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Scottish Passive House: Insights into Environmental Conditions in Monitored Passive Houses

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Abstract: Climate change and sustainability legislation in recent years has led to significant changes in construction approaches in the UK housing sector. This has resulted in the adoption of new building typologies, including the German Passivhaus (Passive House) standard. This standard aims to improve occupant comfort and energy efficiency, potentially changing the ways in which homes operate and how occupants interact with them. With increasing construction of low energy dwellings, there is an emerging gap in knowledge in relation to occupant health and wellbeing, thermal comfort, and indoor air quality (IAQ). Using data collected from a two year Building Performance Evaluation (BPE) study funded by Innovate UK, the environmental data (temperature, relative humidity and carbon dioxide concentrations) from five Certified Passive House homes in Scotland was compared. The results demonstrate problems with overheating with peak temperatures exceeding 30 °C. Imbalanced mechanical ventilation with heat recovery (MVHR) systems were identified in 80% of the dwellings and inadequate IAQ was found due to poor ventilation. Only one of the Passive Houses studied exhibited thermal conditions and IAQ which were, on the whole within Passive House parameters. This paper outlines the insights and the main issues of Scottish Passive House in the broader context of sustainability.

Keywords: passive house; building performance evaluation; thermal comfort; overheating; indoor air quality; ventilation

1. Introduction

As a response to the Bruntland Report in 1987 [1] and the Kyoto Protocol in 1997 [2], there has been increasing legislation for sustainable development, that attempts to minimise the effects of climate change and reduce greenhouse gas emissions [3–5] from a range of sectors. This has impacted on the UK housing sector, which is responsible for over 25% of UK greenhouse gas emissions [6] (p. 6). In 2006, the Zero Carbon agenda proposed by the UK Government [7] and the publication of the Stern Review [8], both served as a catalyst for change in the construction industry [9] (p. 32).

The shift to near Zero Carbon Buildings in Scotland outlined by the Sullivan Report [10], and the rapid transition to "Zero Carbon Homes" (ZCH) by 2016 previously proposed by the UK Government in 2006 [7] (p. 168) led to increased adoption of energy efficient construction legislation and standards for UK housing. This included revisions to the Building (Scotland) Regulations: Section 6 [11] (English Building Regulations: Part L1A [12]) and the development of the Code for Sustainable Homes with its hierarchical levels of environmental performance [13]. The impact of these changes resulted in a "wave of pioneering innovation" in the construction industry [9] (p. 31) with common strategies focusing on reduction of heat loss from the thermal envelope through an increase in insulation levels and improved airtightness. The latter has led to an increase in the installation of domestic Mechanical Ventilation with Heat Recovery (MVHR) systems [14] (p. 4).

In this context, there has been increasing use of the German "Passivhaus" standard [15] (termed "Passive House" in the UK). This is a rigorous standard for thermal comfort and energy efficiency, developed in Germany in the late 1980s, a key strategy of which is a high level of airtightness and use of MVHR [16]. There were 250 completed buildings in the UK by the end of 2013 with nine sites in Scotland (16 homes) [17]. The principle behind Passive House is for the "optimisation of all energy components: building elements of the opaque building shell, windows and doors, ventilation, heating, hot water, auxiliary electricity and also household electricity" [18] (p. 1). The Passive House primary energy consumption is $\leqslant$120 kWh/(m^{2}a) [18] (p. 27), heating demand is $\leqslant$15 kWh/(m^{2}a) with a heat load of $\leqslant$10 W/m^2 [19] (p. 36).

Due to the rapid change to UK wide building typologies and regulations, the design and supply chain has also needed to change quickly and there is growing evidence that energy reduction strategies aimed at the housing sector have not always achieved the intended results. The performance gap between "as designed" and "as built" is increasingly well evidenced [20]. Recent research has identified unintended consequences of energy efficient dwellings for installed technology, building fabric and ultimately occupant health and wellbeing [21].

In 2010, Innovate UK (IUK) instigated a four-year, £8 m programme of Building Performance Evaluation (BPE) studies across the UK. BPE is vital in assessing the actual performance of buildings and provides monitoring a building post construction, generally once the building has been occupied. Monitoring is undertaken for at least one year to determine how the building is performing, being used, and assess whether the occupants are comfortable within their homes and the heating is affordable. This includes the collection of quantitative data for energy consumption and environmental performance, and qualitative data for patterns of occupancy, comfort and satisfaction. This data is analysed and information disseminated to clients and occupants. This process can begin to identify patterns to determine how buildings are affecting the occupants, but also the occupant perception, behaviour and modes of habitation may affect the building's performance [22]. The three main perspectives of Building Evaluation as outlined by Leaman *et al.* [23] (pp. 564–565) are: "Occupants, and how well their needs are met; environmental performance, normally energy and water efficiency; whether the building makes economic sense, such as value for money or return on investment".

Due to the relatively recent adoption of the Passive House standard in the UK, limited BPE research has been reported for the UK market. Sameni *et al.* [24] presented a BPE study of English flats with a focus on overheating. Evidence has been presented based on modelling in building simulation programmes testing different occupant behavior scenarios [25–27]. To date research with a focus on Passive House has not considered the impact of building performance on occupant health and well-being.

1.1. Thermal Comfort

Thermal comfort is an important factor for occupants' health and wellbeing; this is influenced by their thermal balance, which can vary according to personal needs and cultural expectations [28]. The six basic factors of thermal comfort are Environmental parameters: air temperature, mean radiant temperature, air velocity, air humidity; and Personal parameters: clothing and physical activity [29].

A current limitation for thermal comfort research in dwellings is that there are no defined standards for thermal comfort in domestic buildings with the existing parameters having been extrapolated from research assessing comfort conditions in offices. According to Peacock *et al.* [30] (p. 3286) this is a problem in terms of our psychological responses to thermal conditions in that: "Our mental state at home and the range of adaptive behaviours possible is distinct to that in the office and, therefore, perceptions of comfort are likely to be quite different". In Passive House design, the optimum operating temperature is 20 °C, and the building is considered to have overheated if the indoor temperature exceeds 25 °C for more than 10% of the year, although a 4% limit is preferable [18] (p. 79).

Comfort temperature, type of building, solar gains, incidental gains, ventilation levels and occupants can contribute to overheating [31]. There has been increasing interest in overheating in airtight dwellings in the UK [32–35], focusing on two main considerations current summer overheating and future overheating in a warming climate. The future impacts of anthropogenic climate change and urban heat islands on overheating in energy efficient and airtight buildings has been identified as a potential problem [30,32–35] particularly in airtight, lightweight buildings with diurnal temperature fluctuations, requiring adaptation from occupants [30,32,36]. McLeod *et al.* [27] used dynamic thermal modelling to identify that Passive Houses are also at risk of future overheating and these risks could be mitigated through the inclusion of solar shading and adjusting glazing ratios at the design stage. There also needs to be consideration of different climatic conditions and regional weather conditions in modelling to assess overheating risk [37].

Sameni *et al.* [24] studied Passive House flats occupied by social housing tenants and found that 72% of these properties failed to meet the Passive House thermal comfort criteria, the occupants contributed to the overheating which was a concern due to occupant vulnerability. A study of German, Austrian and Swiss Passive Houses by Fiest *et al.* [38] stated that 88% of occupants were satisfied with their summer indoor climate suggested that mean indoor summer temperature range (from about 21 °C to about 27 °C) and reflected occupant conduct and individual preferences, with higher indoor temperatures being repeated in summer and winter months in the same homes. Zhao and Carter's [39] study of perceived comfort in Passive Houses indicated that the adaptive processes to thermal comfort in Passive Houses were impacted by the social aspects of occupants and their evaluation of their homes. In over half of the respondents, it was believed that their comfort level was contributed to by an increased level of "perceived knowledge".

Where overheating has been identified as a current risk in UK homes, the focus has been on the summer months and predominantly in dwellings located in the midlands or south of England [24,40]. However, research by the Mackintosh Environmental Architecture Research Unit (MEARU) has shown that overheating in Scottish homes is occurring throughout the year [41].

1.2. Ventilation

Improved energy standards have increased the requirements for airtightness in dwellings; in Scotland planned ventilation is a legislative requirement however in highly airtight homes (<5 $m^3/(h \cdot m^2)$ at 50 Pa) additional ventilation provision must be provided [11] (p. 191). A commonly used means of meeting this requirement is installation of MVHR; a whole house background ventilation system that uses warmed, extracted air to pre-heat fresh incoming air through a heat exchanger; helping to maintain indoor air quality and comfort levels while keeping energy consumption and running costs low. Its ability to provide energy efficient background ventilation means that it is a compulsory requirement of the Passive House standard [15]. However, MVHR is a relatively new technology for domestic applications and there have consequently been issues with design, installation, commissioning and occupant use that have led to these systems not operating as intended [42]. This can have impacts on indoor air quality, moisture loads and temperature, consequently impacting the building fabric, performance and occupant health and wellbeing [14]. To maximise system efficiency, the supply and extract volumes should be balanced, but at the least they should be within a 10% range. If too high an air change rate is supplied in a dwelling during winter the result could be an internal winter Relative Humidity (RH) of <30%, which, for occupant comfort, is to be avoided [19].

1.3. Indoor Air Quality

Indoor air quality (IAQ) refers to the air quality in buildings particularly in relation to occupants and their health and wellbeing. This is impacted by occupant activities, moisture, temperature, ventilation, building materials, finishes, fittings, and cleaning products [43]. Good air quality in homes requires a fine balance of temperature, RH, Carbon Dioxide (CO_2) and Volatile Organic Compounds (VOCs), in this paper it refers to temperature, RH and CO_2.

The optimal parameters of RH for health are defined by Arundel *et al.* as 40%–60% humidity; beyond this range, RH can impact on respiratory infections and allergies, by reducing the infectivity of airborne-transmitted infectious bacteria and viruses [44]. In Passive House design, the RH optimal comfort range is 35%–55%, for the avoidance of "mould and the fast growth of HDM" [19] (p. 6). The AH comfort range defined by the Passive House standard is 6.0–9.5 g/m^3 with saturation being 17.3 g/m^3 of water vapour at 20 °C [19] (p. 7). Through the supply of dry air and extraction of humid air by MVHR, the AH is reduced below saturation, therefore the concentration of the water vapour corresponds to the RH [19] (p. 8). Domestic activities such as washing and drying of clothing, if not adequately ventilated can contribute to an increase in internal moisture [45].

Internal concentrations of CO_2 >1000 ppm can be indicative of poor rates of ventilation, this corresponds with ventilation rates of 8 L/s per person required to maintain CO_2 concentrations below this threshold [46]. A review paper identified the minimum household ventilation rates of "0.4 ac/h or below 900 ppm CO_2" to mitigate health risks [47]. High levels of CO_2 can make a room feel stuffy and impact on occupants quality of sleep, levels of concentration, and respiration [48]. CO_2 is generally recognised to keep "bad company" when air changes are too low. It can be used as an outline indicator to human occupancy and increase in levels of VOCs and other contaminants that impact on IAQ [49]. While it does not provide accurate readings on specific VOCs and has been criticised by some [50] (p. 33), it can provide low-cost indication for IAQ.

With the increase in building airtightness, reductions in infiltration (and increases in temperature) the levels of indoor pollutants may rise. Many of the construction materials, paints, finishing's and fittings found in homes contain VOCs and formaldehyde, which may be off-gassed affecting IAQ [51]. Whilst there is limited data to substantiate this, evidence indicates pollutants are occurring indoors, which have potential negative health consequences for the occupants [52]. The Passive House standard recognises the health implications of this, however, it does not mandate low emission building materials to reduce the chemical burden of the dwelling [19] (p. 5).

Many VOCs are toxic to humans, and known carcinogens, which has led to regulation of their indoor concentrations [52]. However, different chemical interactions between indoor air, materials and the range of substances they off-gas [52,53] affects the required ventilation rate. Without adequate ventilation negative impacts to the building fabric, include mould growth, toxin build-up: e.g., fatigue, respiratory problems; the extent of health impacts within the home are not yet fully understood [43], but there is increasing evidence of the effects of poor ventilation on health in dwellings [14]. Feist *et al.* [38] recommend the use of non- or low-polluting interior materials for use in Passive Houses where possible. Research into unintended consequences and the avoidance of these suggests that overheating particularly impacts IAQ [34] and that there is potential risk of increased emissions of formaldehyde and VOCs as a result of increased temperature or RH [54].

2. Project Information

The case studies in this paper use data collected from IUK funded studies (Table 1), from five Certified Passive House homes in rural Scotland to provide performance insights in a Scottish context. Site A consists of four semi-detached homes of two house types near Lockerbie in South West Scotland. Site B consists of one end of terrace home overlooking the Clyde estuary on the outskirts of Dunoon in West Scotland. All of the homes are within the affordable social housing sector provided by Registered Social Landlords (RSLs). This sample represents 30% of Scotland's Certified Passive House' dwellings [15].

Table 1. Dwelling characteristics.

Location	Site A				Site B
Dwelling	DA1	DA2	DB1	DB2	TB1
Built form	Semi-detached	Semi-detached	Semi-detached	Semi-detached	End Terrace
Floor area m^2	87	87	103	103	104
Bedrooms	2	2	3	3	2
Occupants	1A 1C	1A 1C	3A 2C	2A 2C	1A 1C
Construction	Closed panel timber system	Closed panel timber system	Closed panel timber system	Closed panel timber system	Closed panel timber system

3. Methodology

The data used in this paper represents one calendar year, 2013. Solar powered Wireless Sensor Technology (WIST) sensors with battery back-up were used to monitor internal environmental conditions, temperature (°C), RH and CO_2 concentration in the living rooms, kitchens and bedrooms in each dwelling. This equipment was used in conjunction with solar powered door/window contact sensors to monitor window opening patterns (WO) these were fitted to the principal windows in each monitored room. Occupant interviews were also conducted during the monitoring period. In addition to the data collected, other tests which inform this study were: Airtightness testing, a thermographic survey and air flow rate measurements at the supply and extract terminals forming part of the MVHR system.

This data was transferred to a wireless data capture system, with the capability to transmit data over General Packet Radio Service (GPRS) networks to a central off site server. This enabled greater flexibility of monitoring in a domestic context decreasing the need for an adjacent electrical socket outlet at each sensor, which reduced the risk of equipment being turned off. However, the remote nature of Site A resulted in some data loss due to transmittance problems.

Qualitative data from occupants includes: semi-structured interviews, survey and occupant diaries, and informs the occupancy behaviour profiling.

Due to the limited number of completed and occupied Passive Houses constructed in Scotland at the time of this study (16 homes [17]), there is insufficient statistical evidence for clear recommendations to be made. However, of the five houses studied, four of these were at Site A, with another four unmonitored houses of the same house types which experienced similar problems. Based on this data, issues have been identified which warrant further investigation. These issues are not limited to Passive House, and other investigations by this team into low energy buildings has demonstrated similar issues.

4. Results

The occupancy behaviour profiling (Table 2) informs the quantitative data collected to explain patterns of use which may influence the data.

4.1. Thermal Comfort

The internal temperature data collected from the five Passive House dwellings was analysed to compare the mean internal temperature against the Passive House design temperature of 20 °C and to determine the extent of time the internal temperature exceeded 25 °C. The data in Figure 1 indicates annual mean dwelling temperatures ranged between 18 °C–24.8 °C. However, the mean of both the minimum and maximum internal temperatures demonstrate swings of 10 °C–15 °C in 80% of the dwellings with mean maximum temperatures exceeding the Passive House design overheating temperature of 25 °C. Surveys of occupants of all homes indicated that rooms overheated, particularly the Site A bedrooms.

Table 2. Occupancy behaviour and building usage profiling.

Location	**Site A**								**Site B**	
Dwelling	**DA1**		**DA2**		**DB1**		**DB2**		**TB1**	
General background										
Occupants	1A	1C	1A	1C	3A	2C	2A	2C	1A	1C
Age (years)	16–25	0–2	56–65	6–15	(2) 36–45 (1) 16–25	(2) 6–15	(1) 16–25 (1) 36–45	(2) 6–15	36–45	6–15
Gender	F	F	F	M	2M/F	M/F	F/F	F	F	F
Smoker	No	No	No	No	No	No	No	No	No	No
Heating (space & water)										
Heating on	No info given		October–March: daytime		No info given		No info given		No info given	
Thermostat temp	Approx. 20 °C		Approx. 20 °C		Approx. 20 °C		Approx. 20 °C		No info given	
Space heating method in priority order	1. MVHR		1. MVHR 2. Wood burner		1. MVHR 2. Wood burner		1. MVHR 2. Wood burner		1. Airheat pump 2. MVHR	
Room adjustment	No		No		No		No		N/A	
Rooms too warm	Both bedrooms		Bedroom 1		-		Bedrooms 1 & 2—summer		-	
Rooms too cold	Utility room		-		Utility room		Utility room		Consistent room temps hard when outside temp low.	
Heating control	Increase when drying laundry		-		-		-		N/A	
Water heating method in priority order	1. Immerser 2. Solar thermal		1. Wood burner 2. Solar thermal		1. Wood burner/Solar thermal 2. Immerser		1. Wood burner 2. Solar thermal 3. Immerser		1. Solar thermal	

Table 2. *Cont.*

Location	Site A				Site B
Dwelling	**DA1**	**DA2**	**DB1**	**DB2**	**TB1**
			Ventilation /IAQ		
Air quality	-	Air too dry in summer	-	-	-
Use MVHR	Yes	Not in summer	Yes	Yes	Yes
MVHR effective at steam & odour removal	Yes	Yes	Yes	Yes	No
Window opening	• Room too warm • Bedrooms at night • Drying laundry	• Room too warm • Summer • Stuffy upstairs • Bedrooms & bathroom at night	• Bedrooms at night • Room too warm • Smells/moisture	• Room too warm • Bedrooms -Summer 24/7	• Room too warm
Door opening	• Bedrooms at night	• Bedrooms & downstairs toilet at night	-	-	• Open living room doors when room too hot.
Condensation	No	No	No	No	No
Mould	No	No	No	No	No

Table 2. *Cont.*

Location	Site A				Site B
Dwelling	**DA1**	**DA2**	**DB1**	**DB2**	**TB1**
			Handover		
• Building introduction	• Shown around pre-completion Manuals hard to understand	• Shown all systems prior to moving in. Needed clearer manuals	• Welcome pack and building workers explained system	• Shown all systems prior to moving in.	• Shown around before moving in. Manuals were complicated.
Building use	• Does not fully understand all systems. • Wood stove didn't work initially.	• Know how to use building efficiently once settled in.	• Did not know how to operate building initially. Systems did not work well but now fixed.	• Understand systems well. Some systems needed fixing.	• Took time to learn to operate heating and air systems. Problems with most systems, most now solved.
Maintenance/Support	-	• Problems quickly resolved.	• Help service quick to respond	• Manuals arrived after moving in. Support very helpful	• System problems were not dealt with well.

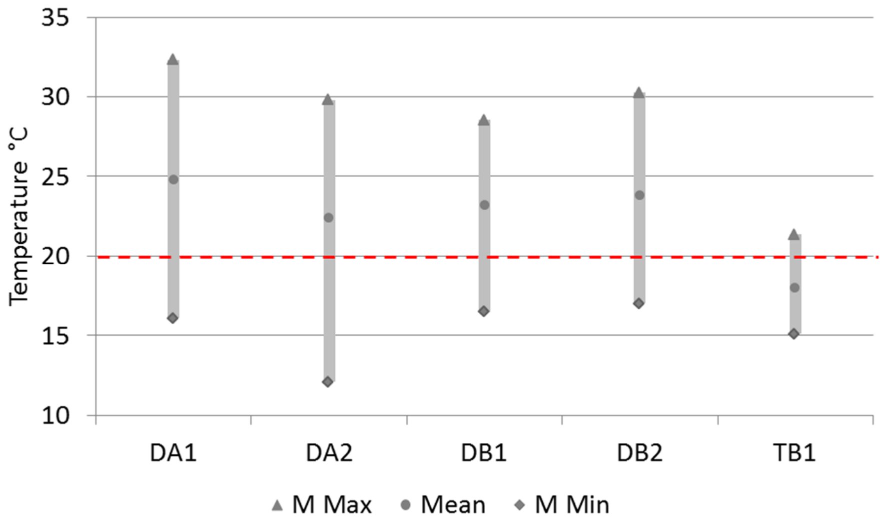

Figure 1. Annual mean of minimum, maximum and mean temperatures in monitored Passive House dwellings for 2013. The dashed line indicates Passive House design temperature.

The annual mean temperatures of monitored rooms in Figure 2 reveals two distinct patterns in terms of potential occupant thermal comfort; this appears to be site based. Concurrent with the occupant feedback, the mean temperatures in all rooms in the four dwellings in Site A exceed 20 °C, with highest peak conditions in the upper floor bedrooms, the lowest temperatures occurred in the ground floor living rooms and kitchens. In contrast, mean temperatures in the dwelling in Site B (TB1) indicate the average room temperatures were relatively stable and were between 17–20 °C, the kitchen displayed the warmest mean temperature of 24 °C and the two bedrooms and living room were the coolest rooms.

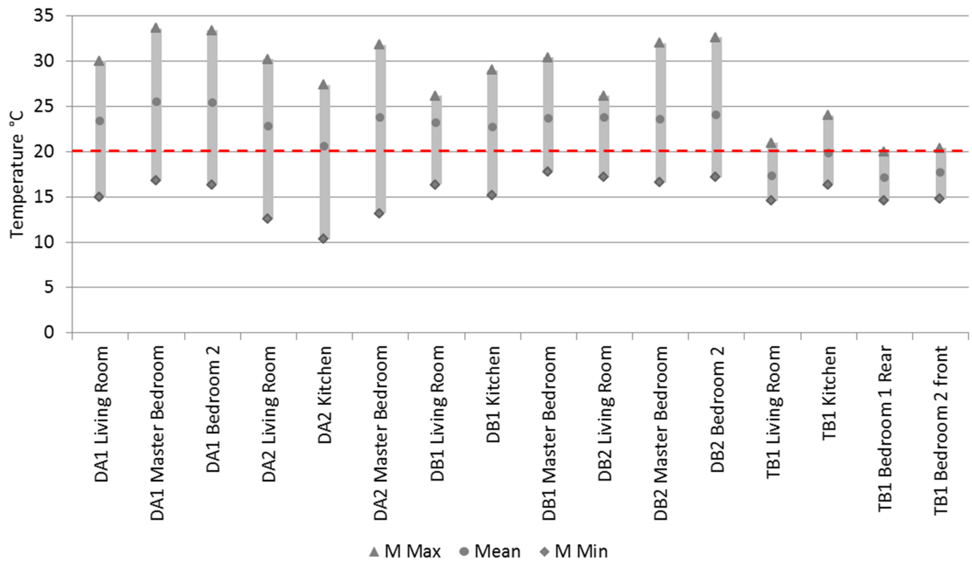

Figure 2. Dwelling by room: annual minimum, maximum and mean temperatures by monitored rooms for 2013. The red line indicates Passive House design temperature.

Both DA2 and TB1 experienced times when the internal temperature dropped below 15°C. In DA2 this was mainly associated with prolonged window opening, however TB1 complained that they were unable to heat the property during the winter to a comfortable temperature. This was further exacerbated in this house by the dwelling orientation and lack of solar gain. The low temperatures experienced in these homes had the potential to reduce the internal surface temperatures below the Passive House 17°C threshold and cause downdraughts and discomfort.

The Passive House design criteria indicate internal temperatures should not exceed 25 °C for more than 10% of the year, with 4% being preferable [18] (p. 79). The temperature profiles are plotted for each dwelling in Figure 3 to illustrate the percentage of time over a one year period that the temperatures were in excess of 25 °C. The chart additionally displays annual percentage of window opening occurrences (diamonds) and indoor CO_2 concentrations (triangles)—these are both discussed later.

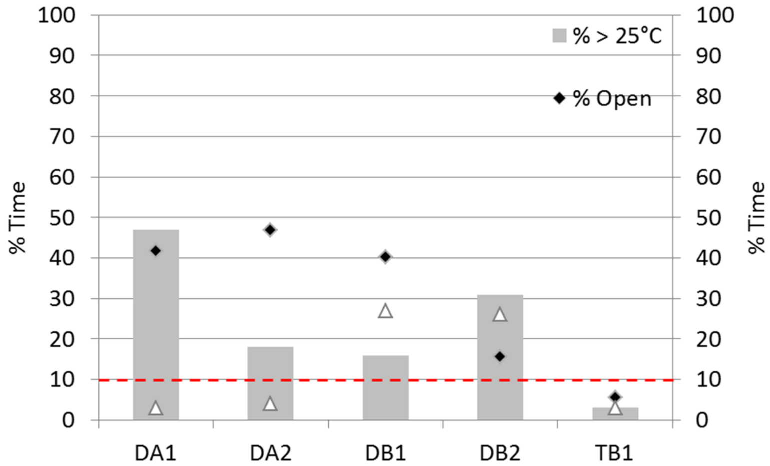

Figure 3. All dwellings: annual percentage of time internal air temperature >25 °C, CO_2 concentrations >1000 ppm and principle windows opened. The dashed line indicates the maximum percentage of time overheating criteria for Passive House.

The data indicates dwellings in Site A overheated 16% (DB1), 18% (DA2), 31% (DB2), and 47% (DA1) of the year, while the mean overheating for dwelling TB1 is 3% of the year, suggesting TB1 to have performed well in terms of thermal comfort. All of the occupants indicated that they opened windows when rooms became too warm, particularly in bedrooms, which were open at night in all Site A properties. This suggests that overheating may have been greater if night-time window opening had not occurred. However, the occupant in TB1 had complained of thermal discomfort during winter citing uneven distribution of heat from the dwellings three heat sources as well as citing the associated expense causing the heating to be rarely operated. The heat sources were located in the two bathrooms (electric towel radiators—not intended as the main heat source) and one in the ground floor hall (air source heat pump—which struggled to operate effectively during cold winters). Due to the ventilation extract points being positioned in the bathrooms, the warm air from radiators was less able to circulate through the dwelling and had greater potential for being extracted. While warm air from the heat source in the hall was pulled towards the extract terminal in the adjacent kitchen; supporting the pattern identified through the data analysis for a warmer kitchen and cooler bedrooms. However, during winter, a significant amount of the heat in the extract air would have been recovered in the heat exchange process and delivered into the living spaces.

In dwelling DA1 the occupant had found their bedrooms to be too hot during the summer months and as an adaptive measure had disabled the solar thermal system due to heat gains radiating from uninsulated pipework (this pipework was later insulated). The MVHR units installed in dwellings DA1 and DA2 are not fitted with heat exchanger bypass for times when the external temperature is warmer, but automatically switch to supply only mode—this could affect the temperature variation between the two dwellings.

The monthly temperature data examined by room (Figures 4–8) illustrates all rooms in each house to have experienced peak temperatures during July, coinciding with the month of highest external temperature in that year. The monthly data displays the maximum, minimum and mean temperatures recorded. The maximum temperature in each month indicates that high internal temperatures occur throughout the year, irrespective of external temperature. This indicates that high temperatures are reached in each of these dwellings throughout the year and the rooms with elevated temperatures are independent of orientation. This suggests the homes were heated actively (by occupants) or passively (through incidental or solar gain) to temperatures that exceed the thermal comfort thresholds. These dwellings are thermally lightweight and as such are considered to be subject to a variance between maximum and minimum temperatures, internal temperatures frequently fell below 15 °C in three of dwellings, DA1, DA2 and DB1, which was linked to regular window opening occurrences.

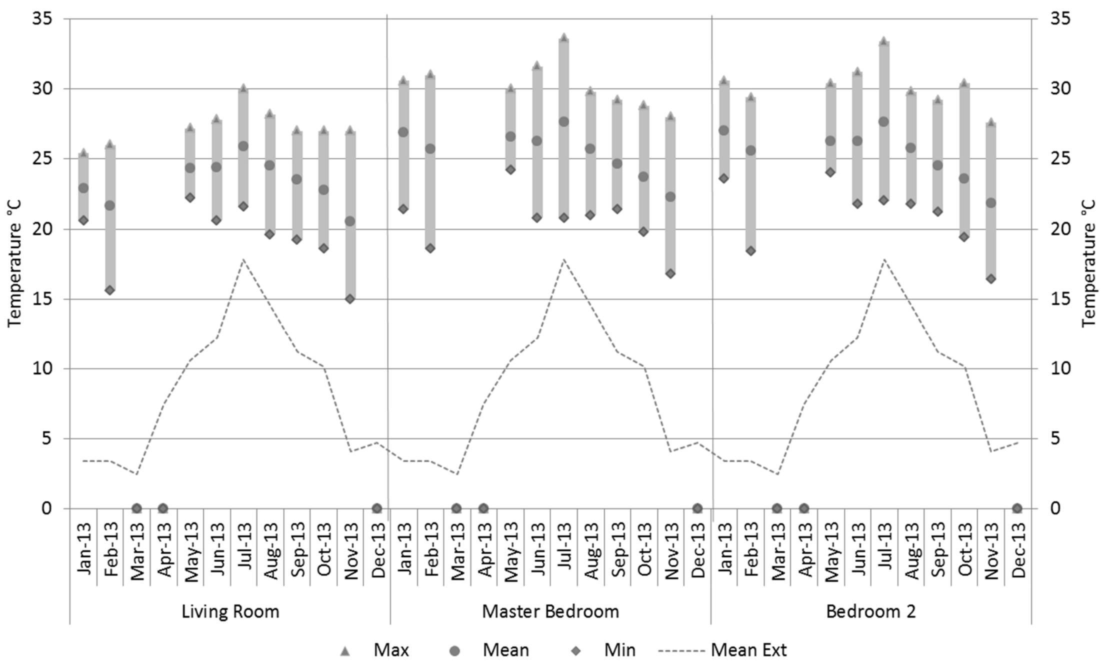

Figure 4. DA1 monthly minimum, maximum and mean temperatures by monitored room for 2013.

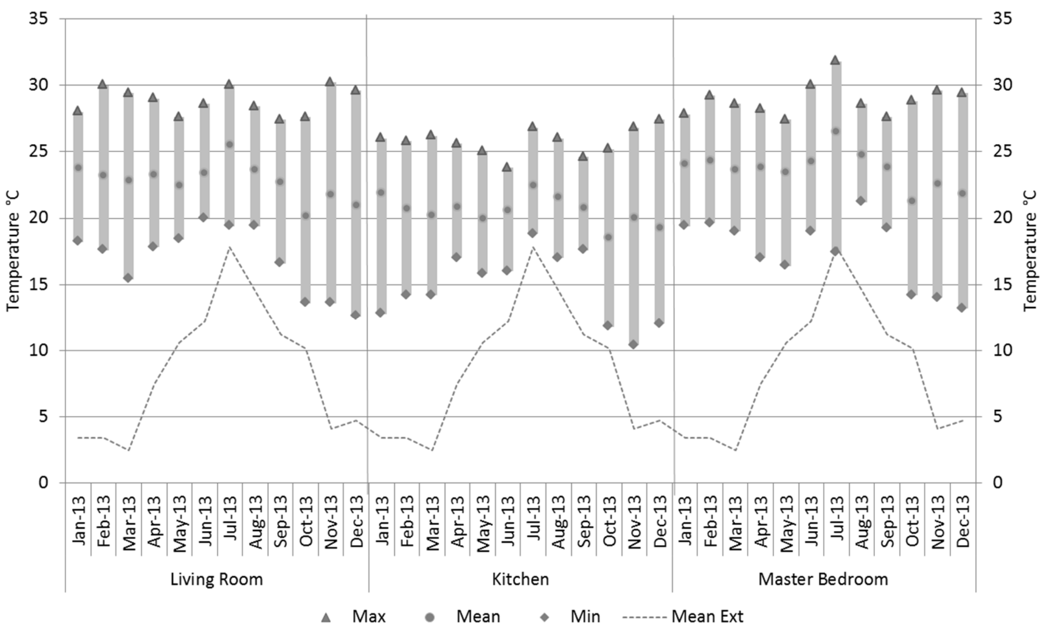

Figure 5. DA2 monthly minimum, maximum and mean temperatures by monitored room for 2013.

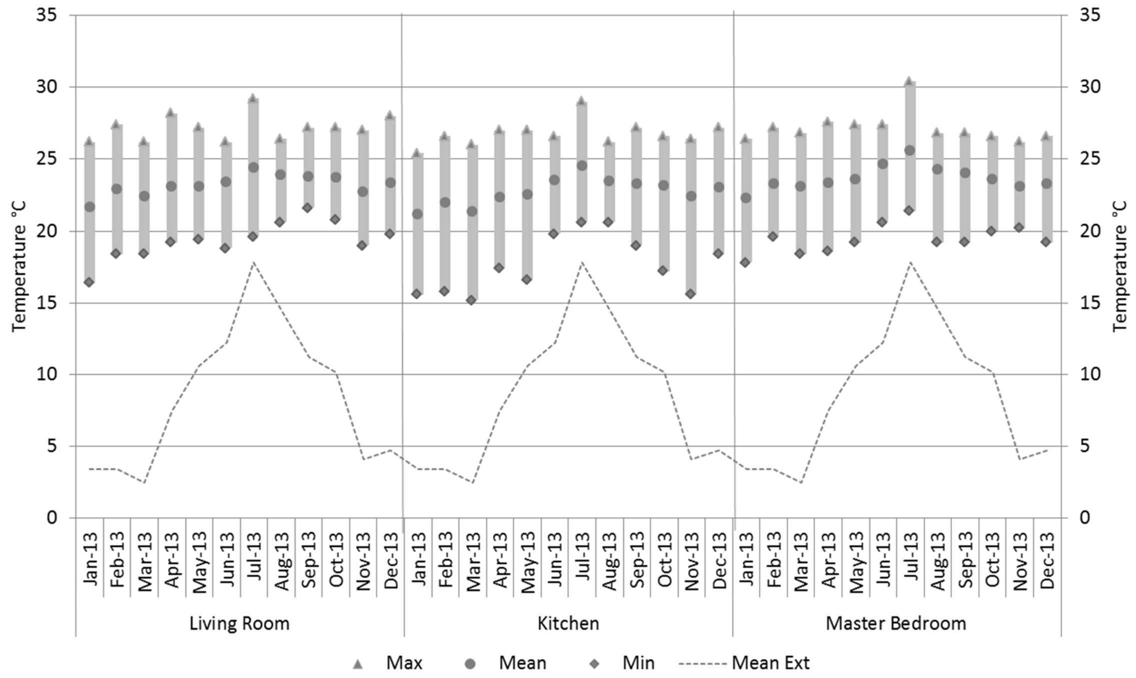

Figure 6. DB1 monthly minimum, maximum and mean temperatures by monitored room for 2013.

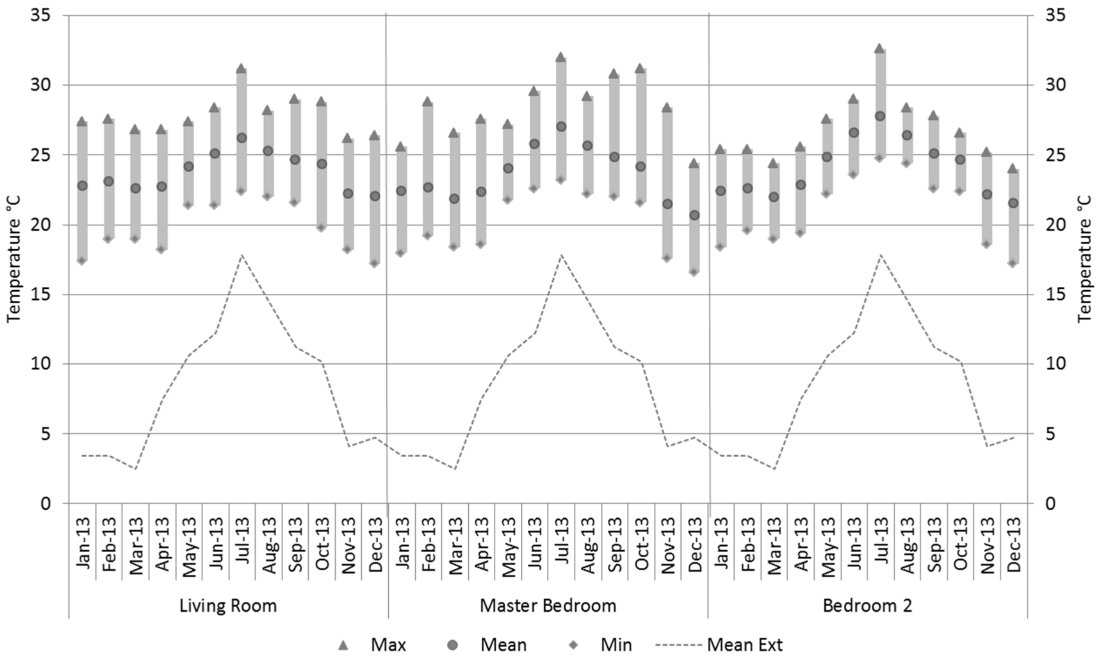

Figure 7. DB2 monthly minimum, maximum and mean temperatures by monitored room for 2013.

According to the Passive House criteria, dwelling TB1 (Site B) was not considered to have overheated. The occurrences of times when peak temperature exceeded the 25 °C threshold were largely during the summer months of June, July and August. The kitchen was close to this threshold temperature through the year. Beyond the summer period, internal air temperature dropped to 15 °C, which gives potential for occupant discomfort, particularly in a dwelling where the heat sources were not operated due to cost. Notwithstanding, the east-west orientation (west façade partially shaded by adjacent elevated terrain) may be a contributing factor for limited solar gain and low internal space temperatures.

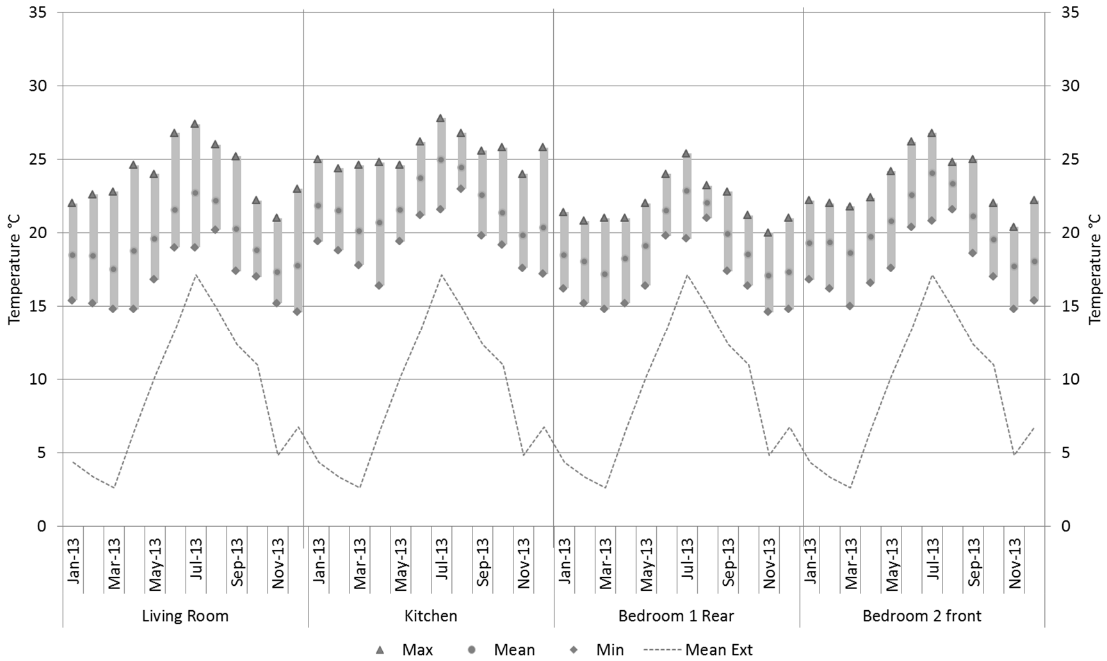

Figure 8. TB1 monthly minimum, maximum and mean temperatures by monitored room for 2013.

4.2. Ventilation

Air flow rates at the mechanical ventilation grille terminals (supply and extract) were measured in each dwelling using a hooded anemometer. The results (Table 3) confirmed that the air supply and extract delivered to the internal spaces from the MVHR unit was balanced in one dwelling (TB1) and unbalanced in the remaining dwellings with a variance greater than the permissible 10% accepted by Passive House in dwellings DA2, DB1 and DB2. Generally, the MVHR units in Site A were imbalanced, which served to positively pressurise these homes, while the dwelling in Site B was found to be negatively pressurised. Both of these conditions could negatively affect the heat loss and the building fabric by drawing cold air through the fabric or forcing warm moist air out of the building, through infiltration pathways. Furthermore, the imbalance could negatively affect the heat exchange efficiency and require more heat input from the post heater (if available) subsequently requiring more energy to meet the space heating demand.

MVHR units in a Passive House are sized based on proposed treated floor area, occupancy levels and an overall air change rate of 0.3 ac/h. Passive House also state a fresh air requirement of 30 m^3/h per person (equivalent to 8.33 L/s/p) is to be provided for adequate indoor air quality conditions. The air flow rates in dwellings DA1 and DA2 (identical in dwelling size and design) in theory should be equal, the measured air flow rates revealed DA1 to receive 29% more supply air in normal mode and 40% more in boost mode than dwelling DA2. However, the supply air flow rate to individual rooms (Table 3 and Figure 9) indicated that in normal operation the supply rate to all rooms to be inadequate for more than one person, except for living room in DB1 and DB2 with supply air for two persons. If boost mode was utilised, then only dwelling DA1 would have sufficient air supply for two persons in all three supply rooms. In boost mode the extract rooms in DA1 were found to provide flow rates marginally above the Passive House extract air requirements of 60 m^3/h (kitchen), 40 m^3/h (bathroom) and 20 m^3/h (WC). The correct extract air volume was provided in DB1 and DB2 but was found to be poorly distributed in the extract rooms with the greatest extract air being from the bathroom instead of the kitchen. This means there is potential for smells from the kitchen to be drawn to other extract points in the dwelling. The extract requirement in DA2 and TB1 was not met and the occupants in TB1 reported the lingering of kitchen smells.

Table 3. Clean filter flow rates for normal and boosted air volume flow rates of MVHR systems in the Passive Houses.

Dwelling	Normal Fan Speed				Boost Fan Speed			
	Supply		Extract		Supply		Extract	
Room	(L/s)	(m^3/h)	(L/s)	(m^3/h)	(L/s)	(m^3/h)	(L/s)	(m^3/h)
DA1	39.89	143.60	36.72	132.19	56.97	205.09	44.91	161.68
Living Room	12.25	44.10	-	-	20.49	73.76	-	-
Bedroom M (s)	15.06	54.22	-	-	20.07	72.25	-	-
Bedroom 2 (n)	12.58	45.29	-	-	16.41	59.08	-	-
Kitchen	-	-	14.06	50.62	-	-	17.27	62.17
Utility	-	-	5.07	18.25	-	-	5.93	21.35
WC	-	-	5.68	20.45	-	-	7.62	27.43
Bathroom	-	-	11.91	42.88	-	-	14.12	50.83
DA2	28.30	101.88	25.10	90.36	33.46	120.46	33.42	120.31
Living Room	9.06	32.62	-	-	10.51	37.84	-	-
Bedroom M (s)	9.34	33.62	-	-	11.37	40.93	-	-
Bedroom 2 (n)	9.90	35.64	-	-	11.58	41.69	-	-
Kitchen	-	-	4.07	14.65	-	-	6.07	21.85
Utility	-	-	7.97	28.69	-	-	9.95	35.82
WC	-	-	5.54	19.94	-	-	7.44	26.78
Bathroom	-	-	7.52	27.07	-	-	9.96	35.86
DB1	42.17	151.81	36.99	133.16	50.60	182.16	44.77	161.17
Living Room 1	7.69	27.68	-	-	9.01	32.44	-	-
Living Room 2	11.42	41.11	-	-	14.38	51.77	-	-
Bedroom M (sw)	6.61	23.80	-	-	7.94	28.58	-	-
Bedroom 2 (se)	6.07	21.85	-	-	7.24	26.06	-	-
Bedroom 3 (n)	10.38	37.37	-	-	12.03	43.31	-	-
Kitchen	-	-	7.54	27.14	-	-	9.29	33.44
Utility	-	-	7.24	26.06	-	-	10.23	36.83
WC	-	-	6.82	24.55	-	-	8.09	29.12
Bathroom	-	-	15.39	55.40	-	-	17.16	61.78
DB2	41.11	148.00	No value	No value	47.17	169.81	38.63	139.07
Living Room 1	5.42	19.51	-	-	6.10	21.96	-	-
Living Room 2	11.16	40.18	-	-	12.52	45.07	-	-
Bedroom M (sw)	7.47	26.89	-	-	8.32	29.95	-	-
Bedroom 2(se)	10.08	36.29	-	-	12.08	43.49	-	-
Bedroom 3	6.98	25.13	-	-	8.15	29.34	-	-
Kitchen	-	-	-	-	-	-	12.86	46.30
Utility	-	-	No access	No access	-	-	No access	No access
WC	-	-	-	-	-	-	5.88	21.17
Bathroom	-	-	-	-	-	-	19.89	71.60
TB1	20.70	74.52	21.50	77.40	29.70	106.92	34.50	124.20
Living Room	4.50	16.20	-	-	5.60	20.16	-	-
Bedroom M (e)	8.10	29.16	-	-	12.50	45.00	-	-
Bedroom 2 (w)	8.10	29.16	-	-	11.60	41.76	-	-
Kitchen	-	-	8.00	28.80	-	-	13.40	48.24
Hall	-	-	3.30	11.88	-	-	5.40	19.44
WC	-	-	4.70	16.92	-	-	6.40	23.04
Bathroom	-	-	5.50	19.80	-	-	9.30	33.48

The occupant in DA2 routinely switched off the MVHR unit for two reasons. The first was the mistaken perception that the MVHR unit was the heating system, and switching it off when feeling thermal comfort had been reached. Secondly the occupant complained of thermal discomfort from draughts arising from air delivery at the living room supply terminal. The air supply rate into the living room was measured as 9.06 L/s at a velocity of 1.39 m/s, suggesting the supply air is being delivered at too high velocity and, thus, not adhering to coanda-effect principles [19].

In dwelling TB1 the treated floor area of the dwelling is of a similar size to three-bedroomed DB1 and DB2 and has the lowest air supply rate of all the monitored dwellings.

Additionally, Passive House principles require the boost mode of the ventilation system to be capable of achieving an air flow rate of 30% greater than the normal operational speed for a short period of time. However Table 3 indicates the 30% requirement is not met in any of the homes with flow rates being approximately 9% less than 130% in DA2, DB1 and TB1, 11% less in DB2 and 9% greater in DA1.

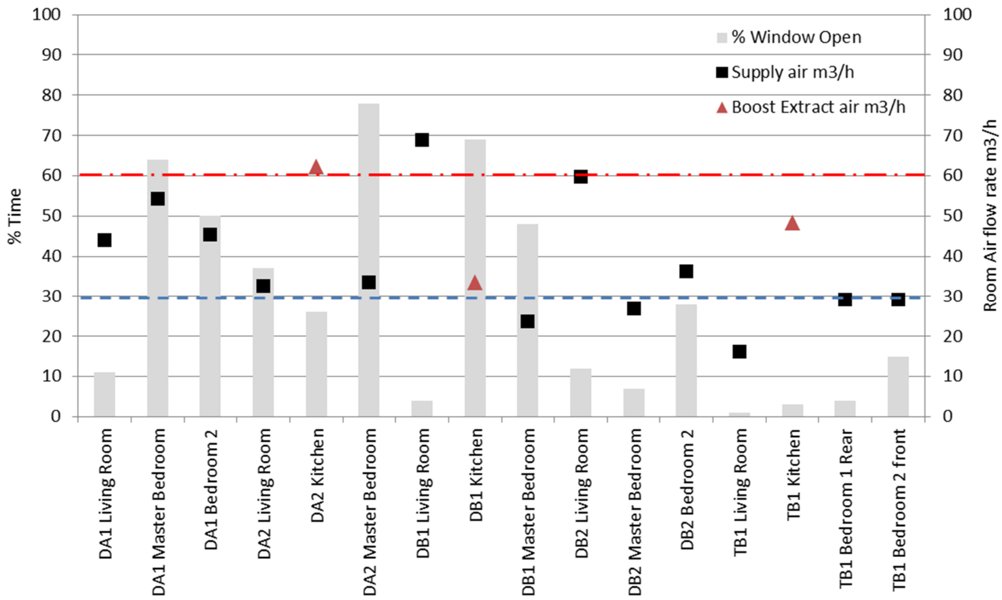

Figure 9. Dwelling by room: annual percentage of window opening and mechanical ventilation flow rate. Passive House requirement is 30 m^3/h per person, indicated by the blue dashed line, and 60 m^3/h extract in kitchens, indicated by the red dashed line.

In a Passive House it is expected that windows may be opened from time to time through the year. The monitoring of the principal windows in each home indicated occupants in DA1, DA2 and DB1 were frequent window openers (Figure 3). Figure 9 indicates the individual rooms where the windows were most frequently opened. For example, the Master Bedroom windows in DA2 were open for at least 78% of the year, correlating with the occupants' perception of being too hot in the bedroom and their need for additional ventilation. However, the extended window opening will prevent the MVHR system from operating as the design intended. The general window-opening pattern of DB2 and TB1 indicated windows were opened less frequently in these dwellings (Figure 3) but more often in the bedrooms (Figure 9), indicating this could be habitual summer opening and independent of adapting indoor conditions to achieve thermal comfort.

4.3. Indoor Air Quality

Figure 3 indicated the mean annual percentage of time the internal CO_2 concentrations were above 1000 ppm. This indicates dwellings DB1 and DB2 to have had CO_2 concentrations over this threshold for more than 25% of the year , inferring there were instances when ventilation air change rates were insufficient at maintaining indoor CO_2 concentrations below the threshold of 1000 ppm [19,46,54] (pp. 4.2–4.3). In particular, Figure 10 indicates the living rooms of identical dwellings DB1 and DB2 had respective CO_2 concentrations 22% and 19% of time over 1000 ppm and their bedrooms exceeded the threshold by 30% in DB1 and in DB2, 34% in the master bedroom and 26% in bedroom 2. Both of these dwellings have similar occupant density and occupants frequently slept in the living rooms overnight. The higher CO_2 concentration occurred in both dwellings despite the more liberal window opening pattern in DB1 bedrooms. The living rooms in both dwellings have slightly better air quality, which could be linked to the higher air supply rate from the mechanical system (Figure 9). The CO_2 concentrations in dwellings DA1, DA2 and TB1 were considerably lower and as an annual percentage rarely exceeded 1000 ppm. However, the occupant density in each of these dwellings was low (one adult and one child in each) and may not be representative performance should these dwellings be fully occupied.

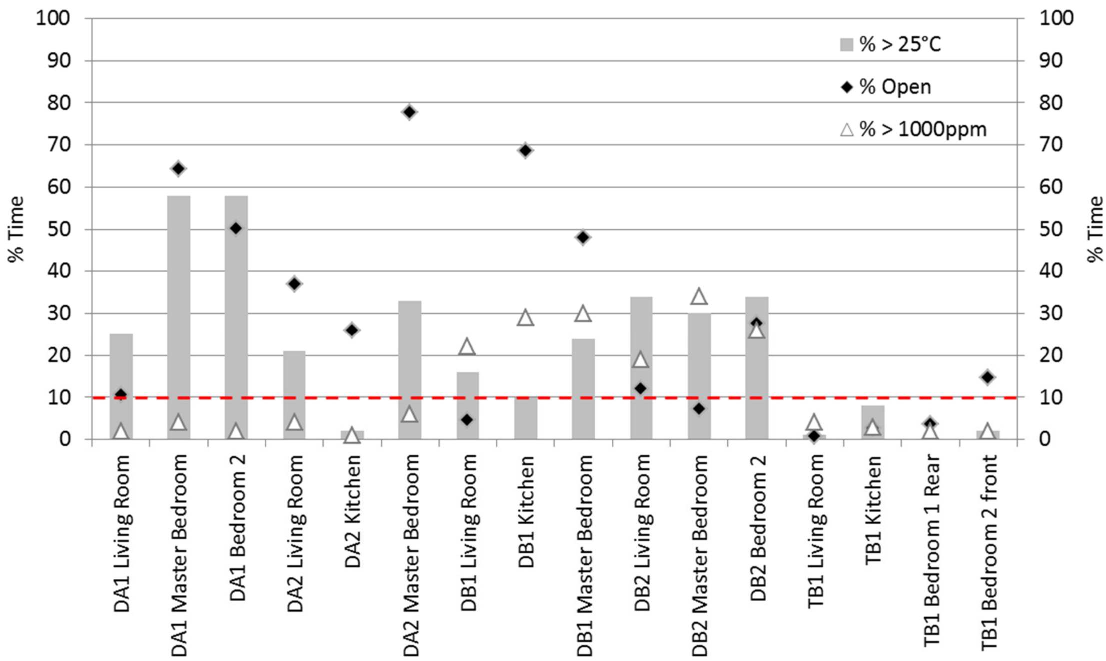

Figure 10. Dwellings by room: annual percentage of time internal air temperature >25 °C, CO_2 concentrations >1000 ppm and principle windows opened. The dashed line indicates the maximum percentage of time overheating criteria for Passive House.

4.4. Relative Humidity

The annual relative humidity range for each room in Figure 11 indicates that the internal RH in each home, with the exception of the bedrooms in DA1 and DA2, lies within the Passive House comfort range of 35%–55%RH for more than 60% of the year. Dwellings DA1, DA2 and the master bedroom in DB2 experienced dry conditions (<35% RH) for between 25%–50% of the year. Some instances of high RH were seen, for example, the bedroom of DA2, which had RH >55% for 23% of the year.

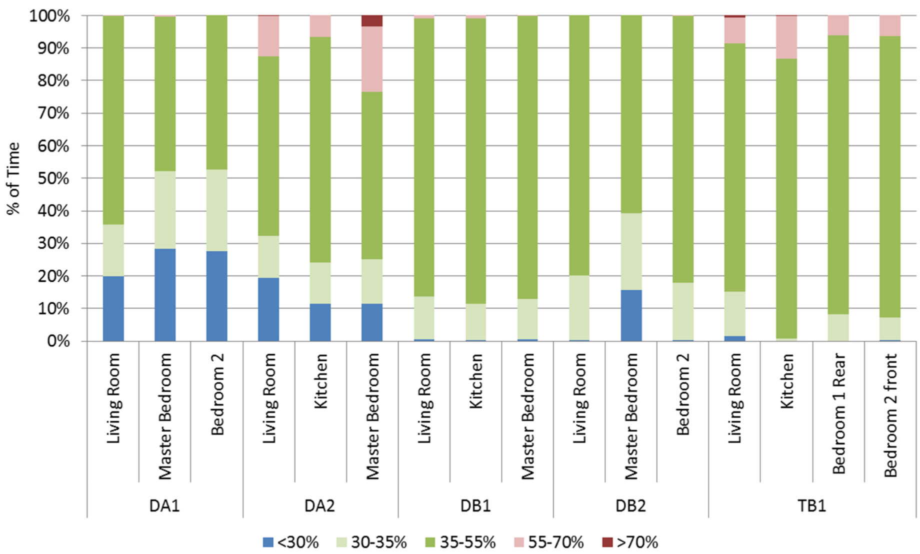

Figure 11. Dwellings by room: Relative Humidity (RH), annual percentage of time.

4.5. Absolute Humidity

Indoor RH was monitored in the dwellings and later converted to an AH (g/m^3) to provide moisture content for comparison with the AH guidance in the Passive House standard (6.0–9.5 g/m^3). Figure 12 shows the moisture content range in each dwelling, expressed as percentage of time, for the respective rooms per dwelling. In Site A, dwellings DA1 and DA2 have similar patterns with very dry air (<5.2 g/m^3) experienced for more than 10% of the year, with the living room in DA2 having experienced these conditions for 19% of the year. High AH (>9.5 g/m^3) was experienced for more than 20% (DA1) and 12% (DA2) of the year. DB1 and DB2 show similar conditions with higher moisture content for more than 30% of the year in each. The occupant from DA2 commented on the dry feel of the air and has since purchased house plants in an effort to improve the air quality, although the air supply was found to be low. It is also of note that the occupant complained of discomfort arising from draughts from the supply grille in the living room which could dry the air if the air change rate is too high.

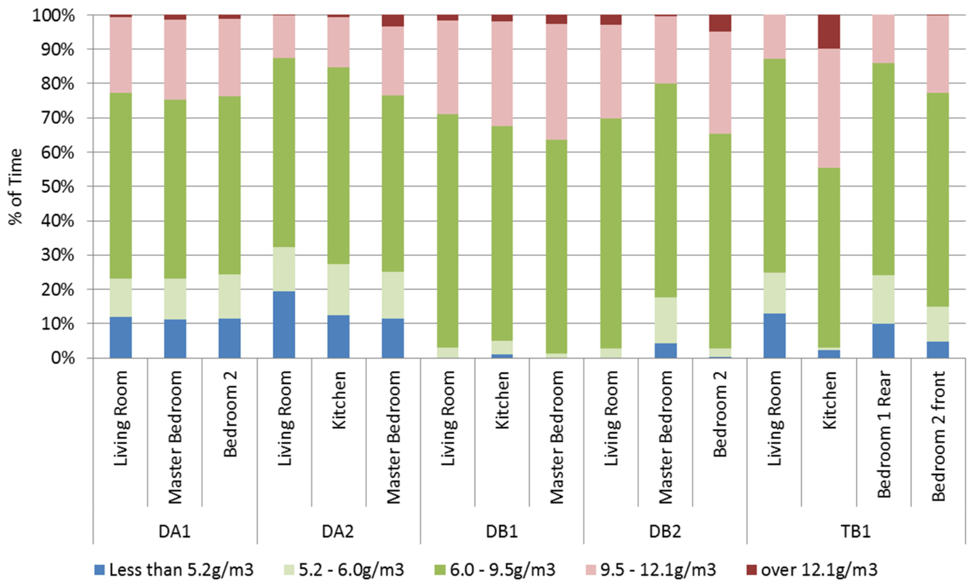

Figure 12. Dwellings by room: Absolute Humidity (AH), annual percentage of time.

In Site B the kitchen shows a distinct pattern from the rest of the dwelling with low AH for 3% of the year and high for 45% of the year, which could be indicative of low flow rates. The remainder of the dwelling has more of an even split between high and low AH with the living room being the driest and bedroom 2 being most humid around 25% of the year respectively. The high moisture levels in bedroom 2 could be linked to increased window opening frequency (Figure 9).

5. Discussion

Key findings from the Passive House dwellings were that the occupants enjoyed their home environments; and found them to be more comfortable and energy efficient compared with their previous homes. However, the data indicates the houses are not performing in line with the Passive House design intent, particularly in terms of thermal comfort, IAQ and ventilation.

5.1. Thermal Comfort

The BPE study identified significant fluctuations in internal space temperatures. This affected the high and low end of the comfort temperature scale, both conditions having the potential to negatively affect the thermal comfort and health and wellbeing of the occupants. Thermal comfort is an important factor in a society where people spend over 95% of their time indoors [55]. The UK Government's

Housing Health and Safety Rating System (HHSRS) states that temperatures exceeding 25 °C may increase cardiovascular strain and trauma [56] with severe effects such as heat exhaustion, mental health issues and heat stroke which can be fatal [32] for vulnerable occupants, including those who are infants, elderly and the obese [57].

As houses become more airtight there is an increased need to actively maintain thermal environments to provide comfort. High temperatures may be a function of heat gains (active heating or solar and incidental gains), an inability to remove heat (insufficient ventilation) or poor design. With reduced ventilation provision it is difficult to rapidly reject heat, this was found to have influenced the behaviour of the occupants participating in the study. For example, one household disabled the solar thermal system during the summer months in an effort to decrease internal temperature in the first floor bedrooms. It was later found that none of the hot water pipework was insulated and the associated heat gains were significant contributors to the heat accumulation.

This also identifies a need for a cultural shift—it is a common expectation, arising from experiences with cold, expensive to heat dwellings, that in a domestic environment any heat is considered good heat. An example of this is that in Site A the hot water pipework was not insulated by the installer. This has previously been the cultural norm in less well sealed houses in Scotland due to higher infiltration rates having capacity to dissipate the heat. This identifies a need for more education of designers and tradespeople who design and install systems within thermally efficient envelopes.

Sameni *et al.* [24] found that the density and overcrowding of social housing flats built to the Passive House standard exacerbated the risk of overheating. This is of particular importance as many people in social housing are vulnerable or in poor health, and the increased use of Passive House in this sector would help reduce utility bills [24], but could potentially be harmful if thermal comfort cannot be achieved. However, this study suggests that even with a modest occupancy level, overheating may still arise.

The bedroom temperatures in Site A dwellings was found to be higher than the ground floor rooms, which has consistencies with findings for lightweight timber construction by Peacock *et al.* (2010) and Dengel and Swainson (2012) [30,32]. The dwellings in Site A have a lower ceiling height than Site B dwelling and do not have high level openable windows above staircases. In Site B, where the first floor bedrooms were cooler than the ground floor, the design included high level openings to assist "purge" ventilation, and vaulted ceilings throughout the first floor, which can allow thermal stratification. Simple passive design approaches, such as this and external shading can help to reduce internal temperatures.

Clearly, occupant behaviour has been demonstrated to have a significant impact on temperature variation and overheating [24] (p. 230). In all of the dwellings in this study, none of the occupants fully understood how to operate their systems and further assistance from their landlords was required for an extended period, which suggests that overheating might be mitigated by better handover procedures to educate occupants as to how to operate their homes. Among the outcomes of this study was the development and distribution of "Quick Start Guides" which were specific to each house type and their controls systems. The format of these was developed by MEARU for the Building (Scotland) Regulations: a mandatory requirement from 2015 [11] (p. 360) in Section 6, these are to be submitted at the design phase of a project. The aim of these non-technical guides is to provide simplified information about the dwelling and to help residents to use their homes effectively. Even though the landlords were pro-active in providing handover assistance, there were still legacy behaviour patterns which meant the Passive Houses were being operated in a similar fashion to the occupants former energy inefficient homes. This is evident in the large internal temperature swings. The legacy patterns were particularly apparent in DA2, where the MVHR unit was switched off to conserve energy, impacting air quality, causing windows to be opened to ventilate, and producing internal temperature fluctuations. However, through continued guidance from the landlord, the occupant eventually understood how to operate the house for improved thermal comfort, but still felt the need to open kitchen and bedroom windows. However, Stevenson and Leaman caution that designers must not use occupant behaviour as an excuse for "performance deficits or unintended consequences" but these must be "understood and influenced properly" in the design [22] (p. 438).

The adult occupants were 63% female, in three of the five homes (DA1, DA2 and TB1). A study by Karjalainen [58] found that females when compared to males, preferred warmer temperatures, feel discomfort more often, and adjust their household thermostats less often. Although greater awareness of thermal comfort was indicated by DA1, DA2 and TB1, DA1, DA2 and DB2 stated that overheating occurred, but only in DB2 was the thermostat adjusted. Analysis of the impact of gender in this study is inconclusive as the occupant interviews in DB1 and DB2 were conducted jointly and there were no single male householders. This may warrant further research, which also considers occupant age, health and cultural norms in Scotland.

5.2. Ventilation

The study found inconsistencies in the capacity of the MVHR units; unbalanced supply and extract rates that were greater than the 10% allowance permissible by Passive House [19], insufficient boost flow rates; and insufficient rates for individual room demands. These inconsistencies impact the ventilation provision, heat loss, and building performance. The positive pressure created in the Site A dwellings provides potential for interstitial condensation and additional heat loss. While increased airtightness necessitates the requirement for MVHR (or controlled ventilation) to avoid poor IAQ, a study by Sharpe *et al.* demonstrated that a dwellings ventilation provision may not be entirely met by MVHR air delivery rates; and that external factors, design, and occupant use, all affect the efficacy of natural ventilation [43].

There was a general lack of understanding from occupants as to when to use the MVHR, resulting in non-optimal use such as: Turning on/off, which affects the background ventilation. This understanding is exacerbated by the fact that MVHR also provides heat, not just recovered heat. It is therefore hard for the occupant to know whether to turn the system up or not if they want more warmth. A lack of understanding can impact the perceptions of the occupants as to the systems in their homes. If they are perceived to be complicated or expensive to run, then people will not engage with them, potentially effecting comfort.

Some natural ventilation is good for the building and IAQ, however, prolonged window opening, especially in the heating seasons will impact on the thermal balance of the building, particularly during winter and at certain times of day during the summer. The study found all of the households were opening windows to a certain extent to provide cooling (and consequently heat loss in winter). In some households, e.g., DA2, window opening was habitual rather than just for cooling (Figure 9). However, the dwellings in Site A would have benefited from a high level opening in the first floor hallway to enable stack-ventilation for summer heat rejection. There is a degree of uncertainty about "mixed mode" operation for occupants; *i.e.*, whether systems can be turned off and when; and whether windows can be opened, and the impact of this on energy efficiency. These should be clarified to the occupants as part of the handover process.

There were issues common to MVHR, including: system imbalances, uncertainty over maintenance responsibility, inadequate filter cleaning and replacement, lack of occupant understanding and installation defects [14,59,60] all of which affect the system performance. The homes in this study are all affordable homes where if they do not perform as intended there could be health and financial consequences for the occupants; this may impact on their disposable income, family spending, and the local economy.

5.3. Indoor Air Quality

Average CO_2 concentrations remained largely below 1000 ppm, indicating reasonable IAQ. However, the more densely occupied dwellings in Site A (DB1 and DB2) had higher concentrations, suggesting the ventilation regime is insufficient at maintaining good IAQ, despite frequent window opening in DB1. The findings can be linked to occupant density as these two dwellings had the lowest floor area per person and both had the poorest CO_2 concentrations. The design allowance of 35 m^2 per person used by Passive House for determination of occupant numbers for mechanical ventilation design [19], differs significantly from the properties studied, occupant densities being; DA1 and DA2: 43.5 m^2 each; DB1: 20.6 m^2; DB2: 25.76 m^2; TB1: 52 m^2. The space standards for new homes in the UK is around 76 m^2 as built [61] which is significantly smaller than the 120 m^2 allowance in Germany [16] (p10) where the Passive House standard was developed. The space standards clearly impacted IAQ, and as noted previously more research in this area is required to determine optimum size to provide comfort for a family home.

When a comparison is made between the different moisture indicators (RH, AH), this demonstrates RH, although widely used, may be an inaccurate indicator of moisture content in the indoor environment. The AH provides a clearer indication of the potential impacts on occupants and building fabric. The extremes of dry and humid air could potentially encourage the growth of bacteria, viruses, fungi, VOCs, and allergies, contributing to poor IAQ.

5.4. Sustainability of Passive House

The wider socio-economic context of Passive House housing needs to be considered. While Passive House is a standard that focuses on energy reduction and comfort, the two developments studied were found to benefit the occupants in additional ways. The occupants had commented that all of the homes were cheaper to heat than where they had lived previously. They have reported that as a result of this, pre-existing medical conditions had improved since living in Passive House dwellings. Each home had additional disposable income and some were able to afford to purchase new white goods for the kitchen (reducing internal heat gain and running cost), afford a holiday and also spend more time together as a family unit. In rural Scotland, there are issues of social isolation and these rural developments allowed the occupants to be housed in affordable homes within their familiar communities. Furthermore, most remote rural houses in Scotland rely on high carbon fuels such as coal, oil and electricity for their space heating needs. The Passive House reduced reliance on fossil fuel input can deliver positive impacts for occupants, local air quality and therefore local economies. This has potential for the occupants to be healthier and happier, with less financial pressure from having a more affordable home, and has a perceptible sustainability benefit to the occupant and their wider community. The study indicated there are significant benefits to Passive House in a social housing context. However, when a home does not operate as anticipated, it can lead to increased fuel costs, thermal discomfort, poor IAQ, and potentially poor health for occupants.

6. Conclusions

This paper presented data from one year of a Building Performance Evaluation study to provide performance insights of five Passive House dwellings located in Scotland. Issues were identified with thermal comfort, MVHR system performance, IAQ, and occupant handover. Due to the low number of houses in the study, there is insufficient statistical evidence for clear recommendations. However, these findings indicate that further research needs to be undertaken in this field. As it stands, the monitoring of these dwellings has provided insight into Passive House in Scotland, where the lessons from this, and patterns identified could be beneficial for future Scottish Passive House dwellings, particularly as homes constructed to the Passive House standard are likely to increase. It is important to better understand the potential unintended consequences of design and construction decisions on building performance, occupants and their comfort.

Thermal comfort was found to be an issue in all of the Passive House dwellings, which had large temperature fluctuations causing discomfort through low and high internal temperatures. The study found that MVHR systems had issues with the installation, commissioning, control and operation. These faults were not detected before the monitoring project, in part because user misunderstanding was assumed to have been the problem. All of the MVHR systems require recommissioning to balance the systems and at this point air valves should be locked in position to avoid accidental movement by the occupant. If users are better informed as to how their systems should operate and the interaction required, this will help them to better identify when there is a problem which may be impacting on the IAQ of their home. There needs to be better systems in place for checking installation, commissioning and handover.

The ways in which specifiers and occupants are educated and supported for Passive Houses needs to be better addressed. The cultural shift to airtight dwellings requires simple, clear information about the systems and their operation. However, social landlords have the added complexity to provide better support during settling in periods, and to provide clear guidance of the importance of maintaining the system, the maintenance frequency, and the responsibility for this.

CO_2 concentrations were high in the densely occupied homes (at their design capacity) and gives rise to IAQ concerns in Passive House dwellings, particularly as domestic MVHR systems are sized for background ventilation and deliver air to rooms irrespective of occupancy. In the sparsely occupied homes the CO_2 concentrations were less of an issue but the air supply rates measured indicate there could be potential air quality issues if a larger family were to move in. Further research is required into the impacts of space standards and density on IAQ and comfort in homes, and the potential for CO_2 linked sensors for the control of MVHR.

Examination of the indoor RH conditions against AH indicated shortcomings with RH for the analysis of potential allergens and contaminants. VOCs become more volatile and House Dust Mite (HDM) population growth increases with rises in humidity [43]. This indicates that methods of analysis of moisture in dwellings need to be improved.

Although not a sustainability standard, there are many aspects of Passive House which have wider positive and negative impacts on social, cultural, environmental and economic sustainability on a range of scales. These need to be better understood, but in parallel the information provided to practitioners as to what sustainability is and how it is achieved needs to be more coherent, otherwise there is a risk that it will be assumed that such standards are sustainable, which is not their purpose or intention.

With Passive House now being widely constructed in the UK, it is important to share successes and failures in a UK and Scottish context in order to build affordable, quality homes that work well in terms of energy efficiency and comfort for occupants.

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Abbreviations

The following abbreviations are used in this manuscript:

AH	Absolute Humidity
Ac/h	Air Changes per Hour
BPE	Building Performance Evaluation
CO_2	Carbon Dioxide
HHSRS	Housing Health and Safety Rating System
HDM	House Dust Mites
IAQ	Indoor Air Quality
IUK	Innovate UK
MEARU	Mackintosh Environmental Architecture Research Unit

MVHR	Mechanical Ventilation and Heat Recovery
RH	Relative Humidity
RSL	Registered Social Landlord
TRV	Thermostatic Radiator Valve
TSB	Technology Strategy Board
VOC	Volatile Organic Compounds
ZCH	Zero Carbon Homes

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