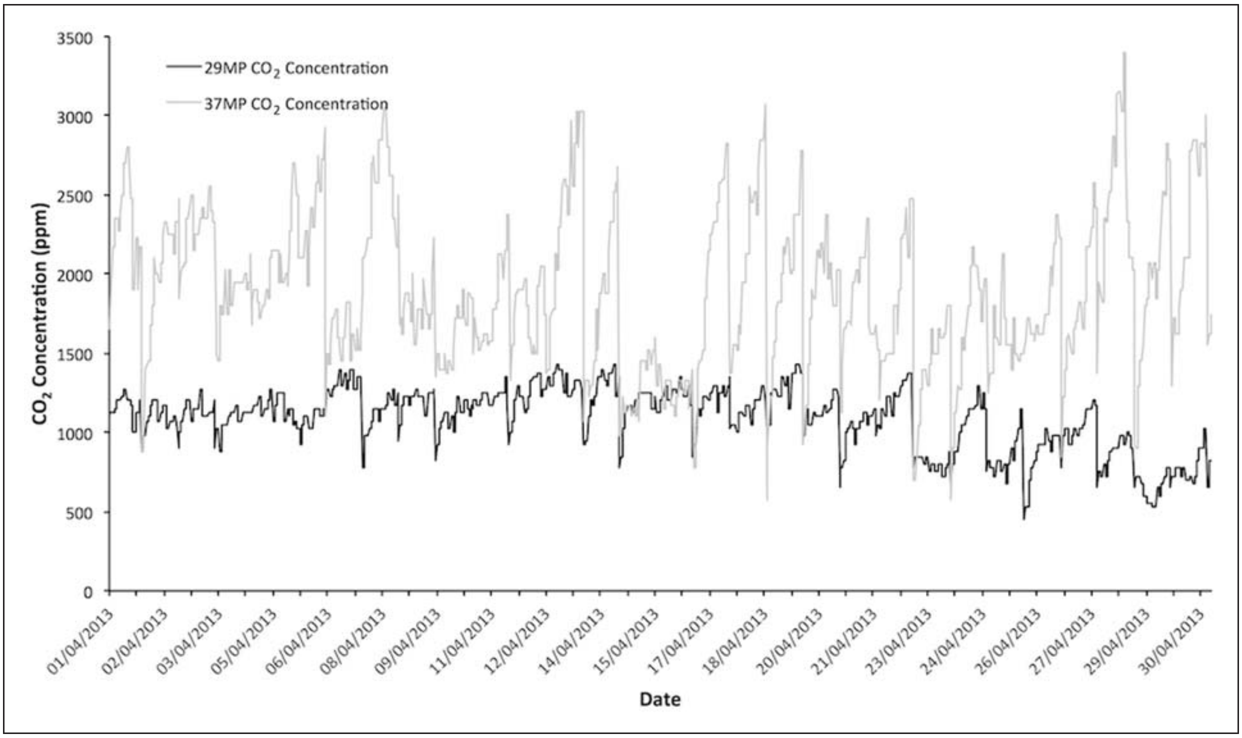

Figure 19. April – Comparison of CO_2 levels 29MP vs. 37MP.

affected by external weather conditions and can affect the acceptability of the measure, for example, moving curtains and blinds giving rise to noise and the perception of draughts. Bedroom volume is also an important consideration – these are small spaces and furniture such as large wardrobes and beds further reduce the net volume. The bedroom volume/person (excluding temporary occupancy such as MF011) varies from 35.7 m^3/person (OC1, double height spaces) to 11.65 m^3/person (6BS1). Whilst conditions in a small volume will deteriorate more quickly, a greater air change rate is achieved for an equivalent opening regime compared with a larger volume.

There are limited opportunities for control of these strategies and this is exacerbated by the nature of bedroom occupancy. In general, a ventilation condition (i.e. window or trickle vents open or closed) is set at the time the occupants go to bed, when conditions may be reasonable, and this will remain in force overnight. Deteriorating conditions will not result in adaptive comfort behaviour overnight, as occupants are asleep, except in extreme circumstances. There are also a number of situations where night-time opening windows are not acceptable. Common responses for keeping windows closed were noise and security, and others included concern over insects and hay fever. Overall diurnal window opening behaviours tend towards the habitual rather than the adaptive – some occupants tended to keep windows open overnight as a lifetime habit. There is a slow adaptive response seasonally – as temperatures increase the window opening becomes more frequent, but conditions have to overshoot desired maxima to trigger behaviour in bedrooms, as the effects on occupants are less immediate.

In general, ventilation rates in the houses with MVHR were better. Peak conditions were not as extreme but there is some important context to this. There was some evidence that (in part due to the limitations of window ventilation raised above) these houses may still rely on the MVHR system in the summer. This may not be sufficient, in that air delivery rates may not meet the needs of the rooms, particularly where there is multiple occupancy and this can lead to under ventilation in other seasons. In OC1 for example estimated ventilation rates, with single occupancy were 4.58 l/s/p – the measured MVHR supply rate for this room was 6.98 l/s. The disabling of the system will reduce ventilation rates with consequent effects on CO_2 levels[74] and there are several instances noted where this has occurred, the most common explanation being that this is conceived of as a heating system.

It is evident that the majority of bedrooms have relatively poor hygrothermal performance characterised by high temperatures and low RH, which in some cases masks fairly high VP levels. Ventilation regimes, both in terms of providing sufficient rates for occupants, but

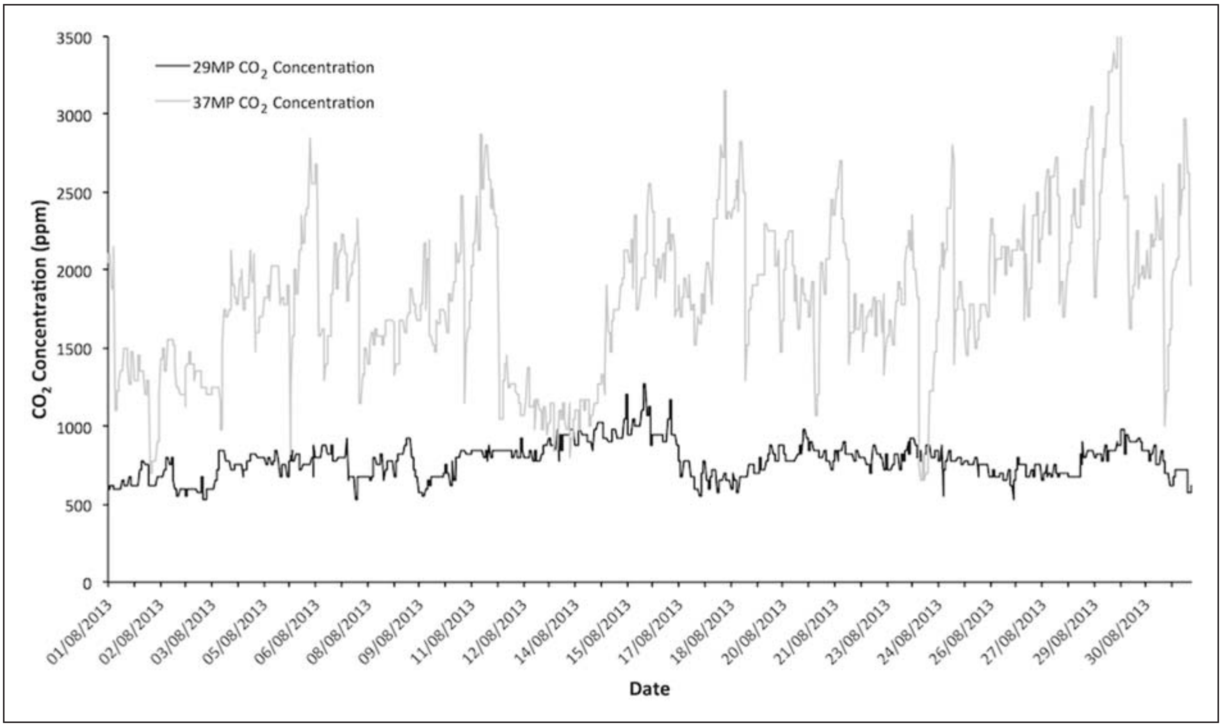

Figure 20. August – Comparison of CO$_2$ levels 29MP1 vs. 37MP1.

also helping to control moisture and other pollutants in these rooms, are compromised. From an examination of the dwellings there are a number of important contributory factors.

Firstly, the dwellings are well insulated and have high air-tightness, but there is little or no insulation between internal spaces. In these circumstances heat will tend to be dissipated throughout the dwelling. Furthermore, thermal buoyancy will transfer this heat to upper rooms more readily. In winter the average temperature of 1st floor bedrooms was 2°C higher than bedrooms in single storey properties.

Secondly, there is a tendency for heating systems to be oversized and poorly controlled, for example combination boilers tend to be sized according to hot water demand and heating systems rely on basic programmers and TRVs and the shortcomings of domestic control systems are well evidenced.[76,77] In terms of passive control these dwellings have very limited capacity for control of temperature through thermal mass. The increase in temperature between winter and spring – average internal temperatures were 21.98°C in winter and 22.24°C in the spring – are indicative of a lack of responsiveness in heating systems and regimes, whereby the heating is set up for winter and settings persist as the weather improves.

Thirdly, in well-insulated dwellings the effects of incidental gains are substantial, and in some seasons provide all of the space heating needs, particularly in the Passivhaus projects. Whilst this is in many ways beneficial, such gains are also largely uncontrolled, and where they are excessive they can contribute to overheating. A specific example of this is identified in the B/C/O/HC houses, which was due to the hot water system, where there is a large hot water cylinder adjacent to the bedrooms fed by a solar thermal system and log stove. The hot water pipework is uninsulated and a circulating pump keeps hot water in the supply pipes. Furthermore, an incorrect setting was sending hot water to the MVHR post heater. The heat gain from this is thought to be leading to the very high temperatures and resulting very low RH in these dwellings. This has now been corrected and the effects will be observed in ongoing monitoring.

RH levels were very low across the sample, but moisture content approached HDM threshold levels in some instances. PID has been identified as an important factor in moisture loads in domestic environments[78] and PID is widespread in the heating seasons, particularly in those dwellings with children. There is little or no dedicated ventilated internal drying space. There are spaces containing hot water cylinders and other associated plant that (due to heat loss) do get warm, but these not generally accessible for clothes drying, and in any case are not otherwise vented. With regard to PID, feedback from occupants was that the speed at which clothes dry in the houses is seen as a positive factor, further encouraging its use. There is some evidence emerging that vapour permeable construction is having a beneficial effect in reducing RH.

As well as effects on health, there is a risk that persistent levels of high temperatures and low RH may lead to other unintended negative consequences. This could include drying and shrinkage of the timber frame systems, which could in turn affect air-tightness. This will be reviewed further after the repeat air-tightness testing in 12 months' time.

The disparity between the design intentions in terms of temperature and RH and actual conditions is further evidence of the performance gap, in both energy and environmental terms. Early indications are that although these buildings are energy efficient, they are exceeding their energy targets by factors of 2–4.[79] This will be reviewed when a full year of energy consumption data are available.

In energy terms temperatures could be reduced, and this would impact on RH levels. For many of the spaces, particularly the MVHR dwellings, this may be beneficial in terms of reducing dryness.

However, a contention here is that better ventilation in bedrooms at night may not have a significant energy penalty. High levels of ventilation are only problematic if heating is active within the dwelling. Overnight, with a heating system turned off, relatively little primary energy would be lost. Modelling of this scenario has indicated that the additional energy penalty may be as little as 2%.[80] The problem would arise if the windows were then left open during the day.

Current legislative requirements for vent free opening area (average of 11,000 mm^2 is provided per room), as recommended in clause 3.14.2 of the Domestic Technical Handbook, Building Standards (Scotland) Regulations[81] are a blunt tool in respect of varying levels of volume and occupancy. The requirements in a family house will be very different to those of a single person or couple. Design and regulatory standards for ventilation of these spaces need to be reassessed and more robust systems of ventilation, capable of meeting varying needs, need to be introduced. Reduction of moisture production at source, for example provision of ventilated drying spaces is critical and may be assisted by more use of vapour permeable construction.

The observation is that the systems in place to control environment are not considered holistically. These are predicated in a series of discrete requirements set by building standards at design stages, but these are not tested in practice. Whilst there are identifiable benefits of the active systems, there are also substantial risk factors due to specification, installation, failure, use and maintenance, any one of which can lead to poorer performance and/or increased energy use.

Conclusions

There is clear evidence of poor levels of ventilation in the bedrooms. In such rooms there are limited opportunities for adaptive behaviour. The provision of trickle vents is not a sufficiently robust measure to ensure satisfactory ventilation rates for varying degrees of occupancy.

Consistently high temperatures were observed in the majority of the dwellings. This level of demand is contributing to a gap between design prediction and actual consumption in terms of both energy use and environmental quality. It would seem that the notion of a bedroom as a cooler space, used infrequently, is outdated and that lower bedroom temperatures may not be (a) easily achieved or (b) acceptable. Calculation and regulation needs to allow for this when predicting energy use to close performance gaps.

Opening windows at night appears to be a mitigating factor and may not necessarily make a significant contribution to energy losses. However, its effectiveness is limited and is relatively inefficient and it cannot be relied on in all circumstances due to external factors such as noise and security. Ventilation strategies need to provide mechanisms for sufficient air exchange – single openings do not enable airflow in and out without leading to draughts.

Contemporary construction techniques such as timber frame construction contain little or no thermal mass and consequently rely on control of the heating system and ventilation to prevent overheating. This suggests a need for much closer control of heat delivery through appropriate system sizing and more responsive controls that rely less on frequent occupant interaction. Furthermore, greater care is needed to reduce uncontrolled incidental gains from appliances and hot water systems.

In the context of the drive for low carbon housing, there is an urgent need for more considered, robust and effective design of ventilation strategies, which rely on fundamental principles. These include: better placed openings which allow for cross ventilation, and high and low level openings that facilitate air flow; consideration of cross flows through the house, taking into account internal doors; ergonomic design that enables occupant to physically interact with the systems; provision of ventilation strategies that account for possible confounding factors such as noise and security; integration of the design of ventilation strategies with the heating system; possible use of automated systems such as CO_2 sensing passive vents; and better feedback to occupants about environmental performance, for example visible thermostats and CO_2 sensors.

Mechanical systems will have a part to play in planned ventilation strategies, but development is needed in the sector to ensure that systems are well conceived, designed, installed, operated and maintained. There may be a role for partial MVHR systems that allow for effective heat recovery and good ventilation delivery to certain spaces (which may rely less on adaptive comfort) whilst allowing other spaces to be naturally ventilated.

Finally, in either strategy (i.e. natural or mechanical ventilation) better information and guidance is required for occupants. This is predicated on a premise that a given strategy is in fact usable by the occupants, and that the intention and required performance is known and must be communicated to users. A common misconception for performance gaps due to occupancy effects is that this is due to 'misuse'. The reality is that most occupants are doing the best they can with limited knowledge of uncoordinated and inefficient systems.

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Declaration of conflicting interests

The authors declare that there is no conflicts of interest.

Authors' contribution

All authors contributed equally in the preparation of this manuscript.

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References

1. IPCC. *Climate change 2013 the physical science basis*, http://www.ipcc.ch/report/ar5/wg1/#.Ul0YQxZaF39 (accessed 15 October 2013).
2. HM Government. *Climate Change Act 2008 (c.27)*. London: HMSO, 2008.
3. Sullivan L. *A low carbon building standards strategy for Scotland.* Livingston, Scotland: Arcmedia, The Scottish Standard Agency, 2007.
4. Palmer J and Cooper I. *Great Britain's housing energy fact file*, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48195/3224-great-britains-housing-energy-fact-file-2011.pdf (2011, accessed 21 March 2014).
5. HM Government. *The Building Regulations 2010: conservation of fuel and power in new dwelling*. Approved Document L1A. London: NBS, part of RIBA Enterprise Ltd, 2010.
6. Scottish Government. *Scottish building regulations*, Edinburgh, Scottish Government. http://www.scotland.gov.uk/Topics/Built-Environment/Building/Building-standards (2010, accessed 21 March 2014).
7. DECC. *Standard Assessment Procedure 2013*, https://www.gov.uk/standard-assessment-procedure (accessed 21 March 2014).
8. Good Homes Alliance. *GHA Monitoring Programme 2009–11: technical report results from phase 1: post-construction testing of a sample of highly sustainable new homes, GHA 2011*, http://www.goodhomes.org.uk/downloads/members/gha-monitoring-report-approved.pdf (accessed 21 March 2014).
9. Green Construction Board Buildings Working Group. *The performance gap: causes & solutions*, http://greenconstructionboard.org/index.php/resources/performance-gap (2012, accessed 21 March 2014).
10. Gill ZM, Tierney MI, Pegg IM and Allan N. Measured energy and water performance of an aspiring low energy/carbon affordable housing site in the UK. *Energy Build* 2011; 43: 117–125.
11. Cutland Consulting Ltd. *Low and zero carbon homes: understanding the performance challenge, NHBC Foundation NF41*, Milton Keynes, National House Building Council. http://www.nhbcfoundation.org/Portals/0/NF_Pubs1/NF41.pdf (2012, accessed 21 March 2014).
12. Crump D, Dengel A and Swainson M. *Indoor air quality in highly energy efficient homes – a review*. NF18, NHBC Foundation 2009. London: IHS BRE Press, 2009.
13. Davis I and Harvey V. *Zero carbon: what does it mean to homeowners and housebuilders?* NHBC Foundation report, NF9. London: IHS BRE Press, 2008.
14. Mendell MJ and Fine L. Building ventilation and symptoms—where do we go from here? *Am J Public Health* 1994; 84: 346–348.
15. Spengler JD and Chen Q. Indoor air quality factors in designing a healthy building. *Annu Rev Energy Environ* 2000; 25: 567–600.
16. Yu CWF and Kim JT. Low-carbon housings and indoor air quality. *Indoor Built Environ* 2012; 21: 5–15.
17. Sundell J, Nevin H, Nazaroff WW, Cain WS, Fisk WJ, Grimsrud DT, Gyntelberg F, Li Y, Persily AK, Pickering AC, Samet JM, Spengler JD, Taylor ST and Weschler CJ. Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor air* 2011; 21: 191–204.
18. Bornehag CG, Sundell J, Hägerhed-Engman L and Sigsgaard T. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor Air* 2005; 15: 275–280.
19. Ridley I, Pretlove S, Ucci M, Momovic D, Davies M and Oreszczyn T. *Asthma/dust mite study – final report: sensitivity of humidity and mould growth to occupier behaviour in dwellings designed to the new air tightness requirements*. Technical report. London: Office of the Deputy Prime Minister, 2006.
20. McKay S, Ross D, Mawditt I and Kirk S. *Ventilation and indoor air quality in Part F 2006 Homes*. BD2702. London: DCLG, NBS, HIS, 2010.
21. Wargocki P. The effects of ventilation in homes on health. *Int J Ventil* 2013; 12: 101–118.
22. Fernandes E, Jantunen M, Carrer P, Seppanen O, Harrison P and Kephalopulos S. *ENVIE co-ordination action on indoor air quality and health effects*, WP1 Final Report – Health effects, www.envie-iaq.eu (2009, accessed 21 March 2014).

23. Dols WS, Persilly AK and Nabinger SJ. Indoor air quality in green buildings: a review and case study. In: *IAQ '96, proceedings of seventh international conference on indoor air quality and climate*. Baltimore, 6–8 October, 1996, pp.139–150.
24. Levin H. Integrating indoor air and design for sustainability. In: *Indoor Air 2005, proceedings of the 10th international conference on indoor air quality and climate*. Beijing, China, 4–9 September 2005.
25. Ward I. The potential impact of the new (UK) building regulations on the provision of natural ventilation in dwellings – a case study of low energy social housing. *Int J Ventil* 2008; 7: 77–88.
26. Yu C and Crump C. Indoor environmental quality-standards for protection of occupants' safety, health and environment. *Indoor Built Environ* 2010; 19: 499–502.
27. NHBC. Technical Extra October 2013, Issue 12, http://www.nhbc.co.uk/NHBCPublications/LiteratureLibrary/Technical/TechnicalExtra/filedownload,53658,en.pdf (accessed 21 March 2014).
28. Mardiana-Idayu A and Riffat SB. Review on heat recovery technologies for building applications. *Renew Sustain Energy Rev* 2012; 16: 1241–1255.
29. Kovesi T, Saloum C, Stocco C, Fugler D, Dales RE, Ni A, Barrowman N, Gilbert NL and Miller JD. Heat recovery ventilators prevent respiratory disorders in Inuit children. *Indoor Air* 2009; 19: 489–499.
30. Wright GR, Howieson S, McSharry C, McMahon AD, Chaudhuri R, Thompson J, Donnelly I, Brooks RG, Lawson A, Jolly L, McAlpine L, King EM, Chapman MD, Wood S and Thomson NC. Effect of improved home ventilation on asthma control and house dust mite allergen levels. *Allergy* 2009; 64: 1671–1680.
31. Zero Carbon Hub. *Mechanical ventilation with heat recovery in new homes*, Interim report, Indoor Air Quality Task Group. London, Zero Carbon Hub, NHBC Foundation, http://www.zerocarbonhub.org/sites/default/files/resources/reports/Mechanical_Ventilation_with_Heat_Recovery_in_New_Homes_Final%20Report.pdf (2012, accessed 21 March 2014).
32. Department of Communities Local Government. *Performance testing of buildings: BD 2535*, London, Communities and Local Government. http://www.bipsolutions.com/docstore/pdf/20548.pdf (2008, accessed 21 March 2014).
33. Dengel A and Swainson M. *Assessment of MVHR systems and air quality in zero carbon homes*, NHBC Foundation, http://www.nhbcfoundation.org/Researchpublications/MVHRsystems.aspx (2013, accessed 21 March 2014).
34. Bone A, Murray V, Myers I, Dengel A and Crump D. Will drivers for home energy efficiency harm occupant health? *Perspect Public Health* 2010; 130: 233–238.
35. Coelho C, Steers M, Lutzler P and Schriver-Mazzuoli L. Indoor air pollution in old people's homes related to some health problems: a survey study. *Indoor Air* 2005; 15: 267–274.
36. Mlecnik E, Schütze T, Jansen SJT, de Vries G, Visscher HJ and van Hal A. End-user experiences in nearly zero-energy houses. *Energy Build* 2012; 49: 471–478.
37. Taylor M and Morgan L. *Ventilation and good indoor air quality in low energy homes: finding proven good practice*, London, Good Homes Alliance. http://www.goodhomes.org.uk/downloads/news/VIAQ%20final%20120220%20-%20PUBLICATION.pdf (2011, accessed 21 March 2014).
38. Bogers R, Jongeneel R, Van Kamp I and Koudijs E. Health and well being in relation to the quality of ventilation systems in newly built dwellings in the Netherlands. *Epidemiology* 2011; 22: S36.
39. Sharpe T and Shearer D. Scenario testing of the energy and environmental performance of the Glasgow House. *Passive and low energy architecture 2013*. Munich, 10–12 September 2013.
40. Raw GJ. *Sick building syndrome: a review of the evidence on causes and solutions*. London: HM Stationery Office, 1992.
41. Howieson S. *Housing and asthma*. Oxford: Taylor Francis Ltd, Routledge, 2005.
42. Carrer P, Fanetti AC, Forastiere F, Holcatova I, Mølhave L, Sundell J, Viegi G and Simoni M. *WP1 final report health effects. EnVIE co-ordination action on indoor air quality and health effects*, http://paginas.fe.up.pt/˜envie/documents/finalreports/Final%20Reports%20Publishable/EnVIE%20WP1%20Final%20Report.pdf (2008, accessed 21 March 2014).
43. Porteous CDA, Sharpe TR, Menon R, Shearer D, Musa H, Baker PH, Sanders C, Strachan PA, Kelly NJ and Markopoulos A. Domestic laundering–environmental audit in Glasgow with emphasis on passive indoor drying and air quality. *Indoor Built Environ*. 2013. 1420326X13508145, first published on October 29, 2013, doi:10.1177/1420326X13508145.
44. Persily AK and Emmerich SJ. Indoor air quality in sustainable, energy efficient buildings. *HVAC&R Res* 2012; 18: 4–20.
45. Levin H. Building ecology: an architect's perspective on healthy buildings. In: *Proceedings of healthy buildings conference '95*. Milan, Italy, 1995, pp.1–2010–15 September 1995.
46. Innovation & Growth Team. *Low carbon construction – final report*, London, HM Government. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31773/10-1266-low-carbon-construction-IGT-final-report.pdf (2010 accessed 21 March 2014).
47. Preiser WFE and Vischer J. *Assessing building performance*. Oxford: Elsevier, 2005.
48. Markus T. *Building performance*. Building Performance Research Unit, School of Architecture, University of Strathclyde. John Wiley & Sons, 1 January 1972.
49. Leaman A and Bordass B. Assessing building performance in use 4: the Probe occupant surveys and their implications. *Build Res Inform* 2001; 29: 129–143.
50. Stevenson F and Hom BR. Developing occupancy feedback from a prototype to improve housing production. *Build Res Inform* 2010; 38: 549–563.
51. Technology Strategy Board. *Building performance evaluation, domestic buildings, guidance for project execution 2011*.
52. Porteous C. Sensing a historic low-CO_2 future. In: Mazzeo N (ed.) *Chemistry, emission control, radioactive pollution and indoor air quality*. Rijeka, Croatia: Intech, 2011.
53. Appleby A. Indoor air quality and ventilation requirements. *Buildings and health, the Rosehaugh guide to the design, construction, use and management of buildings*. London: RIBA Publications Ltd, 1990, pp.167–193.
54. Seppänen OA, Fisk WJ and Mendell MJ. Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air* 1999; 9: 226–252.
55. Erdmann CA, Steiner K and Apte M. *Indoor carbon dioxide concentrations and sick building syndrome symptoms in the BASE study revisited: analyses of the 100 building dataset*. Berkeley: Lawrence Berkeley National Laboratory, 2002, pp.443–448.
56. Batterman S and Peng C. TVOC and CO_2 concentrations as indicators in indoor air quality studies. *Am Ind Hygiene Assoc* 1995; 56: 55–65.
57. Wargocki P. The effects of ventilation in homes on health. *Int J Ventil* 2013; 12: 101–118.
58. Davies I. *Sustainable construction timber – sourcing and specifying local timber*, Edinburg, Arcamedia, Forestry Commission Scotland. http://www.forestry.gov.uk/forestry/INFD-6B2JFB (2009, accessed 21 March 2014).
59. Banfill P, Simpson S, Gillott M and White J. The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery. Energy efficiency first: foundations

of a low-carbon society. In: *Proceedings of ECEEE 2011 summer study on energy efficiency*. Toulon, France, 6–11 June 2011, pp.1401–1412.

60. Persily A. Evaluating building IAQ and ventilation with indoor carbon dioxide. *ASHRAE Trans* 1997; 103: 193–204.
61. BS 5925. *1991 Code of practice for ventilation principles and designing for natural ventilation*. London: British Standard Institution, 1991.
62. CIBSE. *Guide A: environmental design*. 7th ed. London: CIBSE, 2006.
63. Platts-Mills TA, de Weck AL, Aalberse RC, Bessot JC, Bjorksten B, Bischoff E, . . . and Wen T. Dust mite allergens and asthma—a worldwide problem. *J Allergy Clin Immunol* 1989; 83: 416–427.
64. Niven RM, Fletcher AM, Pickering AC, Custovic A, Sivour JB, Preeceb AR and Francis HC. Attempting to control mite allergens with mechanical ventilation and dehumidification in British houses. *J Allergy Clin Immunol* 1999; 103: 756–762.
65. Arlian LG and Veselica MM. Re-evaluation of the humidity requirements of the house dust-mites Dermatatophagoides farinae. *J Med Entomol* 1981; 18: 351.
66. Arlian LG. Water balance and humidity requirements of the house dust-mites. *Exp Appl Acarol* 1992; 16: 15–35.
67. Cunningham MJ. Direct measurements of temperature and humidity in dust mite microhabitats. *Clin Exp Allergy* 1998; 28: 1104–1102.
68. De Boer R and Kuller K. Mattresses as a winter refuge for house-dust mite populations. *Allergy* 1997; 52: 290–305.
69. Crowther D, Wilkinson T, Biddulph P, Oreszczyn T, Pretlove S and Ridley I. A simple model for predicting the effect of hygrothermal conditions on populations of house dust mite Dermatophagoides pteronyssinus (Acari: Pyroglyphidae). *Exp Appl Acarol* 2006; 39: 127–148.
70. CIBSE. *Guide A: environmental design*. 7th ed. London: CIBSE, 2006.
71. Arundel AV, Sterling EM, Biggin JH and Sterling TD. Indirect Health effects of relative humidity in indoor environments. *Environ Health Perspect* 1986; 65: 351–361.
72. Niven R, Fletcher A, Pickering A, Custovic A, Sivour J, Preece A, Oldham L and Francis H. Attempting to control mite allergens with mechanical ventilation and dehumidification in British houses. *J Allergy Clin Immunol* 1999; 103: 756–762.
73. Kondratenko I, Sharpe T and Porteous C. Why are new 'direct gain' dwellings underperforming in Scotland. In: *EuroSun 2004: integration of solar technologies in building design conference*. Freiburg, Germany, 20–23 June 2004.
74. Porteous CDA, Sharpe TR, Menon R, Shearer D, Musa H, Baker PH, Sander C, Strachan PA, Kelly NJ and Markopoulos A. Domestic laundering–environmental audit in Glasgow with emphasis on passive indoor drying and air quality. *Indoor Built Environ* 2013. DOI: 1420326X13508145.
75. Sharpe T and Shearer D. Scenario testing of the energy and environmental performance of the 'Glasgow House'. In: *PLEA2013 – 29th conference, sustainable architecture for a renewable future*. Munich, Germany, 10–12 September 2013. http://mediatum.ub.tum.de/node?id = 1170104 (2013, accessed 11 April 2014).
76. Stevenson F, Carmona-Andreu I and Hancock M. The usability of control interfaces in low-carbon housing. *Arch Sci Rev* 2013; 56: 70–82.
77. Peffer T, Pritoni M, Meier A, Aragon C and Perry D. How people use thermostats in homes: a review. *Build Environ* 2011; 46: 2529–2541.
78. Porteous CDA, Sharpe TR, Menon R, Shearer D, Musa H, Baker PH, Sander C, Strachan PA, Kelly NJ and Markopoulos A. Energy and environmental appraisal of domestic laundering appliances. *Build Res Inform* 2012; 40: 679–699.
79. Sharpe T and Shearer D. Learning from our experiments: monitored environmental performance of low energy buildings in Scotland. In: *CISBAT 2013 – clean technology for smart cities and buildings*. Lausanne, Switzerland, 4–6 September 2013.
80. Ucci M, Biddulph P, Oreszczyn T, Crowther D, Wilkinson T, Pretlove SE, Hart B and Ridley I. Application of a transient hygrothermal population model for house dust mites in beds: assessment of control strategies in UK buildings. *J Build Perform Simulat* 2011; 4: 285–300.
81. Building Standard (Scotland) Regulations. *Domestic technical handbook*. *Part 3 environment Scottish Government*, http://www.scotland.gov.uk/Resource/Doc/217736/0102070.pdf (2010, accessed 21 March 2014).