PassivHaus Bungalows

Phase 2 study
In-use and post-occupancy

This document contains a Building Performance Evaluation report from the £8 million Building Performance Evaluation research programme funded by the Department of Business Innovation and Skills between 2010 and 2015. The report was originally published by InnovateUK and made available for public use via the building data exchange website hosted by InnovateUK until 2019. This website is now hosting the BPE reports as a research archive. As such, no support or further information on the reports are available from the host. However, further information may be available from the original InnovateUK project evaluator using the link below[1].

InnovateUK project number	450070 Related study: 450014 (Phase 1)
Project author	Leeds Beckett University for the Gentoo Group
Report date	2015
[1]InnovateUK Evaluator	N/A

No of dwellings	**Location**	**Type**	**Constructed**
Six	Houghton-le-Spring	Terraced bungalows	2011
Area	**Construction form**	**Space heating target**	**Certification level**
66 m^2	Pre-fabricated timber-frame	N/A	Level 4 Code for Sustainable Homes

Background to evaluation

The BPE report outlines the findings obtained from an in-use performance and post-occupancy evaluation study undertaken on six 66 m^2 2-bedroomed terraced bungalows. All have solar thermal systems installed on their South-facing roof slopes. Dwelling 7 was chosen to be intensively monitored. As it is of the same size, shape and of very similar form to Dwelling 1 studied in Study 450014, the post-construction test results relating to that dwelling were considered likely comparable.

Design energy assessment	**In-use energy assessment**	**Sub-system breakdown**
Yes	Yes	Yes (one dwelling)

Intensive in-use monitoring of one dwelling covered electricity consumption disaggregated by end-use, namely MVHR, lighting, and appliances including cooking devices. The total amount of heat supplied for space heating, heat supplied as top-up for the hot water cylinder, and heat supplied by the roof-mounted solar collector to the hot water cylinder were measured. Cold water supplied to the hot water cylinder (equivalent to total domestic hot water consumption) was also monitored. The main finding was the identification of an overheating risk in the dwelling, exacerbated by the dwelling's inability to purge unwanted heat without increased night-time ventilation. The pressurisation tests revealed that the air permeability of the dwelling had degraded since practical completion.

Occupant survey type	**Survey sample**	**Structured interview**
BUS domestic	4 of 7 (57 % response rate)	Yes

General feedback was positive. Residents found the air in the dwellings to be stuffy, dry and still in both summer and winter, with winter regarded as the poorer season for air quality. The air was monitored as being dry at times, however, particularly during winter when residents open their windows less often due to the cold, thus reducing the introduction of outside air. Both natural and artificial lighting were deemed to be 'too much'; although the research team believed that residents regarded this response and others like it as positives. **Students: see explanatory note on this topic on Page 20.**

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1 Introduction and overview

1.1 Introduction

This report outlines the findings obtained from an in-use performance and post occupancy evaluation study (project no. 450070) that was undertaken on six $66m^2$ 2 bedroomed terraced bungalows (dwellings 2 to 7) as part of the Technology Strategy Board's Building Performance Evaluation Competition. All six bungalows were completed in November 2011 at Houghton Le Spring, Sunderland.

The six bungalows, that are the subject of this study, form part of a development of 28 bungalows in total, all of which were designed to be occupied by older residents. 25 of the bungalows within the development are terraced units, which have been arranged into four separate terraces (see Figure 1), resulting in 8 end-terraced and 17 mid-terraced bungalows. The remaining three bungalows on the development are detached units. The dwellings that are the subject of the in-use monitoring, dwellings 2 to 7, form part of a terrace of seven dwellings, and are highlighted in red in Figure 1. Originally, the intention was to monitor all seven dwellings in this terrace. However, dwelling 1 (one of the end-terrace dwellings), declined to take part in the study due to perceived disruption and an unwillingness to share energy data, despite reassurances that data would be confidential and secure, with minimal disturbance during the monitoring period. It is the right of the occupant to withdraw, and as such this withdrawal was difficult to avoid. Dwellings 1 and 2 were the subject of an earlier Technology Strategy Board Building Performance Evaluation Competition post-construction and initial occupation study (project no. 450014). Details of this study can be found within Johnston & Fletcher (2013).

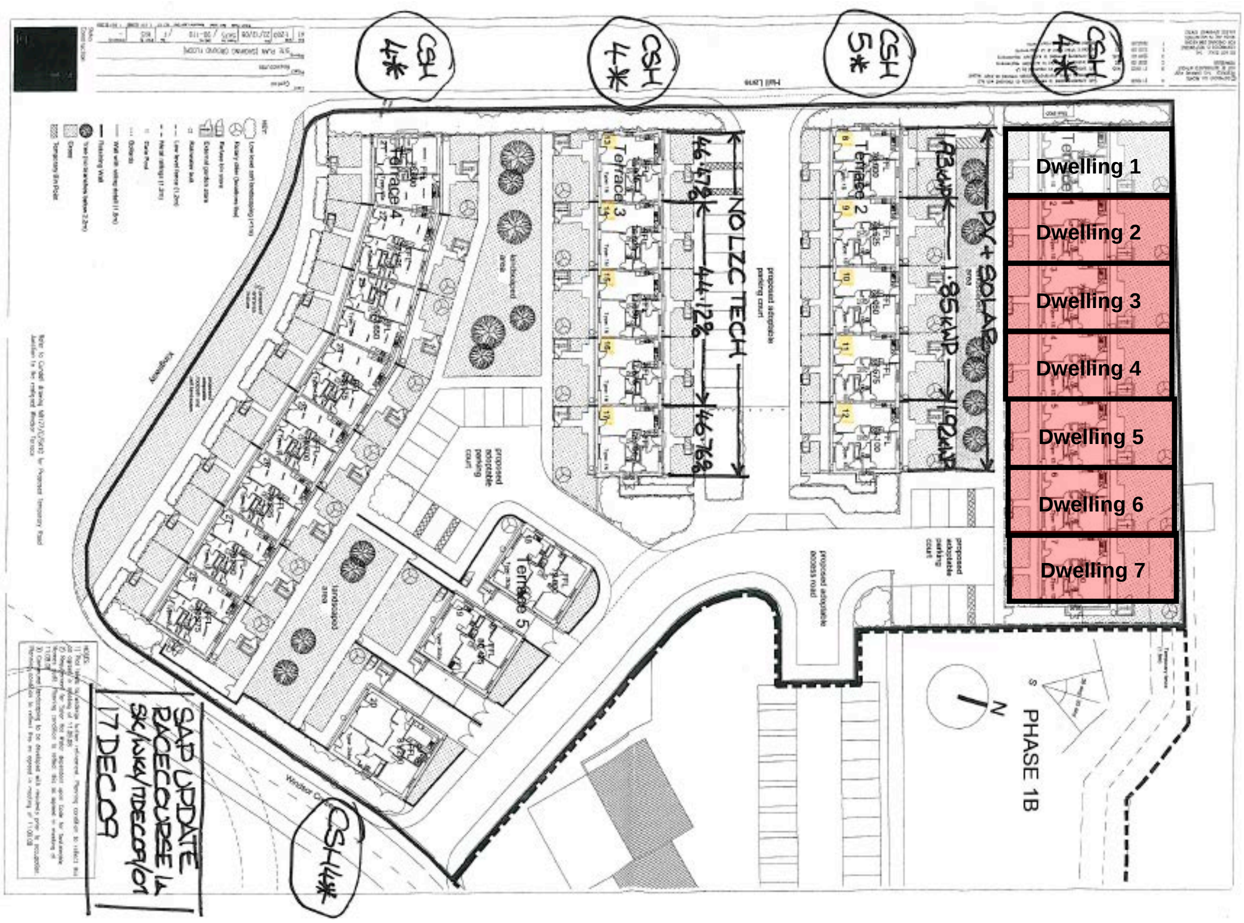

Figure 1 Layout of the development.

The development is located within a large council estate in the North East of England in an area identified for renewal as part of a Citywide Renewal Plan, which aims to replace obsolete and unsustainable housing stock with around 4,000 new high quality homes. The development has been constructed on 0.98 Hectares of previously cleared land (originally housing). This land comprised a network of paths that run across a number of large sloping green public spaces (see Figure 2). The development is approximately ten to fifteen minutes' walk away from the neighbourhood retail centre and there are two bus stops adjacent to the development.

Figure 2 The site prior to development.

Two prominent Passivhaus Designers were appointed, one as the project architect and one as mechanical services engineer for the development. The dwellings were constructed by the new build housing development arm of the client, a Social Housing provider.

All 25 terraced bungalows on the development have been designed to Passivhaus standards and either Code for Sustainable Homes Level 4 or 5. The three detached units have been designed specifically for mobility impaired tenants, and although they have been built to the same fabric and services standards as the terraced dwellings, due to their more challenging dwelling form, they have not been designed to be Passivhaus certified. Specifically, the increased volume to surface area ratio for bungalows makes PassivHaus certification particularly difficult to reach. The project is believed to be the first scheme in the UK of this scale with the intention to achieve formal PassivHaus certification.

In order to score points under the Code for Sustainable Homes, all of the bungalows, including those designed specifically for mobility impaired tenants, were equipped with cycle storage provision. Although all of the dwellings have been designed to achieve Level 4 of the Code for Sustainable Homes without the requirement for any renewable technologies, 18 of the dwellings have solar thermal systems installed on their South-facing roof slope. In addition, 5 of the dwellings with solar thermal systems also have PV systems installed on their South-facing roof slope to enable them to achieve Level 5 of the Code for Sustainable Homes. All six of the dwellings included in this study have been designed to Level 4 of the Code for Sustainable Homes and have solar thermal systems installed on their South-facing roof slope.

1.2 Scope of the Project

The scope of the project is limited to the in-use performance and post occupancy evaluation stage and consists of a combination of in-use energy and environmental monitoring alongside occupancy studies via the Building User Survey questionnaire. Two separate levels of in-use monitoring have been undertaken on the dwellings: intensive and extensive. Details of these different levels of monitoring are as follows:

- **Extensive in-use monitoring –** This has involved monitoring the dwellings overall heat, electric and water consumption only.
- **Intensive in-use monitoring –** As extensive in-use monitoring with the addition of the following parameters:
    - The total amount of electricity consumed by each of the main electrical circuits in the dwellings. This was used to disaggregate electrical energy use down into the main uses for electricity in the dwelling, namely: MVHR system, lights, appliances and cooking.
    - The total amount of heat supplied for space heating.
    - The total amount of heat supplied as top-up for the hot water cylinder.
    - The total amount of heat supplied by the roof-mounted solar collector to the hot water cylinder.
    - The amount of cold water supplied to the hot water cylinder (equivalent to total domestic hot water consumption).

As dwelling 2 had been the subject on an earlier post construction and initial occupation study, it was intended that dwelling 2 would be chosen to be monitored intensively. However, it was not possible to do so. Therefore, dwelling 7 was chosen to be intensively monitored. Although this dwelling did not participate in the earlier post construction and initial occupation study, it is of the same size, shape and of very similar form to dwelling 1, so the post construction test results relating to dwelling 1 are likely to be equally applicable to this dwelling. The remaining five dwellings, dwellings 2 to 6, were all monitored extensively.

A number of physical tests were also undertaken on a number of the dwellings as a check on fabric and system performance. These included: air-pressurisation tests, thermographic surveys and MVHR duct flow measurements. These results obtained from these tests have been compared to those previously obtained as part of the post construction and initial occupation study.

1.3 Key Findings

The key findings from the project are that the housing construction and occupancy performance has largely fulfilled the design intentions. The fabric tests undertaken as part of this project identified no significant areas of unexpected heat loss. However, the pressurisation tests have revealed that the air permeability of the dwelling has degraded since practical completion, particularly over the last six months, and the leakage identification suggests that this increase in air permeability appears to be attributable to wear-and-tear on the door seals. An increase in the air permeability of a dwelling over time is not unusual, and commonly occurs within new build dwellings.

The stable temperature data for dwelling 7 suggests that the PassivHaus design, with high thermal insulation and airtightness, is working very well and effectively maintaining a constant internal thermal environment. In addition, the impact of solar gains on measured internal temperature highlights the effect of passive design to maximise solar effects, another intended consequence of the building design. With this in mind, the main finding from the in-use monitoring is the identification of an apparent overheating risk in the dwelling. Monitoring has shown significant periods of overheating during summer months exacerbated by the dwellings inability to 'purge' unwanted heat without increased night-time ventilation. As design stage, the intention was to leave windows open overnight to expel warm air and allow the dwelling to cool. The reasons for the lack of overnight cooling may stem from earlier instruction given to occupants by the home handover team, who were advised to leave windows closed to increase MVHR efficiency. Although this advice was revised and residents were advised to open their windows during summer, it is possible this has not been done. In addition, the electricity data from the MVHR system appears to show the residents not utilising the boost facility of the MVHR system. The boost function is operated by a switch in the hallway and the residents were aware of this as it is illustrated in the handover documentation, although it is unknown whether the handover document was thorough engaged with. The findings illustrate the risk of overheating in such thermally efficient buildings if they are not used in such a way as to reduce the risks.

User behaviour was seen to be the key driver behind fluctuations in electrical energy use, in addition to socket and cooker loads representing over 87% of total electrical consumption.

Analysis of heating use in all properties displayed a close grouping when compared with degree days (with the exception of dwelling 6 which operated a different heating pattern). This suggests a similar level of performance from all properties. An interesting outcome from this analysis was the poorest performance coming from the end terrace dwelling 1, with further investigation needed to determine the specific reason for this.

1.4 References

JOHNSTON, D. and FLETCHER, M. (2013) TSB BPE Project 450014 – Gentoo Passivhaus Development: TSB BPE Phase 1 Final Report. A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. July 2013. Leeds, UK, Centre for the Built Environment (CeBE), Leeds Metropolitan University.

2 About the building: design and construction audit, drawings and SAP calculation review

2.1 Introduction

All six dwellings that are the subject of the in-use energy and environmental monitoring have been designed to the Passivhaus standard and Code for Sustainable Homes Level 4. They comprise a South-facing open-plan living/kitchen area which runs the full depth of the dwelling, a North-facing master bedroom with an internal storage cupboard, a South-facing smaller bedroom with an internal storage cupboard (this cupboard also houses the main consumer unit for the dwelling), a bathroom and a mezzanine plant area. The mezzanine plant area is situated above the bathroom, corridor and both bedrooms and is only accessible via a loft hatch and ladder, as the client stated a desire that this space did not function as a loft space. Plans and elevations of the dwellings are illustrated in Figure 3 and Figure 4.

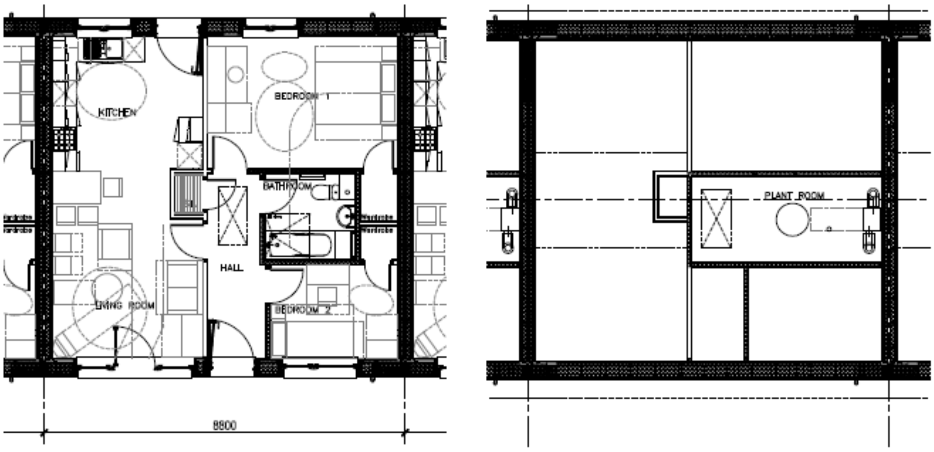

Figure 3 Ground floor and mezzanine floor plan of dwellings 2 to 6. Dwelling 7's floor plan is identical, apart from the fact that it is an end-terrace.

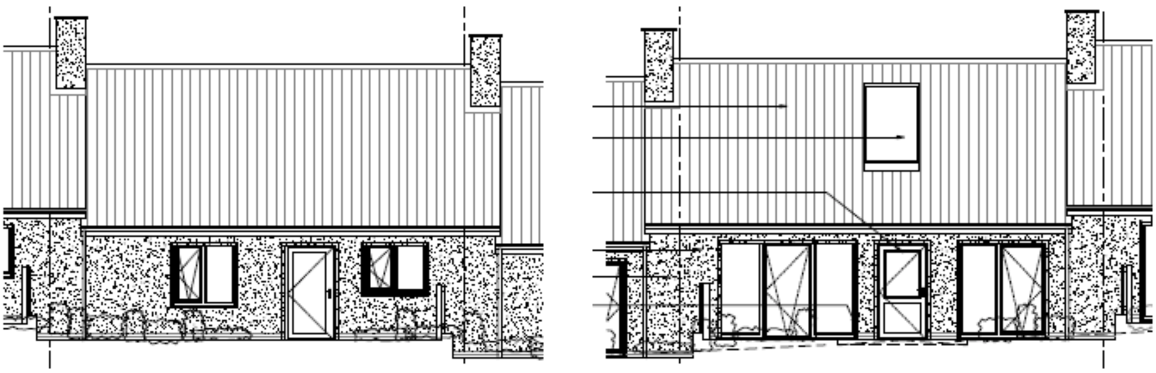

Figure 4 North and South elevation of dwellings 2 to 6. Dwelling 7 is very similar, apart from the fact that it is an end-terrace.

The external walls of the dwellings were constructed using pre-fabricated timber-frame cassettes filled with 300mm insulation and clad externally with 15mm bitroc and either brick or render. Internally, the external walls have a 47mm insulated service void which is lined with 25mm plasterboard. The ground floor comprises a reinforced concrete slab-on-ground, with 300mm insulation above the slab and topped with a 50mm screed. The roof is constructed using a 450mm insulated timber-frame cassette. The windows are triple glazed, low-e krypton filled units. A summary of the U-values for the various elements of the building fabric are contained within

Element	Design SAP worksheet	As-built SAP worksheet	As-built effective U-values
Ground floor	0.10 W/m²K	0.08 W/m²K	Range from 0.07 to 0.18 W/m²K Mean 0.10 W/m²K
External walls	0.12 W/m²K	0.10 W/m²K	Range from 0.08 to 0.23 W/m²K Mean 0.12 W/m²K
Roof	0.09 W/m²K	0.08 W/m²K	Range from 0.09 to 0.20 W/m²K Mean 0.13 W/m²K
Windows	Side 0.90 W/m²K Front (living area and bedroom 2) 0.90 W/m²K Rear (kitchen and master bedroom) 0.90 W/m²K	Side 0.80 W/m²K Front (living area) 0.70 W/m2K Front (bedroom 2) 0.80 W/m²K Rear (kitchen and master bedroom) 0.80 W/m²K Rear door 0.78 W/m²K	**Centre Pane** Range from 0.56 to 0.78 W/m²K Mean 0.68 W/m²K **Reveal** Range from 0.17 to 0.36 W/m²K Mean 0.23 W/m²K
Doors	0.90 W/m²K	0.86 W/m²K	-

Table 1.These figures have been obtained from the Stage D design SAP worksheet for dwelling 1, with measured values taken from the Phase 1 research study. In addition, the target design air leakage rate for the dwelling was ≤0.6 ac/h @ 50Pa and the dwelling was equipped with mechanical ventilation with heat recovery.

Element	Design SAP worksheet	As-built SAP worksheet	As-built effective U-values
Ground floor	0.10 W/m²K	0.08 W/m²K	Range from 0.07 to 0.18 W/m²K Mean 0.10 W/m²K
External walls	0.12 W/m²K	0.10 W/m²K	Range from 0.08 to 0.23 W/m²K Mean 0.12 W/m²K
Roof	0.09 W/m²K	0.08 W/m²K	Range from 0.09 to 0.20 W/m²K Mean 0.13 W/m²K

Windows	Side 0.90 W/m^{2}K Front (living area and bedroom 2) 0.90 W/m^{2}K Rear (kitchen and master bedroom) 0.90 W/m^{2}K	Side 0.80 W/m^{2}K Front (living area) 0.70 W/m2K Front (bedroom 2) 0.80 W/m^{2}K Rear (kitchen and master bedroom) 0.80 W/m^{2}K Rear door 0.78 W/m^{2}K	**Centre Pane** Range from 0.56 to 0.78 W/m^{2}K Mean 0.68 W/m^{2}K **Reveal** Range from 0.17 to 0.36 W/m^{2}K Mean 0.23 W/m^{2}K
Doors	0.90 W/m^{2}K	0.86 W/m^{2}K	-

Table 1 U-values of the main elements of dwelling 1.

2.2 Design and construction review

No design and construction review has been undertaken as part of this in-use monitoring project, as it has previously been reported in an earlier Technology Strategy Board Building Performance Evaluation Competition post-construction and initial occupation study (project no. 450014).

For completeness, the main conclusions and recommendations relating to the design and construction review that were reported in the earlier post construction study are reiterated below.

The design review highlighted that a number of changes were made to the design during the construction. These included changes to the timber-frame cassettes and refinement of some of the airtightness details. The design and construction team also experienced a number of significant challenges during the construction process, the majority of which were completely out of their control. For instance, two timber-frame manufacturers ceased trading during the project, as a result of the economic climate, and unanticipated utilities were discovered below the site. Both of these challenges resulted in significant delays to the construction programme. In addition, difficulties were also experienced sourcing a number of the building products, as they were not readily available in the UK, or obtaining sufficient information from the suppliers, as was the case with the external doors. Despite these changes and challenges, the dwellings were constructed pretty much as intended. In fact, the as-built U-values for all of the elements of the building fabric were lower than those that were used to inform the original design. Given this, the design and construction team should be commended.

The construction observations revealed that overall, the dwellings were being built to a very high standard with considerable attention given to the detail, such as airtightness. However, the observations did highlight a very small number of issues that, if not adequately addressed, did have the potential to have an adverse effect on the measured performance of the dwellings.

3 Fabric testing (methodology approach)

3.1 Introduction

As this project was the subject of an earlier Technology Strategy Board Building Performance Evaluation Competition post-construction and initial occupation study (project no. 450014), only a small number of building fabric tests and surveys have been undertaken on the monitored dwellings as part of the in-use energy and environmental monitoring study. The fabric testing that was undertaken comprised the following:

- Pressurisation testing and leakage detection.
- Thermographic survey.

The results obtained from the above tests have been compared with those results obtained from the earlier post construction study, where applicable.

No coheating test or heat flux measurements have been undertaken as part of this in-use monitoring project, as these tests have previously been reported in the earlier post construction and initial occupation project.

3.2 Pressurisation testing and leakage detection

A number of pressurisation tests have been undertaken on the end-terraced bungalow that is the subject of the intensive in-use energy and environmental monitoring (dwelling 7). The first of these was undertaken on the 9th April 2013, prior to the commencement of the in-use energy and environmental monitoring, and some 15 months after practical completion. The second test was undertaken on the 23rd February 2014 part way through the in-use energy and environmental monitoring and some 25 months after practical completion (see Figure 5). The third and final test was undertaken on the 22nd July 2014 at the end of the energy and environmental monitoring.

All of the pressurisation tests were undertaken using an Energy Conservatory Model 3 Blower Door and a DG700 pressure/flow gauge. The tests were undertaken in accordance with ATTMA Technical Standard L1 (ATTMA, 2010), but using an envelope area and volume based upon the total fabric heat loss area of the dwelling (247.6m^3 and 245.6m^2). These buildings are of an unusual form, as the loft space is used as a plant room, but as this is within the heated space of the dwelling it was included in envelope area. A summary of the results are contained within **Error! Reference source not found.** and **Error! Reference source not found.**.

Figure 5 Pressurisation test being undertaken on the extensively monitored dwelling.

Date	Depressuration only $m^3.h^{-1}.m^{-2}$ @ 50Pa	Pressurisation only $m^3.h^{-1}.m^{-2}$ @ 50Pa	Mean Air Permeability $m^3.h^{-1}.m^{-2}$ @ 50Pa	Comment
09/04/13	0.99	1.02	1.01	Pre in-use monitoring
10/02/14	1.01	1.15	1.08	In-use monitoring
22/07/14	1.45	1.28	1.36	Post in-use monitoring

Table 2 Air permeability results for extensively monitored dwelling.

Date	Depressurisation only h^{-1} @ 50Pa	Pressurisation only h^{-1} @ 50Pa	Mean Air Leakage h^{-1} @ 50Pa	Comment
09/04/13	0.98	1.01	1.00	Pre in-use monitoring
10/02/14	0.98	1.12	1.05	In-use monitoring
22/07/14	1.41	1.24	1.32	Post in-use monitoring

Table 3 Air leakage results for extensively monitored dwelling.

The results contained within Table 2 and Table 3 illustrate that the extensively monitored dwelling is very airtight by UK standards. However, despite this, the latest mean air permeability figure obtained for the extensively monitored dwelling (1.36 $m^3.h^{-1}.m^{-2}$ @ 50Pa) is significantly higher than the value of 0.6 $m^3.h^{-1}.m^{-2}$ @ 50Pa contained within the respective design SAP worksheet for this dwelling. A comparison of the three separate air permeability results that were obtained over the in-use monitoring period has also been undertaken. This suggests that there has been deterioration in the airtightness of the extensively monitored dwelling over the in-use monitoring period, with the greatest deterioration in airtightness occurring over the last 6 months or so of the in-use monitoring period. A measured increase in the air permeability of a dwelling over time is not unusual, and commonly occurs within new build dwellings due to shrinkage and settlement of the building fabric, wear-and-tear of window and door seals and changes to the building fabric made by the occupants.

During each of the pressurisation tests, leakage identification was also undertaken during pressurisation using either a handheld smoke generator or thermal imaging. An advantage of using thermal imaging for leakage detection is that it indicates not only direct infiltration to the habitable spaces, but also where indirect air leakage is occurring. It should be noted that very few areas of air leakage were identified. Those areas of air leakage that were identified within the dwelling were as follows:

- At the threshold corners of the external rear door (see Figure 6).
- At the top corner of the rear door (see Figure 7).
- At the threshold corner of the front door (see Figure 8).
- At the top of the window in the master bedroom (see Figure 9).
- At the window frame joints in the master bedroom (see Figure 10).

Figure 6 Leakage around the bottom corners of the rear external door.

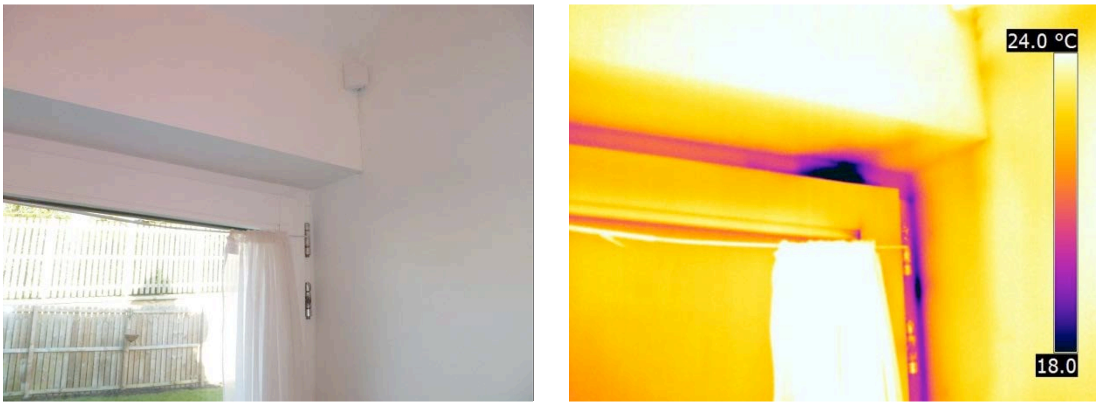

Figure 7 Leakage at the top right had corner of the rear door.

Figure 8 Leakage at the bottom corner of the front door.

Figure 9 Leakage at the top of the window in the master bedroom.

Figure 10 Leakage between the joints in the frame of the window in the master bedroom.

All of the leakage points identified within Figure 6 to Figure 10 are consistent with those that were identified in the earlier post-construction and initial occupation study. Analysis of the leakage points suggests that the increase in air permeability measured over the in-use monitoring period is attributable to wear-and-tear on the front, rear and patio door seals. The results indicate that the performance of these seals has degraded over the last 6 months or so of the in-use monitoring period.

Further details regarding the pressure test results can be found within Appendix 1 and 2.

3.3 Thermographic survey

Two thermographic surveys have been undertaken as part of the in-use energy and environmental monitoring project. One survey was undertaken on the end-terraced bungalow that is the subject of the intensive in-use energy and environmental monitoring (dwelling 7). This survey was undertaken to establish whether there were any unexpected areas of heat loss within this dwelling that had not been previously highlighted in the earlier post construction and initial occupation study. The other survey was undertaken on dwelling 2, which participated in the earlier post construction and initial occupation study. This dwelling was surveying to establish whether any additional areas of heat loss had emerged within this dwelling following completion of the earlier study.

The thermal images recorded during both surveys were captured using a FLiR B620 thermal imaging camera when the dwellings were under depressurisation. Overall, the surveys revealed that both dwellings performed very well, with no significant areas of unexpected heat loss being identified. Excluding those areas that had previously been identified during the leakage identification (see section 3.2), the only areas of unexpected heat loss that were identified within the dwellings were as follows:

- A strip running across the partition wall between the master bedroom and kitchen in both dwellings. In dwelling 2, this strip crosses across the top of the back door and then runs down the North facing external wall to the light switch. It is thought that this may be being caused by the electrical cable that feeds the light switch, which appears not to be installed within a cable duct (see Figure 11).
- A small spot, ~70mm in diameter, on the external wall close to the roof/party wall junction in dwelling 7 (see Figure 12). It is not known what is causing this spot on the external wall using the non-destructive test methods available to the research team alone.
- A small spot on the partition wall between the master bedroom and bathroom in dwelling 2 (see Figure 13). This may be attributable to an uninsulated section of the feed or return pipework to the towel rail which is located on this wall in the bathroom. However, without more extensive investigations, it is difficult to be certain what is causing this hot spot.
- A small hot spot around the communal main from the boiler (the flow) as it penetrates through the partition between the mezzanine plant room and the void above the living/kitchen area in both dwellings (see Figure 14). This may be caused by a break in the pipework insulation at the point where it penetrates through the partition wall.
- In dwelling 2, a visible rectangular section of wall (approximately 1.5m2 in size) on the partition between the mezzanine plant room and the void above the living/kitchen area that is very slightly cooler (~1°C) than the surrounding wall (see Figure 14). It looks as though this may be caused by missing insulation in the studwork partition. As this partition wall is within the dwellings thermal envelope, it does not constitute a heat loss area.
- In dwelling 2, a very slightly cooler area (~1°C cooler) is also visible on the North facing knee wall (see Figure 15). It is not known what is causing this cooler area. It is not known what is causing this spot on the external wall using the non-destructive test methods available to the research team alone.

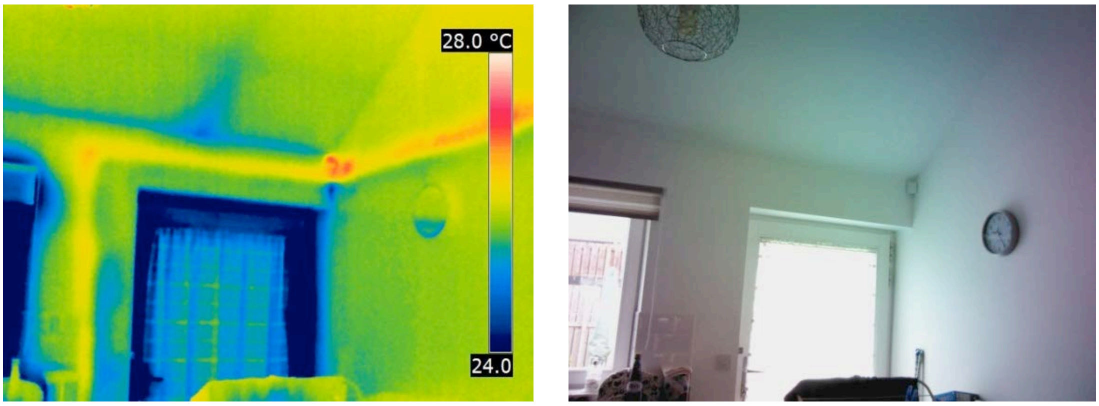

Figure 11 Strip running across the partition wall and above the back door in dwelling 2.

Figure 12 Spot on the external wall of dwelling 7.

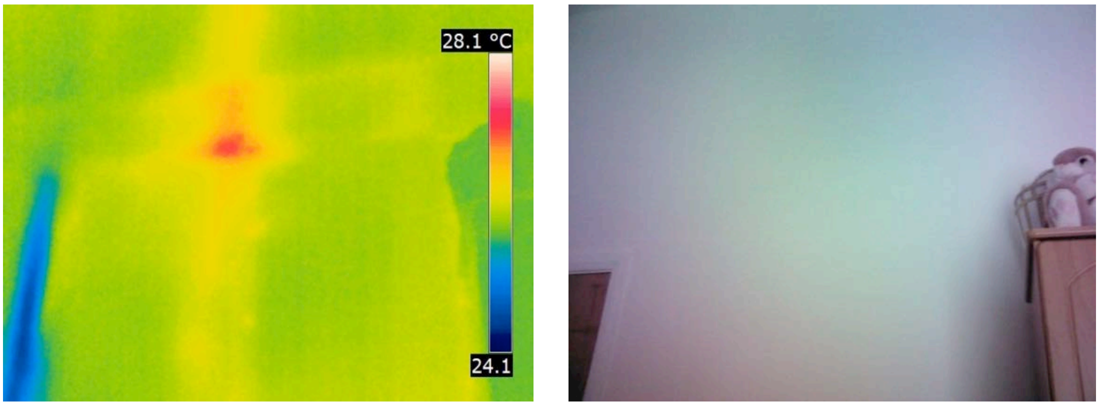

Figure 13 Spot on the partition wall between the bedroom and bathroom in dwelling 2.

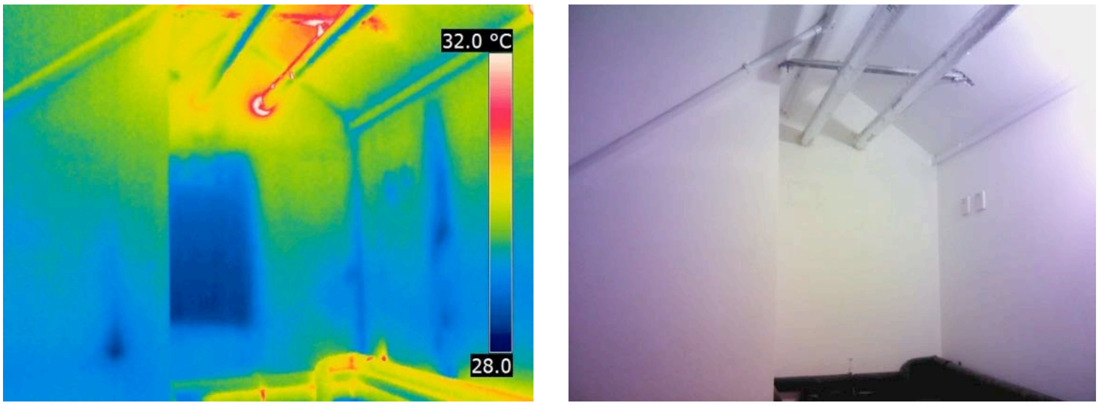

Figure 14 hot spot around the communal main from the boiler and cooler rectangular section observed on the partition wall.

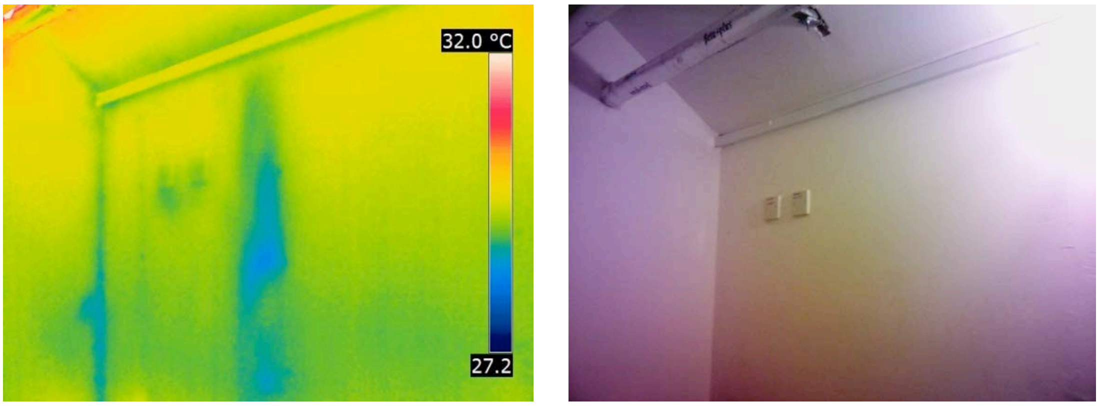

Figure 15 Cooler section observed on the North facing knee wall.

It should be noted that in the majority of the above cases, the temperature differences observed were very small (<1°C), and is unlikely to have any detrimental impact on the fabric performance of the dwellings. In addition, are unlikely to have been picked up if the dwellings were conventional mainstream housing.

None of the heat loss areas highlighted above were identified in the earlier post construction and initial occupation study. The reason for this is likely to be attributable to the fact that a number of the services within the dwellings (both electrical and space heating) were switched off when the earlier thermographic surveys were undertaken. In addition, in those surveys that were undertaken when there was heat input to the dwellings, this heat input had been provided remotely and the dwellings had been completely heat saturated. Therefore, a number of the small temperature effects observed above would not have been noticeable.

Further details relating to the thermographic surveys can be found within Appendix 3 and 4.

3.4 Conclusions and key findings for this section

A number of pressurisation tests and thermographic surveys have been undertaken on the dwellings as part of the in-use energy and environmental monitoring study. The results obtained from the pressurisation tests revealed that the air permeability of the dwellings appears to have deteriorated slightly since they were tested post construction. Whilst this is a relatively large deterioration (almost 35%) in real terms the final value is still very low. This is encouraging and suggests that the airtightness of the dwellings is particularly robust. Leakage detection, using hand-held smoke generators and thermal imaging during depressurisation, revealed very few areas of air leakage. The small areas of air leakage that were identified in the most recent pressurisation tests were consistent with those identified during the earlier post construction and early occupation study.

In terms of the thermal imaging surveys, the surveys identified no significant areas of unexpected heat loss. However, they did identify a small number of areas within the dwellings where small differences in temperature were observed. Due to the scale of the temperature differences involved, it is unlikely that the issues identified will have any detrimental impact on the fabric performance of the dwellings.

4 Key findings from the design and delivery team walkthrough

4.1 Introduction

No design and delivery team walkthrough has been undertaken as part of this in-use monitoring project, as it has previously been reported in an earlier Technology Strategy Board Building Performance Evaluation Competition post-construction and initial occupation study (project no. 450014).

For completeness, the main conclusions and recommendations relating to the design and delivery team walkthrough that were reported in the earlier post construction study are reiterated below.

Discussions with the Project Architect and the client revealed that the finished dwellings were constructed as intended, despite significant difficulties being encountered during the construction phase. A number of positive aspects of the development were also identified. These included: reduced energy bills during the winter period, reduced environmental impact resulting from lower fuel use; improved comfort in winter and appropriate comfort in summer as long as the dwellings are ventilated correctly. Despite this, a number of aspects of the design were identified by the Project Architect that, given the opportunity, would not be replicated in future designs. These related to the use of a disadvantageous form factor of the dwellings (a bungalow) and the placement of the ventilation, heating and hot water services on the mezzanine floor, as this is not ideal for maintenance purposes. In addition, it was also felt that the services were rather complex for tenants and there were concerns associated with the long-term maintenance of the systems.

Feedback from the client and tenants identified some overheating within the dwellings. A range of measures were identified by the Project Architect to address this:

- Night time purging of dwellings – keep windows open to ventilate hot air and allow the building to cool.
- Use the MVHR boost function when dwelling becomes too warm.
- Potential to design a secure louvered vent which allows night time cooling without the security concerns of an open window.

These measures have been implemented or (in the case of a secure vent) are being developed and explored further.

5 Occupant surveys using standardised housing questionnaire (BUS) and other occupant evaluation

5.1 Introduction

The BUS seeks to inform the research team about issues from the side of the user. The information gathered highlights any issues that arise through lived in experience, and can then be cross referenced with measured data to highlight potential reasons for any poor performance.

A total of 7 BUS questionnaires were distributed to residents, of which 4 were completed and returned, representing a 57% feedback.

5.2 Key findings from the Bus Questionnaire

General feedback was positive, with the majority of responses returning either ‘green’ or ‘amber’ ratings on the BUS feedback report. The areas discussed below returned negative feedback under the BUS methodology, and possible reasons for this are explored.

- **Air quality**

Feedback suggested that residents found the air in the dwelling to be stuffy, dry and still in both summer and winter, with winter regarded as the poorer season for air quality. This feedback is displayed in figures 16-21. During monitoring, air quality was not found to be poor, particularly with regards to CO_2 concentration which is often used as an indicator for ‘freshness’. The air was monitored as being dry at times, however, particularly during winter when residents open their windows less often due to the cold, thus reducing the introduction of outside air. Air quality in dwellings with MVHR does sometimes fall under criticism partly because of occupant perception, as fresh air is not seen to be noticeably introduced e.g. through a window, but instead comes through relatively concealed vents. The perception is also likely to be due to a lack of cooling during summer months and the resulting uncomfortable temperatures, in addition to residents not opening their windows during warm periods.

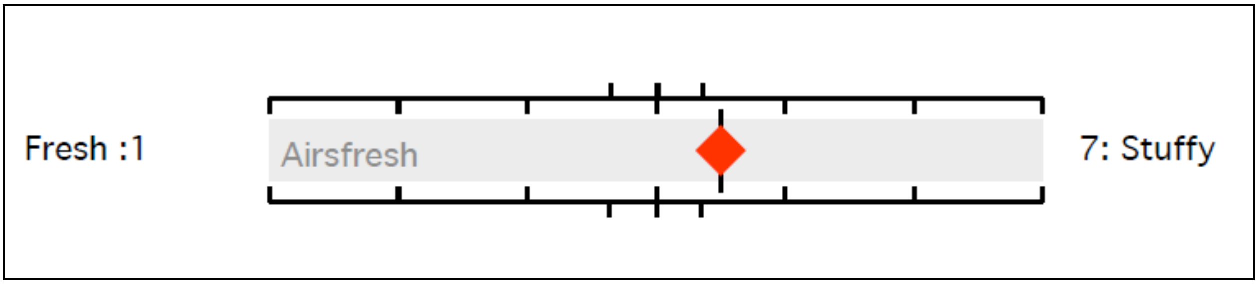

Figure 16 Stuffy air in winter

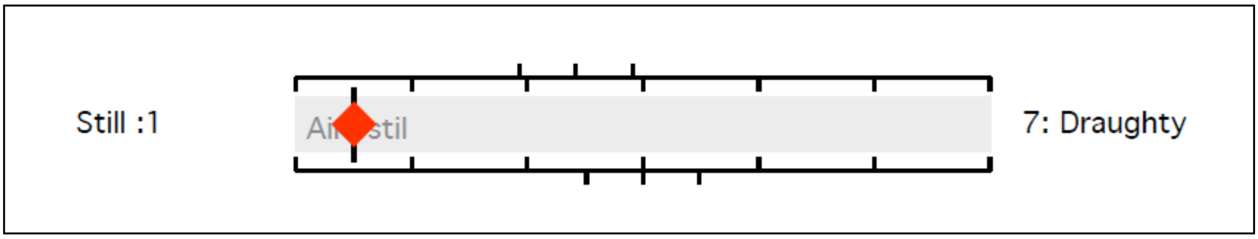

Figure 17 Still air in winter

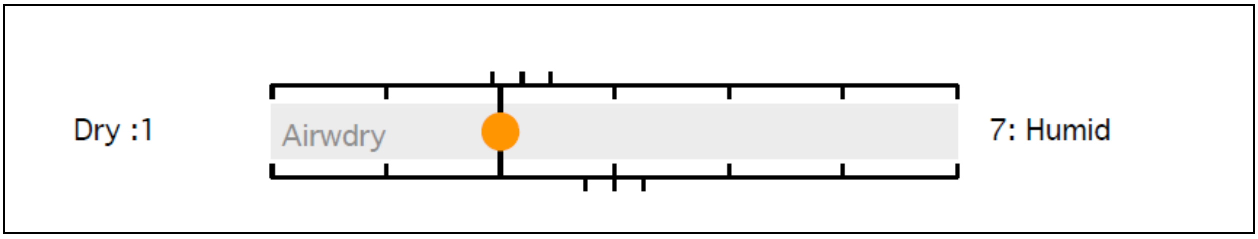

Figure 18 Dry air in winter

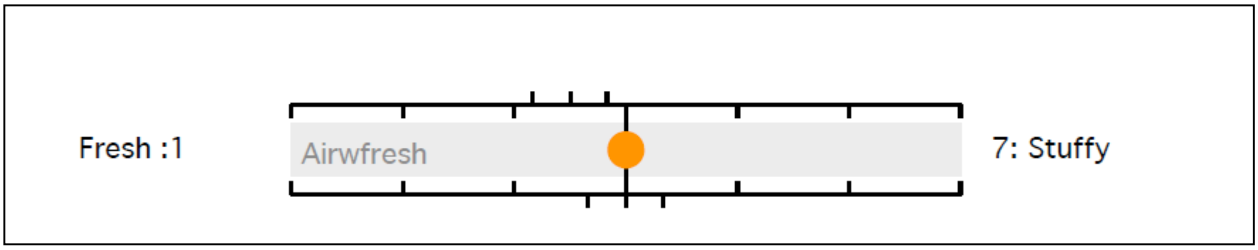

Figure 19 Stuffy air in summer

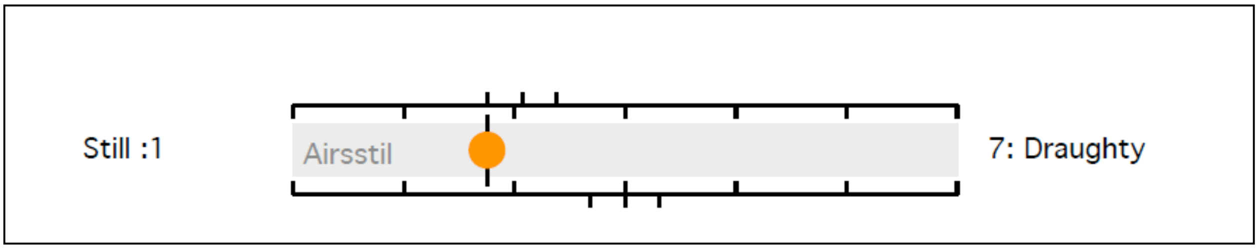

Figure 20 Still air in summer

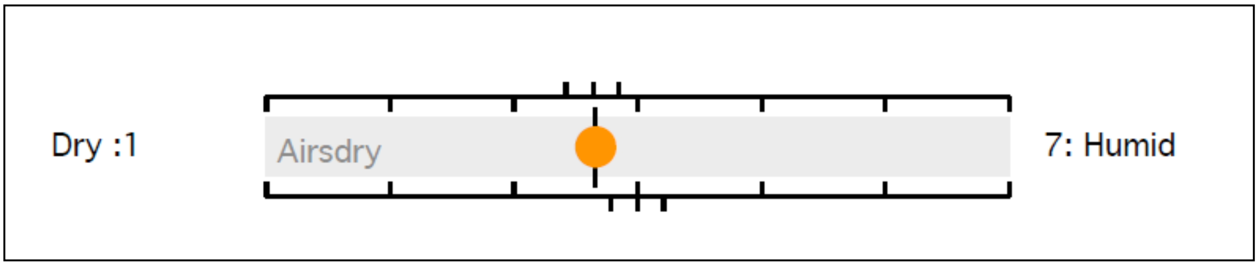

Figure 21 Dry air in summer

- **Lighting**

Both artificial and natural lighting received 'red' feedback under the BUS methodology Figures 22 and 23). This feedback was also registered during the Phase 1 BUS survey. Both natural and artificial lighting was deemed to be 'too much'; however following conversations with residents it was found that this is regarded as a positive. Residents found the additional light from the large south facing glazing to give the home an open and airy feeling. As such, this negative BUS score is not deemed to be an issue in domestic dwellings as it is more relevant in non-domestic dwellings such as office spaces.

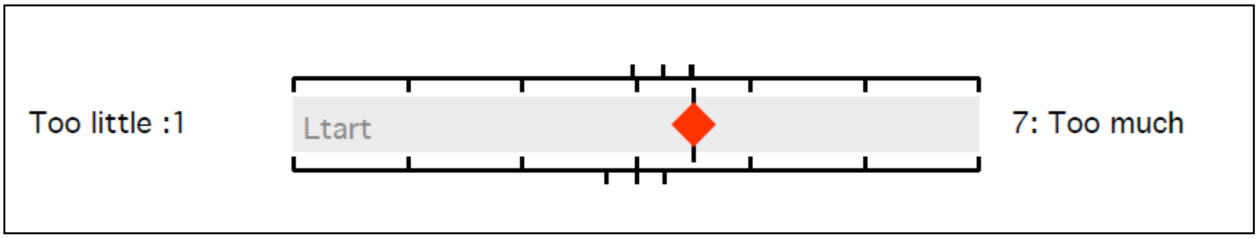

Figure 22 Artificial lighting

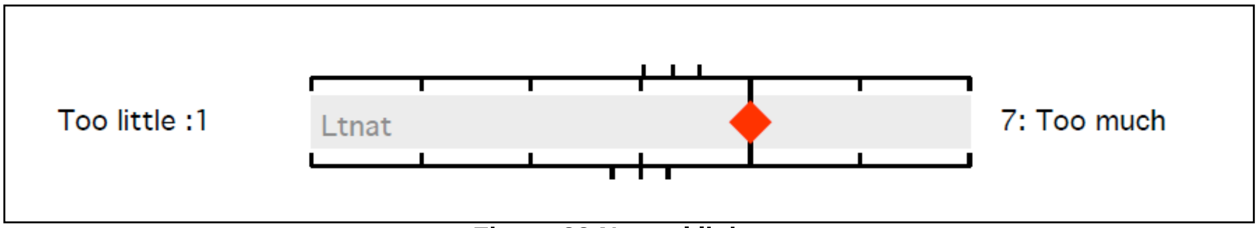

Figure 23 Natural light

- **Noise**

Similar to light levels, feedback indicated that the properties were too quiet (Figures 24, 25 and 26). This was also the case in the Phase 1 BUS survey. As with light levels, this was deemed to be a positive aspect of the home by the residents, and as such is an issue with occupant perception not matching the BUS methodology. This is again a factor that is tailored to non-domestic buildings such as offices. This is reflected in the overall noise feedback which was green (Figure 27).

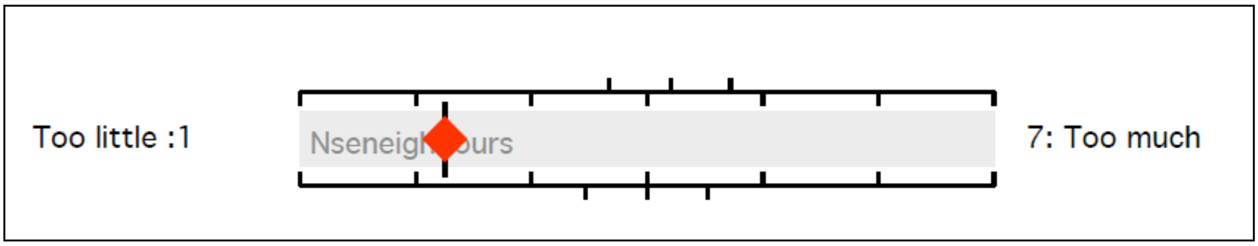

Figure 24 Noise from neighbours

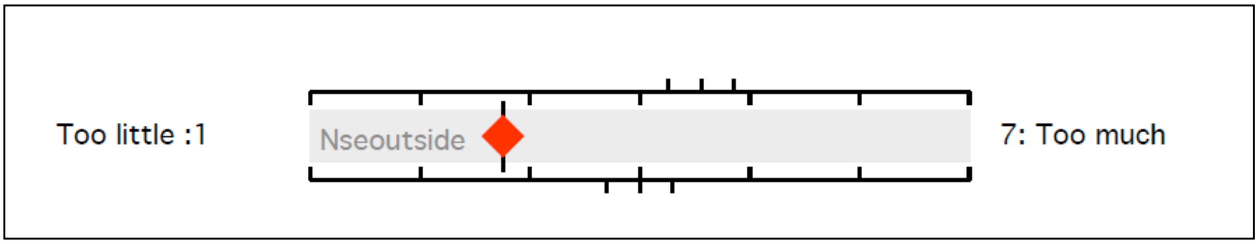

Figure 25 Noise from outside

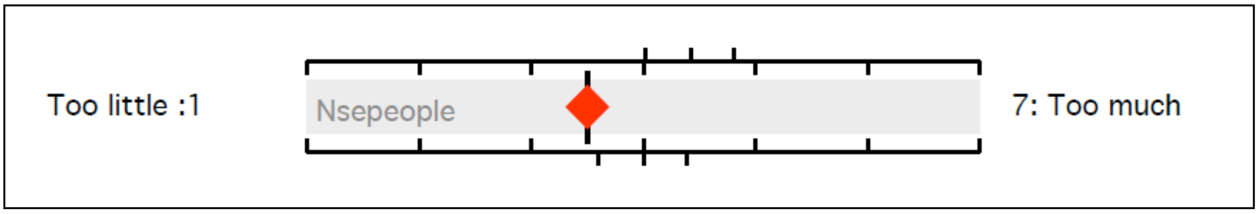

Figure 26 Noise from other people

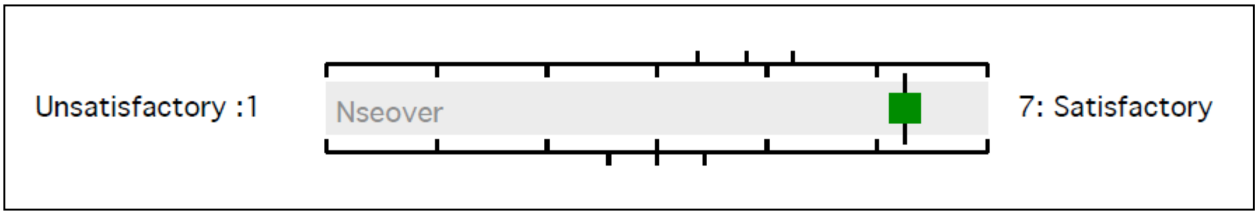

Figure 27 Noise overall

- **Temperature**

Temperatures in the dwelling under the BUS methodology were regarded as being too hot in both winter and summer (Figures 28 and 29). The graphical feedback was substantiated by comments such as:

"The house in summer nights is boiling hot"

Interestingly, whilst overall summer temperature received an amber score, winter temperature received a green score (Figure 30), suggesting residents may prefer hotter temperatures in the home. This may show an issue with the wording of the BUS questionnaire, with 'too hot' being regarded in a positive light for residents such as those in Gentoo. Other feedback was very positive, with comments relaying the positive impact that the homes have had on health and wellbeing.

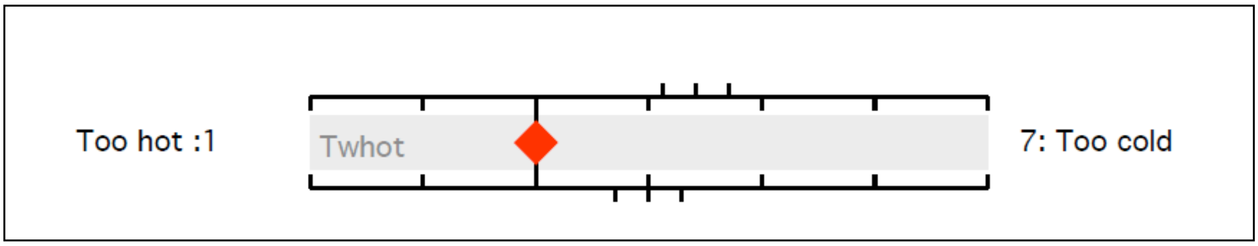

Figure **28 Temperature in winter**

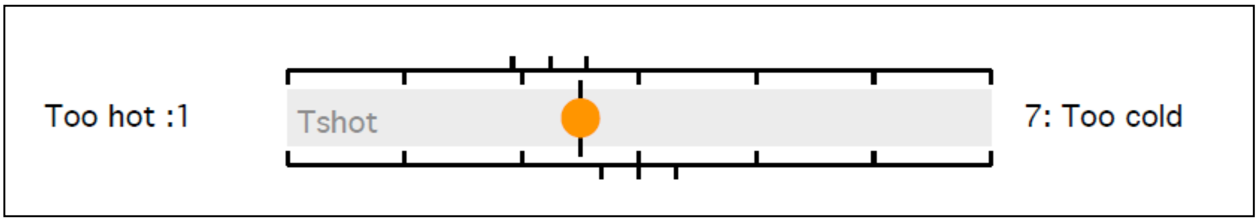

Figure 29 Temperature in summer

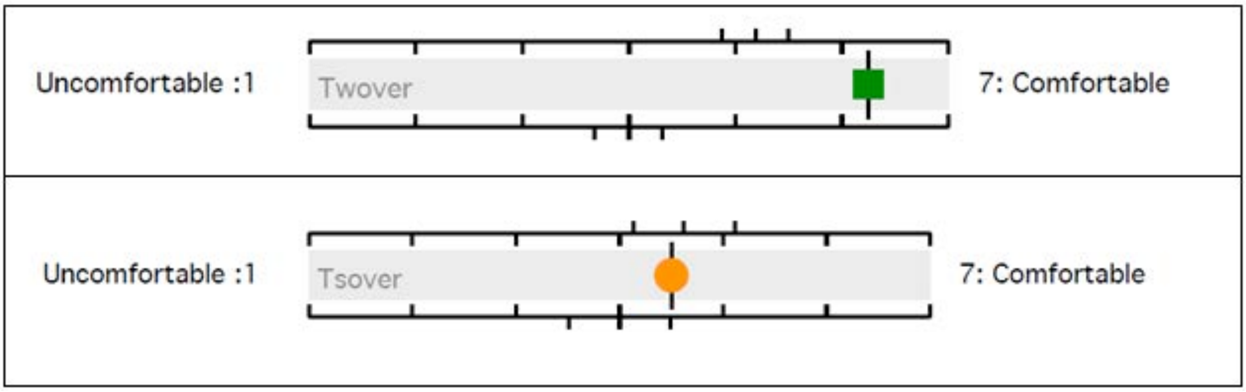

Figure 30 Overall temperatures

5.3 Conclusions and key findings for this section

Overall feedback was positive for the dwellings, with negative responses for noise and lighting resulting from differences between occupant perception and BUS methodology. Points of note were the perceptions of poor air quality and overheating, which are discussed further in the section 7 of this report.

6 Installation and commissioning checks of services and systems, services performance checks and evaluation

6.1 Introduction

As all six dwellings that are participating in the in-use performance and post occupancy evaluation study are built to Passivhaus standards, the space heating energy demand is very low, so a conventional wet central heating system has not been required. Instead, space heating is provided via a small low temperature hot water heater battery installed in the MVHR ductwork, which heats the fresh air supplied to the dwelling from the MVHR system. In addition to the heater battery, a heated towel radiator is provided in the bathroom, along with a small radiator in the drying cupboard. Hot water to the heater battery, towel radiator and small drying cupboard radiator is supplied from a communal boiler, a 38kW Valiant Ecotec plus 438 gas-fired wall-hung boiler, which is located in a small boiler room on the East end of the terrace, adjacent to dwelling 7. The communal boiler supplies hot water to all seven of the dwellings in the terrace, six of which are included in the in-use energy and environmental monitoring, via a communal heat main.

Control of the heater battery is provided via a thermostat located in the living room and a 24 hour programmer (this also controls the water heating) located in the drying cupboard. The heating has been pre-programmed to run continuously throughout the day, 365 days of the year. Although this is not the most accessible location for the programmer, it has been intentionally located in this position to avoid the occupant altering the time control of the heating. The small radiator located in the drying cupboard is controlled via a touchstat in the drying cupboard, which is operated manually and incorporates a boost setting. The towel radiator is controlled both by the room thermostat in parallel with the duct heater, and also via a manually operated boost switch located in the hall, enabling the towel radiator to be activated for a 30 minute, 1 hour or 2 hour period when heating is not otherwise needed.

The communal heat main also supplies hot water to a 200 litre unvented POWERflow 2000 indirect hot water cylinder, located in the mezzanine loft space in all dwellings. This cylinder has a twin coil, with input from the communal heat main and a Viridian V260 solar hot water system, which has a 3m^2 single roof-mounted collector on the South-facing roof slope. A normal cylinder thermostat and heating programmer is used to control boiler input into the cylinder.

Ventilation is provided via a Paul Atmos 175 DC whole house MVHR system which incorporates a frost protection heater. This is installed in the mezzanine loft space of both dwellings. Boost operation of the unit is provided via a manually operated fan boost switch located in the hall or in the kitchen. A remote control keypad, used to control and program the operation of the MVHR unit, is located on the wall inside the drying cupboard.

In terms of internal lighting, pendant or baton lamp holders have been installed in the living area, kitchen and bedrooms of both dwellings, In addition, an IP X4 luminaire has been installed in the bathroom.

6.2 Installation and commissioning checks

As this project was the subject of an earlier Technology Strategy Board Building Performance Evaluation Competition post-construction and initial occupation study (project no. 450014), only a small number of commissioning checks have been undertaken on the monitored dwellings as part of the in-use energy and environmental monitoring study. These checks comprised a series of MVHR supply and extract duct grille flow measurements on dwelling 2 and dwelling 7. The results obtained from these measurements have been compared with those results obtained from the earlier post construction study, where applicable.

No other installation or commissioning checks been undertaken as part of this in-use monitoring project, as these checks have previously been reported in the earlier post construction and initial occupation project and no issues relating to the services installed within the dwellings have been raised by the occupants during the in-use monitoring project.

6.3 MVHR system duct flow measurements

A small number of MVHR supply and extract duct grille flow measurements have been undertaken on two of the dwellings that are participating in the in-use monitoring project; dwellings 2 which is the subject of the extensive monitoring and dwelling 7 which is being intensively monitored. All of the measurements were undertaken using a Swemaflow 125D hot wire lattice anemometer and hood.

For dwelling 7, two sets of duct flow measurements have been undertaken. The first set of measurements were undertaken on the 9th April 2013, prior to the commencement of the in-use energy and environmental monitoring, and some 15 months after practical completion. These measurements were undertaken at this time to determine the duct flow rates of the MVHR system prior to the commencement of the in-use energy and environmental monitoring. It should be noted that as this dwelling did not participate in the earlier post construction and initial occupation study, no previous duct flow measurements had been undertaken on this dwelling by the Leeds Metropolitan University research team. Additionally, no data from commissioning was available at time of writing. The results of the duct flow measurements that were undertaken are detailed within Table 4. Unfortunately, it was only possible to undertake flow measurements under standard flow rates due to an equipment malfunction.

	Standard(ls^{-1})	**Boost (ls^{-1})**
Living area	11.8	-
Master bedroom	10.0	-
Bedroom 2	4.0	-
Total supply	**25.8**	**-**
Kitchen	9.2	-
Bathroom	11.3	-
Drying cupboard	0.6	-
Total extract	**21.1**	**-**

Table 4 Dwelling 7 MVHR supply and extract duct grille flow measurements in ls^{-1} on the 9th April 2013.

Analysis of the data contained within Table 4 indicates that under standard flow rates, the unit is not balanced, with the supply rate being greater than the extract rate by around 22%. Balance of the fan speeds overall is critical in terms of heat exchanger efficiency. Observations of the supply and extract grilles revealed that one possible reason for the imbalance may be related to the condition of the kitchen extract grille and filter (see Figure). A closer inspection of the kitchen area revealed that even though an integrated recirculation cooker hood with carbon filter had been installed in the kitchen above the cooker, it looked as though the previous occupants of the dwelling never used this hood. Instead, all of the grease from cooking was being extracted through the high level MVHR extract grille in the kitchen, rather than through the integrated cooker hood. The reason why the recirculating cooker hood cooker hood was not used was thought to be due to the fact that it had been integrated into the kitchen cupboards, and the previous occupants were simply not aware that it was even there. The hood was of the same design as the cupboards, above the cooker, and was activated automatically when pulled out. As this was quite stiff to pull out and located high up, residents may have assumed it was simply a blank door and purely aesthetical. This has implications in terms of the occupant handover process, and stresses the importance of ensuring that not only are the occupants made aware of all of the services that provided within the dwelling, but that they are also shown and understand how to use them.

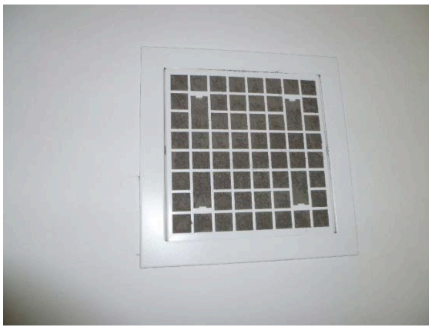

Figure 31 Kitchen extract grille prior to cleaning

The cooker extract grille and filter were cleaned and the duct flow measurement repeated for this extract grille. The flow rate through this grille increased from 9.2 ls^{-1} to 13.6 ls^{-1}, resulting in a total extract rate of 25,5 ls^{-1}. This is comparable to the supply flow rate, resulting in the system now being in balance.

The second test on dwelling 7 was undertaken on the 22nd July 2014, at the end of the energy and environmental monitoring period. The results of these measurements are detailed within Table 5.

	Standard(ls^{-1})	**Boost (ls^{-1})**
Living area	9.1	16.2
Master bedroom	9.9	15.4
Bedroom 2	4.2	6.9
Total supply	**23.2**	**39.5**
Kitchen	10.4	17.8
Bathroom	9.7	14.4
Drying cupboard	3.7	6.0
Total extract	**23.8**	**38.2**

Table 5 Dwelling 7 MVHR supply and extract duct grille flow measurements in ls^{-1} on the 22nd July 2014.

The results contained within Table 5 illustrate that the flow rates of the MVHR system have not altered significantly over the in-use monitoring period and that the system is still in balance.

A set of MVHR duct flow measurements were also undertaken on dwelling 2 towards the end of the in-use monitoring period (23rd May 2014). As this dwelling had participated in the earlier post construction and initial occupation study, these measurements were undertaken to enable a comparative analysis to be undertaken between those results measured post completion and those measured a number of months following occupation. The results of the duct flow measurements are detailed in Table 6 below. The measurements indicate that there is very little difference between the flow rates undertaken post construction and those undertaken during the in-use monitoring, and that the unit is still in balance. This also suggests that the unit is performing as well now (end of May 2014) as it was when the dwelling was fist completed, some 25 months ago.

	Post completion		**During in-use monitoring**	
	Standard (ls^{-1})	**Boost (ls^{-1})**	**Standard (ls^{-1})**	**Boost (ls^{-1})**
Living area	11.9	17.4	13.1	19.1
Master bedroom	6.6	10.5	7.7	9.8
Bedroom 2	6.1	10.2	4.7	6.3
Total supply	**24.6**	**38.1**	**25.5**	**35.2**
Kitchen	14.1	20.8	10.9	17.0
Bathroom	6.1	10.0	9.5	13.1
Drying cupboard	3.3	5.1	5.5	7.0
Total extract	**23.5**	**35.9**	**25.9**	**37.1**

Table 6 Duct air flow rates for the MVHR unit in dwelling 2.

6.4 Conclusions and key findings for this section

A series of MVHR duct flow measurements have been undertaken on the one intensively monitored dwelling (dwelling 7) as well as one of the extensively monitored dwellings (dwelling 2) that participated in the earlier post construction and initial occupation study. The latest measurements obtained from both dwellings revealed that the MVHR units are in balance and have comparable flow rates under both standard and boost settings. In addition, the flow rates measured in dwelling 2 during this in-use monitoring study are consistent with those that were measured post completion, indicating that the unit is performing as well now as it was following practical completion of the dwelling. Despite this, initial measurements undertaken on dwelling 2, prior to the commencement of the in-use monitoring, revealed that the unit was out of balance and that this was attributable to a heavily contaminated kitchen extract grille and filter. Once cleaned, the unit became balanced. The reason why the kitchen extract grille was so heavily contaminated appears to be attributable to the fact that the previous occupants did not use the integrated cooker hood recirculating fan, as they were not aware of it. This has important implications for the occupant handover and walkthrough, and highlights the importance of ensuring that the occupants are fully aware of how to use all of the services that have been incorporated within the dwelling. Otherwise, there is a risk that some of the services may not perform as intended, due to the actions undertaken by ill-informed occupants. It is noted that Gentoo will undertake regular (6 monthly) filter changes for rented properties. Owner occupied homes will be responsible for their own filter changes.

7 Monitoring methods and findings

7.1 Introduction and Monitoring Method

This section summarises the results of 12 months in use monitoring across the 6 properties forming the Gentoo Racecourse development. All 6 properties had some form of monitoring equipment installed. Dwelling 7 was used as the 'intensive' property, and experienced a higher level of monitoring than the 5 other 'extensive' properties. Table 7 details the monitoring equipment for each dwelling. In addition to equipment in the homes, the communal terrace boiler room contained monitoring equipment and local weather conditions were recorded using an on-site weather station.

Data was collected using Eltek telemetry, transmitting at 1 minute intervals and logging at 10 minute intervals for the duration of the research. Data was collected remotely via a 2G modem on a weekly basis, with data checked upon download. Any instances of missing data were corrected by linear interpolation.

Monitoring during the 12 month period was largely uninterrupted, although the following issues should be noted:

- Heat meters for dwelling 2 and the terrace boiler were originally supplied with incorrect calibration, and as such had to be returned and recalibrated leading to a loss of data during the winter period.
- The heat meter for dwelling 1 ceased transmitting between March and May 2014. The issue was noticed quickly but unfortunately access issues led to a delay in resolution.
- Water meters for dwelling 6 and 5 experienced issues during the early monitoring period and had to be replaced, resulting in data loss.
- Data for the period 5th-11th November 2013 became corrupted during a system upgrade and was unfortunately lost for the Extensive properties and weather station.
- During the course of the monitoring period, the resident of dwelling 4 unfortunately passed away. This can be seen in the data.

Equipment	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Boiler Room**
Total Water								
Total Heat								
Total Electricity								
Sub-metered Electricity								
Internal Conditions								
Disaggregated Water Use								
Disaggregated Heat Metering								
Gas Use								

Table 7: Monitoring equipment installation

7.2 12 month monitoring data – Extensive Properties

7.2.1 Electricity

As noted above, electricity usage has been collected throughout the monitoring period at 10 minute logging intervals (see Figure 32 for details of electricity monitoring equipment). This data is represented in Figures 33 and 34 for both daily and monthly totals. All properties have been observed to display a fairly consistent electrical energy use, with a slight increase in consumption during the winter months. This is to be expected as residents may spend more time indoors during winter, in addition to requiring internal lighting for longer periods.

Dwelling 4 was unoccupied for an extended period during the research as noted above. As the heating system and appliances were left running during this period, this allows the research team to determine the unoccupied electrical base load for one of the dwellings, which is around 1.2kWh per day, representing a power demand of 50W.

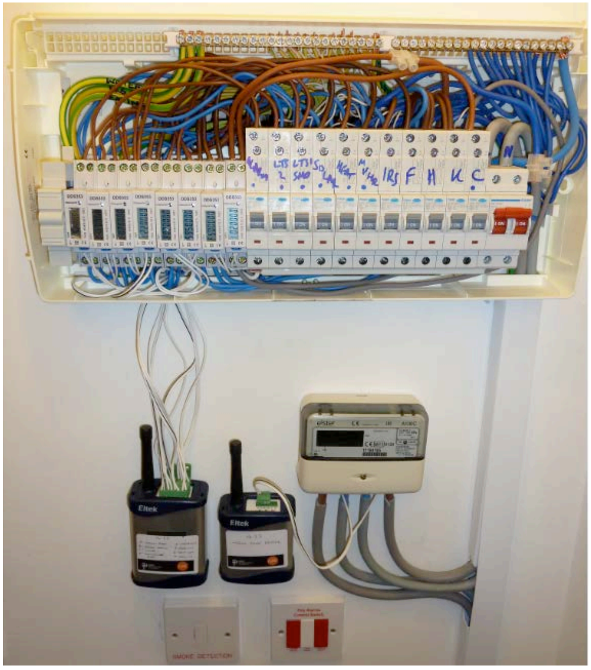

Figure 32: Electricity monitoring equipment

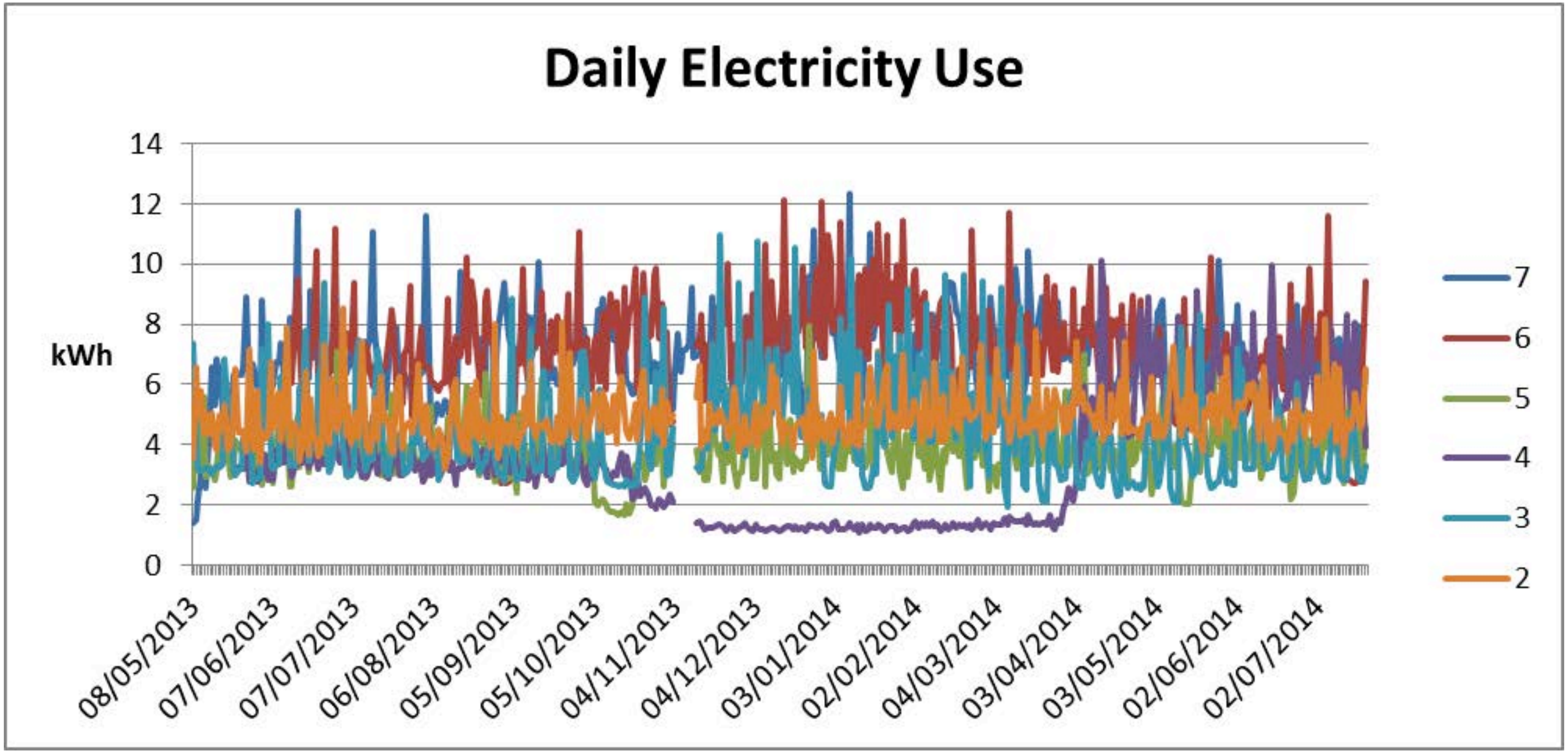

Figure 33: Daily electricity use during monitoring period

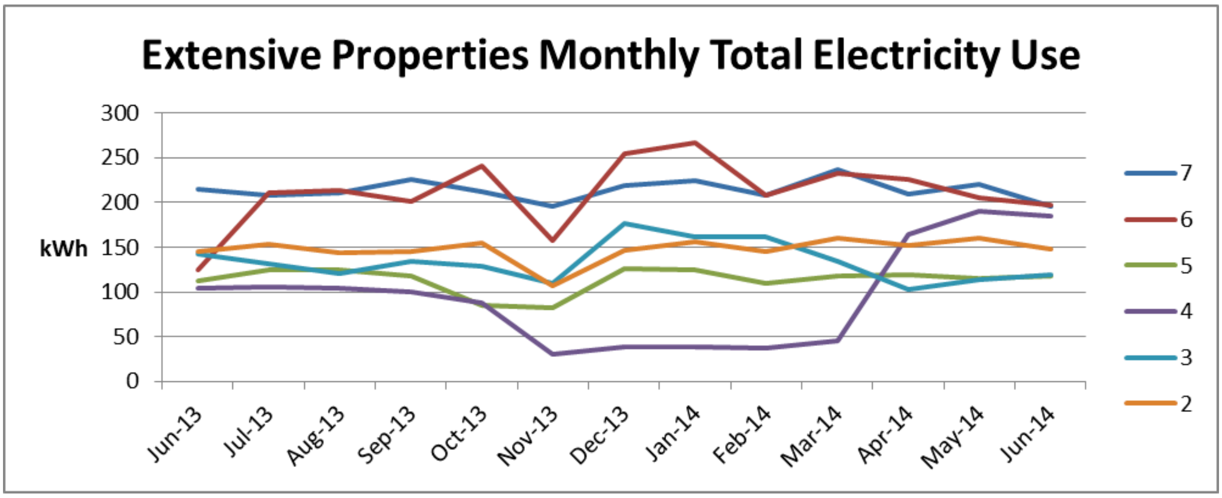

Figure 34: Monthly total electricity use

Table 8 below summaries the comparison of annual (June-June) electrical energy use between the properties, with Figures 35 and 36 giving graphical representation. For CO_2 calculation, the standard of 0.527kg/kWh given by the Carbon Trust/DEFRA for grid electricity was used.

Electricity use is highly dependent on both the number of electrical devices within the home and occupant behaviour. Although all of the BUS questionnaires for this research have not been returned at time of writing, the completed questionaires for dwellings 7 and 5 have been returned. Of interest is that the occupants of dwelling 7 respond that they are in the home 'most of the time' whereas the residents of 5 responded that they are only in the house on 'evenings and weekends'. The difference in occupancy appears to be evident in the data, with dwelling 5 using 47% less electricity over the duration of the monitoring period. As dwelling 7 was subject to intensive monitoring, it is also known through visits that residents use several large electrical devices for extended periods such as a large screen television and a desktop computer, which may also account for the relatively higher electricity use.

Dwelling	**Annual Electricity**		**Percentage of Terrace Total (%)**	**CO_2 Equivalent (Kg)**
	Total kWh	**kWh/m²**		
7	2780	42.2	23	1465
6	2742	41.6	23	1445
5	1479	22.4	13	779
4	1232	18.7	10	649
3	1739	26.4	15	916
2	1918	29.1	16	1011

Table 8: Electrical energy use and CO_2 comparison

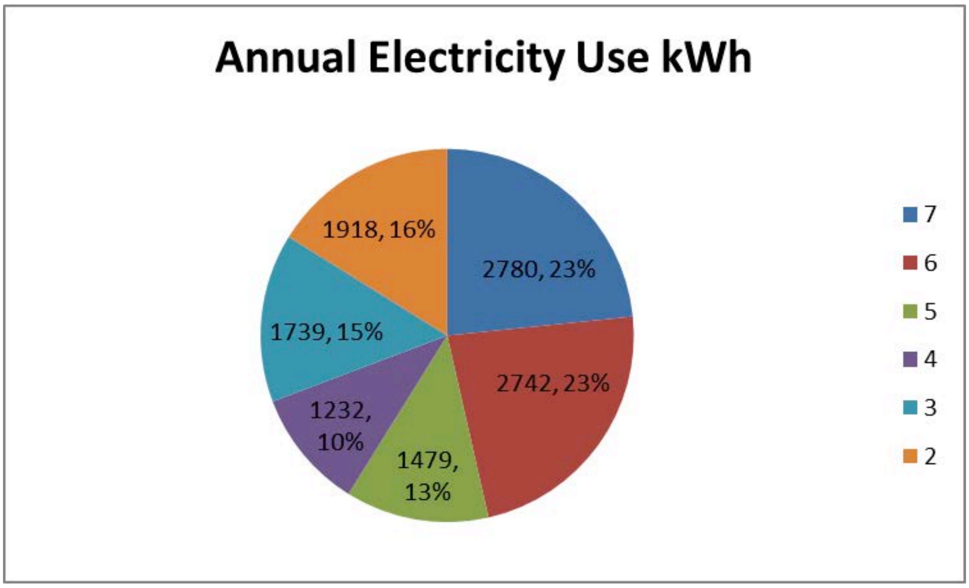

Figure 35: Extensive property Annual electrical energy use

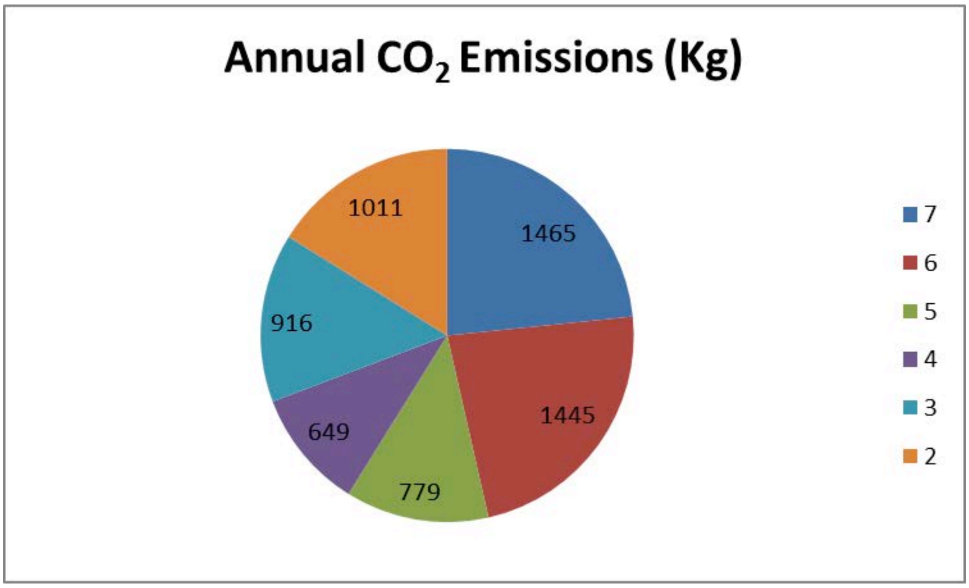

Figure 36: Extensive property Annual CO_2 resulting from electrical energy use

Electrical energy data is explored in more detail in the latter stages of this section, through analysis of disaggregated data collected from dwelling 7.

7.2.2 Water Use

Early monitoring of total water use across the monitoring period experienced issues due to failures in the monitoring telemetry, which necessitated the replacement of transmitters for dwellings 5 and 6. As such, this resulted in data loss for these properties over a significant period (May 2013 – Oct 2013).

The data below does not include a period of high water use on 15th July from dwelling 3 in order to allow better graphical representation.

Several water saving strategies were designed into the dwellings with the intention of meeting the Level 4 Code for sustainable Homes requirement of 105 litres/person/day. These included:

- Lower capacity baths (reducing from 225 litres to 140 litres)
- Low flush toilets (with rates reducing from 6/4litres to 4/2.5litres);
- Flow restricting devices to all taps and thermostatic showers;
- The provision of information to the customer regarding A rated white goods.

Figure 37 displays the total daily water use across all monitored properties, and Figure 38 displays the total monthly usage values. The data appears to show several interesting trends in water use. As with electricity, water use is significantly affected by occupant behaviour. Broadly speaking, all properties show a consistent pattern of water use when aggregated into monthly values, with the exception of dwelling 4 which was unoccupied for a significant period (for reasons stated above) and dwelling 3. Figure 39 shows the daily values across a shorter period, and highlights an interesting pattern in the data for dwelling 3, with residents using no water at all during weekend periods. This trend can also be seen on Figure 20, and continutes until early November, where water use takes on a more consistent pattern before reverting back to no water use on weekends from mid-March. This suggests that the residents of the dwelling significantly alter their occupancy patterns on a broadly seasonal basis, with a resulting effect on water consumption, perhaps because the colder weather limits their ability to leave their home on weekends. Following discussions with residents, this is believed to be the result of them visiting a caravan during weekend when the weather is more favourable. This pattern is not easily seen in the electricity and heating data due to background 'noise', as the heating system is left turned on despite the home being occupied and several appliances are using electricity (although overall electricity use reflects lower bulk use). Water is distinct in its non-usage, and can be clearly seen when data is presented in a graph.

Table 9 compares measured water use with the UK national average of 150 litres per person per day estimated by the local supplier Northumbiran Water. Due to missing data, dwellings 6, 5 and 4 had their average measured use for complete months averaged and extrapolated, and as such may vary slightly in reality.

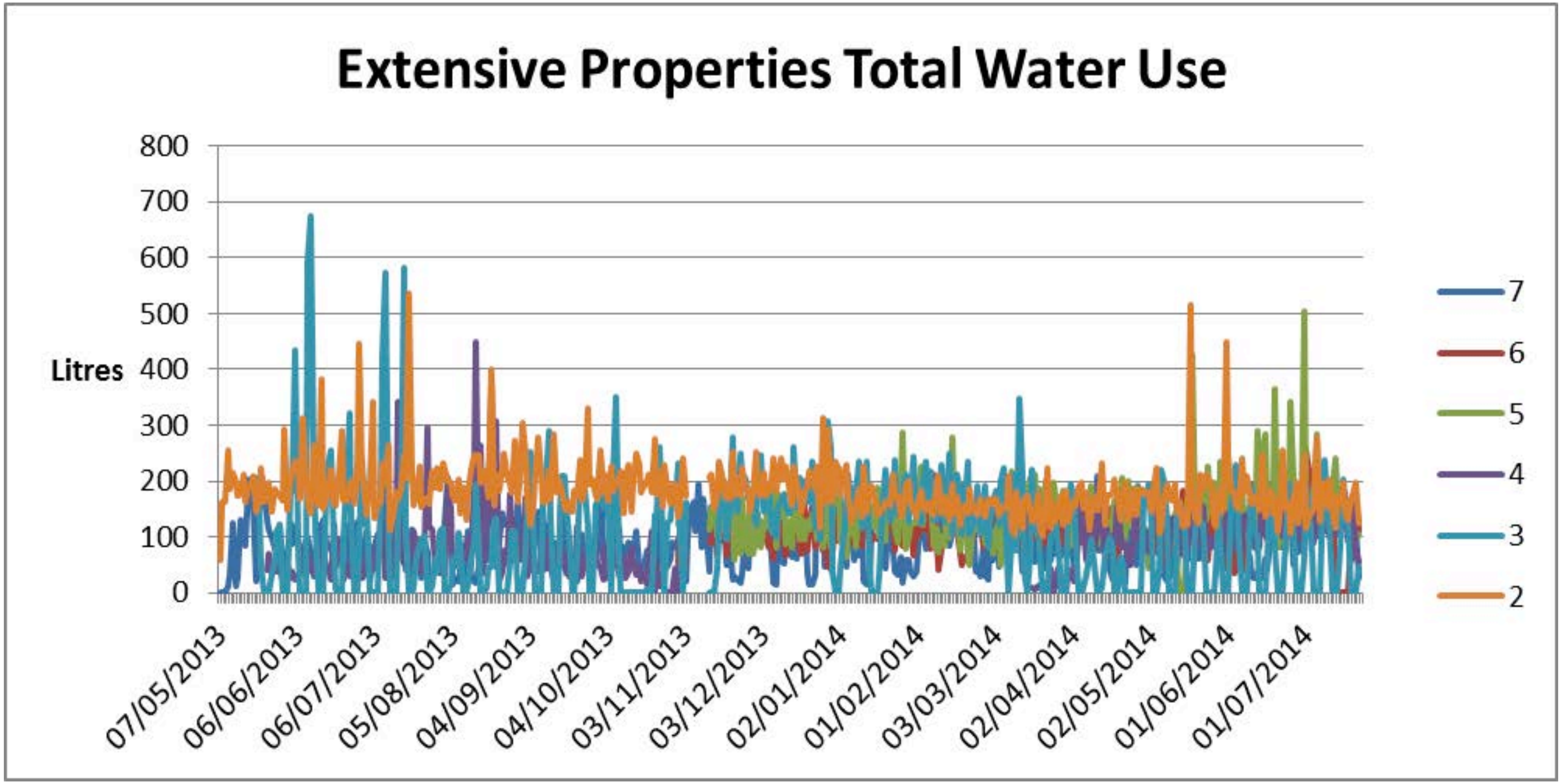

Figure 37: Total daily water use without high peak event.

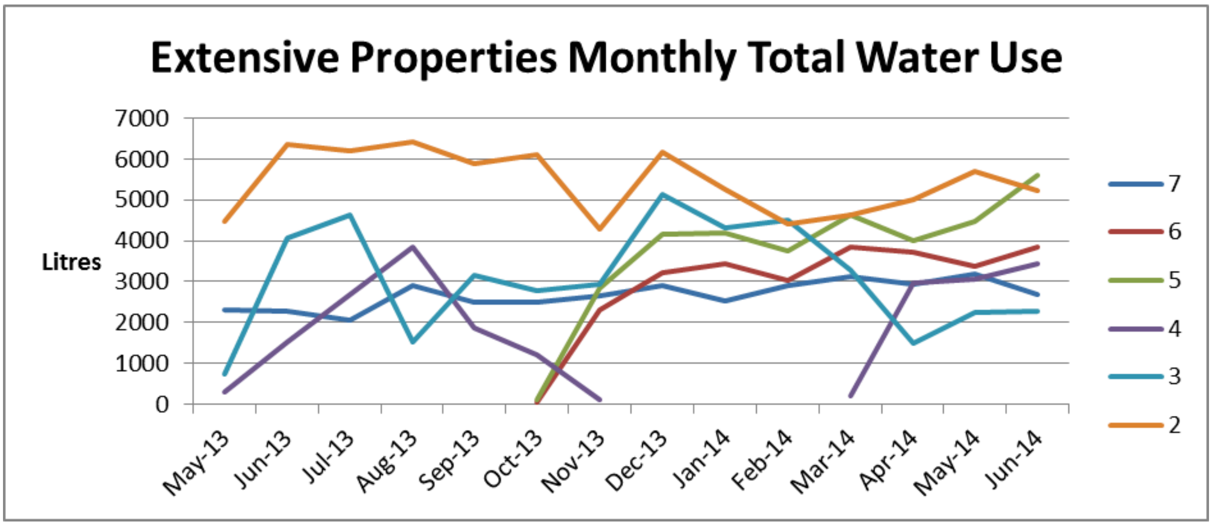

Figure 38: Total monthly water use

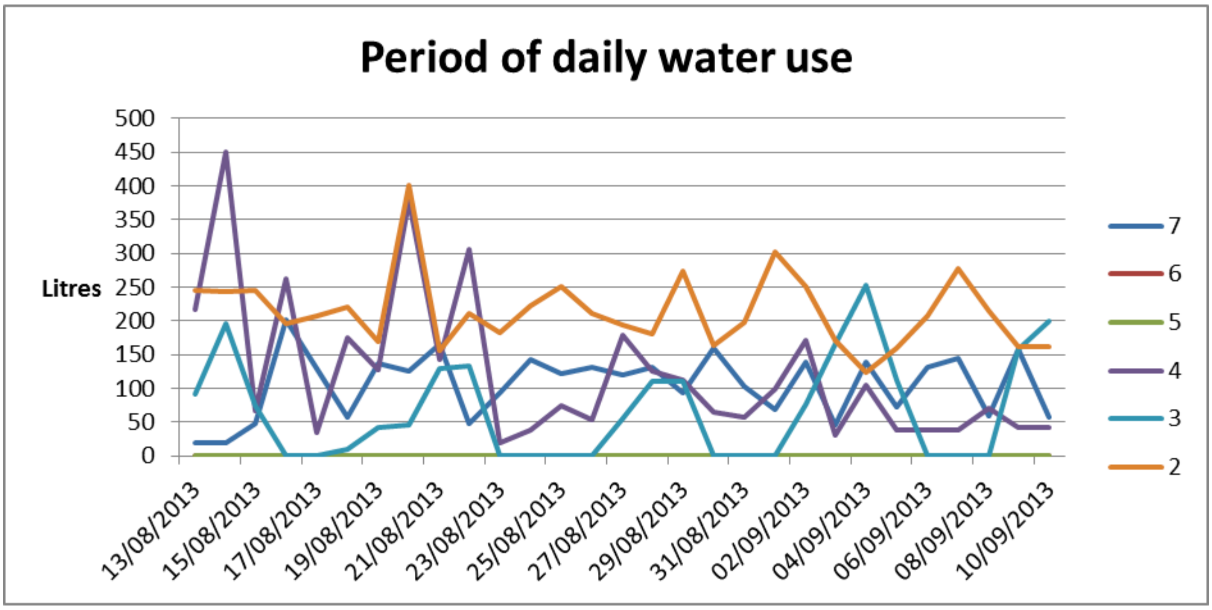

Figure 39: Period of daily water use (13th August – 10th September 2013)

Dwelling	Annual Water use (Litres per person per day)	% Comparison with UK Average (150l/p/d)	% Comparison with target for Level 4 CSH (105l/p/d)
7	48	-68	-54
6	55	-63	-48
5	69	-54	-34
4	42	-72	-60
3	58	-61	-45
2	98	-34	-7

Table 9: Extensive Property Water Use

7.2.3 Heating Use

Heat energy monitoring was possible for all 6 properties in the research. It was also possible to ascertain total heating energy use for dwelling 1, who chose not to participate in the wider study, via a heat meter installed in the adjacent dwelling connected to the communal main in the loft space. This was possible as the property was the end terrace, and so the last house on the communal heating system. As stated above, there were issues with calibration and malfunction of heat meters which led to a period of data loss for dwellings 2 and 1.

Figure 40 displays the daily heat energy use across the monitoring period for each property, measured using a heat meter incorporating heat supplied from both the communal main and the solar thermal system, and the relationship with the external temperature. The data appears to display a relationship between the two variables, with decreasing external temperature leading to increasing heat energy use as would be expected. This relationship is explored further in Figure 41, with heat energy use and DeltaT compared. Figure 41 appears to show a similar relationship, with an increasing temperature difference between the internal and external environment leading to higher amounts of heating energy use.

At handover to the residents, all MVHR and heating systems for each property were set to the same cycle, so it is expected that they should follow the same trend. The hot water cylinder reheating is controlled by a heating programmer. The heating programmer also controls the space heating (i.e. the air heat zone valve). There is also a heated towel rail in the bathroom which is controlled independently on the gas boiler system, and this is operated by an electronic run-back timer, with run time 30 minutes. There is also a heated drying cupboard in the design - this has a small radiator controlled by a combined room thermostat/runback timer, pre-set for 4 hours. Figures 40 and 41 represent the composite of all of these systems, representing total heat use. It has not been possible to disaggregate fuel use for each system. It is noticable, however, that dwelling 6 does not follow the same pattern as the other properties. The exact reason for this is unknown, although it is likely that the resident has at some point altered the heating schedule, resulting in a differing heating pattern.

During monitoring, the heating use pattern was observed and is displayed over a short period in Figure 42. With the exception of dwelling 6, each dwelling appears to use a higher peak of heat energy for a short period (usually 30 minutes) throughout the day, before stabilising at a low constant use (or no use as observed in summer). This is likely due to a combination of increased hot water use during common morning/evening routines for cleaning and bathing and a function of the heating system with the bathroom radiator and boiler cupboard. Although no specific information is available, occupancy pattern appears to be similar in dwelling 6, with the variation in pattern resulting from a difference in system setup.

The relationship between heating use and external conditions is explored further in Figures 43, 44 and 45 using degree days for analysis. Figure 43 displays the data taken from the heat meter on the communal boiler, showing total heat delivered to the full terrace and its relationship with degree days. For this analysis, a standard assumption for degree days was taken, with an external temperature of 15.5°C and perceived set point temperature of 18°C. Due to the occupancy type in these properties and observations made on site, this may not be entirely appropriate, with set point temperatures commonly higher than 18°C, but for the purpose of this reseach a standard is assumed.

Figure 43 indicates that as degree days increase, the amount of heat delivered to the whole terrace increases. This relationship is also displayed in the disaggregated data in Figure 44, and also Figure 45 which shows the linear trend in the data in Figure 44. With the exception of dwelling 6 (which shows almost no relationship owing to the erratic system pattern discussed above) all dwellings are closely grouped, suggesting a similar response in terms of heating requirement relative to degree days. It should be noted that the data displays a poor R^2 value, indicating a poor fit with the trendline suggesting an erratic pattern. Of interest is that dwelling 1, which is an end terrace and furthest from the communal boiler, requires more heat per degree day than the other properties. This may be a result of having a larger area of heat loss envelope as an end terrace, or indicate heat losses in transmission from the communal boiler. Interestingly, the other end terrace (dwelling 7) is in the middle of the distribution. This could be due to several factors, such as its attachment to the boiler room creating a buffering effect from the boiler room itself, unintentional heat gains from the boiler through the party wall or higher grade heat delivery as it is the first house on the communal main.

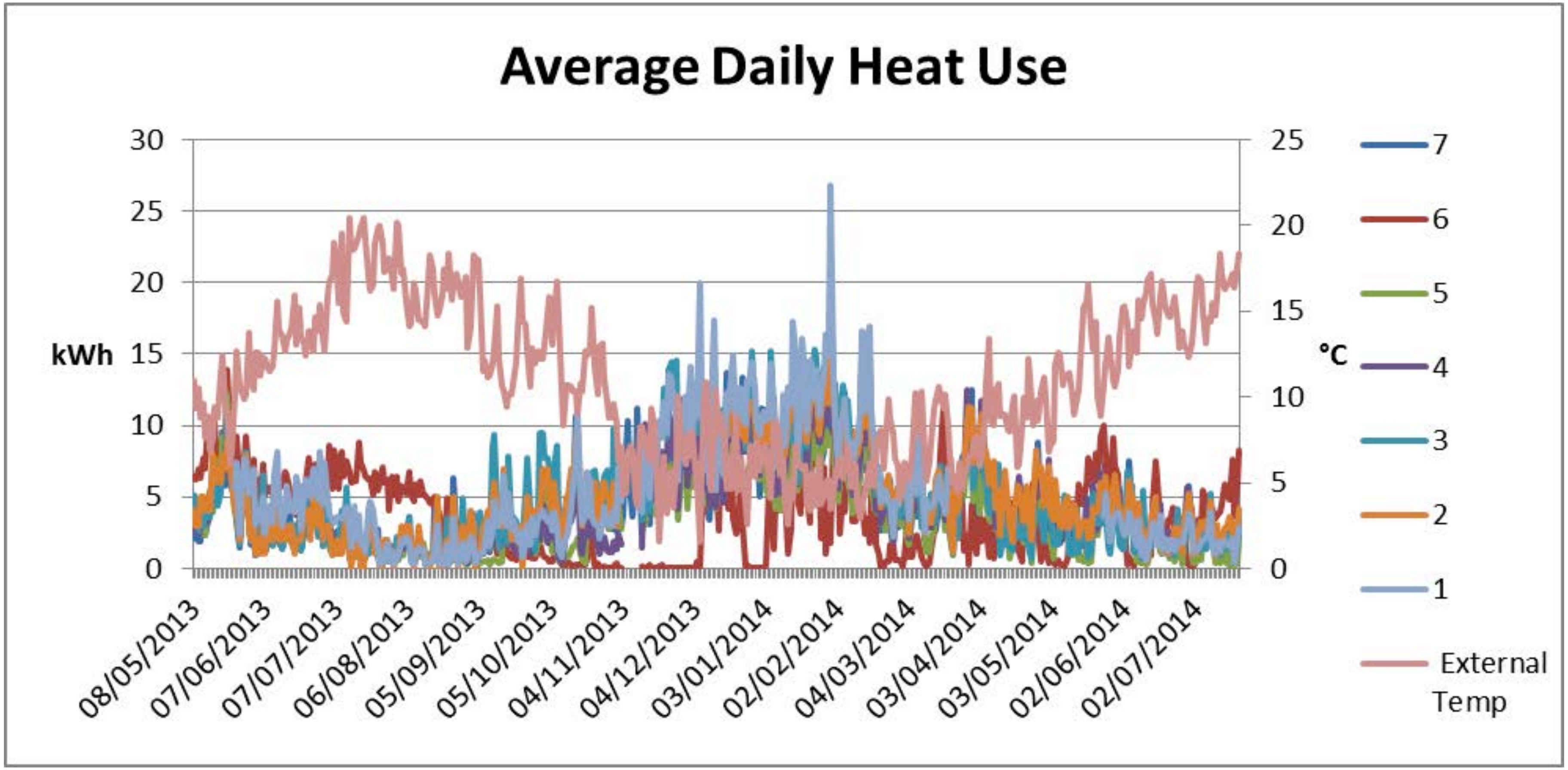

Figure 40: Relationship between heat energy use for all properties and external temperature

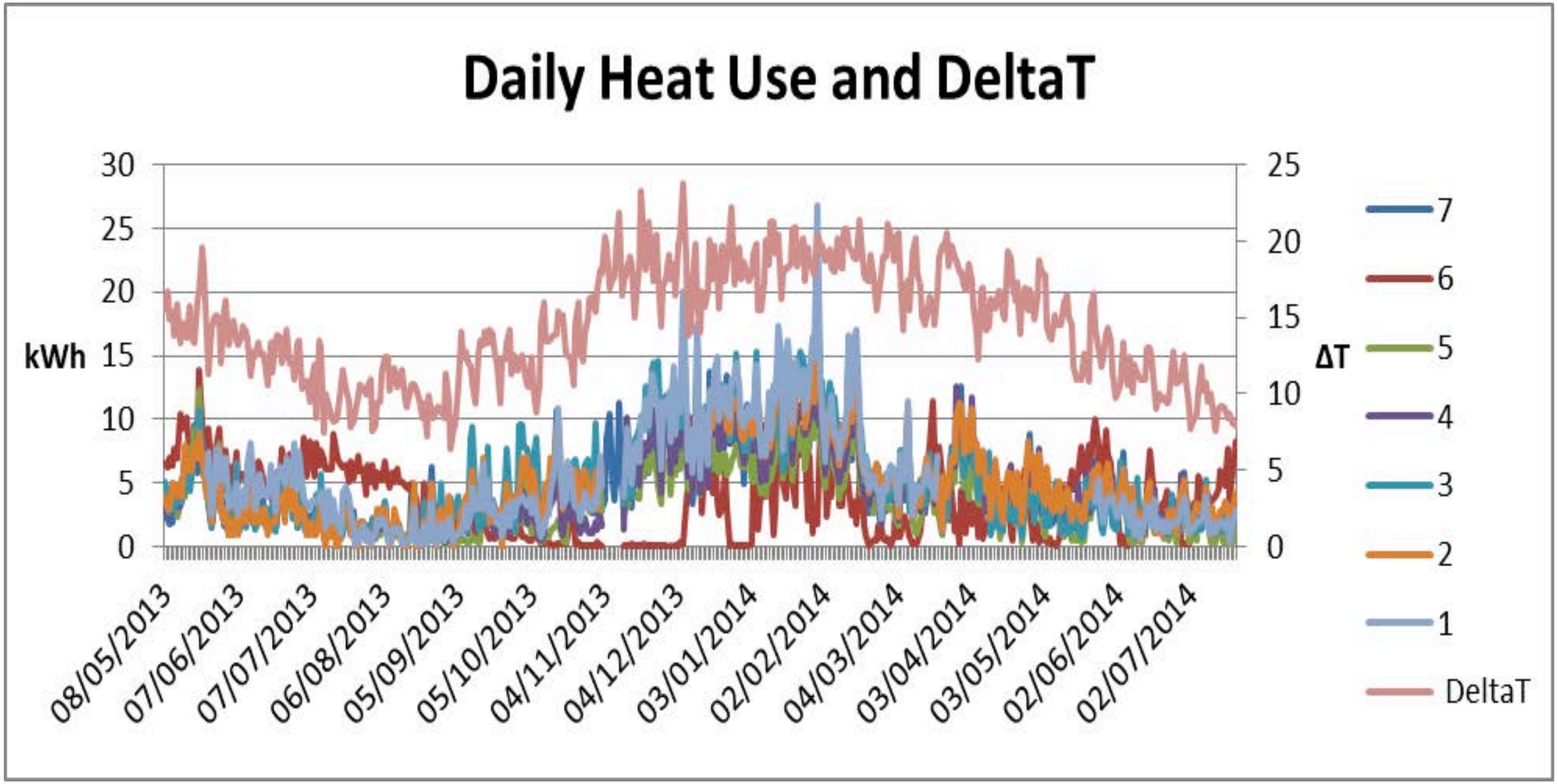

Figure 41: Relationship between heat energy use for all properties and Delta T

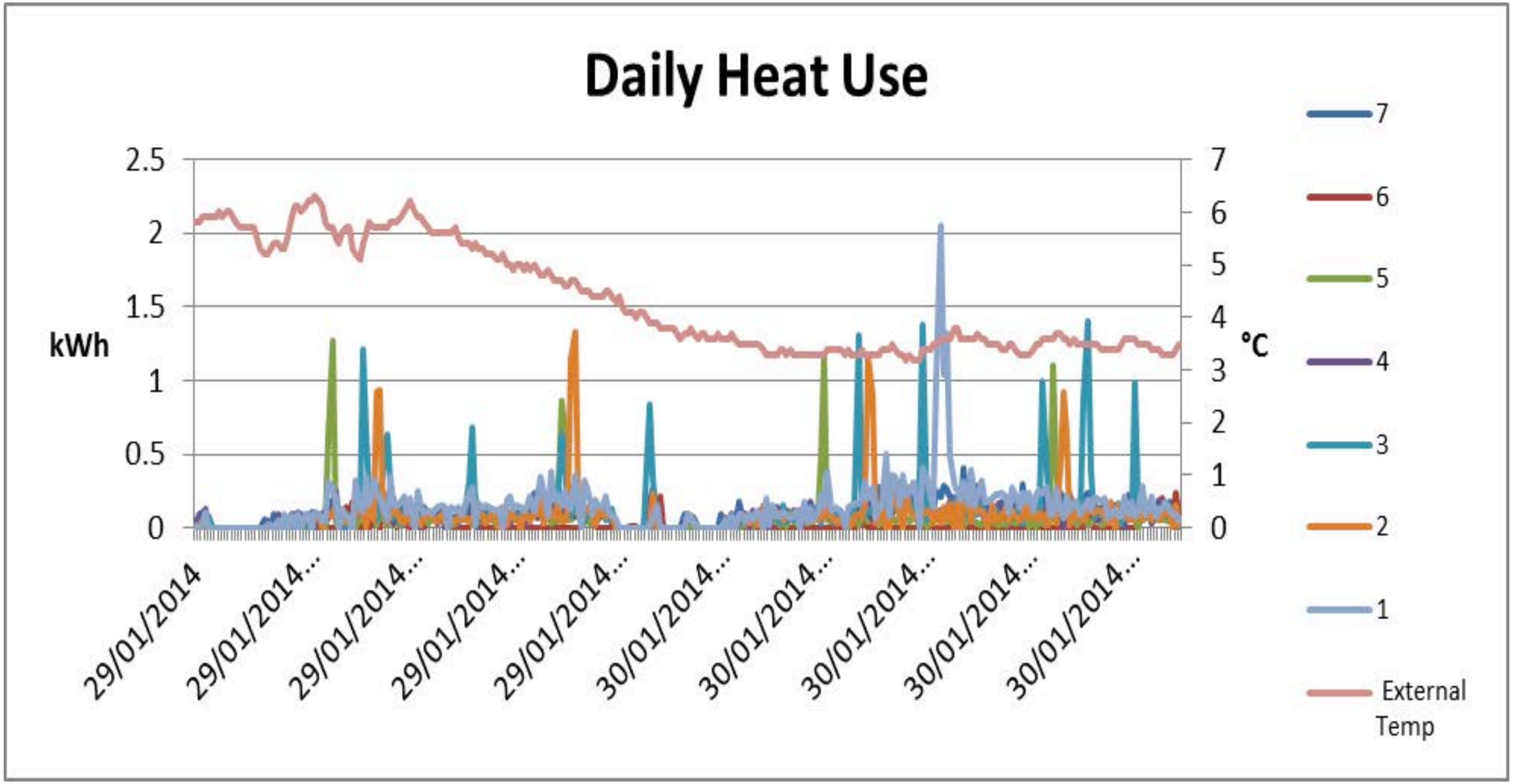

Figure 42: Daily heat use pattern

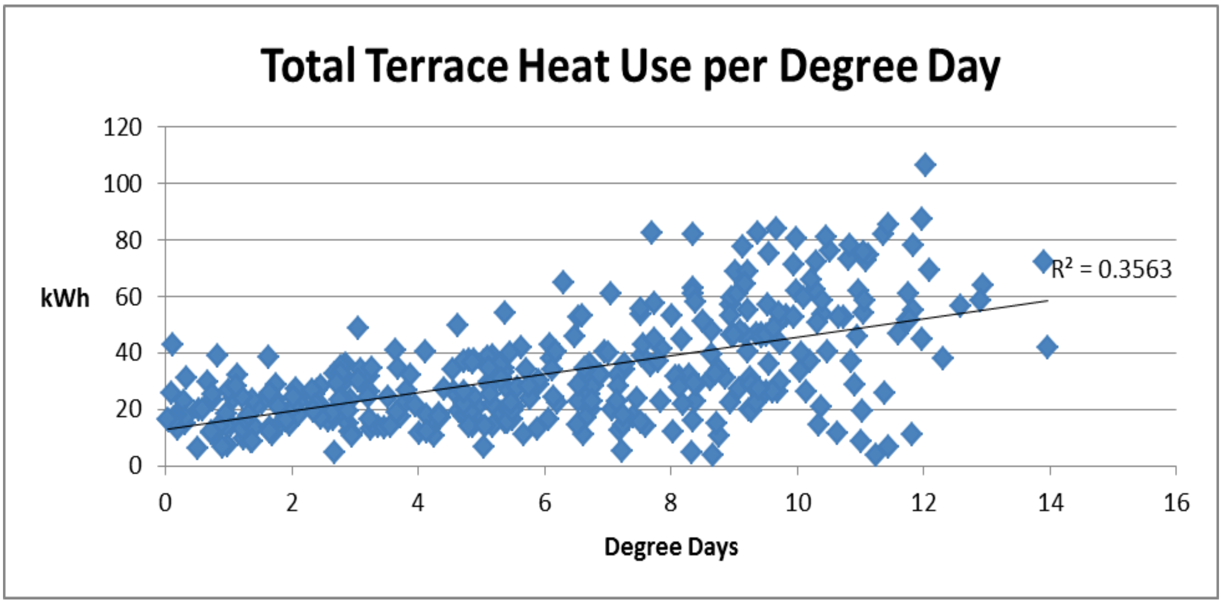

Figure 43: Relationship between terrace heat use and Degree Days

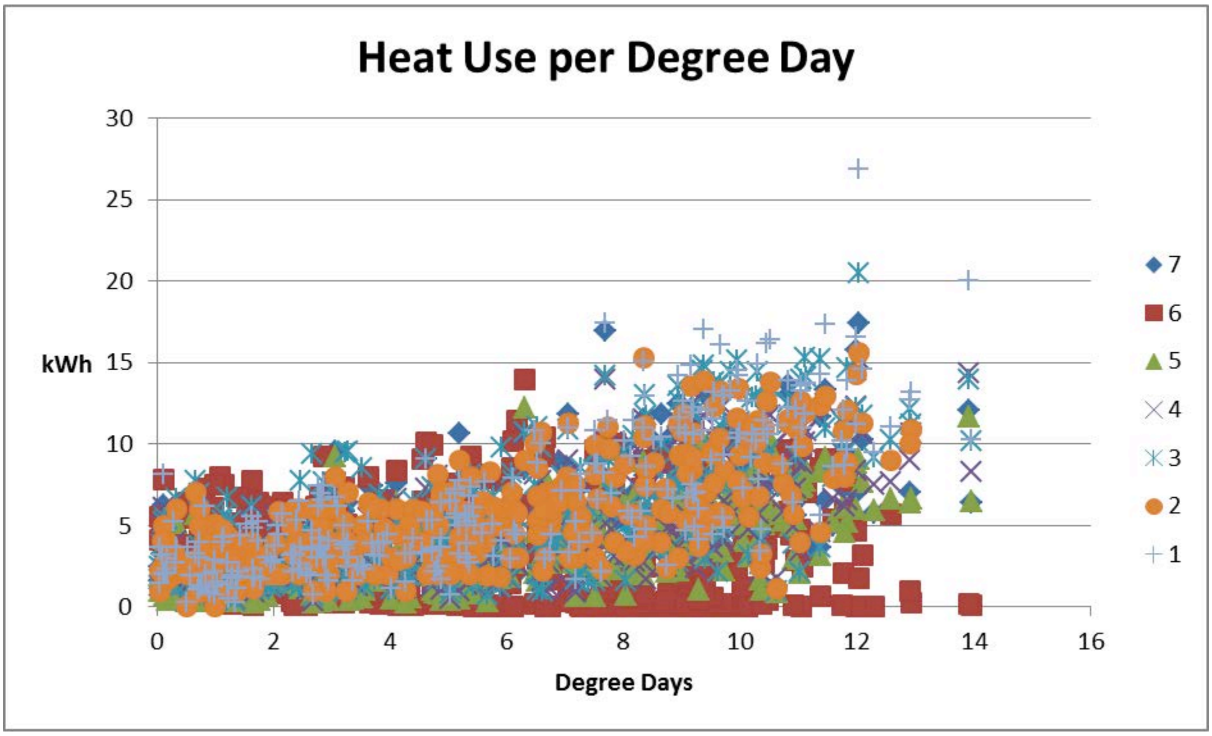

Figure 44: Relationship between dwelling heat use and Degree Days

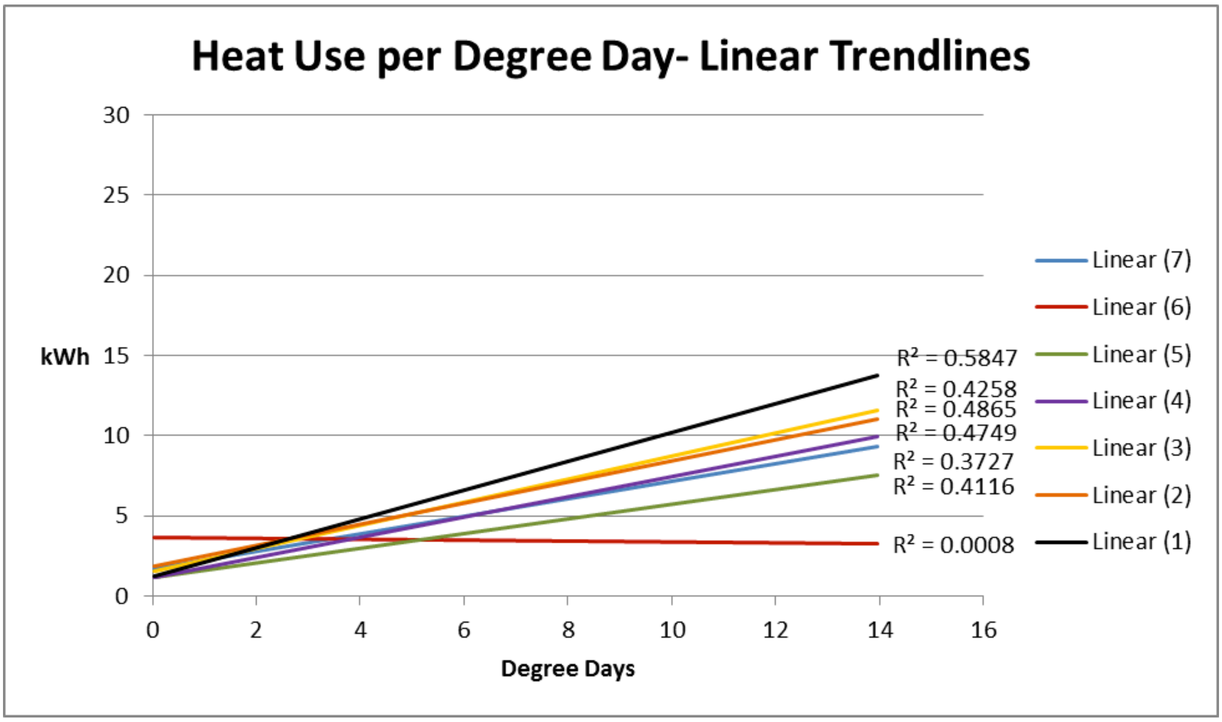

Figure 45: Relationship between dwelling heat use and Degree Days

7.3 12 month monitoring data – Intensive property

7.3.1 Conditions

Temperature, relative humidity and CO_2 were recorded in the living room, bedroom and bathroom at 10 minute intervals for dwelling 7 during the monitoring period. This section will mainly focus on the issue of overheating, which is a challenge facing PassivHaus developments due to their high thermal efficiency and airtightness.

Figure 46 shows the average daily temperature in the three monitored zones (lounge, master bedroom and bathroom) relative to external temperature. The close grouping of the temperatures in the three zones show a good mix of air in the dwelling, and the stability of the data points indicated that temperatures are consistent. This is to be expected in a PassivHaus dwelling with the MVHR combining with high thermal insulation and airtightness. Immediately noticeable, however, is that the temperature is consistently around 25°C which most people would regard as being quite warm. Although it is taken into consideration that the residents may prefer a warmer temperature (the residents in this case are elderly), NHS guidance advises against extended periods of over 26°C for elderly and disabled people, in addition to the ASHRAE comfort guidelines of a comfort threshold of 26°C in the lounge and 23°C in the bedroom, with overheating at 28°C in the lounge and 25°C in the bedroom.

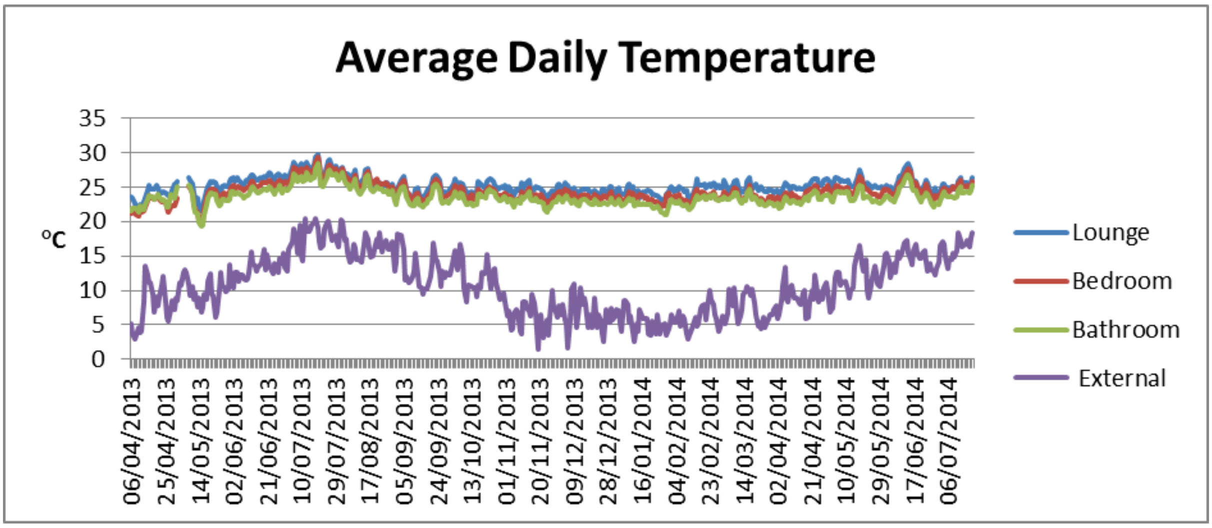

Figure 46: Average Daily Temperature

Figures 47, 48 and 49 display the monthly maximum, minimum and average internal temperatures for each of the three monitored zones. The extremities in the lounge are noticeably larger than in the other two zones, and it is believed that this is due to the large South-facing glazing area which increases the effect of solar, and also increases the ability of the resident to cool the area through opening of the French doors. The average temperatures in the bedroom appear to be consistently above the ASHRAE comfort guidance.

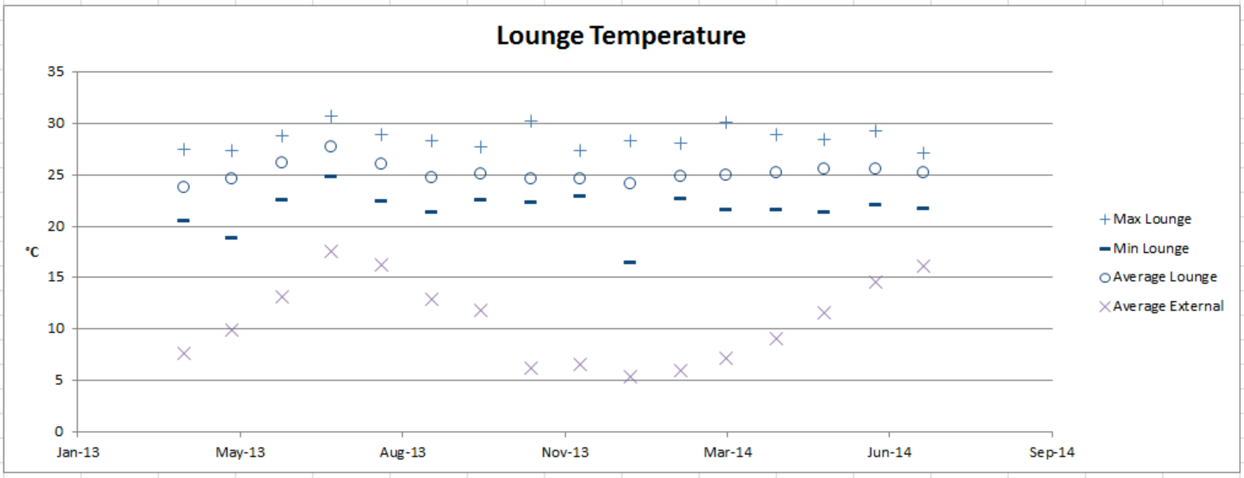

Figure 47: Monthly temperature distribution in the Lounge

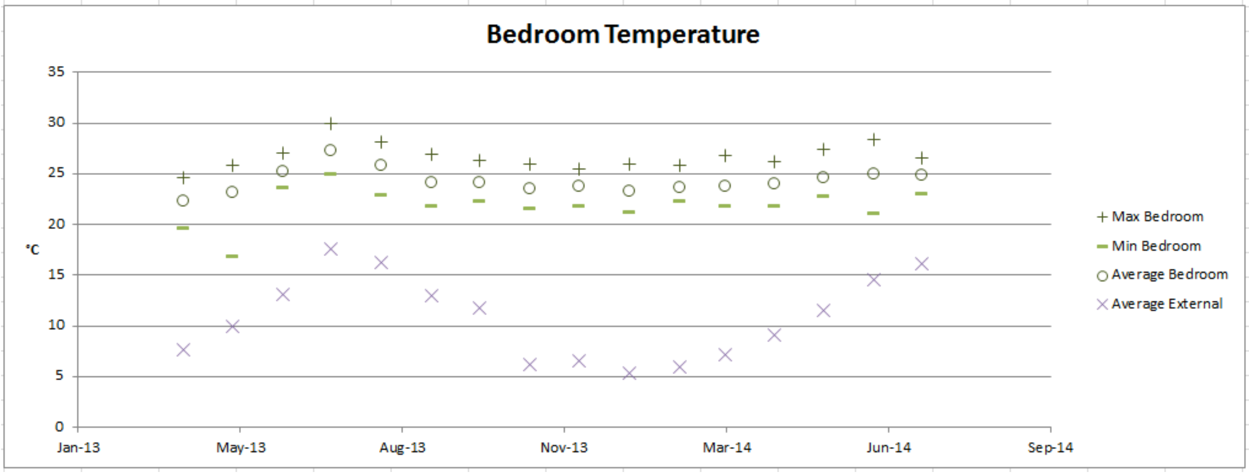

Figure 48: Monthly temperature distribution in the bedroom

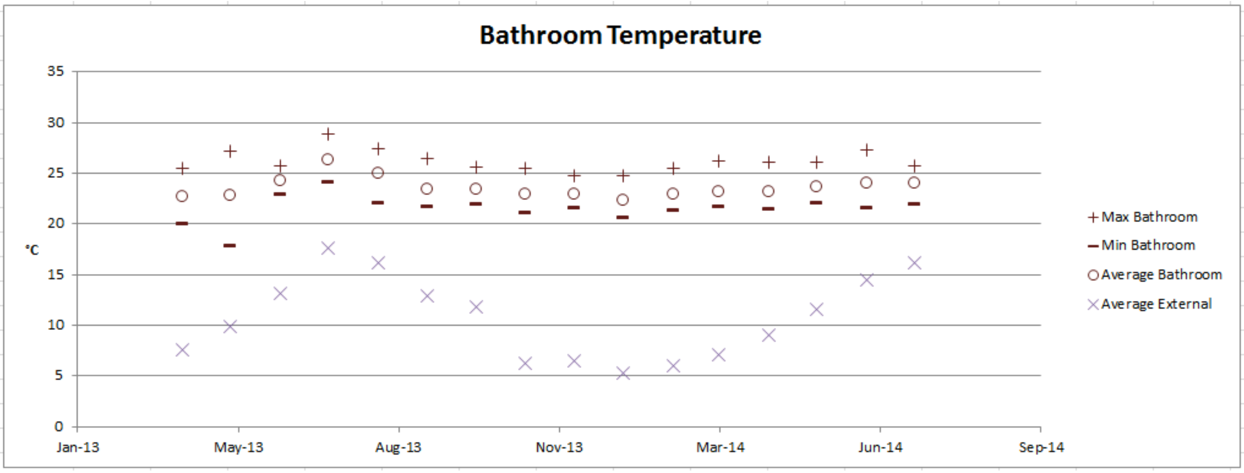

Figure 49: Monthly temperature distribution in the Bathroom

Guidance advises that areas should not be exceeding suggested temperature thresholds for extended periods. With this in mind, Figures 50 and 51 display the total occurrences of overheating in the dwelling as a whole. Internal conditions were logged at 10 minute intervals, and all temperature data logged that was over 26°C has been aggregated to provide a dwelling overheating analysis. Figure 50 shows a high occurrence of overheating periods in June, July and August 2013, with this trend appearing to continue in 2014 as the values for June 2014 are comparable to 12 months earlier. With a variable amount of 10 minute intervals per month due to differing month length, Figure 51 disaggregates the count data and compares it to a 'maximum count' (i.e. all data points collected in the month) and presents in the form of hours. It is surprising to see that in July 2013 almost every instance of 10 minute temperature data logged in the lounge and bedroom was over 26°C.

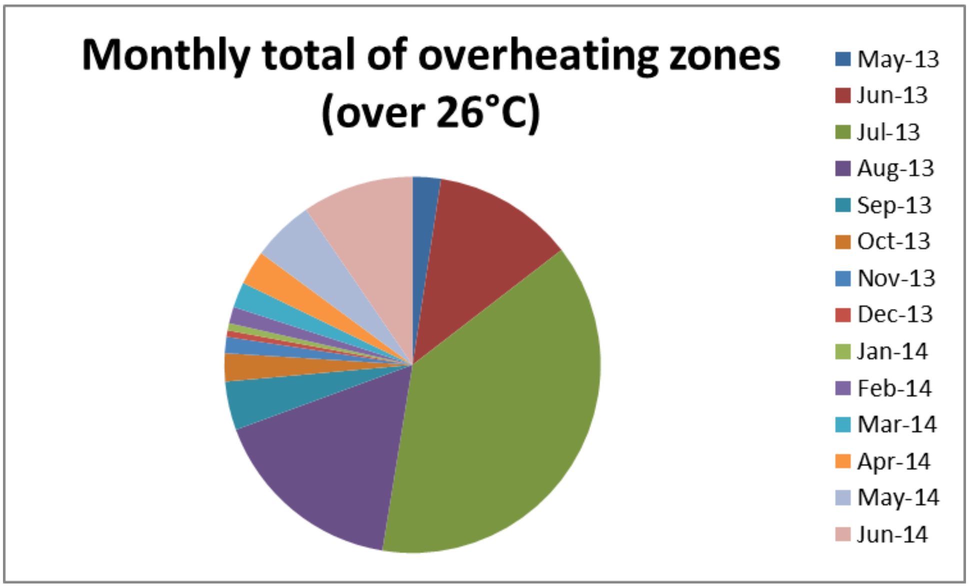

Figure 50: Total occurances of overheating

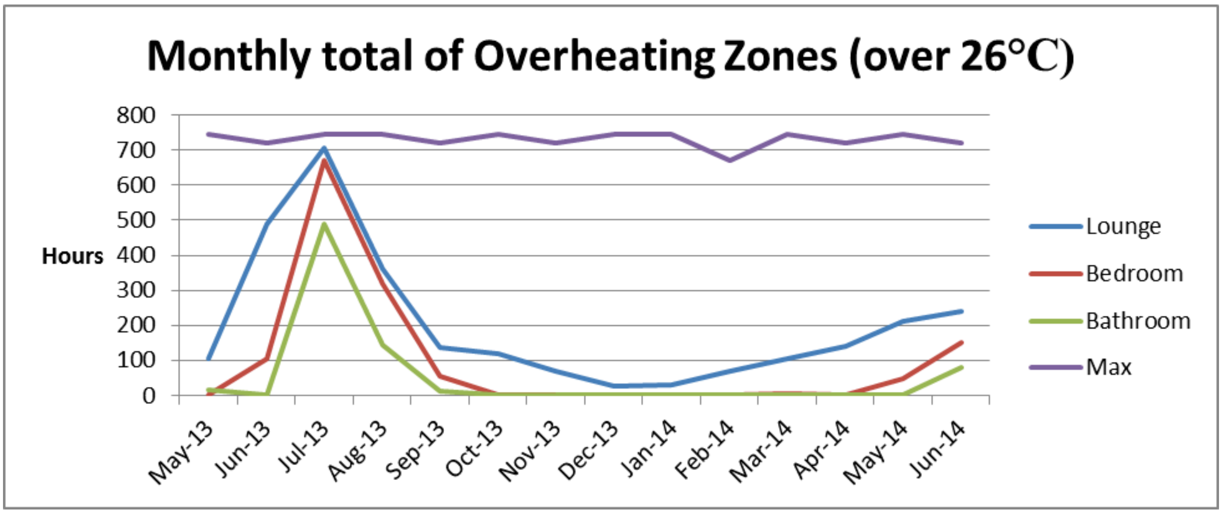

Figure 51: Total occurances of overheating

The ASHRAE guidance for comfort and overheating is explored further in Figures 52, 53, 54, and 55. The guidance suggests living rooms become uncomfortable at 26°C and overheat at 28°C, whereas bedrooms become uncomfortable at 23°C and overheat at 25°C. ASHRAE guidance was used for comparison as opposed to CIBSE guidance which no longer relies on thresholds in the most recent guide from the overheating task force. Figures 52 and 53 show overheating in the lounge and bedroom for 4% and 29% of the time, respectively. Perhaps more concerning, Figures 54 and 55 show an uncomfortable temperature in the living room and bedroom 26% and 88% of the time, respectively. Property 7 is one of the dwellings that have returned a completed BUS questionnaire, and feedback directly corresponds with the measured data, with comments stating that the bedroom is 'too hot'.

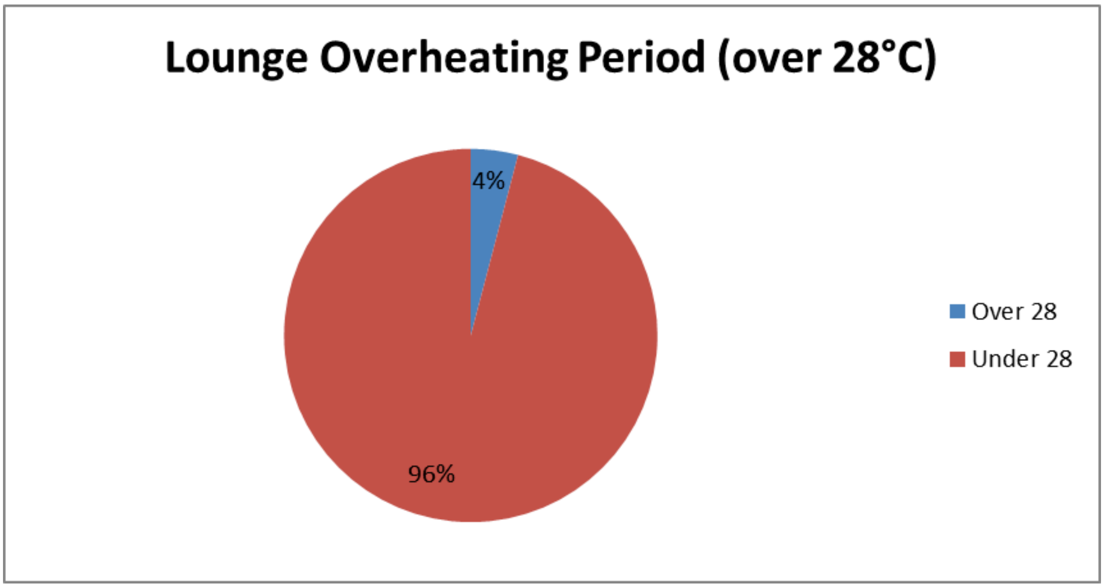

Figure 52: Lounge overheating period

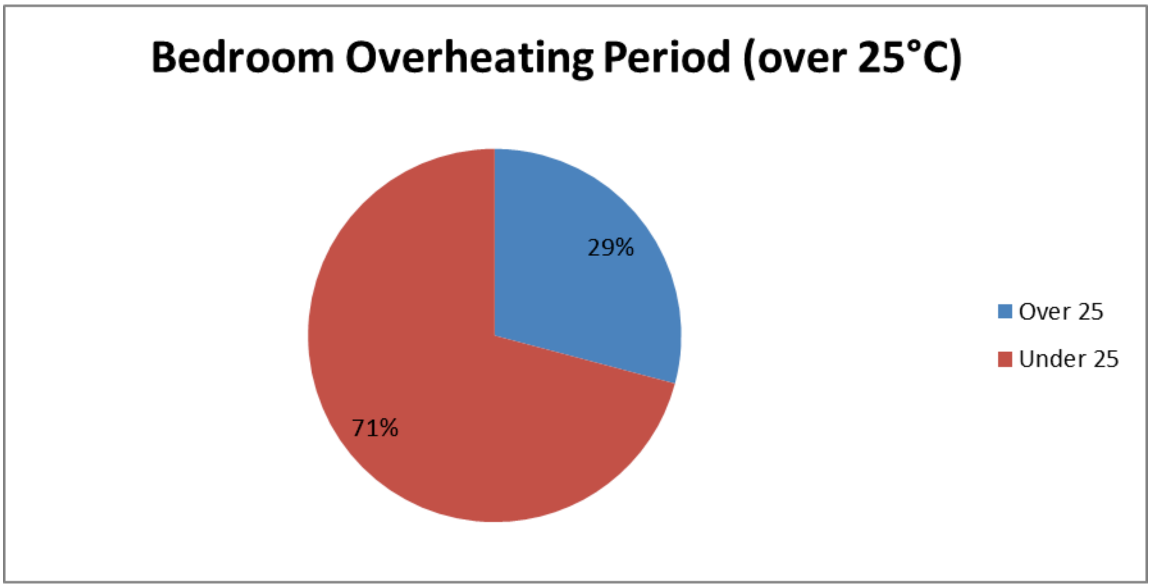

Figure 53: Bedroom overheating period

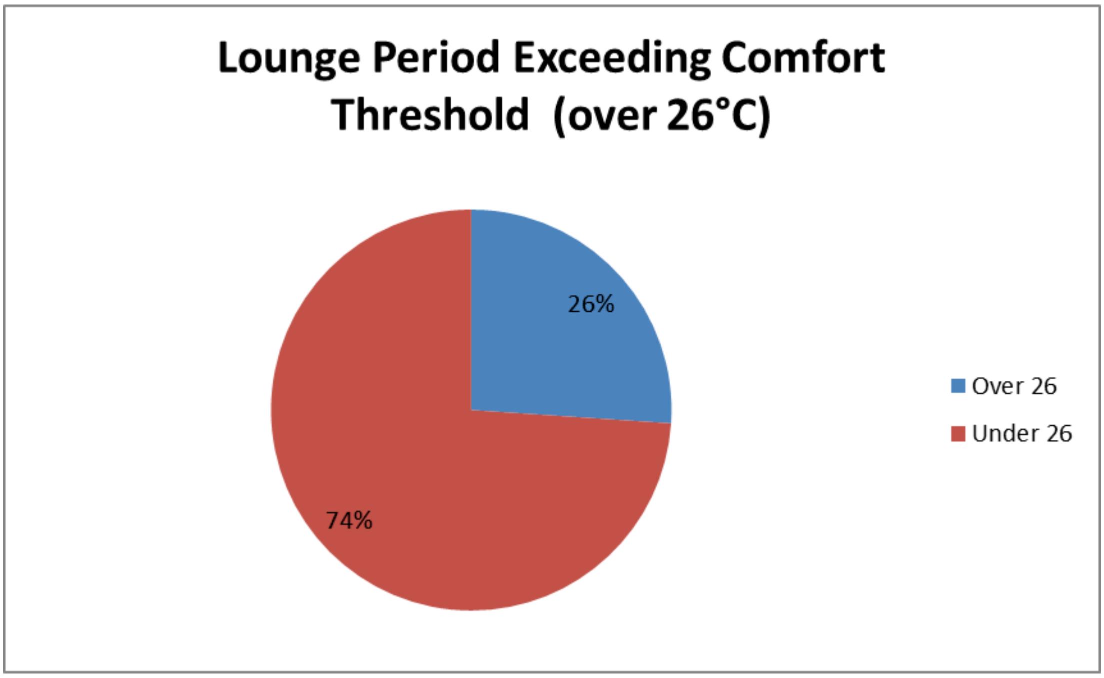

Figure 54: Lounge discomfort period

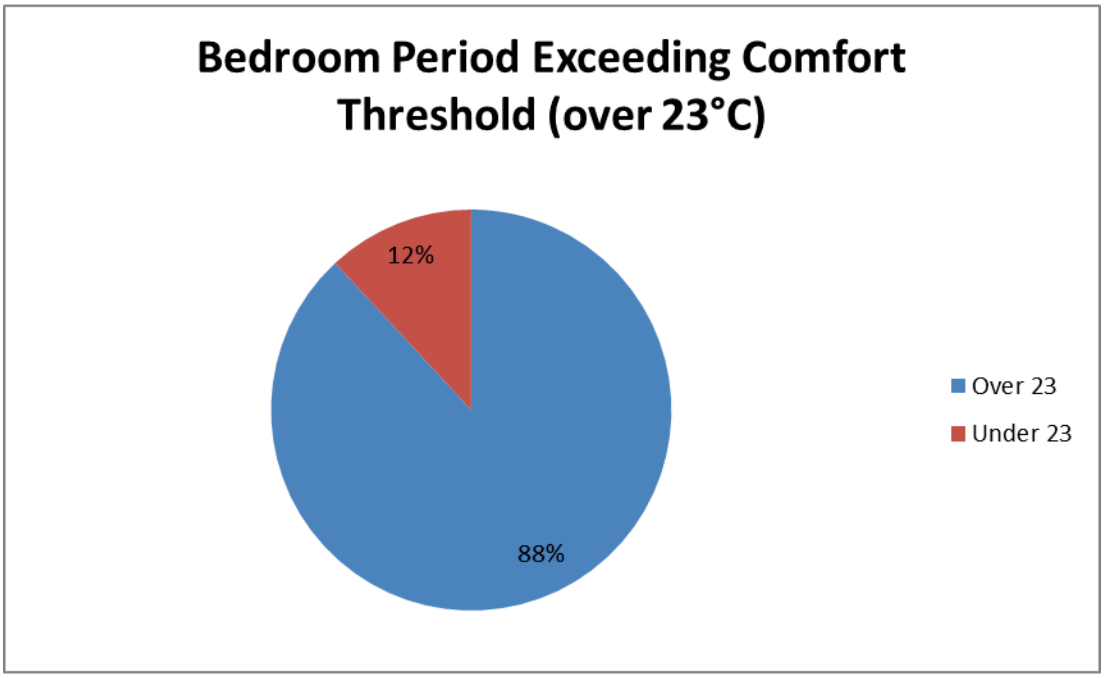

Figure 55: Bedroom discomfort period

In an effort to explain these high temperatures, the month of July 2013 has been explored further in Figures 56, 57, 58 and 59. Figure 56 shows a relationship between the external ambient temperature and internal temperatures, which is to be expected. Average temperatures in this period displayed in Figure 57 are commonly around 27°C, with peaks of around 30°C and rarely dropping below 25°C.

Due to the PassivHaus design and the intention to maximise solar gains, it is the belief of the research team that the high temperature is driven by solar incidence. The relationship between internal temperature and solar gains is not very clear in Figure 58 which covers the entire month, but by focussing on a daily cycle in Figure 59 we can see an interesting apparent pattern. Daily increase in solar incidence cause a step up in internal temperatures. Due to the high level of insulation and airtightness and low thermal mass, internal temperatures are unable to drop to their starting point before the next occurance of solar, leading to a gradual stepping up in internal temperature over time. These dwellings are designed with a low thermal mass and fast response time, such that they heat up and cool down quickly.This suggests that occupants may not be ventilating their dwellings overnight, as night-time cooling would cause a noticable decline in internal temperature. If night-time cooling is not done, warm air is trapped inside the house, increasing the overheating risk for the next day. Residents were reluctant to leave windows open overnight due to security concerns, with no fully secure ventilation option available. Resulting from this finding the project architect is investigating the possibility of a secure vent with louvre.

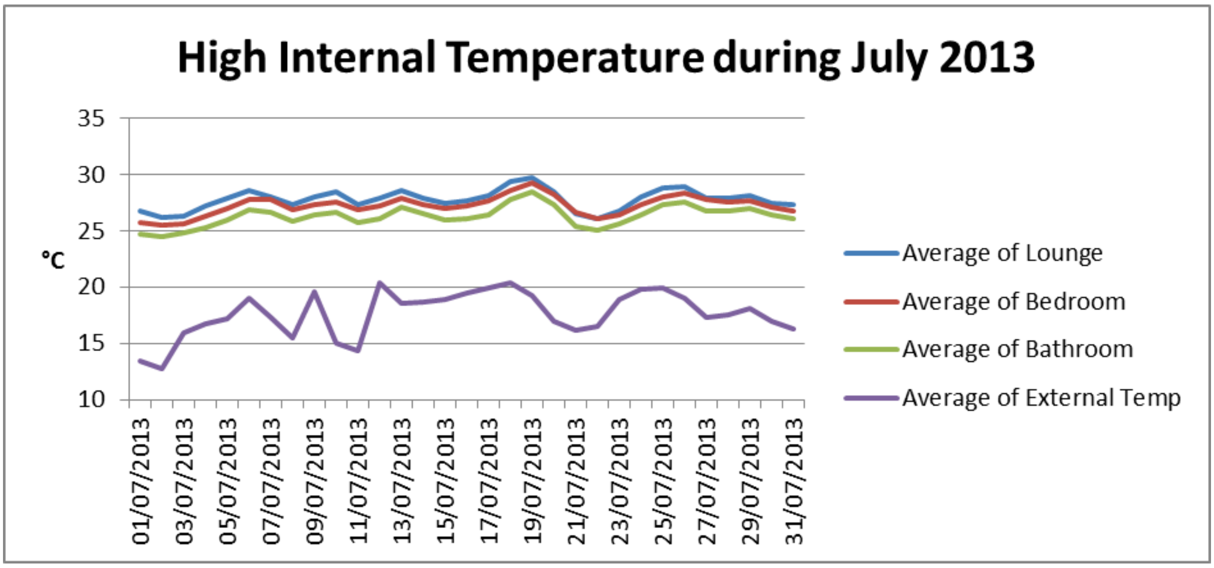

Figure 56: High temperature period

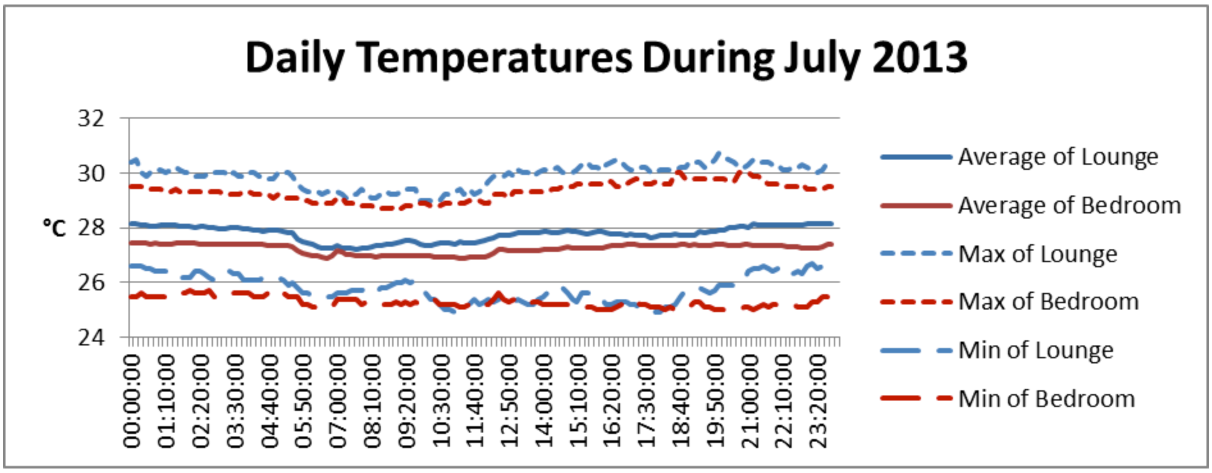

Figure 57: Temperature distribution during high temperature period

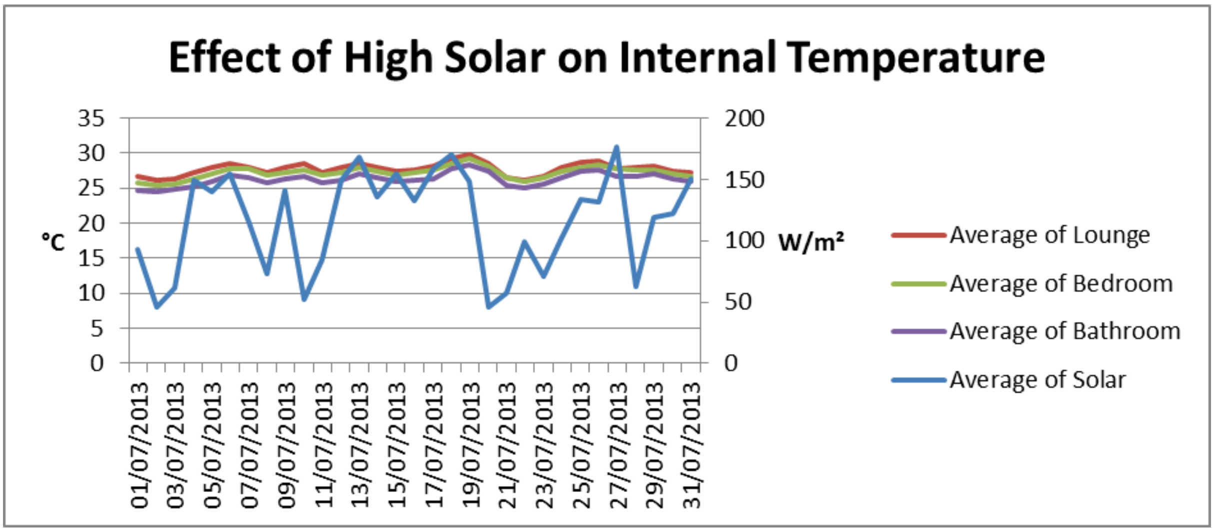

Figure 58: Effect of solar on internal temperature

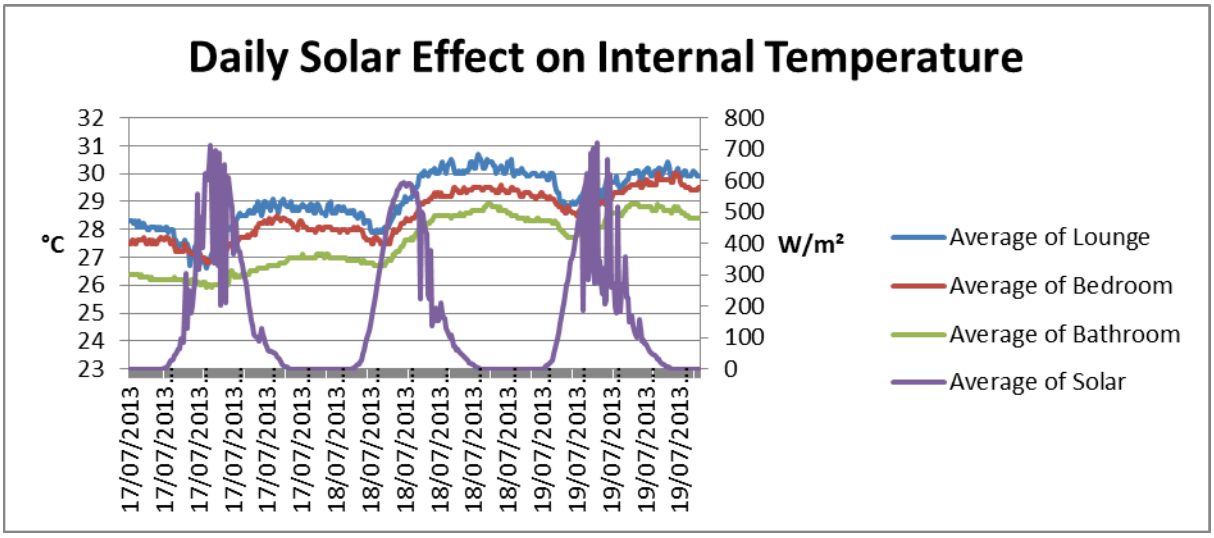

Figure 59: Daily effect of solar on internal temperature

Average daily internal relative humidity is displayed in Figure 60. The relative humidity for the three zones is closely grouped, suggesting that the air is mixing well within the dwelling. As would be expected, the bathroom has consistently higher humidity as it is a wet room. A slight pattern can be observed with higher internal relative humidity during summer. It is possible that this is due to residents being more likely to open their windows during summer, leading to the introduction of moisture from outside. Residents also may not be using the south facing windows to their full capacity to purge the dwelling. The windows are on a dual pivot which allows them to tilt forward creating an opening of almost two inches, but also to pull open from the side and operate as a door. The temperature and humidity data suggests that the wider opening option is not being used effectively.

The monthly measurements displayed in Figures 61, 62 and 63 show a wide range of readings, with average values supporting the observation of higher average relative humidity in warmer months. The introduction of moist air from outside may account for the high maximum values during these months.

Noticably, relative humidity levels never exceed 70%, even in the bathroom. It is sometimes a criticism of properties featuring an MVHR system that the internal air is dry. Levels drop below 30% for a total of 1779 hours in the Lounge and 1479 hours in the bedroom, which represents 15.8% and 13.1% of the time respectively. Part of this time does, however, fall in the early stage of monitoring when the home was unoccupied, so moisture from internal activites and external sources were minimal.

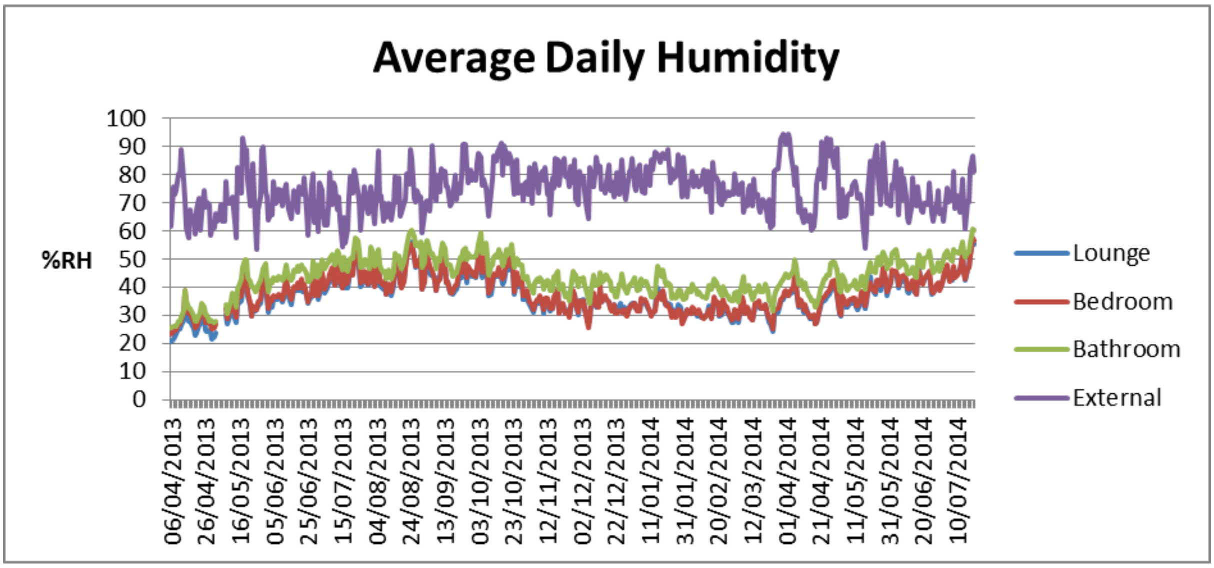

Figure 60: Average daily relative humidity

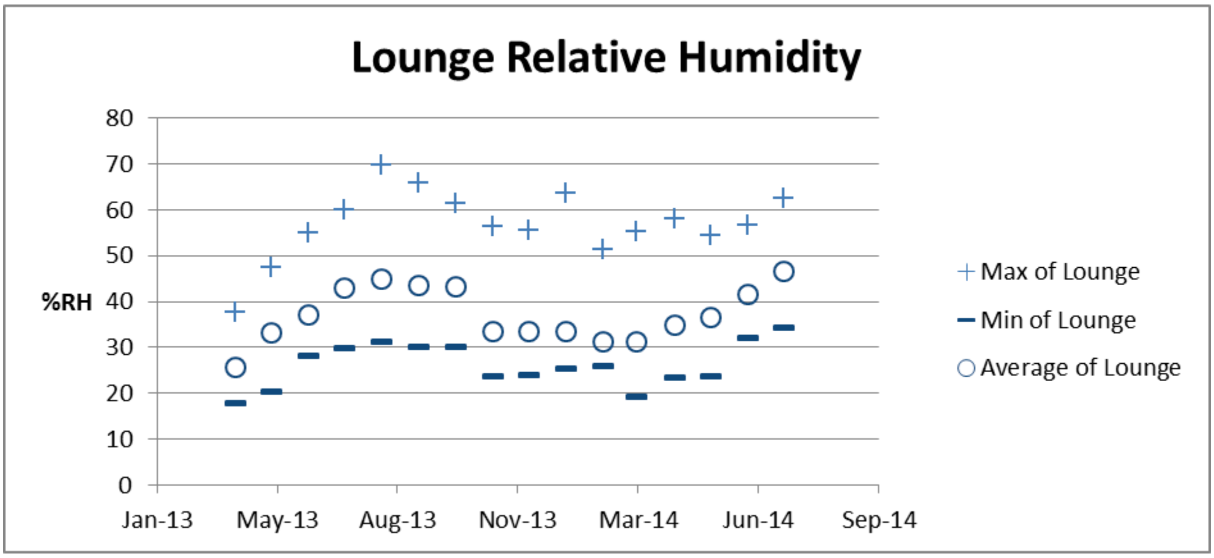

Figure 61: Lounge monthly relative humidity

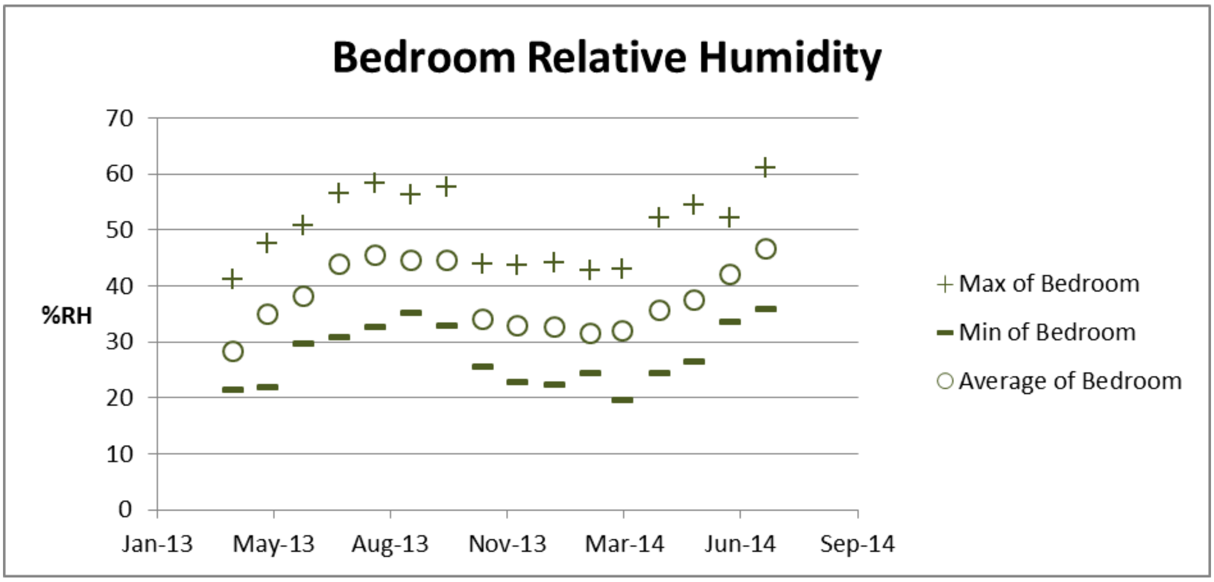

Figure 62: Bedroom monthly relative humidity

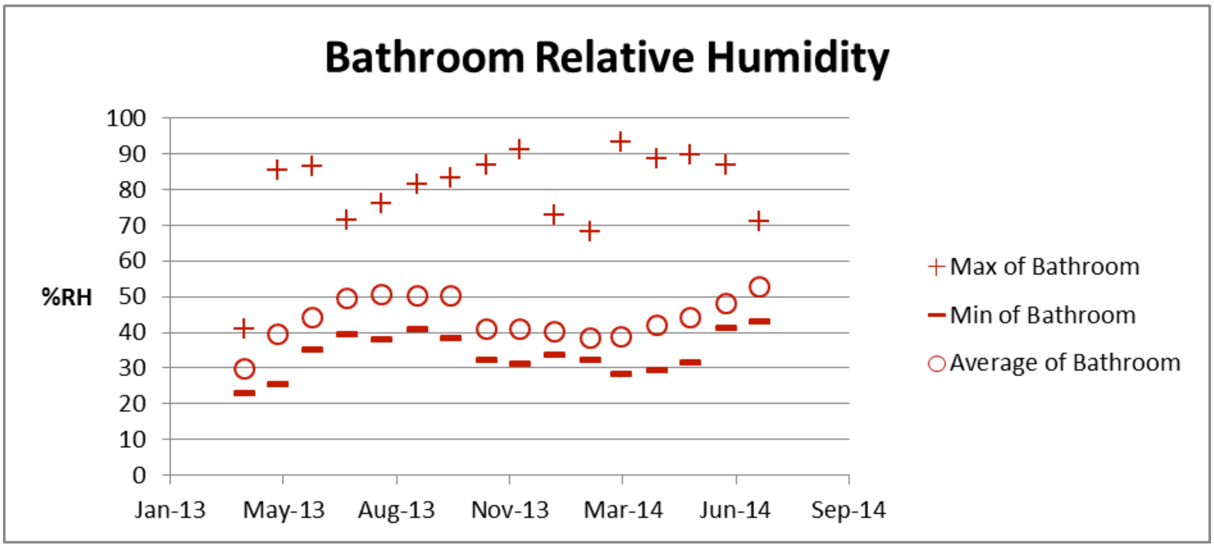

Figure 63: Bathroom monthly relative humidity

Concentration of CO_2 can be used to indicate air quality in dwellings. Figure 64 displays average CO_2 throughout the duration of the monitoring period. Levels should not exceed 1000ppm for an extended period in order for conditions to be comfortable. As is clear in the data, the dwelling receives sufficient fresh air to stay below this for the majority of the time. Figure 65 shows in more detail a period when CO_2 level exceeded the 1000ppm threshold, and it is apparent that this was an isolated peak with a slow return to below the 1000ppm level. This could occur for numerous reasons, such as having several people in the property, and does not represent a cause for concern. Interestingly, Figure 64 shows a slight increase in CO_2 levels during winter, supporting the theory that windows are not opened at this time. Overall, CO_2 analysis suggests the MVHR system is supplying sufficient fresh air.

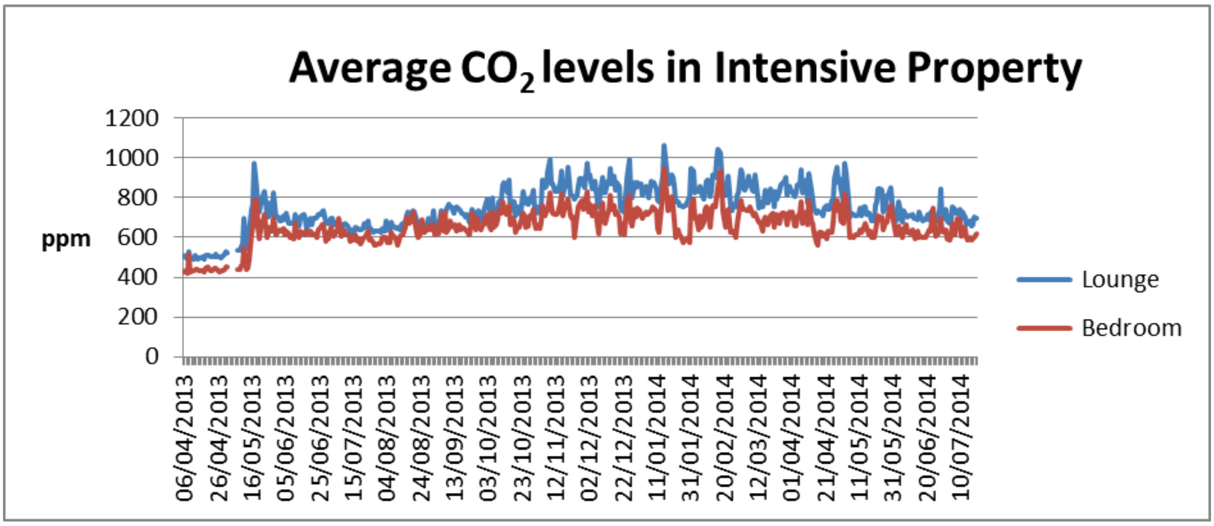

Figure 64: Average daily CO_2 measurement

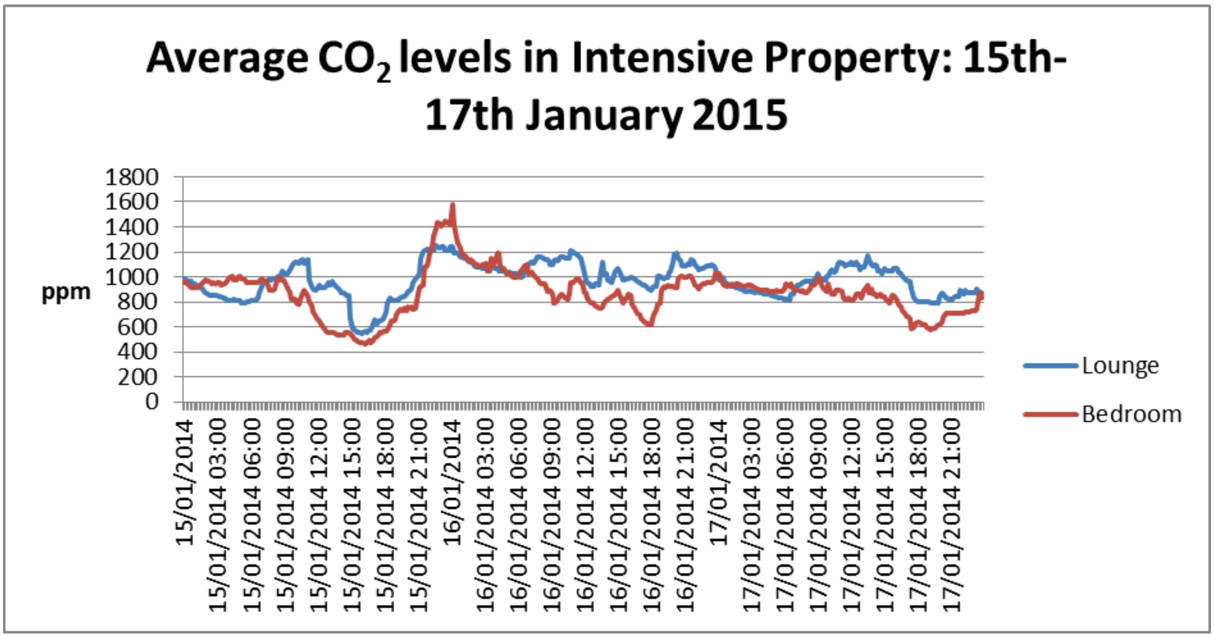

Figure 65: Daily CO_2 measurement during peak period

7.3.2 Electrical use

Both total and sub metered electrical energy use was monitored throughout the duration of the project. Sub-metered circuits were:

- Heating system
- Loft Light
- Security alarm and intercom
- Lights and smoke alarm
- Solar Unit
- MVHR
- Frost Protection for solar thermal system
- Cooker and Sockets (not directly metered but obtained through subtraction from total electricity)

It was recently discovered that sub-metered circuit labelling on the consumer unit and on the physical DIN rail do not correspond, as can be seen in Figure 66, causing delays in the final analysis of data to verify wiring.

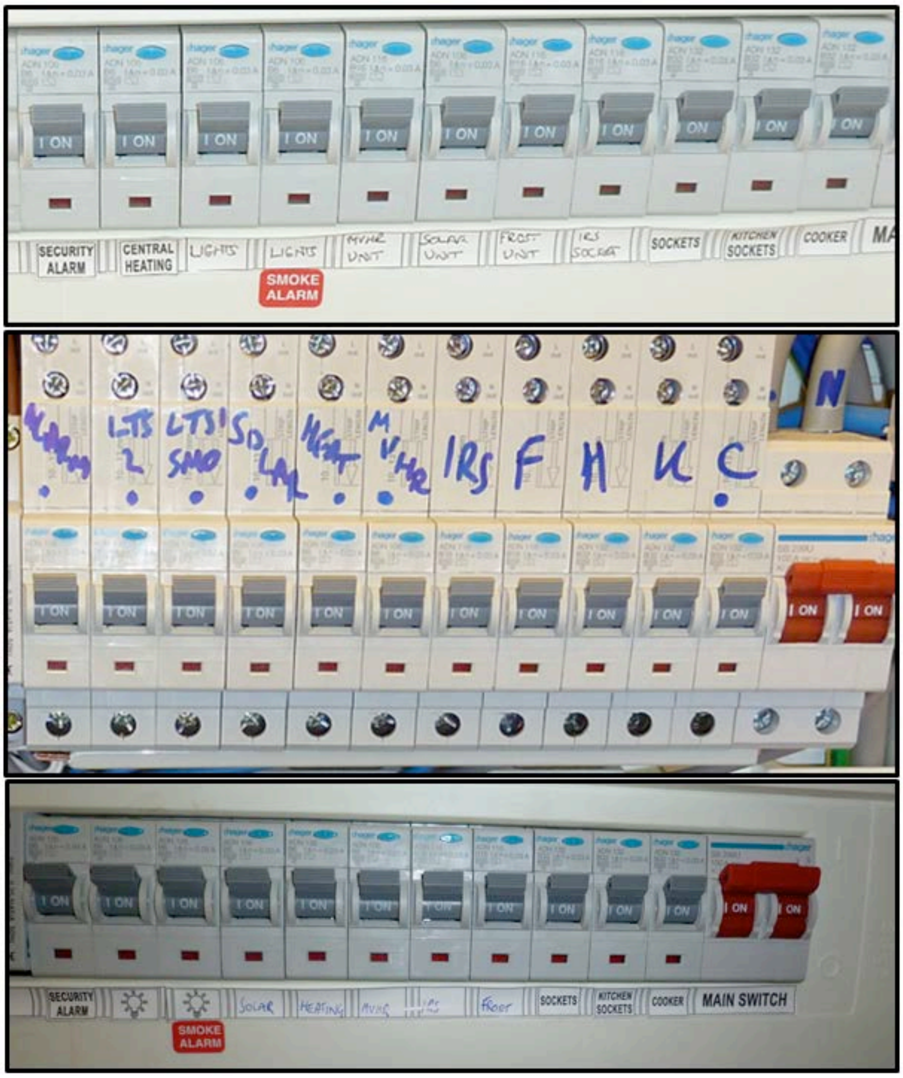

Figure 66: Sub-meter labelling

Figure 67 displays the disaggregated daily total electricity use during the course of the monitoring period, with the sockets and cooker omitted for clearer graphical representation. Unfortunately, only total electricity use for the MVHR was able to be obtained due to issues with the DIN rail kWh meter. As the system is running constantly for 24 hours and conversation with residents determined that the boost function is not used, data has been averaged over a daily period for the duration of the research.

It is noticable that some circuits, such as MVHR, heating and frost protection display a uniform energy demand throughout the duration of the research, which is to be expected as these systems are constantly running at a set level. There is a peak in the heating data which suggests the system was used in a different way on the 30th January, although the specific detail is not known at time of writing. Of the other circuits, the lighting circuits can be seen to use more energy during the winter months, as it is required to light the home for longer periods. Lighting follows an erratic pattern which is to be expected as it is entirely dependent on occupant behaviour. The alarm and intercom usage is stable throughout the monitoring period, as would be expected from a system constantly operating.

The most erratic energy use is displayed by the solar unit, showing lower use during winter and more in summer. Figure 68 investigates this further, showing the clear relationship between solar insolence measured by the external weather station and energy use by the solar unit. Figure 68 also allows us to see the point at which the solar unit is ‘idle’, with energy use at a minumum of 80Wh per day (power consumption around 3.5W) when solar level is low.

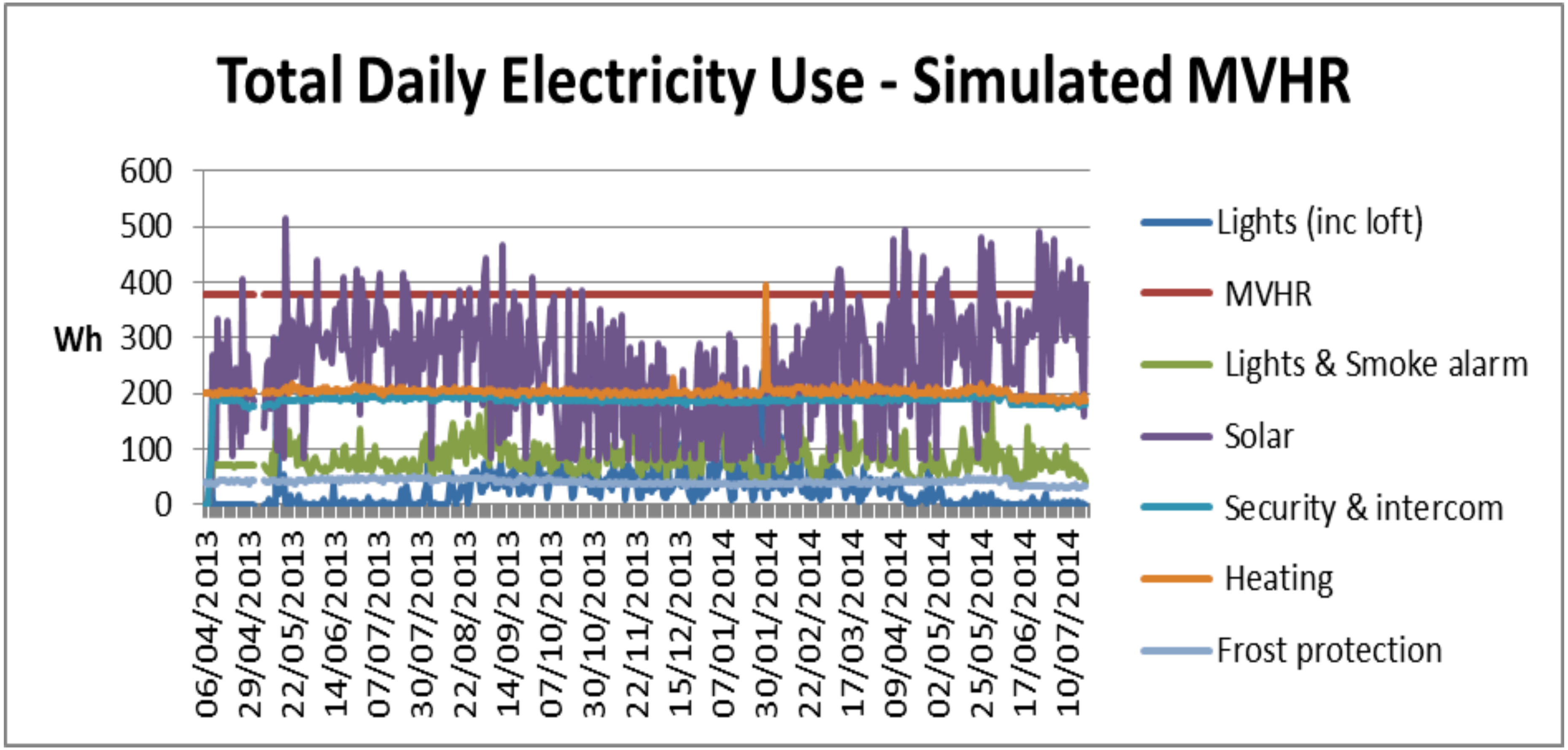

Figure 67: Total daily electric use

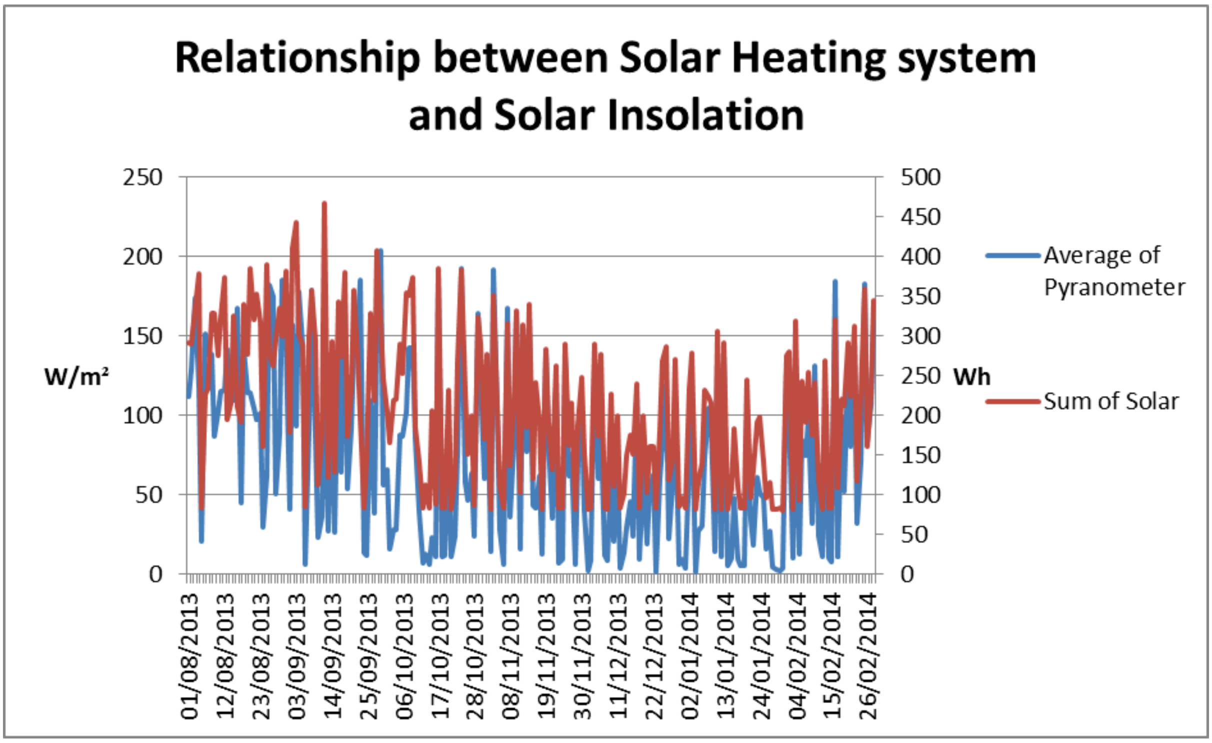

Figure 68: Relationship between solar insolation and soler unit electrical consumption

Figures 69 and 70 display the total electrical energy use for each circuit throughout the duration of the monitoring period. As can be seen in Figure 70, electrical use is dominated by socket loads and cooking. This energy use is entirely occupant driven.

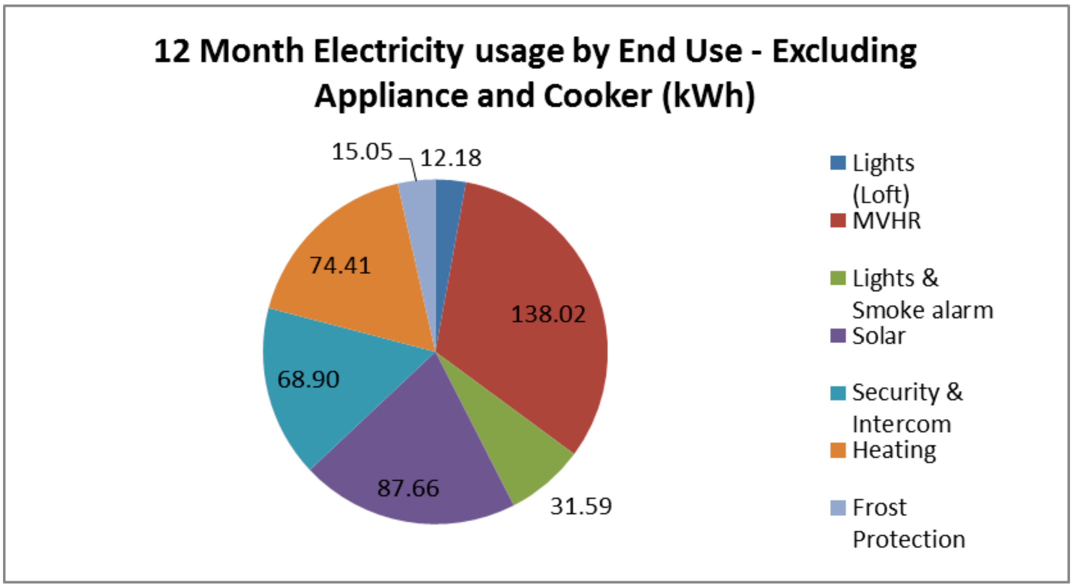

Figure 69: Total consumption by end use (excluding Cooker and Sockets)

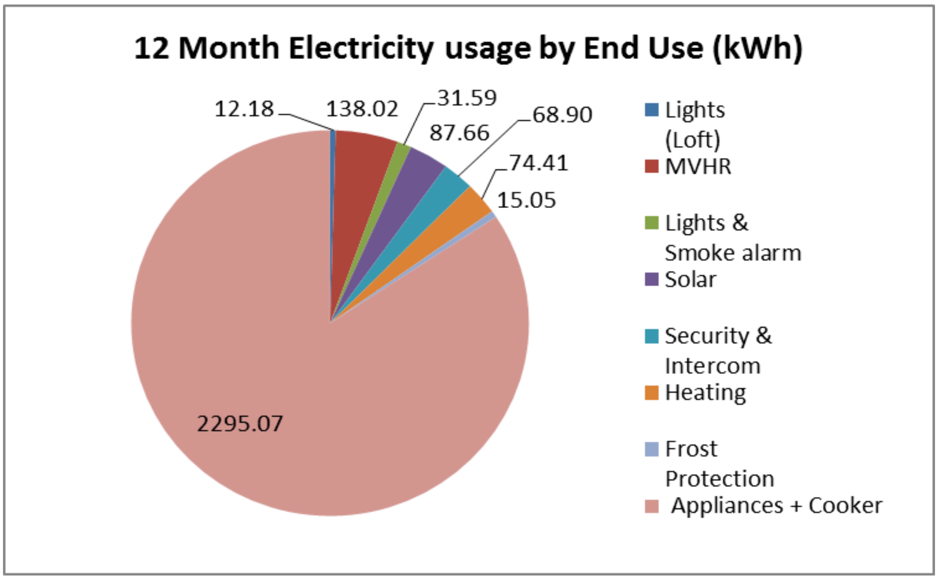

Figure 70: Total consumption by end use

Figures 71, 72 and 73 display total disaggregated electricity use over monthly periods. It should be noted that the differing lengths of the month will have an impact on total monthly aggregated data. In Figure 71, energy use appears to be broadly consistent, with the main variation coming from the sockets and cooker, a factor driven by occupant behaviour. With sockets and cooker omitted, in Figure 72 we can observe the pattern of the other circuits, with variance driven by the change in occupant lighting behaviour. It is important to note that some lighting demand may also be attributed to socket load due to the presence of several plug in lamps. With all occupant driven usage removed (lighting circuits, sockets and cooker), in Figure 73 we see a far more consistent consumption, with variance primarily due to the decrease in use by the solar system during winter.

The SAP worksheet for the dwelling states that annual electrical consumption for the MVHR system, including pumps and fans should be 275 kWh. Measured energy use for the system is 138.02 kWh. It is thought that the difference is due to the boost setting not being used by the occupants as anticipated, which would increase electrcal load and cause a rise in total consumption.

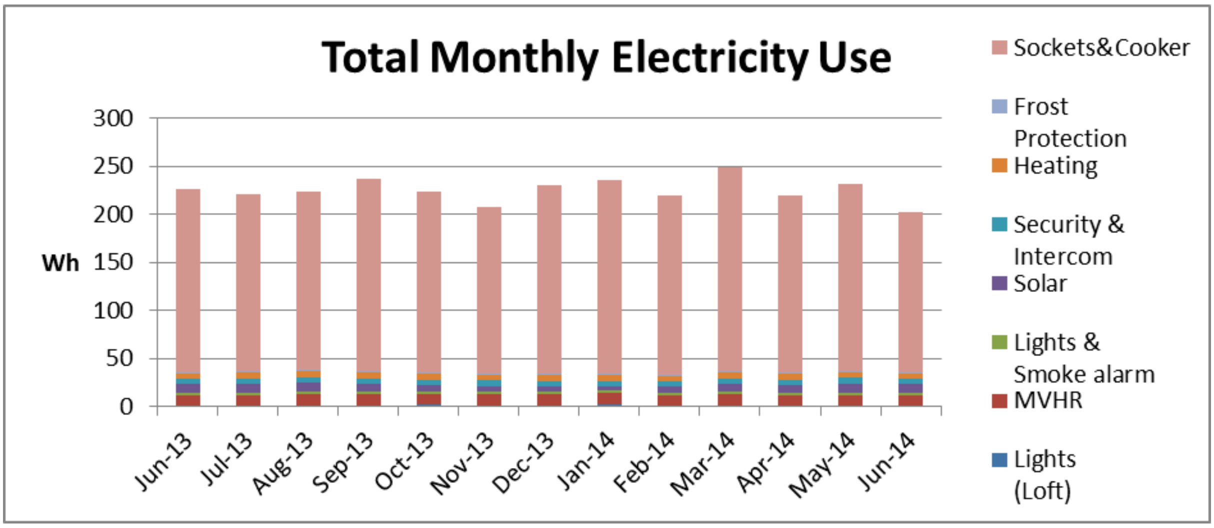

Figure 71: Total monthly use

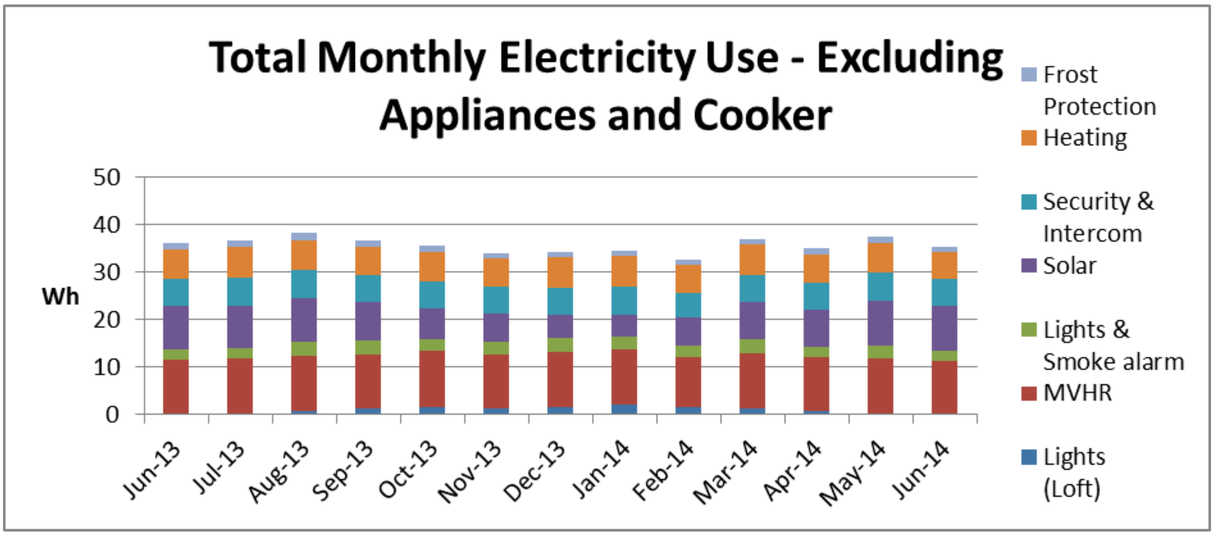

Figure 72: Total monthly use (excluding cooker and sockets)

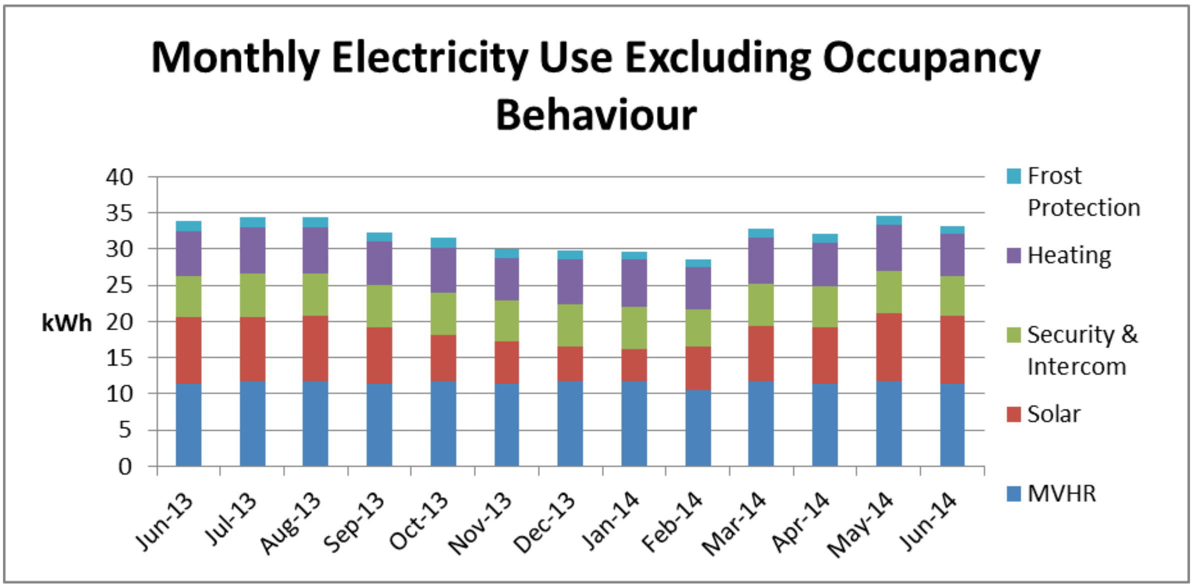

Figure 73: Total monthly use (excluding occupant behaviour)

Table 10 summarises total energy use for the entire monitoring period for each sub-meterd circuit and the kgCO_2 equivalent. For CO_2 calculation, the standard of 0.527kg/kWh given by the Carbon Trust/DEFRA for grid electricity was used. Also represented in Table 10 is a comparison between designed taget energy use and actual use, taken from the design and as built SAP worksheets. The comparions suggest that the installed lighting is used far less than SAP anticipates. This may be due to the impact of high levels of designed natural daylighting and also the use of stand alone lamps as the primary light source.

End Use	Electricity Use (kWh)	Design SAP		As Built SAP		CO_2 (kg)	Total Share (%)
		Target (kWh)	% Difference	Target (kWh)	% Difference		
Light (inc. loft)	12.86	300	-82.7	294	-82.4	7	0
Lights & Smoke Alarm	38.97					99	6
MVHR	187.56	197.5	-5.0	200.1	-6.3	21	1
Solar Unit	114.97	-	-	-	-	61	4
Security & Intercom	86.75	-	-	-	-	46	3
Heating	94.36	-	-	-	-	50	3
Frost Protection	18.87	-	-	-	-	10	1
Sockets & Cooker	2689.88	-	-	-	-	1418	83

Table 10: Energy use and CO_2 equivalent

7.3.3 Water and Heating

Water use throughout the monitoring period was broadly consistent, although daily figures are erratic as use is driven by occupant behaviour. Total water use is represented in Figure 74. Also represented on Figure 74 is the supply of water to the hot water cylinder. We can use this to determine the amount of hot water used by the residents. Daily data is erratic, but by using a 7 point moving average to represent weekly behaviour relationships we can see a close correlation, highlighting the interconnectedness of hot water use and total water use.

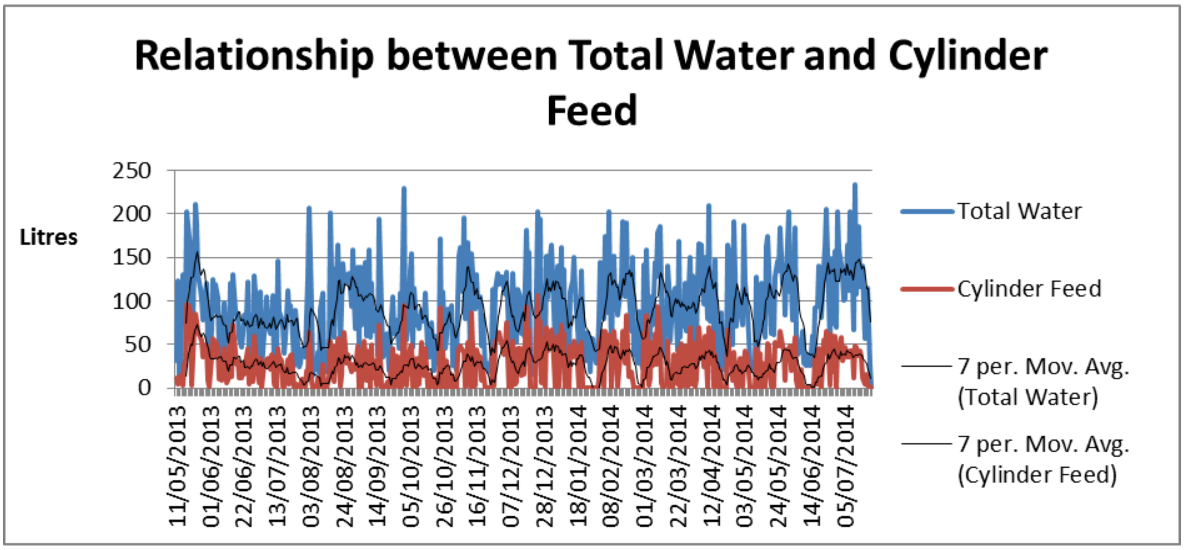

Figure 74: Total water use and hot water cylinder feed relationship

By contrasting the hot water cylinder feed with the data for total heat used, we can determine whether an increased heat demand is due to increased hot water use or a demand for space heating. Figure 75 appears to show close correllation between hot water use and total heat used during the summer months, suggesting that the majority of heating energy is used for hot water. During winter, the two trend lines diverge and total heat increases, suggesting that additional heat demand is required (for space heating). This is supported by the flat linear trend of hot water use.

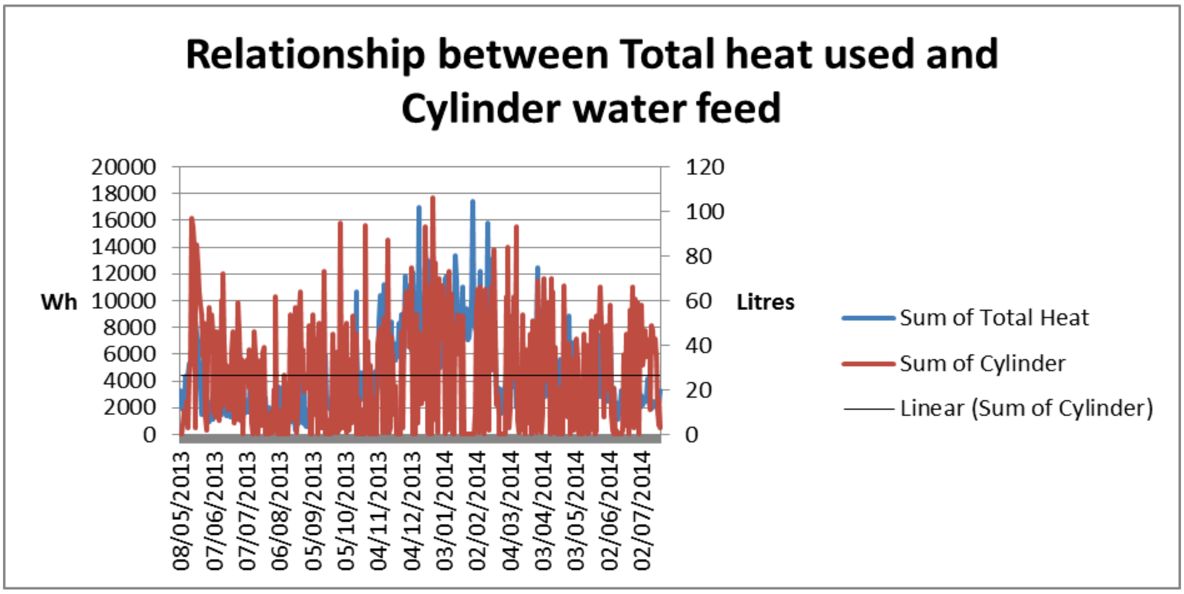

Figure 75: Relationship between hot water use and total heat

Duct temperatures in the MVHR system were measured using probe thermocouples inserted into the ducting at the supply and extract. These are shown in Figure 76. Extracted 'stale' air from the dwelling is consistently warmer than the 'fresh' supplied air, and there does appear to be a relationship between the two. Whilst extract air temperature appears to be broadly consistent, supply air temperature decreases during winter, which is likely due to the decreased temperature of external air being introduced to the dwelling. In order to reach the temperature of the extract, the supply air will be heated, correlalting with the increase in heating energy use for the winter period.

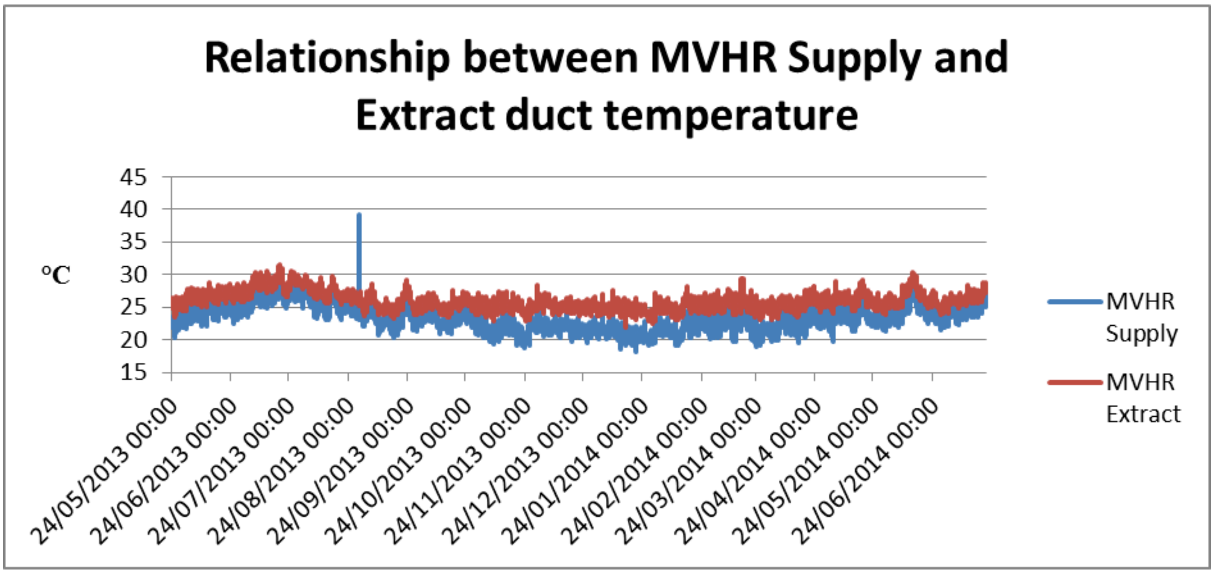

Figure 76: MVHR duct temperatures

7.4 Conclusions and key findings for this section

The stable temperature data for dwelling 7 suggests that the PassivHaus design, with high thermal insulation and airtightness, is working very well and effectively maintaining a constant internal thermal environment. In addition, the impact of solar gains on measured internal temperature highlights the effect of passive design to maximise solar effects, another intended consequence of the building design.

With this in mind, the main finding from the in use monitoring is the identification of an apparent overheating risk in the dwelling. Monitoring has shown significant periods of overheating during summer months exacerbated by the dwellings inability to 'purge' unwanted heat without increased night time ventilation. The reasons for the lack of overnight cooling may stem from earlier instruction given to occupants, who were advised to leave windows closed to increase MVHR efficiency. Although this advice was revised and residents advised to open their windows during summer, it is possible this has not been done. In addition, the electricity data from the MVHR system appears to show the residents not utilising the boost facility of the MVHR system. This illustrates the risk of overheating in such thermally efficient buildings if they are not used in such a way as to reduce the risks.

Electricity data gives an insight into the impact of occupant behaviour on gross usage and the associated CO_2. User behaviour was seen to be the key driver behind fluctuations in electrical energy use, with socket and cooker loads representing over 87% of total electrical consumption.

Analysis of heating use in all properties displayed a close grouping when compared with degree days (with the exception of dwelling 6 operating a different heating pattern). This suggests a similar level of performance from all properties. An interesting outcome from this analysis was the performance of dwelling 1 (end terrace), which requires more heat per degree day than the other properties. Of interest is that dwelling 1, which is an end terrace and furthest from the communal boiler, requires more heat per degree day than the other properties. This may be a result of having a larger area of heat loss envelope due to the fact that this is an end-terraced dwelling, or may be a result of greater heat losses in transmission from the communal boiler, resulting in lower delivery temperatures for the supplied heat to the dwelling. Further investigation is needed to determine the specific reasons for this.

8 Key messages for the client, owner and occupier

8.1 Conclusions and Key findings for this section

Observations of duct filters, particularly in the kitchen, show a higher than expected level of build-up, which is thought to be a result of the occupants not using their kitchen cooker ventilation hood to extract during food preparation. Residents should be advised of the impact this can have on the overall effectiveness of their heating and ventilation system, and advised to use the installed cooker ventilation hood. It is noted that Gentoo will undertake regular (6 monthly) filter changes for rented properties. Owner occupied homes will be responsible for their own filter changes.

Airtightness deteriorated slightly over the course of the monitoring project, with the aging of seals around windows and doors thought to be the likely cause. As deterioration was minor, overall airtightness is still very high, so whilst being an interesting piece of learning is not thought to present a significant issue.

The apparent risk of overheating displayed in the in-use monitoring highlights the importance of educating residents in the correct operation of their homes. The data suggests that residents are not ventilating their homes during the night in summer, leading to uncomfortable internal temperatures. It is the belief of the research team that this stems from advice given during original handover to keep windows closed to increase MVHR efficiency. It is possible that the lack of overnight ventilation is due to other reasons, such as security concerns and a reluctance to leave windows open overnight. The reasons behind this should be investigated moving forward, and the benefit of summer cooling explained to the residents. In addition, this should be fed back to the design team and influence design assumptions for dwellings and occupancy of this type.

Although not its primary function, the lack of MVHR boost may also be contributing to the overheating issues, which suggests that residents are either unaware of the boost function, or are not confident with its operation. This should also be addressed, so that overheating risk can be reduced. In addition, it is apparent that all houses apart from dwelling 6 have left their MVHR systems in the original configuration. It is advised that the heating system for dwelling 6 is checked and reconfigured for optimal performance. At time of writing, it has not been possible to trace whether change was due to occupant intervention or problems in installation.

Residents should also be advised of the effect that their activity has on overall electricity consumption, and encouraged to turn off electrical items when not in use, and to purchase more efficient electrical items.

The apparent higher energy use per degree day of the end terrace (number 1) is an area that may require further study, as it would be interesting to determine whether this higher heat demand is a result of an increased heat loss surface area, distance from communal boiler or something else.

9 Wider Lessons

9.1 Conclusions and Key findings for this section

In order to avoid issues such as overheating and inefficient/ineffective use of the novel energy systems within the home resident handover teams should acknowledge the impact of conflicting guidance, particularly when dealing with residents who may be unfamiliar with the technology and unwilling to seek further guidance. Although the handover documentation was to a very high standard, residents are apparently unaware of summer purging and of the boost/bypass functions – this should receive more focus on handover. Also, residents should be made aware of the importance of using their kitchen cooker hood during food preparation, and the possible impact on the performance of their heating and ventilation system. This should be incorporated into future handovers.

The impact of the occupant on electricity use is clear in the data, and future developments that promote sustainability should ensure that residents are aware of this and give advice on the best way to reduce their consumption habits.

Overheating is a significant risk in properties of this type, and the reluctance to ventilate on ground of security was somewhat unforeseen. The development by industry of a secure ventilation method, such as a louvered vent that retains airtightness when closed, would be welcomed in this instance. This has been fed back to the project architect who is currently developing a solution.

Equipment issues during the project presented a particular challenge, often entailing a loss of data for extended periods as it was not possible to remedy issues immediately. These issues could be reduced by conducting daily checks on equipment (both remotely and on site) although this may present issues practically.

There were many positive outcomes from this project. One positive in particular is the success of the community heating and MVHR systems. Feedback from residents has been extremely positive, with low fuel bills and comfortable temperatures during winter. In addition, the MVHR systems tested remained in balance over the duration of the monitoring phase. There were no complaints of noise or ‘draughts’ that sometimes occur with MVHR, further supporting the use of the PAUL system.

The building fabric has also performed very well throughout the monitoring phase. Whilst there was a relatively large deterioration in building airtightness (almost 35%) in real terms over the course of the monitoring period, the final value is still very low by UK standards. This is encouraging and suggests that the airtightness of the dwellings is particularly robust. Leakage detection, using hand-held smoke generators and thermal imaging during depressurisation, revealed very few areas of air leakage. The small areas of air leakage that were identified in the most recent pressurisation tests were consistent with those identified during the earlier post construction and early occupation study. Analysis of the leakage points suggests that the increase in air permeability measured over the in-use monitoring period is most probably attributable to wear-and-tear on the front, rear and patio door seals, which has degraded over the last 6 months or so of the in-use monitoring period. Adjustments to the doors or replacement of the seals should limit this air leakage.

Feedback from residents is illustrated to some degree in section 5 of this report, but informal discussions have added further support to the conclusion that people are very happy with these properties and enjoy living in them. Low energy bills and an improved perception of comfort and quality of life are common topics when talking to residents. Strong emphasis should be placed on the positive light in which these dwellings are viewed by their occupants, and credit should be given to Gentoo and the everyone involved in their construction and maintenance.

Feedback on the project overall to the residents has been provided via a 1 page summary document that was delivered by hand by the research team. During the delivery of this document, the residents were encouraged to ask any questions about the project and the findings.

10 Appendices

There are numerous appendices associated with this report which are available as separate documents. These are as follows:

1. JOHNSTON, D. MILES-SHENTON, D. and PEAT, M. (2013) In-use Performance and Post Occupancy Evaluation Study, Sunderland – Pressurisation Test Report. A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. June 2013. Leeds, UK, Centre for the Built Environment (CeBE), Leeds Metropolitan University.
2. JOHNSTON, D. MILES-SHENTON, D. and FLETCHER, M. (2014) In-use Performance and Post Occupancy Evaluation Study, Sunderland – Pressurisation Test Report. A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. February 2014. Leeds, UK, Centre for the Built Environment (CeBE), Leeds Metropolitan University.
3. JOHNSTON, D. MILES-SHENTON, D. and FLETCHER, M. (2014) In-use Performance and Post Occupancy Evaluation Study, Sunderland – Thermal Imaging Report. A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. March 2014. Leeds, UK, Centre for the Built Environment (CeBE), Leeds Metropolitan University.
4. JOHNSTON, D. and FLETCHER, M. (2014) In-use Performance and Post Occupancy Evaluation Study, Sunderland – Thermal Imaging Report. A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. June 2014. Leeds, UK, Centre for the Built Environment (CeBE), Leeds Metropolitan University.