LEARNING FROM OUR EXPERIMENTS: MONITORED ENVIRONMENTAL PERFORMANCE OF LOW ENERGY BUILDINGS IN SCOTLAND

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ABSTRACT

This paper reports on six Technology Strategy Board funded projects that are examining the performance of a range of new build low energy houses throughout Scotland. These are two-year monitored projects that capture quantitative data on energy consumption and environmental conditions including air quality, but also qualitative data through interviews and surveys with occupants and designers. The projects (n=26) have a number of varying characteristics, including different types of construction and design intention, including some Passivhaus, and more mainstream social housing. The paper will examine and compare early observations of comparative performance in respect of air quality. Factors include occupancy and ventilation behaviours, but also include room volume, openings, and mechanical systems. The study identifies trends in terms of high temperatures and CO_2 levels, particularly in bedrooms overnight.

Keywords: Indoor Air Quality, CO2, Occupancy, Behaviour, Comfort, Health, Ventilation

INTRODUCTION

The increasing importance of climate change has led to governments establishing targets for carbon reduction [1]. The primary mechanism for achieving these targets has been increasingly stringent requirements for energy performance [2]. This in turn has led to the adoption of new designs, materials and technologies for buildings that seek to reduce energy consumption. However it is increasingly apparent that there can be significant performance gaps between design intentions and actual performance of buildings and this is increasingly well-evidenced [3], [4], [5], [6].

The main focus of primary legislation is on energy and carbon performance, but there is also increasing concern about other areas of environmental performance, particularly Indoor Air Quality (IAQ) and overheating [7]. [8]. As well as being causes for concern in their own right [9], these issues can also undermine energy strategies, for example overheating being controlled by liberal window opening, leading to increased energy consumption.

To investigate these questions the UK Technology Strategy Board has funded a 4-year £8m programme of Building Performance Evaluation for both domestic and non-domestic buildings across the UK. MEARU is engaged in 6 domestic projects in Scotland, which include detailed monitoring of environmental conditions (including air quality) and energy consumption (including sub-metered energy) over a 2-year period. This is contextualised with a review of construction, testing of fabric performance and gathering of qualitative data from residents about their patterns of behaviour and occupancy. This paper will discuss a broad comparative analysis of the initial results and identify key issues and areas for deeper investigation.

METHOD

The projects being monitored are in 6 different geographic locations across Scotland: Inverness IN (n=8), Livingston LI (n=2), Lockerbie LO (n=4), Barrhead BA (n=3), Glasgow GL (n=6) and Dunoon DU (n=3) Total n=30. The general form and construction of the dwellings is summarised in Table 1. Additional information is provide for bedrooms – room volume, Trickle vents, Occupants, Window opening, and Time Weighted Average (11pm – 7am) CO_2 levels.

									Bedrooms				
Loc	Ref	Const Type	Type	MVHR	Bed	Air Perm	GIFA (m^2)	Heating	Vol	TrV	Occ	WO	TWA
BA	*27MP*	*TF*	*H MT*	*No*	*2*	*4.25*	*93.9*	*Gas CH*	*31.23*	*Yes*	*2A*	*N*	*1888.80*
BA	*29MP*	*M*	*F GF*	*No*	*2*	*2.88*	*75.8*	*Gas CH*	*31.50*	*Yes*	*1A*	*Y*	*1124.44*
BA	*37MP*	*TF*	*H ET*	*No*	*2*	*4.98*	*75.4*	*Gas CH*	*30.34*	*Yes*	*2A*	*N*	*2101.49*
LO	**BC**	**TF**	**H SD**	**Yes**	**2**	**2.42**	**87.3**	**MVHR**	**33.68**	**No**	**1A**	**N**	**n/a**
LO	**CC**	**TF**	**H SD**	**Yes**	**2**	**2.14**	**87.3**	**MVHR**	**33.68**	**No**	**1A**	**N**	**762.98**
LO	**HC**	**TF**	**H SD**	**Yes**	**3**	**2.72**	**102.8**	**MVHR**	**35.76**	**No**	**1C**	**N**	**1111.24**
LO	**OC**	**TF**	**H SD**	**Yes**	**3**	**2.41**	**102.8**	**MVHR**	**35.76**	**No**	**1C**	**N**	**1073.33**
DU	P5	CPTF	H SD	No	3	4.04	113.6	ECH	30.77	Yes	1A	N	1852.98
DU	P14	CPTF	H SD	No	3	4.29	113.6	Elec CH	30.77	Yes	1A	N	872.84
DU	**P15**	**CPTF**	**H SD**	**Yes**	**2**	**0.96**	**103.4**	**ASHP**	**37.85**	**No**	**1A**	**Y**	**913.65**
IN	3BS	TF	H ET	No	3	3.82	109.0	Gas CH	28.08	Yes	2A	N	1457.70
IN	4BS	TF	H MT	No	3	4.21	109.0	Gas CH	28.08	Yes	2A	N	n/a
IN	6BS	TF/M	F GF	No	2	5.71	76.00	CB CH	23.30	Yes	2A	N	701.30
IN	7BS	TF/M	F GF	No	2	4.53	76.00	CB CH	21.86	Yes	2A	N	1335.12
IN	4BG	TF	H SD	No	3	5.82	90.00	Gas CH	28.70	Yes	1A	N	1501.86
IN	5BG	TF	H SD	No	3	6.07	90.00	Gas CH	28.70	Yes	2A	N	1457.70
IN	9BB	TC	F GF	No	1	5.93	52.00	ECH	28.32	Yes	1A	Y	701.30
IN	11BB	TC	F TF	No	1	6.00	52.00	ECH	28.32	Yes	2A	N	n/a
GL	M02	M	F GF	No	2	3.61	67.57	CB CH	26.04	Yes	2A	N	n/a
GL	M03	M	F GF	No	1	7.91	72.15	CB CH	21.60	Yes	1A	N	3638.50
GL	M22	TF	F MF	No	1	4.59	67.57	CB CH	27.00	Yes	1A	N	1762.20
GL	*S02*	*TF*	*F TF*	*No*	*1*	*n/a*	*49.53*	*CB CH*	*21.60*	*Yes*	*1A*	*Y*	*735.97*
GL	*S17*	*M*	*F GF*	*No*	*2*	*10.39*	*49.53*	*CB CH*	*35.14*	*Yes*	*1A*	*Y*	*1044.27*
GL	*S32*	*TF*	*F TF*	*No*	*2*	*7.59*	*75.50*	*CB CH*	*35.14*	*Yes*	*2A*	*Y*	*818.79*
LI	*25BC*	*TF*	*H MT*	*No*	*3*	*3.71*	*106*	*Gas CH*	*27.40*	*Yes*	*1A*	*N*	*1239.84*
LI	*26BC*	*TF*	*H ET*	*No*	*3*	*3.73*	*105.9*	*Gas CH*	*27.40*	*Yes*	*1A*	*N*	*1318.12*

TF=Timber Frame, M=Masonry, CPTF=Closed panel Timber Frame, TC=Timber Cassette H=House, F=Flat: MT=Mid Terrace, ET=End Terrace, GF=Ground Floor, MF=Mid Floor, TF=Top Floor, SD=Semi-detached; CH=Central Heating, CB=Communal Boiler, ST=Solar Thermal, EI=Electric Immersion. *Italics*=elderly/disabled occupants, **Bold**=Passivhaus

Table 1:Key construction, heating and bedroom occupancy data.

This paper provides an overview of the comparative environmental performance of these houses during a 2-week period between 25 Feb 2013 and 10 Mar 2013, taken in the context of a longer monitoring programme and is representative of the use and overall performance of these houses.

AIR PERMEABILITY

Air permeability figures are within design expectations, but result ranges from 0.955 $m^3/m^2.h$ in P15 to 10.39 $m^3/m^2.h$ 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 m³/m².h and all but 5 meet the current requirement of 7 m³/m².h and the average is 4.59 m³/m².h. The Passivhaus projects (P15, CC, OC, BC and HC) are the best performers and average at 2.45 m³/m².h, but it is noted that the levels are all above the Passivhaus requirement of 0.6 m³/m².h. In the case of the Lockerbie houses, original airtightness met this value and there has been some deterioration over time. They remain within the recommended figure of 3-5 m³/m².h for MVHR systems [10]. Outwith these projects there is no obvious pattern associated with construction, for example flats in Glasgow having figures at opposite ends of the spectrum. Nevertheless a reasonable standard of air-tightness is present across the sample and suggests that standards in general are improving.

TEMPERATURE

Mean temperatures for living and bedrooms over this period are shown in Figure 1. There is a difference of 8.19°C across the range (excluding MO2 which was unoccupied during this period) but 88% of dwellings having mean living room temperatures above 21°C and 50% of properties having a mean above 23°C. These demand temperatures are above design assumptions, but higher temperatures may reasonable or desirable in those houses occupied by disabled or elderly users (n=8). However relatively high temperatures are observed across the house types. Causes can include unintentional heating due to poor heating controls, oversizing of heating systems or uncontrolled incidental gains; or they may be due to occupants raised expectations or requirements of comfort.

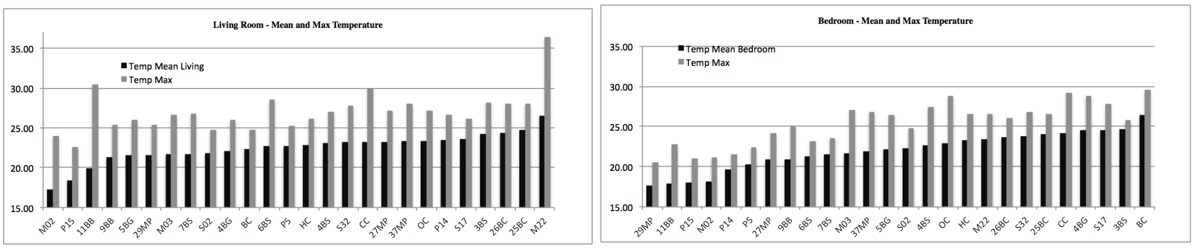

Figure 1: Left - Living room Mean and Maximum: Right - Master Bedroom Mean and Maximum temperature

Mean bedroom temperatures are also consistently high, with 70% of houses having mean temperatures above 21°C and 42% having a mean of over 23°C. The average mean in living rooms was 21.86°C and bedrooms 22.48°C.

CO_2 LEVELS

In these studies CO_2 is being monitored as a useful indicator of 'bad company' with regard to IAQ [11]. Key differences in ventilation strategies are those dwellings relying on natural ventilation (mechanical extract ventilation from kitchens and bathrooms, n=21) and those with MVHR system (n=5).

Mean CO_2 levels are shown in Figure 2 for both living rooms and bedrooms. Bedrooms are of particular interest as they are the spaces where occupants spend the longest uninterrupted time and with the least changes in occupancy. The ventilation strategy that is established when occupants go to bed tends to prevail overnight and provides a reasonably stable condition in which to observe the effects of ventilation.

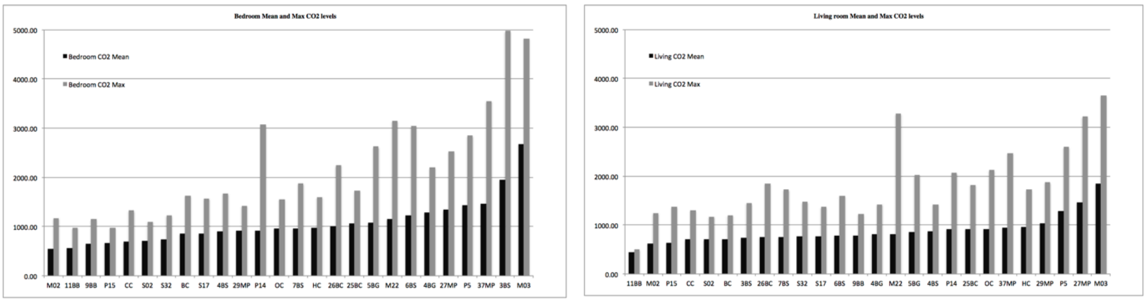

Figure 2: Left - Bedroom, mean and max CO_2 levels; Right – Living room, mean and max CO_2 levels

Levels were found to be above 1000ppm in at least half of the bedrooms, with peak levels in almost all cases well above 1000ppm, typically 1500-3000ppm but in some cases as high as 5000ppm. Comparing mean levels of CO_2 in bedrooms and living rooms indicates that in almost all cases bedroom levels exceed those in living rooms and this difference becomes more marked at mean values rise.

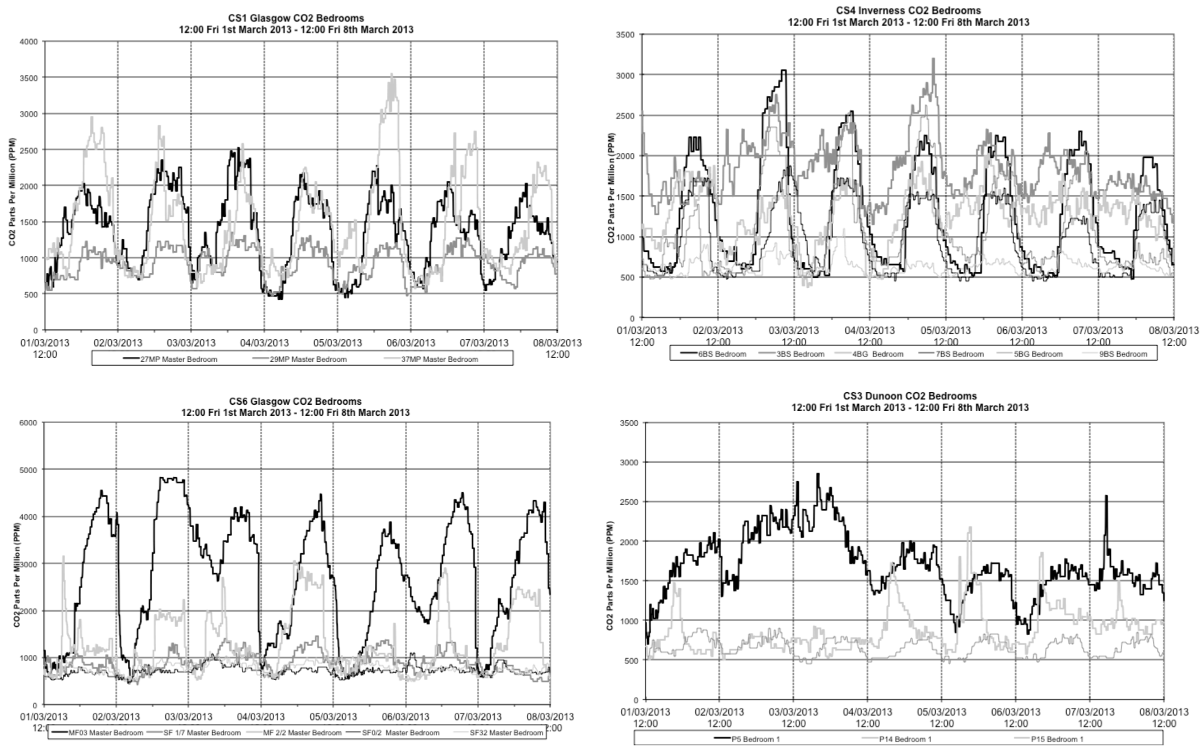

Figure 3: Typical diurnal CO_2 levels Barrhead (top left); Inverness (top right); Glasgow (bottom left); Dunoon (bottom right).

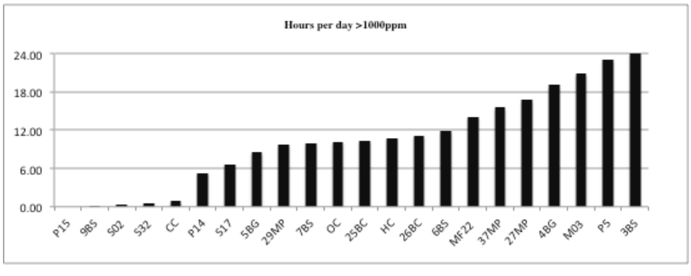

Figure 4: Bedroom exposure to CO2 – Hours per day >1000ppm

Examining CO_2 levels in bedrooms over a three-day period reveals a consistent diurnal pattern that can be observed over the entire monitoring period to date (Figure 3). The degree of exposure to CO_2 levels is shown in Figure 4, which indicates 70% of bedrooms having exposure to CO_2 above 1000ppm for more than 7 hours a day.

DISCUSSION

The high temperatures and general trend of CO_2 levels, especially in bedrooms may be the result of several conditions. Aside from the use of MVHR systems, several factors are relevant. These include the room volume, number of occupants, night ventilation regime (door, window or trickle vent opening). In some case IAQ is less problematic due either to reduced occupancy or more frequent window opening habits. This is illustrated in 29MP, which contains a single occupant and opens windows at night, also leading to the low mean bedroom temperatures, as compared with 27MP and 37MP, which have double occupancy. Urban context can also be important. The houses in Glasgow are in an urban setting, near to a busy road. M03, which has very high CO_2 levels, is on the ground floor adjacent to this road and rarely opens windows, and the couple also have child who sleeps in the same room. Levels of CO_2 in houses with MVHR systems were not as intense as in those relying on trickle ventilation but periods of CO_2 above 1000ppm were seen at night in OC and HC. Continuously high CO2 levels were seen in some properties. This may be due to continual occupancy due to elderly or disabled occupation, use of bedrooms as workspaces, shift work and in one case a new-born baby.

For those bedrooms relying on trickle ventilation alone (where windows were kept closed n=12) CO_2 levels were noticeably higher, with an occupied mean peak of 2317ppm and an occupied time weighted average of 1834ppm measured between 11pm and 7am. All these bedrooms are characterised by a rapid increase in CO_2 on first occupancy then levelling out presumably due to the background ventilation characteristics. There is no clear pattern emerging from locations or types of construction.

Overheating is also an issue across the dwellings particularly given that average external temperature in this period varied from 3.8^{o}C in Inverness to 7.3^{o}C in Livingston. There is also emerging evidence of overheating due to uncontrolled residual gains. For example, in the Dormont houses the domestic hot water pipework is largely uninsulated, and this appears to be contributing to significant heat gains in the houses, particularly in the upstairs bedrooms where temperatures are typically 3^{o}C higher than downstairs.

CONCLUSION

Comparison of these projects reveals a range of levels of performance and two significant trends are seen. Firstly there are consistently high temperatures observed in the majority of the dwellings, both in the living spaces, but also the bedrooms. This level of demand is leading 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. It is suggested that heat delivered into a thermally efficient envelope - particularly where volumes are small - is easily transferred to other spaces such as bedrooms through thermal stratification. This suggests a need for much closer control of heat delivery and that incidental gains may take on much greater importance in low energy dwellings.

The second observation is a tendency toward poor ventilation levels, particularly in bedrooms. For the most part the bedrooms rely on trickle ventilation. Those houses with MVHR systems performed at the better end of the spectrum, and generally did not result in the peak conditions observed in other properties, but were not exempt from poor IAQ and were equivalent to those houses known to keep bedroom windows open at night.

The major concern is for spaces that rely on trickle ventilation as the sole 'planned' ventilation strategy. When considered as a discrete volume, an occupied apartment will require a substantially greater ventilation rate than can be provided solely by trickle ventilators with a free vent area of 12000mm^2. This will be compounded by occlusion from curtains or blinds and the habitual closing of controllable vents. Further research is being conducted to gather more detailed information on ventilation habits and attitudes as the work progresses.

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