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Winter Indoor Air Temperature and Relative Humidity in Hard-To-Heat, Hard-To-Treat Houses in Wales: Results from a Household Monitoring Study.

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Disclaimer

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The views and opinions expressed in this report are those of the authors and do not necessarily reflect those of the PHR programme, NIHR, NHS or the Department of Health.

Contents

Abstract

This working paper presents the descriptive results of the first phase of a household monitoring study that is part of a wider research project examining the health impacts of energy-performance investments in Wales under the Arbed programme, which aims to improve energy efficiency of homes in low-income neighbourhoods. The study monitored the internal environmental conditions of 99 dwellings, of which 50 were located in five low-income areas where Arbed domestic energy-performance investments were planned and 49 in matched control areas where no such investments were planned. The monitoring took place before the Arbed energy efficiency upgrades were made. The results described in this working paper therefore reflect the energy performance of typical ‘hard-to-heat, hard-to-treat’ houses in Wales.

The indoor air temperature and relative humidity of the living room, kitchen and main bedroom were recorded every 15 minutes for a minimum of 28 days during the 2013-14 heating season. The monitoring data was used to determine the length and weighted amount of sub-standard internal conditions (i.e. <18˚C, <16˚C, and >60% relative humidity). Local weather stations were installed in or close to the five monitoring areas to record external meteorological conditions. Data from the weather stations were used to determine the heating demand in Heating Degree Days (HDD) for the different areas.

The monitored data were analysed in three different ways. First, the indoor air temperature and relative humidity were summarised for a fixed 28-day period (3 February to 2 March 2014). Second, all the readings of internal conditions were described according to different levels of heating demand. Third, indoor air temperature and relative humidity were determined for 28 non-consecutive days when heating demands exceeded 6 HDDs to describe internal conditions when supplementary energy is needed to heat a building.

The study found large differences in heating demand across the different monitoring areas. In particular, Cardiff had a lower heating demand than the other four monitoring areas. As a result, the dwellings in Cardiff had more favourable internal conditions than those in the other areas. While the Arbed dwellings had longer and a greater amount of sub-standard internal conditions with higher levels of heating demand, the opposite was the case for the control households. Control dwellings had shorter and a smaller amount of sub-standard internal conditions with higher levels of heating demand. The study further found that the spot-measured indoor air temperature was slightly lower and the spot-measured relatively humidity higher in the Arbed dwellings than in the control dwellings. No major differences in self-reported thermal comfort were found between the two groups.

Data from this first phase of the household monitoring study will become part of the controlled monitoring study to examine whether and how energy performance investments improve internal conditions of ‘hard-to-heat, hard-to-treat’ houses, and, at a later stage, be used to explore how sub-standard internal conditions may affect people’s health.

Key Words: Arbed; Household Monitoring; Indoor Air Temperature; Relative Humidity; Energy Use.

Acknowledgments

We would like to thank the NIHR Public Health Research Programme for funding the research, the Welsh Government and the two Arbed scheme managers (Melin Homes and Willmott Dixon) for their continued support throughout the project, and the Local Authorities involved in the selection of Arbed schemes for their valuable input and support, as well as the Communities First groups in South Wales for their advice. Last but not least we would like to thank the respondents who have taken part in the research.

Introduction

It is widely acknowledged that living in cold conditions poses various health risks, in particular to low-income, fuel-poor households. The Marmot Review Team (2010, 2011) identified cold homes and fuel poverty as major factors in health inequalities that could easily be addressed through energy efficiency interventions. Low internal temperatures have been linked to poor respiratory, circulatory and mental health, as well as excess winter mortality. Improving the energy efficiency of the housing stock could therefore bring multiple health gains (ibid).

Existing World Health Organisation (WHO) recommendations are to maintain a minimum indoor air temperature of 18˚C for healthy sedentary occupants, and a minimum temperature of 20˚C for rooms occupied by vulnerable groups (Public Health England, 2014). However, a recent systematic review of the literature found that there is limited robust evidence on the effects of specific indoor air temperature thresholds (Public Health England, 2014). The majority of studies in the area are small and cross-sectional in nature, and often have only conducted a single indoor air temperature measurement. Public Health England (2014) concluded that more work is needed on the health impact of indoor air temperatures in different parts of the house, as well as large longitudinal studies to show the long-term effects and levels of exposure that precede illness. Furthermore, little is known about how internal conditions may be improved by energy performance investments to homes, and what impact they may have on the health and wellbeing of the occupants.

Arbed is Welsh Government's investment programme designed to improve the energy efficiency of existing homes in low-income neighbourhoods. The programme has been delivered in two phases across Wales. The first phase (Arbed 1) took place in 2010 and 2011, and the second phase (Arbed 2) between 2012 and 2015. All houses selected for the Arbed improvement work were offered multiple energy efficiency measures, free of charge, and without means-testing (Welsh Government, 2014).[1]

In this working paper we describe the findings of a household monitoring study that is part of a wider research project examining the health impacts of domestic energy-performance investments in Wales under the Arbed programme. This involved detailed indoor air temperature and relative humidity measurements in a subset of 'hard-to-heat, hard-to-treat' households that were surveyed in the community-based study (see Grey et al., 2015). The measurements were conducted to make a reliable assessment of the internal conditions of these houses in low-income areas, and to examine in what way they may be improved by energy performance investments to make the homes more energy efficient. Measures undertaken could include connection to the gas mains network for a number of off-gas areas, boiler and heating system upgrades, and external wall insulation to reduce heat loss.

[1] http://gov.wales/topics/environmentcountryside/energy/efficiency/arbed/?lang=en (accessed 16 October 2016).

The study was conducted in five low-income areas where Arbed energy-performance investments were planned and in five matched control areas where no such investments were planned. The baseline measurements were taken in the 2013-14 heating season before the Arbed energy-performance investments took place. Follow-up measurements were conducted in the 2014-15 heating season after the Arbed improvements were finished.

This working paper presents the descriptive findings of the baseline measurements made in the 2013-2014 heating season only.

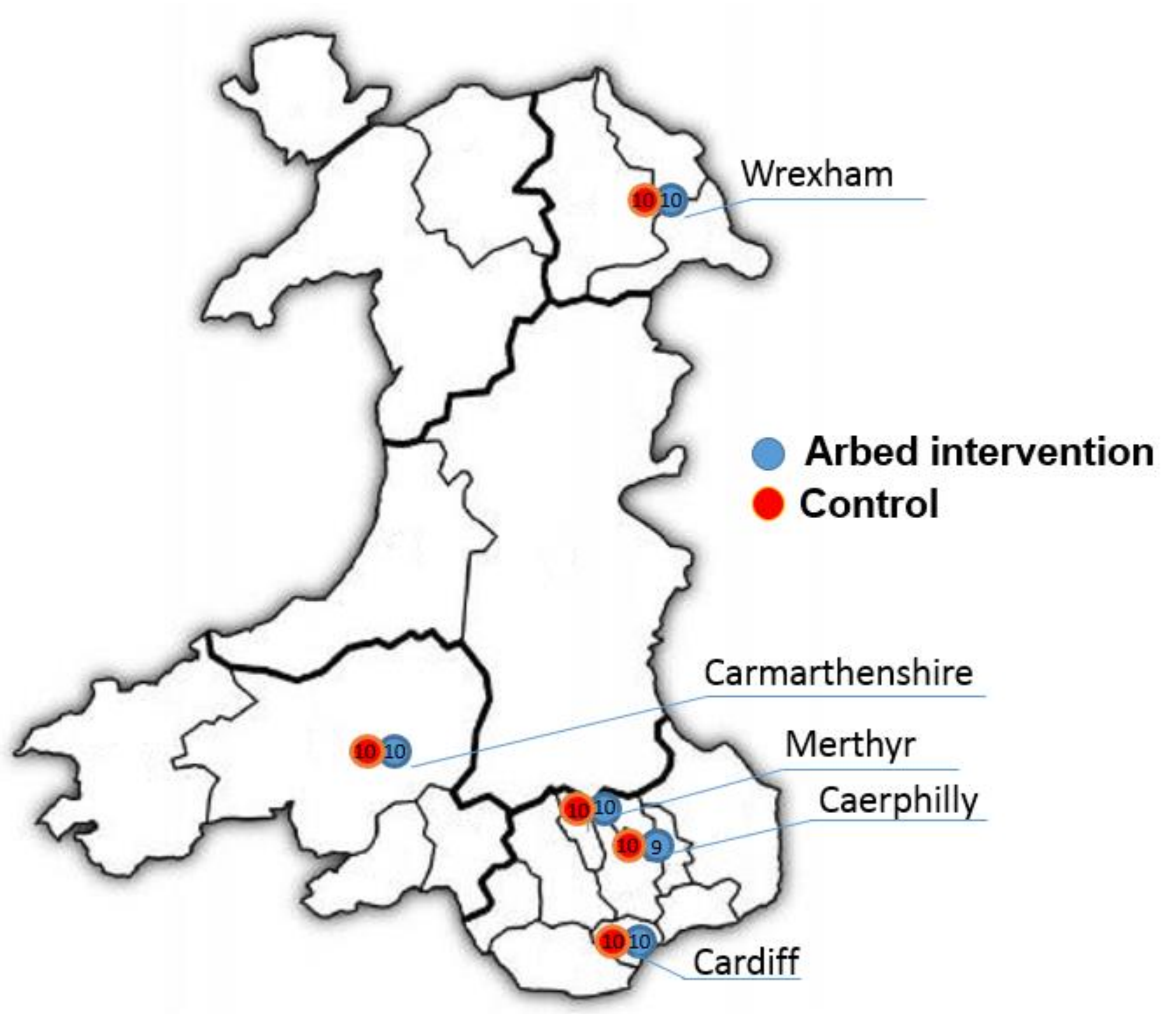

Figure 1. Locations of the Arbed and control areas in the household monitoring study.[2]

[2] The five areas for the household monitoring study were Brynamman, Carmarthenshire (Arbed 10; control 10); Caerau, Cardiff (Arbed 10; control 10); Llay, Wrexham (Arbed 10; control 10); Hollybush, Caerphilly (Arbed 10; control 9); and Pennydarren, Merthyr (Arbed 10; control 10).

Methodology

Procedure and Sample

Households for the monitoring study were recruited from a community sample used for examining the health impacts of structural energy performance investments under the Arbed programme. The community study consisted of respondents from 14 low-income areas where Arbed energy-performance investments were planned and 13 matched control areas where no such investments were planned (see Grey et al., 2015). The control areas were selected to resemble the intervention areas as much as possible in terms of housing type and level of deprivation. This was done using the Welsh Index of Multiple Deprivation (WIMD) and with the help of Local Authorities where the Arbed schemes were taking place. The household monitoring study took place in five of the Arbed areas and their matched control areas (Figure 1). Respondents from these areas who provided consent to be recontacted were invited to have their home monitored. In total, 99 houses were monitored, of which 50 were located in the five Arbed intervention areas and 49 in the five matched control areas. Three of the households (one from the Arbed areas and two from the control areas) were excluded from the analyses, as they had energy-efficiency work done during the monitoring period. The Arbed and control areas in Carmarthenshire and the Arbed area in Caerphilly were off-gas. No gas meter readings were taken in those areas.

Households taking part in the study were visited between 11 November 2013 and 1 February 2014 to install indoor data loggers (see *Internal Monitoring*). Spot measurements of the indoor air temperature and relative humidity were taken during the installation visits, and participants were asked to fill out a short thermal comfort questionnaire (see Appendix A). The spot measurements were used as a snapshot of the indoor condition of the monitored dwellings, and contributed to the assessment of thermal comfort at the time of installation. The data loggers were collected between 19 January and 31 March 2014. Dwellings were monitored for a minimum of 28 consecutive days and a maximum of 71 days. On average, the households were monitored for 58 days, with a standard deviation (SD) of 7 days. Gas and electricity meter readings were taken during the installation and collection visits. The meter reading therefore only provide information about the total energy use during the monitoring period, and cannot be disaggregated to different usages. The gas meter readings provide an indication of the effectiveness of energy performance investments, as most of the metered gas will have been used for space and water heating (see e.g. DTI, 2005). Local weather stations were installed in or close to the five monitoring areas to record external meteorological conditions (see *External Monitoring*).

Table 1 shows the characteristics of the monitored households. While the matched control areas were selected to be comparable to the Arbed areas, there were a number of differences. Most of the Arbed and control houses were built between 1945 and 1964 (58% and 57%, respectively). However, more houses in the Arbed areas were built between 1965 and 1979 (10% versus 2%), and more houses in the control areas were built between 1910 and 1944 (41% versus 32%). More than half of the Arbed properties were British Steel Framed (BISF) (57%), compared to 30% of the control properties. In contrast, 60% of the control houses were of solid wall construction, compared to 39% of the Arbed properties.

Table 1 shows that there were no major socio-demographic differences between the two groups. The overall sample was balanced in terms of gender, and a great majority of the occupants had lived at their current address for at least 5 years. The control group was slightly older than the Arbed group.

Table 1. Characteristics of the monitored households (%).

		Arbed (n=50)	**Control (n=49)**	**Overall (n=99)**
Building age	1910-1944	32.0	40.8	36.4
	1945-1964	58.0	57.1	57.6
	1965-1979	10.0	2.0	6.0
Building type	British Steel Frame, Terraced	57.1	30.0	43.7
	Masonry Terraced, Solid Wall	38.8	60.0	49.3
	Masonry Terraced, Cavity Wall	4.1	10.0	7.0
Gender	Female	50.0	46.9	48.5
	Male	50.0	53.1	51.5
Age (years)	Under 35	8.0	12.2	8.1
	35-44	24.0	18.4	21.2
	45-54	16.0	6.1	11.1
	55-64	38.0	32.7	35.4
	65 or above	18.0	30.6	24.2
Time lived at current address	Less than 1 year	8.0	0.0	4.0
	1-2 Years	10.0	6.1	8.1
	3-5 years	14.0	18.4	16.2
	More than 5 years	68.0	75.5	71.7

Internal Monitoring

Each household had three *Tinytag Ultra 2* data loggers installed to record indoor air temperature and relative humidity: one in the *living room*, one in the *kitchen*, and one in the *main bedroom* (see Figure 2). These rooms were selected as they represent the key living spaces in domestic dwellings. The data loggers were positioned away from any direct heat source (such as a lamp or radiator) and external windows. They were placed in a location where they would cause the least disturbance to the occupants and were unlikely to get covered by materials that block air circulation, typically on top of a cupboard or shelf at a height of about 2 meters. Due to practical issues of placing loggers in dwellings in diverse circumstances, furnishings, and personal preferences, the exact locations where they were positioned within the rooms varied.

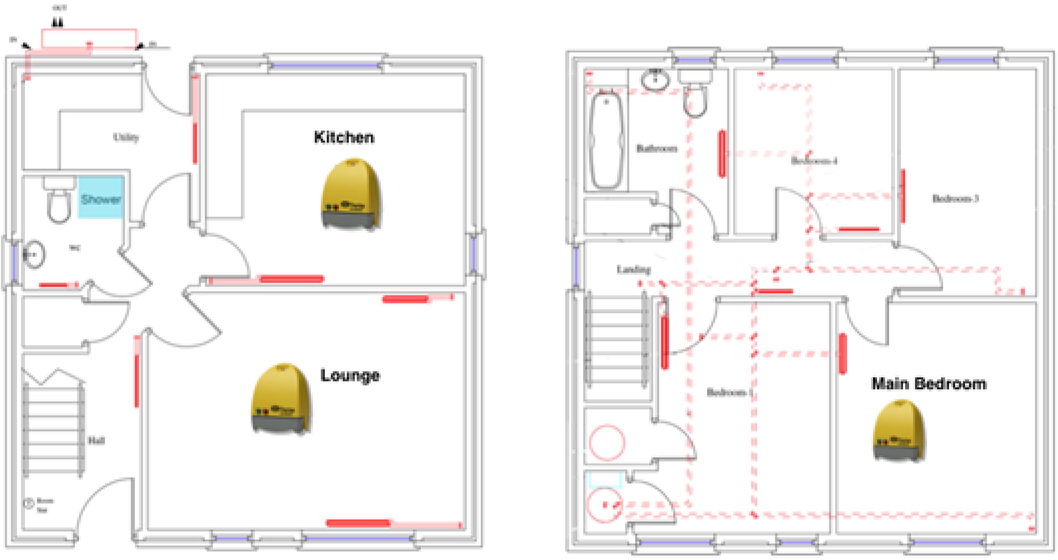

Figure 2. Locations for the Tinytag Ultra 2 data loggers.

Indoor air temperature and relative humidity were recorded every 15 minutes. Every measurement represents the averaged value for the 15-minute time intervals. The *Tinytag Ultra 2* data loggers have an air temperature reading range of -25°C to +85°C, with a resolution of 0.01°C and an error range of ±0.35˚C; and a relative humidity reading range of 0% to 95%, with a resolution of 0.3% and an error range of ±3.0% at 25°C.

External Monitoring

The weather stations were installed in or close to the five monitoring areas, typically in a participating household's gardens. The weather stations were placed in an open area away from any tall object, at least four times the height of the nearest tall object (see Figure 3).

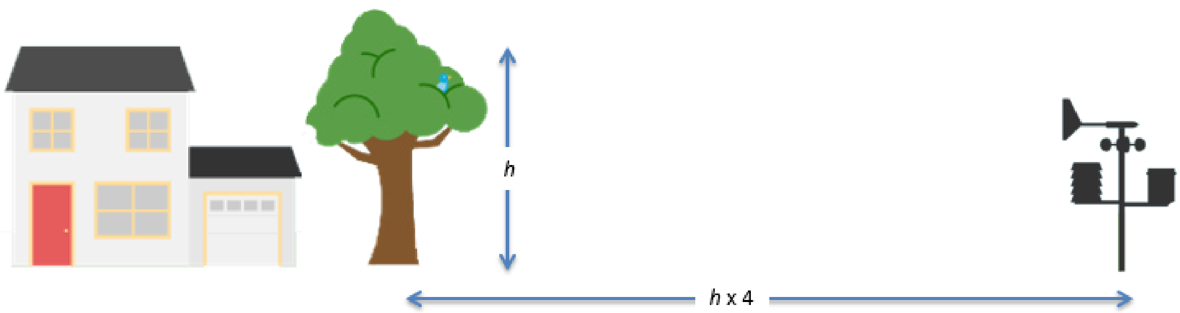

Figure 3. Positioning of the Delta-T-GP1 weather stations.

External air temperature and relative humidity were recorded every 15 minutes by *Delta-T-GP1* weather stations. *Delta-T-GP1* weather stations have an air temperature reading range of -20˚C to 70˚C, with a resolution of 0.05˚C and an error range of ±0.3˚C; and a relative humidity reading range of 0% to 100%, with a resolution of 0.2%, and an error range of ±2% between 5 and 95% and of ±2.5% for <5% and >95% relative humidity. Wind speeds are measured between 0 and 75 m/s, with a resolution of 0.4 m/s and an error range of ±0.1 m/s for wind speeds up to 10 m/s and ±1.1% of reading over 10 m/s. The wind direction covers 0˚ to 360˚, with a resolution of 0.01˚ and an error rate of ±4˚. The reading range for solar radiation is from 0 to 1.1 kW/m^2, with a resolution of ±300 kW/m^2 and an error range of ±5%. The *Delta-T-GP1* weather stations has a rainfall gauge with a 188mm funnel, a resolution of 0.2mm, and an error range of ±0.2mm (see Delta-T, 2014)

Thermal Comfort Questionnaire

Householders were asked to fill out a short thermal comfort questionnaire at the time when the data loggers were installed. The purpose of the thermal comfort questionnaire was to determine the perceived level of thermal satisfaction in relation to internal conditions, and socio-demographics and behavioural factors, such as activity level, clothing preferences and adaptive measures taken to keep warm.

The questionnaire included questions on respondents' perceived thermal comfort at the time of answering, their thermal comfort preferences, and retrospective reports of thermal conditions of their house in the previous/current winter. It asked about respondents' average activity level at home, clothing preferences, and adaptive behaviours to make themselves warmer in winter, as well as their understanding of heating controls. The full thermal comfort questionnaire can be found in Appendix A.

Data Analysis

In this working paper we describe the data collected in the first wave of the household monitoring study. Data from the weather stations were used to calculate the Heating Degree Days (HDDs), as an indicator of the demand for energy needed to heat buildings in the different areas. HDDs are essentially the summation of temperature differences over time, and hence they capture both extremity and duration of outdoor temperatures. The temperature difference is between a reference temperature and the outdoor air temperature. The reference temperature (T_{base}; 15.5˚C in the UK), is known as the base temperature which, for buildings the outdoor temperature at which the heating systems do not need to run in order to maintain comfort conditions (Hitchin, 1983).

The daily HDD was calculated according to the formulae below. The formulae cover the four possible cases with different minimum and maximum external air temperatures (T_{max} and T_{min}):

Condition	**Formula**
$T_{min} > T_{base}$	HDD = 0
$(T_{max} + T_{min})/2 > T_{base}$	HDD = $(T_{base} - T_{min})/4$
$T_{max} \geq T_{base}$	HDD = $(T_{base} - T_{min})/2 - (T_{max} - T_{base})/4$
$T_{max} < T_{base}$	HDD = $T_{base} - (T_{max} + T_{min})/2$

HDDs provide some advantages over other methods that use mean outdoor temperatures to calculate energy demand. They take account for fluctuations in the external air temperature and exclude periods when space heating is not needed, therefore capturing extreme conditions in a way that mean temperature methods cannot. This makes them more reliable in estimating energy consumption, particularly in milder conditions and in periods with extreme cold snaps where they capture both magnitude and duration of an event. HDDs also have a number of shortcoming (see e.g. Valor et al., 2001). They are based on assumptions when additional energy is needed to heat a building, and ignore that buildings are only heated during specific periods. To increase the accuracy of the HDD calculations, weather station were installed close to the monitored dwellings and short time intervals were used for monitoring internal and external conditions.

The Tinytag data loggers were used to monitor the internal conditions in *living room*, *kitchen* and *main bedroom*. The internal monitoring data were used for the three locations separately, and combined to estimate the average indoor air temperature and relative humidity for the whole house. Subsequently, the data were divided into four different time segments, i.e., *morning* (6am-9am), *day* (9am-6pm), *evening* (6pm-11pm), and *night* (11pm-6am). This provides more detail of how internal conditions vary across the day.

The length of sub-standard internal conditions was determined by recording the time the indoor air temperature was below 18˚C or 16˚C, and relative humidity was above 60% (see Figure 5). These thresholds were based on the literature showing that indoor air temperatures of at least 18°C in winter pose minimal risk to the health of healthy persons as well as to people over 65 years of age or with pre-existing medical conditions (Public Health England, 2014a). Indoor air temperatures below 18°C increase the risk of high blood pressure, with the risks being further heightened with temperatures under 16 temperatures under 16°C. Indoor air temperatures below 16°C may further diminish resistance to respiratory diseases (Public Health England, 2014b). Relative humidity above 60% has been linked to respiratory and allergic conditions, as well as fungal growth and house dust mite infestations (e.g. Arundel et al., 1986; Baughman & Arens, 1996). The weighted amount of sub-standard internal conditions is a composite of the length and depths under or above the chosen threshold. The weighted amount of sub-standard internal conditions thus represent the 'area' under the 16˚C or 18˚C threshold or above the 60% relative humidity threshold (see Figure 5). The weighted amounts are expressed in in °*C·Hour* and *%RH·Hour*, respectively.

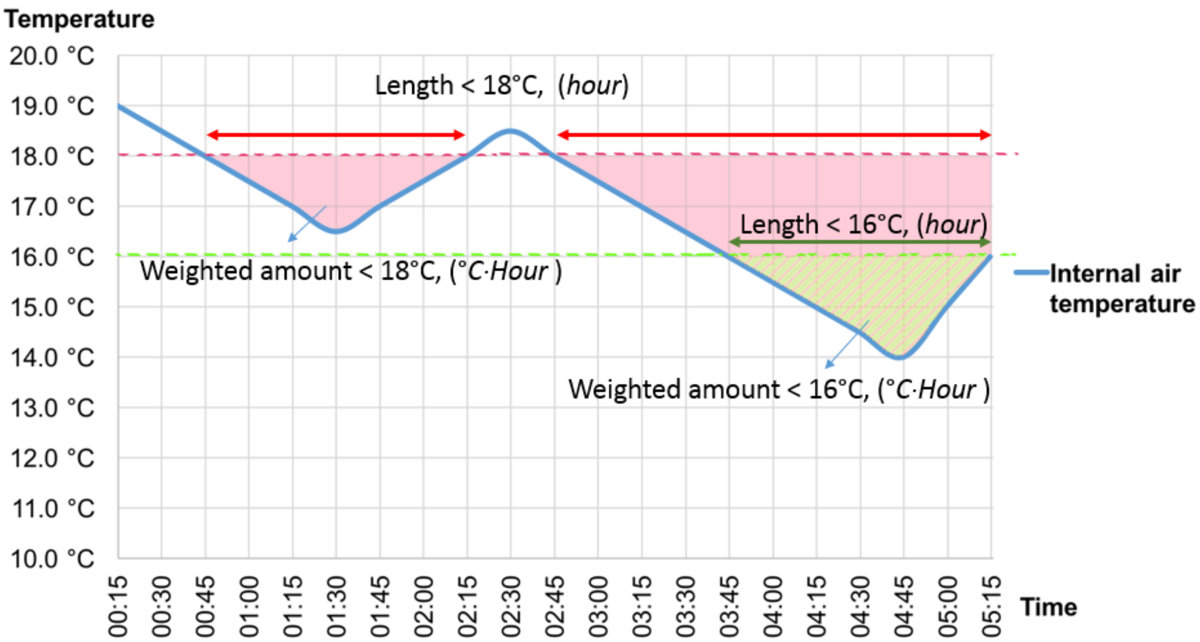

Figure 5. Length and weighted amount of sub-standard temperatures.

The internal readings of the monitored houses were analysed in three different ways. The first method (*Method 1*) used the indoor air temperature and relative humidity readings for the same 28-day period (3 February to 2 March 2014). This method shows the internal condition over a fixed period of time, irrespective of external conditions. The second method (*Method 2*) describes the indoor air temperature and relative humidity according to heating demand. This method first banded days in terms of their heating demand (i.e., <6 HDDs, 6-8

HDDs, 8-10 HDDs, 10-12 HDDS and >12 HDDs), after which the internal conditions were determined for the different days. This analysis shows the indoor air temperature and relative humidity of the monitored houses under different external conditions. Data from the whole monitoring period were used to conduct this analysis. The third method (*Method 3*) involved a selection of 28 (non-consecutive) days when heating demand exceeded 6 HDDs to describe internal conditions when supplementary energy is needed to heat a building to a comfortable temperature. Method 3 shows how buildings perform when supplementary heating is required to achieve a certain indoor temperature.

Appendix B consists of a series of figures and tables describing the internal conditions of the monitored households in detail. Figures B1 to B4 present the mean indoor air temperatures at different locations and times of day according to heating demand (Method 2), and indoor relative humidity at different locations and times of day according to external relative humidity. Tables B1 and B2 present the length and weighted amount of sub-standard internal conditions in the different monitoring areas over a fixed 28-day period (Method 1) and on days with heating demand exceeding 6 HDDs (Method 3), respectively. Tables B3 and B4 present the length of weighted amount of sub-standard internal conditions at different locations and times of day over a fixed 28-day period (Method 1) and on days with heating demand exceeding 6 HDDs (Method 3), respectively. Tables B5 and B6 present the weighted amount of sub-standard internal conditions at different locations and times of day over a fixed 28-day period (Method 1) and on days with heating demand exceeding 6 HDDs (Method 3), respectively.

Results

External Conditions

Figures 6 and 7 show the external air temperature and relative humidity in the five monitoring areas for the period of 3 February 2014 to 2 March 2014 (the period used for Method 1, see Page 14). The figures show large variations in time and space, with the external air temperature ranging between about 1°C and 11°C over the 28-day period. Monitoring areas in urban locations, such as Cardiff and Wrexham, had higher external air temperatures than those in semi-rural locations that were more exposed, such as Merthyr, Caerphilly and Carmarthenshire (see Figure 6).

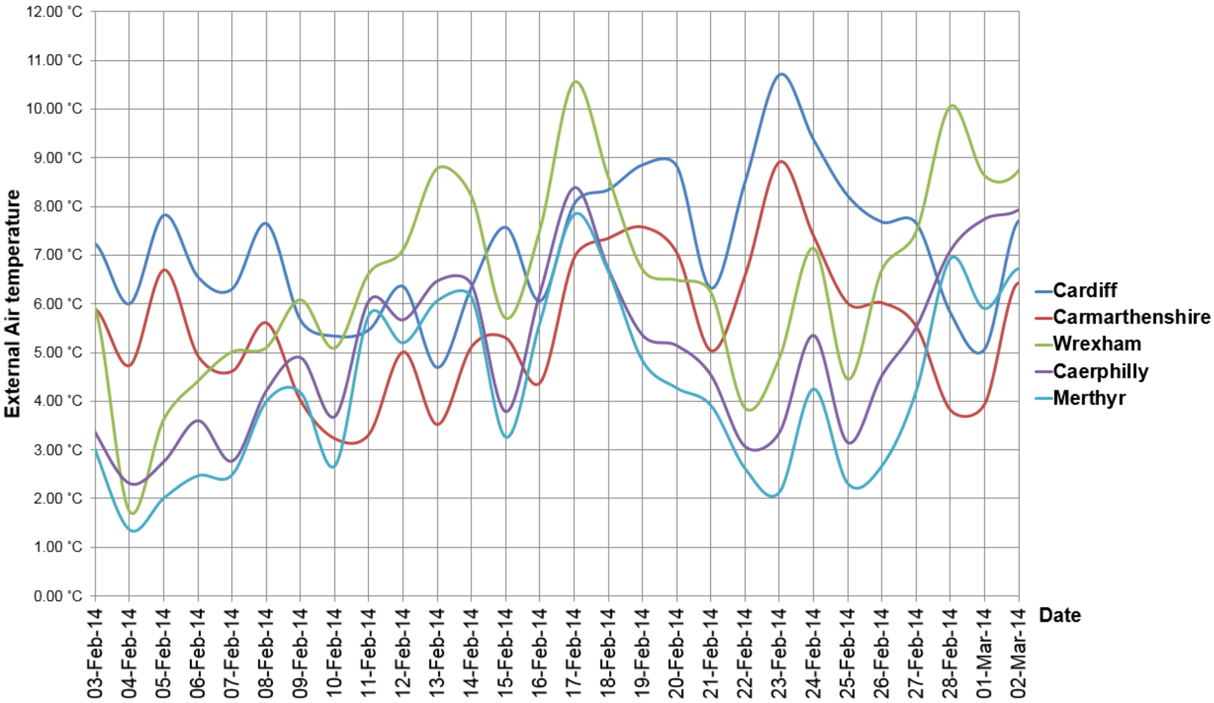

Figure 6. External air temperature for the five monitoring areas.

Figure 7 shows that there were also great variations in external relative humidity. Relative humidity ranged between 65% and nearly 100% over the 28-day period. External relative humidity tended to be lower in Cardiff and higher in Merthyr, Caerphilly and Carmarthenshire.

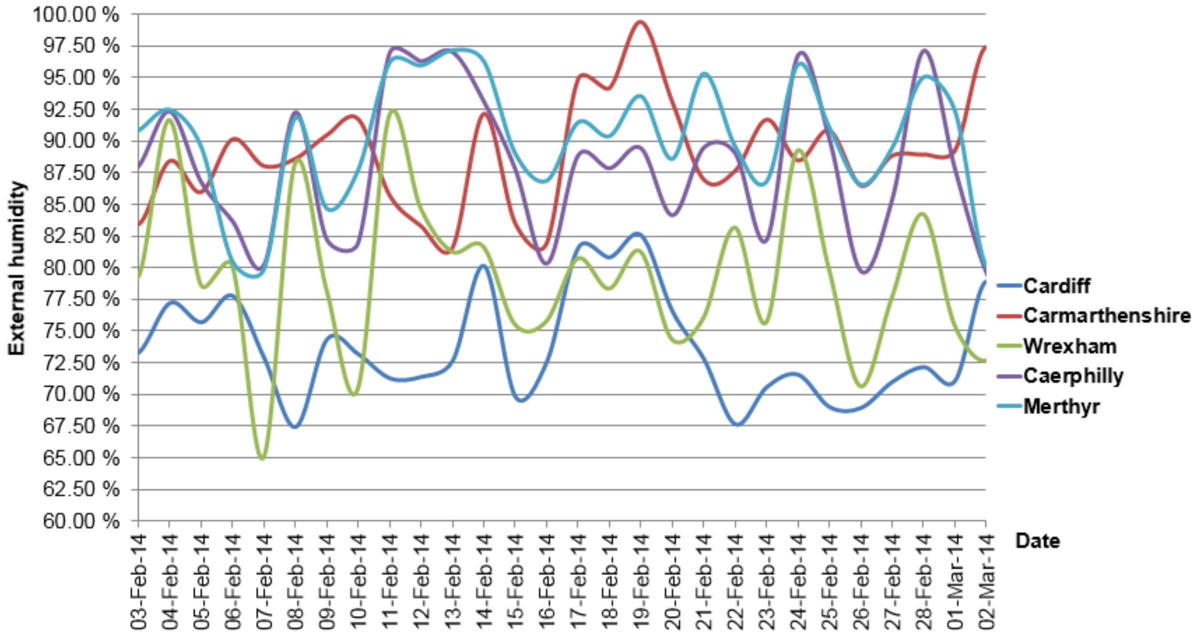

Figure 7. External relative humidity for the five monitoring areas.

The external air temperature readings were used to calculate the heating demand for the five monitoring areas. Figure 8 shows the number of days from the fixed 28-day period with different levels of heating demand (i.e., <6 HDDs, 6-8 HDDs, 8-10 HDDs, 10-12 HDDS and >12 HDDs). It shows great differences between the five monitoring areas. For example, Merthyr had 12 days with a heating demand greater than 12 HDDs, whereas both Cardiff and Carnarthenshire had none. In contrast, both Carmarthenshire and Cardiff had 14 days with a heating demand below 8 HDDs, whereas Merthyr, Caerphilly and Wrexham had none.

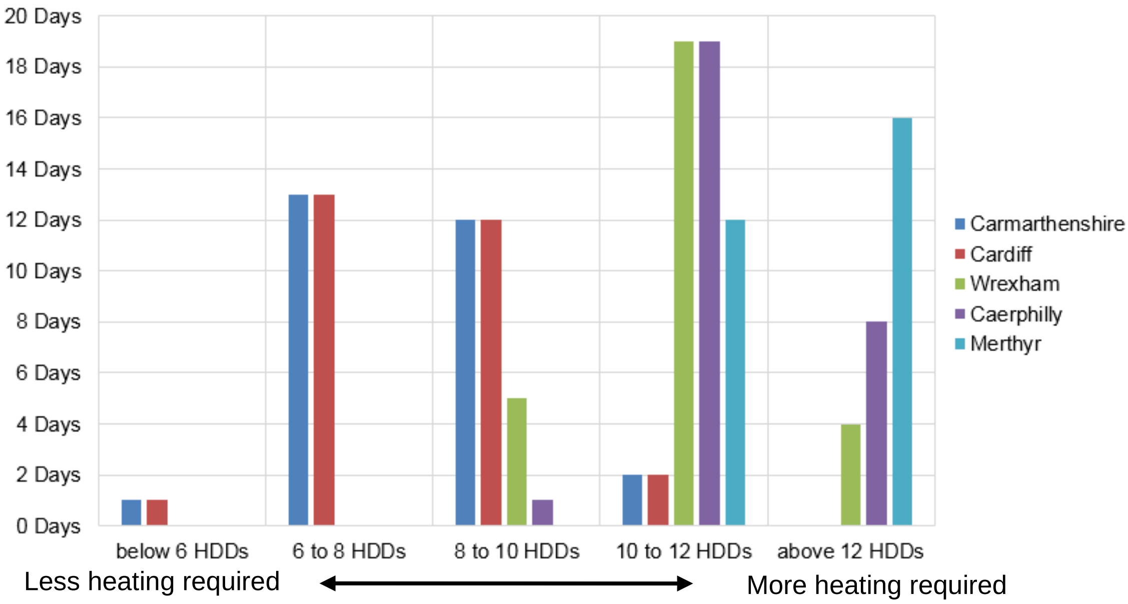

Figure 8. Heating demand distribution for the five monitoring areas.

Internal Conditions

Internal conditions over a fixed 28-day period (Method 1)

Figure 9 shows the distribution of the whole house indoor air temperature over a fixed 28-day period for the Arbed and control households, respectively (Method 1, see page 14). It shows that, on average, the control households had higher indoor air temperatures than the Arbed households. The Arbed households had indoor air temperatures below 16˚C for 37% of the time, as compared to 21% of the time for the control households. In contrast, the control households had an indoor air temperature between 18-24˚C for 55% of the time as compared to 41% of the time for the Arbed households. Both the Arbed and control household had indoor air temperatures between 16-18˚C for 20% of the time.

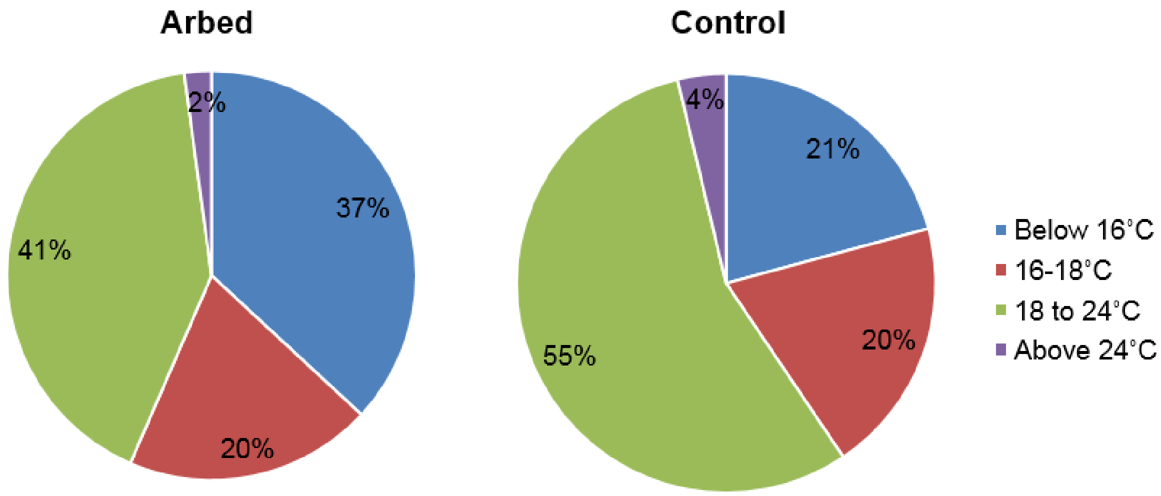

Figure 9. Whole-house indoor air temperature for the Arbed and control households.

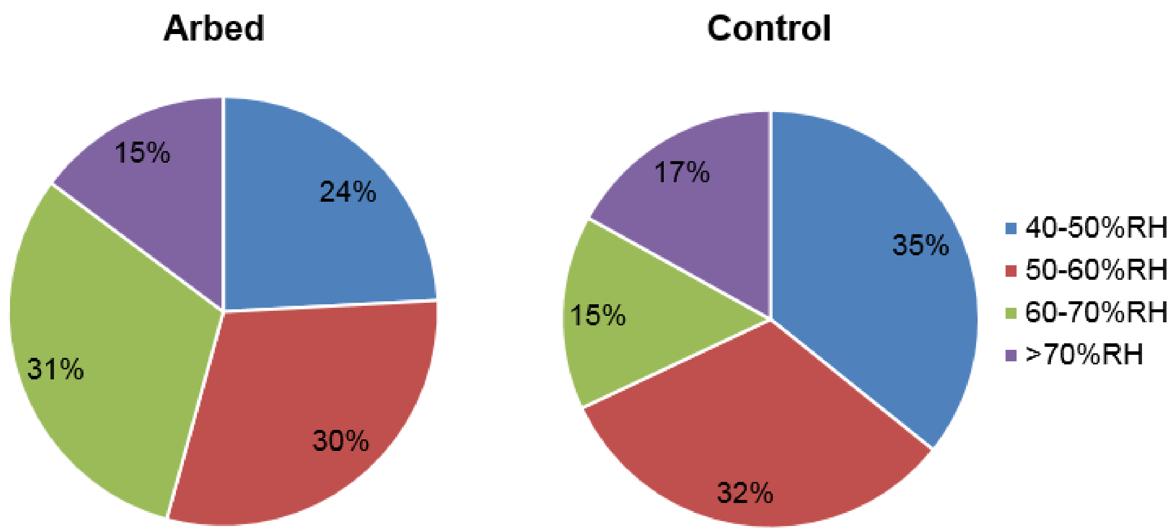

Figure 10. Whole-house relative humidity for the Arbed and control households.

The whole-house indoor relative humidity distribution is shown in figure 10 for the same 28-day period. Neither the Arbed nor the control group had a relative humidity reading below 40%RH. The Arbed group had twice as long relative humidity levels between 60-70%RH (31% versus 15% of the time), and one third shorter to relative humidity levels between 40-50%RH (24% versus 35% of the time). The two groups had similar lengths of relative humidity levels of 50-60%RH (30% v 32% of the time) and above 70%RH (15% v 17%).

Figure 11 shows the average lengths of sub-standard internal conditions over the fixed 28-day period for the different monitoring areas (Method 1). Households in Carmarthenshire had the longest periods of low indoor air temperatures and high relative humidity levels. They had indoor air temperatures under 18˚C for 18.07 hours per day (75% of the time), temperatures under 16˚C for 10.30 hours per day (43% of the time), and relative humidity levels exceeding 60% for 16.16 per day (67% of the time). Households in Merthyr had the shortest periods of indoor air temperatures under 18˚C and humidity exceeding 60%RH. Households in Wrexham had the shortest periods of indoor air temperatures under 16˚C.

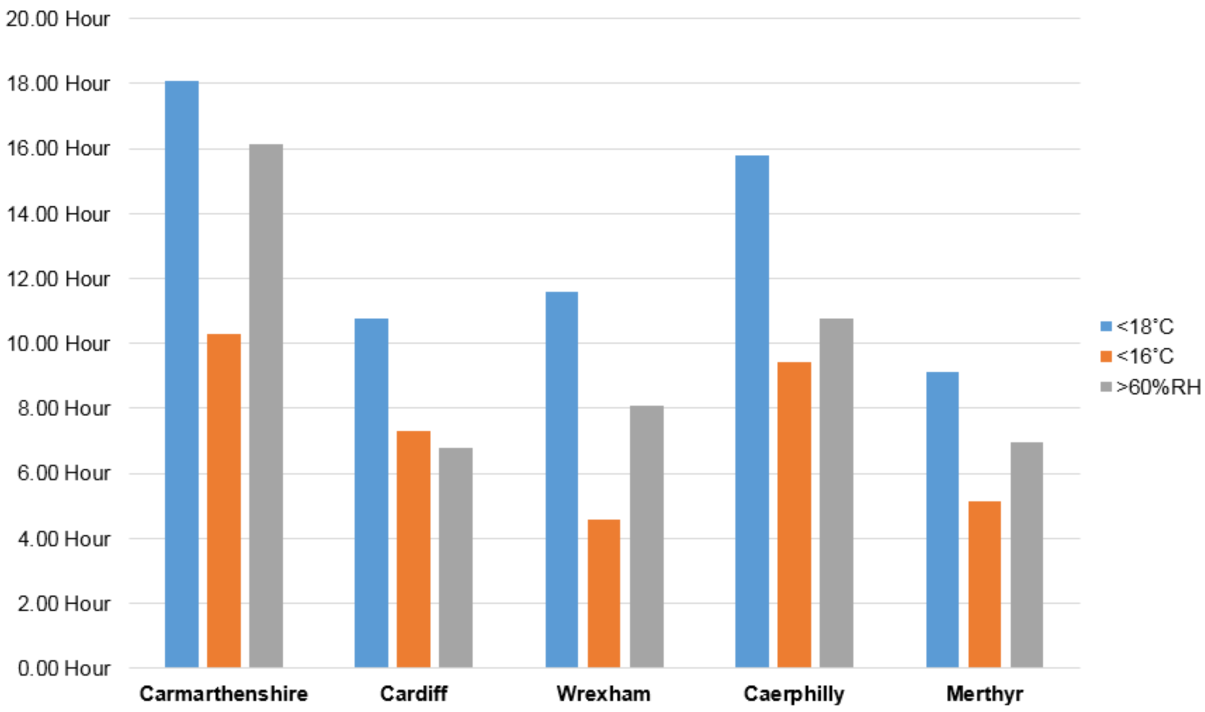

Figure 11. Average daily length of sub-standard internal condition over the fixed 28-day period (in Hours).

Figure 12 to 14 show the weighted amount of sub-standard internal conditions in the monitoring areas over the fixed 28-day period. Figure 12 shows that, on average, households in Carmarthenshire had 47.85 °C·Hour of indoor air temperatures under 18˚C per day, as compared to 23.60 °C·Hour in Wrexham. Figure 13 shows that, on average, households in Cardiff had 6.86 °C·Hour of indoor air temperatures under 16˚C per day, as compared to 4.72 °C·Hour in Wrexham. Figure 14 shows that, on average, households in Carmarthenshire had 143.56%RH·Hour of indoor relative humidity levels exceeding 60%RH per day, as compared to 38.95%RH·Hour in Cardiff.

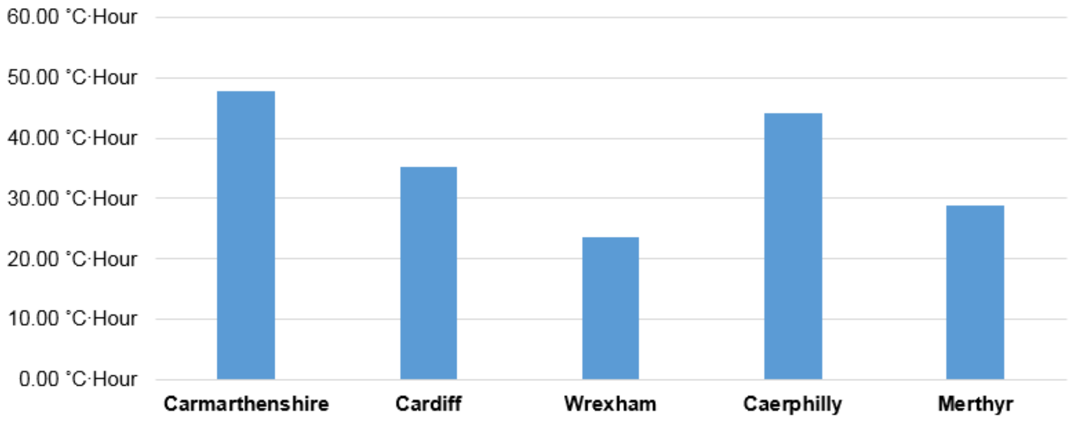

Figure 12. Average daily weighted amount of indoor air temperatures <18˚C over a fixed 28-day period (in °C·Hour).

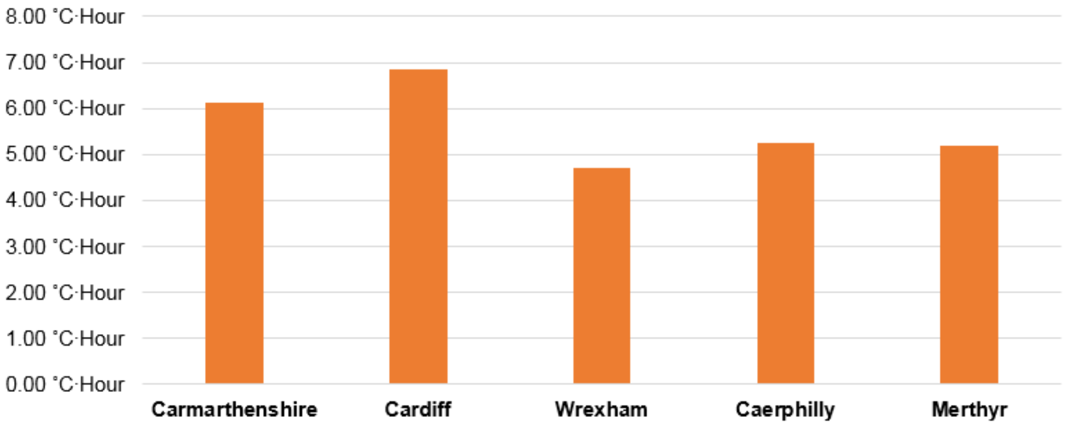

Figure 13. Average daily weighted amount of indoor air temperatures <16˚C over a fixed 28-day period (in °C·Hour).

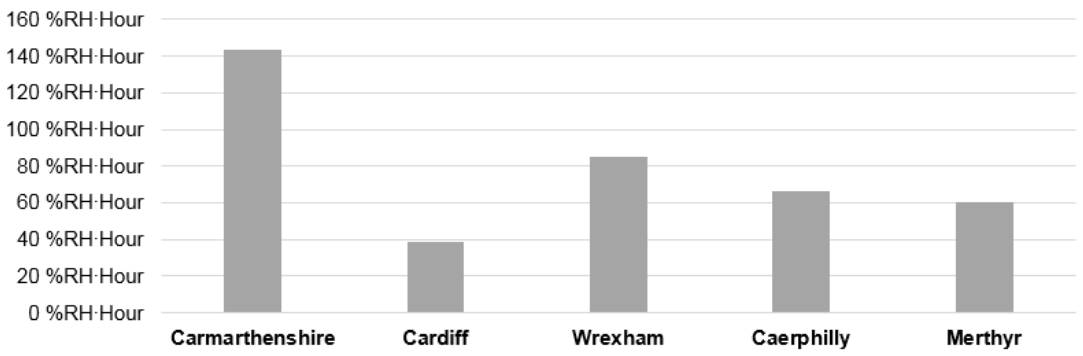

Figure 14. Average daily weighted amount of relative humidity >60%RH over a fixed 28-day period (in %RH·Hour).

Internal conditions for different levels of heating demand (Method 2)

Figure 15 and 16 present the indoor air temperatures for different daily heating demand (HDD) bands for Arbed and control properties respectively (Method 2, see page 14). It is clear from the two figures that the Arbed and control properties perform differently under different external conditions. The Arbed properties show a general trend of lower indoor air temperatures on days with higher energy demand (see Figure 10). The proportion of the time the indoor temperature was within the 18˚C and 24˚C band (the recommended comfort zone), decreased from 80% on days with a heating demand under 6 HDDs to 31% on days with a heating demand exceeding 12 HDDs.

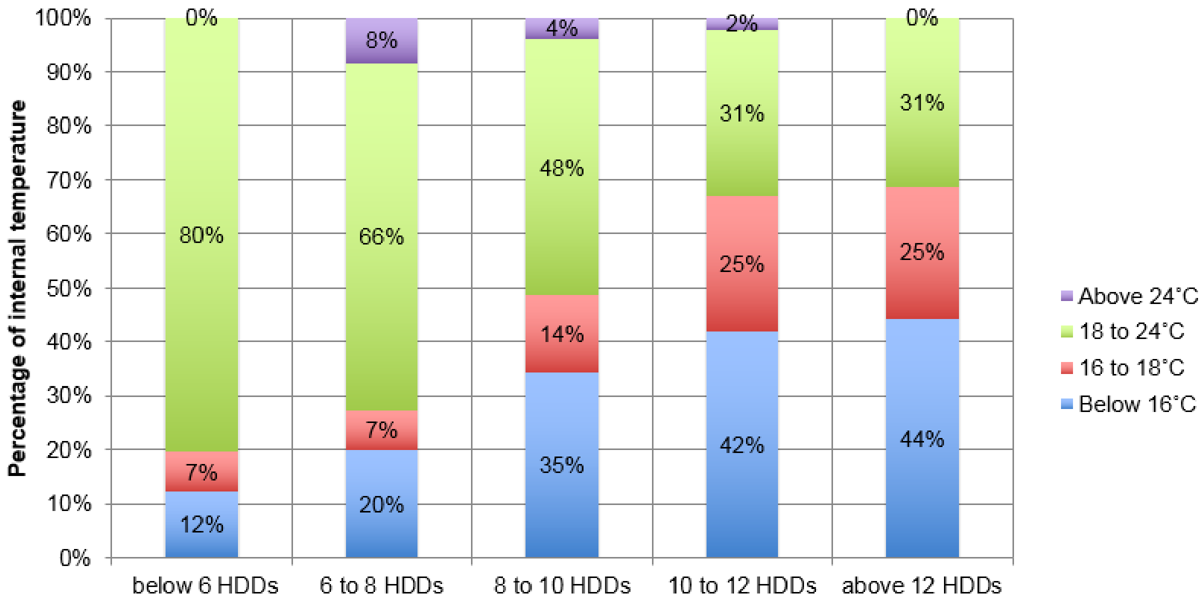

Figure 15. Indoor air temperature in Arbed properties for different daily heating demand (HDD) bands.

An opposite trend was found for the control properties (see Figure 16). Here the proportion of time the indoor temperature was within the 18˚C and 24˚C band increased from 44% on days with a heating demand under 6 HDDs to 66% on days with a heating demand exceeding 12 HDDs. In contrast, the proportion of the time the indoor temperature was below 16˚C increased for Arbed household with higher heating demand (from 12% on days with daily heating demand under 6 HDDs to 44% on days with heating demand exceeding 12 HDDs) but decreased for control households with higher heating demand (from 40% on days with heating demand under 6 HDDs to 11% on days with heating demand exceeding 12 HDDs). This suggests that control households heat their homes in a different way than Arbed households do. The meter readings suggests that the control households have a higher energy consumption than the Arbed households (see *Energy Consumption*), which would be consistent with these results.

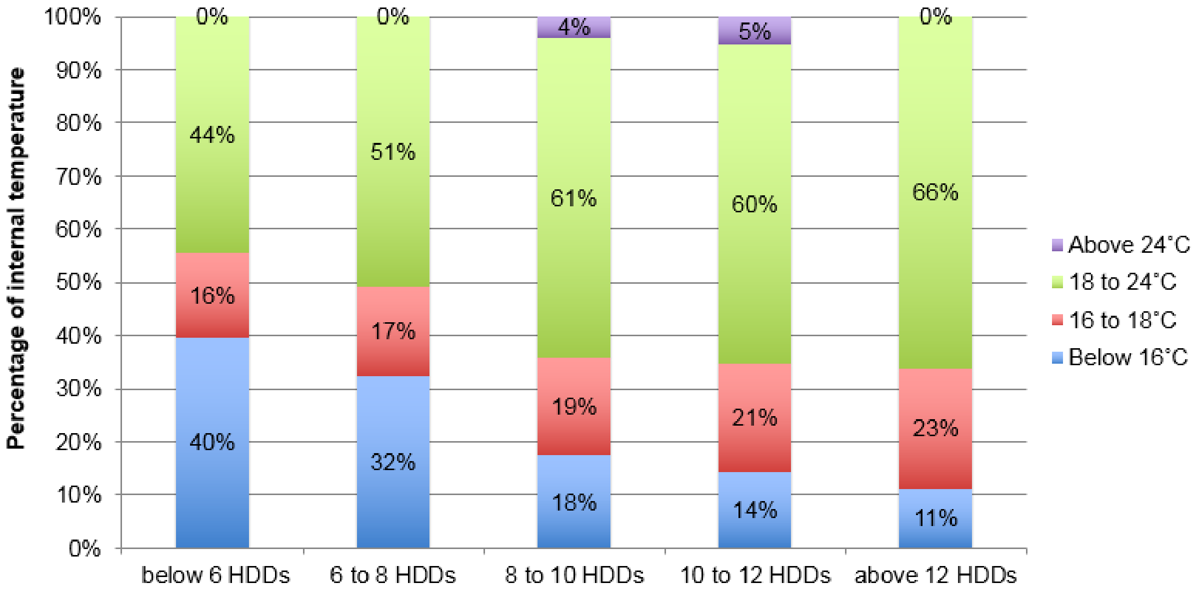

Figure 16. Indoor air temperature in control properties for different daily heating demand (HDD) bands.

Internal conditions when supplementary energy is needed (Method 3)

This section presents the internal conditions on days when heating demand exceeded 6 HDDs (Method 3, see page 15). This reflects the length and amount of low indoor air temperatures and high relative humidity levels on days when supplementary energy is needed to maintain thermal comfort.

Figure 17 shows the average daily length of sub-standard internal conditions for the five monitoring areas on days with heating demand exceeding 6 HDDs. It shows that households in Carmarthenshire had the longest periods of low indoor air temperatures and high relative humidity levels on cold days. On average, households in Carmarthenshire had temperatures under 18˚C for 19.97 hours per day (83% of the time), temperatures under 16˚C for 15.09 hours per day (63% of the time), and relative humidity levels exceeding 60%RH for 22.42 hours per day (93% of the time). Households in Cardiff, Wrexham and Merthyr had much shorter periods of sub-standard internal conditions on days with heating demand exceeding 6 HDDs.

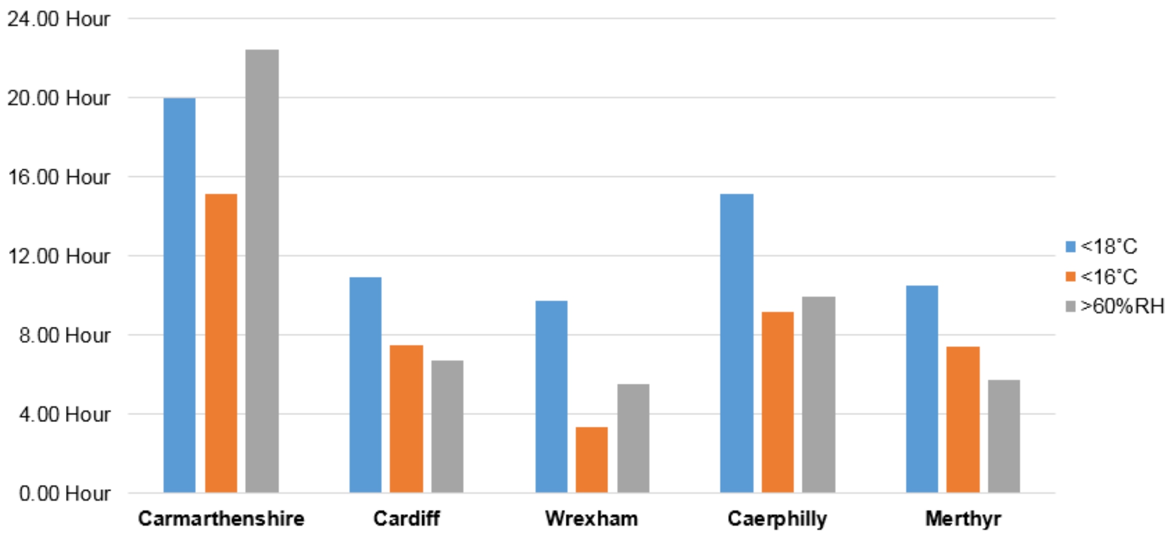

Figure 17. Average daily length of sub-standard internal conditions on days with heating demand exceeding 6 HDDs (in Hours).

Households in Carmarthenshire also had the greatest weighted amount of sub-standard internal conditions (see Figures 18, 19 and 20). Figure 18 shows that, on average, households in Carmarthenshire had 68.85 °C·Hour of indoor air temperatures under 18˚C per day, as compared to 17.37 °C·Hour in Wrexham. Figure 19 shows that, on average, households in Carmarthenshire had 8.99 °C·Hour of indoor air temperatures under 16˚C per day, as compared to 3.41 °C·Hour in Wrexham. Figure 20 shows that, on average, households in Carmarthenshire had 193.95%RH·Hour of indoor relative humidity levels exceeding 60%RH per day, as compared to 37.90%RH·Hour in Cardiff.

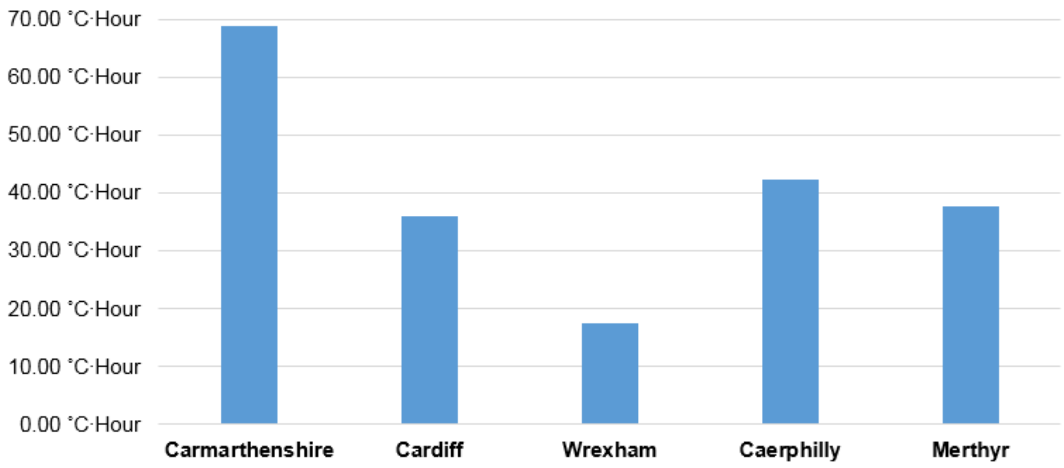

Figure 18. Average daily amount of indoor air temperatures <18˚C on days with heating demand exceeding 6 HDDs (in °C·Hour).

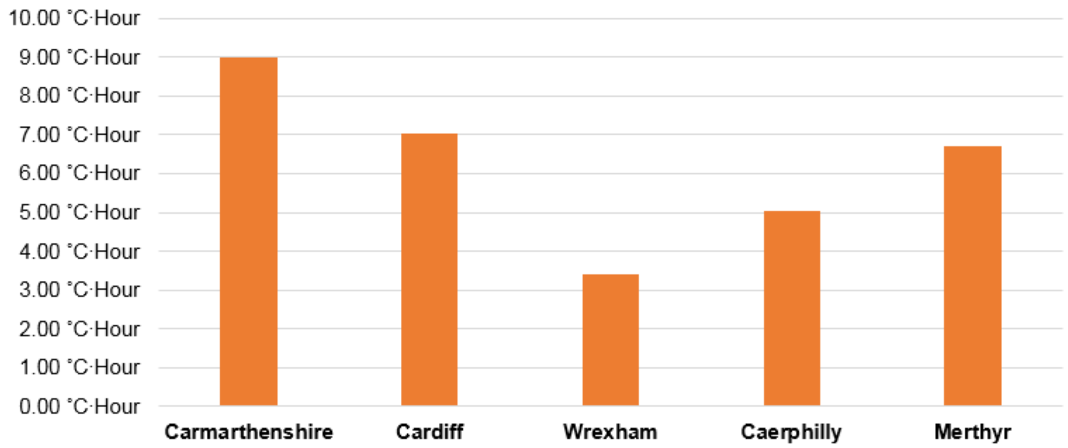

Figure 19. Average daily weighted amount of indoor air temperatures <16˚C on days with heating demand exceeding 6 HDDs (in °C·Hour).

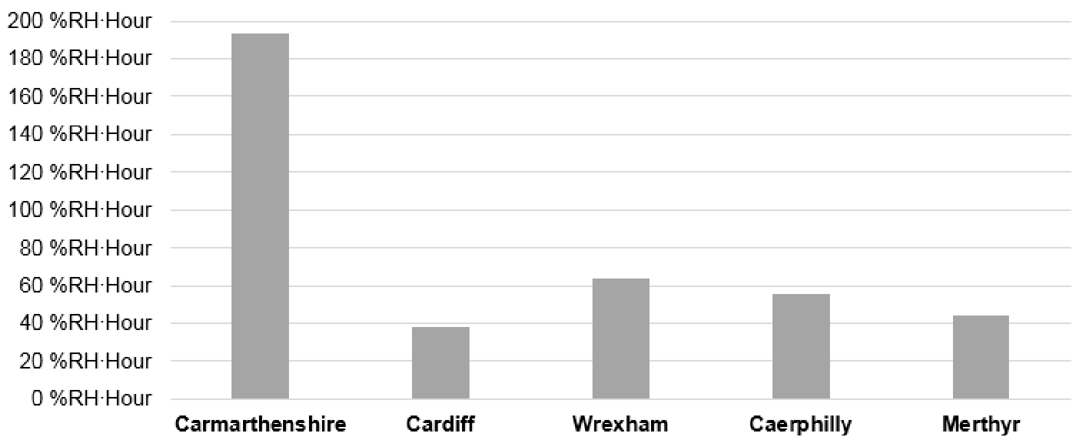

Figure 20. Average daily weighted amount of relative humidity >60%RH on days with heating demand exceeding 6 HDDs (in %RH·Hour).

Method 3 was further used to explore how internal conditions vary across the house (living room, kitchen, and main bedroom) and times of day (morning, day, evening, and night). The results therefore reflect the length and weighted amount of sub-standard internal conditions at the different locations and times of day on days when supplementary energy is needed to maintain thermal comfort. The maximum length of sub-standard internal conditions is 3 hours in the morning (6am-9am), 9 hours in the day (9am-6pm), 5 hours in the evening (6pm-11pm), and 7 hours in the night (11pm-6am).

Figure 21 shows the average daily lengths of indoor air temperatures under 18˚C in the living room at different times of the day. It shows that households in Carmarthenshire had the longest indoor air temperatures under 18˚C in the morning, evening, and day (for 49%, 38%, and 41% of the respective periods). Households in Wrexham had the shortest indoor air temperatures under 18˚C in the morning, evening, and day (for 26%, 13%, and 19% of the respective periods).

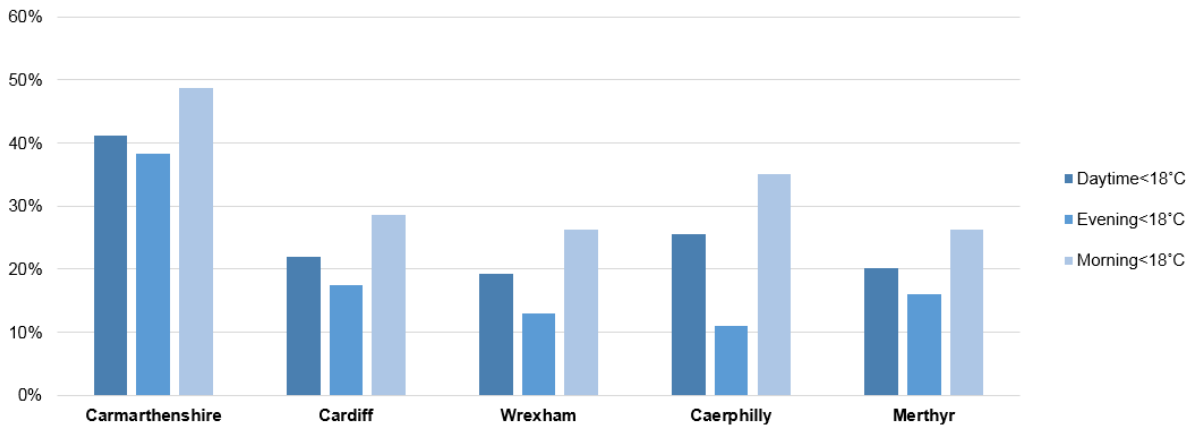

Figure 21. Average daily lengths of indoor air temperatures <18˚C in the living room at different time of day (% of time).

Figure 22 shows a similar pattern for the average length of indoor air temperatures being under 16˚C in the living room at different times of day. Households in Carmarthenshire had the longest indoor air temperatures under 16˚C in the morning, day and evening (38%, 38% and 28% of the respective periods). Households in Caerphilly had the shortest indoor air temperatures under 16˚C (13%, 9% and 11% of the respective periods).

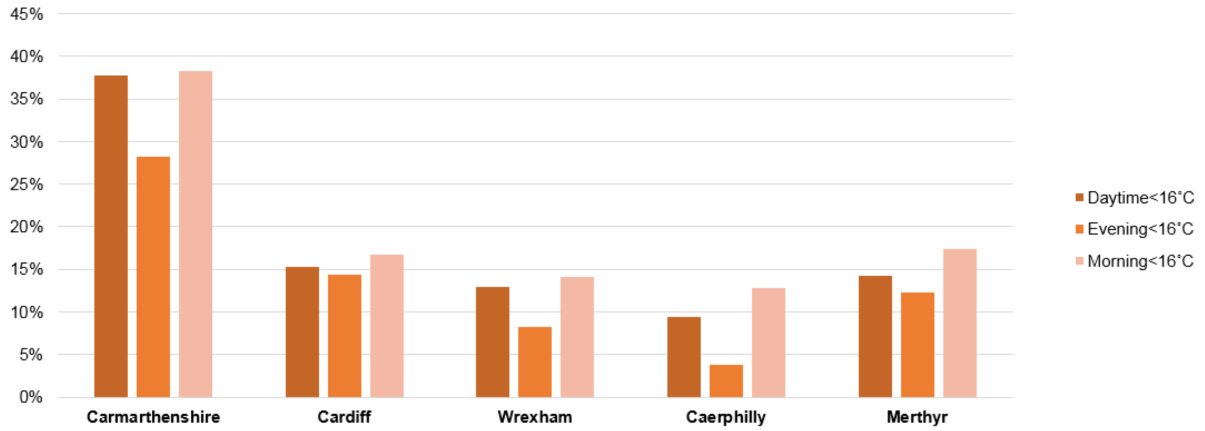

Figure 22. Average daily length of indoor air temperatures <16˚C in the living room at different time of day in (% of time).

Figure 23 shows the average length of indoor air temperatures being under 18˚C in the bedroom during the night and morning. Households in Caerphilly had the longest time of indoor air temperatures being under 18˚C at night (40% of the time), and households in Cardiff the shortest (15% of the time). Households in Caerphilly had the longest time of indoor air temperatures being under 18˚C in morning (44% of the time). Households in Merthyr had the shortest time of indoor air temperatures being under 18˚C in the morning (23% of the time).

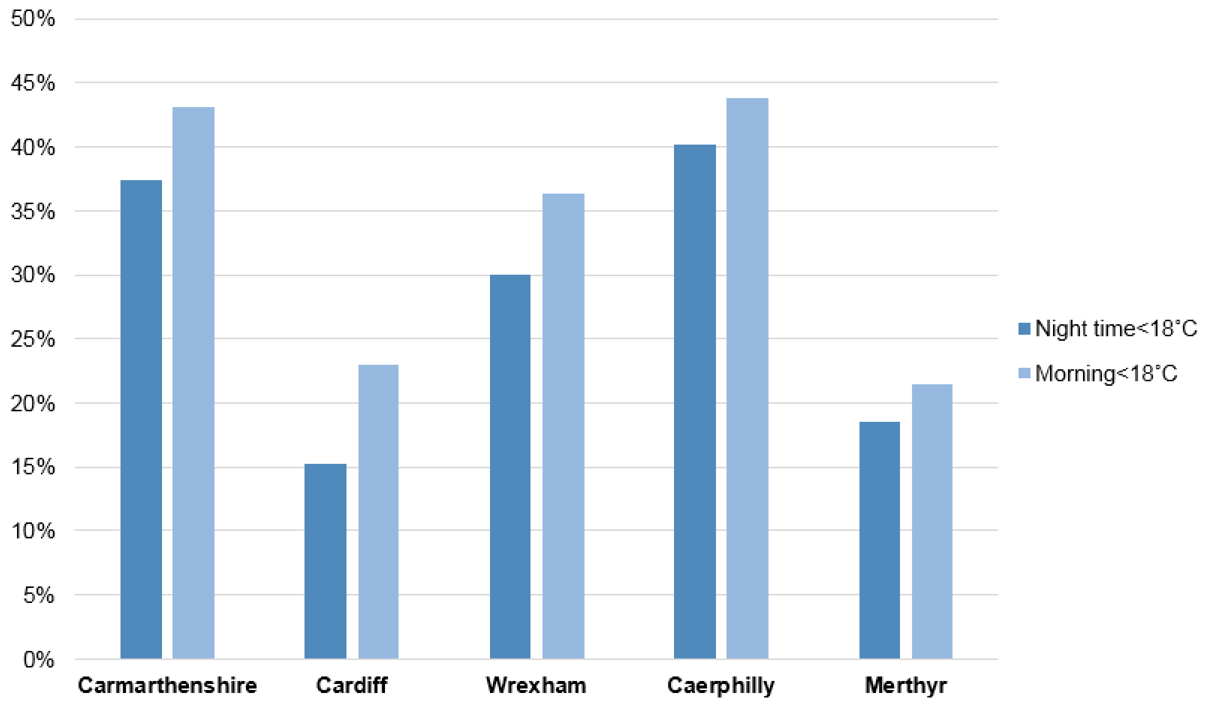

Figure 23. Average daily length of indoor air temperatures <18˚C in the main bedroom at night and in the morning (% of time).

Figure 24 shows the average length of indoor air temperatures being under 16˚C in the bedroom during the night and morning. Households in Carmarthenshire had the longest time of indoor air temperatures being under 16˚C at night (28% of the time), and households in Cardiff the shortest (10% of the time). Households in Carmarthenshire had the longest time of indoor air temperatures being under 16˚C in morning (35% of the time). Households in Cardiff had the shortest time of indoor air temperatures being under 16˚C in morning (13% of the time).

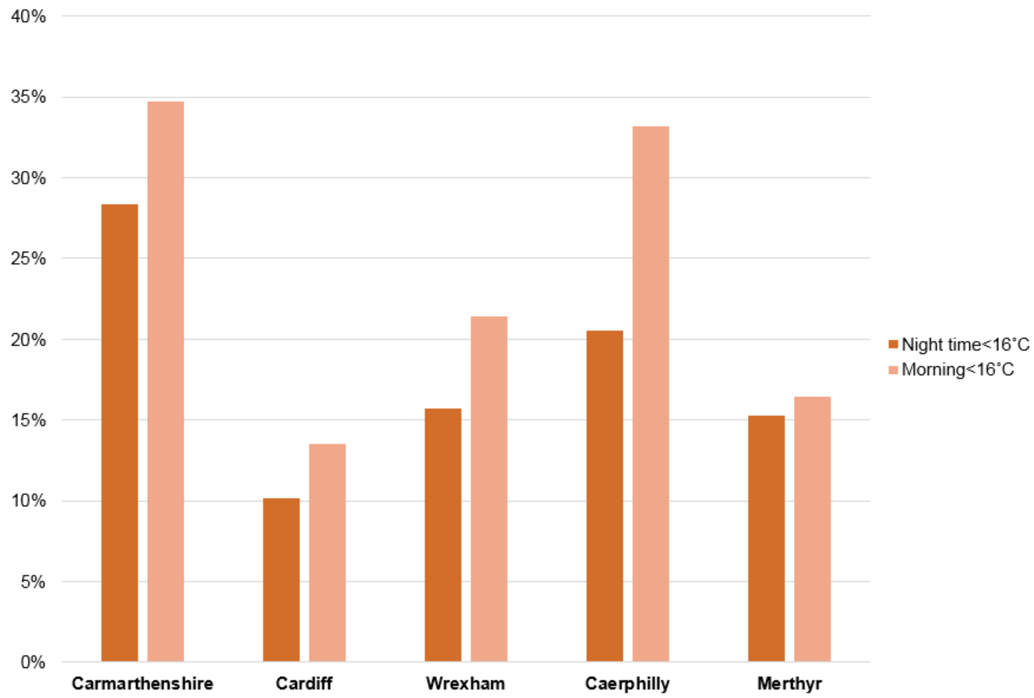

Figure 24. Average daily length of indoor air temperatures <16˚C in the main bedroom at night and in the morning (% of time).

Thermal Comfort

Table 2 summarises the overall thermal satisfaction during the current winter and the occupants' thermal comfort preferences. Overall, about a quarter (27%) felt that the indoor conditions of their house were 'cold', and a further 37% that they were 'slightly cool'. Twenty eight percent (28%) rated the indoor conditions of their house as 'neutral'. A majority expressed a preference for being warmer (61%) and about a third (35%) expressed a preference for 'as it is'. There were some differences between the Arbed and control group participants. More participants from the control group felt that the indoor conditions of their house were 'cold' as compared to those from the Arbed group (31% and 24% respectively), but fewer participants from the control group felt that the indoor conditions of their house were 'slightly cool' as compared to those from the Arbed group (33% and 42% respectively).

Table 2. Thermal comfort in the current winter (%).

		Arbed (n=50)	**Control (n=49)**	**Overall (n=99)**
How would you describe the indoor conditions of your house in the current winter?	Cold	24.0	30.6	27.3
	Cool	6.0	4.1	5.1
	Slightly Cool	42.0	32.7	37.4
	Neutral	26.0	30.6	28.3
	Slightly Warm	2.0	2.0	2.0
	Warm	0.0	0.0	0.0
	Hot	0.0	0.0	0.0
Would you prefer to be:	Cooler	0.0	0.0	0.0
	Slightly Cooler	0.0	4.1	2.0
	As it is	38.0	32.7	35.4
	Slightly Warmer	40.0	28.6	34.4
	Warmer	12.0	16.2	12.1
	Much Warmer	10.0	18.4	14.2

Spot measures of the indoor air temperature and relative humidity were taken in the living room at the same time as residents filled out the thermal comfort questionnaire. Table 3 shows that most houses had an indoor air temperature between 18˚C and 22˚C (63%), and a further 14% an indoor air temperature between 16˚C and 18˚C. Fourteen percent (14%) had an indoor air temperature below 16˚C and 9% an indoor air temperature above 22˚C. there were only small differences between the Arbed and control groups. There were greater differences in terms of the spot-measured relative humidity. On average, the Arbed houses had higher relative humidity levels than the control houses. Half of the Arbed houses (50%) had relative humidity levels of at least 56% (compared to 25% of the control houses). In contrast, 56% of the control houses had a relative humidity level between 51% and 55% (compared to 32% of the Arbed houses). Twenty percent (20%) of the Arbed houses had relative humidity levels below 50%, as had 22% of the control houses.

Table 3. Spot-measured indoor air temperature, relative humidity, and thermal comfort (%).

		Arbed (n=50)	Control (n=49)	Total (n=99)
Spot-measured indoor air temperature	<16˚C	12.0	16.3	14.1
	16˚C-18˚C	13.3	13.6	13.5
	18˚C-22˚C	64.7	61.9	63.3
	>22˚C	10.0	8.2	9.1
Spot-measured relative humidity	<40%	2.0	0.0	1.0
	40-45%	4.0	14.0	8.9
	46-50%	12.0	8.2	10.1
	51-55%	32.0	56.1	43.9
	56-60%	28.0	20.4	24.2
	>60%	22.0	4.1	13.1
How would you describe your thermal comfort at present?	Cold	4.0	16.3	10.1
	Cool	10.0	16.3	13.1
	Slightly Cool	14.0	2.0	8.1
	Neutral	56.0	51.0	53.5
	Slightly Warm	12.0	4.1	8.1
	Warm	4.0	6.1	5.0
	Hot	0.0	4.1	2.0

Table 4 lists a number of behavioural aspects related to thermal comfort. Participants from the Arbed group were more likely to walk around than participants from the control group (58% versus 27%). Participants from the control group were more likely to report their average activity level as 'seated relaxed' or 'sedentary activity' as compared to those from the Arbed group (22% and 27% versus 10% and 2%, respectively). There were also some differences regarding clothing preferences. Table 4 shows that participants from the control group had lighter clothing preferences than those from the Arbed group. The average *clothing insulation value* was 0.75 clo for Arbed occupants and 0.59 clo for control occupants. A clothing insulation value was 0.60 clo reflects typical summer clothing, such as wearing a t-shirt and shorts.[3] This suggests that participants prefer to wear lightweight clothing at home even during winter. However, when occupants were asked what they have done to make themselves warmer in winter, "putting more clothes on" was selected the most often (81%) followed by taking a hot drink (70%) and adjusting the thermostat (67%). Less than half of the occupants indicated using a portable heater (50%) or adjusting the setting of a radiator (44%). The differences between the Arbed and control groups were small regarding the things they do to make themselves warmer in winter. A majority of 84% indicated that they understand the heating control in this home very well.

[3] Clo is a unit to measure the insulation provided by garments and clothing ensembles (ASHRAE, 2014).

Table 4. Behavioural aspects of thermal comfort (%)

		Arbed (n=50)	Control (n=49)	Total (n=99)
How would you describe your average activity level at home?	Seated relaxed	10.0	22.4	16.1
	Sedentary Activity	2.0	26.5	14.1
	Standing Light Activity	24.0	10.2	17.2
	Standing Medium Activity	6.0	14.3	10.1
	Walking around	58.0	26.5	42.4
What would you prefer to wear in your house during winter?	T-Shirt	56.0	73.5	64.7
	Pyjama	12.0	16.3	14.1
	Robe	10.0	8.2	9.1
	Hoody	12.0	10.2	11.1
	Sweater	56.0	36.7	46.4
	Shorts	6.0	8.2	7.1
	Trousers	82.0	75.5	78.8
	Woolly Hat	10.0	4.1	7.1
	Scarf	10.0	12.2	11.1
	Socks	76.0	55.1	65.7
	Flip flop	36.4	63.6	49.9
	Slippers	84.0	63.3	73.8
Have you done any of the following to make yourself warmer in winter?	Put more clothes on	78.0	83.7	80.8
	Adjust the setting of a radiator	44.0	42.9	43.5
	Use portable heater	37.5	62.5	49.9
	Draught proof windows/doors	60.0	53.1	56.6
	Taking a hot drink	66.0	73.5	69.7
	Adjust thermostat	72.0	61.2	66.7
	Close a window	50.0	67.3	58.6
How well do you understand the heating control in this home?	Not at all	0.0	4.1	2.0
	A little	0.0	4.1	2.0
	About right	2.0	0.0	1.0
	Quite well	18.0	4.1	11.1
	Very well	80.0	87.8	83.9

Energy Consumption

Figures 25 and 26 show the average daily gas consumption and the daily electricity consumption for the Arbed and control groups, respectively. Control households consumed more gas than Arbed households did over the monitoring period (see Figure 25). The average daily gas consumption was 4.63 m^3 for the control households and 3.62 m^3 for the Arbed households. This comparison of gas excluded households from three off-gas areas. The gas consumption estimates were therefore based on 29 Arbed households and 30 control households. Arbed and control households consumed a similar amount of electricity (see Figure 26). The average daily electricity consumption was 9.67 kWh for the Arbed households and 10.01 kWh for the control households. The differences in gas consumption between the Arbed and control households may reflect different heating behaviours, as gas is mainly used for space and water heating, and to a lesser extent for cooking. This would be in line with the observed indoor air temperature patterns for the two groups (see Figures 9 and 10).

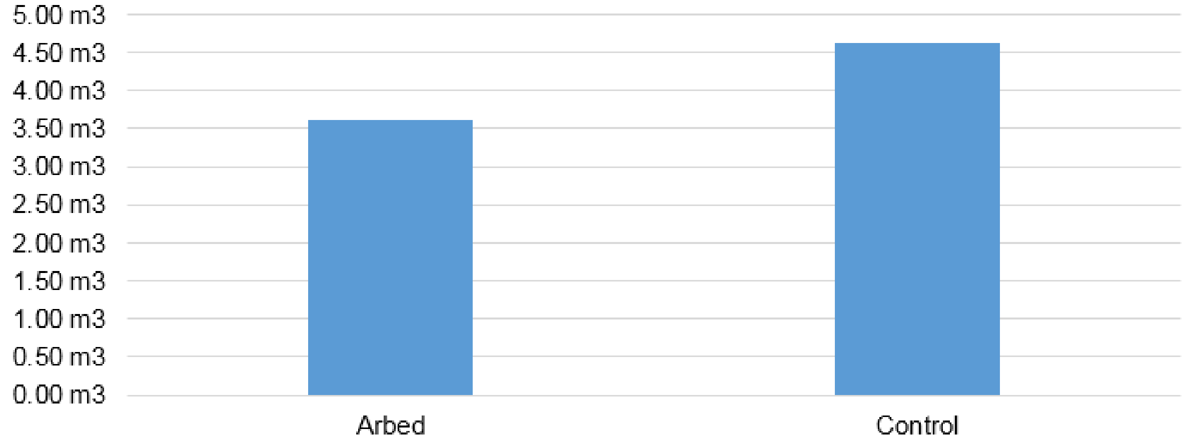

Figure 25. Average daily gas consumption per household

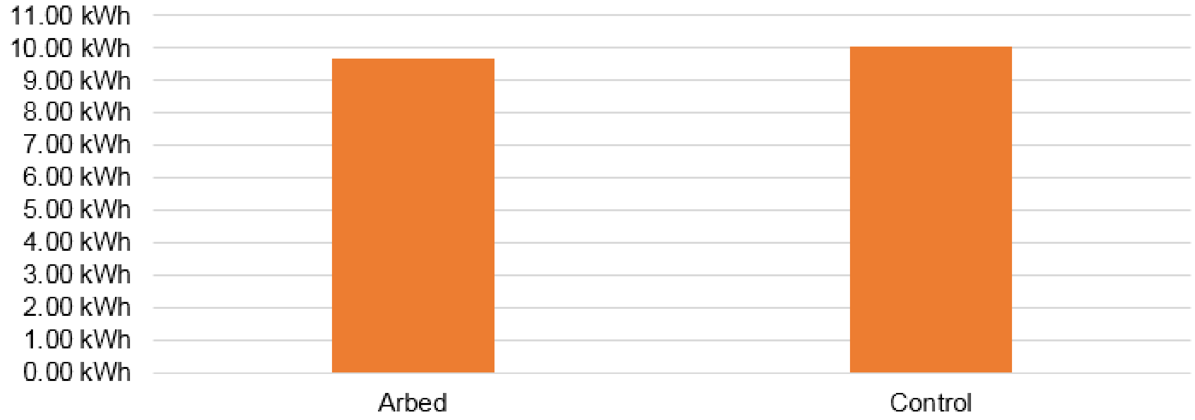

Figure 21. Average daily electricity consumption per household

Summary and Conclusion

This working paper presented the descriptive results of the first phase of a household monitoring work package of research project on the health impacts of structural energy performance investments in Wales. Data for the first phase of the monitoring study were collected in the heating season of 2013-2014, from 19 January to 31 March 2014. The internal conditions of 99 dwellings, of which 50 were located in five low-income areas where Arbed energy-performance investments were planned and 49 in five matched control areas where no such investments were planned. The monitoring data was used to determine the length and weighted amount of sub-standard internal conditions (i.e. <18˚C, <16˚C, and >60% relative humidity). In addition, the study recorded external meteorological conditions in the different monitoring areas. Data from the weather stations were used to determine the heating demand in Heating Degree Days (HDD) for the different areas. Participants were further asked to fill out a short thermal comfort questionnaire, and assessed energy consumption over the monitoring period.

The household monitoring data were analysed and described in three different ways. First, the indoor air temperature and relative humidity were summarised for a fixed 28-day period (3 February to 2 March 2014). Second, all the readings of internal conditions were described according to different levels of heating demand (HDD). Third, indoor air temperature and relative humidity were determined for 28 non-consecutive days with heating demands exceeding 6 HDDs to describe internal conditions when supplementary energy is needed to heat a building.

The results show that the Arbed dwellings had longer and a greater amount of sub-standard indoor air temperatures over the fixed 28-day period as compared to the control dwellings. Similarly, the Arbed dwellings had longer and a greater amount of sub-standard relative humidity readings as compared to control dwellings. There were further differences between the two groups regarding the relationship between external and internal conditions. Whereas the Arbed dwellings showed a general trend of lower indoor air temperatures on days with higher energy demand, the control dwellings showed a reverse trend of higher indoor air temperatures on days with higher energy demand. This suggests that control households heat their homes in a different way than Arbed households do. The higher average daily energy consumption of the control households would consistent with these results.

Despite the control dwellings generally having higher indoor air temperatures than the Arbed dwellings, participants from the control areas were more likely to report that the indoor conditions of their house are cold winter and that they prefer it to be warmer or much warmer. This would be in line the participants from the control areas having lower activity levels at home and preferring to wear lighter clothing.

The study further showed that local climatic condition vary considerably across the five monitoring areas. External air temperatures were generally higher in areas located in urban locations than in semi-rural locations. A similar pattern was found for external relative humidity, which tended to be lower in urban locations than in semi-rural locations.

The differences in internal conditions between the five monitoring areas were in line with the observed external conditions. Households in the more exposed semi-rural locations had longer and a greater amount of sub-standard internal conditions than those in the less exposed urban locations. These differences varied across different rooms in the house and different times of day. In general, households in the Carmarthenshire and Caerphilly areas had longer sub-standard internal conditions than those in Cardiff and Wrexham. However, these differences were generally smaller in the evening and morning. Furthermore, households in Caerphilly had the shortest sub-standard indoor air temperatures in the living room throughout the day, and for the whole house during the evening.

The study has shown that internal conditions and thermal comfort are closely related to external climatic conditions, building type and fabric, heating behaviours, as well as activity levels and clothing preferences. Understanding how energy performance investments impact upon internal conditions of dwellings requires all these factors to be taken into account. While the study involves detailed monitoring of internal and external conditions, it only recorded aggregated energy consumption over the monitoring period, and provided a snapshot of thermal comfort, activity levels and clothing preferences as collected in the thermal comfort survey. That limits the ability of the study to disentangle the factors in detail; it is, for example, not possible to disaggregate energy consumption to specific appliances or periods. Despite these limitations, the study is set up to allow a detailed before and after comparison of internal conditions, while controlling for external meteorological conditions.

The presented results will become part of the controlled monitoring study to examine whether and how energy performance investments improve internal conditions of 'hard-to-heat, hard-to-treat' houses in low-income areas in Wales. The data will be combined with follow-up measurements taken during the 2014-15 heating season after the Arbed improvements were finished. The impact of the energy-performance investments on energy consumption will be determined at the property level, taking into account overall heating demand over the monitoring period.

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Appendix A: Thermal comfort survey

Index No. ☐☐☐☐☐☐ Date:_/_/___

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

NHS National Institute for Health Research

Thermal comfort survey

The intent of this survey is to solicit anonymous responses on thermal comfort.

Air Temperature (°C):	Location:
Relative Humidity (%):	Gender: M F
Air Movement (m/s):	Age (optional): 4-15, 16-29, 30-44, 45-54, 55-65, 65+
WME internal wall (%):	Moved in for: ☐less than 1 year ☐1-2 years, ☐ 3-5 years, ☐more than 5 years

1. How would you describe of your thermal comfort at present?

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2. Would you prefer to be:

-3	-2	-1	0	+1	+2	+3
Much cooler	Cooler	Slightly cooler	Neutral	Slightly warmer	Warmer	Much warmer

3. How would you describe the following indoor conditions of your house in last/current winter?

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

4. How would you describe your average activity level at home?

☐Seated relaxed ☐Sedentary activity ☐Standing light activity
☐Standing medium activity ☐Walking around

5. What would you prefer to wear in your house during winter?

6. Have you done any of the following to make yourself warmer in winter? (Check all that apply)

☐Put on more clothes
☐Adjust the setting of a radiator
☐Portable heater
☐Draught proof windows and doors
☐Hot drink
☐Thermostat
☐Close a window
☐Other actions, please describe: ____

____

____

____

____

7. How well do you understand heating control in this home?

Appendix B: Detailed description of the internal conditions of the monitored households

Figure B1. Mean and standard deviation of indoor air temperature in different locations according to heating demand (HDD)

Figure B2. Mean and standard deviation of whole-house indoor air temperature at different time of day according to heating demand (HDD)

Figure B3. Mean and standard deviation of indoor relative humidity in different locations according to external relative humidity

Figure B4. Mean and standard deviation of whole-house indoor relative humidity at different time of day according to external relative humidity

Table B1. Length and weighted amount of sub-standard internal conditions in the monitoring areas over a fixed 28-day period (Method 1)

Table B2. Length and weighted amount of sub-standard internal conditions in the monitoring areas on days with heating demand exceeding 6 HDDs (Method 3)

Table B3. Length of sub-standard internal conditions at different locations and times of day over a fixed 28-day period (Method 1)

Table B4. Length of sub-standard internal conditions at different locations and times of day on days with heating demand exceeding 6 HDDs (Method 3)

Table B5. Weighted amount of sub-standard internal conditions at different locations and times of day over a fixed 28-day period (Method 1)

Table B6. Weighted amount of sub-standard internal conditions at different locations and times of day on days with heating demand exceeding 6 HDDs (Method 3)

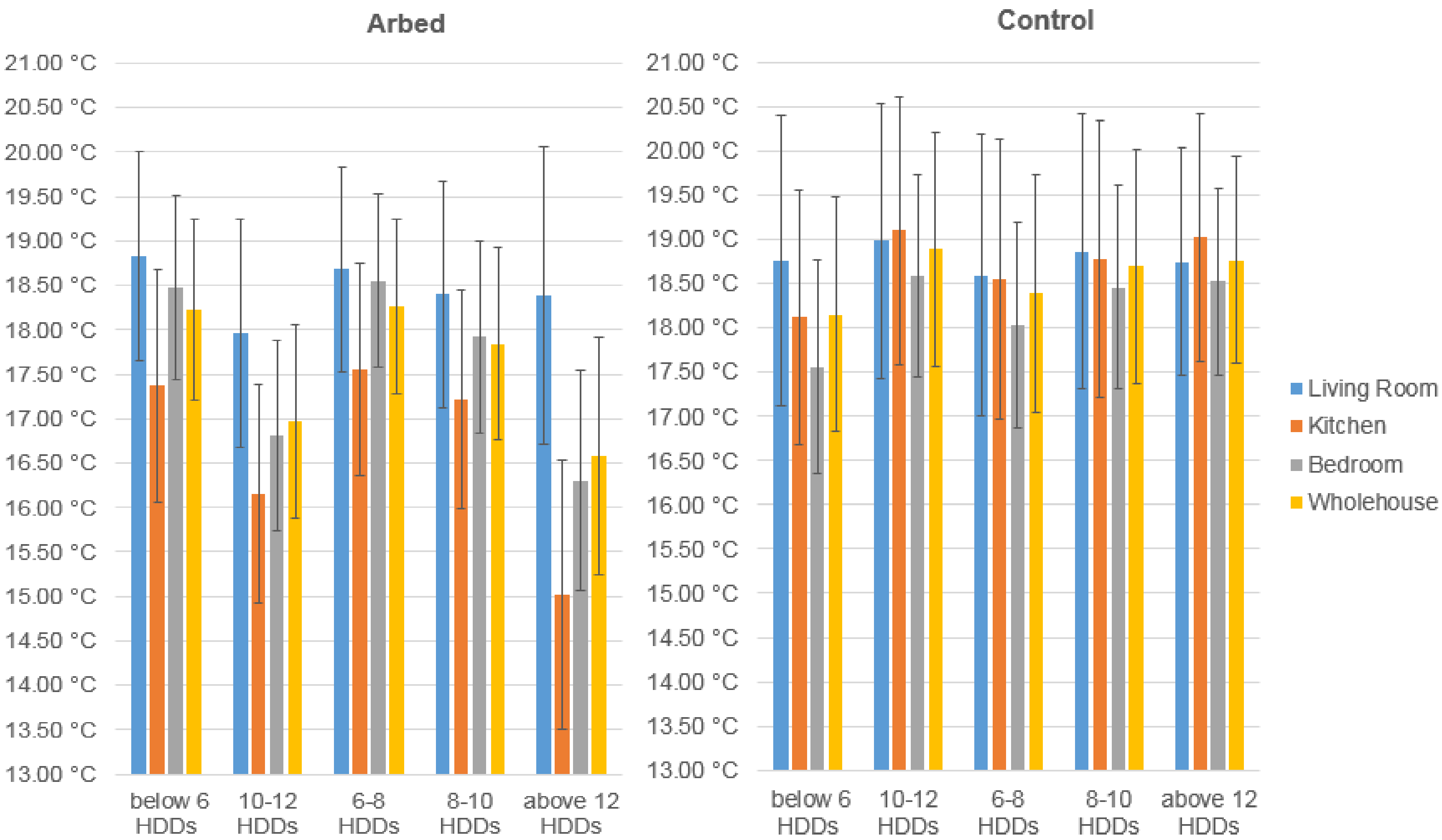

Figure B1. Mean and standard deviation of indoor air temperature in different locations according to heating demand (HDD)

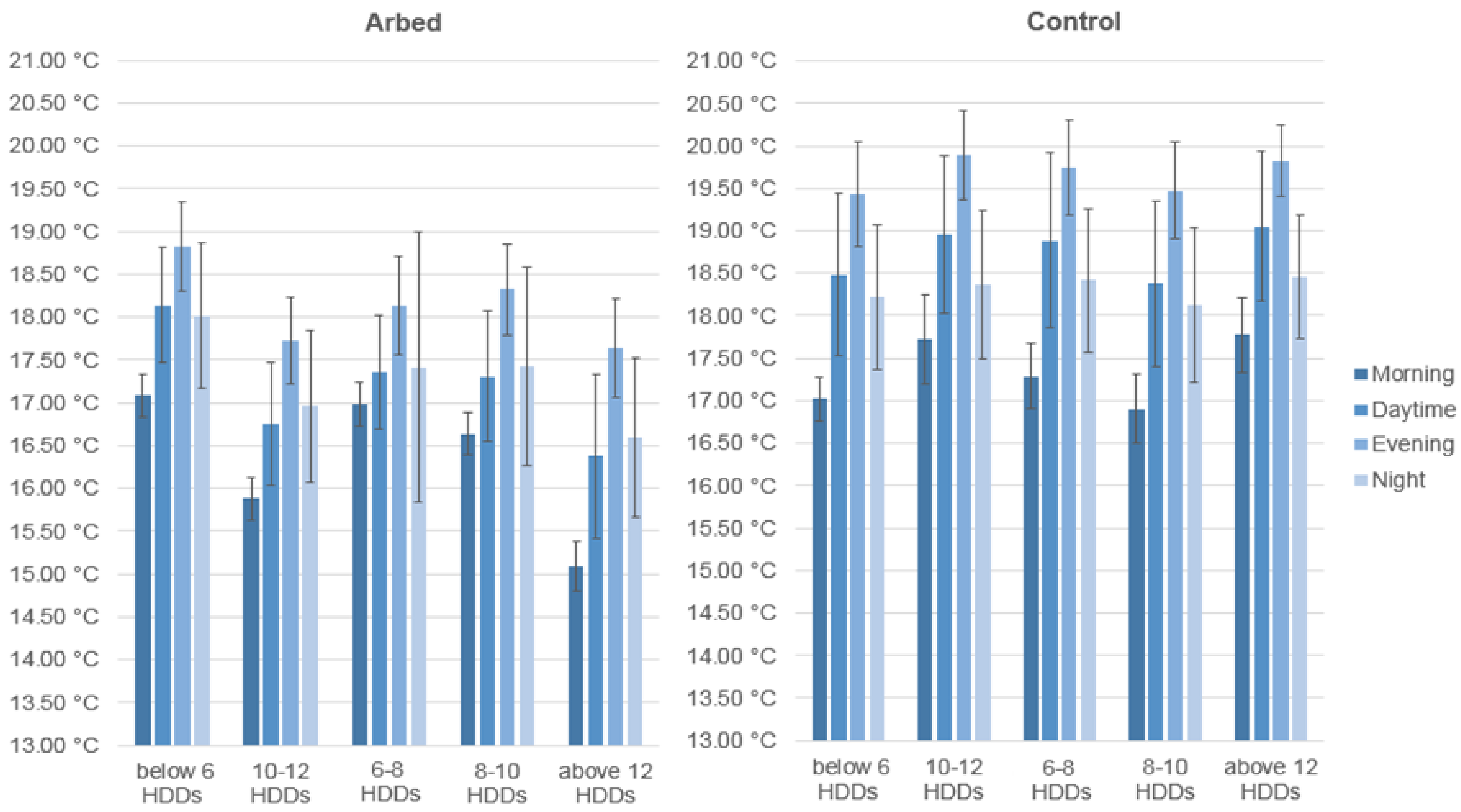

Figure B2. Mean and standard deviation of whole-house indoor air temperature at different time of day according to heating demand (HDD)

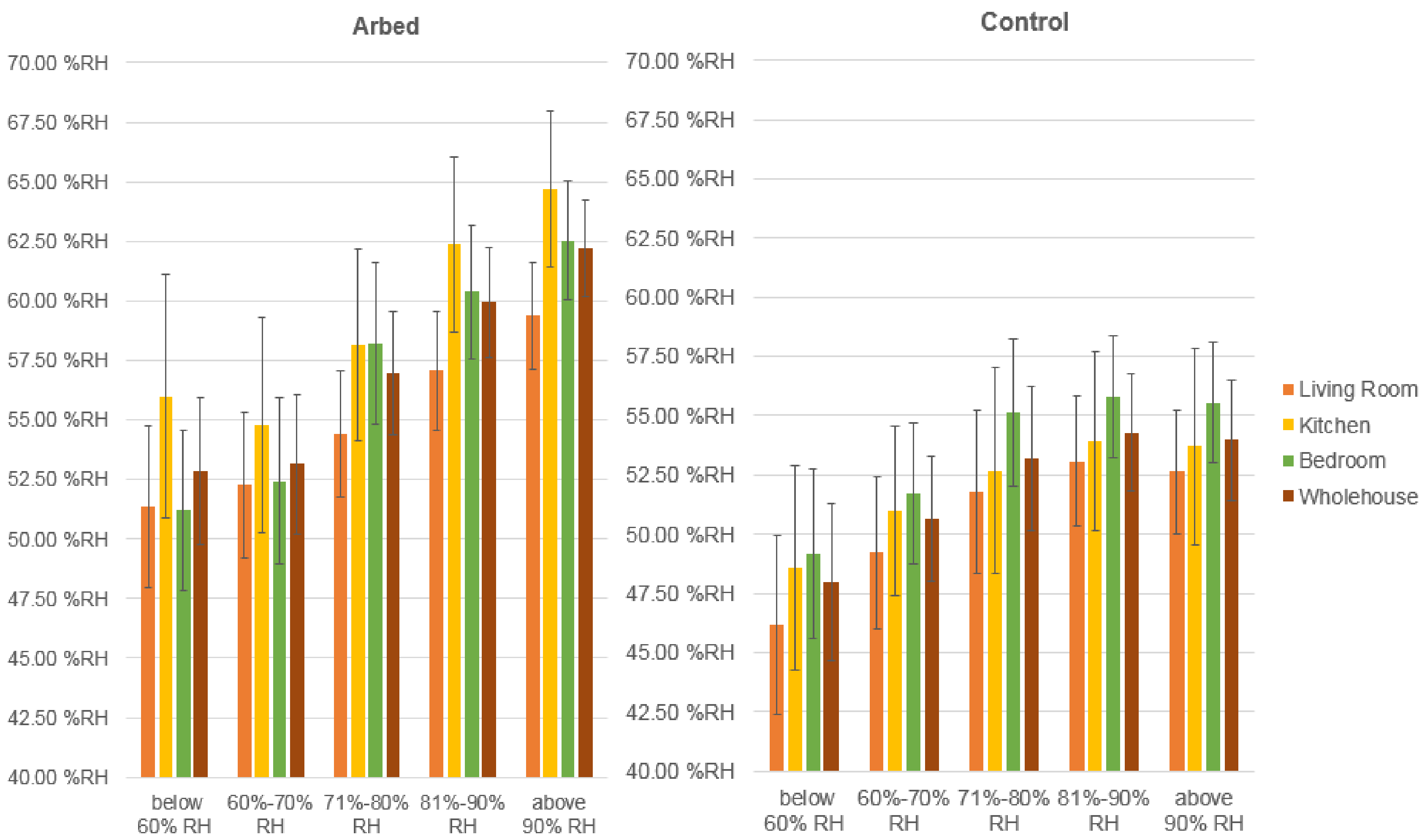

Figure B3. Mean and standard deviation of indoor relative humidity in different locations according to external relative humidity

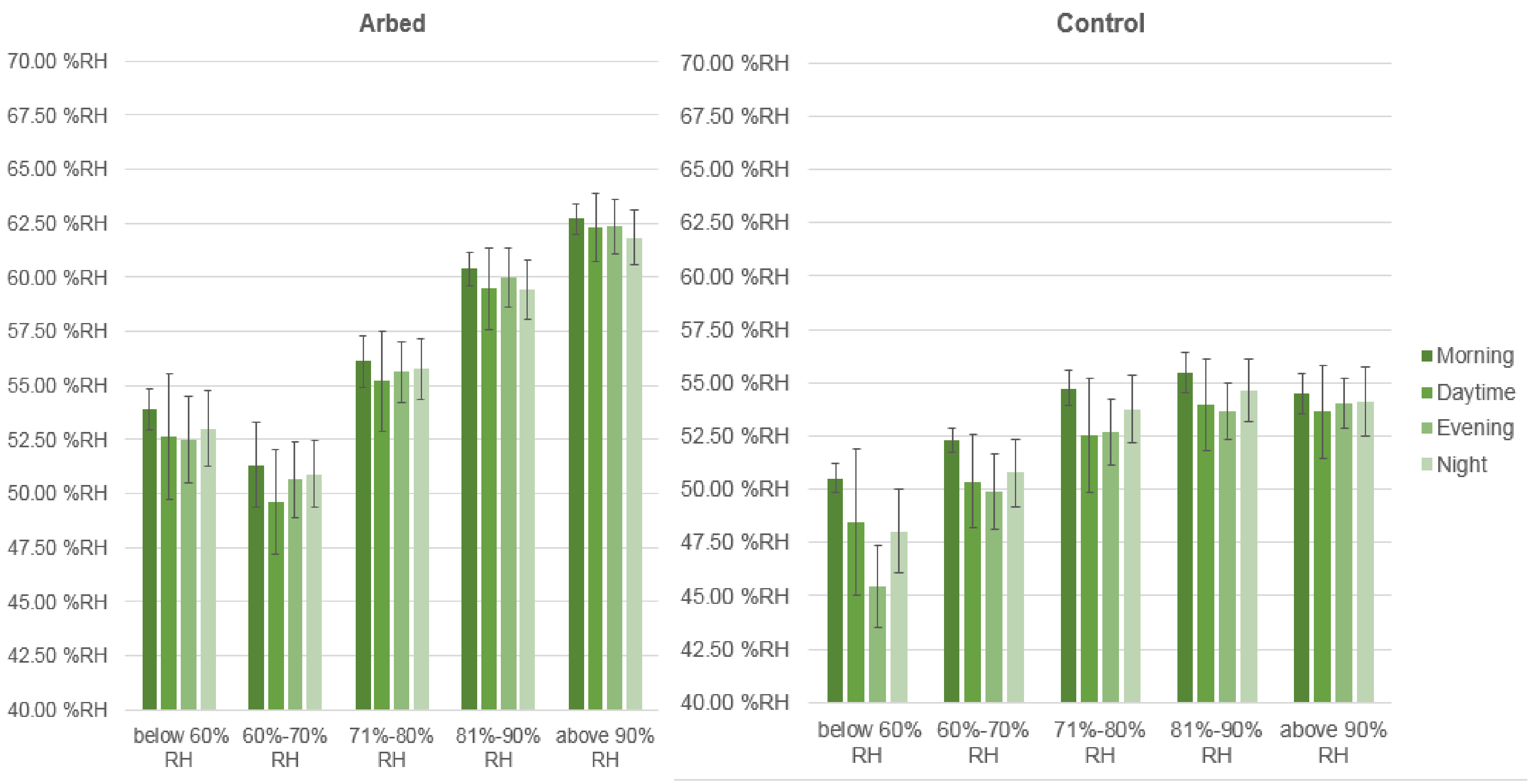

Figure B4. Mean and standard deviation of whole-house indoor relative humidity at different time of day according to external relative humidity

Table B1. Length and weighted amount of sub-standard internal conditions in the monitoring areas over a fixed 28-day period (Method 1)

		Length (% of time)			Weighted Amount (in °C·Hour and RH%·Hour)		
		Temperature		Relative Humidity	Temperature		Relative Humidity
Area	**Group**	**<18°C**	**<16°C**	**>60%**	**<18°C**	**<16°C**	**>60%**
Carmarthenshire	Arbed	86%	64%	71%	70	11	207
	Control	65%	9%	25%	10	1	32
Cardiff	Arbed	35%	25%	33%	29	6	51
	Control	54%	65%	42%	74	13	49
Wrexham	Arbed	49%	22%	29%	25	5	110
	Control	47%	16%	39%	22	4	60
Caerphilly	Arbed	77%	41%	67%	46	3	106
	Control	55%	67%	41%	76	13	48
Merthyr	Arbed	37%	28%	27%	39	7	71
	Control	39%	15%	31%	19	4	50
Overall	**Arbed**	57%	36%	45%	42	6	109
	Control	52%	34%	36%	40	7	48

Table B2. Length and weighted amount of sub-standard internal conditions in the monitoring areas on days with heating demand exceeding 6 HDDs (Method 3)

		Length (% of time)			Weighted Amount (in °C·Hour and RH%·Hour)		
		Temperature		Relative Humidity	Temperature		Relative Humidity
Area	Group	<18°C	<16°C	>60%	<18°C	<16°C	>60%
Carmarthenshire	Arbed	81	61	83	83	39	276
	Control	52	46	82	45	18	274
Cardiff	Arbed	27	17	22	23	12	32
	Control	55	37	22	47	22	28
Wrexham	Arbed	46	19	27	44	16	196
	Control	37	13	31	31	10	88
Caerphilly	Arbed	80	44	71	53	20	59
	Control	70	38	45	60	25	51
Merthyr	Arbed	47	39	39	68	42	127
	Control	43	37	37	55	33	120
Overall	**Arbed**	**56**	**36**	**49**	272	129	689
	Control	**52**	**34**	**43**	237	108	560

Table B3. Length of sub-standard internal conditions at different locations and times of day over a fixed 28-day period (Method 1)

	Location	Time of day	Risk threshold	Carmarthenshire	Cardiff	Wrexham	Caerphilly	Merthyr	Overall
Length (*% of time*)	Whole house	24 hours	<18˚C	75	45	48	66	38	54
			<16˚C	43	30	19	39	21	31
			>60%RH	67	28	34	45	29	41
	Living Room	Daytime	<18˚C	72	46	35	50	35	47
			<16˚C	29	31	20	26	21	25
			>60%RH	49	25	22	28	22	29
		Evening	<18˚C	37	30	26	24	28	29
			<16˚C	22	19	16	9	20	17
			>60%RH	68	26	37	49	28	42
		Morning	<18˚C	95	69	48	76	43	66
			<16˚C	31	45	25	41	26	34
			>60%RH	50	26	26	27	20	30
	Main bedroom	Night	<18˚C	80	41	52	64	36	55
			<16˚C	45	27	27	37	24	32
			>60%RH	67	25	49	46	33	44
		Morning	<18˚C	92	56	60	76	42	65
			<16˚C	70	39	36	59	28	46
			>60%RH	81	27	57	49	36	50
	Kitchen	Evening	<18˚C	40	37	34	64	30	41
			<16˚C	27	25	21	45	22	28
			>60%RH	62	32	38	54	32	44
		Morning	<18˚C	95	70	61	87	49	72
			<16˚C	77	44	37	68	32	51
			>60%RH	70	33	41	54	29	46

Table B4. Length of sub-standard internal conditions at different locations and times of day on days with heating demand exceeding 6 HDDs (Method 3)

	Location	Time of day	Risk threshold	Carmarthenshire	Cardiff	Wrexham	Caerphilly	Merthyr	Overall
Length (*% of time*)	Whole house	24 hours	<18˚C	83	45	40	63	44	55
			<16˚C	63	31	14	38	31	35
			>60%RH	93	28	23	41	24	42
	Living Room	Daytime	<18˚C	60	46	29	48	44	45
			<16˚C	42	31	15	25	30	29
			>60%RH	63	25	16	25	17	29
		Evening	<18˚C	48	31	20	24	29	30
			<16˚C	29	19	9	9	18	17
			>60%RH	60	26	31	44	27	38
		Morning	<18˚C	96	69	41	72	65	69
			<16˚C	47	46	20	40	45	39
			>60%RH	63	26	18	25	15	29
	Main bedroom	Night	<18˚C	83	40	45	62	42	54
			<16˚C	58	27	23	35	31	35
			>60%RH	81	24	42	41	23	42
		Morning	<18˚C	92	56	54	73	53	66
			<16˚C	73	39	31	56	40	48
			>60%RH	96	26	47	44	23	47
	Kitchen	Evening	<18˚C	65	38	25	61	34	45
			<16˚C	55	26	13	43	25	32
			>60%RH	82	32	28	51	30	45
		Morning	<18˚C	87	69	53	84	63	71
			<16˚C	72	45	27	66	46	51
			>60%RH	80	33	30	52	26	44

Table B5. Weighted amount of sub-standard internal conditions at different locations and times of day over a fixed 28-day period (Method 1)

	Location	Time of day	Risk threshold	Carmarthenshire	Cardiff	Wrexham	Caerphilly	Merthyr	Overall
Weighted Amount ***(°C·Hour*** **and** ***RH%·Hour)***	Whole house	24 hours	<18˚C	48	35	24	44	29	36
			<16˚C	6	7	5	5	5	6
			>60%RH	144	39	85	66	61	79
	Living Room	Daytime	<18˚C	16	13	10	10	11	12
			<16˚C	7	7	5	4	6	6
			>60%RH	55	17	38	12	18	28
		Evening	<18˚C	3	3	2	1	3	2
			<16˚C	2	3	2	4	4	3
			>60%RH	31	12	23	6	10	17
		Morning	<18˚C	9	7	4	9	5	7
			<16˚C	2	3	2	2	3	2
			>60%RH	17	7	13	4	5	9
	Main bedroom	Night	<18˚C	14	10	7	12	8	10
			<16˚C	5	5	2	5	4	4
			>60%RH	40	16	35	24	26	28
		Morning	<18˚C	9	7	5	9	5	7
			<16˚C	4	4	2	5	3	4
			>60%RH	22	7	17	12	13	14
	Kitchen	Evening	<18˚C	9	6	4	12	5	7
			<16˚C	6	3	1	7	3	4
			>60%RH	40	13	18	31	18	24
		Morning	<18˚C	12	8	5	12	5	8
			<16˚C	7	5	2	8	3	5
			>60%RH	23	8	14	19	8	15

Table B6. Weighted amount of sub-standard internal conditions at different locations and times of day on days with heating demand exceeding 6 HDDs (Method 3)

	Location	Time of day	Risk threshold	Carmarthenshire	Cardiff	Wrexham	Caerphilly	Merthyr	Overall
Weighted Amount ***(°C·Hour*** **and** ***RH%·Hour)***	Whole house	24 hours	<18˚C	69	36	17	42	38	40
			<16˚C	9	7	3	5	7	6
			>60%RH	193	38	64	56	44	79
	Living Room	Daytime	<18˚C	19	14	7	10	13	12
			<16˚C	10	7	3	3	6	6
			>60%RH	76	16	26	10	7	27
		Evening	<18˚C	4	3	1	1	2	2
			<16˚C	3	4	2	4	5	3
			>60%RH	44	12	15	5	3	16
		Morning	<18˚C	11	7	3	8	7	7
			<16˚C	3	3	1	2	3	3
			>60%RH	24	8	9	3	2	9
	Main bedroom	Night	<18˚C	21	10	5	12	11	12
			<16˚C	10	5	1	5	6	5
			>60%RH	45	15	32	21	24	27
		Morning	<18˚C	9	7	5	8	8	7
			<16˚C	4	4	2	4	5	4
			>60%RH	25	7	15	10	10	14
	Kitchen	Evening	<18˚C	24	7	3	12	6	10
			<16˚C	18	3	1	6	3	6
			>60%RH	79	14	13	27	16	30
		Morning	<18˚C	18	8	4	12	8	10
			<16˚C	13	5	1	8	4	6
			>60%RH	47	7	9	17	6	17