Building Performance Evaluation

Lessons from studies of 26 Scottish low-energy homes

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CONTENTS

1 INTRODUCTION

This report has been jointly funded by The Gannochy Trust and the Construction Scotland Innovation Centre (CSIC) and disseminates the key outcomes of research into the building performance of 26 Scottish new-build dwellings. All of the dwellings were evaluated by The Glasgow School of Art's Mackintosh Environmental Architecture Research Unit (MEARU) under Phase 2 of the £8 million Innovate UK[1] Building Performance Evaluation (BPE) Programme. Full reports of all project are available on the Building Data Exchange website at https://buildingdataexchange.org.uk/reports/.

BPE is the study of occupied buildings typically lasting for at least one-year post completion. These studies provide a 'snap-shot' or a long term view of how well a building performs in use. This picture is developed both in terms of quantitative measured data (energy and environmental) and qualitative data obtained from engagement with the building occupants and the design and construction teams. Collected data is analysed and compared against the design intent in order to identify any *performance gaps* and establish why these may have occurred. Understanding how a building performs - and feedback of this - enables design refinement, resulting in buildings that are more useable, affordable and comfortable for occupants.

Figure 1: Locations of MEARU TSB BPE housing

MEARU's study covered 26 new-build dwellings in a variety of new housing developments across Scotland, as indicated in Figure 1. Monitoring took place for a two –year period starting in 2012 and concluding in 2014. These contained a mix of mainstream housing and sheltered accommodation for supporting independent living. The developments were commissioned by Scottish landlords in order to provide high quality homes for affordable rent and shared equity opportunities for first time buyers. Various quality issues emerged over the course of the study and, while the dwellings studied represent a small sample of Scottish housing constructed each year, the common themes identified suggest the need to share information across the Scottish construction industry in order to improve the quality of housing as well as to help to meet the Scottish Government's objectives for homes fit for the 21st century.

This baseline report sets out an overview of the monitoring process and highlights the key findings and areas where the performance gap between the predicted and actual performance was evident. The key lessons learned through the BPE process are highlighted for the intention of wider dissemination. This is of particular relevance to clients, housing providers, architects and other

[1] Formerly the Technology Strategy Board (TSB)

building professionals involved in the procurement, design, construction and delivery of new dwellings or the refurbishment of existing buildings.

In an effort to put these findings into practice the lessons set out in this document were shared throughout the design process with the design and contracting team for the delivery of 48 healthy homes, commissioned by The Gannochy Trust in Perth. These homes are currently under construction at the time of this report and, once complete, a two-year BPE programme will be undertaken on eight of the homes.

2 PROJECT SUMMARY

Twenty-six homes in six developments across Scotland were selected through a competitive tender process for a two-year BPE monitoring programme as part of the '*in-use and post occupancy evaluation*' performance category of the Building Performance Evaluation (BPE) programme funded by Innovate UK. The BPE aimed to gain insight and understanding of the intended design performance against actual performance of these recently-constructed 'low-carbon' homes. This included review of building fabric performance, building services systems, energy and environmental monitoring, and interviews with the design teams and occupants of the homes. The BPE was carried out to fully comply with the monitoring protocols specified by the funder.

Bloom Court, Livingston.
A housing association development, completed in spring 2010, for tenants with special needs. This development includes a terrace of six three-bedroom, 1.5 storey houses each of timber-frame construction with vapour permeable insulating materials in the external walls. **Two** of the dwellings in the terrace underwent detailed BPE while the gas and electricity consumption of the terrace of six were collected. (LA1, LA2). (2010 Building Regulations)

Dormont Park, Lockerbie.
A rural development consisting of eight certified Passivhaus two-storey dwellings. The development was commissioned by a private landlord and consists of eight houses, made up of four two-bedroom and four three-bedroom houses. The homes were developed off-site from a timber frame system and were occupied from summer 2011. Detailed BPE monitoring was undertaken on two of each house type (**four** in total). (DA1, DA2, DB1, DB2). (2010 Building Regulations)

Murray Place, Barrhead.
A development consisting of 16 dwellings designed specifically to provide a safe residential environment for elderly residents. All dwellings are arranged around a central garden courtyard. The dwellings were designed with vapour permeable external wall construction and each incorporated passive and active solar strategies to provide affordable, energy-efficient dwellings. **Three** two-bedroom dwellings with similar occupancy profiles were monitored. These represented the three different housing typologies on the site: one two-storey house, one single storey cottage and one first floor flat. (BA1, BB1, BC1). (2010 Building Regulations)

Garscube, Glasgow.
A housing association development in Glasgow. The development is a mix of mainstream and sheltered flats all with solar thermal arrays and combined heat and power feeding into communal heating and hot water generation within each close. The dwellings are constructed with the ground floor properties being of brick construction and timber frame construction for the upper floor levels. The monitoring undertaken assessed the performance of **three** two-bedroom mainstream flats and **three** one-bedroom sheltered flats. (GA1, GA2, GA3, GB1, GB2, GB3). (2007 Building Regulations)

Scotland's Housing Expo, Milton of Leys, Inverness.
A first of its kind in Scotland mixed development of 52 dwellings that formed Scotland's first housing expo. The expo was set up to promote best practice in design innovation and to mainstream sustainable design where each plot was architect designed. After the August 2010 Expo, 32 dwellings were sold on the open market and 20 were made available for affordable rent or to be purchased under a shared ownership scheme. The BPE monitoring was undertaken on four pairs of affordable dwellings. These were **two** four-bedroom houses, **two** three-bedroom houses, **two** two-bedroom flats and **two** one-bedroom flats. (IA1, IA2, IB1, IB2, IC1, IC2, ID1, ID2). (2007 Building Regulations)

Tigh-Na-Claddach, Dunoon.
A housing association development in a rural coastal site. The dwellings are constructed of prefabricated closed panel timber system and consist of a mix of houses and flats forming 15 dwellings in a linked terrace. The homes are designed to be low-energy homes and one dwelling is a certified Passivhaus. **Three** two-storey dwellings were monitored: two three-bedroom low-energy houses and the two-bedroom Passivhaus. (TA1, TA2, TB1). (2010 Building Regulations)

3 FABRIC PERFORMANCE

Building fabric testing was undertaken as part of the BPE, which included air permeability testing, thermography and in-situ u-value measurement of a range of building elements forming the opaque external envelope in each development.

Although all the developments were completed at a similar point they were designed at different times. As a result some developments had to comply with the 2007 Building (Scotland) Regulations while others had to comply with the more onerous 2010 Building (Scotland) Regulations. The development summaries in Section 2 identify this. Five homes were constructed and certified to the Passivhaus standard and complied with the corresponding additional requirements and assessment criteria using the Passivhaus Planning Package (PHPP).

3.1 Air Permeability Testing

Air permeability testing was a mandatory element of the BPE project and was used to identify areas of heat loss due to draughts. Two tests were required in each of the participating dwellings, comprising one test at the beginning of the project and the other towards the conclusion of the two-year project period. This testing recorded the air permeability rate of each dwelling as well as identifying the sources of air leakage. These results were compared with the design air permeability target. The second test permitted comparison against the first test and provided an insight to the durability of the airtightness sealing methods over a two-year time period.

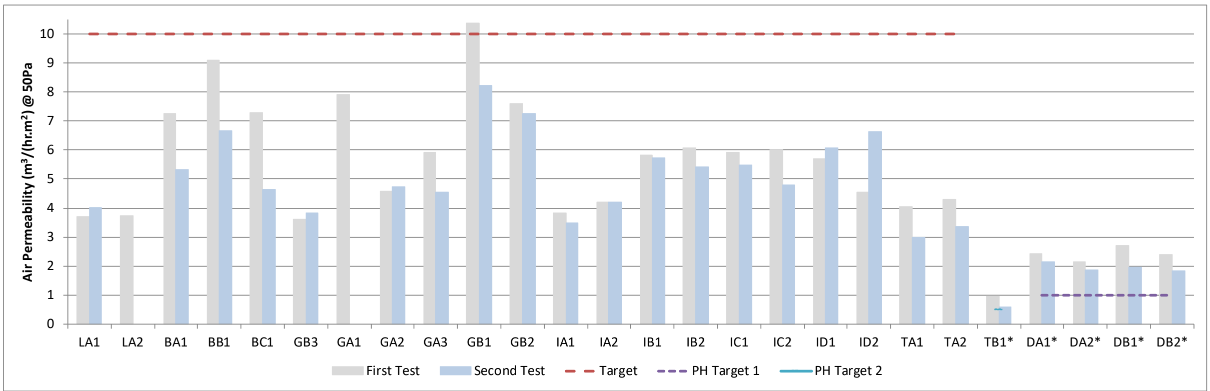

Figure 2: Air permeability ($m^3/h.m^2$ @ 50Pa) test results for housing subject to BPE.

The results from the air permeability tests, as well as the design targets, for each of the 26 dwellings monitored are shown in Figure 2. This indicates that one dwelling exceeded the 10 $m^3/h.m^2$ @ 50 Pa design target and all five Passivhaus dwellings (indicated with an asterisk in Figure 2) failed to meet their more stringent air permeability design targets.

The 21 non-Passivhaus dwellings were designed and constructed following the methodology of the then current '*Accredited Construction Details (Scotland)*'. This meant that, under the Building Regulations, these dwellings were exempt from post-construction air permeability testing due to the assumption that the design details inherently produce an air permeability rate lower than 10 $m^3/h.m^2$ @ 50Pa. The measured results illustrate this to be the case in all but one of these 21 dwellings, where air permeability rates were better than their design target. Of these, the results of 43% of homes were measured to be below 5 $m^3/h.m^2$ @ 50Pa. This air permeability rate is the threshold where the Building Regulations recommend additional ventilation measures be provided to ensure that both the indoor air quality and the control of internal condensation are not compromised.

For a variety of reasons the research team were unable to gain entry to all of the participating dwellings for the second phase of air permeability testing. However, improvements in air permeability were recorded in 70% (17) of the homes when comparing the first and second tests. All three dwellings in the Barrhead development (BA1, BB1 and BC1) indicated substantial air leakage reductions due to retrofitted insulation works that were required in the loft spaces. Similarly, following continued occupant complaints of draughts, remedial sealant works were undertaken at the end of the two-year defects liability period in a Garscube property (GB1) which initially had an air permeability rate exceeding 10 $m^3/h.m^2$ @ 50Pa. The sealing works consisted of the application of silicone sealant at the junctions where the internal walls met the top of the skirting and beneath window sills throughout the property. This application was two weeks before the second air permeability test and resulted in a 20% reduction compared to the initial test. Despite the measured improvement the researchers question the longevity of the sealing method used. Notwithstanding, the sealing method still permits the uncontrolled entry of external air behind the finished wall, floor and ceiling surfaces. During the winter this will result in thermal bypass and has the potential to excessively cool the internal wall and ceiling surfaces, increasing the risk of condensation and mould growth within the property.

During the tests all dwellings were held under negative pressure to draw in the cooler outside air and allow the location of the air leakage pathways to be identified using smoke pencil and thermography. Common areas of air leakage were identified and are presented in Figure 3. More than 50% of the dwellings exhibited air leakage above and below skirting boards and 78% of the dwellings exhibited air leakage from beneath fitted kitchen units. As this testing was non-destructive, the tester and researchers were unable to probe behind the fitted kitchen units to identify the origin of the air leakage. However, it is likely that this is attributable to poorly sealed water supply and drainage pipe penetrations serving the sink, as well as poorly finished building fabric. This may be due to the pipes and building fabric being ‘hidden’ on completion.

Air leakage from around the edges of window and door frames, and beneath window sills, were found in over 80% of the dwellings. Air leakage was commonly identified at pivot hinges at the top and bottom of side hung sash casements. 70% of dwellings had air leakage occurrence in the cupboard associated with the incoming electrical supply cable that entered the properties. It is also of note that 60% of dwellings exhibited air leakage around the bath panel. This was found to be significant in the majority of homes where some occupants reported feeling cold draughts in their bathrooms. Six dwellings (four in Dormont Park and two in Scotland’s Housing Expo site) were fitted with wood burning stoves. Testing around the stove installations identified air leakage at the air supply flue, exhaust gas flue and, in Dormont Park, penetrations associated with the route of the piped hot water service connections.

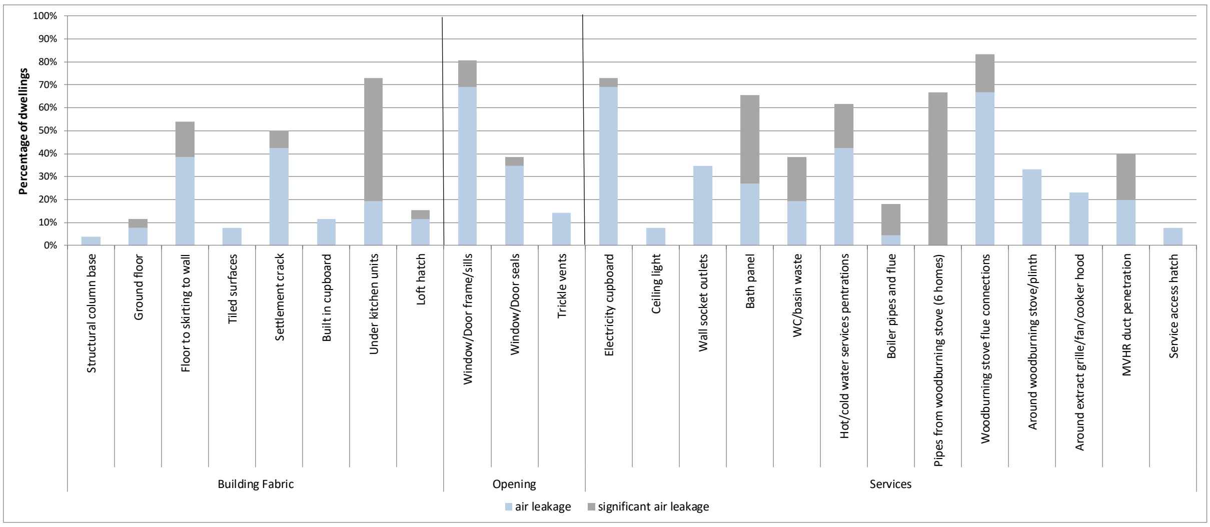

Figure 3: Common areas of air leakage identified during air permeability testing.

The negative effects of air leakage were self-reported by occupants to the researchers during interviews. It is worthy of note that complaints of draughts were also made by occupants of homes where the air permeability test results were lower than 5 $m^3/h.m^2$ @ 50Pa – the threshold at which Building Regulations deem the dwellings to be relatively ‘airtight’. This suggests that an absolute numerical test result is likely to be of little value unless the sources – and proportion of draughts from those sources – can be qualified.

There were complaints of discomfort and altered behaviour patterns through the colder months of monitoring. In one dwelling an occupant reported that they had resorted to wearing slippers in the open plan kitchen due to cold draughts originating from below the kitchen units. Another occupant only used their bathroom when absolutely necessary due to the cooling effect of the draughts and the bathroom being noticeably cooler than the remainder of the house, despite the bathroom being located in the middle of this property and not having any windows. The most extreme example was an occupant who did not use two rooms in the home during very cold, windy periods as the draughts entering the property caused significant discomfort and distress and the occupant perceived that the room could not be heated to a comfortable temperature.

The research team learnt a number of lessons about appropriate commissioning of independent airtightness testing. Although there is specific guidance set out for the testing and reporting methodology for airtightness testers it was discovered that each had their own interpretation of the guidance. To overcome this MEARU produced a detailed specification for air permeability testing, leakage audit and test report. This successfully aligned with both the Air Tightness Testing & Measurement Association (ATTMA) standard testing methodology and the BPE testing methodology. This helped both parties understand what was expected and the tester to quote accordingly. However, some testers indicated their intention to charge significantly more for a test that incorporated both negative and positive pressurisation.

As a result of the air permeability testing experience during the BPE project MEARU encourage those instructing air permeability testing to write a detailed specification to meet their exact requirements and to include negative and positive pressure tests (with the final result being the mean of both), the tracing and recording of air leakage paths and a written report outlining the result and findings of the test. A copy of MEARU's testing protocol can be requested, but it is important to note that this was written for a specific set of criteria and should only be used as a guide. Adopting a concise written protocol across developments will help to achieve consistency in testing and reporting, allowing for easier comparison of air permeability results and identification of common air leakage points. It is also important for the airtightness test and corresponding result to be commissioned and witnessed independently by the client or a separate party. It should not be commissioned by the contractor. The air permeability testing process, leakage identification and ultimate result should be used as an opportunity by the client, design team and construction team for improving design details at weak points in the fabric.

3.1 Air Permeability Testing **Case Study**

The occupant did not use two rooms in this flat (north-east facing living room and bedroom) during cold, windy periods in winter as the draughts that entered the property caused significant discomfort. It was perceived that the flat was difficult to heat to an even continuous temperature due to the draught being drawn across the living room to be heated by the radiator on the opposite side of the room.

The first air permeability test was recorded at 10.39 $m^3/h.m^2$ @ 50Pa, which exceeded the design target of 10 $m^3/h.m^2$ @ 50Pa. During this test significant areas of air leakage were identified and the fitted carpet was seen ballooning upwards, highlighting significant air leakage from below the finished floor. At the end of the two-year defects liability period and two years of complaint by the occupant, remedial sealing works were undertaken. These consisted of the contractor applying silicone sealant to the top edge of the skirting boards and beneath the window sills. These sealing works were undertaken a few weeks ahead of the second air permeability test where a result of 8.23 $m^3/h.m^2$ @ 50Pa was recorded. The BPE researchers have concerns over the suitability of this method for the remedial works and the longevity of this. In the long-term, the issue of draughts will continue to be present in this property and will impact the occupant's comfort, health and on-going energy bills.

3.1 Air Permeability Testing	Lessons Learned

- Airtightness and ventilation are separate design issues and require separate, compatible strategies.
- Air infiltration increases energy consumption for heating during the winter and allows warm air to enter during the summer.
- Any air leakage feels like a draught even in airtight homes, this can lead to occupant discomfort and lead to changes in occupant behaviour.
- 43% of homes were below the 5 $m^3/h.m^2$ @ 50Pa air permeability rate at which Building Regulations recommend additional ventilation measures.
- Common areas of air leakage (in more than 50% of homes) are generally attributed to hidden areas: edges of skirting boards, beneath kitchen units, penetrations for the electrical supply cable, drainage and water pipes, edges of window and door frames, beneath window sills, around bath panels, boxing for WC waste pipes and around flues when wood burning stoves were fitted. More attention is required in these areas both by the designers and building contractors.
- Carrying out two air permeability tests at least one year apart is useful to show durability and settlement, and also offer an opportunity for testing improvements in airtightness. Two tests can be undertaken during the construction phase in line with best practice (e.g. *SEDA Guide: Design and Detailing for Airtightness)*
- Improvements made to increase airtightness post-construction may not always be durable, and it is better to design a robust and continuous airtight barrier from the outset.
- If the building is occupied, clearly communicate with occupants and fit in with their schedules as much as possible to gain access for testing.
- Passivhaus dwellings did not meet their air permeability targets, indicating a performance gap.
- Different air tightness testers interpret the ATTMA guidance differently. The issue of a clear airtightness brief that includes both negative and positive pressure tests can help overcome this.
- Testing should be commissioned, undertaken and witnessed by parties independent of the contractor.

3.2 Thermography

Thermography was undertaken in selected homes in each development to identify the extent of thermal bridges and cooler wall and ceiling surfaces due to missing or poorly fitted insulation that could give rise to condensation or support mould growth. This type of testing for the detection of building defects is highly effective but can be challenging due to the temperature differential required between inside and outside, and changeable external weather conditions. The thermographic surveys were taken both internally and externally during the heating season when external weather and conditions permitted.

Common areas of fabric weakness were identified across all developments. These include skirting boards, wall heads (Figure 4), eaves details, loft hatches (Figure 5), areas around entrance doors and the doors leading to gardens or balconies.

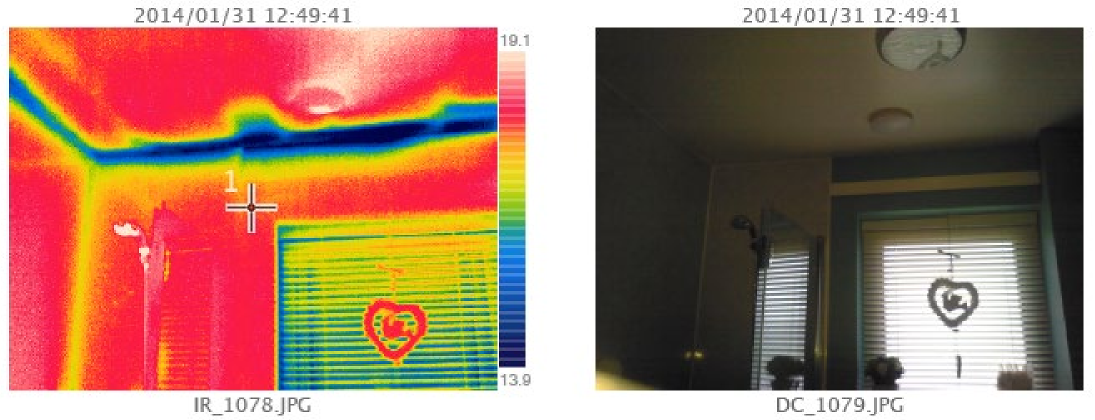

Figure 4: Significant cold areas at ceiling and external wall junction in first floor bathroom.

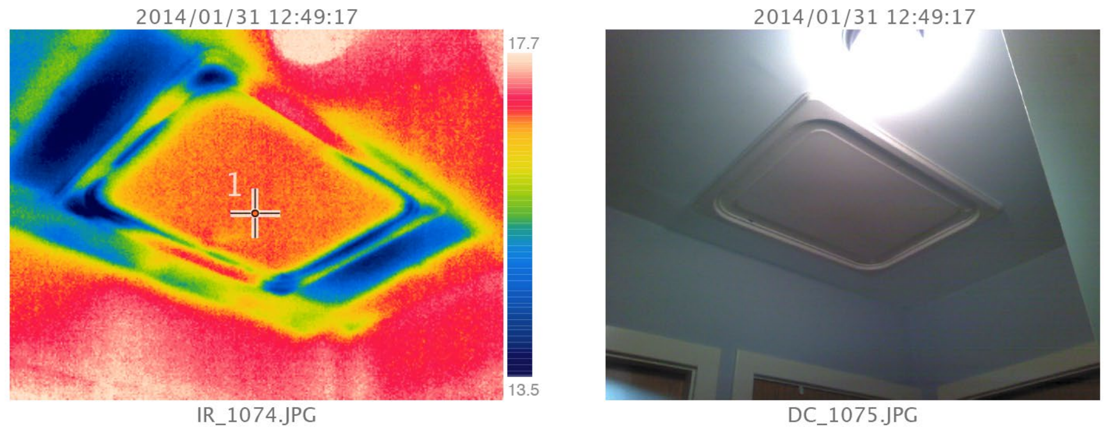

Figure 5: Missing insulation and heat loss around loft hatch.

Some of the external doors exhibited thermal weakness at their perimeters and all homes exhibited weakness at door thresholds (Figure 6). This type of defect is not normally identified during an air permeability test as the blower door fan is normally installed in the door opening. Window and rooflight installations exhibited cooler internal surfaces at the structural openings into which the windows were installed. Thermography commonly identified heat loss at window and door seals, as well as areas of missing insulation surrounding roof lights (Figure 7).

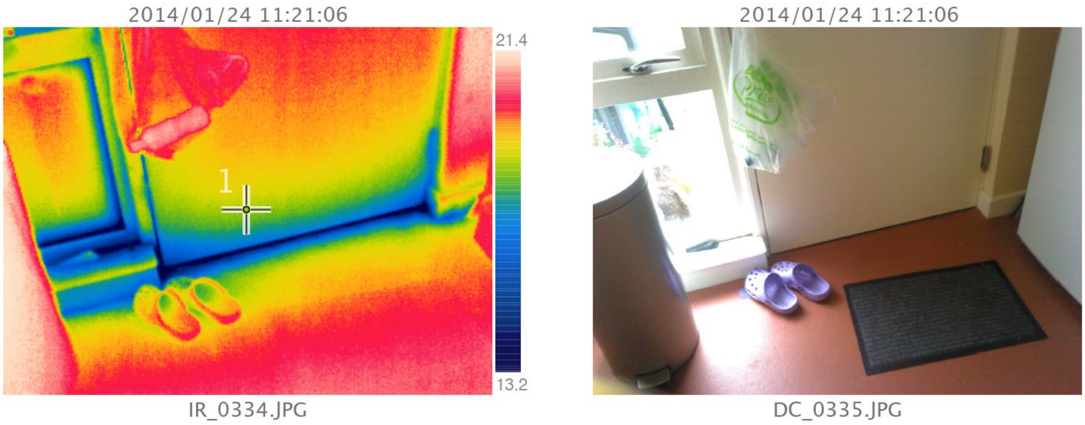

Figure 6: Heat loss at door threshold and at seals of windows to the left of the door.

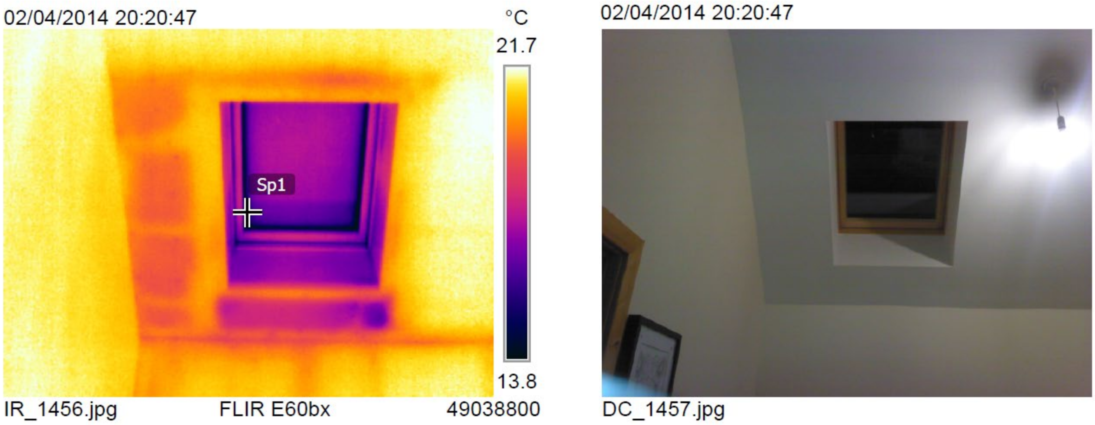

Figure 7: Missing insulation at bottom and left of rooflight, window reveals also exhibit significantly cooler temperature.

The timber framed dwellings exhibited heat loss through repeating thermal bridges at the timber studs. Two of the monitored timber frame houses were designed with an insulating layer applied externally over the timber I-joists in order to reduce thermal bridging. However, when constructed this insulated layer was not included due to inconsistent information between the design drawings and specification that was not queried. As a result, thermal bridges were evident (Figure 8).

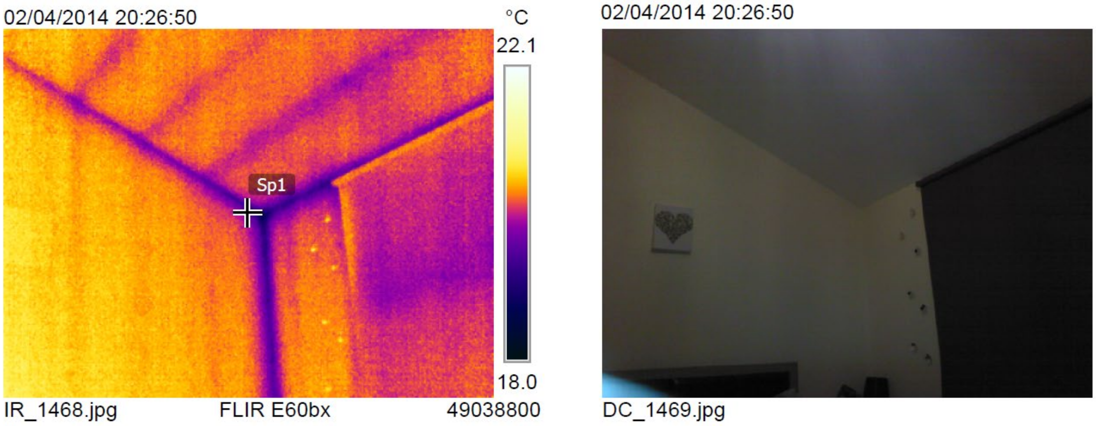

Figure 8: Thermal bridging at ceiling joists that are designed to minimise thermal bridging.

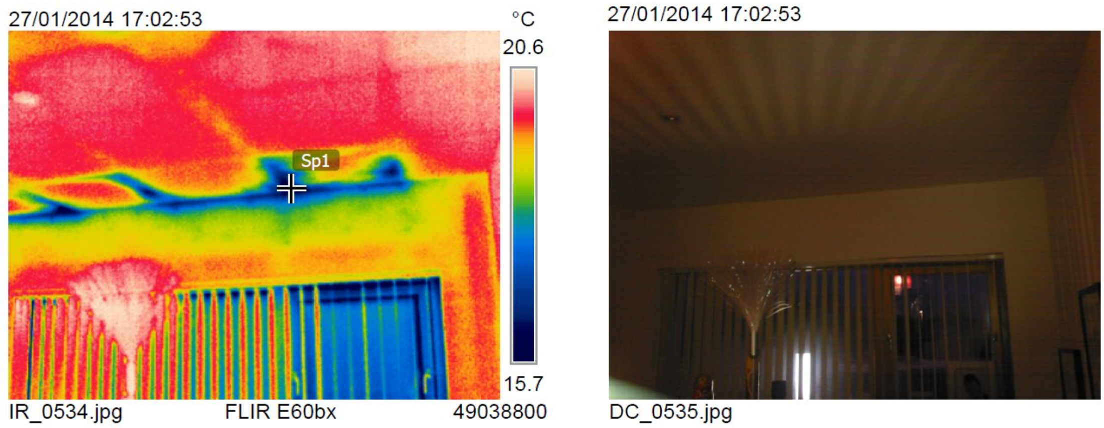

Figure 9: Repeating thermal bridge at intermediate floor level in a two-storey house.

Thermal bridging at joist ends (Figure 9) at intermediate floor levels was commonly found in all houses.

Poorly fitted or missing insulation was also an issue in each of the developments. These were predominantly located in isolated areas of walls or ceilings, however these cooler surface temperatures could give rise to surface condensation and mould growth. Missing insulation was widespread in the development in Barrhead, particularly in the ceiling spaces (Figure 10 -Figure 11) and at the eaves details. Following the feedback post thermographic survey, the housing association and architect investigated the defects and ensured that the missing and poorly fitted insulation was rectified to the best of their ability. The architect has since changed their eaves details as a direct result of this finding to ensure continuity of thermal insulation at the eaves.

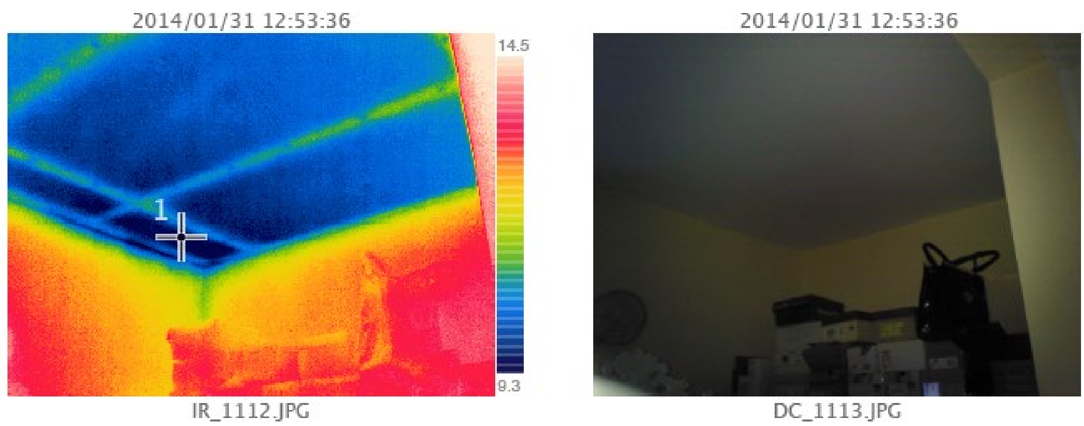

Figure 10: Missing insulation over a built in storage cupboard off a bedroom.

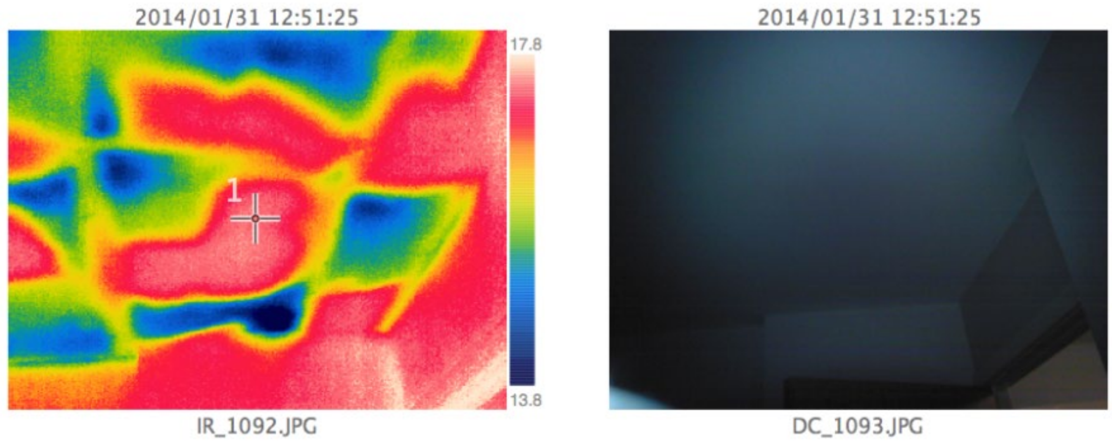

Figure 11: Poorly fitted insulation within an insulated ceiling.

The fabric of the Passivhaus was found to be more robust with uniformity of surface temperatures across the walls and ceilings, and reduced cold spots at windows and joist ends. Thermal images indicated that the fabric is more prone to weak spots in areas such as holes made in the external fabric for electric doorbell fitting and cables that were retrofitted post construction, for example satellite dishes.

The thermographic survey found cold areas in the homes that were related to the building services installations. These were often reported by the occupants as areas that caused discomfort, particularly in their bathrooms and kitchens. These were found to be due to lack of sealing around mechanical extract fan installations, piped services penetrations for hot and cold water pipework and foul waste pipes serving kitchen sinks (Figure 12), bathroom basins, baths and toilets. It was of note that the toilets installed in homes were all the close-coupled ceramic type. The thermograms of these highlighted the cold surface temperature of the cisterns (Figure 13) and in some instances condensation was present on the toilet cisterns and pooled on the WC pan. Consideration should be given to the sealing details for all piped services penetrations during the design stage of the project. Specification of insulated toilet cisterns along with insulated cold water pipework could reduce the risk of condensation forming and causing damage locally.

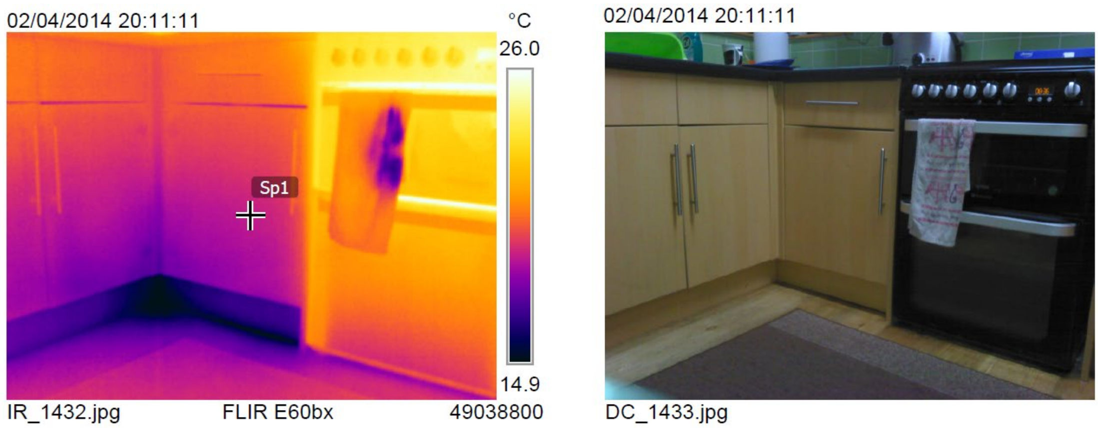

Figure 12: Cold air leakage from beneath plinth of built-in kitchen cabinets, possibly due to poor or lack of sealing at piped penetrations serving kitchen sink (just visible on top left).

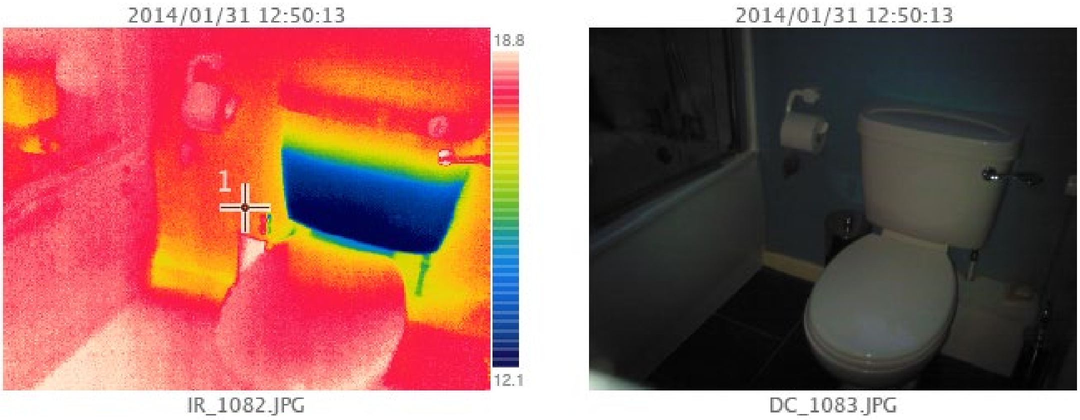

Figure 13: Cold water within un-insulated toiler cistern, condensation was common on this type of toilet cisterns.

There were six homes with wood burning stoves. In each case thermal bridging and heat loss were identified where penetrations were made at floor level for the stove air supply and at the fire stop plate at ceiling level (Figure 14).

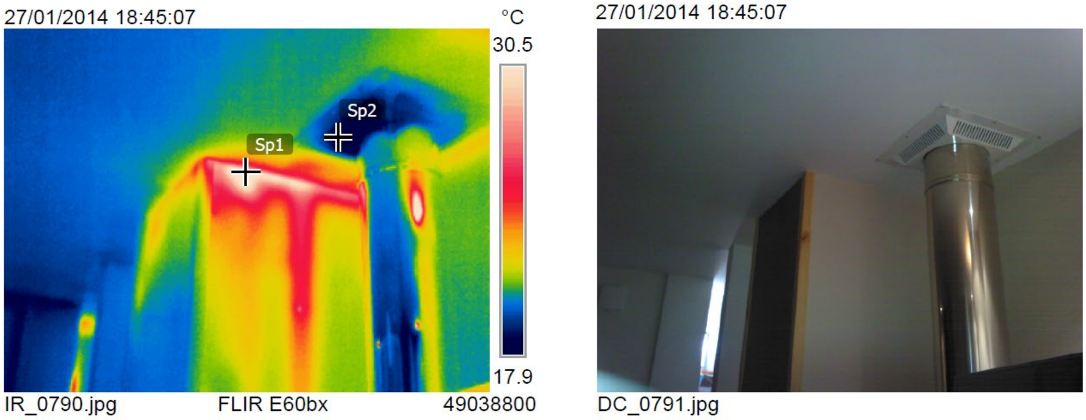

Figure 14: Cold air falling in to room through fire stop plate at top of wood stove flue, heat gain visible at top of boxing out that houses wood stove flue from property below.

In contrast, the thermography highlighted areas of heat gain arising from uninsulated hot water pipework. This was found to be problematic by the occupant of one house in the Dormont Estate where excessive heat gains from solar thermal pipework caused discomfort. Heat gains were found in all six developments due to fridge/freezers (Figure 15), gas boilers and hot water storage tanks where they were present. In one flatted dwelling the heat gains from the fridge/freezer were sufficient to increase the temperature of a separating wall between the kitchen and master bedroom to a temperature where space heating was not required in the bedroom. This was welcome in the winter months but caused considerable discomfort during the summer. Heat interface units forming part of district heating networks for space heating and domestic hot water, as well as the pipework serving these, were found to give off significant heat gains (Figure 16). This was due to inadequate thermal separation / thermal insulation.

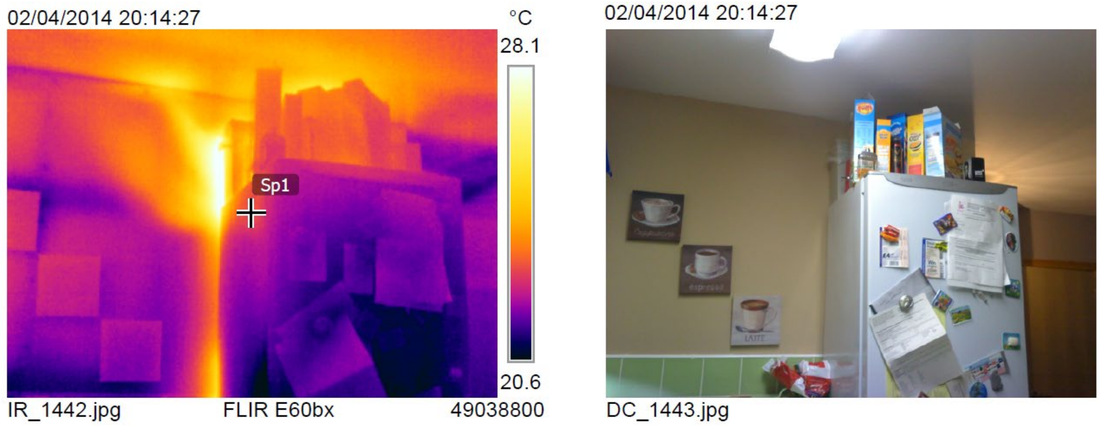

Figure 15: Heat plume from fridge/freezer creating warmer wall and ceiling surfaces.

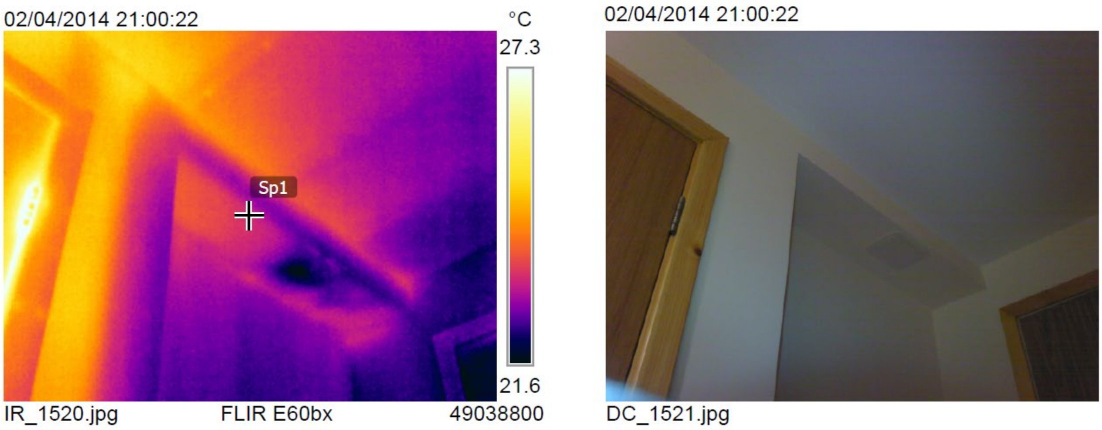

Figure 16: Heat gain from district heating pipework and heat interface unit in cupboard to the left, note that highest temperature is 27°C, heat gains from this unit are emitted year round.

3.2 Thermography	**Case Study**

At the Barrhead site the installation of insulation at the wall head/eaves and around perimeters was generally found to be problematic due to the practical difficulty of installing insulation over the wall plate, due to limited space for installation. This problem was detected in all three of the monitored homes and prompted remedial work as well as a review of the architect's details, which were based on industry wide 'standard' details.

The thermogram in Figure 17 indicates that cool external air is entering the building at the eaves and cooling the plasterboard finishes. This problem has been exacerbated by poor quality installation leading to increased heat loss, higher fuel bills and an increased risk of condensation and mould forming on these internal surfaces. The insulation at the original eaves detail was to be installed at a pinch point, where a builder would have difficulty in fitting the insulation in-situ, and there was a thermal bridge present.

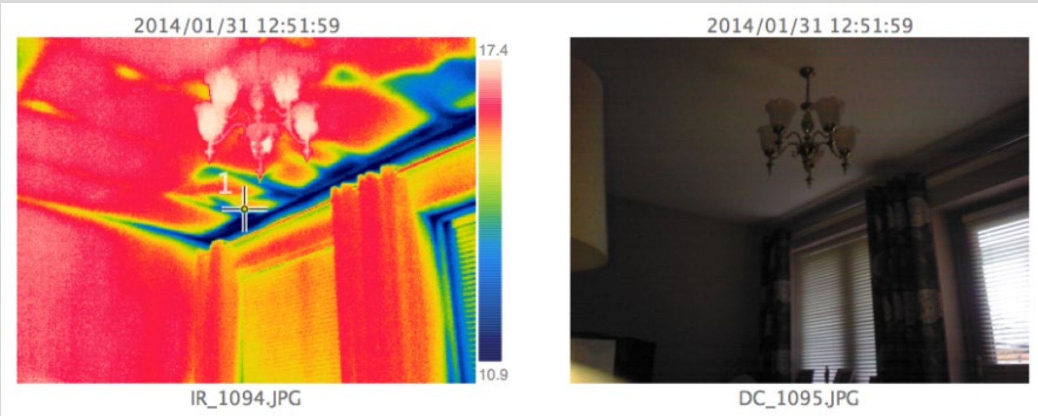

Figure 17: Thermal bridge to eaves detail.

3.2 Thermography	**Lessons Learned**

- Thermography identified undesired heat gains and heat losses across all projects, both of which can cause significant occupant discomfort.
- Significant fabric weakness through repeating thermal bridges was identified, particularly at timber studs and joist ends in timber framed dwellings.
- A continuous layer of insulation is needed on all external fabric elements (i.e. walls and roofs) to prevent thermal bridging. This applies even when using structural elements such as I-joists and I-studs.
- Designers should check standard details for buildability and ensure that thermal bridges are minimised.
- Common areas of heat loss were found at skirting boards, wall heads, eaves details, loft hatches and areas around external entrance doors.
- Issues were identified at windows and rooflights with colder internal surfaces in the structural openings. Heat loss was also identified at window and door seals and where insulation was missing around rooflight installations.

- Poorly fitted or missing insulation was a common issue, mainly in isolated areas in walls, ceilings and eaves.
- There is concern that areas of thermal bridging will give rise to condensation and mould growth on internal surfaces.
- There was more uniformity of surface temperatures and significantly fewer thermal bridges in the Passive Houses.
- Poorly sealed and finished building services installations such as pipework and toilet drainage result in localised cold areas, which can lead to condensation. Inadequate insulation to cold water pipework and toilet cisterns can also cause this problem.
- Inadequate insulation to hot water pipework and other services causes localised heating that can result in discomfort to occupants.
- When installing heat interface units for district heating systems, consider their location to prevent heat transfer to other rooms.
- The building fabric is more prone to heat loss when penetrations are made post construction (e.g. for telephone or satellite dish cables).
- Allowance should be made, both during design and construction, for all likely incoming and outgoing services so that these can be correctly detailed and installed to prevent unforeseen heat loss.
- More consideration should be given to sealing pipe penetrations and insulating services during the design stage of the project.
- Thermography can provide valuable evidence for designers and builders to improve standard details.
- Thermography should be carried out by those with appropriate equipment training who are skilled in interpreting thermograms.

3.3 In-situ u-value measurements

The measurement of the in-situ u-value of individual construction elements was mandatory to the monitoring programme. Using thermography representative measurements of external wall and ceiling/roof elements were selected at each development site. The heat flux plates used to take these measurements remained in-situ for three weeks, with the resulting u-values calculated and compared against predicted design values and Building Regulations backstop u-values. Testing, analysis and reporting were undertaken in accordance with ISO: 9869, with all calculations conforming to the '*results average method of analysis*'.

Dwellings in the Garscube and Scotland's Housing Expo developments were designed to meet the 2007 Building Regulations. The remaining dwellings were designed to meet the updated backstop u-values in the 2010 Building Regulations, and the Passive House dwellings were designed with u-values in accordance with the design criteria of the Passive House standard.

Figure 18 indicates the measured u-values for external walls measured in each development and compares these against the design and backstop u-values. Excluding the result of two measurements – one of which was where a thermal bridge was deliberately measured - 58% of wall elements had a lower (better) u-value than their corresponding design targets, while the measured u-values of 33% of wall elements were higher (worse) than the design target. Most were lower (better) than the backstop u-values for the relevant building regulations they were designed to comply with. Five of the houses were certified Passive House dwellings, where all wall elements measured in these houses had in-situ u-value results below (better than) the Passive House design criteria.

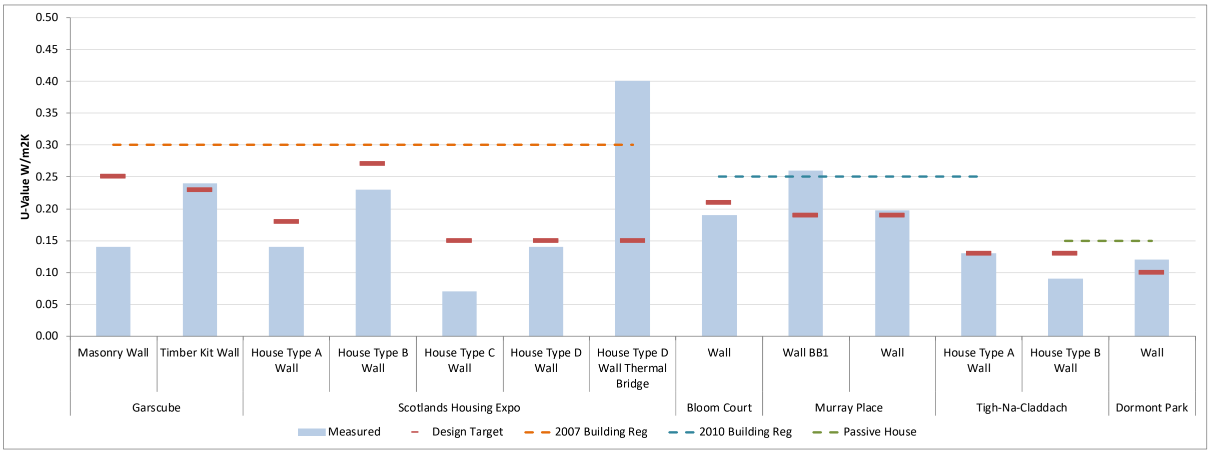

Figure 18: In-situ u-values measurement results for each wall type, compared against the relevant backstop u-values.

Thermography was used by the researchers when positioning the heat flux plates. This ensured that measurements were taken on areas of insulated wall and not on thermal bridges that may have been present. While doing this the researchers discovered a large area of external wall in one flatted property in Scotland's Housing Expo where there appeared to be missing or ill-fitting insulation. As a result the u-value equipment was set up to simultaneously measure two external wall areas, on the same wall, to determine the effect that this 'cold spot' had on the in-situ u-value. The *intended* u-value for the wall was 0.15 W/m^{2}K. While the measured u-value of the insulated area was recorded at 0.14 W/m^{2}K, the 'cold spot' was found to have a measured u-value of 0.40 W/m^{2}K - nearly three times the rate of heat loss of the rest of the wall. This will have a significant risk of localised lower surface temperatures, potentially leading to condensation, mould growth and damage to the building fabric and finishes.

Design u-value targets for all roofs were lower than (better) the Building Regulation backstop values. 25% of roof measurements were better than their corresponding design target, while the remaining 75% of roofs failed to meet the design targets (Figure 19). In two developments heat loss from the roofs was significantly greater than expected. In one development, Barrhead, the in-situ result prompted investigation by the Housing Association. They found the insulation to be very poorly installed, which led to remedial works to improve the situation. Two Passive House dwellings on separate developments were included in the in-situ u-value testing. This revealed that while the roofs of neither achieved the design u-values, one exceeded (was better than) the backstop Passive House u-value target of 0.15 W/m^2K.

For compliance with the Building Regulations the design u-value is used for the dwellings' carbon dioxide emission calculation and subsequent Energy Performance Certificate (EPC). In turn this informs home occupiers and owners of the energy efficiency of their homes. The negative results highlighted by the in-situ testing may increase the actual carbon dioxide emission and costs for space heating for the occupants. This suggests that the EPC may give homeowners and tenants a misleading picture of the energy performance and running costs of their house.

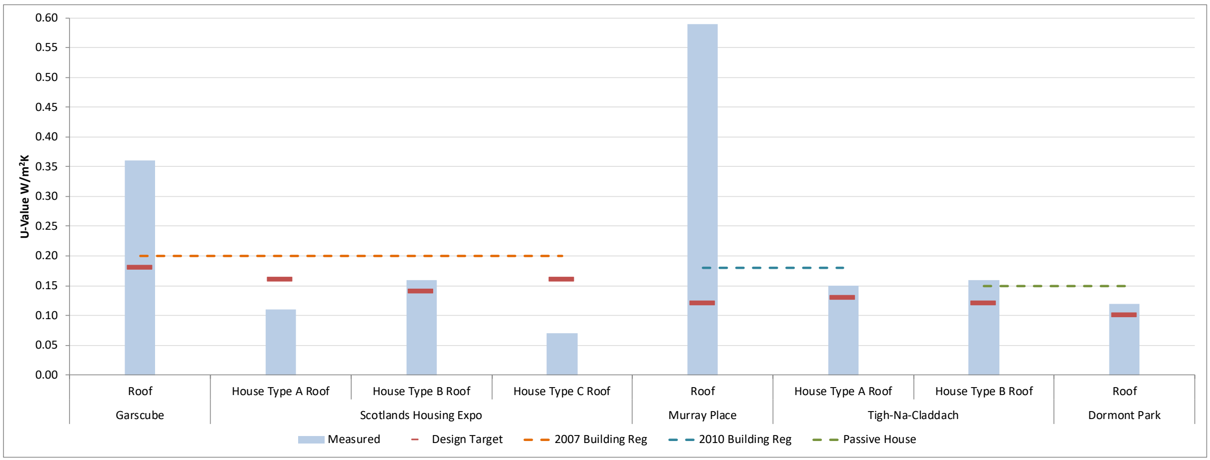

Figure 19: In-situ u-values measurement results for each roof type, compared against the relevant backstop u-values.

These in-situ u-value measurements show that the majority of external walls and roofs met the Building Regulation backstop values of the time. However, some design targets were not met, particularly for the roof elements.

The u-values for external walls and roofs at all developments were intentionally designed to exceed the Building Regulations in force at the time. This demonstrates an ambitious and positive approach by the Housing Associations to reducing heat loss and carbon dioxide emissions from dwellings, as well as mitigating other factors such as fuel poverty. This approach may also reduce the frequency with which building owners may need to carry out thermal upgrades.

However, this ambition has been undermined by poor quality detailing, lack of site inspections and poor workmanship. This will inevitably lead to increased heat loss, as illustrated by the measured u-value results.

Designing with a 'fabric-first' approach, which specifically sets lower u-value and airtightness targets, will, in theory, deliver more energy efficient housing. The calculation process for determining the design u-values warrants further research to ensure that they correlate more closely with the in-situ value. A concerning issue is the lack of continuity of insulation in external wall and roof elements. There were numerous examples of ill-fitting thermal insulation, all of which pose long-term effects on the overall energy efficiency of a dwelling. Poor quality detailing at the design stage coupled with poor workmanship during the construction phase creates a greater risk of localised cooler surface temperatures that will increase heat loss. This, in turn, could increase the risk of condensation, mould growth and building fabric degradation.

The researchers learned lessons regarding in-situ u-value apparatus set-up. These were principally to ensure thermography is used to identify the most appropriate fixing location for the heat flux plates to avoid placing on thermal bridges, and to ensure the use of robust and non-damaging fixings for adhering heat flux plates to minimise damage to finished surfaces.

3.3 In-situ u-value elements	**Case Study**

In House Type D at the Expo site (a ground floor flatted dwelling) the thermography (Figure 20) indicated an area of wall at high level that exhibited a considerable cooler surface temperature compared with the remainder of the wall. This is likely to have been caused by missing or ill-fitting insulation within the timber framed wall structure. Heat flux plate (HFP) B was set up in the vicinity of the thermal bridge and HFP A was located in an area representative of the fully insulated wall. The results indicate HFP A to have achieved a u-value of 0.14 W/m^{2}K - 6% lower than the design u-value of 0.15 W/m^{2}K and 53% lower than the then backstop value of 0.30 W/m^{2}K. In contrast, the test at HFP B revealed a u-value of 0.40 W/m^{2}K - 240% poorer than the design intent and 33% poorer than the building regulations backstop u-value. This highlights the significance of missing or ill-fitting insulation and can have a large impact on the heat loss from that area of wall, potentially impacting energy bills, occupant comfort and health due to the risk of condensation and mould growth.

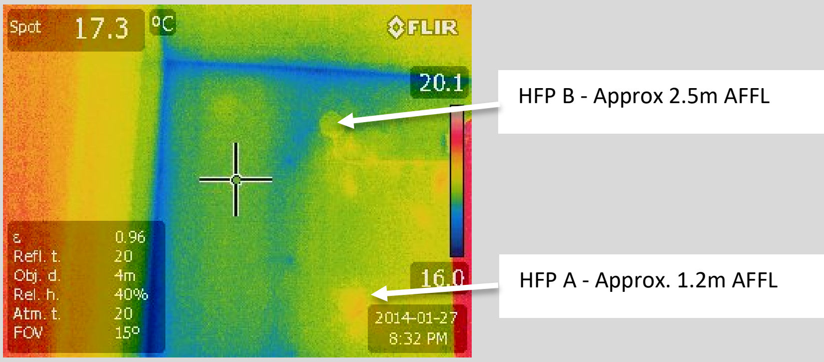

Figure 20: Thermal image of wall under test, highlighting location of HFPs mounted at 1.2m and 2.5m above finished floor level (AFFL).

3.3 In-situ u-value measurements — Lessons Learned

- Thermography should be utilised when setting up in-situ u-value equipment to identify and avoid placing sensors on thermal bridges and areas of missing insulation.
- 58% of wall elements and 25% of roof elements performed better than u-value design targets with most Building Regulations backstop values being satisfied.
- Higher than anticipated u-values were measured in areas with poorly fitted and missing insulation.
- Poor workmanship can negatively impact energy efficiency and also present a risk of condensation and mould growth on cooler internal surfaces.
- Homes designed with thermal elements designed to meet backstop u-values are at risk of requiring fabric insulation upgrades in the future.
- Wall and roof elements of the Passive House dwellings measured in this study were generally lower than the Passive House u-value threshold.

4 ENVIRONMENTAL MONITORING AND PERFORMANCE

Indoor environmental monitoring was undertaken across all 26 dwellings using remote sensing equipment. This consisted of combined sensors set to simultaneously record internal temperature, relative humidity and carbon dioxide concentrations. A separate sensor captured the window opening occurrences in each of the monitored rooms. The monitored rooms were:

- 24 living rooms (wood burning stoves were fitted in six of these)
- 2 open plan living room and kitchens (the sensor was mounted at the mid-point between the two rooms)
- 18 kitchens
- 35 bedrooms
- 2 sunrooms

Measurements were taken every five minutes for a period of two years in three to four rooms in each dwelling.

4.1 Temperature

Temperature data for one year (2013) has been plotted in Figure 21 and indicates an average internal temperature of 22°C for each monitored room type. The range and extremes of temperatures recorded are concerning as sustained high or low heating extremes could pose health risks for occupants, in particular those considered most vulnerable.

<u>Low temperatures</u>

The data illustrates that temperatures in some of the monitored rooms did not meet the World Health Organisation's (WHO) minimum thermal comfort benchmark of 18°C for non-vulnerable households. The lowest recorded internal temperature fell below 12°C in 7 (8%) of monitored rooms. While the data were not analysed in detail against occupancy profiles the low internal temperatures recorded may have occurred at times on no occupancy. It is also of note that low internal temperatures, particularly those below 12°C, are known to increase respiratory and cardiovascular risk for occupants.

This is concerning as the homes monitored were all designed as new, energy efficient homes. The low temperatures recorded in some of the dwellings suggests that fuel poverty remains a risk in new low-energy homes.

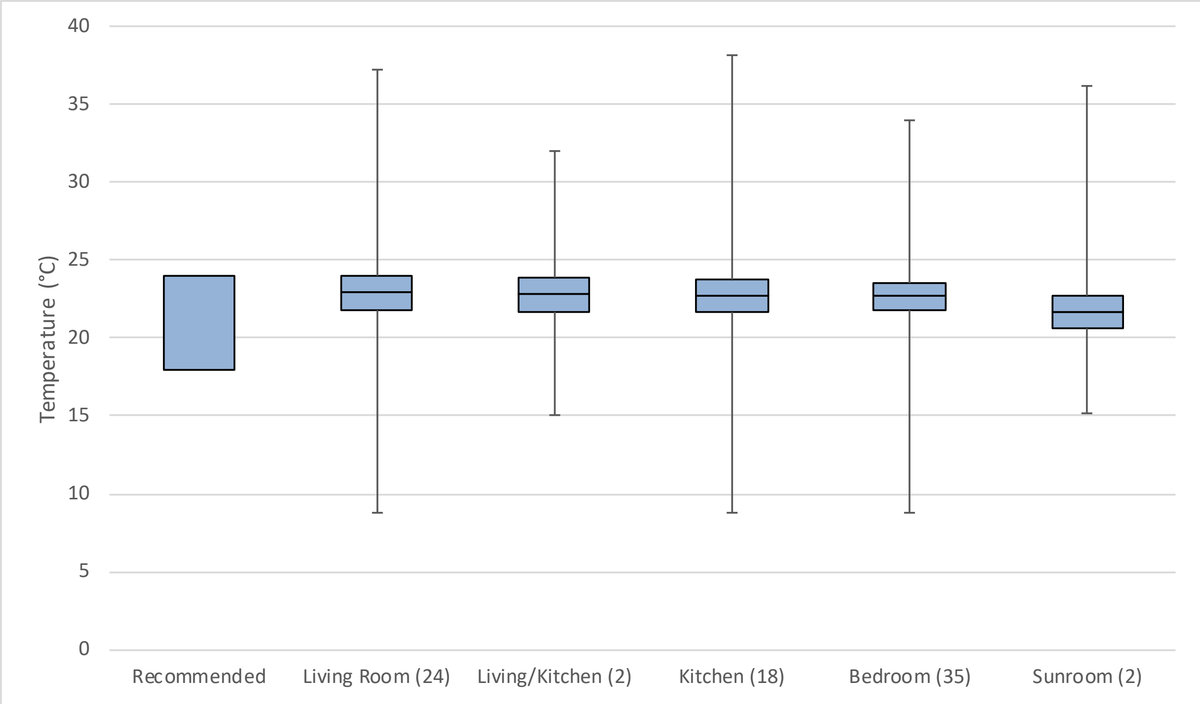

Figure 21: Summary of annual minimum, maximum and mean temperature from a range of rooms within 26 monitored homes plotted against World Health Organisation thermal comfort range for non-vulnerable groups.

High temperatures

At the opposite end of the scale, temperatures as high as 38°C were recorded inside some of the dwellings. While this was a peak, temperatures over 25°C were frequently recorded [2]. The data plotted in Figure 22 suggest that some occupants are heating their homes more than they need to during the winter months and that they may have become accustomed to higher internal air temperatures. High temperatures are associated with heat stress, heat stroke and mental health issues.

The highest internal temperatures occurred in March, June and September. During March and September – the 'shoulder' seasons – external weather conditions in Scotland are highly changeable, with strong sunshine and cold overcast conditions being experienced over the course of a typical day. Two issues were identified: the first was that occupants were not clearly informed about how to operate their heating systems effectively at different times of year; the second is that heating controls were overly complicated to understand. As a consequence energy use and heating costs were higher than predicted in the SAP calculations. This caused significant anxiety with one of the residents.

Interviews with occupants revealed that dwellings with radiators reacted noticeably quicker to these changing conditions than dwellings with underfloor heating. Diurnal temperature swings were not generally evident in any homes, indicating that heating systems are switched on day and night.

The research found that nearly half (46%) of households did not use their heating programmers and 15% did not adjust thermostatic radiator controls. There is a strong case for clearer communication of

[2] 25°C is the threshold temperature used by the Passive House Institute to signify overheating, and is used here as the sample includes Passive House dwellings.

the heating system design intent and issue of a dwelling-specific non-technical quick start guide for the occupants when they move in.

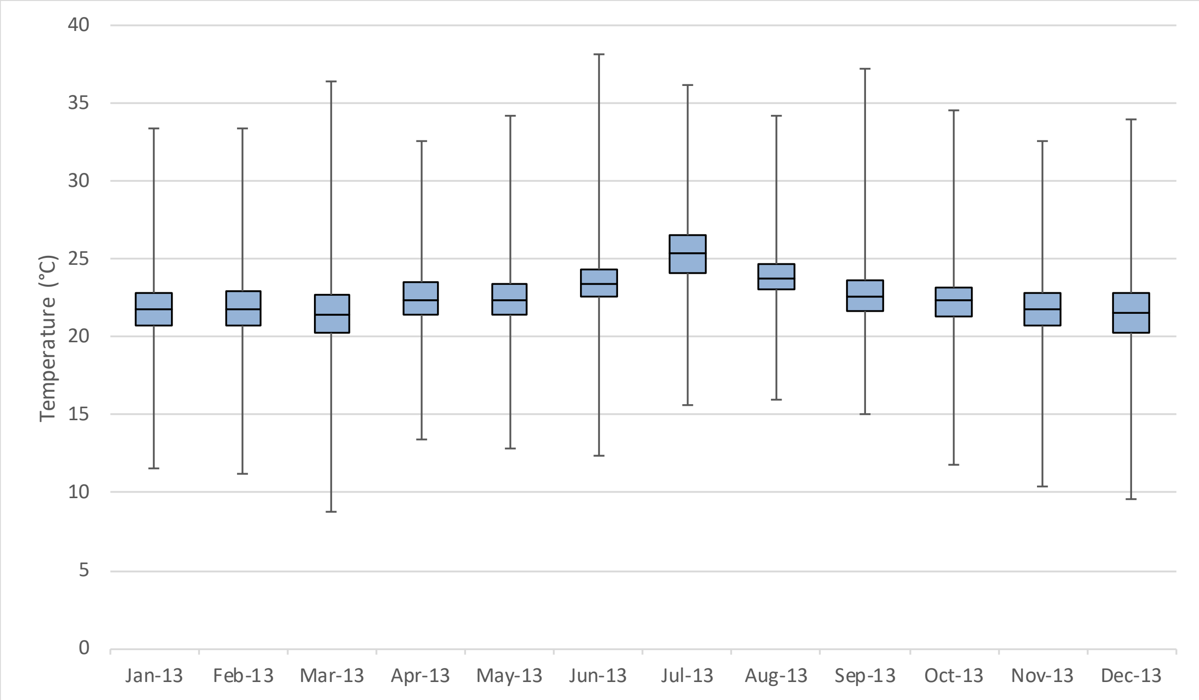

Figure 22: Summary of monthly minimum, maximum and mean temperature from monitored rooms within 26 homes.

Another consideration is the boiler size. Dwellings are being designed for thermal energy efficiency and many are fitted with combination boilers for domestic hot water needs. This means that the boiler is sized based on the number of 'appliances' (e.g. taps, showers etc.) that need hot water. As a result boilers are oversized for space heating, which may contribute to the high internal temperatures that were recorded. A mechanism for appropriate heating system sizing requires to be:

a) considered at the design stage,

b) properly implemented during the construction phase, and

c) communicated effectively to occupants so that heating systems do not contribute to overheating risk.

Uncontrolled heat gains within some homes were identified through thermography. These include heat gains from kitchen appliances, un-insulated pipework, solar thermal systems, domestic hot water storage and heat interface units. These gains are often mistakenly considered as 'free' heat during the winter. However, as they are also present during the warmer months, they can contribute to overheating and cause significant thermal discomfort. This phenomenon was identified through the monitoring. Using the Passivhaus overheating threshold of 10% of year over 25°C it was found that 70% of monitored homes exceeded this benchmark. It was also of note that temperatures were high in all houses through July. 23% of the homes exhibited high temperatures for more than 10% of every month of the year. See Figure 23.

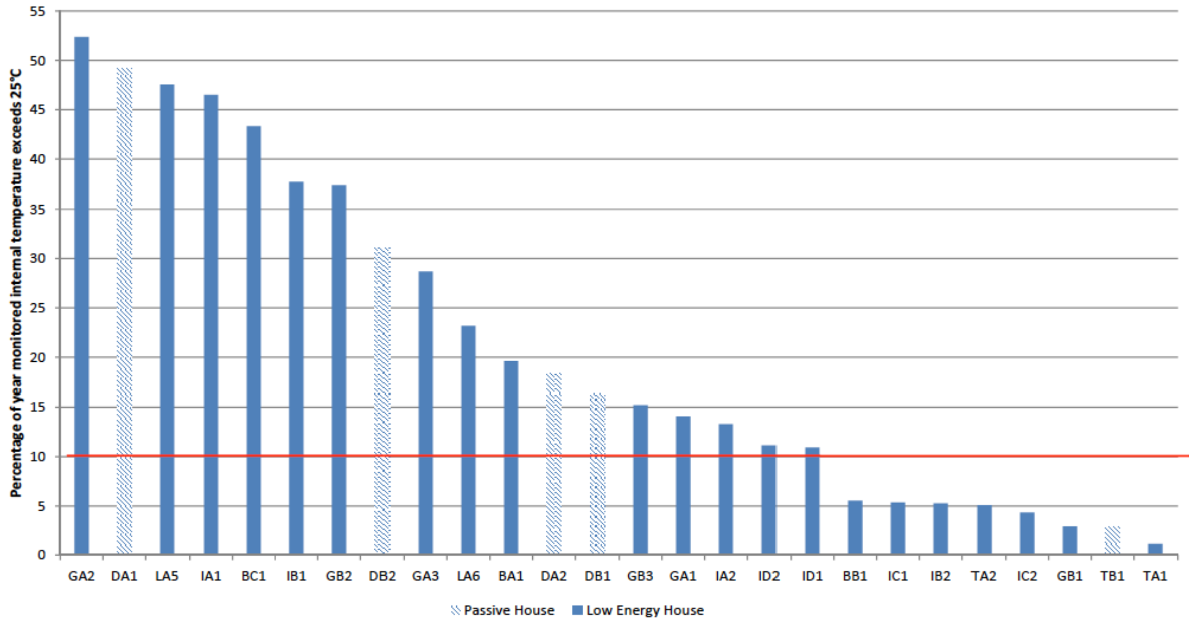

Figure 23: Percentage of year monitored internal temperature exceeds 25°C in Passive House and Low Energy Homes. The Passive House 10% of year over 25°C was used as the overheating threshold.

Overheating was found to be caused by a variety of contributing factors including lack of designed ventilation. MVHR systems in two of the Passive House dwellings were found to be lacking 'summer bypass' (where the heat from exhaust air is not used to preheat incoming fresh air), contributing to high internal temperatures. Occupants were generally unaware of how to effectively cool their houses during warm periods. Details of when occupants opened and closed windows can be found in Section 4.2

<u>Building orientation</u>

Orientation of rooms in the monitored dwellings had a direct effect on internal temperatures and occupant comfort. In one of the Passive House dwellings, for example, there was a lack of solar gain in the east facing living area, which caused the occupants to feel cold. On another site the bedrooms in one monitored dwelling faced south – resulting in excessive solar gains and high temperatures – while the living room and kitchen faced north, resulting in fewer solar gains, a feeling of darkness and high heating demand.

External solar shading was designed for the west-facing elevations of a number of the monitored dwellings at the Expo site to help reduce the risk of overheating but was removed during a value engineering process. It is likely that the overheating experienced by these occupants was, in part, a consequence of this removal.

4.2 Ventilation

Ventilation is the controlled exchange of air to remove and dilute odours and pollutants within a building. It should not be confused with 'infiltration' (commonly referred to 'draughts'), which is the uncontrolled admittance of external air through pathways in the building fabric. Infiltration is undesired and can cause discomfort and increases risk of moisture and mould issues in the building fabric. Airtightness is the strategic approach to minimising infiltration. Refer section 3.1.

Ventilation requires careful design. The majority of the 26 monitored homes (21no.) were naturally ventilated with opening windows and trickle ventilators together with some form of extract ventilation from the 'wet' rooms, i.e. kitchens and bathrooms. The extract ventilation included intermittent extract fan units (17no.), continuous mechanical extract ventilation (2no.) and passive stack ventilation (2no.). The remaining houses (5no.) were fitted with mechanical ventilation with heat recovery (MVHR) systems to provide background ventilation. Manually operated windows were present in all homes and the frequency of window opening in the monitored rooms was recorded in all homes except Bloom Court.

Ventilation effectiveness is often measured by concentrations of CO_2 within the internal environment. High CO_2 concentrations affect an individual's physical and cognitive performance as well as their quality of sleep. Continued exposure to high concentrations may mean an elderly person may be more prone to trips and falls in the home or the academic performance of a child at school may be negatively affected.

The benchmark maximum CO_2 concentration for an adequately ventilated house is 1,000 parts per million (ppm). Figure 24 illustrates the maximum, minimum and mean CO_2 concentrations of all of the monitored dwellings. It shows that all monitored rooms exceeded the recommended benchmark, suggesting occupant ventilation regimes were poor at times. The monitoring equipment had a high range of 5,000ppm, which was reached in most spaces.

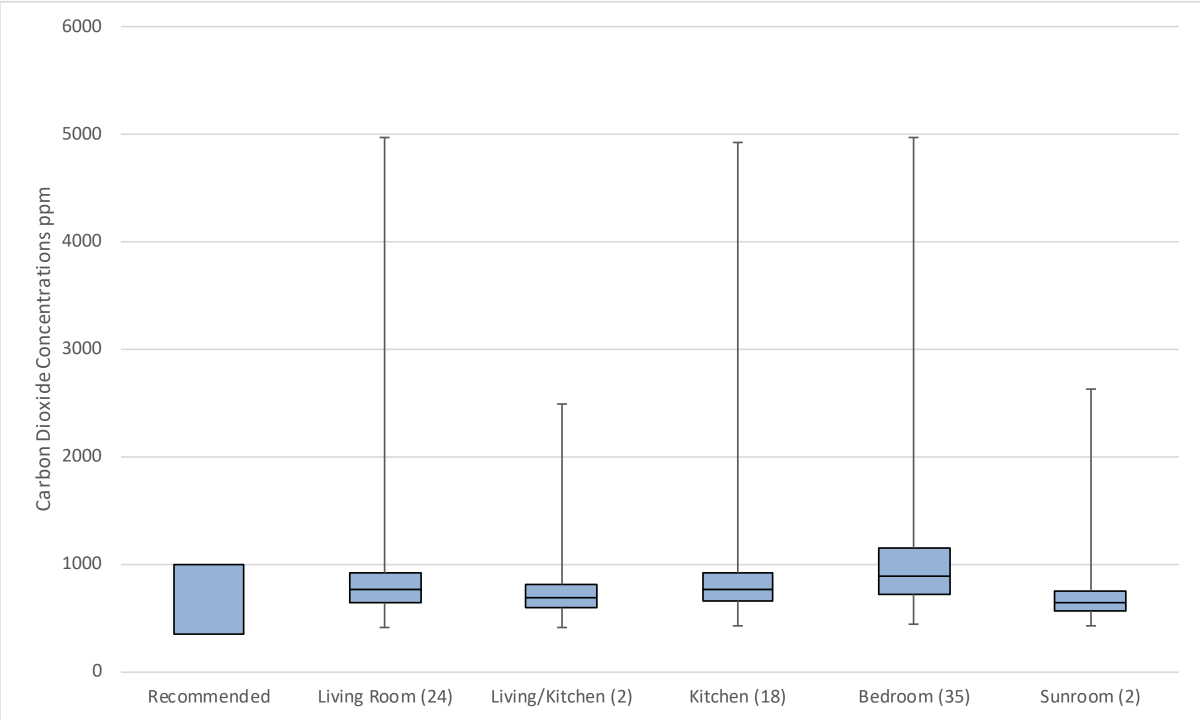

Figure 24: Summary of annual minimum, maximum and mean carbon dioxide concentrations measured in a range of rooms within 26 monitored homes plotted against recommended levels.

Mean CO_2 values of all rooms were below 1,000ppm except for the bedrooms, which indicates that ventilation provision in bedrooms requires more consideration. The building regulations now require installation of a CO_2 monitor in the principal bedroom. The aim of this is to raise awareness of indoor air quality to those using the bedroom.

There was a clear pattern for window opening occurrences in living rooms (Figure 25), bedrooms (Figure 26) and kitchens (Figure 27). Windows were opened more frequently between the months of May and October with opening becoming more frequent during June, July and August. Windows were opened most frequently during the summer, and kitchen windows were opened more often than other rooms during the colder months.

It was of note that most windows were inward opening 'tilt and turn' style. Ventilation rates were found to be relatively low in occupied rooms when the tilt function was used, which could be partly due to the deeper window reveals that reduce the effective area for ventilation. The types of windows installed in the dwellings did not allow occupants to fine tune ventilation, for example by having multi-position latches. Closed curtains or blinds restricted airflow into rooms. Ventilating bedrooms on the ground floor caused security concerns for occupants and they were less likely to use their windows through the day or night. In dwellings where the ground floor bedroom windows were full height (i.e. more like doors) some occupants had security concerns; others were concerned for the safety of their children at night and worried that their child may sleep walk into the street.

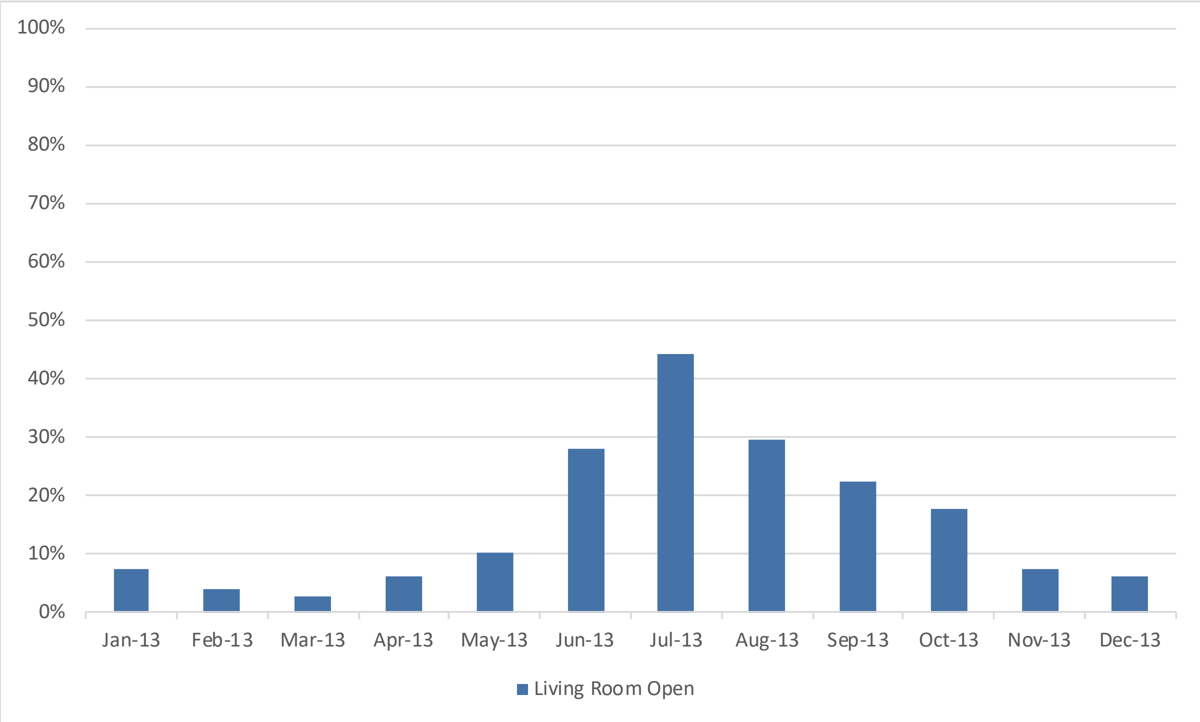

Figure 25: Annual window opening in living rooms across 24 homes.

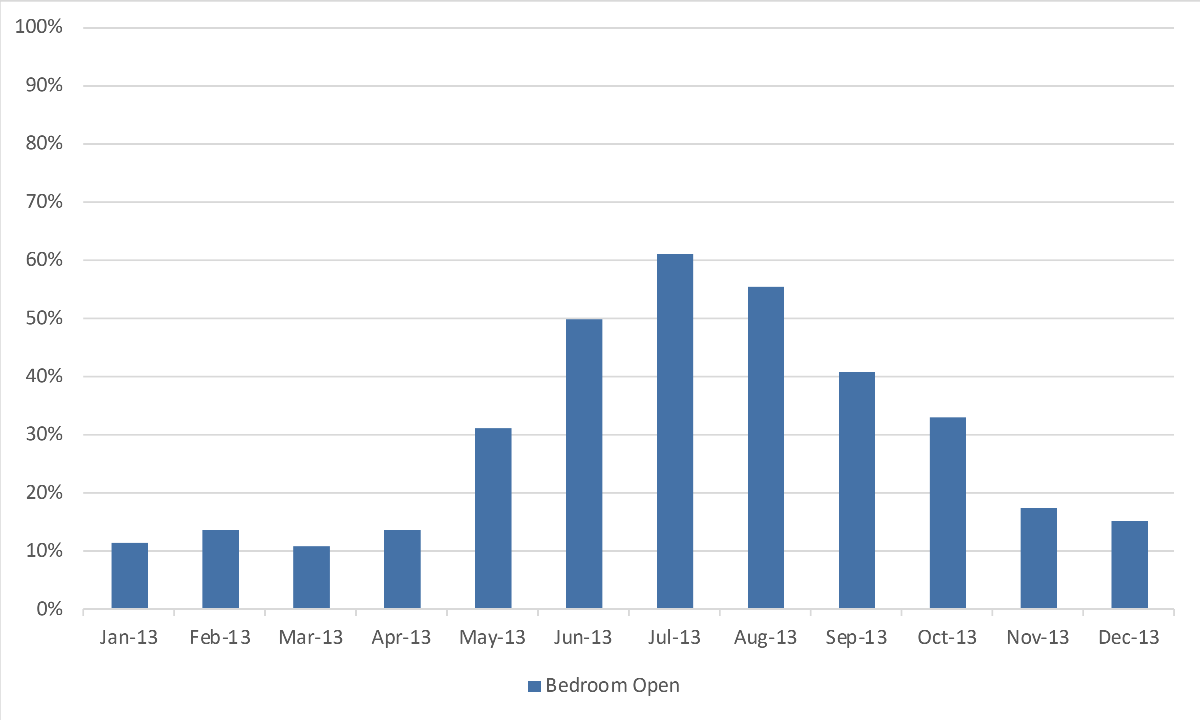

Figure 26: Annual window opening in 33 bedrooms across 25 homes.

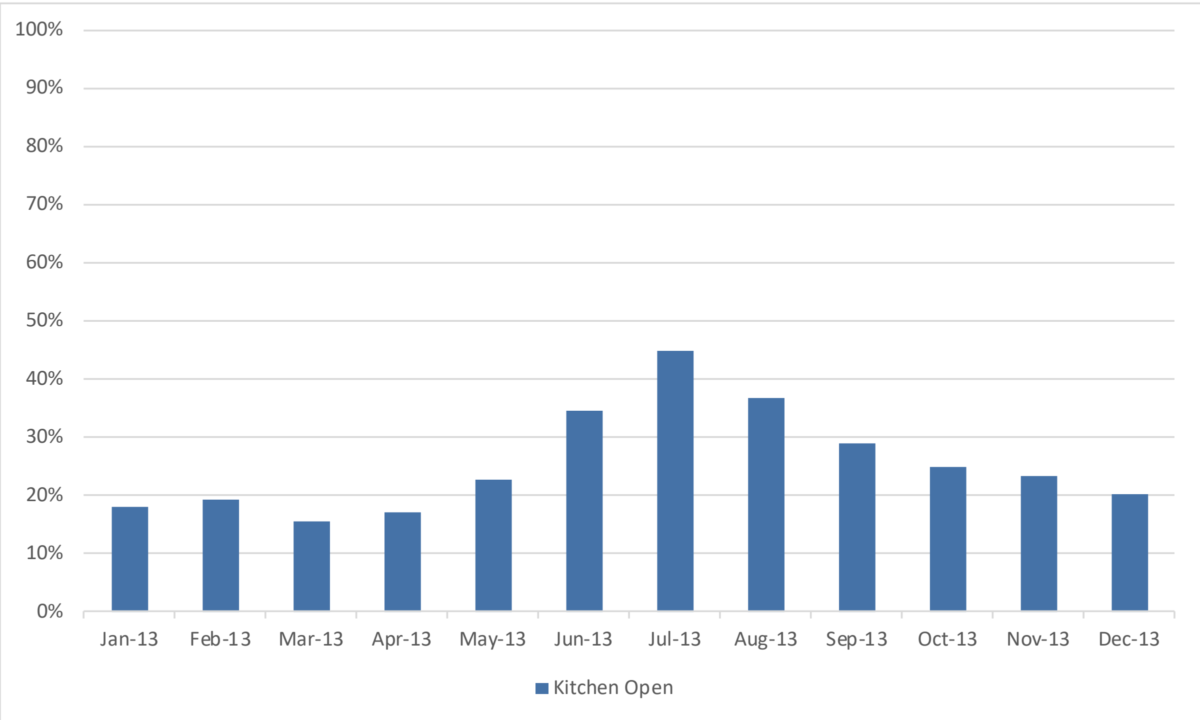

Figure 27: Annual window opening in kitchens across 13 homes.

Trickle ventilators were provided for background ventilation in all 21 of the non-Passive House homes. Most were fitted in the head of windows though some homes were fitted with a through-wall type of ventilator; some dwellings had both. These were often obstructed by blinds, curtains or cushions and, in some instances, occupants were not able to reach the trickle vents without climbing on furniture, even in sheltered accommodation for the elderly. In most homes furniture placement affected the occupants' ease of access to trickle vents. Reviewing the CO_2 concentrations, it was questionable whether the intended background airflow was provided, though the POE recorded many complaints of draughts from both window head and through-wall trickle vents. Thermal imaging surveys indicated that the wall vents presented a thermal bridge and poor sealing around the wall duct provided an infiltration route.

Some occupants made complaints about under performance of extract fans. In one bathroom extensive mould growth was observed on the ceiling surface, walls and the tile grout. Airflow measurements indicated that the extract fan was operating at five litres per second (l/s) - well below the 15 l/s specified in the building regulations for moisture control in bathrooms. This instigated testing of airflow rates for all intermittent extract fans installed in the monitored buildings, excluding the Passive Houses. Twenty-seven intermittent extract fans were tested, of which only 20% (5no.) were found to achieve their intended flow rate (Figure 28).

The fans tested were all fixed speed and were most likely selected on the basis of meeting the building regulations guidance. This demands extraction flow rates of: Kitchen, 30 l/s above a hob or 60 l/s if fan is located elsewhere; Utility 30 l/s; and Bathroom or Shower room 15 l/s. Some landlords replaced defective units with new units. However, in a dwelling in Inverness (IA1), the replacement fan was disabled by the occupants due to the high noise levels, resulting in the purpose of the extract fan being overridden by occupant comfort demands.

This testing clearly indicates that extract fans need to be appropriately selected, carefully installed and properly commissioned to ensure they meet the minimum ventilation requirements of the building regulations. In addition to this ducted exhausts should have calculations made for the additional pressure drop associated with the duct runs to ensure there is enough fan power to exhaust the moisture laden air to outside. In all cases noise criteria should form part of the specification rather than a selection being made on capital cost alone: occupants will not use fans that are noisy and also perceive noisy fans to cost more to run.

Some extract grilles were difficult to reach and others were installed out of sight due to their positioning above wall-mounted kitchen cabinets, illustrating that access for maintenance requires consideration during the design phase. Many extract grilles were found to be dirty, which, over time, increases air resistance and will further reduce the performance of the extract units.

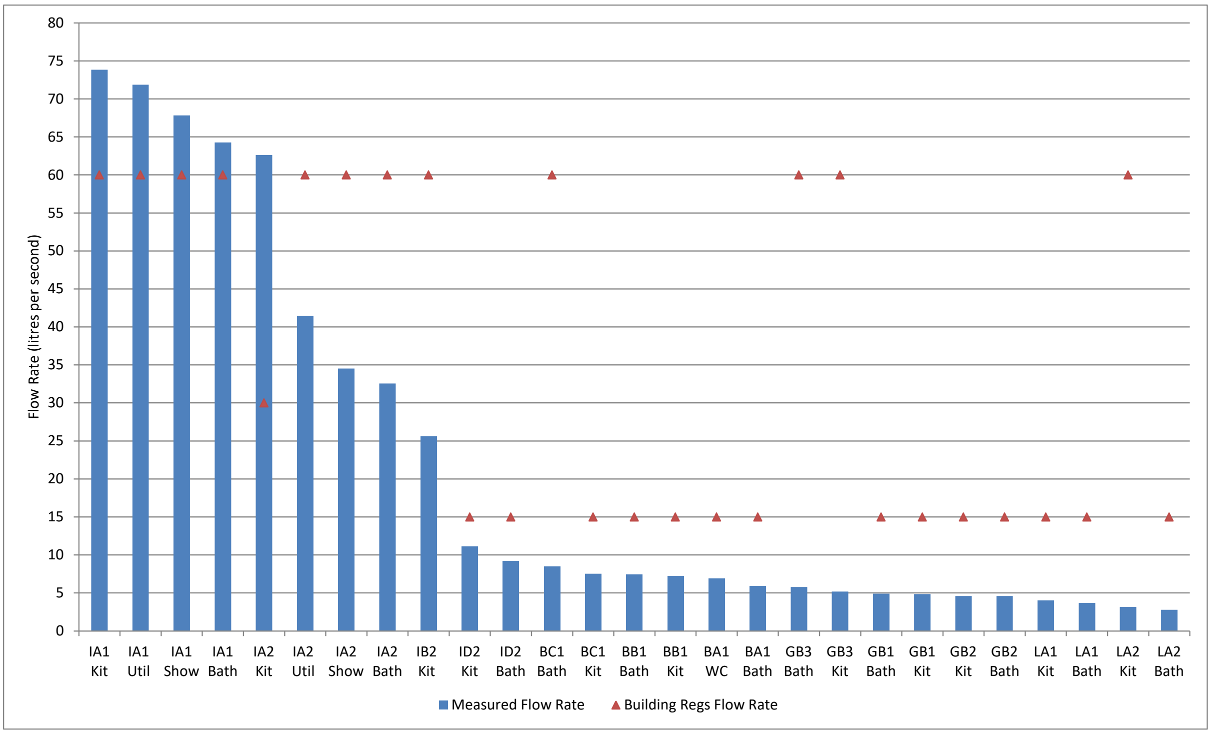

Figure 28: Measured airflow rates of kitchens and bathrooms compared with Building (Scotland) Regulation minimum airflow rates.

Airflow rates from the mechanical ventilation with heat recovery (MVHR) units were measured for each of the five Passive Houses (Figure 29). Testing identified system imbalances, incorrect airflow rates in wet rooms, dirty filters, boost rates lower than the necessary 30%, draughts reported from grilles and different air change rates for identically sized dwellings. However, there were few issues with the quality of the installation. It took a while for occupants to fully understand how to operate the central MVHR units but, in all homes after a settling period, the occupants gained confidence in operating these. The Passive House dwellings had higher ventilation rates than the naturally ventilated dwellings but Passive House occupants were not fully adept at purge ventilating their homes. Two of the MVHR units did not have a summer bypass mode, meaning that air was still being heated during the summer while the MVHR unit was operating. It is important that the MVHR unit has an automatic summer bypass to avoid external air being heated further during the summer. The combined lack of summer bypass and purge ventilation has the potential to contribute to overheating (refer section 4.1).

Dwelling	Whole House	Normal flow (m^3/h)	Boost flow (m^3/h)
DA1	Supply	144	205
	Extract	132	162
	Imbalance	+ 9%	+ 27%
DA2	Supply	102	120
	Extract	90	120
	Imbalance	+ 13%	0%
DB1	Supply	152	182
	Extract	133	161
	Imbalance	+ 14%	+ 13%
DB2	Supply	148	170
	Extract	no value	no value
	Imbalance	-	-
TB1	Supply	75	107
	Extract	77	124
	Imbalance	- 3%	- 14%

Figure 29: Passive House Mechanical Ventilation with Heat Recovery (MVHR) airflow rates in five houses.

4 Environmental monitoring	Case Study

Temperature measurements in the Passive Houses in Dormont Park identified that all exceeded the Passive House overheating threshold of 25 °C for more than 10% of the year. The Passive House Planning Package (PHPP) predicted that there would be 0.2% overheating throughout the year. In home DA1, high temperatures were recorded for almost 50% of the year. See Figure 30. In the south facing master bedroom temperatures were generally within the 25-30 °C band (dark red) during summer 2013, sometimes peaking at 32 °C or above. Both bedrooms experienced significant high temperatures throughout the year with temperatures generally above 23 °C and exceeding 26 °C in all four seasons. The BPE found that the occupant would heat the home to high temperatures to ensure their baby was warm enough. This is reflected in the annual energy use of the dwelling, which is significantly higher than the other Passive House dwellings at Dormont Park. Refer section 5.

Internal temperatures were found to be higher in first floor bedrooms. This might be due to the natural stack effect of warm air rising through the house. Also of note is that high temperatures were observed in *south* facing living room and main bedroom, and the *north* facing rear bedroom, suggesting little difference in impact of orientation and solar gains on these rooms. Once this occupant moved out and new occupants moved in, the incidence of high internal temperatures was much lower, suggesting the effect occupant behaviour can have.

Window opening was monitored and had a minimal impact on the high temperatures. External solar shading could have helped to reduce the effect of solar gain and the timing of window opening could also have an impact on internal temperatures. In the UK occupants are unaccustomed to closing windows during the day and opening windows at night when it is cooler.

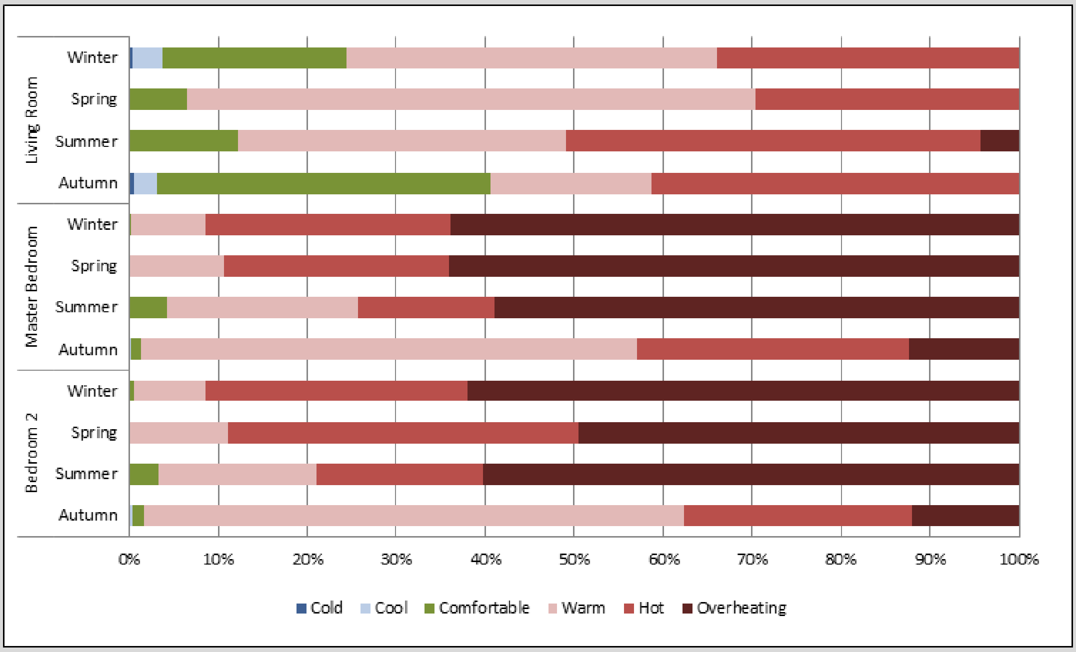

Figure 30: Chart indicating temperature range in dwelling DA1 for 2013. Dark red indicates temperatures above 25°C.

4 Environmental monitoring **Lessons Learned**

4.1 Temperature

- Some rooms are not achieving the World Health Organisation's (WHO) minimum thermal comfort benchmark of 18°C for non-vulnerable households.
- 70% of monitored homes exceeded the Passive House 25°C overheating threshold for more than 10% of the year, some reaching temperatures above 30°C.
- Homes above and below the 18-25°C comfort range could negatively impact occupant health and impact on fuel poverty.
- Both summer and winter temperatures were found to be problematic. The highest internal temperatures occurred during March and September when highly changeable weather conditions come into conflict with a typical daily heating programme, suggesting issues with heating control.
- 46% of occupants did not use heating programmers. 15% did not adjust thermostatic controls.
- Diurnal temperatures fluctuations were considerable in lightweight homes, especially those with electric heating.
- Solar gain admittance and lack of designed ventilation contributed to overheating.
- Change in tenancy in the same dwelling affected recorded internal temperatures.
- Clearer communication between the design team and occupants is essential at building handover stage. This should use a dwelling-specific quick start guide.
- Orientation, window design, ventilation strategy and solar shading all require careful design to avoid thermal discomfort in dwellings.

4.2 Ventilation

- Windows were opened most frequently in June, July and August.
- Bedroom windows were opened more frequently during the summer, and kitchen windows more often during the colder months.
- Trickle ventilators on windows were often obstructed and/or difficult to reach to adjust.
- Window design requires careful consideration of security, fine-tuning and privacy to ensure they will be used by occupants to ventilate dwellings appropriately.
- Issues were found with kitchen and bathroom extract fans.
- Mechanical ventilation systems of all types were poorly commissioned and usually poorly maintained.
- Design and installation of MVHR units and ductwork in the Passive Houses were generally found to be of good quality.
- Various issues were identified with MVHR systems, including system imbalances, incorrect airflow rates, dirty filters, inadequate boost rates, draughts and inconsistent air change rates for identical dwellings.

5 ENERGY CONSUMPTION

The annual energy consumption data for gas, electrical and renewable heat was examined to determine the overall energy consumption compared to a building regulations compliant home and the Code for Sustainable Homes level 4 criteria[3]. Figure 31 includes four additional dwellings located at the Bloom Court site.

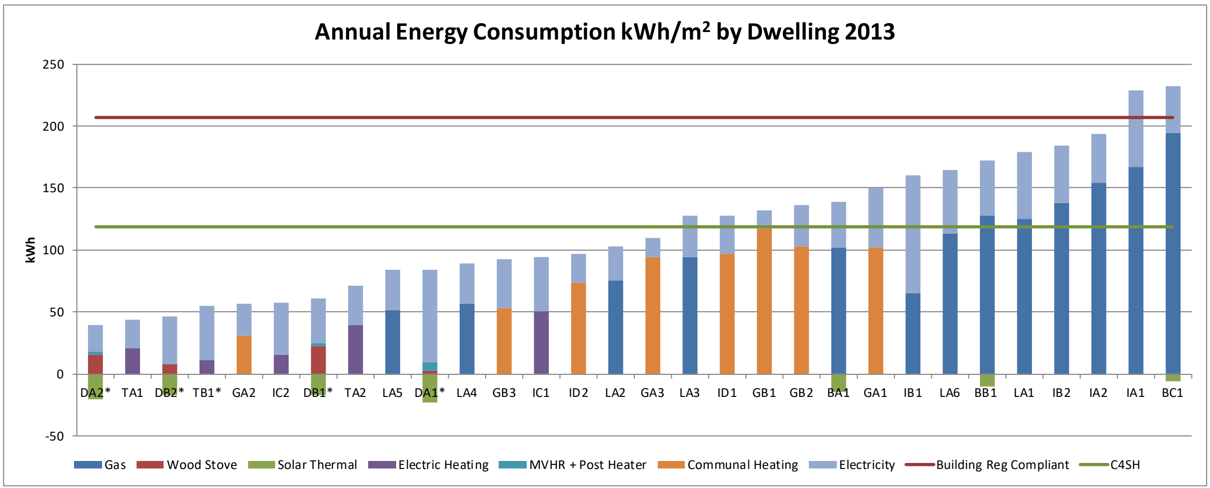

Figure 31: Annual Energy Consumption kWh/m² by dwelling 2013.

The chart identifies that two homes consumed more energy than the maximum permitted by building regulations and just over 50% (16, including all five Passive House dwellings) used less energy than permitted by the Code for Sustainable Homes. The data additionally identify that in all but two homes the greatest proportion of energy consumption was attributed to space heating (denoted by proportion of gas, wood stove, electric heating and communal heating in each column).

Electricity consumption for other uses, e.g. sockets, lighting and cooking, accounts for less than half of annual energy consumption in most dwellings. These are termed 'unregulated' loads, and are not controlled by building regulations as they are, for the most part, dictated by occupant use of household appliances and mobile devices. However, as electricity costs around three times more per unit than gas, those dwellings that appear to have relatively low electricity use may, in fact, spend more on electricity than heating. Occupants fitting inefficient appliances can increase energy consumption, undermining design intent and increasing carbon dioxide emissions. This was found to be a result of occupant perception – for example occupants replacing standard low energy bulbs with halogen bulbs in the belief that the latter were brighter – and affordability, which prevented some occupants from buying LED light fittings or A-rated cookers and fridge-freezers.

Through occupant interviews it was established that those in the social rented sector had to provide their own cooker and fridge freezer, whereas those in shared equity dwellings had A-rated appliances fitted as part of their purchase. Those who had to provide their own appliances tended to select less efficient, and sometimes second-hand, models to minimise outlay. This was exacerbated by the same occupants also having to fit their own floor coverings, further adding to financial pressures.

[3] The Code for Sustainable Homes (C4SH) was one of the comparative benchmarks included in the Innovate UK BPE programme, and was replaced in 2015. C4SH was only applicable for new dwellings in England and Wales.

There were examples of misuse of energy. The majority of homes studied were pairs of homes and there was a significant electrical heating difference in two identical flatted homes. In a two-storey block of flats, IC1 was located on the ground floor and IC2 on the top floor. The heating consumption in IC1 was higher due to the occupant's desire to ensure that the pet dog was kept warm through the day while the single occupant was out at work. One person out of the two occupants in IC2 worked shift patterns, which often meant that at least one occupant was at home during the day. Despite this their space heating consumption was considerably lower than IC1.

In home BC1 the energy consumption was considerably higher than the other two monitored dwellings on this site, BA1 and BB1. BC1 consumption was driven by one occupant who had recently had surgery and spent much of the day in nightwear; the other occupant in BC1 would openly complain to the researchers about the high temperatures. The research revealed that the wall mounted thermostat and radiator valves were all set to their highest position and timers were not utilised. The heating was controlled by the hall thermostat.

The key lesson is that no two homes are the same. Monitoring of housing and discussion with occupants revealed that occupant behaviour and lack of understanding of installed systems can increase energy consumption. Occupants reported having too many other things on their minds for setting up their new homes and were simply unable to digest all of the information. Handover guidance and information is required to be clear and easy to understand, and the handover process should extend beyond a quick instruction on the day house keys are handed over to a dwelling-specific quick start guide, walk through and follow-up visits. A handover procedure is required for occupants who move in during the summer to ensure they know how to use the heating once the cooler weather arrives.

5 Energy Consumption	Case Study

Occupant habits play an important part in energy consumption and the performance of a home. House IC1 in Inverness was excessively using the electric heating. The graph below shows the difference in energy consumption between IC1 and IC2, there is also a significant change in electrical consumption before and after July 2013 when there was change in occupancy. The consumption is now similar to neighbouring IC2 where both occupants prefer to use their wood burning stoves more frequently to reduce running costs of the electric heating. See Figure 32.

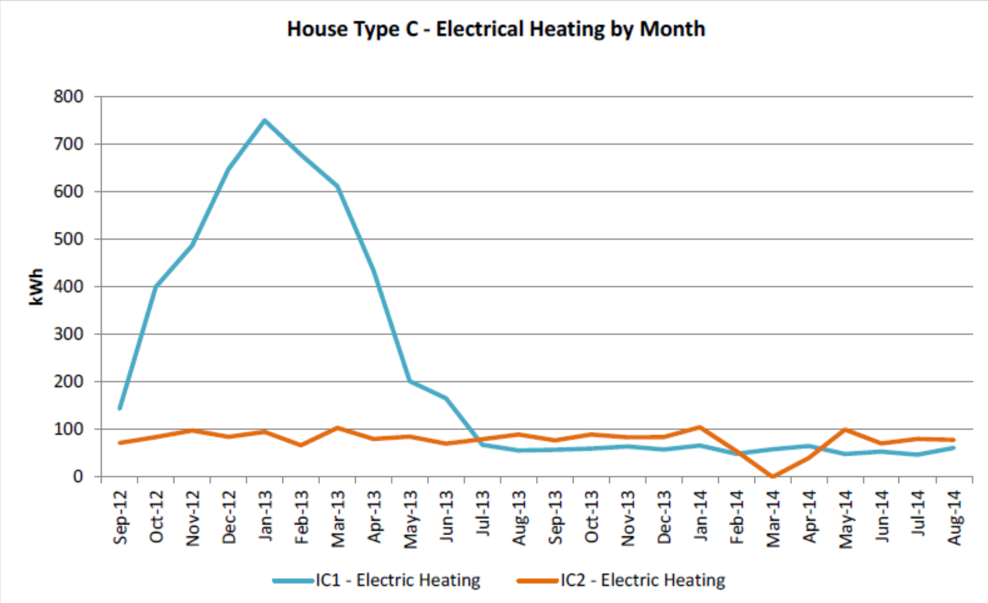

Figure 32: Graph showing the electrical heating profile by month for two years in House Type C in Inverness.

5 Energy Consumption	Lessons Learned

- Although homes may have an identical layout and construction, individual occupant behaviour and a lack of understanding of installed systems can increase energy consumption.
- More than 50% of homes, including the five Passive Houses, out-performed the Code for Sustainable Home benchmark target.
- Space heating consumed the greatest proportion of energy.
- There were examples of misuse of energy through both high temperatures and appliance use.
- Design, layout and specification, e.g. room orientation and position and selection of light fittings, can affect how energy is used in a home, causing occupant behaviour that can increase energy consumption beyond the design intent.
- Energy efficiency of electrical white goods have an impact on a dwelling’s energy consumption.
- Clear handover procedures are vital, as misunderstanding of operation can cause significant financial burden.
- Follow up visits to occupants after moving in day are advised.

6 OCCUPANT SURVEYS

Semi-structured interviews were developed and conducted with occupants in the participating households at the start of each monitoring project. Where a known change of tenancy had occurred during the monitoring period these interviews were repeated with the new tenants. The interviews provided an insight into how people were using their homes, and their usual occupancy patterns and daily routines. The survey also provided an overview of ease of use of the heating and ventilation systems and polled their comfort levels as well as an indication of the monthly expenditure in relation to energy consumption.

Over two separate weeks, one in summer and one in winter, each participating household completed detailed diaries of occupancy and activities that took place in the home. A further survey was undertaken to record each household's electrical items, the corresponding energy rating and frequency and typical pattern of use.

At the monitoring mid-point a further survey known as Building Use Surveys (BUS) was undertaken to benchmark the new developments against other new developments around the United Kingdom that were also participating in the Innovate UK study. The BUS included participation from as many other willing households on each of the new developments as possible, which were not being monitored. The wider responses gave an insight to satisfaction levels with each new development and also investigated how the respondents rated the development location, house design, layout and storage provision. The survey specifically probed to determine what helped or hindered living experiences and how lifestyles may have altered since moving to the new developments.

The combination of these surveys was fundamental to the monitoring process as they added context to the collected data files, and helped to establish the 'how' and 'why' that the researchers so often asked when reviewing the raw data files.

Much of the survey information revealed helped to add context that would not have otherwise been identified by examining the data in isolation. An example, which may become more commonplace, is in the Garscube development in Glasgow. A district heating system provides space heating and hot water in each of the mainstream blocks. Two key issues were identified with this arrangement in this development. In one case the occupants were unable to take advantage of setting up dual-fuel direct debits with their electrical energy supplier as the gas consumption was too low (only from a gas hob, where installed). As a result, on receipt of quarterly bills for gas consumption, the occupants found that the gas supply standing charges were far greater than the charges for the actual gas consumption. Those who had purchased gas hobs had indicated their intention to replace these with electric ones as soon as they could afford to do so. In the second case there was added complexity with the purchase of district heat. In support of the local shop, the pre-payment for district heating was made through a card that could only be used in the one local shop, which only accepted cash payments and there were no cash machines (ATMs) in the local area.

Occupants of other monitored homes where thermal energy was provided by district heating also felt at a disadvantage. They reported the inability to shop around for lower tariffs and felt tied to a system that they perceived not to be transparent. This was particularly the case for a block of six flats located at Scotland's Housing Expo where the newly formed Energy Supply Company (ESCo) was unfamiliar with operating and maintaining a biomass district heating scheme, and estimating the charging structure for consumed energy was problematic. Energy meters were located within the heat interface units inside each of the properties. These were read once a year and heating fuel charged one year in advance. There were additional problems where the biomass boiler had failed to operate for a sustained period and heat was supplied by a backup centralised gas-fired boiler. The occupants believed the unit price of gas to be cheaper than biomass wood pellets and questioned the unit rate charged. During interview some of the occupants expressed their dissatisfaction and indicated their intention to determine whether they would be able to install individual gas boilers in their homes in order to bypass the ESCo and be able to seek more affordable pricing structures.

It was through the surveys that one parent residing in a three-bedroom house in Dormont Park indicated that she slept in a cupboard under the stairs in the living room, and that two parents in another three-bedroom property on the same development also slept on the living room sofa bed. In both instances this was to ensure that all of their children had their own bedrooms instead of having to share. Both of the sets of parents later moved to sleep in bedrooms, when one child in each household had moved away from home. The spikes in environmental data were affected by this occupancy pattern, which would have been difficult to ascertain from reviewing the raw data in isolation.

Where possible the same researchers visited the same homes. This developed trust and allowed for good dialogue to develop between the researchers and occupiers, whereby valuable information would be given in casual conversation. During an exit interview some of the occupants had indicated that they would miss the 'company' of the researchers now that the monitoring was completed. This was particularly the case for those living alone as well as elderly participants.

6 Occupant Surveys **Case Study**

Occupant surveys helped to identify other issues that may have been missed in other methods of analysis. In the Garscube sheltered flats the building use surveys identified accessibility issues. Even though wide doors were provided, the internal hallways were too tight for electric wheelchair users to turn and there were also issues for a partially sighted resident in the mainstream flats where bathroom doors opened outwards to the hall. Some occupants complained that the location of the flats at the brow of a hill, with no nearby bus stops, made it difficult to reach local amenities, resulting in a sense of isolation. Comments received include:

> *"Sharp corners for wheelchair. Can't reach bedroom window from wheelchair so need to get home help to open and close windows. Kitchen worktop too high and kitchen wall cupboards too high so unused"*
>
> *"I am confined to a wheelchair. Front door is a fire door and too heavy for me to open. I have added a special electric door opener that works remotely"* [and the lone occupant shouts from her living room for the potentially unknown person at the door to enter the home – potentially introducing security concerns].
>
> *"My husband is partially sighted and his needs are not properly catered for. There is no light in the entrance hall* [outside the front door] *so my husband finds it hard to put key in front door lock. No natural light in the hall, which makes it difficult for him to walk from room to room. He has often walked into the bathroom door* [that opens outwards into the hall]*".*
>
> *"I have changed my eating habits since moving here, as it is too hot in the kitchen* [which has no windows and inadequate ventilation] *to want to cook. I now eat microwave meals, which I had never done previously."*

Some occupants also mentioned that they were unable to easily use the large drying green due to the steps between the building and green (which made it difficult to carry a laundry basket down) and the height of the washing lines, which required a lot of stretching. As a result many occupants dried their clothes indoors or used the communal tumble driers, which have implications on health, energy consumption and carbon dioxide emissions.

These findings are important as part of the development is aimed at catering for older occupants who live independently, but who may have individual needs, e.g. for accessibility.

6 Occupant Surveys **Lessons Learned**

- Clear insight into daily routines of occupants can be used to better understand data.
- Information was provided on occupant routines and pattern of use for heating and other installed systems.
- Insight provided as to satisfaction levels of the new development projects and their surroundings.
- A better understanding was given as to the impact on occupant lifestyles since moving into the new developments.
- It is important to communicate systems clearly with occupants and building factors/managers.
- It was important to have consistency in the research team attending the homes to develop a rapport with occupants and gain trust.

7 INSTALLATION AND COMMISSIONING CHECKS

A wide range of systems was installed in the houses monitored, all of which went through a process of design, installation and commissioning. This included heating systems, ventilation systems and solar thermal systems. Many of these were considered overly complex as some technology was new to designers, contractors and occupants. This often led to issues due to a lack of understanding of the systems, installation and operation.

A general inspection of the installed systems was made by the BPE researchers, which identified a series of issues that required attention. A number of predominant issues emerged across all homes, including: underperformance and imbalance of mechanical ventilation systems; unclear instructions on how to set heating programmers, thermostats and immersion heaters; and underperformance and inadequate instructions on how to operate the solar thermal hot water systems (STHWS). As well as affecting the energy efficiency of the dwellings, these also had potential to impact occupant comfort and health.

Wall thermostats located in the hall were often used to control the space heating rather than the use of individual thermostatic radiator valves (TRVs) on radiators. The research team found that TRVs were generally set to their highest point. These controls communicate with the boiler for operation and this lack of understanding of the basic functioning of controls often contributed to high indoor temperatures and overheating. Problems with non-use or ineffective extract fans and passive stack vents frequently resulted in mould growth in bathrooms. Many residents also opened kitchen windows where possible instead of using extract fans, finding this ventilation method more effective and often less noisy.

Issues identified with STHWS tended to relate to the poor communication of responsibilities, installation and commissioning of the systems. The monitoring identified that a number of different trades are required to work together in order to successfully install a fully functional STHWS system. The problems identified were mostly related to poor controls integration, however there was one instance where packaging debris – polystyrene beads – was found inside copper pipework, affecting system operation and output. Despite the heating engineer and solar thermal engineer having been called out separately on numerous occasions, this defect was only discovered and fixed more than a year after occupation when both attended at the same time and worked together.

At Dormont it was found that the STHWS pipework had not been insulated, leading to overheating in one the dwellings which resulted in the occupant disabling the STHWS completely. The lack of insulation was only identified by the BPE researchers, at which point the issue was rectified and the STHWS enabled.

Access and maintenance of system equipment was not adequately considered in some properties. In Murray Place, Barrhead, for example, where the dwellings were designed for the elderly, hot water tanks and controls were installed in loft spaces, preventing them from being easily seen and adjusted. This resulted in an extended period of time to identify and report faults. Once the fault was identified, the draining of the system caused considerable water damage to the living room ceiling and other internal finishes. The prolonged period between resolving the STHWS operation issues and repair to the ceiling caused considerable concern for the occupants.

An inadequate handover process with occupants was an issue identified in a number of homes. Clearer information and support to users on how to use heating and ventilation system controls, and how to use window restrictors, would be helpful to occupants. As part of the BPE programme, MEARU developed user guides specific to each home. In discussion with the occupants, many disclosed they would have preferred these quick start guides when they moved in rather than only the technical manuals. These user guides have now been adopted into Building (Scotland) Regulations.

Scottish Building Regulations lack any statutory testing and commissioning procedures. The effects of this were highlighted when BPE testing for mechanical and passive stack ventilation systems identified that most “off the shelf” mechanical fans were underperforming.

The research identified that the design and environmental objectives of a project were not effectively communicated through the project chain, i.e. from designers to contractors to building owners and occupants. Some of the systems that were installed had controls that were difficult to understand. In addition, some occupants were unfamiliar with controls that many found ‘normal’, such as 7-day programmers. This suggested that clear operating instructions were required for all system controls, no matter how complex.

Handover information to building users needs to be clearer with user guides produced specific to each home with clear visual information that relate to the equipment that is actually installed. It is important to engage with tenants to obtain feedback on their homes and how they use them. This enables better engagement with tenants to change occupant behaviour. It is important to ensure that the housing teams maintain a good relationship with tenants during ‘teething’ problems to enable better fine-tuning of the building. Tenant-facing staff should also be trained to know more about the systems that are installed in the homes to allow better understanding should a tenant make contact to report a problem with a system.

7 Installation and commissioning checks — Case Study

The Barrhead project has a solar water heating system that works in parallel with a gas boiler, both of which feed into a hot water tank. Difficulties arose on site as a result of poor communication between the plumbing and heating sub-contractor and the sub-contracted installer of the solar thermal hot water installation. There was a lack of understanding as to the responsibility for installation of specific components of the system as well as controls integration for successful operation. This resulted in problems with annual maintenance from Scottish Gas and disputes between installers over responsibility.

In house BC1, the solar water system did not function correctly due to poor controls installation to the hot water cylinder. This resulted in additional cost for the occupant due to the gas boiler providing all hot water during this time. The hot water cylinder did not have an accessible drain down valve and the placement in the loft space also meant that there was no space to place a container under the unit. When the unit required to be drained down for repair, water leaked through the ceiling to the living room and caused water damage. The staining on the living room ceiling resulted in significant distress for the occupants. See Figure 33.

Figure 33: Left: Water damage due to a leak from the solar thermal system. Right: Cylinder located on the floor of the loft.

7 Installation and commissioning checks — Lessons Learned

- Lack of communication between design and installation can have far reaching effects.
- Inadequate system installation and commissioning can lead to inefficient operation and subsequent impacts on energy efficiency and increased operational cost.
- Robust design and specification documentation is required for electrical and plumbing contractors.
- Engagement of sub-contractors with demonstrable experience in Passive House, low energy and renewable installations is needed for most domestic projects.
- Clear and accurate “as-built” drawings and specifications must be provided as part of the contract.
- Standard ‘O&M’ (operation and maintenance) manuals are too technical for tenants; many do not read or understand these.
- It is necessary to have a clear handover process with demonstrations and explanations of all active systems and controls. This is essential for handover to housing associations and future occupants.
- Building owners should ensure that staff handling complaints from occupants are familiar with the installed systems so that issues can be clearly identified and resolved quickly.

8 ACKNOWLEDGEMENTS

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