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York Passivhaus Building Performance Evaluation

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Executive Summary

The York Passivhaus is a 3-bed home in York, North Yorkshire, that achieved Passivhaus certification on completion in 2015. The project aim is to evaluate the building fabric and system performance of the home seven years post-completion against design targets and initial performance tests. Areas of interest are energy consumption, ventilation and air quality, thermal comfort, airtightness and building fabric.

Looking at these in turn, fuel bills were used to explore how gas and electricity consumption had changed since occupation in 2016. Gas use was higher during the first year post-completion in 2016 but has steadily declined since. Electricity use has remained relatively constant. The annual energy consumption in 2023 was 2467kWh for gas (20kWh/m2/year) and 1652kWh (13kWh/m2/year) for electricity, which is between 60 and 74 per cent less for gas and between 9 and 39 per cent less for electricity than the average UK house.

The mechanical ventilation heat recovery (MVHR) system was not balanced when flow rate test results were compared against commissioning figures, as extract air flow rates were higher than intake air flow rates. This meant that the system no longer satisfied Passivhaus requirements.

Air quality was monitored inside and outside of the home over 12 months. For CO_2, a high level of IAQ was recorded, with an average of less than 872 ppm. CO_2 levels dropped when the MVHR filters were changed coupled with the onset of warmer weather. Higher noise levels associated with the MVHR system ceased following a service. Higher levels of particulate matter (PM) were recorded at the front of the house, close to a car parking area. Three peak periods were examined to see how particulates generated externally or internally rose and fell over time. Spikes in internal PM levels were generally due to cooking or use of the wood-burning stove and dissipated quickly. Elevated PM level patterns recorded outside were often mirrored inside but at a much lower level.

Twenty internal sensors monitored temperature and humidity levels. Temperatures remained constant above 15°C throughout winter with all sensors staying within a 3-4°C range, indicating a low level of thermal variation across the home. However, internal temperatures were quite low – usually under 20°C, despite the space heating system defaulting to set points of 24°C during the day and 15°C at night during the winter months. This suggests that the space heating system was undersized for the current occupancy level, as design calculations were based on higher occupancy assumptions. It was assumed at the design stage that the wood-burning stove would meet 30 per cent of the home's heating demand when during the monitoring period it was rarely used. During warmer weather, higher temperatures were recorded across the two southwest facing first-floor bedrooms. There was no evidence of overheating when the home was occupied during warmer weather.

In general, the house is still extremely airtight with a mean permeability of 0.86 m3/(h.m2) @ 50Pa. However, this is a significant increase in air leakage in relative (rather than absolute) terms since certification was carried out in October 2015, where a mean permeability of 0.39 m3/(h.m2) @ 50Pa was recorded. The little air leakage detected appears to come from window seals at casements, the boiler flue, plus some air movement behind plasterboard in the upstairs rooflights, and at wall-to-ceiling, or wall-to wall-junctions. The air leakage area has increased only slightly – from around 73cm^2 to 104cm^2. Therefore, after seven years the home now satisfies EnerPHit rather than Passivhaus airtightness requirements.

A QUB test was used to measure fabric performance. First, a design-stage heat transfer coefficient (HTC) for the home was calculated, which was 69.5 W/K and then tested against. Three tests were done in the summer/autumn of 2022 and two in the winter of 2023. The average measurement was 76.3 W/K. This is a low HTC but 10 % greater than the design-stage performance calculation.

Overall, as a seven-year-old Passivhaus, the home's performance is still exceptional compared to current-day new-build homes. Some performance aspects have deteriorated since completion, such as the airtightness and MVHR performance, which could be associated with wear and tear. It is not possible to compare changes to air quality, thermal comfort and HTC, as they were not monitored post-completion. The only area of note is thermal comfort in winter depending on the temperature sought by occupants, as the space heating system is not designed for the current occupancy level and could be considered on the cool side of comfortable.

Contents

1 Introduction

The York Passivhaus (see Figure 1-1) is a 3-bed detached home in York, North Yorkshire, with a floor area of 124.7m^2. It was completed and achieved Passivhaus certification in 2015 and is lived in by the Client, who is joined one or two nights a week by a family member.

It is built using brick-faced masonry construction with a 300mm full-fill cavity and a wet plaster internal finish. A solid concrete floor sits on top of 400mm rigid insulation. The roof is insulated with a combination of sheep's wool and recycled cellulose insulation to a depth of 450mm. The windows and doors are triple-glazed. Space and water heating are provided by a combination gas boiler. Space heating is delivered by a single radiator and a wood-burning stove. Mechanical ventilation heat recovery (MVHR) is provided through a Paul Focus 200 system. There are no renewables installed and there is a gas hob for cooking.

Figure 1-1 Photo of the York Passivhaus, taken in winter 2022.

The project aims to evaluate the fabric and system performance of the home seven years post-completion against design targets and initial performance tests.

To receive Passivhaus certification, the home had to meet set performance criteria relating to space heating demand, space heating load, primary energy and airtightness. At the design stage, target U-values for the fabric were set. Space heating and primary energy demands were predicted and the efficiency of the MVHR unit was estimated using the Passivhaus Planning Package (PHPP). Post-construction, the building fabric was pressure tested.

To evaluate current dwelling in situ performance against design targets and post-construction airtightness tests, the following areas were investigated and covered sequentially in this report:

- **Energy use** involving desk-top energy use study of historic fuel bills.
- **Ventilation** through the one-off measurement of MVHR flow rates and 12 months monitoring of internal and external CO_2 and particulate levels.
- **Thermal comfort** by monitoring internal air temperature and humidity with 20 sensors over 12 months and carrying out a desk-based overheating analysis using CIBSE TM52 [1].
- **Airtightness** using an airtightness test, coupled with a thermographic survey.
- **Building fabric** by conducting several QUB tests to measure the home’s heat transfer coefficient (HTC).

2 Energy use

2.1 Desktop study analysis

Fuel bills were used to explore how gas and electricity consumption had changed since occupation in 2016. Both annual and monthly profiles were plotted for gas and electricity. Annual data was taken from January 2016 to January 2024, and monthly data between August 2022 and August 2023.

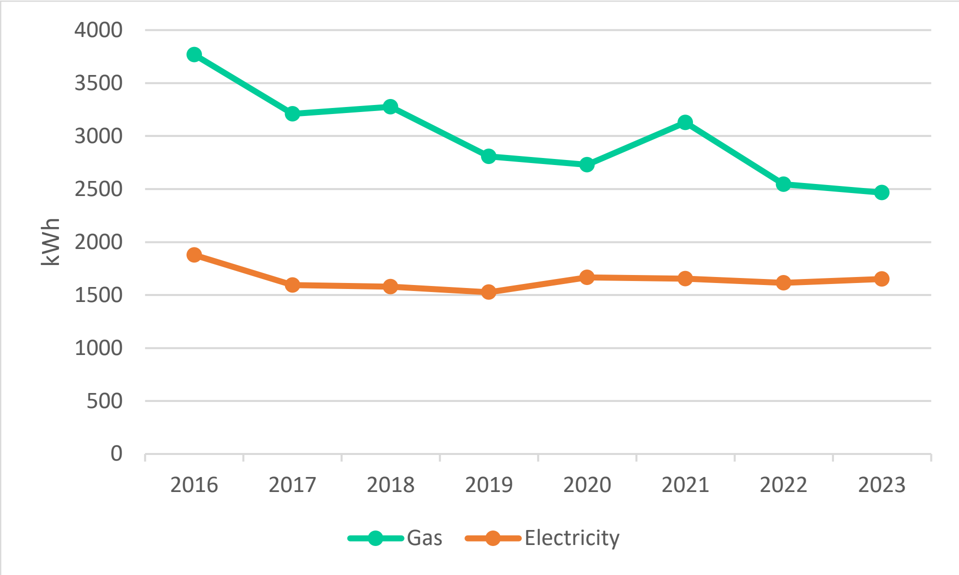


Figure 2-1 Annual energy use

Firstly, looking at annual consumption (Figure 2-1), the overall trend is that gas use has fallen steadily since 2016, despite a rise in use during 2021 (although this could be due to a colder than average winter). In 2023, the occupants used just over 1300kWh less of gas than in 2016, representing a reduction of 35%. Conversely, electricity use has stayed fairly constant over the same time period. From the data we have, it is not possible to determine why this is the case, although the level of occupancy is low given the number of bedrooms. The figures also do not take external temperatures each winter into account.

Table 2-1: Comparison of York Passivhaus average energy use here against UK averages and percentage savings

Average energy use	Gas (kWh)	Electricity (kWh)	**Percentage** reduction in gas	**Percentage** reduction in electricity
York Passivhaus (3 bedroom with 1-2 people)	2992	1645	-	-
Average UK home [2] (1-2 people)	7500	1800	60%	9%
Average UK home [2] (2-3 bedrooms)	11500	2700	74%	39%

On average, as shown in Table 2-1, energy use equates to 2992kWh of gas and 1645kWh of electricity used per annum. This is a 60% and 9% saving respectively compared to the average home with 1 or 2 occupants or a 74% or 39% saving compared to the average 2- or 3-bedroom home.

Focusing in on energy use per m^2 of floor area (Figure 2-2), it is possible to see the trend in more detail, with consumption being slightly higher during 2016. Averaging energy use out between 2016 and 2023, consumption was 24kWh/m^2/year for gas and 13kWh/m^2/year for electricity.

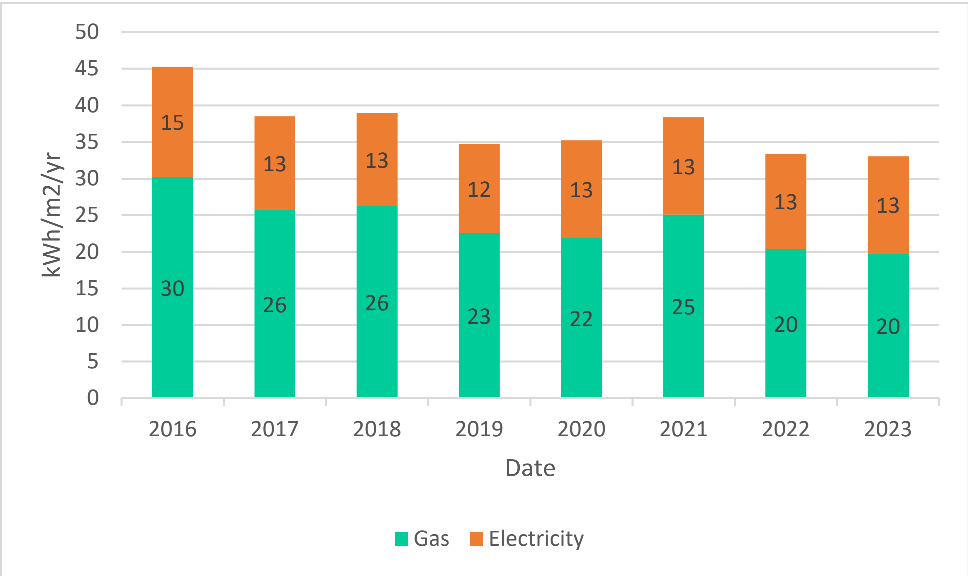


Figure 2-2 Annual energy use per fuel per m2 of floor area

Secondly, examining monthly energy use data during the in-depth monitoring period, which was August 2022 to August 2023 (Figure 2-3), gas and electricity consumption were higher during the winter months, which is as expected. As energy use was measured using meter readings rather than installing sub-meters, assumptions have been made about how much gas was used for space heating. As there was unlikely to be any demand for space heating during the summer months, it has been assumed that on average 72kWh of gas a month, or around 7kWh/m^2/year was required to meet cooking and domestic hot water demands. Removing monthly domestic hot water and cooking assumptions from annual gas use figures suggests that 1443kWh gas was used over the year for space heating. This is around 11kWh/m^2/year and falls considerably below the annual energy demand figure in the home's PHPP worksheet of 30.7kWh/m^2/year. The difference between the figures may stem from PHPP assuming an occupancy level of between three and four people, whereas only one to two people live in the home.

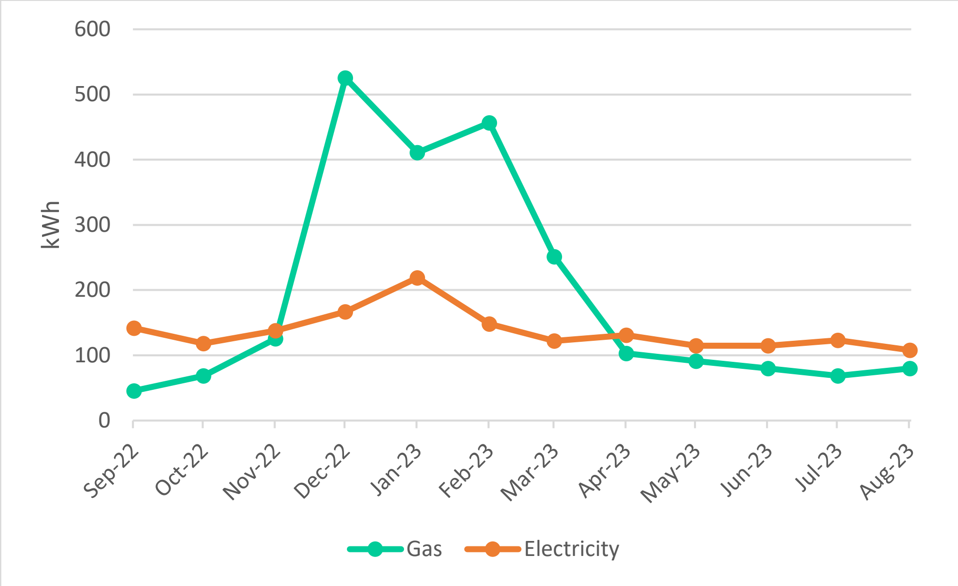


Figure 2-3 Monthly energy use per fuel

2.2 Conclusion

Gas use was higher during 2016 but has steadily declined overall, with a slight increase in 2018 and a greater increase in 2021, which may be due to those being colder than average winters. Electricity use has remained relatively constant. In 2023, the annual use was 2467kWh for gas (20kWh/m^2/year) and 1652kWh (13kWh/m^2/year) for electricity. Compared to the annual energy consumption of the average UK house, this home used a lot less gas and a little bit less electricity, even when taking the occupancy level into account.

By looking at monthly usage figures it is possible to estimate how much energy is used for space heating. Annual gas use for space heating was lower between September 2022 and September 2023 than the values stated in the home's PHPP worksheet (11kWh/m^2/year and 30.7kWh/m^2/year respectively). The discrepancy may be due to PHPP assuming three to four people are living in the home when it has only been one or two.

3 Ventilation and IAQ

3.1 Introduction

This section covers the MVHR flow rates which were measured across the home, and results from the 12-month internal and external air quality monitoring period.

3.2 MVHR

The ventilation performance of the MVHR system was assessed by measuring the air flow rate at each supply and kitchen extract vent, as well as measuring the external intake and exhaust airflow rates (see Figure 3-1 and Figure 3-2 for vent locations). Air flow rates were measured using a Swemaflow air flow hood where there was sufficient space to use the device. However, it was not possible to measure the ground-floor WC and the first-floor bathroom extract vents, as the Swemaflow could not be placed over the vent[1]. Measurements using the Swemaflow air flow hood were taken on 6th December 2022.

Air flow rate measurements were recorded in litres per second (l/s) which were converted to metres cubed per hour (m^3/h) for comparison with the initial 2015 commissioning report for the MVHR system. Measurements were taken under the normal operation setting of the MVHR system, referred to as level 2 in the original commissioning report.

Table 3-1 Comparison of 2015 commissioning and 2023 measurement air flow rates

MVHR Flow rate (m^3/h)	Supply					Extract			
	Living Room	Bed 1	Bed 2	Bed 3	Supply total	Kitchen	WC	Bathroom	Extract total
2015	28.0	27.0	20.0	21.0	**96.0**	48.0	24.0	25.0	**97.0**
2022/23	25.7	23.0	18.1	17.6	**84.5**	39.0	-	-	-

Table 3-2 Comparison of 2015 commissioning and 2023 external air flow rates

MVHR Flow rate (m^3/h) - External	Intake	Exhaust
2015	91	92
2022/23	87.8	101.6

[1] Extract flow rates for the bathroom and WC were measured on 19th May 2023 using a TSI Airflow however these results have been excluded as the MVHR filters were changed on 13th April 2023.

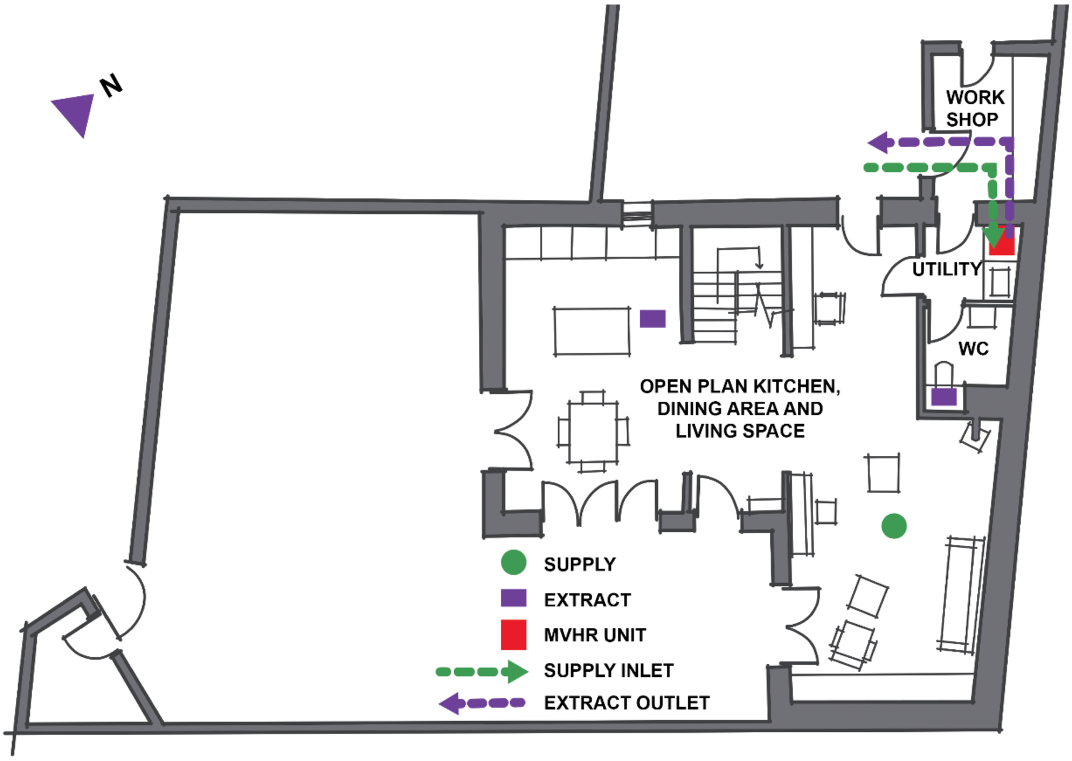


Figure 3-1 Ground floor MVHR system.

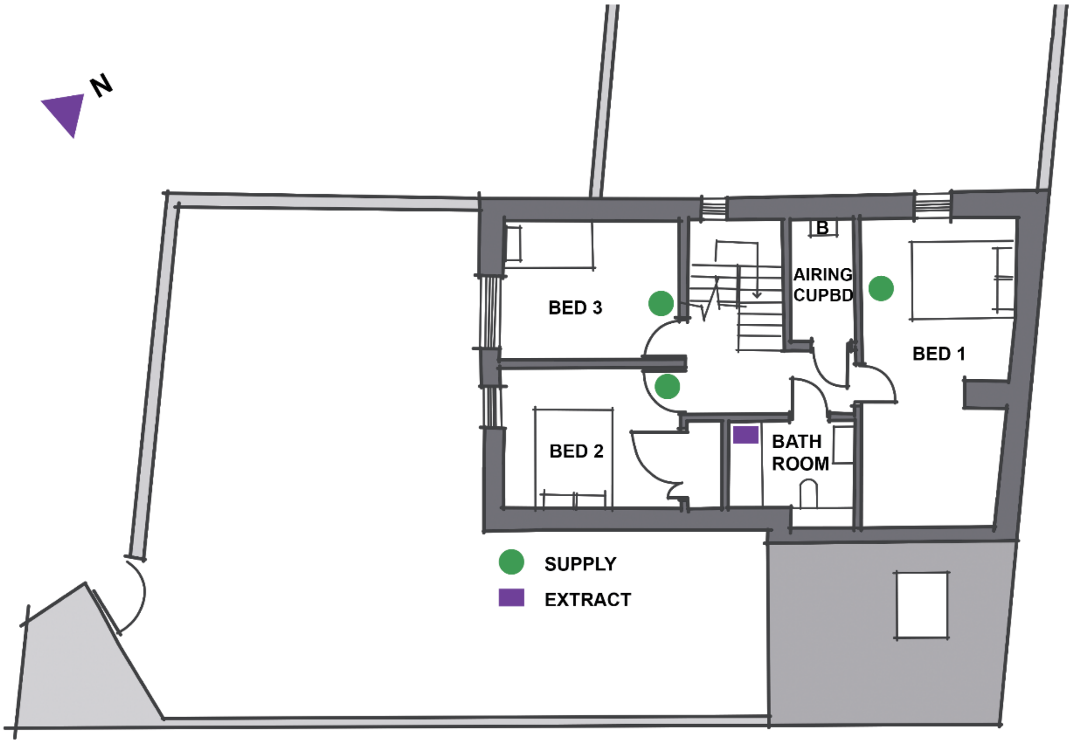


Figure 3-2 First floor MVHR system.

Supply air flow rate measurements (Table 3-1) and external air flow rate measurements (Table 3-2) carried out indicate that the MVHR system was no longer operating as it was when initially commissioned in 2015. Supply air flow rates were all measured below the air flow rate at commissioning, likely due to clogged air filters. The kitchen extract air flow rate was also lower than it was at commissioning in 2015. There is an imbalance between the external intake and exhaust flow rates when comparing 2022/23 rates with those taken in 2015. In 2015, the system was balanced; however, now the discrepancy between intake and exhaust is over 10 per cent, meaning that the home at the point of testing did not satisfy Passivhaus requirements.

It is unclear why there was a change in the air flow rate measured; however, the occupants reported a steady increase in fan volume over winter 2022 and spring 2023 and had resorted to turning the MVHR off at night to be able to sleep undisturbed. Sound levels were recorded on 6th December 2022 and 19th May 2023 which suggested that the MVHR system was operating at a higher than desirable decibel level. The average sound level recorded in the utility room next to the MVHR unit on those dates was 49dB(A) and 67.5dB(A) respectively. This is louder than the ≤30 dB(A) recommended by the Passivhaus Trust for utility rooms [3]. The occupants reported that the MVHR system was serviced on 30th May 2023 and that the intake side fan was replaced on 5th July 2023, whereby the system was near silent again.

3.3 Indoor Air Quality

Air quality was monitored inside and outside of the home over a 12-month period. Observations of air quality conditions are reported in the section, which includes five subsections. The first of these describes the air quality variables that were monitored and the second presents the air quality targets from the World Health Organization (WHO) and the Department for Environment, Food and Rural Affairs (DEFRA) to provide context for the analysis. The remaining subsections evaluate data for each of the three air quality variables included in this study.

3.3.1 Monitored air quality conditions

Short-term and long-term exposure to harmful gases and pollutants has direct implications for human health, ranging from simple respiratory irritation to premature death in the most extreme cases [4]. Increased understanding of these risks has led to more common monitoring and measurement of air pollution, in both internal and external environments. There is a particular case for air quality to be monitored in more airtight buildings (such as Passivhaus dwellings) as mechanical ventilation is required due to there being inherently less air changes from background infiltration.

Air quality inside and outside of the dwelling was measured using Sensorbee sensors that simultaneously measure Carbon Dioxide (CO_2) and Particulate Matter (PM) at seven different sizes. Air quality was sampled at 2-minute intervals in the external and internal environments using four sensors (two internal and two external), which were positioned as shown in Figure 3-3 and Figure 3-4. One internal sensor was installed in the ground floor living space, and the other in bedroom 1. External sensors were positioned at the front of the property, near a parking courtyard for this and neighbouring properties and at the rear of the property in the garden near the MVHR inlet and outlet.

External and internal air quality was monitored between 5th August 2022 and 30th August 2023. There were a few periods during this time that sensors failed briefly: 19:00 3rd October 2022-03:00 5th October 2022; 20:00 28th November 2022-19:00 30th November 2022; 14:00 26th January 2023-09:00 27th January 2023; and 19:00 22nd April 2023- 23:00 23rd April 2023. At an hourly resolution, this represents <1.2% of the monitoring period.

It is first important to establish that CO_2 is a naturally occurring gas in the air and therefore, in general terms, not a pollutant. It is often considered as a pollutant at higher levels inside buildings and is used as a proxy for internal air quality. Although very high levels of CO_2 can have serious health implications, this type of exposure does not commonly occur in domestic environments. Higher levels of CO_2 related to inadequate ventilation can however lead to discomfort in domestic settings, causing headaches and drowsiness; exhaled air is the main source of CO_2 in internal environments [5]. The sensors used in this work report CO_2 in parts per million (ppm) which describes the proportion of CO_2 within the sampled air. A photoacoustic sensor was used in the work with a measurement accuracy of ±50 ppm.

Particulate matter is more complex and comes from both anthropogenic and natural sources. Anthropogenic sources are largely attributable to combustion (in vehicles and buildings) and dust from activities such as construction and agriculture [4]. Sources are classified as primary when they are emitted into the air directly, or secondary when they are formed through chemical reactions (nucleation) and can grow through a coagulation [6]. Particulates can also come from natural sources such as pollen, sea salt, soil particles and even Saharan dust, as PM can travel over significant global distances once airborne WHO, [7].

Observations of particulate matter in this study are for sizes $PM_{0.1}$, $PM_{0.3}$, $PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5 and PM_{10}. Particulate matter is classified in terms of size, with the numerical values relating to their diameter using micrometres as the classifying metric. A micrometre is equivalent to 0.001 millimetres or 1000 nanometres, all of which are at the microscopic scale WHO, [7]. Of the PM sizes measured in this work, $PM_{2.5}$ and PM_{10} are of the greatest concern in terms of human health and have been linked to a range of health problems as understanding of their prevalence has developed and can be transported through the bloodstream to the body's major organs [4].

Concentrations of PM are reported using the metric micrograms per cubic metre (µg/m^3). These mass concentrations describe the total volume of pollutants below the identified threshold; for example, the level of $PM_{2.5}$ indicates the total mass of particulates at that size and below (so includes $PM_{0.1}$, $PM_{0.3}$, $PM_{0.5}$, PM_1, and $PM_{2.5}$). An optical particle counter detects different sizes by measuring the amount of light scattered by particles that pass through a laser, with an accuracy of ±5 µg/m^3 below 50 µg/m^3 and ±10 µg/m^3 above 50 µg/m^3.

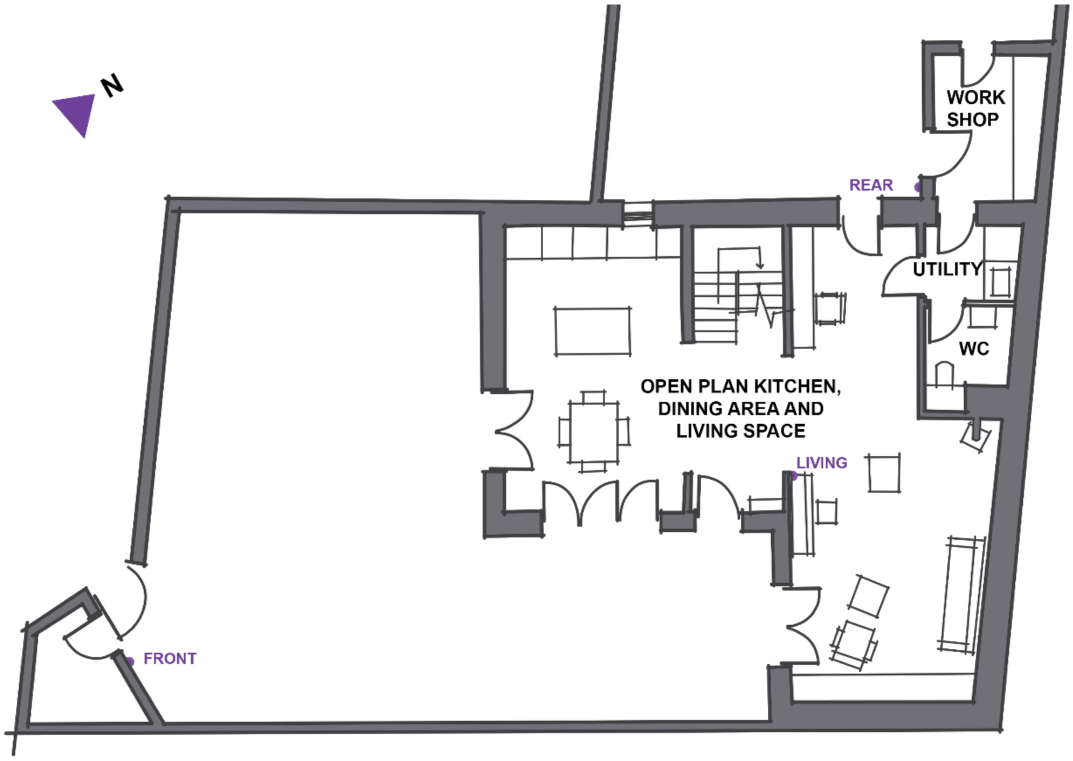


Figure 3-3 Ground floor Sensorbee sensor locations marked in purple.

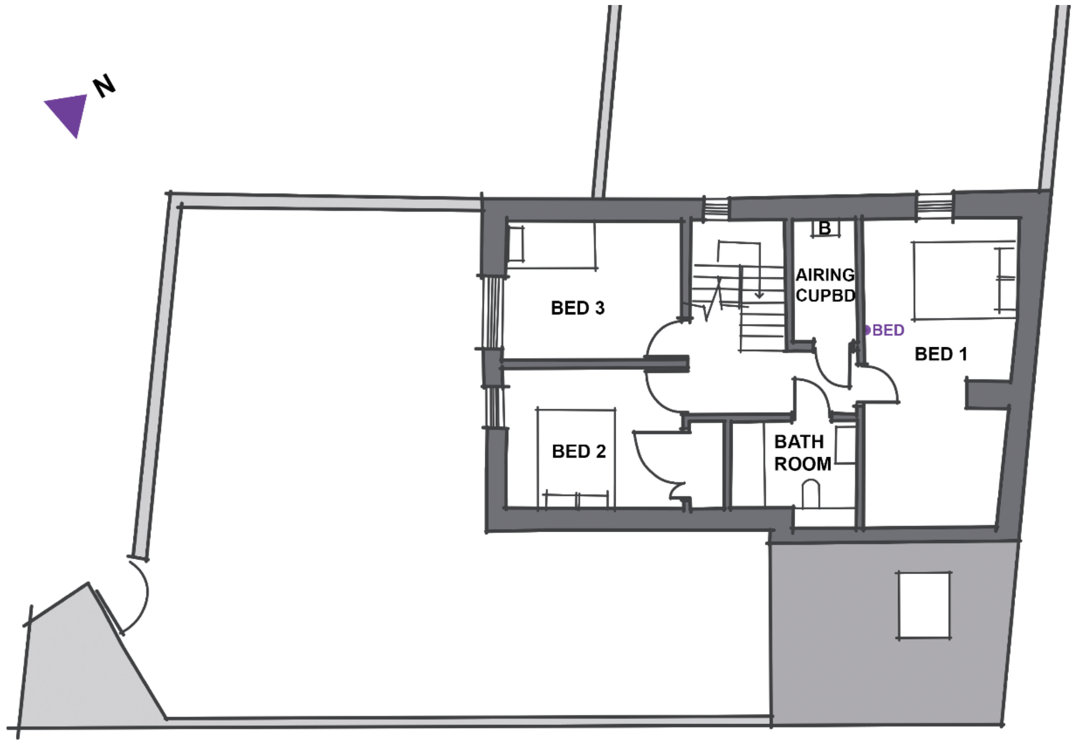


Figure 3-4 First floor Sensorbee sensor location marked in purple.

3.3.2 Air quality targets

There are currently no formal legal levels or thresholds for internal PM or CO_2 in the UK. There is however guidance from the Chartered Institute of Building Services Engineers (CIBSE) on levels of internal CO_2 that represent good air quality. These are based on a value above the background (ambient) CO_2 levels in a particular location [8]. These are shown below in Table 3-3. The mean for ambient levels of external CO_2 during the monitoring period was 472 ppm, the fourth column in Table 3-3 therefore defines the thresholds used in this study.

Table 3-3 Table 5-3 CIBSE Guide A CO_2 concentration for different levels of Indoor Air Quality (IAQ)

Ref.	IAQ level	Above ambient by (ppm):	Absolute range (ppm):
IDA1	High IAQ	<400	<872
IDA2	Medium IAQ	400-600	872-1072
IDA3	Moderate IAQ	600-1000	1072-1472
IDA4	Low IAQ	>1000	>1472

As of 2024, there are established thresholds for safer levels of external ambient air pollution, but the WHO stress that there are no truly safe levels of $PM_{2.5}$ and PM_{10}. There are however threshold levels that are considered to represent lower levels of risk to human health WHO, [7]. There are however no formal thresholds or limits on PM exposure for internal environments, although WHO suggests that the thresholds for ambient air provide a sensible reference.

Table 3-4 Comparison of WHO and DEFRA guidance for ambient PM concentration levels

Pollutant	Averaging period	WHO 2005 ($\mu g/m^3$)	WHO 2021 ($\mu g/m^3$)	DEFRA 2010 ($\mu g/m^3$)	Exceedance limit
$PM_{2.5}$	Annual mean	10	5	20	N/A
	24 hour mean	25	15	N/A	3 days/year
PM_{10}	Annual mean	20	15	40	N/A
	24 hour mean	50	45		3 days/year*

*This is set at 35 days/year in the DEFRA targets

The thresholds for $PM_{2.5}$ and PM_{10} set by WHO are lower than those currently set by the UK Government through the Air Quality Standards Regulations WHO, [7], [9]. An interim target to limit $PM_{2.5}$ to an annual average of 12 µg/m^3 by 2028 has been set in the Environmental Improvement Plan, with a limit of 10 µg/m^3 to be reached by 2040 [4]. The WHO and UK Government targets for PM concentrations in the ambient air are compared in Table 3-4. The increased understanding of health risks related to PM concentrations is illustrated by the reduction in the WHO's Air Quality Guidance level from the 2005 thresholds to those defined in 2021. The exceedance limits represent days within the 99th percentile.

3.3.3 Carbon Dioxide monitoring

Average and maximum levels for the daily mean of CO_2 ppm can be seen in Figure 3-5. These results suggest that high levels of air quality in terms of CO_2 concentration were maintained throughout the monitoring period. The average concentration is well within the range defined as having a high level of IAQ (<872 ppm). The average value for the bedroom is slightly higher than the living space which would be expected due to the smaller volume of the space and the extended periods of constant occupation during the night.

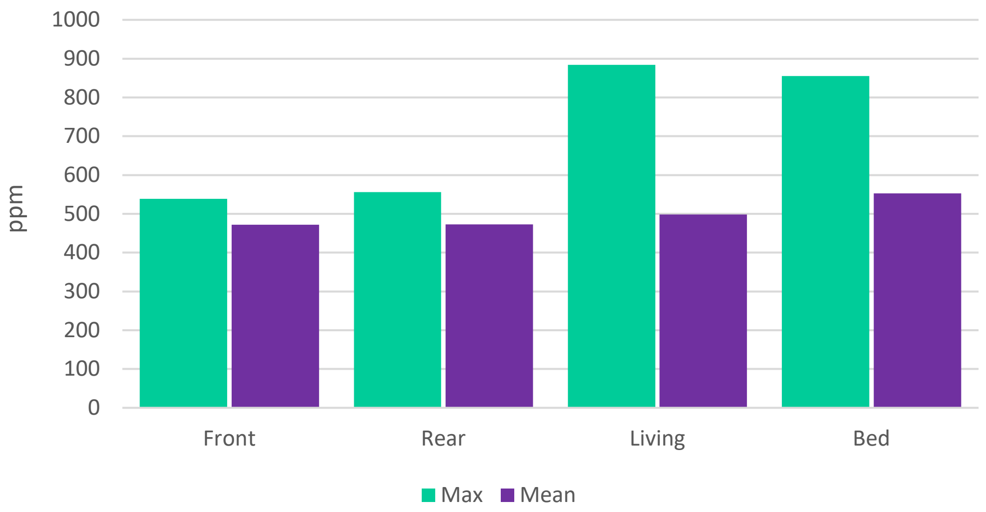
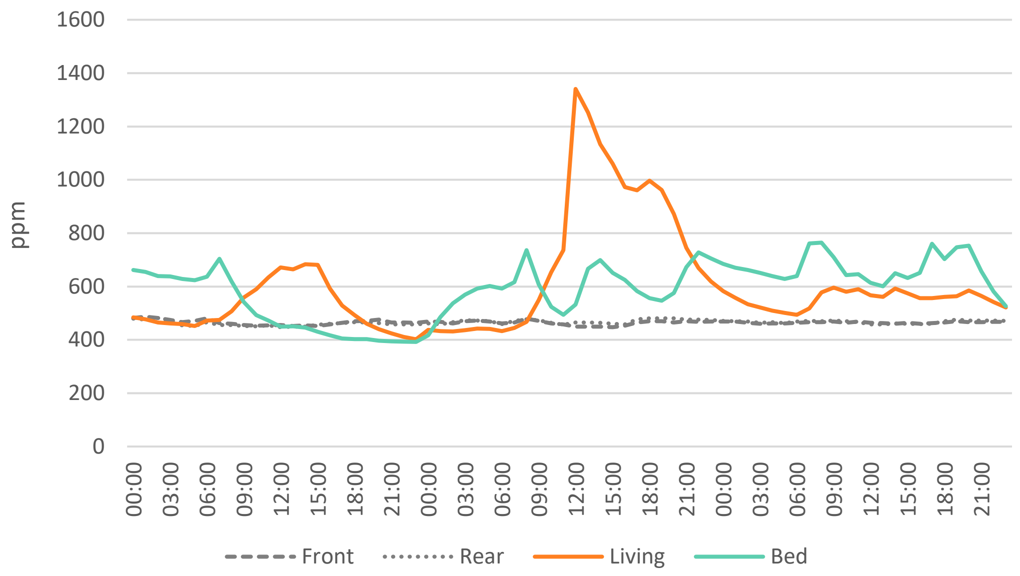
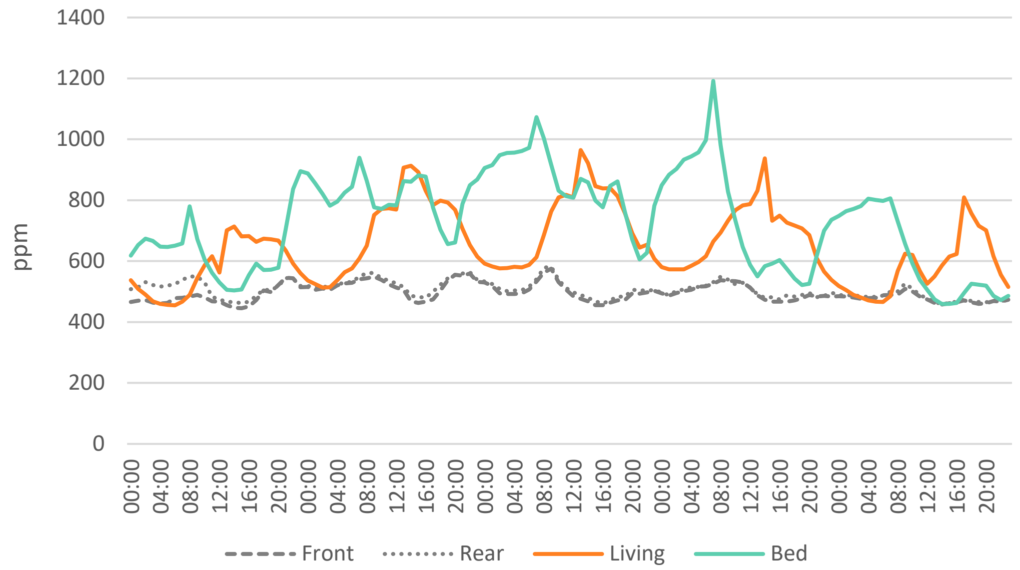


Figure 3-5 Maximum 24-hour average and annual mean values of CO_2 concentration

The peak hourly average value recorded in the living space was 1,340 ppm which falls within the moderate IAQ range, which is similar to the peak hourly average of 1,192 ppm observed in bedroom 1; these peaks occurred on 12:00 19th February 2023 and 07:00 8th February 2023 respectively. These two peaks are illustrated in Figure 3-6, which indicates that higher internal levels are independent of the ambient external air conditions, so must be related to occupancy levels. It is important to note that there were only 23 hours in total (<0.3 % of observed hours) that were in the range considered to be of moderate IAQ. In total, 94 % of observed hours in the living space were under the high IAQ threshold in the living space, with the remainder (5.7 %) in the medium IAQ range. Similar results were evident in bedroom 1, with 45 hours (<0.5 %) in the moderate IAQ range, with approximately 13.5 % of hours under the medium threshold, and 86 % under the high quality IAQ threshold.



(a) Hourly CO_2 concentration between 18th-20th February 2023



(b) Hourly CO_2 concentration between 5th-9th February 2023

Figure 3-6 Peak hourly CO_2 concentration in living and bedroom 1

Monthly averages for CO_2 concentration are shown in Figure 3-7. There is a visible fall in CO_2 concentration from April 2023. It is reasonable to assume, although not definitively, that the improvement in air quality coincides with the following factors: MVHR filters being changed on 13 April 2023; increased ventilation due to the MVHR being deactivated overnight during early 2023 (only recorded anecdotally); and/or increased window opening during warmer periods. The diurnal pattern due to spaces being occupied can be seen from the average hourly values across the monitoring period shown in Figure 3-8.

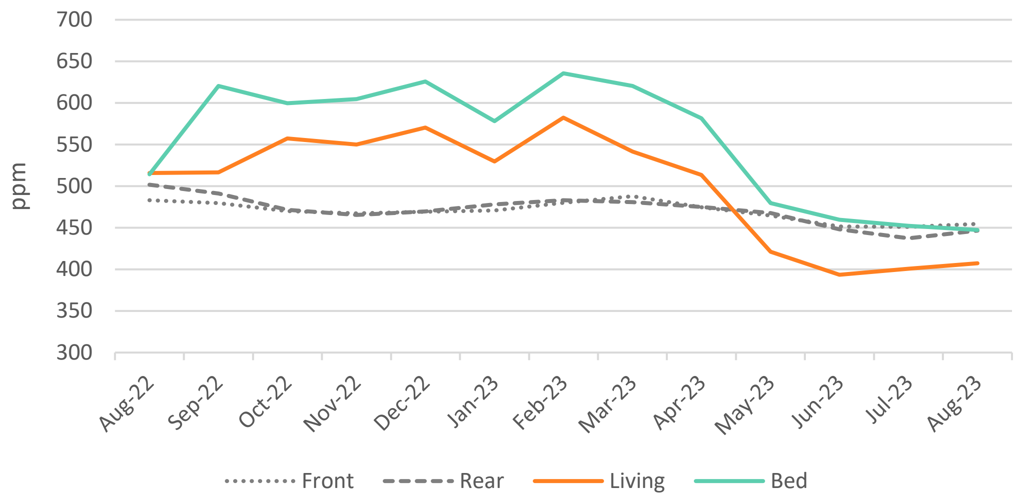


Figure 3-7 Monthly average values of CO_2 concentration

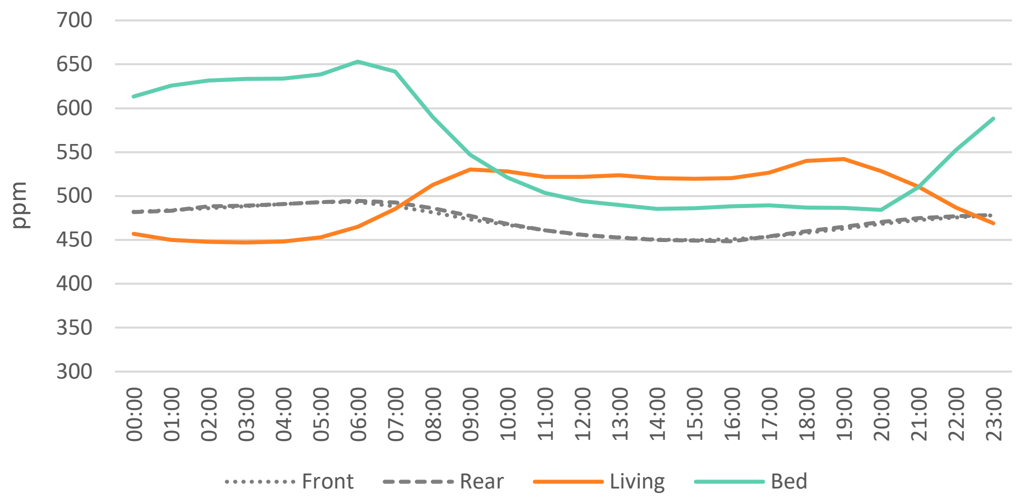
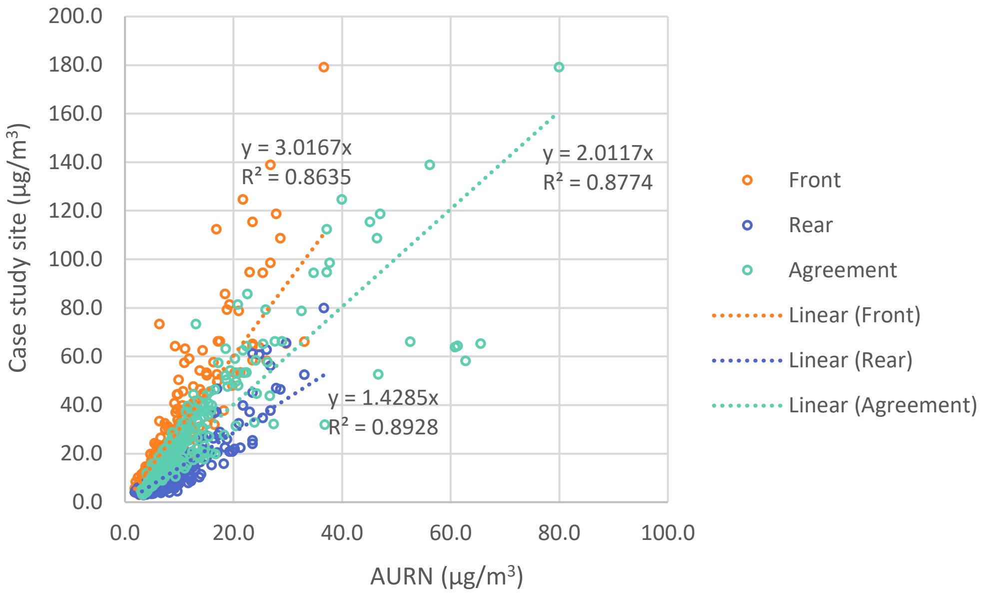


Figure 3-8 Hourly average values of CO_2 concentration

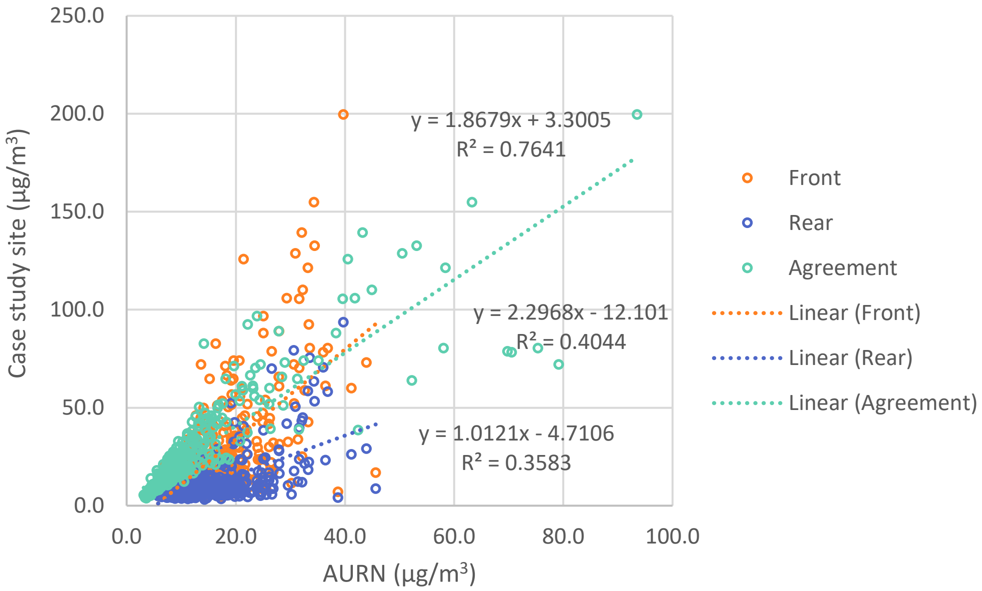
3.3.4 Particulate Matter monitoring

Results in this section are mainly concerned with the two sizes of PM that are subject to global and local targets using monitoring campaigns in the ambient environment, $PM_{2.5}$ and PM_{10}. These are also currently considered the greatest risk to human health. The values measured here are considered within the context of the WHO Air Quality Guidance levels defined for annual mean and the 24-hour average.

Sensors used in the home were compared with one another in an empty office environment before being deployed to ensure they were returning consistent readings. It was also possible to access hourly average observations from the DEFRA Automated Urban and Rural Network (AURN) air quality station at Fishergate in York. AURN stations are maintained by DEFRA to provide robust reference data from calibrated high-cost sensors. They therefore provide a reliable cross-reference for the measured data here, the Fishergate site is the nearest AURN site to the home’s location. Values for 24-hour averages of $PM_{2.5}$ and PM_{10} from the two external sensors and the AURN site are compared in Figure 3-9.



(a) Comparison of $PM_{2.5}$ µg/m³ 24-hour averages

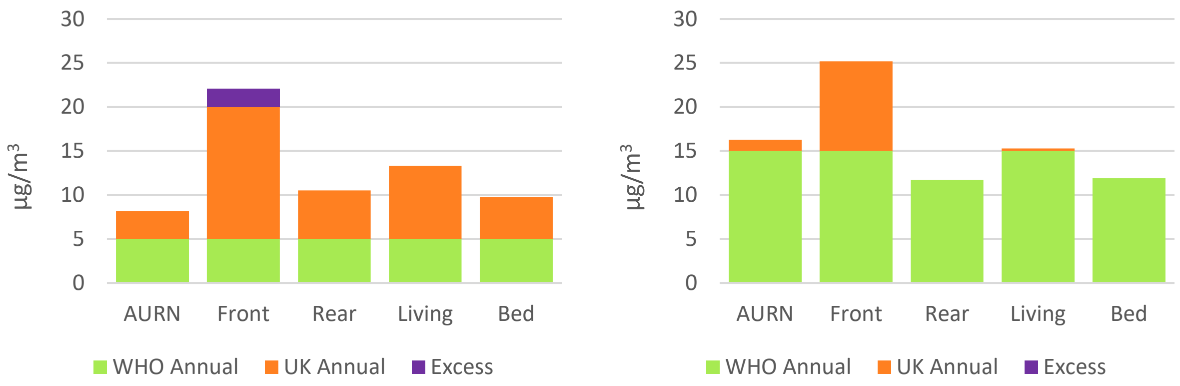


(b) Comparison of PM_{10} µg/m³ 24-hour averages

Figure 3-9 Comparison of 24-hour average values from AURN and home's external sensors

In Figure 3-9 the orange data points compare the AURN readings with those from the front external sensor. In chart (a), it is shown that observations of $PM_{2.5}$ from the front of the site tended to be higher than those at the AURN site, although there is relatively low variance between the two, as with the sensor at the rear of the dwelling (blue data points). However, absolute values more similar to those at the AURN site were recorded at the rear. Turquoise data points compare the two home sensors. All of the sensors recorded similar levels of $PM_{2.5}$, although there is some degree of variance between all observation locations. Relatively, there is a much greater variance between observations of PM_{10} from the home and the AURN station. Although agreement between the two sensors on site is relatively high. It is important to note that variance between sites could be related to local conditions, but also that the accuracy of the relatively low-cost sensors used here is lower than the high-cost AURN sensors.

The variance between the AURN site and the sensor at the front of the home is emphasised in Figure 3-10 below. In both charts, green portions of the bars are within the WHO annual mean, orange portions exceed the WHO threshold but are within the DEFRA threshold, purple portions exceed the DEFRA threshold. Mean values for both PM sizes are significantly higher at the front of the home. This suggests that there is a local influence on these readings, perhaps due to this being a parking area for multiple vehicles, although this is entirely speculative. It could perhaps be due to solid fuel burning, although this seems unlikely as higher readings are evident in warmer months as well. However, the higher readings in this location can't be apportioned to sensor error, as the living space and front sensor were swapped around at 15:00 on 6th December 2022. This was actually due to a faulty CO_2 sensor in the internal unit but was however opportune in eliminating sensor error from this analysis as both sensors provided consistently higher readings in this location.



(a) $PM_{2.5}$ µg/m³ annual mean   *(b) PM_{10} µg/m³ annual mean*

Figure 3-10 Comparison of annual mean concentration of particulate matter between locations

In all locations, the $PM_{2.5}$ concentration exceeded the annual mean level recommended by WHO and exceeded the DEFRA threshold at the front of the dwelling. Both the AURN and front locations exceeded the WHO targets for PM_{10}. This threshold was also exceeded in the living space, but by a marginal amount. Excluding the front of dwelling mean, annual mean PM ambient external levels and internal levels were similar across the full monitoring period. The mean from the living space was however higher in both instances.

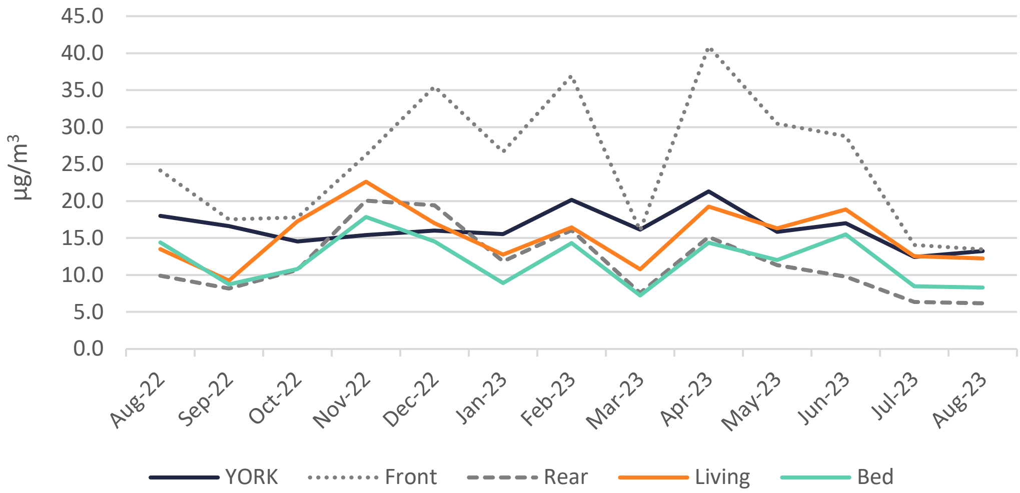
The charts in **Error! Reference source not found.** illustrate the number of days that exceed the WHO thresholds for the 24-hour average in each of the different locations. To fall within the acceptable 99th percentile, no more than 3 days can exceed a 24-hour average of 15 µg/m³ for $PM_{2.5}$ and 45 µg/m³ for PM_{10}. A non-trivial number of days exceeds this limit for $PM_{2.5}$ in all locations, with the front location exceeding this target for a total of 191 days. Bedroom 1 of the house was the only location not to exceed the WHO limit for PM_{10}, although this number was much higher at the Fishergate site than it was across the home.

(a) $PM_{2.5}$ days of exceedance   *(b) PM_{10} days of exceedance*

Figure 3-11 Comparison of number of days exceeding WHO limits for PM between locations

Monthly average values for $PM_{2.5}$ and PM_{10} for all sites are presented in Figure 3-12. It is again evident that there are consistently significantly higher levels measured by the sensors that were positioned at the front of the house. Although there is no obvious seasonal pattern, the shape of the curve is often similar for all internal and external spaces, which suggests that, at a monthly resolution, specific locations are influenced by the background ambient level of particulate matter. This is especially the case for the levels measured at the rear and inside the home.

(a) Monthly average $PM_{2.5}$ concentration



(b) Monthly average PM_{10} concentration

Figure 3-12 Monthly average PM levels during monitoring period

As noted earlier, the sensors used in this work measure seven different sizes of PM, between the sizes of 0.1 and 10 micrometres in diameter. The smaller sizes of PM are not currently monitored as part of the AURN network, and monitoring at these smaller scales is not yet a mature technology. It is therefore important to note that there is no means of cross-checking these data, other than between the sensors installed at the home. The average mass concentration for each of the PM sizes is shown in Figure 3-13. These results suggest that there was a greater concentration of small particulates outside at the rear of the dwelling, which was near to the MVHR inlet and exhaust. No conclusions can be drawn from these data in this instance, but it is an area for further work. Understanding of fine (<1 μm) and ultrafine particulates (<0.1 μm) is the focus of ongoing investigations [10].

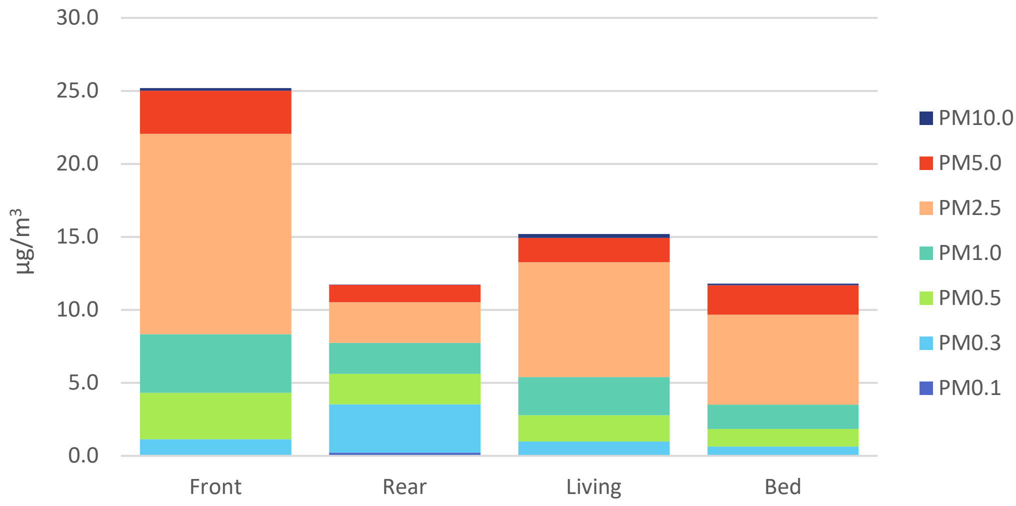
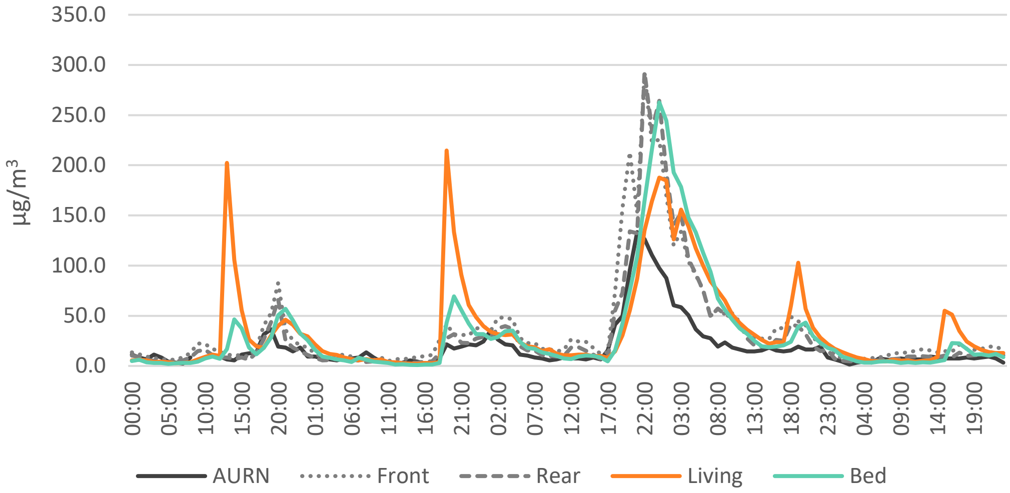


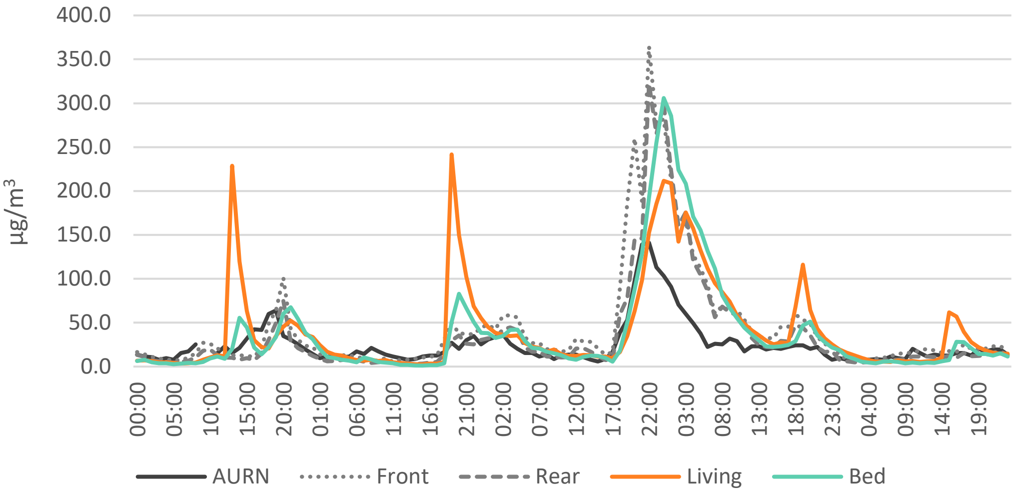
Figure 3-13 Annual mean concentration of different PM sizes

In addition to the analysis presented for the aggregated concentrations of PM, it is also useful to consider some specific events, either at a local or dwelling level. Hourly data over specific periods are evaluated to explore the relationship between the internal and external levels of PM. Specific events considered here include two external peak days identified from the York Fishergate AURN data, 5th November 2022 (Guy Fawkes Night) and 14th February 2023. Internal events included are days that the living space wood-burning stove was used (27th and 28th December 2022). Finally, a period when the home was unoccupied was selected to compare internal and external levels, 10th-13th June 2023.

Figure 3-14 illustrates the external and internal concentrations of $PM_{2.5}$ and PM_{10} between 3rd and 7th November 2022. There is a clear spike in PM levels on the 5th of November, and a delay between external peaks and internal peaks is evident. It is interesting to note that peaks in the living space on preceding days are higher than the peak on the 5th. Due to the time of these, it is assumed that these were from cooking. These are also much shorter in duration than the peak on the 5th which means total exposure is much lower during the preceding days, as the concentration rises and falls relatively quickly when compared with the 5th. Although the absolute values vary slightly in terms of mass concentration, the curves for both $PM_{2.5}$ and PM_{10} are almost identical. For the sake of simplicity, the remaining analysis in this subsection presents only data for $PM_{2.5}$, as the shape of the curves in the charts was again very similar for both particulate sizes.



(a) Hourly average $PM_{2.5}$ concentration

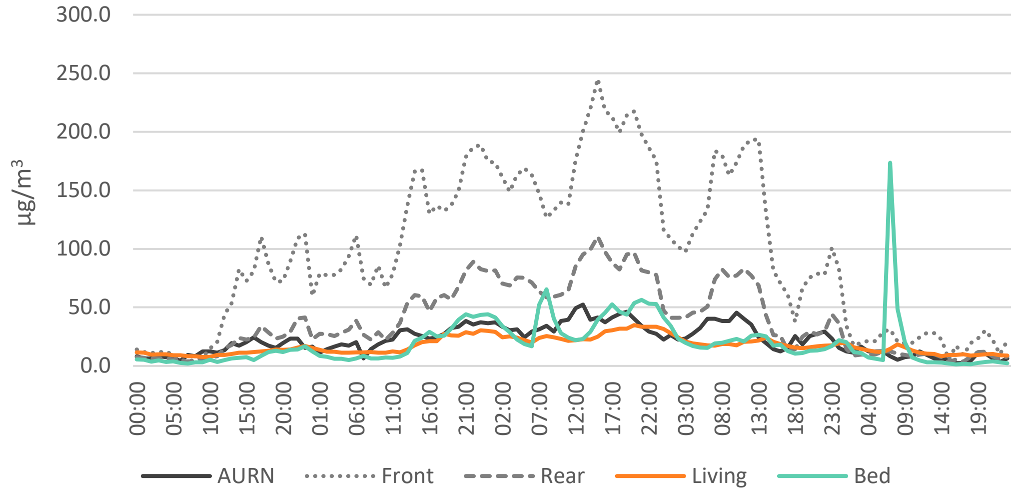


(b) Hourly average PM_{10} concentration

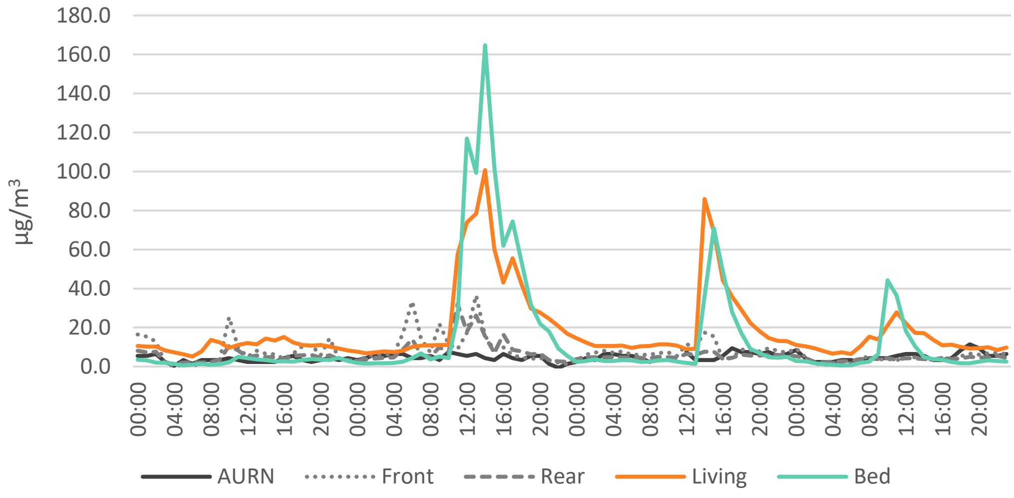
Figure 3-14 Hourly average PM levels during monitoring period 3rd-7th November 2022 (peak external)

Data presented in the remainder of this subsection suggest that PM levels are relatively well controlled and that spikes in concentrations inside the dwelling are often generated by internal sources, such as cooking or the wood burner in the living space (which, anecdotally, is very rarely used). The pattern of concentration internally does sometimes follow the external background levels, with a slight delay, but the absolute concentration is lower inside the dwelling when levels are higher outside.

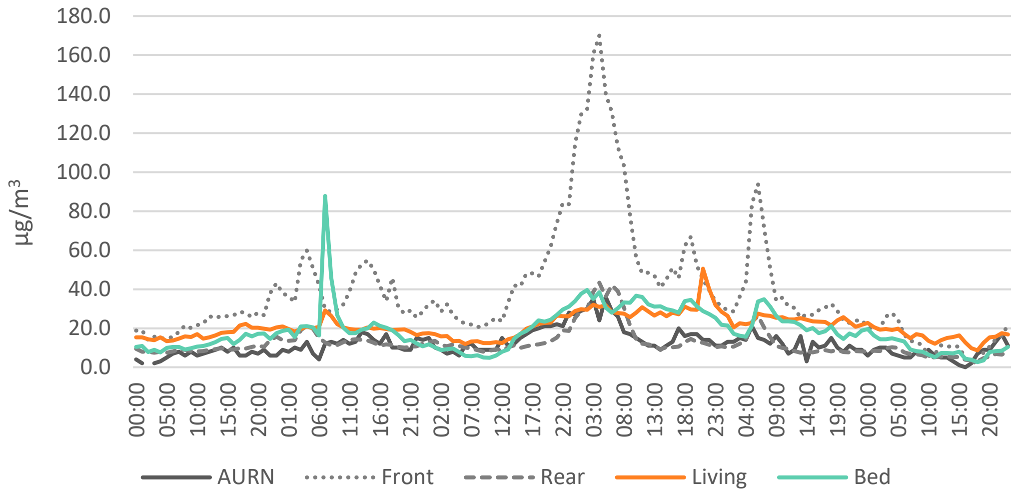
In chart (a) of Figure 3-15, external levels of PM2.5 are higher than usual over a period of several days. Internal levels roughly follow the external pattern and while they are higher than usual, the absolute values are lower internally. In chart (b), there are clear spikes when the wood-burning stove is used, but these return to relatively low levels quickly after the burner has been used. During the unoccupied period in the middle of chart (c), internal levels are similar to those externally although do stay at a relatively higher level after high concentration spikes from the sensor at the front of the dwelling.



(a) Hourly average PM2.5 concentration 12th-16th February 2023 (peak external)



(b) Hourly average PM2.5 concentration 26th-29th December 2022 (wood burner)



(c) Hourly average PM2.5 concentration 9th-14th June 2023 (unoccupied)

Figure 3-15 Hourly average PM2.5 concentration during specific events related to air quality

3.4 Conclusion

Air quality was monitored by two external and two internal sensors between 5th August 2022 and 30th August 2023. CO_2 and seven sizes of PM were measured and compared against CIBSE, WHO and DEFRA thresholds for context. The airflow through the majority of the MVHR system was also measured during the monitoring period.

The MVHR system was not balanced when tested compared against commissioning figures, with extract air flow rates being over 10 per cent higher than intake air flow rates, meaning the system no longer satisfied Passivhaus requirements. The system was also noisier than the recommended levels. However, the excessive noise ceased when the system was serviced and a fan was replaced later in the year.

CO_2 levels on average were less than 872 ppm which equated to a high level of IAQ across the home, although the average was slightly higher for the bedroom. Peak CO_2 readings were recorded on 19th February for the living area, and 8th Feb in the bedroom. These equated to a moderate level of IAQ. There was a visible drop in CO_2 levels from April 2023, which seems to align with when the MVHR filters were changed and the arrival of warmer weather for increased door and window opening.

When comparing $PM_{2.5}$ and PM_{10} particulate levels against a DEFRA monitoring station at Fishergate, WHO and DEFRA annual thresholds were exceeded between 53 and 191 days for $PM_{2.5}$ and up to 47 days for PM_{10} depending on the sensor location. For $PM_{2.5}$, the number of days exceeded was higher at the home than at Fishergate, whereas for PM_{10}, conversely, the number of days exceeded was far higher at Fishergate. Higher levels of particulate matter were recorded by the sensor at the front of the house, compared with the other three sensors.

Three peak periods were examined to see how particulates generated externally or internally rose and fell over time. Spikes in PM levels were generally due to cooking or use of the wood-burning stove if generated internally, and dissipated quickly. Elevated PM level patterns recorded outside were often mirrored inside but at a much lower level, suggesting that particulates are filtered by the MVHR system.

4 Thermal Comfort

4.1 Introduction

One of the central arguments for Passivhaus construction is the claim that Passivhaus dwellings provide a superior level of thermal comfort for occupants when compared to traditional construction methods. This is due to:

1. The thermal insulation of the building fabric being capable of maintaining a stable internal temperature and minimising thermal drift. In practice, this means keeping heat within the home during winter and out of the home (in combination with purge ventilation) during summer.
2. Reduced thermal variation, both horizontally and vertically, with a more consistent air temperature throughout the dwelling.
3. Uniform surface temperatures throughout the dwelling, reducing uncomfortable radiant asymmetry.

To investigate this, 20 temperature sensors were installed throughout the home to measure air temperature at 30-minute intervals between 5th August 2022 and 30th August 2023. The location of the sensors, labelled PH01–PH20, is shown in Figure 4-1 and Figure 4-2. Data were then analysed to investigate temperature uniformity across the home, thermal comfort, and overheating.

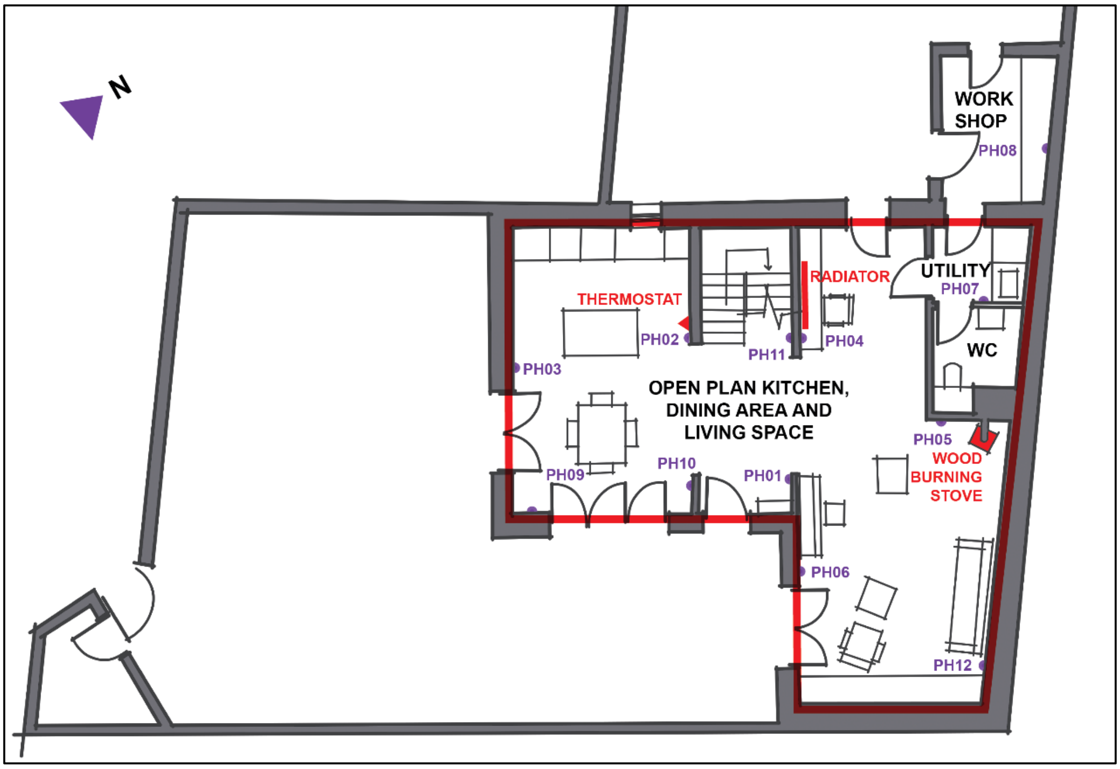


Figure 4-1 Ground floor temperature sensor locations

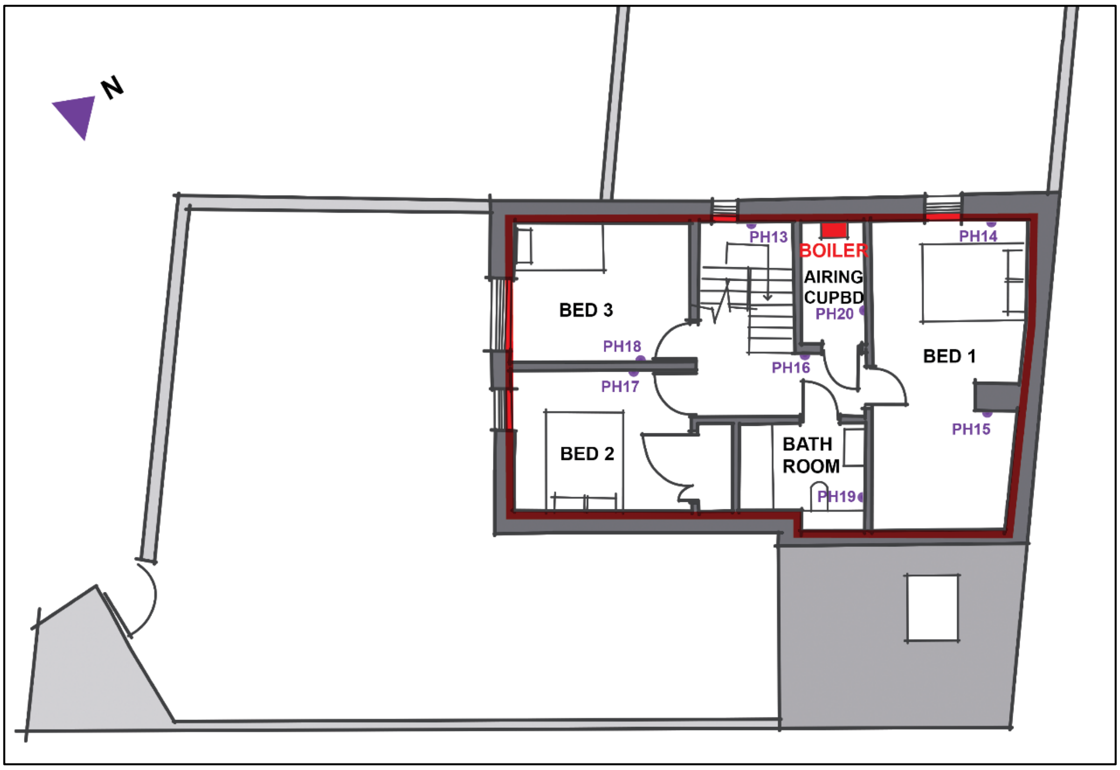


Figure 4-2 First floor temperature sensor locations

4.2 Uniformity of temperatures

Initial analysis explored the uniformity of temperatures throughout the home across the full monitoring period. Figure 4-3 shows that, except for sensor PH08 which was located outside the thermal envelope (marked in red in Figure 4-1 above) in the adjoining workshop, temperatures appear to remain in good agreement throughout monitoring. Whilst there appears some relationship between internal and external temperature during warmer months this does not occur in winter, with internal temperatures remaining above ~15°C even during cold events. The agreement in internal temperatures is shown in more detail in Figure 4-4 with external and workshop temperature data removed to compress the y-axis.

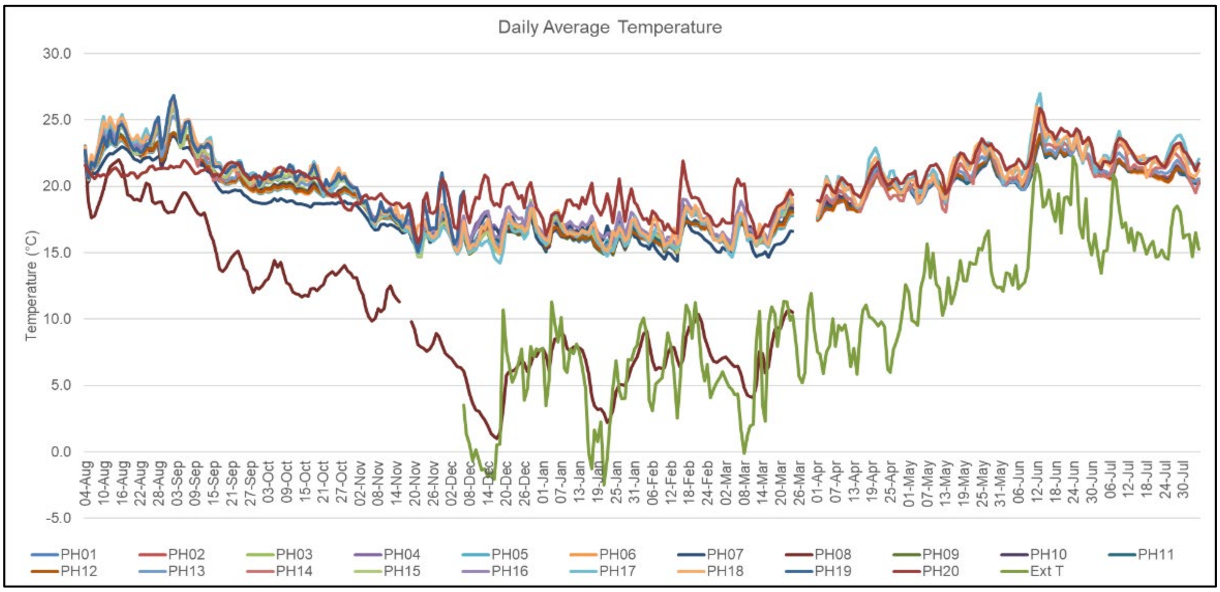


Figure 4-3 Mean daily temperature

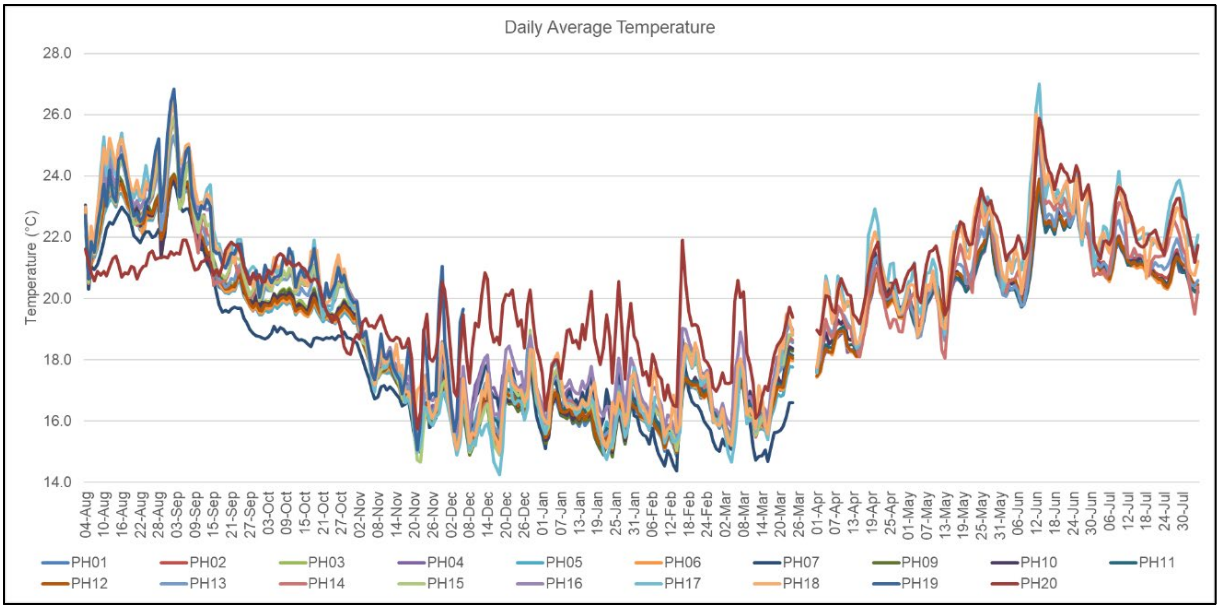


Figure 4-4 Mean daily temperature (excluding External and Workshop data)

Thermal uniformity may be explored further by considering the temperature range between the coldest and warmest sensor, with a smaller range indicating a more uniform temperature throughout the home.

Figure 4-5 illustrates the range of 30-minute temperature data across all sensor locations within the thermal envelope. As may be seen, although there were fluctuations across shorter periods, temperatures were typically within a 3°C range throughout the home (75.8%), with 90.9% of total measurements within a 4°C range. This indicates a low level of thermal uniformity, with a relatively consistent temperature throughout the dwelling.

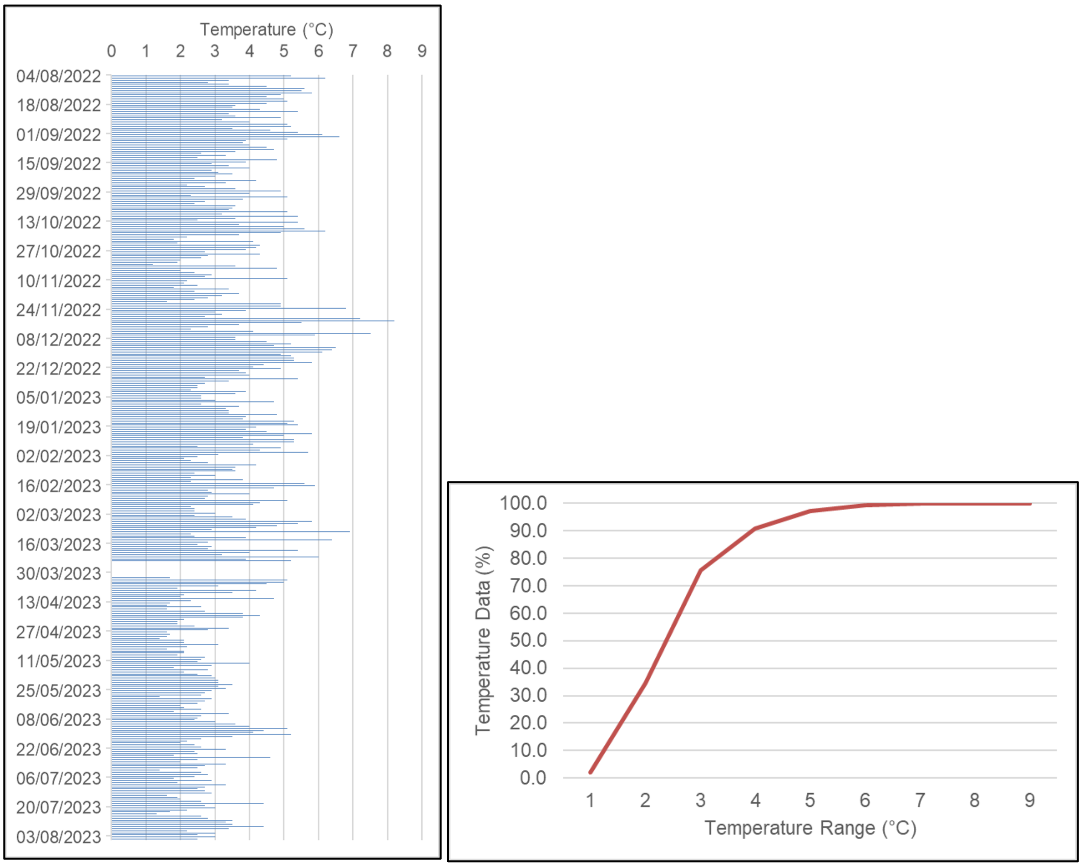


Figure 4-5 Between-sensor temperature range

4.3 Thermal comfort

Having established that thermal conditions within the home were generally uniform, the next consideration is how this may translate into thermal comfort for the occupants. For this analysis, the coldest and hottest weeks during the monitoring period were extracted from the dataset for detailed interrogation.

Figures Figure 4-6 and Figure 4-7 show 30-minute temperature data for the coldest week during monitoring, where external temperatures were predominantly below 0°C and as low as -5°C. Despite these low external temperatures, the internal temperature remained above 14°C consistently.

In general, internal temperatures were observed to be quite low, remaining under 20°C in most zones, except for the airing cupboard where the boiler was located (PH20), which may not be representative of the dwelling given the likelihood of internal heat gains. The heating programmer defaulted to the daytime and nighttime temperature set points of 24°C and 15°C respectively during the winter months. Consequently, the original PHPP file was reviewed to see what assumptions had been made at the design stage about the home's heat gains. As a 3-bed house, higher occupancy levels and associated heat gains had been assumed. This suggests that the home's space heating system was sized to meet the needs of a three to four-person household as opposed to the one to two people who were living there during the monitoring period. A further assumption in the PHPP software was that the gas boiler would meet 70 per cent of the home's space heating demand and the wood-burning stove the other 30 per cent; however, the wood-burning stove was only used twice during the monitoring period (27th and 28th December 2022 when family members came to stay at Christmas).

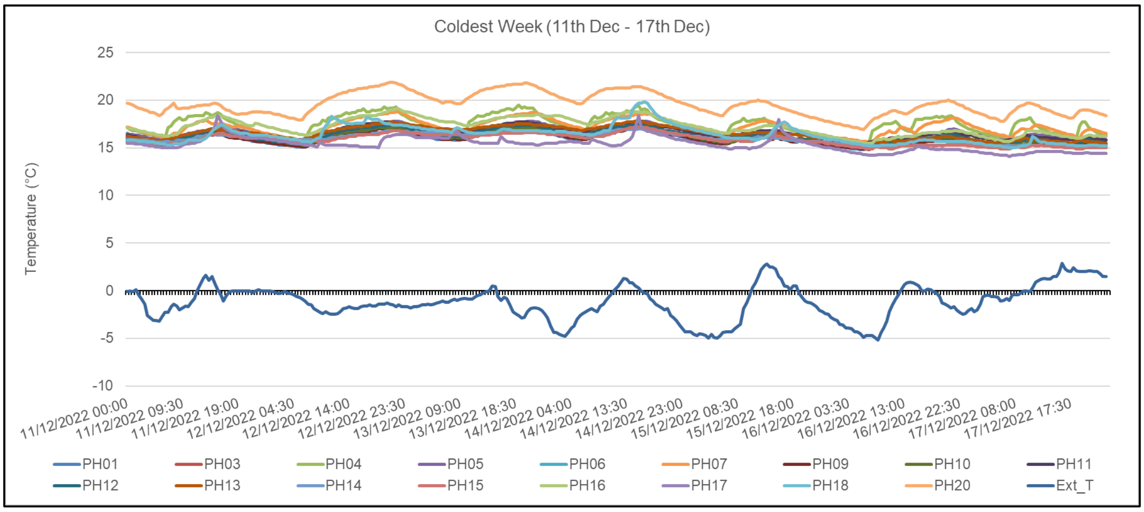


Figure 4-6 Temperature data for the coldest week during monitoring

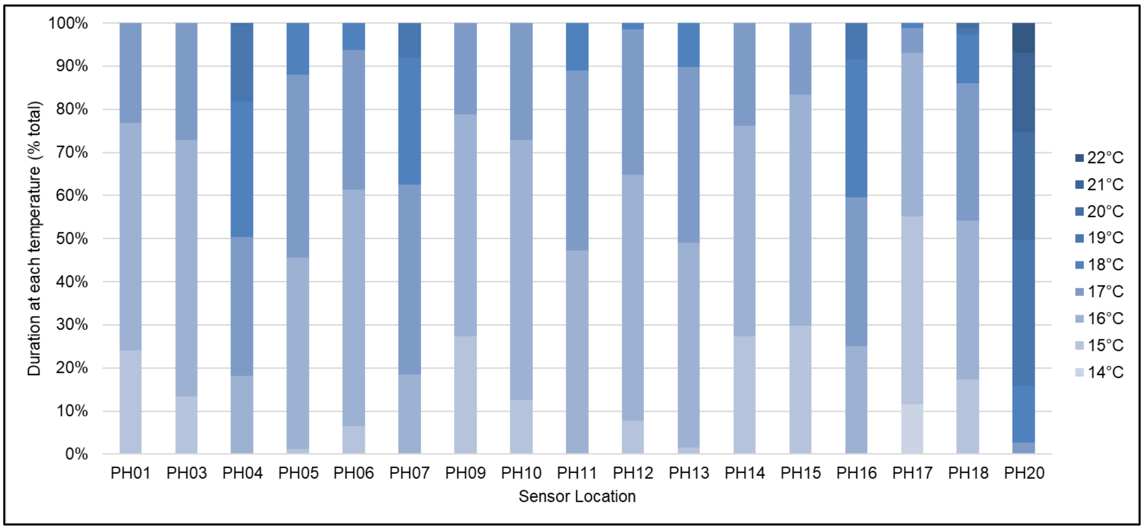


Figure 4-7 Temperature durations for each monitoring location

Warm periods are particularly relevant when considering Passivhaus dwellings, which have been observed to overheat excessively when not operated properly with overnight purge ventilation[11]. Figures Figure 4-8 and Figure 4-9 show temperature data for the hottest week during monitoring, where external daytime temperatures exceeded 29°C at points.

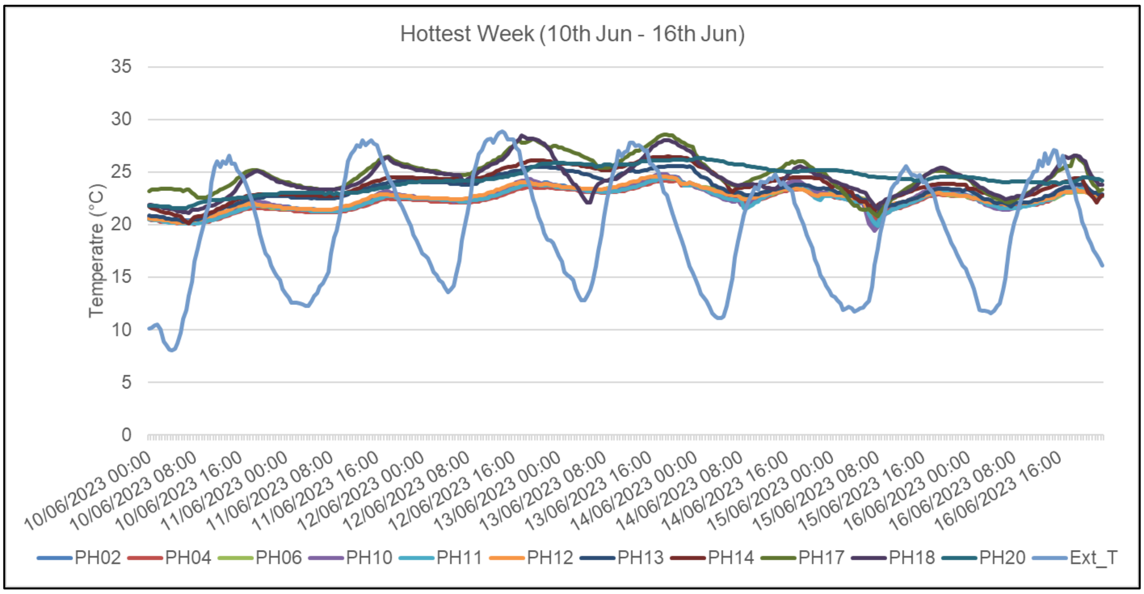


Figure 4-8 Temperature data for the hottest week during monitoring

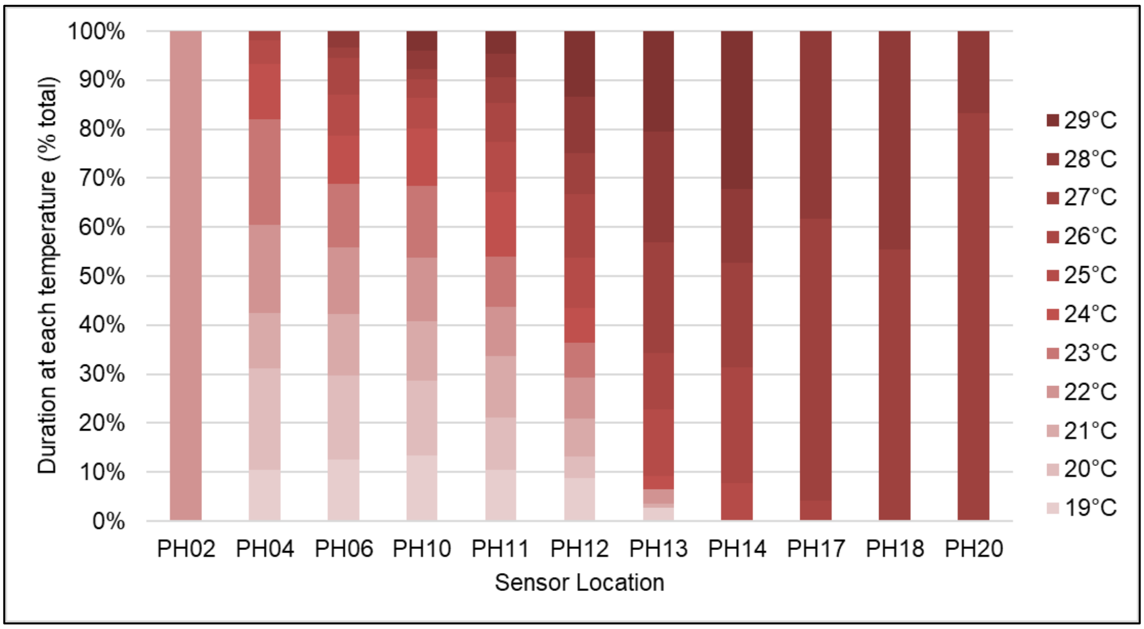


Figure 4-9 Temperature durations for each monitoring location

As can be seen, the internal temperatures appear to respond to diurnal day/night temperature patterns, with some lag, which is likely due to solar gain. Coincidentally, the warmest weather period during monitoring coincided with an unoccupied period in the home (10th – 13th June). During this period the home was effectively 'free running' with no manually operated natural ventilation and reduced internal heat gains. It is noteworthy that there is evidence of temperature 'ramping' during this period, where internal temperatures at the end of the day have not cooled down to their temperature at the start of the day, leading to a stepping up of internal temperature as each day progresses. This suggests an inability to effectively purge the excess heat overnight without additional occupant-operated ventilation.

Figure 4-9 illustrates that there is some thermal variation within the dwelling during the hottest week. Temperatures upstairs (PH13 – PH20) were found to be statistically significantly warmer than downstairs when evaluated using independent t-test ($t(2807.654) = -38.612$, $p = <.001$), with a mean difference of 1.6°C. This points to the influence of solar gains, in addition to heat rising generally in the property. This is important when considering overnight thermal comfort, with bedrooms on the upper floors showing evidence of much warmer temperatures that may affect comfort during sleep. Temperatures were also observed to be statistically significantly different on the horizontal axis when evaluated using one-way ANOVA ($F(3,3692) = 63.256$, $p = <.001$), with a post-hoc Games Howell test identifying temperatures were statistically cooler at North-Westerly measurement locations.

Although thermal comfort is an inherently subjective phenomenon, there are numerous metrics for objective evaluation based on the predicted comfort perception of a population. One such metric is adaptive thermal comfort, the method for which is described in detail in BS EN16798 [12]. Adaptive thermal comfort presents upper and lower temperature thresholds based on the exponentially weighted running mean of external temperature. These thresholds vary in lenience, with Category 1 being the strictest and allowing a range of 5°C around a theoretically comfortable temperature. For this analysis, the Category 2 threshold has been used, which considers a medium level of expectation from the internal environment (a range of 7°C) and is shown by the parallel lines on the graphs below. For temperature to be regarded as thermally comfortable, the data points must be within the threshold lines.

Figure 4-10 shows the 30-minute temperature data for all locations during June, the hottest month during monitoring. As can be seen, the majority of the measured temperatures were within the Category 2 adaptive comfort threshold, suggesting there is a generally acceptable comfort level within the home during this warm period. There were, however, some locations where the upper threshold was exceeded, which are shown in detail in Figure 4-11 and Figure 4-12.

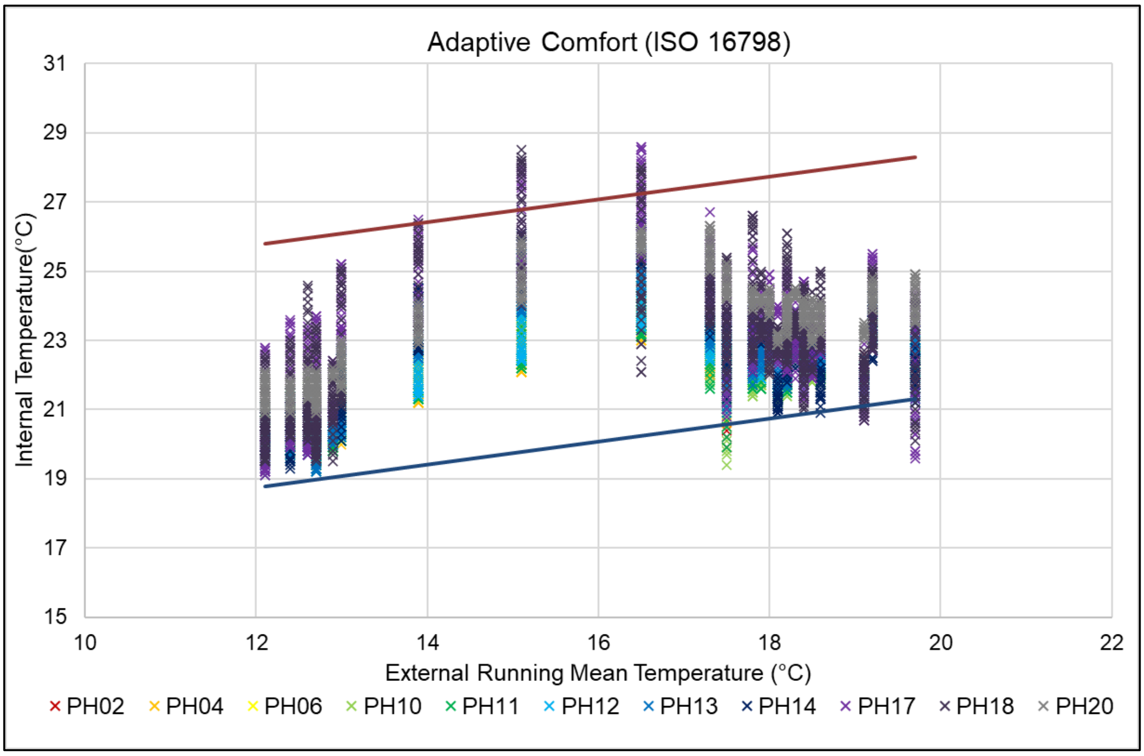


Figure 4-10 Adaptive comfort during the hottest month - All locations

The upper threshold was exceeded on 3 occasions in bedrooms 2 and 3, which are located upstairs and on the southwest façade of the property. This suggests that in these locations it was not possible to fully avoid the influence of solar gains. This may have been exacerbated by their westerly aspect, presenting heat gains later in the day and limiting the capacity for overnight purging.

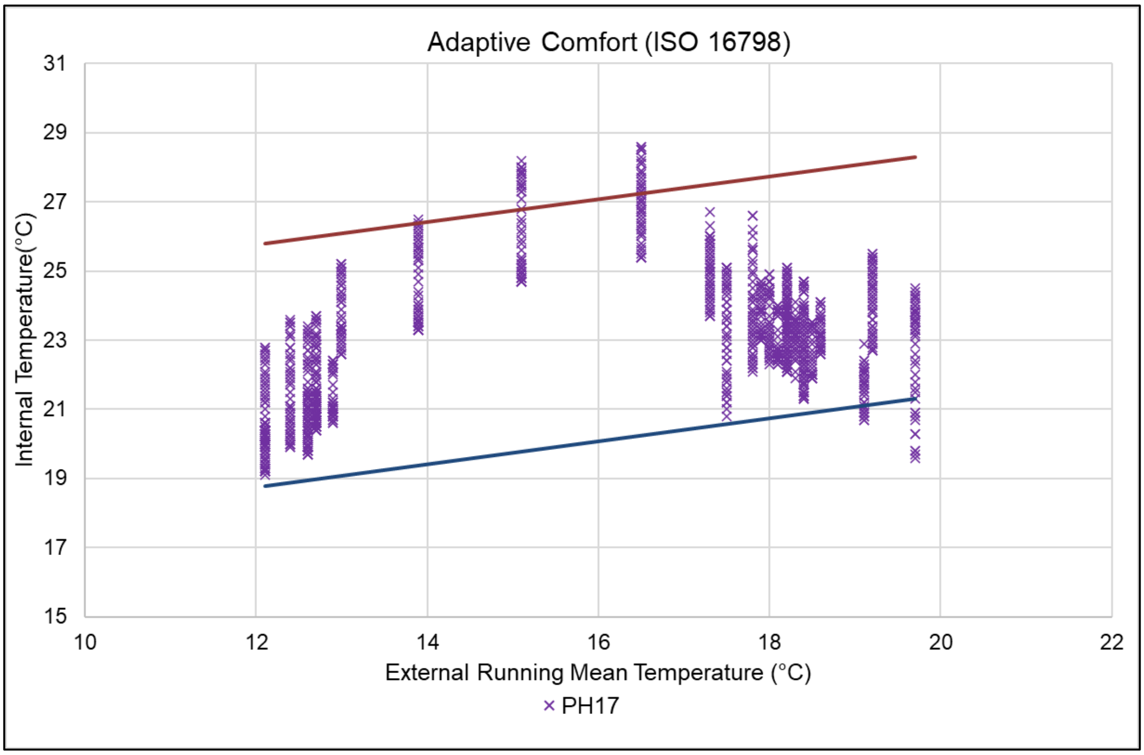


Figure 4-11 Adaptive comfort during the hottest month - PH17 (bedroom 2)

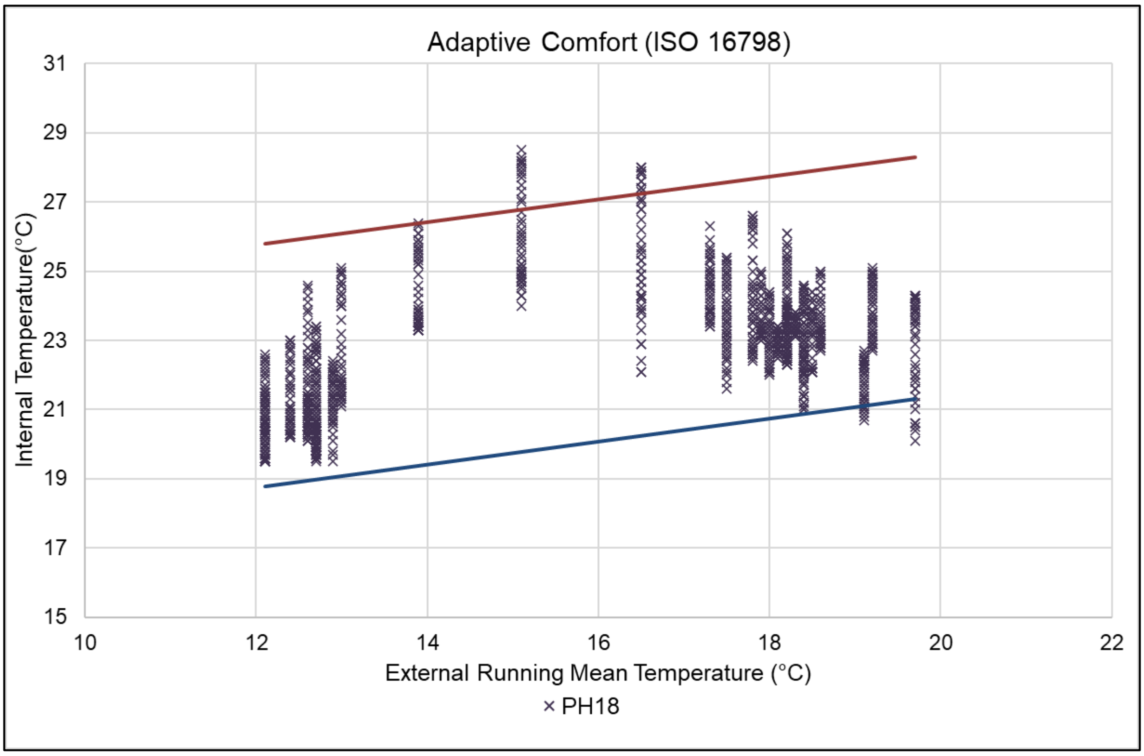


Figure 4-12 Adaptive comfort during the hottest month - PH18 (bedroom 3)

4.4 Overheating

The preceding analysis has shown that although there appears to be a good degree of comfort during summer, there were some periods of overheating when evaluated using the adaptive thermal comfort index. To explore overheating further, firstly it is appropriate to consider the overheating metric applied during the design stage. When designing a Passivhaus, PHPP is used to evaluate predicted overheating risk. To pass the overheating risk assessment at planning stage, the criteria is that internal temperatures must not exceed 25°C for more than 10% of the year [13].

Measured data were, therefore, evaluated against the PHPP threshold, with values for each sensor shown in Table 4-1. As can be seen, the measured data did not exceed the PHPP limiting threshold for overheating, suggesting that the design has performed as intended with regard to overheating mitigation. The room with the highest percentage of exceedance was the bathroom, which is not necessarily representative of the whole house due to the short-term temperature spikes caused by shower/bath use. For additional context, the PHPP threshold is illustrated during the hottest month (June) by Figure 4-13, which shows that the threshold was only exceeded for short periods in rooms on the south-facing upper level of the building. It is worth noting that the occupants were away from home between 10th and 13th June 2023 so unable to purge the home at night.

Table 4-1 Measured temperature data exceeding PHPP overheating threshold

Sensor	%Data over 25°C	Result	Sensor	%Data over 25°C	Result
PH01	0.1	PASS	**PH11**	0.0	PASS
PH02	0.0	PASS	**PH12**	0.0	PASS
PH03	0.2	PASS	**PH13**	0.8	PASS
PH04	0.0	PASS	**PH14**	1.3	PASS
PH05	0.1	PASS	**PH15**	1.3	PASS
PH06	0.0	PASS	**PH16**	2.7	PASS
PH07	0.1	PASS	**PH17**	3.6	PASS
PH08	0.1	PASS	**PH18**	3.3	PASS
PH09	0.2	PASS	**PH19**	5.0	PASS
PH10	0.0	PASS	**PH20**	0.6	PASS

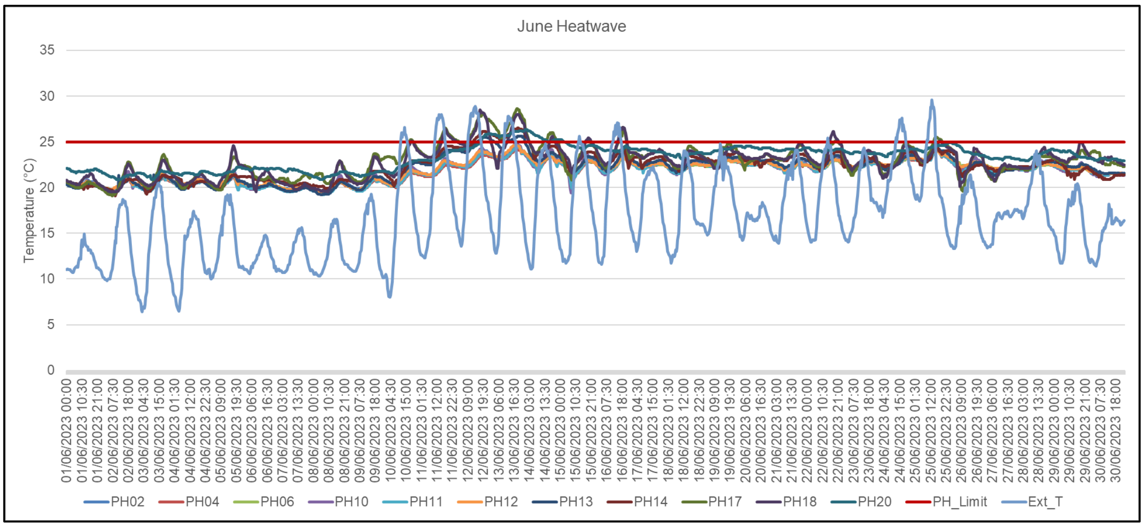


Figure 4-13 Internal temperature during the hottest month relative to PHPP threshold (red line)

4.5 Conclusion

Twenty sensors were installed across the home, recording temperature and humidity levels at 30-minute intervals between 5th August 2022 and 30th August 2023, to monitor thermal uniformity, thermal comfort and overheating.

Temperatures remained constant at above 15°C throughout winter even during cold events. Temperatures across the sensors were generally within a 3-4°C range for the duration of the monitoring, indicating a constant temperature across the home with a low level of thermal non-uniformity.

When focusing on thermal comfort, internal temperatures were found to be quite low and usually under 20°C. The high default daytime set point of 24°C was unobtainable, indicating an undersized heating system for the occupancy level during the monitoring period. This could be due to the design assumption in PHPP for occupancy and heat gains that was based upon between three and four people living in the home when, post-completion, it was only one or two people. Plus it was assumed that the wood-burning stove would meet 30 per cent of the home’s heating demand when during the monitoring period it was rarely used.

During warmer periods of weather, internal temperatures predominantly remained below external temperatures. This suggests that an increase in solar gains did not increase internal temperatures beyond the occupants’ ability to cool the home using passive and active ventilation methods, which is positive. Nighttime temperatures were higher across the first floor during hotter periods of weather, which could affect occupant thermal comfort when sleeping. Bedrooms 2 and 3 were most affected during the monitoring and were found to exceed set upper comfort thresholds on three occasions. The south-westerly orientation of these rooms is likely to be a contributor towards this.

There was no evidence of overheating when using the PHPP design stage overheating metric across the entire data set. While there were three days of overheating recorded during a heat wave, they coincided with the property being empty. This suggests that the building’s MVHR system is not capable of maintaining thermal comfort during warm weather, requiring manual interventions such as window opening and night-time purging to provide cooling.

5 Airtightness

5.1 Introduction

This section details the findings from an airtightness test using a blower door and thermographic survey carried out on 06 December 2022. As the home, completed in 2015, met the Passivhaus standard with an average air change rate of 0.40 ACH @ 50Pa, this blower door test aimed to establish whether the home still meets the Passivhaus target of 0.60 ACH @ 50Pa. The thermographic survey was conducted alongside the blower door test to identify any potential areas of air leakage.

5.2 Observations

A $\Delta T > 10K$ was sufficient for internal thermographic leakage detection to be undertaken, this was carried out immediately following the depressurisation phase of the blower door test at an average -50 Pa. However, due to solar irradiation on the building's façade, external thermography was not possible.

5.3 Conditions

External Temperature	6 °C	Internal Temperature	17 °C
External RH	62.3 %	Internal RH	66.8 %
External Pressure	1020.1 mbar	Internal Pressure	1020.6 mbar
Wind Speed	Average 0.5 ms^{-1}		
Weather conditions	Dry, broken cloud with some sunshine, there had been rain in the previous 24hrs.		

5.4 Airtightness result

The table below shows the results of the air tightness test, both under pressurisation and depressurisation at a pressure differential of 50 pascals. The table contains the air permeability of the building; the rate at which air leaks through the external envelope ($m^3/(h \cdot m^2)$ @ 50Pa), and air change rate; the number of changes in the internal air volume of the building (h^{-1} @ 50Pa) The mean values of both the pressurisation and depressurisation stops of the test are also given.

Depressurisation Only			Pressurisation Only			Mean	
Permeability	Air Change Rate	r^2	Permeability	Air Change Rate	r^2	Permeability	Air Change Rate
$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa
0.82	0.84	0.996	0.87	0.89	0.998	0.86	0.85

(See the Appendix for the airtightness spreadsheet and summary of 2015 airtightness results).

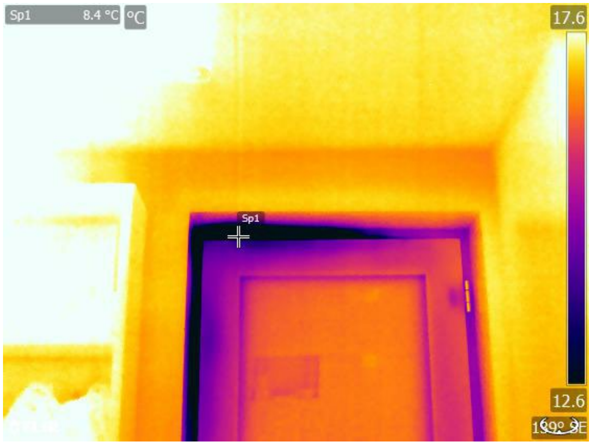
5.5 Thermographic survey

The thermographic survey part of this report is split into two sections: the first section examines the home before the blower door test is carried out to see how the house performs under normal conditions (i.e., there is no induced pressure differential). The second part looks at these areas again while the home is in a state of negative pressure (under depressurisation), i.e., air is being pulled out of the house to draw cold air in through air leakage paths. The purpose of this is to make cold spots more apparent so that they are easier to detect using a thermal camera.

A thermal or infrared image, taken by a thermal camera, is a visual representation of the energy emitted from the surface of an object. As hotter surfaces emit more energy than cooler surfaces, it is possible to differentiate these temperature differences through colour changes across an image. In this survey, hotter surfaces are represented by lighter colours, e.g., white, yellow and orange shades, whereas cooler surfaces appear darker e.g., blue and purple. In some instances, spot temperatures have been recorded, which are displayed in the top left-hand corner of the thermal image. Wherever possible, the thermal images have been adjusted to a 5˚C span. This is to provide some consistency between the images and make direct comparisons possible.

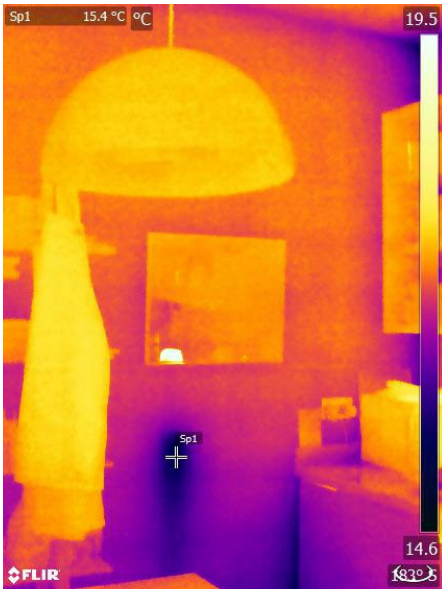
5.6 Internal Thermographic Observations (no induced pressure differential):

Front door



It appears that while the front door is closed, there is some cooling visible between the door and frame in the top corner. This may be due to the door seal becoming less effective, as the weight of the door over time has caused it to sag slightly in the frame, or it could be due the door being recently open.

Kitchen/dining area

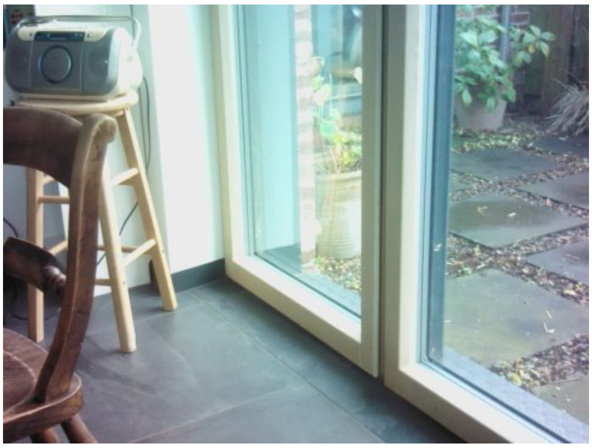


It is possible to see the wall mounted meter box location (and presumably gas supply) from inside the house, as the wall is colder behind it.

Dining area

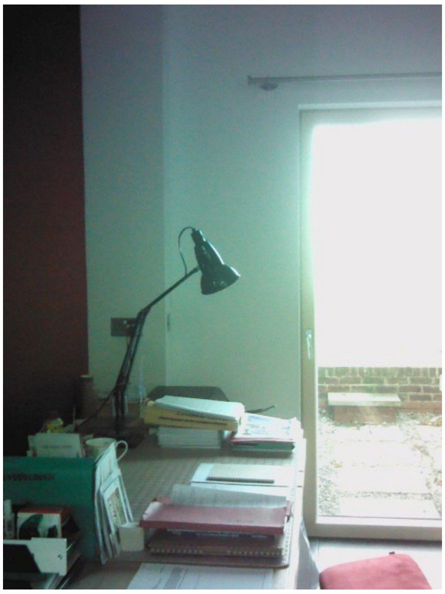
Under normal conditions, there appears to be no evidence of increased air leakage between the frames and French doors.

Dining area



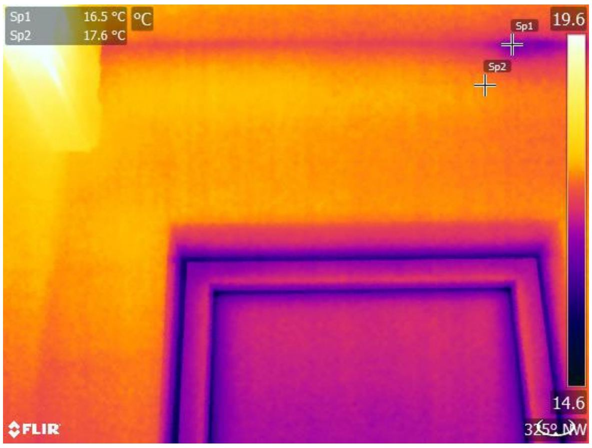
However, some cooling is evident where the French door meets the ground and skirting board in the door reveal and at the threshold.

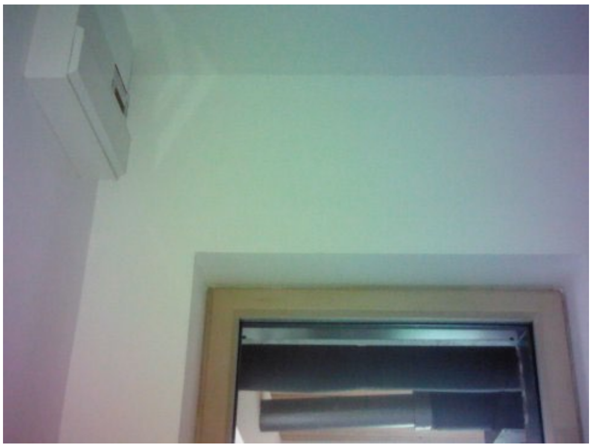
Study space in open plan area



While the external door appears cooler at the bottom, it appears that the seal around the door and frame are functioning satisfactorily.

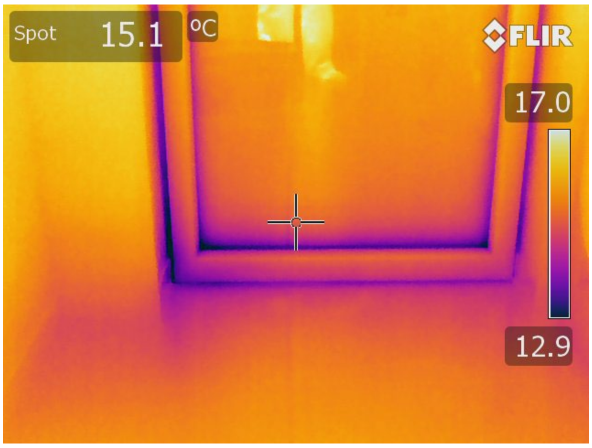
Utility room

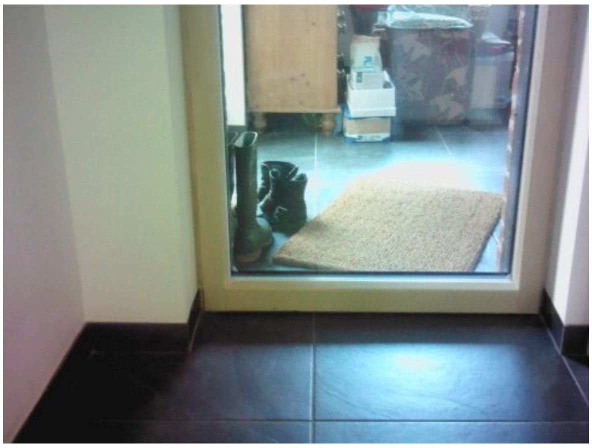




Similarly, the seal between the frame and door in the utility room are the same. However, there is evidence of cooling between the wall and ceiling which may indicate some thermal bridging or cooler air from the floor void above entering the room.

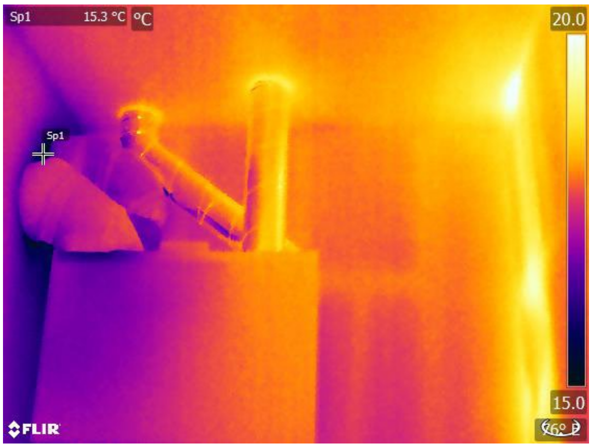
Utility room





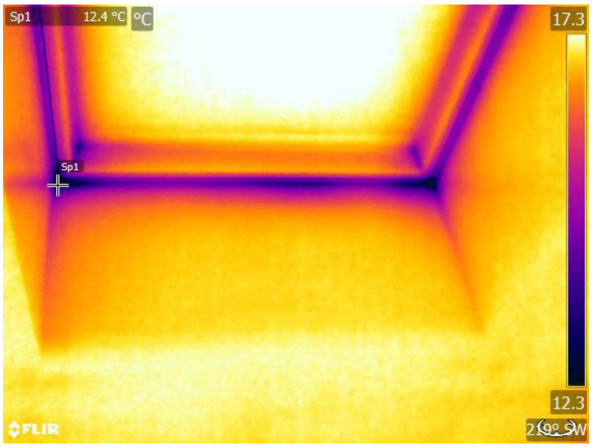
While the bottom of the door looks slightly cooler than the top, the seals around the bottom of the door appear to be working well.

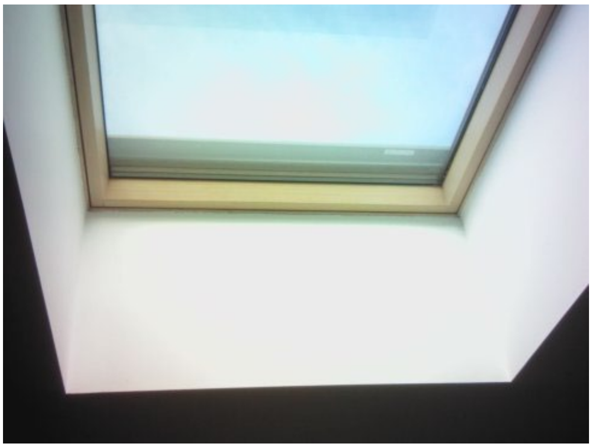
Utility room



The wall is cooler around the ducts from outside and warmer where internal pipe work meets the ceiling, which is to be expected. There appears to be no signs of leakage under passive conditions.

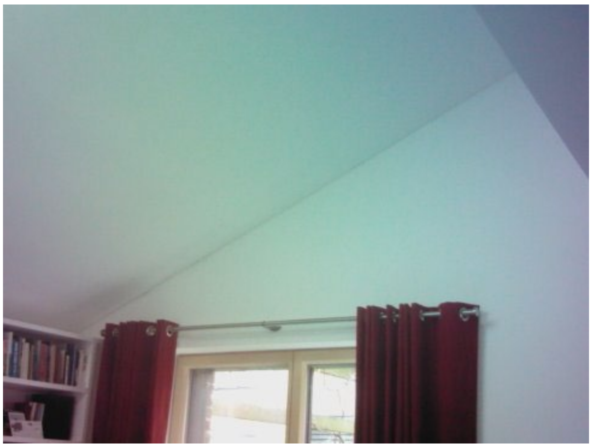
Living area





Darker colours between the window frame and reveal are normal, however, the line of purple along the bottom of the junction where the window meets the wall is not uniform, suggesting some cooling between the window frame and reveal.

Living area

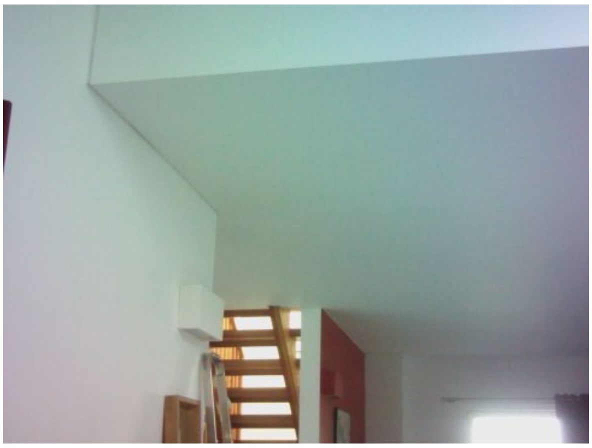


There is a change in surface temperature across the wall above the door, suggesting cooler air circulation at the junction where the sloping ceiling meets the corner of the wall. This could indicate slightly less insulation in this area, or that there is some uneven heat distribution in the room. It is worth noting that dead zones in corners like this are not uncommon in homes that have MVHR where the supply is distant from the corner and the velocity is low.

Living area

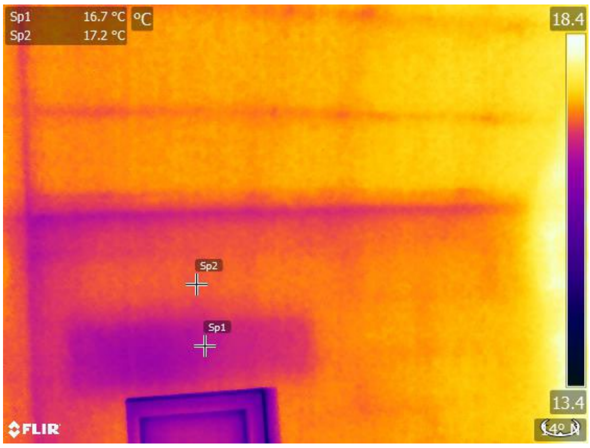
The larger area of purple where the spot temperature is suggests that the seal between the window and reveal is potentially starting to degrade.

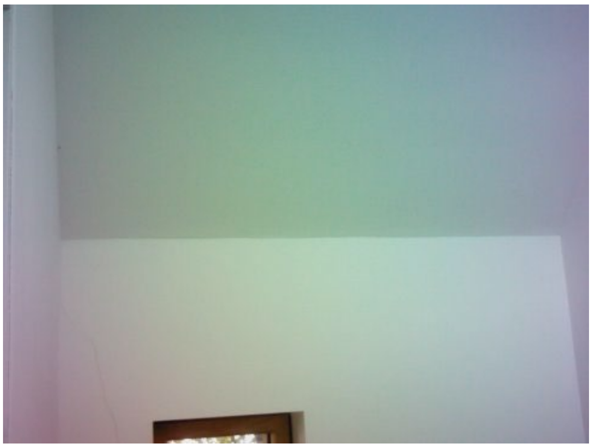
Living area



The dark spot in the ceiling indicates a slow water leak coming from the floor above.

Landing



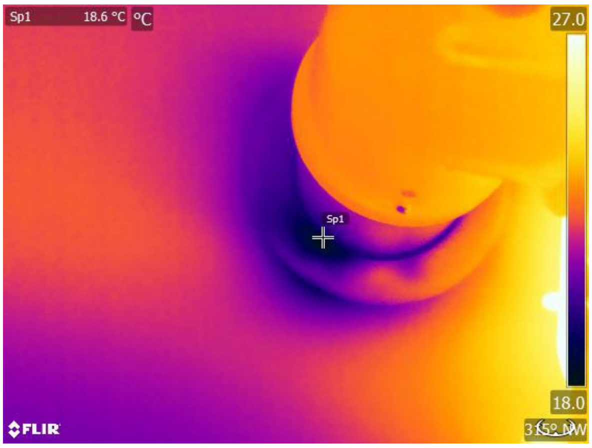


The different thermal properties between the wall and lintel can be seen in this image, as the lintel is slightly cooler.

Airing cupboard

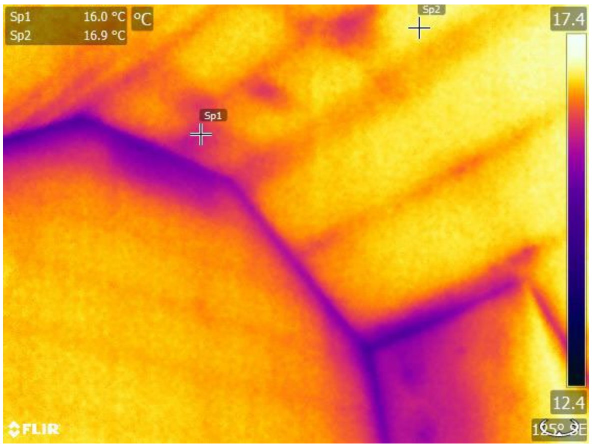
There appears to be a small amount of cooler air coming into the room from around the boiler flue.

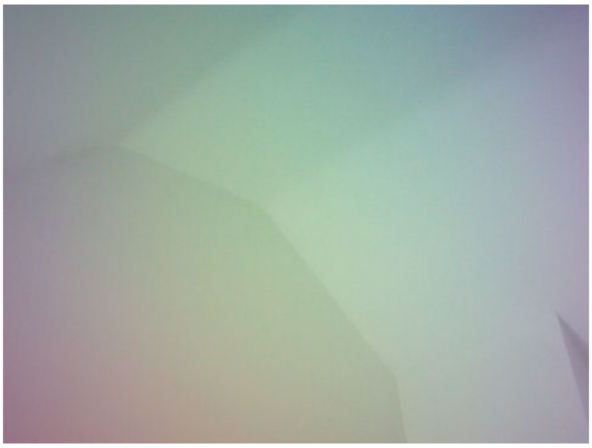
Airing cupboard



This small amount of air infiltration is illustrated in this image.

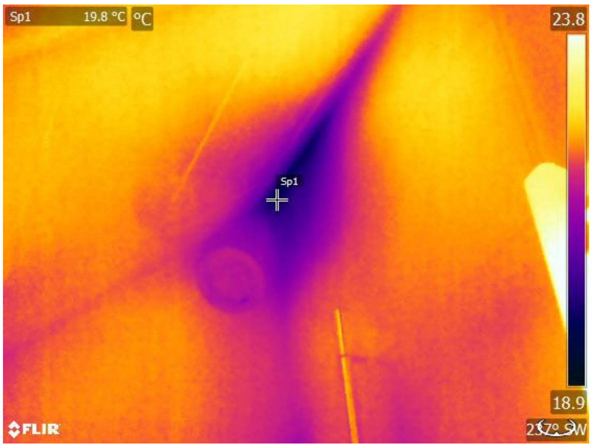
Bedroom 1

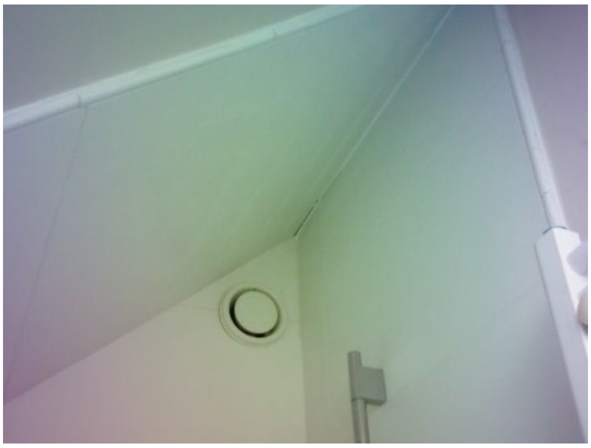




The darker orange spots at ceiling level suggest that the insulation in the ceiling is slightly uneven. There are also darker spots in the stud wall that projects into the room, indicating possible cooler air movement behind the plasterboard.

Bathroom



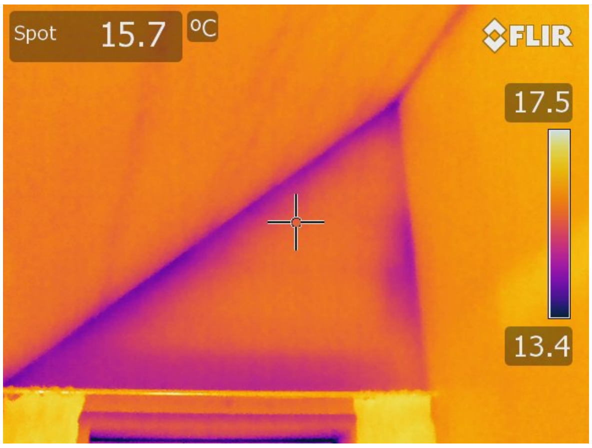


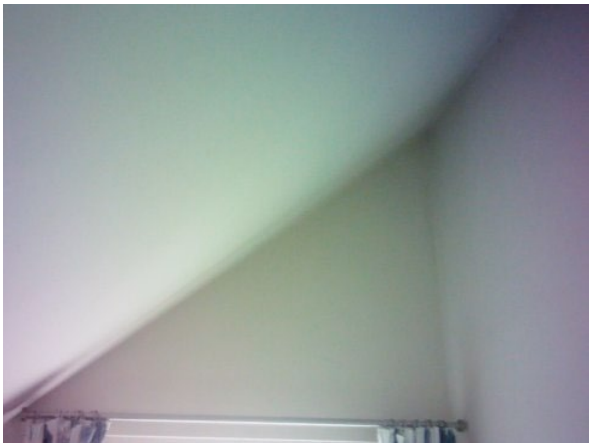
The dark colours in this corner could suggest condensation and moisture, as moist air is drawn towards the bathroom extract grille, and damp surfaces appear cooler than dry ones. It is worth noting that the temperatures in this room are generally higher than those across the rest of the house, so this area may simply appear cooler as the rest of the room is far warmer. Another possibility is that there could be some thermal bridging in this corner.

Bedroom 2

This junction appears satisfactory under passive conditions.

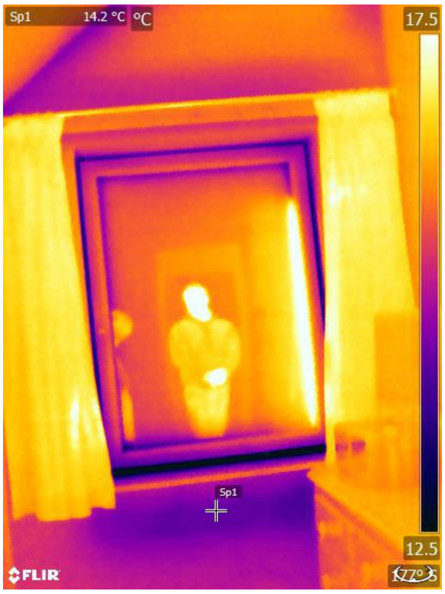
Bedroom 2

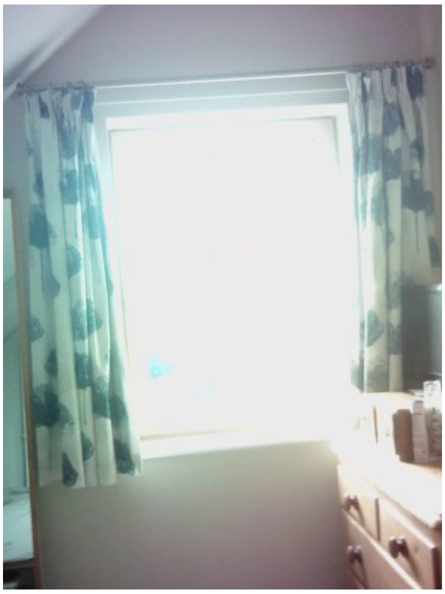




The lower corner where the wall meets the ceiling looks slightly cooler, as the purple line along the junction is uneven. This could be due to a thermal bridge at the eaves junction. Cooler surface temperatures are also observed above the window where the lintel is.

Bedroom 2





There is some sign of cooling across the wall underneath the window. This could be due to a change in material to frame out the window.

Bedroom 3

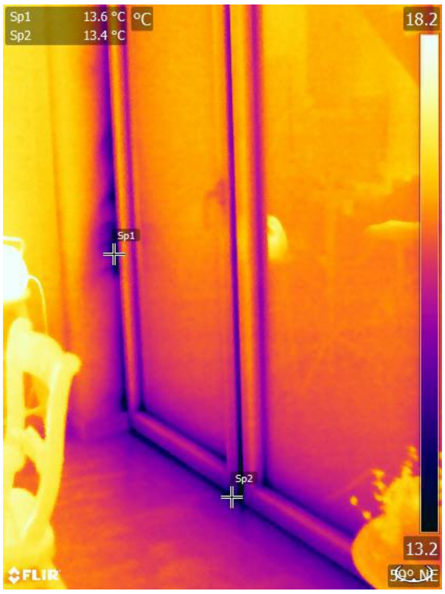
In a similar way to Bedroom 2, the ceiling to wall junction looks slightly cooler, which could be attributed to a thermal bridge at the eaves junction. There is also a more pronounced cooler area where the lintel is compared to the wall. The dark line in the ceiling suggests that the ceiling level insulation may not have been laid evenly.

5.7 Thermographic Leakage Detection (-50Pa):

Dining area

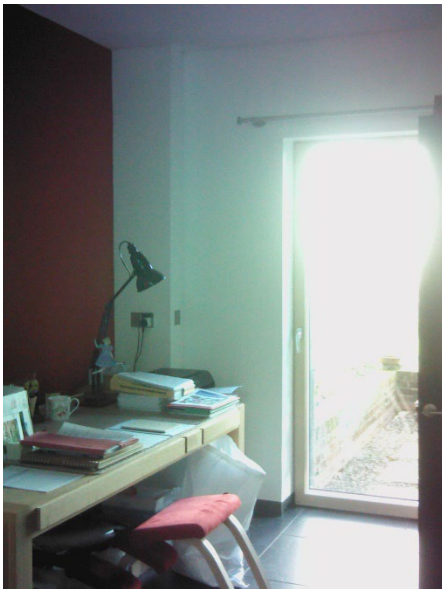
It is possible to see cold air movement between the door frame and reveal, suggesting that the seals are starting to fail.

Dining area



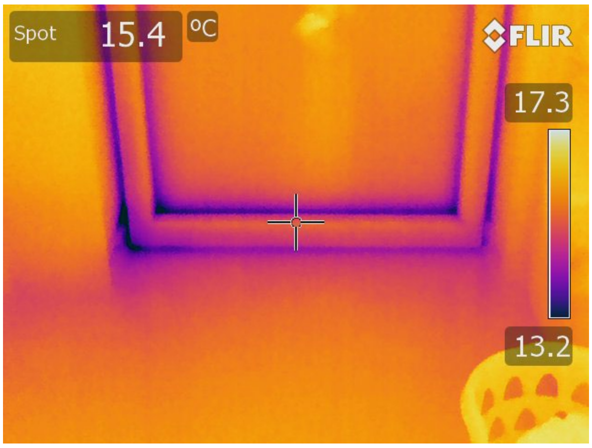
Similarly, it appears that the seal between the door and wall is also starting to degrade.

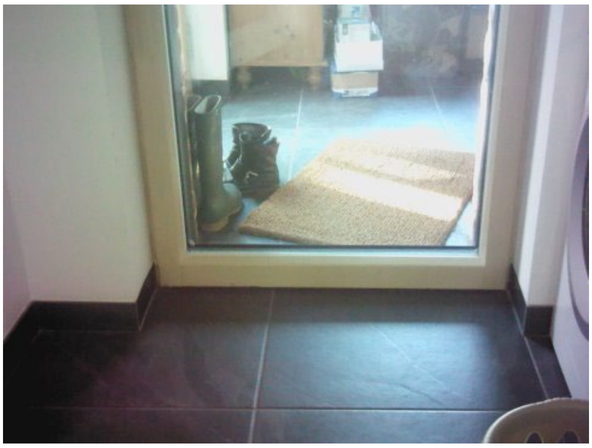
Study



For this door, there appears to be little change under depressurisation, suggesting that the seals are relatively intact.

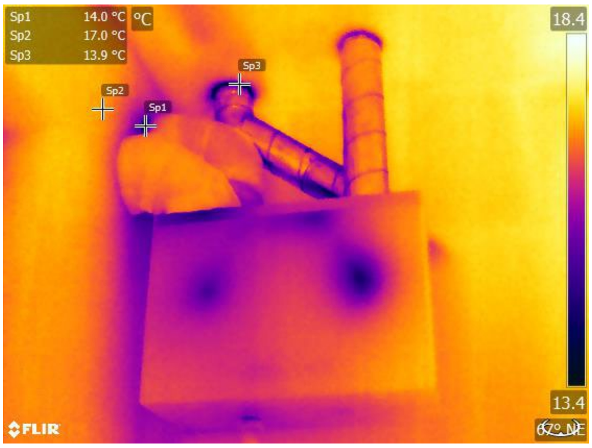
Utility room





However, for this door, there is a small amount of cooler air coming past the seal and wall near the skirting board.

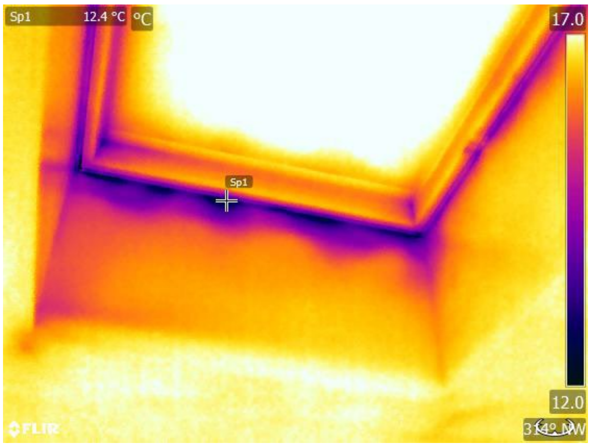
Utility room



For the airtightness test, the internal ducts of the MVHR system were sealed, but not the external ducts. The change in surface temperature across the unit and internal pipework suggests that under negative pressure, a small amount of cooler external air is being pulled into the system, as the external ducts were not sealed. This may suggest that the internal ducts were not quite 100% sealed. However, the image does imply that the seal between larger diameter MVHR ductwork and outside appears to be functioning well.

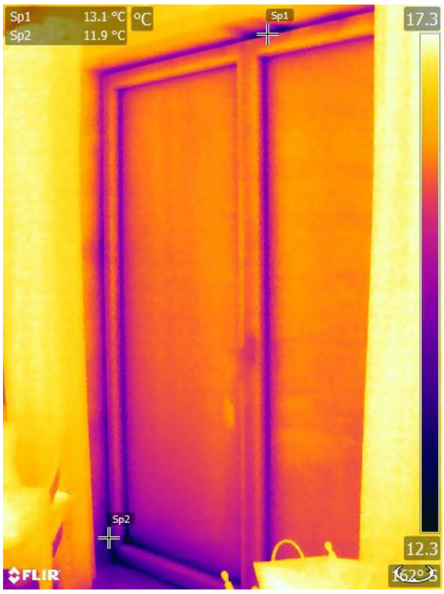
It is worth noting that there are several different materials captured in this image, each with a different emissivity, or ability to emit infrared energy. Therefore, this makes what is happening in the image somewhat challenging to interpret.

Living area



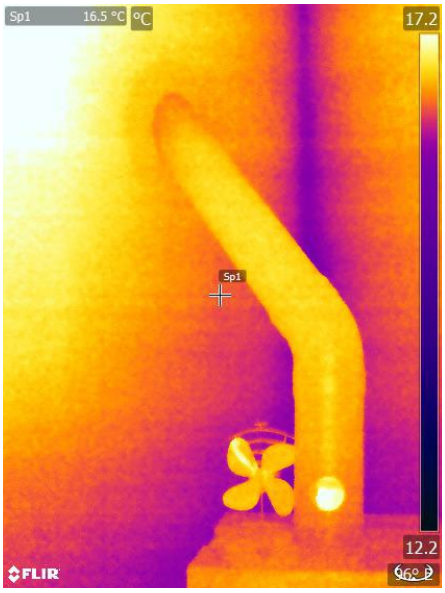
The ripples of cooler air indicate signs of air movement at the interface between the window frame and the plasterboard.

Living area



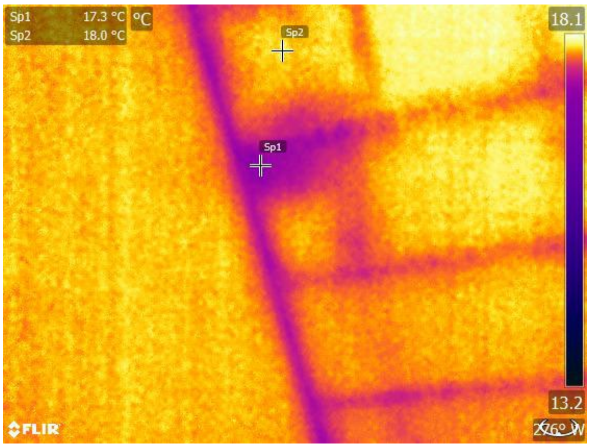
The areas of cooler air coming in between the interface between the door and frame, particularly at the top, indicate that the seals around the frame may be starting to degrade when under pressure.

Living area



There do not appear to be any signs of air leakage coming from the living area fire flue.

Landing



The large pink area of cooler air at this junction suggests some air movement inside the sloping ceiling. This may be due to air barrier damage.

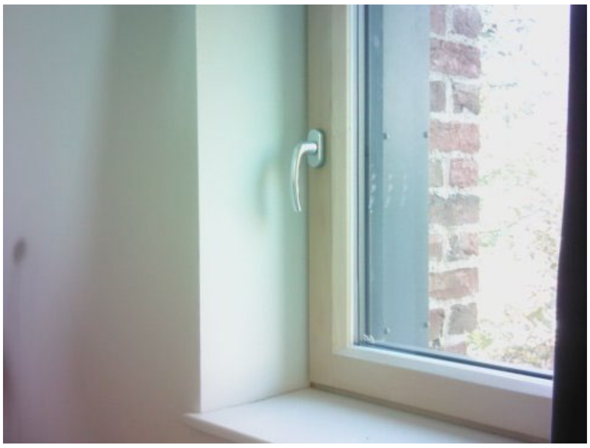
Airing cupboard

Under negative pressure, it is possible to see a significant amount of cooler air being drawn in past the boiler flue

Airing cupboard

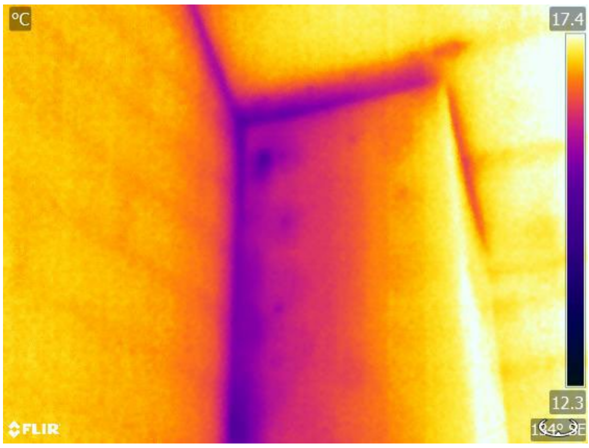
Looking at this in more detail, cooler air appears to be coming from all around the flue and not just in one area as shown in the image where there was no pressure differential.

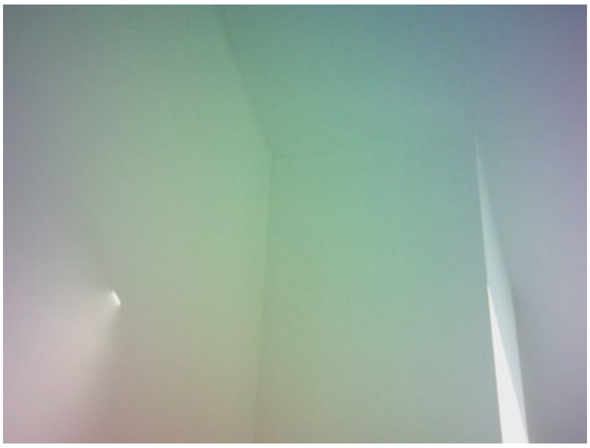
Bedroom 1



Under depressurisation, there appears to be some cooler air coming in at the bottom corner of inward opening windows. This may be due to seals starting to degrade or a characteristic of the window, i.e., trying to open inwards, when under negative pressure.

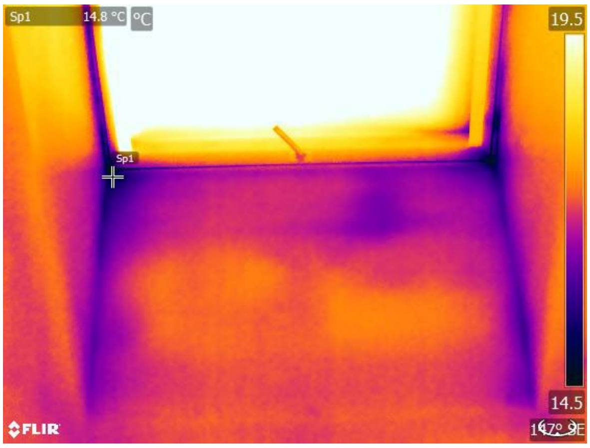
Bedroom 1

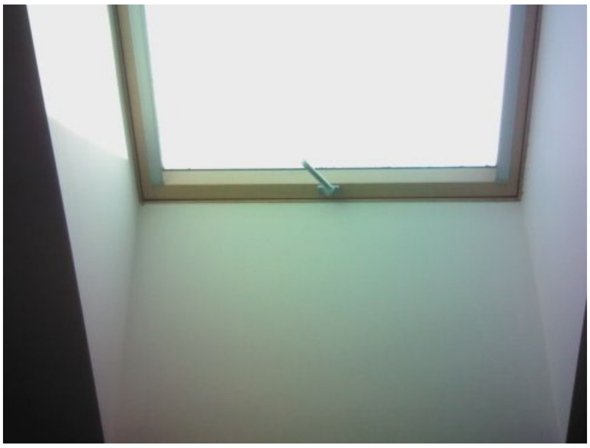




There are cool spots towards the top of the projecting wall suggesting air movement behind it.

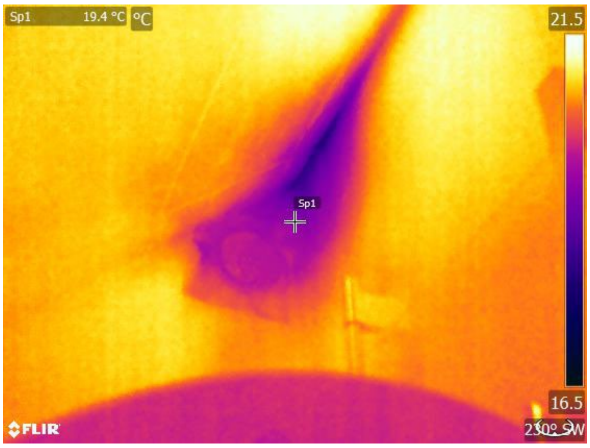
Bedroom 1





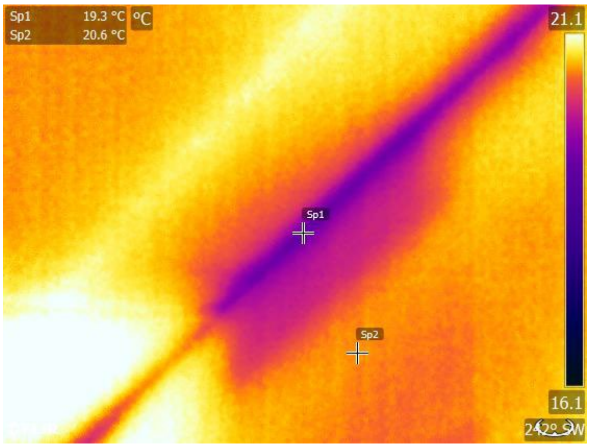
The cooler area under the window to the right suggests that there may be air circulating behind the plasterboard.

Bathroom



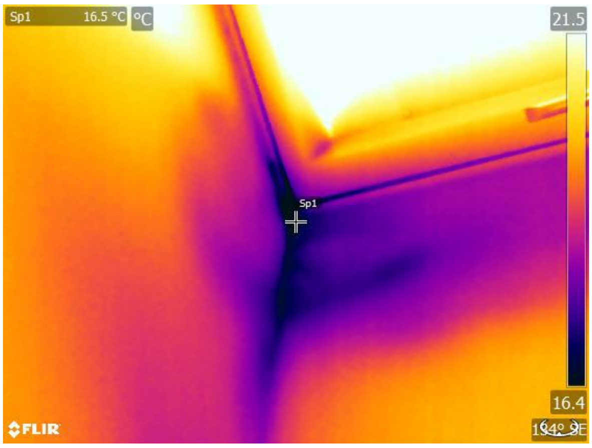
This area looks the same as when it was photographed without any pressure differential. This suggests that the surface moisture content in the corner is higher than the surrounding area, rather than evidence of thermal bridging. This is not surprising given it is above a bath and shower.

Bathroom



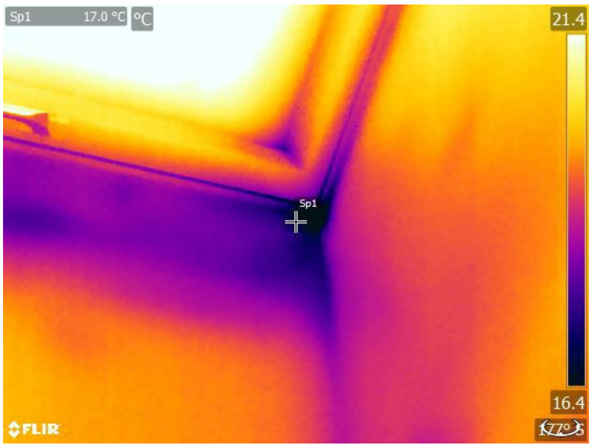
However, this cooler area was not apparent when there was no pressure differential, suggesting some air leakage, as cooler air has been drawn in behind the plasterboard, and is moving within structure at this junction.

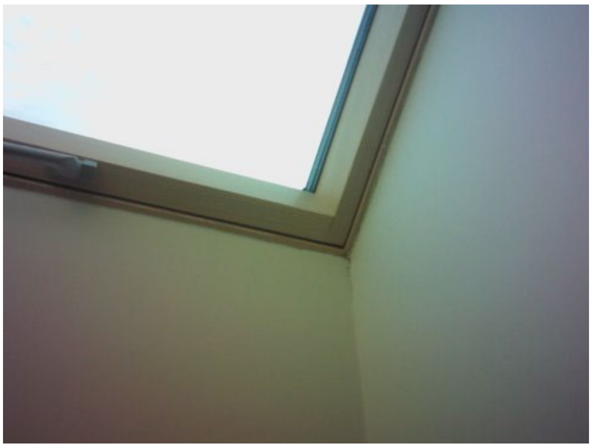
Bathroom



In a similar way to bedroom 1, it looks as though cooler air has been drawn into the structure behind the plasterboard at both window corner junctions.

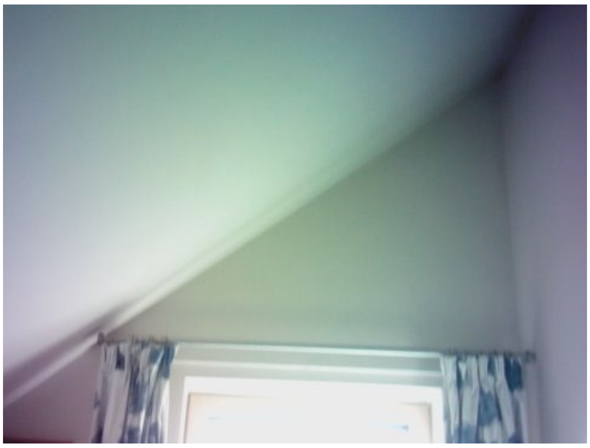
Bathroom





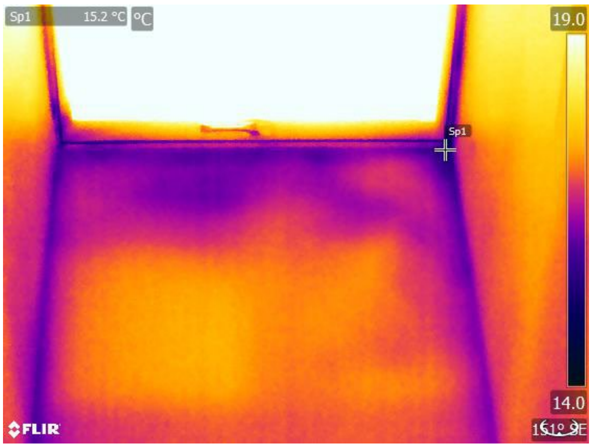
There is also a cooler area towards the middle of the window implying that colder air has been drawn into the structure here too.

Bedroom 2



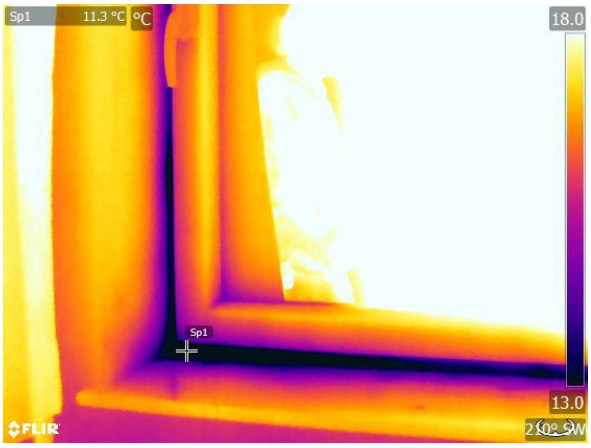
The change in colour and shape of the darker areas at the wall to ceiling junction indicates that air is being drawn in within the roof and ceiling structure.

Bedroom 2



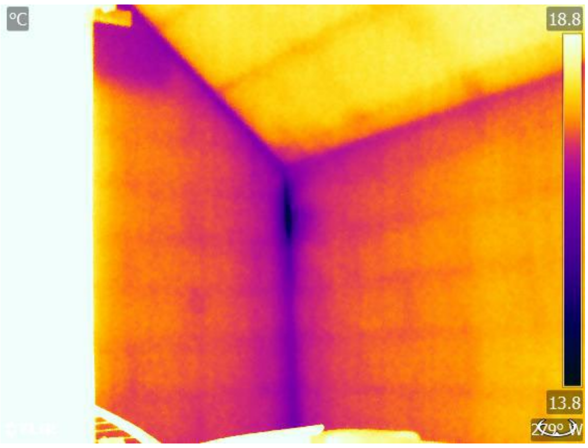
It looks as though all the first floor rooflights in the home show some movement of cooler air behind the window reveal plasterboard as it is evident in this room too.

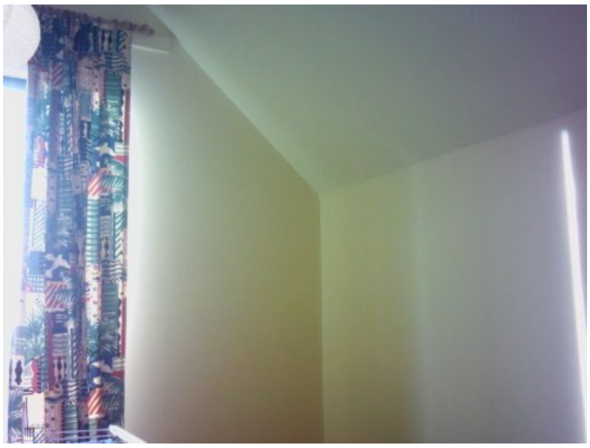
Bedroom 2



The darker purple at the bottom corner of the window suggests that, under negative pressure, there is minor air leakage here.

Bedroom 3





The small dark area at the corner of the wall junction suggests that there is some minor air leakage here. As the walls are wet plastered, this could be due to a crack in the blockwork at the edge of the wall.

5.8 Conclusion

Overall, the house is still extremely airtight with a mean permeability of 0.86 $m^3/(h.m^2)$ @ 50Pa. However, this is a significant increase in air leakage in relative (rather than absolute) terms since certification was carried out in October 2015, where a mean permeability of 0.39 $m^3/(h.m^2)$ @ 50Pa was recorded. The little air leakage that has been detected appears to come from window seals that may be starting to degrade. There is also evidence of some air movement behind plasterboard in the upstairs rooflights, and at wall-to-ceiling, or wall-to-wall junctions. There was also some air leakage detected around the boiler flue. Whilst the home no longer meets the Passivhaus target of 0.60 ACH @ 50Pa for airtightness, the air leakage area has increased only slightly - from around $73cm^2$ (an area approx. 8.5cm by 8.5cm in size) to $104cm^2$ (an area just larger than 10cm by 10cm in size). Therefore, after seven years post-construction and an increase in air change rate to 0.85 ACH @ 50Pa, the house now satisfies the EnerPHit airtightness requirement of one air changes per hour.

6 Building fabric (QUB) tests

6.1 Introduction

The QUB test is a rapid measurement technique to determine the whole house fabric performance of a building or heat transfer coefficient (HTC) [14]. The HTC describes the rate of heat transfer for a given temperature difference between the internal and external environment with units of W/K.

The QUB test measures the HTC of a building within a single night. It works by heating a building for a given length of time and then allowing it to cool. By calculating the rate at which the building heats up and then cools, and taking into account the amount of power used and external temperatures, it is possible to estimate a building's HTC. The typical temperature and power profiles for a QUB test are shown in Figure 6-1.

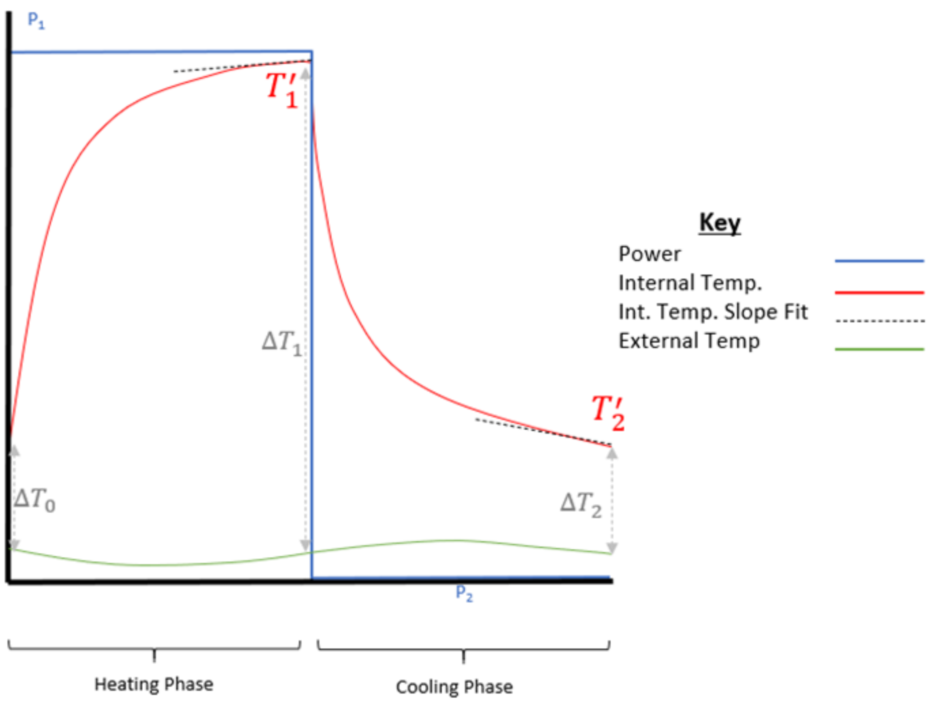


Figure 6-1 Typical Temperature and Power Profiles of QUB Test

6.2 Methodology

Six QUB tests were attempted to measure the home's HTC. They were conducted in two phases: a summer/autumn phase in August to September 2022 and a winter phase in January 2023. Both phases consisted of three QUB tests, however only two tests from the winter phase were successful.

The MVHR was deactivated for the duration of both phases with the extract and supply points sealed. This ensured that only infiltration (uncontrolled ventilation) was measured during the QUB tests. The required heat input was achieved with 7x 250 W electric heaters resulting in a total heat input of ~1.75 kW. Timer and thermostatically controlled heaters were used during the day to maintain an optimal starting temperature for the QUB test (24.5°C in the summer/autumn and 17.0°C in the winter).

As part of the LSI's ongoing research into the QUB test method, additional measurements of ground temperature and heat flux density through the ground floor were taken. This was to identify any impact of the slab-on-floor construction on QUB measurements. Figure 6-2 shows the location of this equipment on the home's ground floor plan.

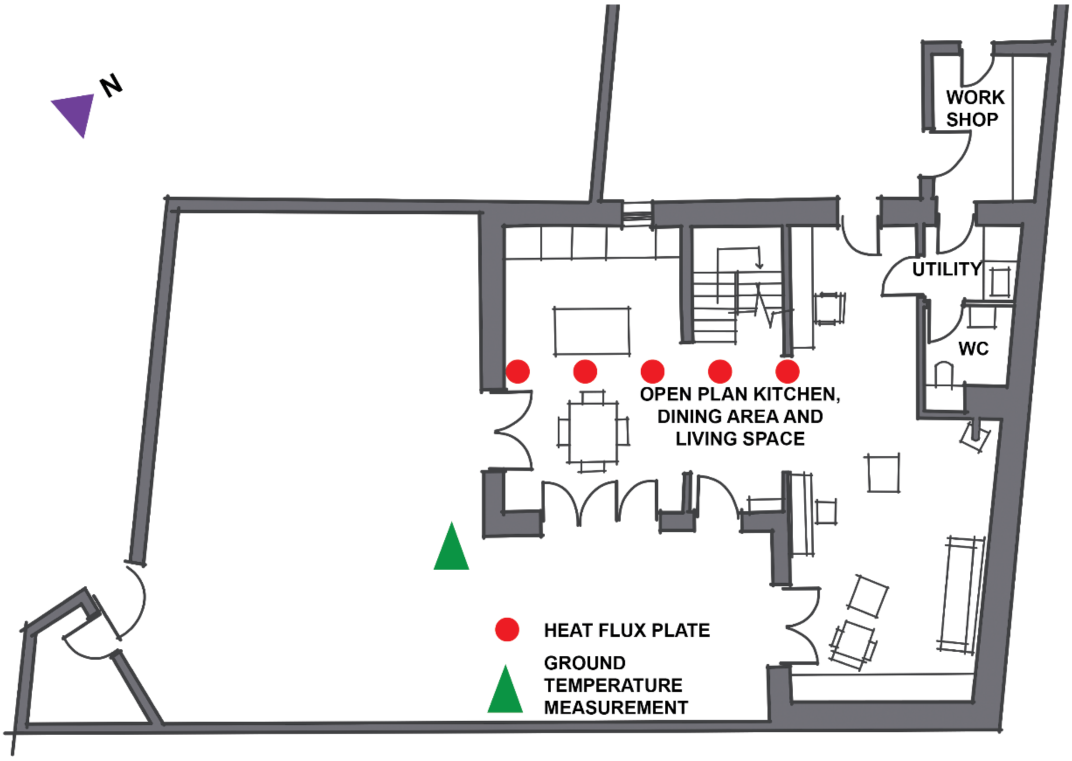


Figure 6-2: QUB Equipment Locations

Table 6-1 Elemental Breakdown of Design Heat Loss

Fabric Element	Design Heat Loss - WK^{-1} (Percentage of total HTC)
External Walls	20.7 (30%)
Ceiling	8.5 (12%)
Floor	5.8 (8%)
Windows & Doors	28.2 (41%)
Airtightness	2.2 (3%)
Thermal Bridges	4.1 (6%)

As the Client had provided the PHPP documentation from the design phase, the original design of the property (see Appendix 9.3 for a summary of the PHPP worksheet) was used to determine a reference HTC for the home. It is worth noting that a sole HTC is not computed within the modelling package but instead by calculating heat loss through the different elements. However, the relevant construction information was used to compute the HTC mirroring the methodology applied in the SAP process [15]. The calculated design HTC for the home was 69.5 W/K. A breakdown of the design performance of each fabric element is detailed in Table 6-1. It is not known how the actual elemental performance of the building fabric compares to the design performance.

6.3 Results

The results of the QUB measurements are presented in Figure 6-3. Due to an equipment error, Test 4 failed and hence only 5 valid measurements were completed. The error bars indicate the uncertainty associated with each individual measurement.

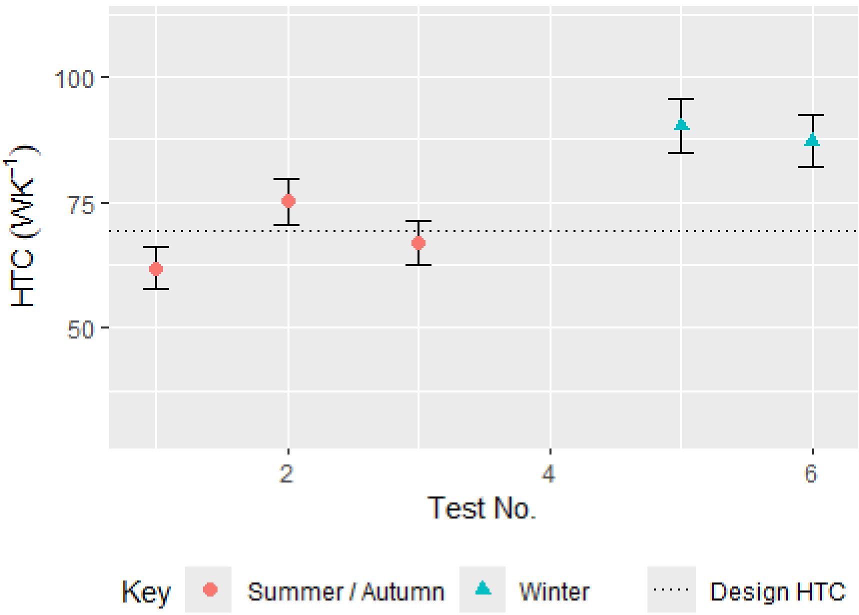


Figure 6-3 QUB HTC Measurements (Dotted line: Design HTC 69.5 W/K)

The QUB measurements made in the summer/autumn are comparable with the design HTC, the average HTC measurement being within 1.8 WK^{-1}, 3% of the design. The winter results are comparatively greater in magnitude and less comparable to the design HTC, on average 19 WK^{-1}, 27% larger. The average value of all the presented tests is 76.3 W/K, 10% higher than the design HTC. All measurements were within ±19 % of the mean measurement and only one test (test number 3) overlaps with the design HTC. The average uncertainty of each measurement was ± 6.2 %.

Seasonal variation is common in HTC measurement techniques [16], [17]. One such contributing factor is the presence of the slab-on-ground type floor construction as is present here. As the slab rests directly on the ground, the heat lost is dictated by the ground temperature rather than the external air temperature. Monitoring the ground temperature throughout the QUB tests revealed that in the winter QUB tests, the ground temperature was lower than the air temperature, whereas in the summer QUB tests, it was higher than the external air temperature. The ground temperature measurements were not taken directly underneath the property; therefore, this may not be fully representative of the ground temperature impacting ground floor heat loss. The magnitude of the apparent change in HTC measurements is more than could solely be explained by the change in ground temperature. The Heat Flux Density measurements recorded in the QUB test appeared unrealistically high, possibly caused by the ground slab being in a state of thermal charging. Therefore, this data could not be used to analyse this effect further. Other factors that can cause seasonal change in HTC measurement include but are not limited to: changing rates of infiltration with environmental conditions such as wind conditions, moisture content in materials and variable levels of solar radiation incident on the property in the day before the QUB test commencing introducing stored solar contributions [18]. These environmental conditions were not monitored, so the relationship between them and the QUB measurements could not be determined. It is also noted that the QUB method can be considered a novel technique and the measurement uncertainty and its impacting factors are still being researched.

6.4 Conclusion

A QUB test, which is a rapid measurement technique capable of measuring a building’s HTC in a single night, was used to measure a current HTC for the home. The design HTC of 69.5 W/K was derived from the construction details provided in the design stage PHPP model; however, it is not known to what extent the current design performance of the house reflects its original design intent. Five successful QUB tests were conducted on the home: three in the summer/autumn of 2022 and two in the winter of 2023. The average measurement recorded was 76.3 W/K, which is 10 % greater than the design performance. There was one unsuccessful test in winter which had been excluded from the results.

The summer/autumn tests gave better agreement with the design performance, as higher values of HTC were recorded in the winter tests. There are several causes for seasonal variation in HTC measurement, which are predominantly due to changing environmental conditions, which were not comprehensively monitored in this testing campaign. The explicit cause or causes of the variation found here could not be determined through the data gathered in the tests undertaken.

7 Conclusions

The project aimed to compare the current performance of this three-bedroom Passivhaus against its post-completion performance now that seven years have passed. Areas of interest were energy consumption, ventilation and air quality, thermal comfort, airtightness and building fabric.

Looking at these in turn, annual figures show that gas use was higher during the first-year post-completion in 2016 but has steadily declined since. Electricity use has remained relatively constant. The annual energy consumption in 2023 was 2467kWh for gas (20kWh/m^2/year) and 1652kWh (13kWh/m^2/year) for electricity, which is between 60 and 74 per cent less for gas and between 9 and 39 per cent less for electricity than the average UK house. Monthly energy use figures suggest that around 11kWh/m^2/year is used for space heating, which is just under 20kWh/m^2/year less than PHPP predicted. The discrepancy between the figures may be due to higher than the home's current occupancy levels being assumed for PHPP.

The MVHR system was not balanced when tested compared against commissioning figures, with extract air flow rates being over 10 per cent higher than intake air flow rates. This meant that the system no longer satisfied Passivhaus requirements.

For CO_2, a high level of IAQ was recorded, with an average of less than 872 ppm. Peak CO_2 readings recorded a drop to a moderate level of IAQ in the living area, and bedroom on separate occasions. There was a visible drop in CO_2 levels from April 2023, aligning with when the MVHR filters were changed plus an assumed increase in door and window opening with the warmer weather. Noise associated with the MVHR system ceased following a service.

When examining PM, two sizes were looked at in more detail: $PM_{2.5}$ and PM_{10}. Higher levels of particulate matter were recorded externally at the front of the house, close to a car parking area. Comparisons were made between levels measured at the home and a local DEFRA monitoring station using WHO and DEFRA annual thresholds. The thresholds were exceeded between 53 and 191 days for $PM_{2.5}$ and up to 47 days for PM_{10} depending on the sensor location at the home. For $PM_{2.5}$, the number of days exceeding thresholds was higher at the home than at the local monitoring station, whereas this trend reversed for $PM_{10.}$ Three peak periods were examined to see how particulates generated externally or internally rose and fell over time. Spikes in PM levels were generally due to cooking or the wood-burning stove if generated internally, and dissipated quickly. Elevated PM level patterns recorded outside were often mirrored inside but at a much lower level.

To measure thermal comfort, twenty sensors monitored thermal uniformity, thermal comfort and overheating. Temperatures remained constant at above 15°C throughout winter with all sensors remaining within a 3-4°C range, indicating a reasonable level of thermal uniformity. However, internal temperatures were quite low - usually under 20°C. The high daytime set point of 24°C, which the programmer defaulted, to was unobtainable, suggesting that the space heating system is undersized for the current occupancy level. This could be due to assumptions being made at the design stage where occupancy levels are based on the size of the home, which are far lower in reality. Plus it was assumed that the wood-burning stove would meet 30 per cent of the home's heating demand, when during the monitoring period it was rarely used.

During warmer periods of weather, internal temperatures suggest that occupants could cool the home using passive ventilation methods, which is positive. Higher nighttime temperatures were recorded across the first floor during hotter periods of weather, with south westerly-facing bedrooms 2 and 3 being the most affected. While there were three days of overheating recorded during a heat wave, they coincided with the property being empty. This suggests that the building's MVHR system is not capable of maintaining thermal comfort during warm weather, requiring manual interventions such as window opening and night-time purging to provide cooling.

Overall, the house is still extremely airtight with a mean permeability of 0.86 $m^3/(h.m^2)$ @ 50Pa. However, this is a significant increase in air leakage in relative (rather than absolute) terms since certification was carried out in October 2015. The little air leakage that has been detected appears to come from window seals that may be starting to degrade. There is also evidence of some air movement behind plasterboard in the upstairs rooflights, and at wall-to-ceiling, or wall-to-wall junctions. There was also some air leakage detected around the boiler flue. While the home no longer meets Passivhaus standards for airtightness, the air leakage area has increased only slightly - from around $73cm^2$ (an area approx. 8.5cm by 8.5cm in size) to 104cm2 (an area just larger than 10cm by 10cm in size). Therefore, after seven years the home now satisfies EnerPHit airtightness requirement of one air changes per hour.

Using a QUB test, it was possible to calculate a current HTC for the home. This was compared against a design HTC of 69.5 W/K, which was derived from the construction details and PHPP worksheet provided by the Client. Five successful QUB tests were conducted on the home: three in the summer/autumn of 2022 and two in the winter of 2023. The average measurement recorded was 76.3 W/K, which was 10 % greater than the design HTC, however, the summer/autumn tests gave better agreement with the design HTC compared to the winter tests. The explicit cause of the variation could not be determined but could be attributed to changing environmental conditions or inherent uncertainties associated with the test method.

Examining these results in the round, as a seven-year-old Passivhaus, the home's overall performance is still exceptional compared to current-day new-build homes. Some aspects of the home's performance have deteriorated since completion, such as the airtightness and MVHR performance, which could be associated with general wear and tear. The home is still extremely airtight despite now satisfying EnerPHit rather than Passivhaus certification standards.

It is not possible to compare changes to air quality, thermal comfort or post-construction HTC over time, as conditions were not monitored post-completion. However, the air quality across the home is currently good and improves when the filters are changed and the MVHR unit is serviced. Temperatures across the home remain consistent in winter and without overheating when occupied in summer, which is positive. Also, it is not possible to establish whether the performance of the building fabric (or HTC) has worsened over time, as it was not measured post-completion. The 10% difference found here could be due to the design-stage calculation being an incorrect assumption, as opposed to a deterioration of performance or due to inherent uncertainties associated with the test method; it is not possible to say.

The only area of note is thermal comfort in winter depending on the temperature sought by occupants, as the space heating system is not designed for the current occupancy level and could be considered on the cool side of comfortable.

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9 Appendix

9.1 Airtightness spreadsheet

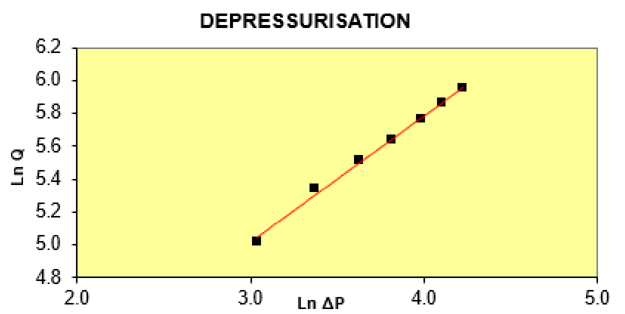
LEEDS BECKETT UNIVERSITY — Leeds Sustainability Institute

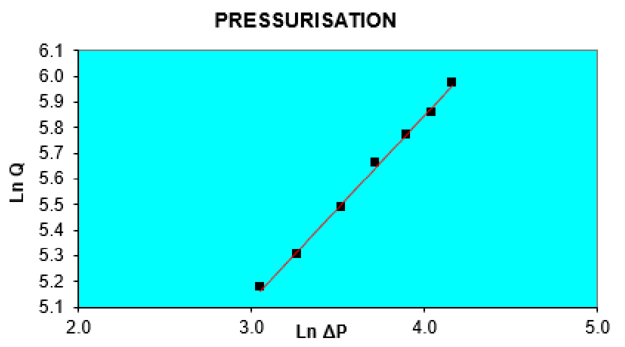
MINNEAPOLIS BLOWER DOOR DATA INPUT AND CALCULATION

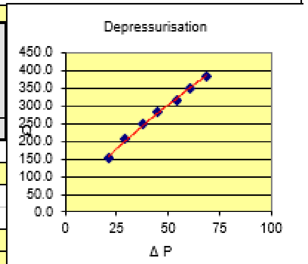
date:	06/12/2022	Version 16e	###############	
test house address:	Meeting House			
company:				
house type:	detached passivhaus			
tester:				
test reference number:			Blower Door & Gauge Used	Model 3 with DG700
outdoor temp (°C)	6	°C	Note: ENSURE THAT FLOW SETTINGS ARE IN m3/h - When using the DG700 gauge run baseline pressure adjustment for minimum 60s with fan switched on but not rotating	
indoor temp (°C)	17	°C		
outdoor humidity (%rh)	58.6	%RH		
indoor humidity (%rh)	66.8	%RH		
outdoor barometric pressure	1020.1	mbar or hPa	Calculated Outdoor Air Density	1.27 kg/m³
indoor barometric pressure	1020.6	mbar or hPa	Calculated Indoor Air Density	1.22 kg/m³
temperature corr. fact. depress.	0.962	WARNING!!	description of main construction details:	
temperature corr. fact. press.	1.039	Extreme Test		
wind speed (m/s):	0.5	Conditions		
baseline pressure diff (Pa) (+/-)		Pa		
house width:		m		
house depth:		m		
house height:		m		
floor area:		m²		
volume:	367	m³		
envelope area including floor:	373.6	m²		
Pressure Difference for ELA	10	Pa		
RESULTS:				
Q50 Mean Flow at 50Pa =	317.33	m³/h		
Mean Air Leakage at 50Pa =	0.86	h⁻¹		
Mean Air Permeability at 50 Pa =	0.85	m/h or m³/h/m²		
Equivalent Leakage Area =	0.011	m² at	10	Pa

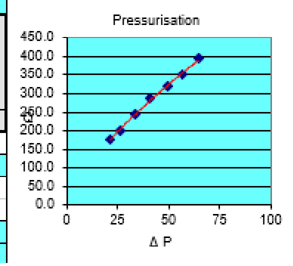
DEPRESSURISATION	RING - O,A,B,C,D,E for BD3 0,1,2,3 for DuctBB	MEASURED FAN PRESSURE (Pa) Max. 90 Pa	MEASURED FLOW (m³/h)	ADJUSTED FLOW (m³/h)	FLOW RANGE OK FOR SELECTED RING?	Adjusted Pressure (Pa)	Ln delta P	Ln Q	Q50 Calculated Flow at 50Pa (m³/h)	Permeability Depressurisation Only (m³/(h.m²))	Air Leakage Depressurisation Only (h⁻¹)
Approx 65 Pa	2	68.3	400	384.0	OK	68.3	4.224	5.951	308.10	0.82	0.84
Approx 57 Pa	2	60.6	366	351.3	OK	60.6	4.104	5.862	r²	0.996	
Approx 49 Pa	2	53.9	331	317.7	OK	53.9	3.987	5.761	C_env	15.458	m³/h.Pa^n
Approx 41 Pa	2	45.1	293	281.2	OK	45.1	3.809	5.639	n	0.761	
Approx 33 Pa	2	37.7	258	247.7	OK	37.7	3.630	5.512			
Approx 25 Pa	2	29.1	217	208.3	OK	29.1	3.371	5.339	C_L (corrected)	15.669	m³/h.Pa^n
Approx 20 Pa	2	20.8	158	151.7	OK	20.8	3.035	5.022			

PRESSURISATION	RING - O,A,B,C,D,E for BD3 0,1,2,3 for DuctBB	MEASURED FAN PRESSURE (Pa) Max. 90 Pa	MEASURED FLOW (m³/h)	ADJUSTED FLOW (m³/h)	FLOW RANGE OK FOR SELECTED RING?	Adjusted Pressure (Pa)	Ln delta P	Ln Q	Q50 Calculated Flow at 50Pa (m³/h)	Permeability Pressurisation Only (m³/(h.m²))	Air Leakage Pressurisation Only (h⁻¹)
Approx 65 Pa	2	64.3	378	393.8	OK	64.3	4.164	5.976	326.55	0.87	0.89
Approx 57 Pa	2	56.8	337	351.1	OK	56.8	4.040	5.861	r²	0.998	
Approx 49 Pa	2	49.3	308	320.9	OK	49.3	3.898	5.771	C_env	19.514	m³/h.Pa^n
Approx 41 Pa	2	41	276	287.5	OK	41	3.714	5.661	n	0.719	
Approx 33 Pa	2	33.8	233	242.7	OK	33.8	3.520	5.492			
Approx 25 Pa	2	26.2	193	201.1	OK	26.2	3.266	5.304	C_L (corrected)	19.603	m³/h.Pa^n
Approx 20 Pa	2	21.1	170	177.1	OK	21.1	3.049	5.177			









9.2 2015 Airtightness test results

Depressurisation Only				Pressurisation Only				Mean	
Permeability	Air Change Rate	Equivalent air leakage area	r^2	Permeability	Air Change Rate	Equivalent air leakage area	r^2	Permeability	Air Change Rate
$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa	cm^2@ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa	cm^2@ 50Pa		$m^3/(h.m^2)$ @ 50Pa	h^{-1} @ 50Pa
0.41	0.42	76.9	1.000	0.37	0.38	68.7	1.000	0.39	0.40

Taken from spreadsheet of airtightness test results conducted on 9th October 2015 by Paul Jennings at Aldas

9.3 Passivhaus Planning Package worksheet overview

Adobe Acrobat Document