Technology Strategy Board
Driving Innovation

Building Performance Evaluation

Final report: The Camden Passive House

Domestic Buildings

Phase 2: In-use performance and post occupancy evaluation

Technology Strategy Board BPE ref no:	450049
Project title:	Camden Passivhaus
Lead organisation name:	bere:architects
Number of properties as part of BPE:	

Date:	25th July 2014
Version:	1 rev B18
Prepared for:	The Technology Strategy Board
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1 Introduction and overview

This report forms the conclusion of a two year building performance evaluation (BPE) study of London's first certified Passive House; a two-bedroom, two storey, south-facing single family detached house in North London. It is the result of the collaborative effort of the project lead (bere:architects), Professor Dr Ian Ridley of University College London / RMIT Melbourne, Sam Stamp of UCL, the building services engineer Alan Clarke and the ventilation expert Andrew Farr.

The research work was carried out in two study phases and this report follows on from the Phase 1 report, containing results and conclusions drawn from both phase 1 (January 2011 to July 2011) & phase 2 (October 2011 to October 2013; voluntarily extended to March 2014).

Phase 1 of the BPE study consisted of an analysis of the fabric of the building and an analysis and re-commissioning of the mechanical and electrical systems. Phase 2 consisted of the installation of comprehensive in-use performance monitoring equipment and the down-loading and analysis of the data produced by this equipment for a period of two years. Phase 2 also included the design and testing of a new long-life ventilation system filter concept developed by bere:architects to facilitate easy changing of filters without third parties needing to enter the property. It is thought that this could be of particular benefit to social housing providers.

The research has been funded by the Technology Strategy Board (TSB) which is in turn funded by the UK government.

The 'Camden Passive House' (as it is known for the purpose of this paper) is a two-storey detached house of 118 m^2 gross (or using the Passive House method of measurement of the heated envelope, 101m^2 'treated floor area'[1]), designed by bere:architects with mechanical and electrical services design by Alan Clarke, ventilation design by Andrew Farr, structural engineering of the substructure by Mervyn Rodrigues and structural engineering of the superstructure by Kaufmann Zimmerei und Tichlerei. The main contractor was Visco, and the timber superstructure and cladding contractor was Kaufmann Zimmerei und Tichlerei. The house was completed in the Summer of 2010 in the London Borough of Camden. It was the first house in London to be designed and certified to meet the Passive House standard. Certification was completed by Warm Consulting in the summer of 2010 on behalf of the Passivhaus Institut, Darmstadt. The occupants moved into the Camden Passive House over the Christmas of 2010.

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[1] TFA based on the German floor area ordinance Wohnflachenverordnung, which roughly translates as 'residential regulation'. The main purpose of using 'treated floor area' is that in measurements of the energy consumption used to heat a building, the energy use is accurately measured only if one is referring to usable space inside the relatively cold walls. Using the gross figure, as in the UK, makes the energy consumption sound lower than it in fact is, because the amount of heat is claimed to be heating a larger area, whereas in fact the walls get much colder throughout their thickness (moving towards the outside of the house) and any heat in the wall is being lost and is not useful to count.

The Passive House standard is a method of engineering a building for a high level of comfort and very low energy consumption. It is a voluntary building standard conceived and developed by Professor Wolfgang Feist who founded the Passivhaus Institut as a research organisation and to certify buildings that comply with the standard. The design software, the Passive House Planning Package (PHPP), uses local average weather data to tune the building to its precise location. The main objectives of a Passive House building are to achieve:

- Very low energy consumption and very high comfort
- Optimal balance of energy consumption and energy gains
- Excellent quality fabric, well insulated, carefully detailed for draught-free construction and avoidance of cold bridging.
- Excellent window performance with the minimum of energy losses due to triple glazing and insulated, air-tight frames in winter, and secure opening in summer.
- Excellent indoor air quality due to heat recovery ventilation.

The primary objective of the Camden Passive House project was to achieve a comfortable and healthy home for the occupants while minimising its energy use. Bere:architects suggested designing the house to the Passive House standard at an early stage. The client was at first concerned about the perceived cost risks associated with a pioneering project, but in the end was supportive of this approach for several reasons: (a) he envisaged improved chances of winning planning consent, (b) he was persuaded of the potential health benefits for his daughter who suffers from asthma (c) he was aware of the potential benefit of low utility bills.

Figure 1-1a. First floor living area with large south facing windows

Figure 1-2b. South facing street elevation of the Camden Passive House, with living room on the first floor and bedrooms on the ground floor. Cladding is Austrian larch.

The Camden Passive House was designed as a heavily insulated prefabricated timber structure with larch cladding. The ground floor is up to 3 metres lower than the adjacent gardens and the ground floor of the timber frame is therefore built within a concrete retaining wall. Windows are triple glazed and well-sealed for air-tightness, so contributing to excellent heat containment and sound insulation. Retractable venetian blinds outside the south facing windows provide the opportunity for summer shading to reduce solar gains. There is a small external terrace over the cycle store on the South side of the building. The flat roof on top of the building contains a solar thermal panel and an ecological wildflower meadow. The steeply sloping north facing roof to the rear also contains wildflower meadow planting.

The mechanical systems include a heat recovery ventilation system located in the cycle store, a water filtration system, an underground rainwater-harvesting tank which provides water for irrigating the green roofs and the garden, and a solar thermal collector which supplies hot water to a combined unit consisting of a solar water tank and small gas boiler.

To help with gaining knowledge of advanced timber engineering, bere:architects employed Matthias Kaufmann as an internee for 18 months. The timber frame was prefabricated and erected by

Matthias’ family business, the timber construction company Kaufmann Zimmerei und Tischlerei of Reuthe, Vorarlberg, Austria.

Delivery team:

Architect	bere:architects
Timber frame supplier and engineer	Kaufmann Zimmerei und Tichlerei
Substructure engineering	Rodrigues Associates
Building Services designer	Alan Clarke
Ventilation designer	Andrew Farr, Green Building Store
Main contractor	Visco
Airtightness champion	Dominic Danner

Building Performance Evaluation

To assess the effectiveness of the design and delivery strategy, the research was carried out in two distinct phases:

- Phase 1: During this phase of the BPE study the fabric and services were extensively tested.
- Phase 2: At the start of this phase of the BPE study, a monitoring plan was prepared and equipment was installed to provide detailed monitoring of:
    - Internal conditions in the living spaces and the master bedroom, and external conditions. (Measurements included indoor and outdoor temperatures, relative humidity, CO2 and solar insolation at 5 minute intervals for the two years of the study)
    - Detailed sub-metering of electrical energy usage, 5 minute intervals
    - Gas energy usage, 5 minute intervals
    - Water usage, 5 minute intervals

  The automatically-recorded data was downloaded and stored by bere:architects and UCL staff and analysed by Dr Ian Ridley of UCL and latterly of RMIT who carried out a rigorous analysis of the actual in-use performance of the building and compared it with the designed performance according to the PHPP design data.

  Additionally, a study was undertaken to assess the occupants’ perspective of the building in operation. An official BUS study was carried out by ARUP who are a licensee of Building Use Studies Ltd. The survey was carried out and assessed by ARUP using BUS methodology (ref **www.busmethodology.org.uk**)

Finally, co heating and in-situ U value analysis was carried out by Sam Stamp (UCL), the five airtightness tests were all carried out by Paul Jennings, and air quality sampling and analysis was carried out by Dr Derrick Crump of Cranfield University.

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

The Camden Passive House is located in the affluent residential area of 'Fortune Green' in the Borough of Camden, in North London. The street contains mainly large, detached houses developed during the early to mid-20th century. Most of the houses are traditionally constructed from un-insulated solid brick walls. Most appear well-maintained and expensively appointed but a thermal imaging study shows that most of them lose significant heat through their un-insulated walls and poor quality windows. Some houses also lose significant heat through their roofs, particularly around special features such as dormer windows.

Figure 2-1. This thermal imaging picture shows significant heat leakage from a house in the same street as the Camden Passive House. Problem houses typically feature un-insulated solid brick walls, poorly insulated roofs and open windows.

The site consisted of a domestic back garden containing a single garage. Planning permission is not normally granted to build in back gardens spaces in this part of London and the owner of the site had previously had a planning application for a house on the site rejected by the local authority. Bere:architects were favoured by previously winning a design award from Camden Council and had also been trying to obtain support from various clients since 2005 to build the UK's first Passive House building. Their well-known advocacy of the Passive House approach is considered a key factor in gaining the support of Camden Council who were at this time developing an environmental design policy under the guidance of the energetic advocate of the Passive House standard, Councillor Alexis Rowell. The project eventually provided Camden with the accolade of being the home of London's first certified Passive House, and of the joint-first Passive House in England, but delays in agreeing the project budget meant that it was not to be the UK's overall first Passive House, that prize being won by a project in north Wales.

The design was developed in consultation with the building owner who introduced his daughter to the project during the later stages of construction. After the daughter decided to take up residency with her fiancée, some late design changes were made in consultation with her mother, an interior designer. The changes were mostly of a superficial nature. However one change would turn out to have an effect on the way the building was used. This change was the substitution by the client of a stone-filled gabion wall at the front (intended to afford the master bedroom on the ground floor with complete privacy from passers-by) by a chain-linked fence covered by ivy. The ivy subsequently died from lack of water. The result is that the external blinds of the ground floor are kept closed to maintain privacy from people in the street in summer and winter, which ensures good summer shading of the bedroom but denies the bedroom of the advantage of solar gains in the winter.

It is thought that a key factor in the daughter's decision to occupy the building was her history of asthma, and the expectation that a Passive House would provide her with air quality benefits that would be beneficial to her.

The Passive House Standard

The Passive House standard is a technical building standard established in Germany by Wolfgang Feist after he completed the world's first scientifically designed Passive House in 1989. The design approach was the result of years of discussion and research collaboration between Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist, subsequently the founder of the Passive House Institute. The primary principles of Passive House design are outlined on page 2 of this report. In this project the ventilation also supplies any heat that is required to maintain the set temperature and the designed heating demand is so low that a conventional heating system can be omitted.

In order to achieve Passive House certification, a building needs to meet three basic criteria (Feist, 2007):

- Specific Space Heat Demand max 15 kWh/m^2
- Entire Specific Primary Energy Demand max 120 kWh/m^2
- Pressurization Test Result max 0.6 h-1@50Pa

Project design calculations are made with a sophisticated, precise spreadsheet-based modelling software called PHPP (the Passive House Planning Package). The software is effectively a design tool produced by the Passivhaus Institut to model the expected performance of a domestic or non-domestic building. It is used to calculate energy balances, U-values, design a comfortable ventilation system, calculate heat and cooling load as well as the domestic hot water system and to anticipate summer comfort conditions.

2.1 Building design strategy

The primary objective of this project was to achieve a comfortable and healthy home for the occupants while minimising its energy use. The site had some tight constraints such as shape and orientation and over-shadowing from adjacent buildings. Height restriction was another problem - the house could not go higher than the existing neighbouring garage. Thus, the building was set lower in the ground than neighbouring houses, although this is not readily appreciated from the street or from inside the house.

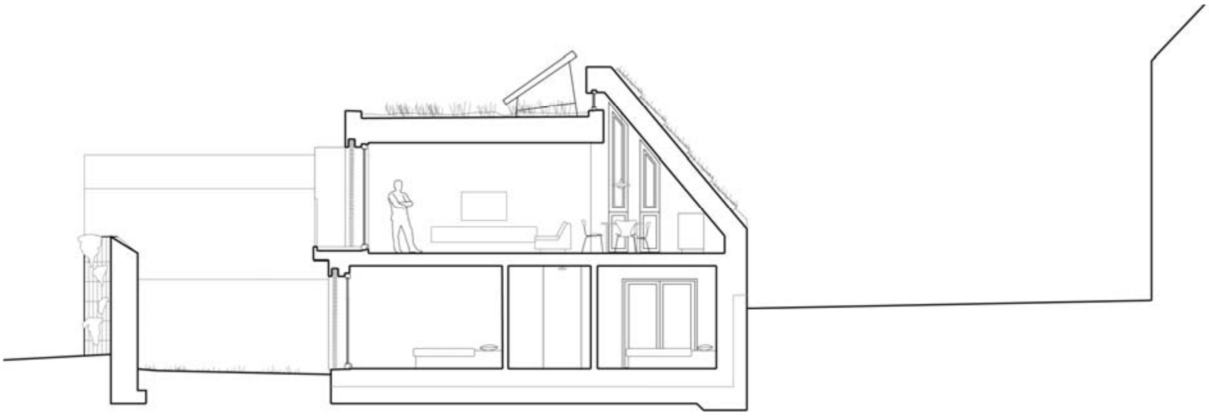


Figure 2-2. Camden Passive House section

The local authority planning constraints effectively determined the floor heights. The ground floor has a slightly lower floor to ceiling height than the first floor.

The client agreed to commit to Passive House design to achieve his aspirations and was aware that success would depend on a higher quality of construction than required by building regulations, including careful design and site work in order to minimise fabric air leakage which would need to be at least ten times better than the statutory air-tightness requirements for a new building.

A variety of design solutions were tested following an iterative process using the Passive House Planning Package (PHPP) tool to optimize the low energy design. In this way decisions were made with a clear knowledge of future likely energy demands.

The first idea that was tested was to create a small garden at the back of the house on the NW side of the building as well as a small garden at the front. This meant including north facing glazing to the rear and while this was found to be workable, the PHPP demonstrated that money would need to be spent on additional insulation in order to compensate for the north facing windows and for some winter overshadowing of the ground floor. It quickly became clear that this would add unnecessarily to cost when it was easy to orientate the building optimally, so use of the PHPP demonstrated the advantages of moving the building to the north of the site, with the garden and major glazed areas almost entirely SE, with good access to low angle winter sun. This provided the best opportunities to reduce energy losses and maximise solar gains and was also preferred by the owners of the site as it meant that the house was kept away from the street, therefore providing traffic noise reduction.

So the PHPP was used to understand the summer and winter implications of the window areas, their orientation and the effect of the horizon line. This enabled a balancing of the heat losses and gains through N and S facing glazing, respectively. NW windows are minimal and are sized only for day lighting whereas those facing south are significantly bigger to benefit from the winter solar gains. To control summer overheating, the opportunity for summer shading is provided by means of external retractable venetian blinds with automatic solar control. Large windows are a key feature of the design and their high quality of airtightness makes them draught-free and has helped achieve good sound reduction and a thereby a sense of privacy. They are triple-glazed with a tilt and slide opening mechanism. The tilt and slide mechanism is inward opening and this provides the opportunity for a good level of secure summer night purge-ventilation and resistance to rain penetration even when open.

The ‘upside down’ layout of the building maximises the first floor access to daylight and sunlight, for the open-plan kitchen, dining room and living room. The ground floor accommodates the two bedrooms with private bathrooms, plus a WC.

The front garden was originally intended to have a gabion wall facing the street in order to maximise the privacy of the ground floor bedroom at the front of the house. The occupant decided to opt instead for an ivy-clad fence which provided less privacy than the wall originally planned. This eventually died and has been replaced by a hedge of Cotoneaster. Until this provides a full screen, the ground floor blinds will remain closed day and night for privacy. While this is beneficial in the summer, it is not so in the winter when ideally the blinds would be open during the day.

Biodiversity was also important in the overall concept design, and there are two wild flower green roofs. Installing the green roofs was encouraged by Camden Council; indeed it was a condition of the planning permission. The architects worked with Dusty Gedge, a leading green roof expert, on the specification of the plants for the two green roofs.

Figure 2-3. Sloping green roof facing neighbour’s garden

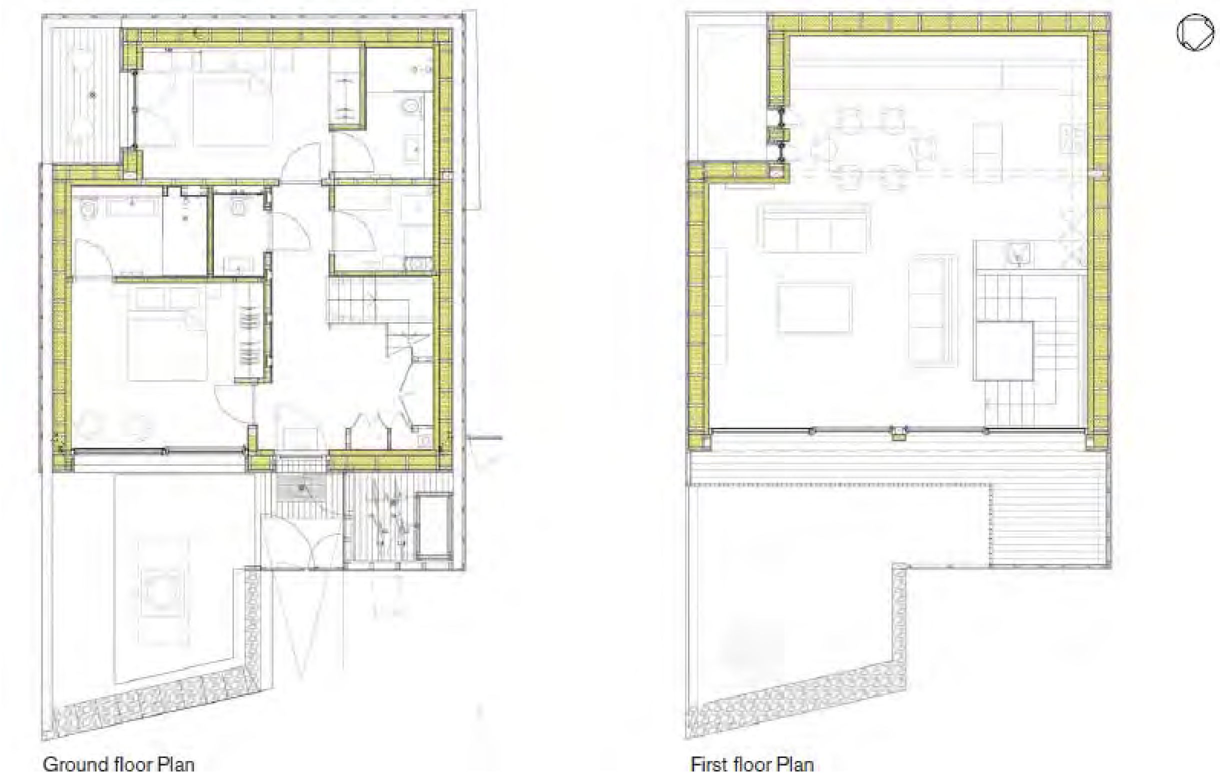


Figure 2-4. Camden Passive House floor plans. The ground floor is slightly sunk into the ground with concrete retaining walls on the boundaries to the back and sides of the building. The main glazing faces southwest.

The house has a concrete substructure with the ground floor walls being partly retaining walls. The main structure is timber. The house has high levels of insulation with the following design values:

- Walls: include 340-370mm of insulation (100mm wood fibre and the remaining mineral fibre) overall u-value upper walls 0.110 lower walls 0.122 W/(m^2K).
- Flat roof: includes 280mm of high performance foam insulation and 120mm mineral fibre, overall u-value 0.067 W/(m^2K).
- Sloping roof: 380mm of mineral fibre in the sloping roof, overall u-value 0.110 W/(m^2K).
- Ground floor: 400mm of mineral wool insulation, overall u-value 0.103W/(m^2K). The *Passive House* standard requires thermal bridges of less than 0.01W/mK, and all bridges greater than 0.01W/mK must be calculated and fed into PHPP to assess their impact on the overall energy use. Bere Architects used HEAT2 software to analyse all junction details – because it was the practice's first *Passive House* project and it was not at that stage possible to estimate which bridges might be non-compliant. The sum of all thermal bridges in PHPP was negative, showing that the building details performed very well and would not have an adverse impact on the peak heat load.

2.2 Building services strategy

Building services were designed by Alan Clarke with heat recovery ventilation for all-year use, designed by the Green Building Store.

The house has fully opening windows to allow for additional cross and stack ventilation on both floors during the summer months. The street facade windows are of a design that is reasonably secure when tilted.

The client was receptive to implementing modern technologies to achieve an exemplar building. The house includes a heat recovery ventilation system, a solar collector to provide hot water, and rainwater recycling from green roofing.

The ventilation unit:

This is a Paul Thermos 200, supplying and extracting air to and from the house with heat recovery. According to manufacturers, the heat recovery equipment is 92% efficient. The system is designed to provide a constant background ventilation rate of 130m^3/hr (36l/s), 0.48 ach^{-1}. It can also provide space heating by using a 1kW heater battery in the supply air duct of the ventilation system, supplying warm air at 50-53°C. The heater battery is supplied with hot water from the central energy system at a nominal flow temperature of 60 °C. The space heating is complemented by heated towel rails in the bathrooms, operated by demand switches with run-on when required. The ventilation unit includes a summer bypass to avoid warming the incoming air in the warmer months.

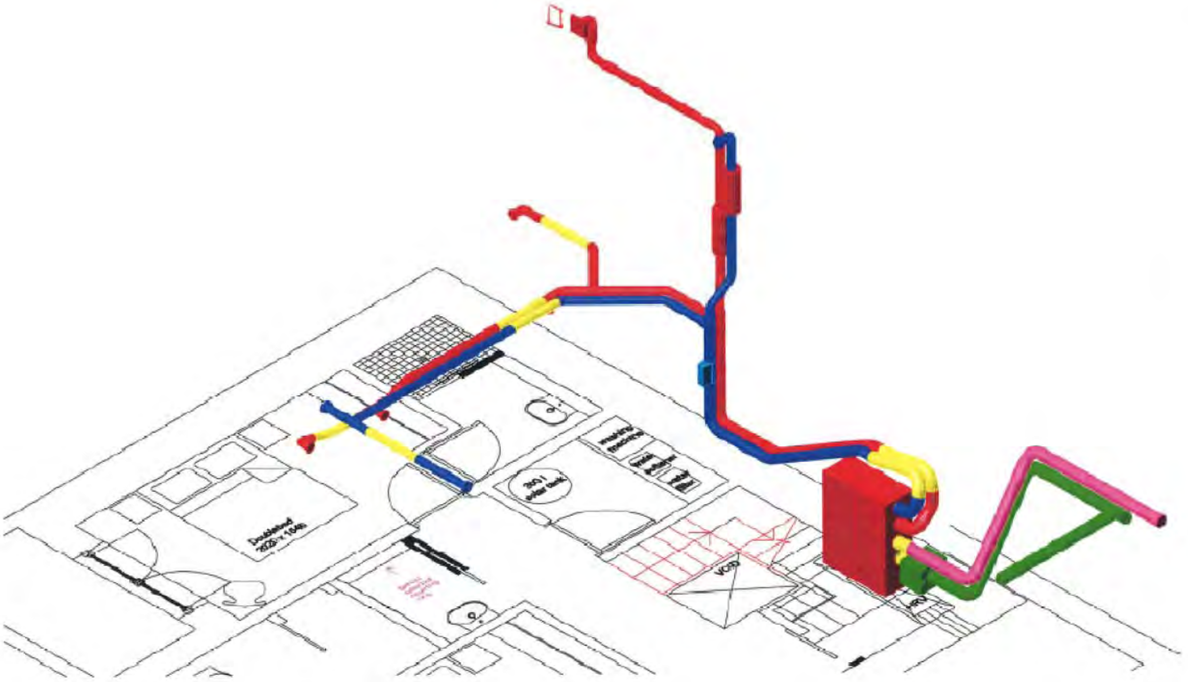


Figure 2-5. Heat Recovery Ventilation diagram designed by Green Building Store

Warmed air is carried in insulated ductwork to the two bedrooms and the living room. Air is extracted from the two en-suite bathrooms, the WC, the utility room, and the kitchen area - returning to the ventilation unit to give up heat to the incoming air. In the kitchen the extract terminal includes a filter and flow rates at all inlets and outlets are adjustable locally for accurate balancing at the commissioning stage. All ductwork connections are Lindab with double-lipped rubber sealing gaskets connecting to spiral wound galvanised metal ductwork. Indoor heated supply ductwork is insulated with mineral fibre and foil. To avoid heat loss and condensation on the very short length of ductwork between the ventilation unit in the cycle store and the fabric of the house, the duct is heavily insulated with black 'Armaflex' sheeting which is impermeable to vapour. The duct intake is from the garden side of the bike shed, at approx 2m above ground level and the exhaust is to the pavement side of the shed. After a year of operation, the ventilation system was fitted with a prototype 'long life filter' at the intake (containing a deep bag filter instead of a pleated filter normally located inside the ventilation unit). This reduces the effect of duct pressure loss caused by particles of pollution in the incoming air and significantly lengthens maintenance intervals and, with a little further development, has the potential to facilitate access for filter changing which it is thought will be particularly helpful for service providers of rented accommodation.

Originally the ventilation unit was planned to be located under the stairs. However, shortly before construction started, the client decided that this would take up useful storage space. So it was decided instead to locate the ventilation unit in a frost-protected enclosure in the external bike shed with the shortest possible ductwork between the unit and the treated floor area to reduce thermal losses caused by this move to the minimum possible. The air heater unit remains inside the house (under the stairs) relatively close to the combined tank and boiler.

Figure 2-6. Heat Recovery Ventilation unit (BEFORE DUCTWORK WAS INSULATED) inside the frost-protected unit in the external bike shed.

The ventilation speed can be adjusted by the occupants of the house via the main control panel in the living room to any of three settings: ‘low’, ‘normal’ and ‘party’. Changing the setting is not normally felt to be necessary unless the occupancy level changes for an extended period of a few hours or more. The controls are located in the main living space. Additionally there is a ‘boost’ button outside the master en-suite bathroom to increase the air change rate for a short period of 15 – 30 minutes. This button could be used to extract excessive moisture from a long shower, but the occupants say they seldom feel the need for it.

At ‘normal’ ventilation rate it is possible to meet the calculated peak heat demand without the need for an additional heating system. The towel radiators provide an additional boost that might be useful in extra cold weather conditions.

Heating the house:

As it was their first Passive House, the design team was a little nervous about the absence of radiators or underfloor heating. So pipework was discretely installed under the living room floor so a radiator could be easily installed in the future if necessary. However during their first two winters, including the exceptionally cold winter of 2012-2013, the occupants have remained comfortable in their home at all times and there has been no need to connect up a radiator in the living room. More details on the internal conditions, monitored temperatures and occupant perception are contained in the following chapters.

At detail design it became apparent that the boiler would have trouble maintaining a steady temperature if supplying just the air heater battery, this has very low thermal capacity and output limited to about 1kW whereas the minimum output of the boiler is around 5kW. At 50C flow temperature efficiency is 96% at both min and max output, at 90C flow efficiency is 86% at min output and 90% at max. - ie at 60C flow we shouldn't be losing significant efficiency. Although the boiler and hot water are integrated into a single unit, it functions as a standard boiler + hot water cylinder arrangement, and there is no thermal buffering on the heating side.

The low thermal capacity of the system was addressed by including the towel radiators in parallel – so whenever the controls call for heat the towel rails are heated along with the air heater, with towel rails limited by TRVs. The BUS has shown that occupants are happy with the heating systems and do not feel these need to be improved.

Additionally the towel radiators are under user control by means of run-back timers providing a choice of ½ hour, 1 hour or 2 hours heating. Each ensuite has a runback timer but for simplicity they both operate the two towel rails together. The towel rail runback timers call for heat from the boiler, via an additional switch input to the boiler controls. There are no zone valves on the towel rail circuit, so they are heated whenever the boiler provides heating. The duct heater has a zone valve controlled on room temperature (via a relay on the ventilation controls), and the end switch of this valve also calls the boiler via the same switch input as the towel rails.

The boiler does not have the standard weather compensation normally supplied with the Vitodens 343, but instead has simpler controls since the air-heating system requires a constant heating temperature. Weather compensation would vary the heating temperature according to outside air temperature and this could have resulted in too high a temperature to the heater battery which might have resulted in hot smells in the air by heating it above the recommended maximum of 52°C. Weather compensation is generally thought to be unnecessary anyway in a Passive House because unlike an ordinary house the rate of fabric heat loss is relatively unaffected by outdoor temperatures.

Replacing the weather compensation control panel by a basic control panel ensures that the water is supplied at a constant temperature according to the boiler's set flow temperature ie using the boilers own internal thermostat. This limits the temperature to which the air is heated. There is a band of around 5°C between boiler set point and the maximum the flow temperature reached. Room temperature control is by the ventilation control unit, which is located in the dining area and includes a room temperature sensor and user thermostat.

The room temperature is set within the ventilation controls as these also control the summer bypass to provide summer cooling. Summer bypass operates automatically based on internal & external temperatures and to avoid simultaneous heating and free-cooling, the ventilation controller only allows the summer bypass to operate when the heating is set to "off".

This is the reason that the ventilation unit leads the boiler. If the heating had been controlled with boiler controls then the occupant could increase the heating set point above the summer cooling set point, and then on high room temperature the fresh air would automatically bypass the heat recovery, bringing cool air into the house.

Figure 2-7. Ventilation control installed in the living room

As mentioned above, it is recommended to limit air supply temperatures in the duct to around 52°C to avoid "hot" smells in the supply air. Control of the heater battery on duct temperature was not used so as to avoid extra complication and potential for controls conflicts. Instead the boiler flow temperature was adjusted to give the correct air temperature – the heater battery selection software indicated that the air temperature would only vary by 1-2 degrees for the various airflows used, and that water flow temperature needed to be approx 10°C higher than desired air temperature. Boiler temperature was initially set at 65°C then reduced to 60°C on seeing that it tended to run above the set point.

Domestic hot water:

The solar thermal panel is a Viessmann Vitosol 200, 3m^2 evacuated tube solar collector installed on the flat roof. The solar collector connects directly to the 200 litre domestic hot water cylinder integrated in the Viessman Vitodens 343F compact energy tower system (which also includes a condensing gas boiler).

Rain water:

This is collected and stored in an underground tank that provides water to the garden, reducing mains water consumption. Bathing and drinking water is cleaned through a water filtration system.

2.3 Procurement, Construction and Delivery

The procurement route for this project was traditional with selective tendering. The pioneer aspect of the project meant that there were no Passive House experienced contractors within the UK but the architects' R&D work over a number of years on their previous projects and on Passive House precedents in Europe made them well-placed to lead such a pathfinder project with reasonable confidence of success.

Working closely with the timber frame manufacturer from the outset enabled the project to benefit from good knowledge transfer from design office to construction site, and this was one of the key factors in the success of the project.

Figure 2-8. The timber frame was prefabricated in Austria by Kaufmann Zimmerei of Reuthe

An Austrian prefabricated timber framing contractor was selected. It was felt that on this occasion the benefits of this collaboration outweighed the transportation costs and emissions associated with importing the frame from Austria. Indeed the techniques that were learnt proved to be instrumental in the design of the Welsh social housing Passive Houses prototypes at Ebbw Vale which used Welsh timber and Welsh labour in their manufacture. *(Refer to TSB File Ref 450066, BPE domestic buildings phase 1 & 2 studies for the Larch and Lime House at Ebbw Vale, due for completion Summer 2014, running in parallel with this study).*

A local main contractor was needed to prepare the site excavations, drainage, piling, retaining walls and incoming services, as well as completing the M&E services and finishes. The design team and building owner interviewed three main contractors for the project. The selected firm was Visco whose director had attended the International Passive House conference the previous year in Germany. They were led in this regard by a part-German project manager who had recently completed the Passive House Designer course in Germany and was keen to apply his new knowledge on his first Passive House.

Visco became responsible for the substructure and drainage, for employing the specialist timber frame subcontractor, and for the services, finishes and commissioning.

A number of variations to the procurement route were investigated between January and July 2009. The contract Bere recommended for the project and used was the JCT Intermediate form of contract, ICD05. This gave adequate control to the architects as contract administrators and it also allowed the naming of sub-contractors. This was an important point because the service installations required specialist knowledge and the architects had built up a good team of sub-contractors that they wanted to write into the contract. ICD05 allowed them to do this.

Previously Bere Architects had also approached two other prefabrication companies with bases in England and Ireland, to provide a price for the prefabricated superstructure. The English timber frame company provided a more competitive price than Kaufmann but excluded many of the key elements of the airtightness envelope, leading the design team to question their ability to deliver to the Passive House standard. In the end the client agreed to proceed with Kaufmann.

Construction started in September 2009. The house was certified to the Passive House standard in April 2010, but was still not finished internally, as the client wished to carry out parts of the interior design. The occupants moved in during 2010 Christmas holidays.

Some problems were encountered on site – an inevitable result of working in new ways and learning-by-doing. The design team found, as expected, that most of the construction team needed training and close supervision to ensure the necessary quality was achieved. The critical factor in the project was the quality control of the construction, particularly because of the airtightness and thermal performance of the building as required for Passive House certification. Kaufmann had responsibility for initial airtightness of the fabric, which they achieved, and the contractor's 'airtightness champion' had responsibility for maintaining the airtightness during the mechanical and electrical subcontract stages, through to completion. He also took on the important role of briefing all workers on the construction team about the aims of the project and importance of airtightness, experiencing difficulties with some sub-contractors, noting that they quickly fell back into old habits if not constantly monitored.

In general, the contractor observed that: ‘Passive House Construction is much more exact and requires a much higher quality of works and tradesmen than we envisaged. It was a very steep learning curve. We made mistakes, which I hope and believe that we have learned from.’

To help the new occupants understand the Passive House, the architects provided a user guide with information about how to use and manage the building, see Appendix 7. The handover also included a visit from the design team to discuss the operation of the various systems. The occupant says she is satisfied with the handover process and finds the user manual inside the utility room easy to understand and useful.

2.4 SAP Assessment

Due to the nature of the design project, which was focused on using the Passive House Planning Package as a design tool for achieving very low energy consumption, and was aiming for Passive House certification, the PHPP calculation was considered more important than SAP. In early conversations with the local authority’s building control department, the design team requested to use the PHPP calculation to comply with Part L of Building Regulations but this request was declined by the local authority as they were legally obliged to obtain a SAP report. While PHPP calculations were done by the design team, the SAP calculation was carried out by Brookes Devlin Associates, independent SAP advisors.

A comparison of both assessment tools was carried out during Phase 1 of the BPE of the project by the Welsh School of Architecture. The report (Guerra-Santin and Tweed, 2011) highlighted that in general there is less detail in SAP calculation than PHPP, one of the reasons cited being that SAP is a compliance tool while PHPP is a calculation tool. Other highlighted differences are the criterion used in area measurements, and the fact that PHPP requires closer attention to thermal bridging and infiltration heat loss. It was also noted that none of SAP’s predetermined options for heating patterns and heating systems is similar to the conditions in a Passive House and that solar energy at the time was also not considered in SAP (although we understand that the latest version of SAP now includes a contribution to hot water from solar thermal panels). All this leads to PHPP and SAP providing very different results. The authors concluded however that the building passed both assessment methods.

During Phase 2, the independent SAP advisors Brookes Devlin revisited the SAP calculations to compare the predicted thermal and electrical energy consumption (calculated under SAP 2009) with measured data obtained from Camden Passive House between August 2011 and July 2012.

In the report (Devlin, 2012) it was again noted that SAP is a compliance tool with some limitations as an energy consumption prediction tool. Following is a summary of the report analysis:

- The space heating consumption was predicted by the SAP model, using SAP standard weather data, to be just 593kWh/yr which is less than half that calculated, more realistically as it turns out, by the PHPP calculation and less than half of the measured data of 1237kWh/yr. In other words SAP in this case did not provide a reasonably accurate prediction of the energy use of the building, proving to be significantly over-optimistic about the space heat demand of the building compared to the actual measured consumption (see appendix 2).
- SAP uses weather data based on a typical climate in the North Midlands. If the weather data had been adjusted to match the site location in London, SAP would have further lowered its predicted space energy consumption, further increasing the gap between the SAP prediction and actual use.
- SAP space heating consumption is based on averaged internal gains which are much higher than those usually found in a Passive House, with its firm requirements to use only the most energy efficient appliances and to minimise wasted heat energy. SAP assumes internal heat gains (eg from appliances, lighting and pipework) of 5-6Watts/m^2 whereas PHPP assumes just 2.1W/m^2. This means that SAP expected the house to get more ‘free’ heat from appliances etc than it does in reality.
- SAP calculations predict that the building and its occupants will use over a third more electricity than measured. It should be noted that this is in spite of the fact that the default figure of 2.85 occupants has been adjusted to 2 occupants.
- Thermal bridging and the in-use ventilation efficiency are less detailed in SAP than PHPP.
- The measured DHW consumption value is significantly lower than the SAP prediction, but it does not include standing losses from the DHW cylinder. When these additional losses are estimated (based on the manufacturers declared values) and added to the measured DHW consumption, there is a probable correlation between the gross SAP predictions and measured data values (ie within 10%).

The differences between SAP and either PHPP or actual measured data highlighted the limitations of SAP and provides a strong indication that SAP is not suitable as an energy consumption prediction tool, at least for low energy buildings. When SAP is used by the Department of Energy and Climate Change as the basis for assessing CO2 emissions of the UK housing stock, this study would suggest that CO2 emissions may be significantly under-estimated.

The overall SAP rating for the Camden Passive House was 88, or a ‘B’ rating which is a surprisingly poor result given the exceptionally good insulation levels, airtightness, heat recovery ventilation and other low energy aspects of the house, and the fact that it’s performance is even better than the 2016 zero carbon fabric compliance standard for CO2 emissions. These results can be considered indicative of a weakness in SAP in assessing very low energy homes. SAP and PHPP worksheets are included in the Appendix.

2.5 Conclusions and key findings for this section

1. The Passive House Planning Package (PHPP) is a technical design tool that can be used alongside traditional creative design methods. Its purpose is to enable an architect to predict the energy use and occupant comfort conditions of a building. Outputs default to the predicted habits of average users but alterations can be made to test less or more favourable user habits if desired in order to assess the design of a building under different conditions. PHPP acts as a method of calculating the best fabric and services specification to achieve any given size, shape or orientation of a building in a specific location using precise local weather data.

2. "The Standard Assessment Procedure (SAP) is the methodology mandated by the Department of Energy & Climate Change (DECC) to assess and compare the energy and environmental performance of dwellings. Its purpose is to provide accurate and reliable assessments of dwelling energy performances that are needed to underpin energy and environmental policy initiatives"… "SAP works by assessing how much energy a dwelling will consume… Related factors such as…carbon dioxide (CO2), can be determined from the assessment. (**www.gov.uk/standard-assessment-procedure**). The statement that SAP is used to determine CO2 emissions is worrying because if the findings reported in this section are typical, it would indicate that when SAP is used by the Department of Energy and Climate Change as the basis for assessing CO2 emissions from UK dwellings, the CO2 emissions may be significantly under-estimated.

3. While it is often said that SAP's purpose is to provide a single building standard for all regions in the UK, the result of this is that people in the colder regions of the UK may suffer from a combination of the following: higher energy bills, colder indoor temperatures and a poorer quality of living compared to those in milder regions, because their houses are no better than those in the warmer parts of the country.

4. The SAP and PHPP comparison seems worthy of greater academic investigation, not least because in order to comply with building regulations, SAP is widely used as a design tool and is the usual source of quoted CO2 emission predictions. So SAP may be giving designers falsely optimistic expectations about the energy consumption of their buildings. If the findings in this report are typical, they would indicate that SAP itself may be a key factor in creating a large performance gap between design and actual energy use.

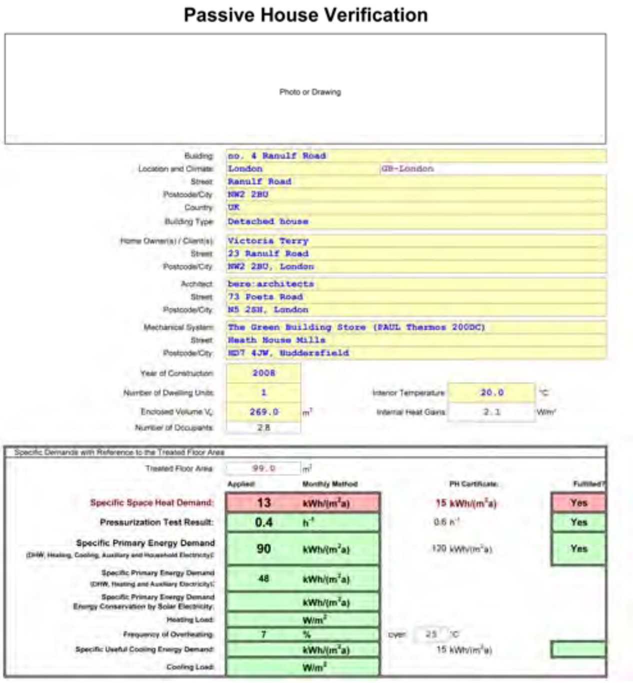
5. The authors concluded that using PHPP to design the Passive House dwelling enabled it to also meet the SAP requirements.

6. To meet the ambitions of Passive House design, construction teams must commit to delivery of very high quality detailing and to much higher levels of construction quality than is the current norm in the UK. A successful Passive House requires a meticulous and careful contractor. If the entire team shares a commitment to conscientious workmanship this will help deliver the necessary standard.

7. Even with a good contractor it is clear from this project (and others in the UK) that a knowledgeable Passive House architect is required to guide the process through to completing a contract on site. This project demonstrated how the architect needs to provide more than the service normally offered under a traditional building contract. In other words, the traditional role of managing a construction contract is insufficient to deliver a successful Passive House and an unusually high level of construction expertise from the architect is needed.

8. To reduce the risk of damaging the air tightness of a Passive House by future service penetrations it is essential to install service penetration grommets or other proprietary sealing systems for pipes and cables.

9. It is a requirement of the Passive House certification process that ventilation systems must be designed and commissioned to a more demanding standard than is required by the UK Building Regulations. Rooms must be individually commissioned and overall intake and exhaust figures must be compared to check for defective ductwork. The quality assurance methods contained within Passive House design and delivery provide valuable insights that could be incorporated into improved UK Building Regulations to improve air quality and comfort in UK homes, while at the same time reducing energy consumption and CO2 emissions.



Passive House Verification

Photo or Drawing

Building:	no. 4 Ranulf Road	
Location and Climate:	London	GB-London
Street:	Ranulf Road	
Postcode/City:	NW2 2BU	
Country:	UK	
Building Type:	Detached house	
Home Owner(s) / Client(s):	Victoria Terry	
Street:	23 Ranulf Road	
Postcode/City:	NW2 2BU, London	
Architect:	bere:architects	
Street:	73 Poets Road	
Postcode/City:	N5 2SH, London	
Mechanical System:	The Green Building Store (PAUL Thermos 200DC)	
Street:	Heath House Mills	
Postcode/City:	HD7 4JW, Huddersfield	

Year of Construction:	2008				
Number of Dwelling Units:	1		Interior Temperature:	20.0	°C
Enclosed Volume V$_e$:	269.0	m^3	Internal Heat Gains:	2.1	W/m^2
Number of Occupants:	2.8				

Specific Demands with Reference to the Treated Floor Area

Treated Floor Area: 99.0 m^2

	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	13	kWh/(m^{2}a)	15 kWh/(m^{2}a)	Yes
Pressurization Test Result:	0.4	h^{-1}	0.6 h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	90	kWh/(m^{2}a)	120 kWh/(m^{2}a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	48	kWh/(m^{2}a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m^{2}a)		
Heating Load:		W/m^2		
Frequency of Overheating:	7	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m^{2}a)	15 kWh/(m^{2}a)	
Cooling Load:		W/m^2		

3 Fabric testing (methodology approach)

3.1 Co-heating and other fabric tests

During Phase 1 of this BPE study, several post-construction fabric tests were carried out by Sam Stamp, a research student at the UCL Energy Institute, working under the guidance of Ian Ridley, UCL Bartlett School of Graduate Studies and subsequently of RMIT.

Fabric performance is an important factor in the success of any building and particular emphasis is put upon the quality of the fabric of Passive House buildings. These are therefore important and significant tests.

The co-heating test is a particularly important test because it involves heating a building under carefully controlled conditions and measuring its heat loss. The building is unoccupied during the test which normally lasts about two weeks and because occupant behaviour is excluded as an influence on results, this is the most objective way we have of testing whether a building performs according to design. The two co-heating tests on the Camden Passive House were held in the context of quiet failures under testing of a number of well-known and much-trumpeted non-Passive buildings that previously claimed low energy credentials.

A brief description of the tests and summary of the results is given below:

1. **The first co-heating test** (20th March 2011- 1st April 2011) essentially a co-heating test utilises an energy balance to determine the heat loss coefficient of the building as a whole. By maintaining a constant internal temperature inside a building, 25°C, and carefully monitoring the energy used to maintain this temperature, the heat being lost is calculated.

   The first test identified a total heat loss of 35±15 W/K, which was much better than the design value of 63.6 W/K. However weather conditions were not ideal during the test, the date of which was determined by the date that the occupants took a short holiday. Problems included bright skies which tend to provide sufficient insolation to distort the results in a very low energy Passive House, which is why the first test had an error of ±15 W/K. Sam Stamp, the UCL university researcher who carried out the test advised that the test be repeated in colder weather at another opportunity. The results of the second test are included in section 3.3 of this report.

2. **Air infiltration test.** A CO_2 decay test was carried out in April 2011 to measure the air infiltration rate during the co-heating test. The method involves monitoring the decay of the internal CO2 concentration following an injection of the tracer gas. The result should correlate to the blower door test. The CO2 decay test gave a result 14% better than had previously been measured by the blower door pressurisation test. The result was ACH_{50}=0.38± $0.08h^{-1}$.

3. **Heat flux measurements.** During the co-heating test in April 2011, sensors were placed on the interior wall and floor to measure the heat flux through the fabric and therefore measure the respective u-values. The study found that the thermal performance of both the floor and walls was very close (slightly better) than the design intentions, indicating that PHPP is a reliable method of measuring u-values:

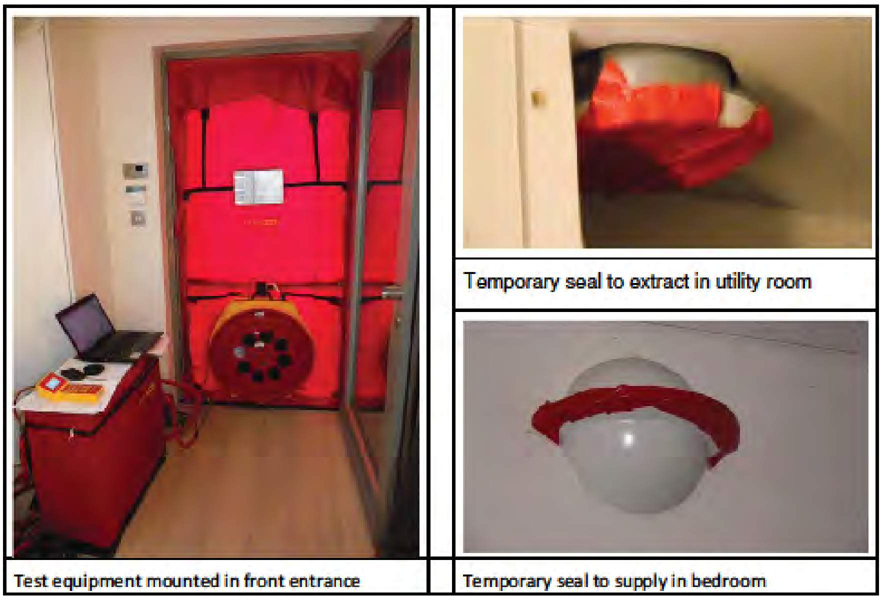
    a. floor design U value: 0.103W/m^{2}K, measured: 0.099± 0.013W/m^{2}K

    b. lower wall design U value: 0.122W/m^{2}K, measured value: 0.097± 0.020W/m^{2}K.

4. **A thermographic survey** was carried out on 1st April 2011, during a co-heating test with higher than normal indoor temperatures to highlight any defects (25°C inside temperature and 11-12°C conditions outside): No defects were found in the walls. Some heat loss was spotted at the top of a pair of ground floor windows at the rear of the house due to air leakage. The windows and doors have hinges which are multi-adjustable. Adjustment of the hinges corrected this problem.

5. **A fourth air-test** - this was the first airtightness post-completion check (carried out 7th September 2011), with the good result of 0.53m3/m2/h, @50Pa, which represents an air change rate of 0.59h^{-1}@50pa, maintaining the design target of 0.6h^{-1}@50pa which is required by the Passive House standard. This was however a poorer result than the construction final test result of 0.44h^{-1} or the tracer gas test result of 0.38h^{-1} measured 5 months earlier in April 2011. This is attributed to a damaged mechanism in one of the first floor tilt-and-slide windows which was later repaired.

3.2 Fifth Airtightness test (2nd post completion BPE air test)


Temporary seal to extract in utility room

Test equipment mounted in front entrance

Temporary seal to supply in bedroom

Figure 3-1. Camden Passive House: airtightness testing equipment

The airtightness test was repeated in June 2013, as required by the TSB BPE protocols. This was the fifth air test carried out on the building over a period of three years. Although it was carried out by a very reputable tester, it did raise a few questions about methodology and stimulated some ideas about how to improve air testing methods.

It is normal procedure in the UK to address potential leakage through the heat recovery ventilation unit by either:

(a) disconnecting ductwork from the ventilation unit and sealing the exposed extract and supply ducts of the ventilation unit or

(b) sealing each supply and extract cowl of the ventilation system.

The former test is popular with some contractors but does not test for leakages in the supply and extract ductwork, and it exposes the air tester to the risk of damaging the ductwork installation.

The second method tests the integrity of the ductwork and reduces the risk of damage to the installation, but relies on careful sealing of every supply and extract cowl in the dwelling.

At first the air tester thought that he had found a serious airtightness problem. However on inspection it was found that the extract cowl in one of the bathrooms had not been sealed at all, so air was leaking out of the building through this route. When the bathroom cowl was correctly sealed, the results were found to be very much better. To avoid this risk in the future, we would suggest that a method statement is prepared by the air tester in the days before a test, using the architect’s drawings which would show the position of each supply and extract duct. The method statement would be checked by the architect or services engineer prior to the air test, and the resulting paperwork would provide a site checklist for the air test operator to use on the day of the test.

Complete sealing of the supply or extract cowl itself is not easy. Air can escape through the back of the flanges if they are not taped on their rear face. Also a perfect seal between cowl and the ductwork behind may be unrealistic, even with double-sealed Lindab ducting because these cowls do not connect with the same rubber sealing method as the Lindab ducting, and instead use sticky-backed foam strips which are unlikely to be air tight. To overcome this problem it would be possible to remove the cowls and seal the end of the ductwork behind each cowl.

Figure 3-2. Example of ventilation system extract cowl

The test results were 0.71 m3/m2/h @50Pa, with an average air change rate of 0.79 h^{-1}. Some leakage points were again identified at the top of the large living room and kitchen windows. On 28th February 2014 the German window manufacturer, Bayer, visited the UK and carried out a maintenance check and adjustment of the windows to improve their air tightness. The lessons from this visit are:

1. Avoid angled window heads (see interior view, fig 1.1). The top of the window cannot be made as airtight as is ideal, and the window is less strong than a rectangular window, so airtightness will deteriorate in time.
2. Few people in the UK are familiar with tilt-and-turn windows and the mechanism is not the easiest or most intuitive for unfamiliar users. It was noted that the windows have been roughly treated in the past, evidenced by the fact that the closing mechanism of one tilt-and-slide window had to be replaced after a metal component was broken. Rough treatment of the window mechanisms was also witnessed during construction.
3. Airtight windows use fine tolerances to achieve thin window sections while maintaining good contact surfaces for twin rubber seals. Even the best mechanisms used by window manufacturers (products from German and Swiss companies such as Siegenia and Roto) are reliant on maintenance to maintain optimum performance.

While this fifth and final air test result is not quite as good as the design team hoped for, it still found a good level of airtightness two years post-completion, even with some window damage and after the building has been subjected to the rigours of five powerful and sometimes lengthy air test sessions.

After completion of the final blower door air test the building was not returned to its correct state by the air tester who forgot to switch the ventilation system on again after the test. This was noticed ten days later as a result of monitored data which showed elevated CO2 levels in the house. Monitored CO2 levels indicated that even after ten days without mechanical ventilation, the CO2 levels and relative humidity remained at safe levels (see fig 6-15).

While this is a test that one could never have knowingly endorsed without the occupants’ permission, the accidental conditions have produced valuable results. It is surprising that the young couple who occupy the house did not notice that the ventilation was switched off, but this is perhaps testament to the fact that the system is so silent and unobtrusive.

3.3 Second Co-heating test

Figure 3-3. Camden Passive House: co-heating test equipment

A second co-heating test was performed by Sam Stamp of University College London between 21st - 30th December 2012 during Phase 2 of the BPE study (see appendix 6). The weather was cold and overcast throughout the co-heating test and these were considered to be good conditions for the test and much more suitable than the weather conditions during the previous co-heating test reported above.

The heat loss coefficient measured during this test was 56 ± 5 W/K. This result was very close to, and even better than, the Passive House planning package (PHPP) design assumption for the heat loss value, of 63.6W/K.

The major difference between the first and the second co-heating tests was due to the uncertainties in the first test resulting from significant solar gains, causing the house indoor temperature to go above the co-heating set point. This second test was performed under almost ideal weather conditions; therefore the result is far more reliable, being based on far less uncertainty.

The conclusion of the UCL report on the 2nd co-heating test states: "*the indication is that the Camden Passive House is one of only a few co-heating tested dwellings in the UK that meets its design intent. This is a positive reflection on the design and the built quality of the house and is especially encouraging considering the low heat loss that was targeted here.*"

3.4 Indoor air quality test

A broad range of indoor air quality (IAQ) tests were performed both in the new build Camden Passive House and, for comparison, in another house located about two hundred metres down the same road (Crump and Walton, 2013 - see appendix 11). The house that was used for the comparison was the occupants' parents' house which is a typical mock-Georgian house with brick walls. The report also compares the results found in another two occupied Passive House homes in Wales that bere:architects have designed as prototypes for social housing and that were completed in 2010. The aim of the test was to measure and compare a range of indoor air quality parameters under normal conditions of building use, but with windows and doors closed. The parameters investigated were: (a) volatile organic compounds (VOCs) including formaldehyde, and (b) PM10 and PM2.5 particulate concentrations. Passive samplers were left for a period of weeks or months to determine mean concentrations of NO_2, SO_2 and Radon. Spot measurements of CO2 and temperature were also taken (although the building also has on-going readings of CO2 concentration at five minute increments).

The conclusion of the report (submitted as part of the TSB BPE study) was that the measurements of volatile organic compounds, including formaldehyde, were within the range reported to occur in homes in England. International or UK-based guidelines are in place for only a relatively small number of the wide range of compounds commonly occurring in indoor air, indicating acceptable levels for the protection of the health of occupants; these guidelines were not exceeded.

The concentration of one compound, decamethylcyclopentasiloxane (DMCPS) was notable because it dominated the VOC mixture. The concentration was high in comparison to the majority of the homes included in the Indoor Air Quality Survey of England. However it is not considered harmful and there is no indoor air quality guideline for this substance which is widely used in personal care products as well as in industrial manufacturing and construction products.

In the traditionally built home (the parents' house located on the same street in Camden) the dominant VOC was a glycol ether compound used in a range of consumer products including cosmetics, paints and cleaning products.

Particulate PM10 and PM2.5 concentrations in the Passive House properties were significantly less than those sampled outdoors. By contrast, the particulates concentrations in the traditional house were generally higher than outdoors.

Concentrations of nitrogen dioxide and sulphur dioxide were well below guideline values recommended by the World Health Organisation and indoor concentrations were similar to those outdoors.

Radon concentrations ranged from under 10 Bq m^{-3} to under 20 Bq m^{-3}, well below the the UK action level of 200 Bq m^{-3} and the UK Target Level of 100 Bq m^{-3}.

3.5 Conclusions and key findings for this section

A. The second co-heating test found that the building's overall heat loss coefficient is slightly better than designed. Although the airtightness of some of the first floor windows was not at the optimum level, the heat losses through fabric and ventilation combined are still slightly lower (i.e. better) than the design targets.

B. The project also helped the academics involved in co-heating research to widen their study of co-heating protocols to include an important section on testing extremely low energy buildings.

C. Building performance, as defined by the co-heating test, was found to be better than the design intentions. In other words, the ‘performance gap’ between design and testing with regard to heat loss was found to be completely closed in this building.

D. The IAQ study found that the VOC levels were better than the international and UK guidelines and also that particulates levels were lower than in a traditional house located on the same street, and lower than outside levels. (This same finding was also found by a separate study of two Welsh Passive House prototypes at Ebbw Vale in Wales. Particulate concentrations were below outdoor levels. It is thought that this may be due to the filtering performance of the F8 pollen filters in the ventilation systems. NO_2, SO_2 and Radon concentrations were also better than the recommended maximum values. This may indicate that the filters on the ventilation system are performing well, helping to deliver clean and healthy fresh air inside the house.

E. The damage or poor adjustment of mechanisms used in tilt-and-slide windows were found to be the cause of minor air leakage in testing on at least one occasion.

F. With the ventilation system not working for ten days, it is considered surprising that the occupants were unaware of this, although this may be testament to how quietly the ventilation system operates under normal conditions. The findings (described further in Chapter 6, the monitoring analysis) showed that the CO2 levels peaked at around 5000ppm with ventilation switched off, and this did not pose any health problems, and the relative humidity in the house ranged between 45% and 75%, which is satisfactory in the circumstances. While failure of the ventilation system does not appear to be, in the short term at least, a health hazard, it may be beneficial for manufacturers to embed a battery-powered warning signal, so that the occupier is aware when the system is not running (by accident or malfunction).

Recommendations for other projects:

A. Co-heating tests of very low energy buildings should always be carried out in dull/overcast weather (as well as cold weather) to avoid solar gains from adding a high level of uncertainty to the overall result, particularly where the house has a high glazed area fraction.

B. Depending on the purpose of the IAQ sampling, it may be necessary to ask the occupants to ensure that all the windows are closed on the test date and to avoid excessive cooking, decorating or cleaning, although for some sampling, highlighting the effects of household chemical usage might be an important outcome.

C. It is desirable to perform an air permeability test directly before and after the co-heating test if possible, so that the results can be interpreted together.

D. Tilt-and-slide windows should not be used in conditions where they might be considered vulnerable to damage, such as in housing for the elderly, disabled or in social housing projects generally.

E. The reliability of the air testing methodology and veracity of the results might be improved by adopting method statement protocols prior to each test. A written method statement could be checked by the architect and the services engineer before the air test. It could include a plan with locations of all the proposed interventions such as sealing up of extract and supply air cowls prior to testing.

4 Key findings from the design/ delivery team walkthrough

4.1 Observations from the design and delivery team

Overall, the design team felt that the outcome of the work met the original project objectives. The architects' comments were that '*The rigorous and detailed design requirements needed for Passive House certification are easily fulfilled by an experienced, conscientious architect who is prepared to undertake training in Passive House advanced construction skills. The spatial requirements requested by the occupant (a warm, healthy house with two bedrooms with en-suite bathrooms, and a brightly lit, contemporary, open-plan living space with ample daylighting) were also fulfilled.'*

The client made several late changes to the building contract:

- Moving the ventilation unit from inside to outside the building, in the cycle store, happened at a late stage in order to create more storage space internally in the entrance hall. The reason for this was that the specified unit, which was selected because it had one of the best heat recovery efficiencies available at the time, was larger than expected by the client. Subsequently much smaller units are manufactured by Paul and these smaller units can be more easily accommodated inside a house as specified in later projects by the same architect. However the client's late change meant that openings required for ducting had not been designed into the timber frame. Fortunately the timber frame contractor Kaufmann completed this work at no extra cost, but otherwise there could have been problems.

- The front garden was intended to have a gabion wall towards the street. The change to an ivy-covered fence significantly reduced the levels of privacy to the bedroom windows, so the blinds were used differently (more often in the winter than if the bedroom window had faced into a private garden, reducing the solar gains indoors);

- The late involvement of the client's wife in the interior design of the project resulted in changes that on the whole did not affect the technical aspects of the building but there were a few more significant changes. For example, the finely-finished timber ceilings were covered with plasterboard, requiring some special dished cutouts to allow for the already-installed sprinkler system to function as intended in the event of a fire.

- The client, who is a developer, insisted on using his own plumber and electrician and, living only a couple of hundred meters from site, visited almost daily, issuing his own instructions to them. Both the plumber and electrician were of a poor quality and caused a number of problems highlighted in this section of the report.

- The lighting layout was changed, and some of the specified LED fittings were substituted by cheaper LED fittings which were incorrectly wired in one bedroom (using 12v dichroic wiring methodology in spite of being shown that LED circuits must be wired differently) so that they do not illuminate properly. Some light switches were also incorrectly positioned without proper regard to the drawings but these errors were considered acceptable to the client who would not allow them to be changed as he wanted to maintain a good relationship with the electrician on his other development projects.

- The client also decided to make changes to the staircase design. This was resisted in vain by the architect. The templates for the solid painted handrails were used by the client as templates to purchase glass handrail panels. The architects were not involved in the mounting of the glass handrail design which has some clumsy chrome fixings and brackets. Furthermore the sides of the staircase were veneered on site since the client's change to a glass handrail exposed the side of the staircase to view. The staircase had also been detailed to be freestanding on its final flight, but the client built cupboards beneath the staircase and filled the gaps between the stair and the wall.

Key elements that influenced the design and the construction process were:

- One key design decision which was taken from the start of the project was that the superstructure would be a prefabricated timber structure, including the façade cladding. There were three main reasons for this: (1) the architect's interest in ecological construction materials led it towards timber as an effective utilisation of a renewable resource (2) the architect's interest in prefabrication to reduce cost, construction times and waste. (3) the architect's timely employment of a timber engineering and construction graduate and draughtsman from Austria, the son of the owner of a leading Austrian timber construction company.

- A key construction decision was to have an 'airtightness champion' on site, with Passive House construction expertise, employed by the main contractor, who briefed all the workers on the construction team about the aims of the project and the importance of the airtightness layer.

- The task of the 'airtightness champion' on site was a difficult one. The subcontractors needed to be constantly monitored on site. This was particularly the case with the client's own plumber and electrician since they were not considered sufficiently conscientious, so the quality of their work needed to be regularly checked. Drawing on his German background, the contractor's airtightness champion, Dominic Danner, introduced the team to a new role, that of a 'Process Technologist', responsible for the integration of the M&E through design and into construction. His role in this early project was considered an important factor in the success of the project.

- The M&E consultant (Alan Clarke) was crucial to the success of the design since, like the architect, he brought with him several years of research into low energy Passive House techniques which the architects have been unable to find in other local M&E consultants in London. However, living in Gloucestershire, his site visits were less frequent than ideal in this early Passive House project and the Process Technologist was a useful link between him and the site operations.

- As described in section 2.2, mechanical innovation in this project included a ventilation boost button adjacent to each bathroom. The intention was to enable the occupants to easily boost the ventilation to clear excess humidity in the ground floor bathrooms without the need to use the main control panel on the first floor. In practice the occupants of this dwelling say that they do not feel the need to use the boost buttons, however occupants of another project say that they do use them due to the fact that the main control panel may not always be conveniently located and may, moreover, present a more confusing interface than a simple rocker switch or timed boost button.

- As described in section 2.2, another mechanical innovation was to provide a towel radiator boost button giving a choice of ½ hour, 1 hour or 2 hours running time. This was in order to prevent towel radiators being left on unnecessarily in a house in which it was expected that optimum relative humidity (RH) levels would facilitate quick drying of towels without the need for hot towel radiators. Warm towel rails were intended to reassure the client that the bathrooms would be warm since they originally wanted underfloor heating. In use, the occupants say that they rarely use the towel radiator option and do not feel they would benefit from underfloor heating. They say that they are completely satisfied with the comfort of the bathrooms and they rarely use the towel radiators.

Solar thermal

- It became evident that on a warm day the Viessmann solar thermal system was not generating as much thermal energy as expected. Examining the roof showed that the installation was incorrect. The original design was for the panel to be mounted on an A-frame, facing south; this was shown on the tender and construction drawings. After work had started on site, though, the suppliers for the system recommended that the panel should instead be installed flat with tubes running East-West, and each tube rotated approx 30 degrees so the collector surface in each tube in angled towards the sun. Viessmann recommended this change due to problems of stagnating water with the same unit in previous installations.

- No new drawings were issued with this instruction, with the client's own plumber confirming that he would enact this variation. However, when inspected on site the panel was actually installed with tubes running North-South. In addition about a third of the tubes were upside down, which inevitably cuts output significantly. The plumber had installed the panel to match the orientation of the original A-frame design but in the flat position, ignoring the architect's instruction. When Viessmann attended site to commission the system, their commissioning report was issued to the main contractor but a copy was not sent to the architect or the client. When the architect asked Viessmann for a copy of the report (which they had only sent to the contractor) it showed that Viessmann had highlighted the problem with the panel orientation and had stated that this must be corrected. This clearly did not happen but was picked up by the architect when it was noted that the panel was delivering less energy than expected.

- To prevent errors of this kind, it is important that clear drawings are issued with instructions relating to any changes from the construction drawings – especially with regards to the orientation of specialist equipment. In addition, a copy of the commissioning report should be provided to the design team for review.

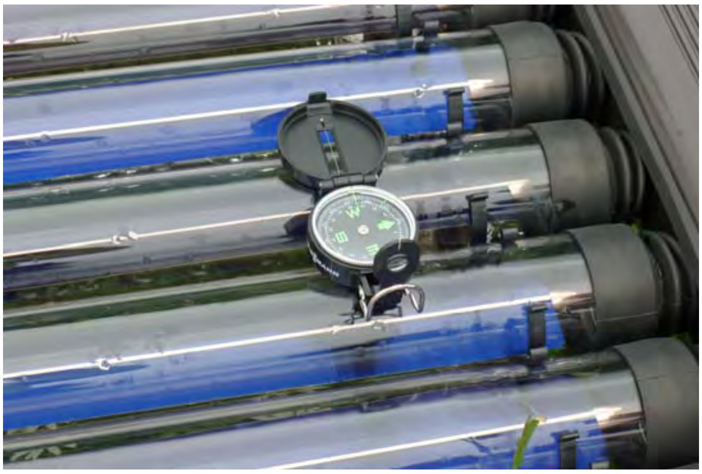


Figure 4-1. Solar thermal tubes were installed north-south instead of east-west, and a third of them were installed upside-down

- Subsequently during monitoring, as mentioned in section 6.3.1, excessive electricity consumption was found in the solar pump electrical supply and even after the alterations described above, the Viessmann solar thermal system was not generating as much thermal energy as expected. A site inspection revealed that the solar pump was running continuously day and night. At first it was thought that this might have been due to incorrect programming of the new basic controller that replaced the weather compensation controller. (As explained in section 2.2, the weather compensation controller that is supplied as standard on the Viessmann combined solar tank and boiler was replaced by a simple controller without weather compensation for reasons explained in section 2.2.) But after investigation and interviews with the client's own plumber, it was found that when the control panel was replaced, the solar control wire behind the control panel was disconnected by the plumber and reconnected to the wrong terminal which resulted in the pump running day and night, discharging tank heat to the night sky via the solar panel. When the plumber's wiring error was corrected, monitoring showed that the solar system operated as intended.

- Bere Architects have now tried to address the risk of this happening again in a future project by developing strong relationships with suitably skilled and committed plumbing subcontractors.

Heating system

- The operation of the heating system was checked at the on-site review. The heater battery was turned on using the ventilation controls. Air temperature in the duct after the heater battery was in range 51-54^{0}C, for a boiler flow temperature of 60-64^{0}C and return of 51-54^{0}C.
- The boiler flow temperature was found to rise gradually above the set-point of 60^{0}C because the heat output of towel rails and the air heater is slightly less than the minimum boiler output, but the rise in flow temperature is controlled and takes several minutes. Eventually the boiler stops firing, but the pump continues to run until the heat has been discharged by the circuitry and the flow temperature drops below 60^{0}C. This was seen to maintain air temperature at a suitably high level despite the boiler cycling on and off a little more than intended.
- The ventilation controls do include a limiting cut out to avoid high air temperatures in the ductwork. This is set at 55^{0}C with 5^{0}C hysteresis, so this will not cut the air duct heating until the air temperature reaches 60^{0}C. This was not seen to be happening. If it did, it is expected that the boiler heat would be dissipated via the pump run on through the towel rails and the air temperature would drop fairly quickly to 50^{0}C as the duct heater zone valve would be closed, and then the boiler would fire again.
- Heating balance is a little complicated with air heating, although in this house it worked out well. As air is carrying the heat, the more air you get the more heat you get. This might be a problem if there was a desire to get high airflow into bedrooms and yet keep the bedrooms cooler than the living area. While that isn't what the occupants of this house want, it is what is wanted by the occupants of another project.
- In this project the airflow was adjusted to be 50:50 to each floor and the occupants cannot alter this. If the occupants had radiators, this would enable them to reduce heat output in particular rooms if they wanted to, which isn't thought to make economic sense in a Passive House. This wasn't wanted in this instance but such a feature would, on another project, enable an occupant to continue old habits.
- Bere:architects would use air heating again as it proved to work well in this house and provides significant cost savings by avoiding the cost of a wet heating system. Since completing this project bere:architects have used both air heating and radiators or underfloor heating in other UK Passive House projects, and both systems appear to be working well.
- It seems that the upside down arrangement of the house (with bedrooms downstairs) helped, since buoyancy circulation tends to keep the upstairs at least as warm as downstairs. Upstairs also has the higher solar gain. The addition of towel radiators downstairs doesn't seem to have upset the temperature distribution.
- One factor not anticipated in the heating design was the high heat loss from the ducts and the reduced air supply temperature. Supply air temperature is around 15C lower than off-heater

temperature in bedrooms and 5C lower in the living room. The reason for the difference is unknown, probably down to relative duct length, although it is also possible that concealed ductwork has not been insulated properly.

- The supply air ducts are specified to be insulated in most areas of the house but where they are exposed for a distance of about 1 metre while they cross the ground floor space between the plant room and the bedroom, it was decided to leave them un-insulated for aesthetic reasons. This does not appear to have caused any technical problems.

Heat recovery ventilation system

- As the result of a late client requirement to maximise indoor coat and shoe storage in the entrance hall, the location of the ventilation unit (a particularly large and now superseded unit by the German manufacturer Paul) was changed from under the main staircase to outside the thermal envelope, in the bike shed. The unit was housed in a moderately insulated cabinet in close proximity to the thermal envelope. Particular care was applied to ductwork penetrations and insulation.

- The project team is also testing a long-life filter concept on the building's air intake. A key benefit of the new filter is to allow it to be changed externally by a service agent without prior appointment to enter the house. It is considered that this would be equally helpful for filter maintenance operatives in social housing and in private developments.

- This was the first project by bere:architects which does not rely on radiators or underfloor heating to maintain comfort. When heating is required, it is only required in tiny amounts which can be supplied through the ventilation air supply ducts. As a precaution in this early project, towel rails were also specified. They can switch on automatically or for a short period by touching a demand switch. Further, pipe work connections were installed in the living room to allow for a radiator to be easily fitted if necessary in the future. During the first two years of performance monitoring, the occupants consistently reported that they are completely satisfied with the comfort of the house and that they have no need for radiators.

- The team found that the occupants occasionally used electric heaters when returning after the winter holidays, and on one occasion for a few weeks seemed to fall back into old habits and forget that they were not needed in this house. Although the energy consumption to maintain constant warm temperatures in the house would be very small if the top-up heating was left on, it is understandable that people do want to switch off the heating when they go away. It is perhaps surprising that a boiler manufacturer hasn't added a simple boiler control dial that switches the boiler off for a period ranging from just a few hours during the day to a few weeks for a long holiday. By this means the householder could also ensure that the boiler comes back on before they return home.

- The occupants also sometimes used fans during the night in the summer. In interviews, the occupants say that they are nervous about summer night purge cooling via the windows, due to concerns about safety and privacy. Tilt and turn windows are usually considered to give reasonable security and it was expected that they would be opened for secure night time ventilation in the summer. In future projects, to provide increased reassurance about the security of occupants when night time natural ventilation is used during the summer months, we would suggest offering a small, say 300mm wide, inward-opening window with an external steel security grille. This method of night cooling was successfully utilised in a later project, the Mildmay Community Centre in Islington, London which is the subject of another TSB-funded BPE project.

- The display of the ventilation control that was panel originally supplied was written in German. This was the first unit supplied in the UK by the German manufacturer Paul, and subsequently at our request an English version of the control panel was manufactured and this is now provided to all UK imports. The German control panel was replaced with the new English one and the client quickly became conversant with it.

- Room temperature is also set by means of the ventilation control unit and this has been found to operate successfully and the client is pleased with the single control panel for air supply volume and air supply temperature.

4.1 Conclusions and key findings for this section

1. The team had a proactive post-completion approach, aimed at a close performance check of the systems via a monitoring log, and aimed at familiarising the occupant with the way the house was designed and the systems which were not traditional in the UK (heating via air and towel radiators only, integrated solar and boiler system). The detailed monitoring log recorded activities related to systems operation after completion, site visits, findings and interventions made to the systems. A full *Interventions Report* (attached in the Appendices of this document) was submitted to the TSB as part of one of the quarterly reports and this highlights in greater detail the findings and changes made to the systems during Phase 2 of the BPE study.

2. The solar thermal system and its recurring malfunctioning enabled several lessons to be learnt: (1) the importance of employing a knowledgeable plumber (2) the risks associated with changing the manufacturer’s standard controls to make them more suitable for a low energy building. The subsequent problems with air gathering in the system led to a question whether a de-aerator valve should have been part of the initial installation kit.

3. Architects must become construction skills experts as they cannot rely on the UK construction industry alone to offer up the necessary skills for delivery of Passive Houses. Bere Architects have learned to actively seek suitably motivated contractors and sub contract specialists and

provide them with appropriate installation and commissioning training which pays dividends on future projects in which they are employed as nominated suppliers.

4. The Passive House requirements are more demanding of quality than current UK Building Regulations. Where PH goes beyond Building Regulations it was difficult in this project to get the client's own mechanical and electrical subcontractors to understand why the PH standards should be adopted. To avoid this problem in future projects, suitable firms are trained and specified as noted in 3 above.

5. Main contractors that want to become successful in Passive House work need to adopt excellent quality assurance systems. To this end they may partner with suitably qualified sub-contractors and may benefit from employing someone dedicated to training and to raising awareness about the elements typical of very low energy building design and construction. The main techniques which need to be applied by the contractor are: achieving a continuous insulation layer without air gaps (ie avoiding thermal by-passes behind insulation); avoiding thermal bridges due to incomplete or badly installed insulation; adopting a carefully defined and planned airtightness layer and carrying out virtually faultless installation of the airtightness layer including the crucial wall connections with windows and doors; understanding the importance, role and the need to protect the airtightness layer during construction; applying the appropriate staging of air tests timed with the sequencing of trades and a thorough commissioning of all the systems.

6. Suitably skilled and experienced M&E consultants are essential to success but at present are hard to find in the UK.

7. Thoroughly designed and constructed Passive House buildings are proving to be reassuringly robust in use.

8. Counter to general intuition, bathrooms and other rooms without any underfloor heating or towel radiators can be exceptionally warm and comfortable.

9. In this project, Summer night time purge cooling by means of natural ventilation is not practiced optimally due to occupant concerns about security and flying insects. We have found the same problem in another TSB-funded BPE project in Wales, where the children are afraid that opening windows will let spiders into the house. These concerns could be addressed by means of external fixed metal louvres outside a small window or solid panel, or by the provision of insect mesh screens where appropriate.

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

The Camden Passive House occupants are a young working couple. Initially the house was to be built for investment but a later stage of the process, already through construction, it was decided the client's daughter and her partner would live in the house. The final occupants were not involved in the design process and requested some changes –which were mostly internal design aspects since it was too late to make any drastic changes. They also changed the proposed gabion wall facing the street for an ivy planted fence which greatly reduces the privacy levels.

During the previous BPE Phase 1, roughly 7 months after the occupants move, UCL researchers conducted a semi structured interview combined with a walkthrough with one of the occupants and one of the architects of the design team (Durdev and Ridley, 2011). Below is a summary of the report findings:

- The occupant is satisfied with the handover process and find the user manual located inside the utility room to be easy to understand and very useful. It is also satisfied with the aesthetics of the house and its modern styling and state that it is a nice place to live in.
- The occupant is happy with the room sizes but would prefer more wardrobe space.
- Due to privacy issues of big glazed windows, external blinds are always down in the living room when the occupants are at home
- The extra bedroom, which is less used, has NW orientation and thus generally has lower temperatures which are not a problem.
- The occupant claims to be satisfied with the MVHR (silent, responsive and easy to use) stating that the *Passive House* concept of heating through heat recovery is better than a conventional system as the house is always warm, "warmer than my parents' house".
- The occupant shows understanding of the principles of the MVHR and the importance of minimising natural ventilation according to use and regularly changing the filters. Ventilation rate is only adjusted by using the boost ventilation in bathroom, only occasionally after showers. There are no reported problems with humidity. Otherwise the ventilation rate is never adjusted, even when the number of people increases. The occupant instead prefers to open a window to get additional fresh air.
- The occupants are not using the bedroom windows tilt option for summer night ventilation because they don't feel safe leaving a window open at night, despite the fact the windows have special security measures. Instead on occasions they use an electric fan.

The first year of the BPE Phase 2 study was strongly focused on monitoring energy consumption and internal environmental conditions which gave a deep understanding of not only the house performance but also the residents' behaviour and interaction with the house technologies. Subsequently occupant interviews and evaluations were undertaken: a Building Use Survey (BUS methodology), a window use analysis and a post-occupancy evaluation interview.

5.1 BUS methodology

The occupants of the Camden Passive House have answered two post-occupancy BUS methodology questionnaires. The first was in the BPE Phase 1 in July 2011 and the second for BPE Phase 2 in June 2013. Both BUS surveys were only undertaken by one of the occupants; the first by the client's daughter who lives in the house with her fiancée and small dog, and the second by her fiancée.

With only one sample, the results are not really comparable with other residential building studies. Nevertheless, the BUS methodology outcome shows the resident to be in general very satisfied with all aspects of thermal comfort and general house performance.

The BUS methodology indices provide an overview of the building performance and are compared with a limited number of domestic houses already in the BUS methodology database. As seen on Table 5-1, the Camden Passive House has very high levels of performance on the Comfort, Satisfaction and Summary indices, with results positioned on the higher percentiles.

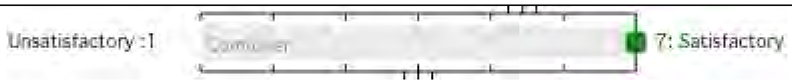
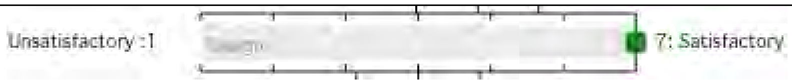
The Forgiveness index is a measure of tolerance of users with the building environmental performance and takes in consideration the results of the overall variables. Since these were also very positive (Table 5-2), the result is close to a neutral value, meaning the occupants don't feel the need to overlook any aspect of the building performance.

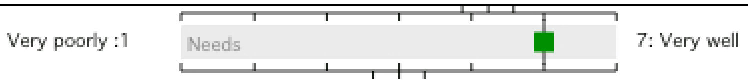
Table 5-1. BUS indices

	Mean	Percentile	Scale
Summary	2.81	99	[-3 to +3]
Comfort	4.2	99	[-3 to +3]
Satisfaction	1.42	99	[-3 to +3]
Forgiveness	1.02	26	[-0.5 to +1.5]

Table 5-2 shows the results for the variables that assess overall satisfaction. The resident rated the Camden Passive House as comfortable, with satisfactory design, capable of supplying for her needs and of improving her health.

Table 5-2. Summary of BUS overall variables

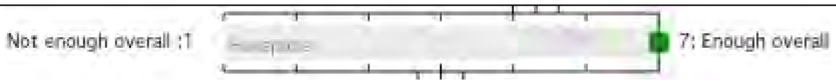
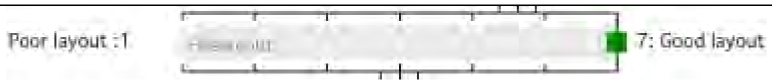
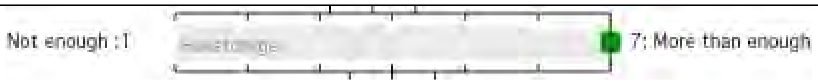
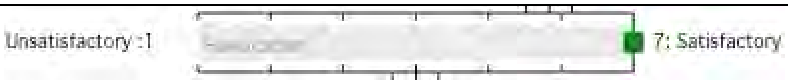
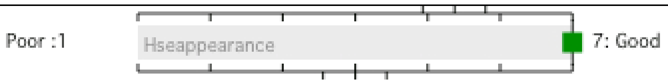
Variable	**Result**	**Percentile**
Comfort: overall		99
Design		99

Health (perceived)		99
Needs		99

In the home overall section respondents can rate several aspects of their homes. The Camden Passive House achieved outstanding results with the occupant rating to be highly satisfied with the house space, layout, storage availability, location an appearance (Table 5-3).

On the comment section it was noted an issue with not enough privacy in the bedroom (due to the client's decision to omit a stone wall from the contract) but a prickly Berberis hedge has now been planted to address this.

Table 5-3. Summary of BUS methodology Home Overall variables

Variable	Result	Percentile
Space		99
Layout		99
Storage		99
Location		99
Appearance		99

To describe the thermal comfort of the houses, several variables are assessed in terms of air and temperature. Camden Passive House occupants reported a good air quality throughout the year with winter and summer conditions rated as the highest possible level of satisfaction (See Table 5-4 and Table 5-5). Air was noted as odourless, fresh (slightly less in summer) and with good moisture content (not dry or humid). Both in winter and summer, air was considered still, i.e. the opposite end of the range from 'draughty'. This result is considered as negative in the BUS methodology scale, and the ideal result would be a middle range value. However this question is commonly misunderstood, and since the occupants have never complaint of air quality and the overall satisfaction is so high, it is thought that this was intended as a positive comment.

Table 5-4. Summer air quality variables – the red mark was a misunderstanding of the question – the response of 'still air' was intended to confirm that there are no unpleasant draughts.

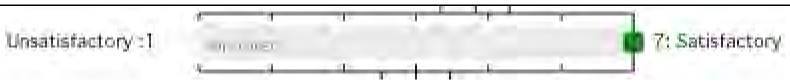
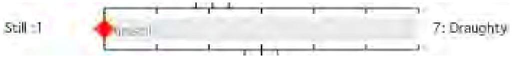
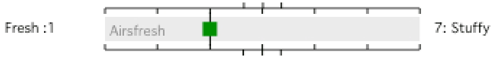
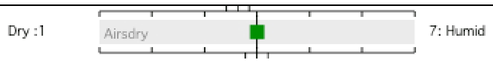
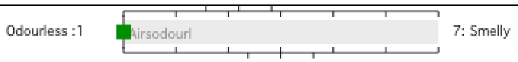
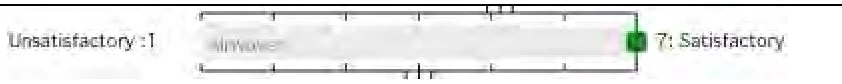
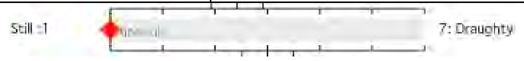
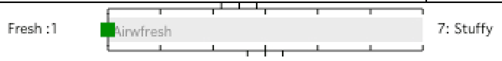
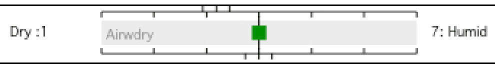
Variable	Result		Percentile
Air in summer: overall			99
			
			

Table 5-5. Winter air quality variables – the red mark was a misunderstanding of the question – the response of 'still air' was intended to confirm that there are no unpleasant draughts.

Variable	Result	Percentile
Air in winter: overall		99
	 	
	 	

Winter temperatures are perceived to be even more comfortable than summer. Summer temperatures were noted slightly hot but still the house was rated comfortable throughout the year.

Table 5-6. Temperature variables in winter

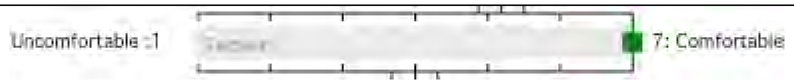
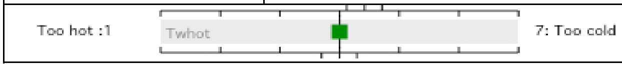
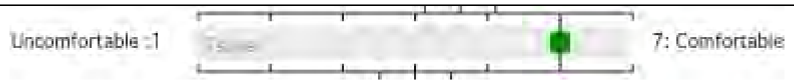
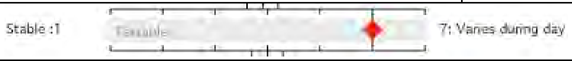
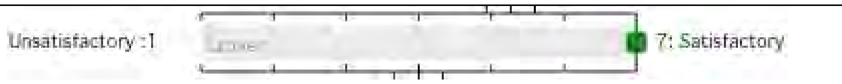
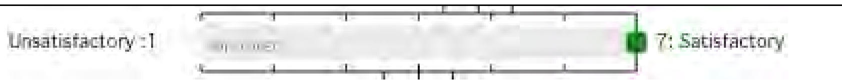
Temperature in winter: overall		99
	 	

Table 5-7. Temperature variables in summer

Variable	**Result**	**Percentile**
Temperature in summer: overall		99
	 	

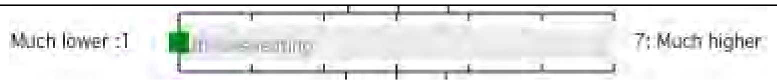
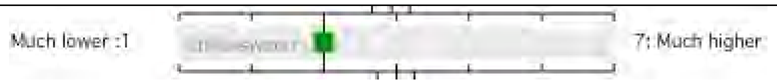
Lighting and noise were overall rated satisfactory although the comments noted the bathroom to be too dark and that the gaps under the doors allowed for noise between the rooms. Internal doors include a 10mm gap under the door for cross flow ventilation. The house also has wooden floors throughout and it should be noted that the parents' home that the occupant move from is carpeted.

Table 5-8. Lighting and Noise variables

Variable	**Result**	**Percentile**
Lighting: overall		99
Noise: overall		99

Utility bills were stated to be lower or much lower than previously. The water comment section noted *"No bath, don't miss it"* indicating a notion that showering consumes less water than bath.

Table 5-9. Summary of BUS methodology results for utilities cost in comparison to a previous residence.

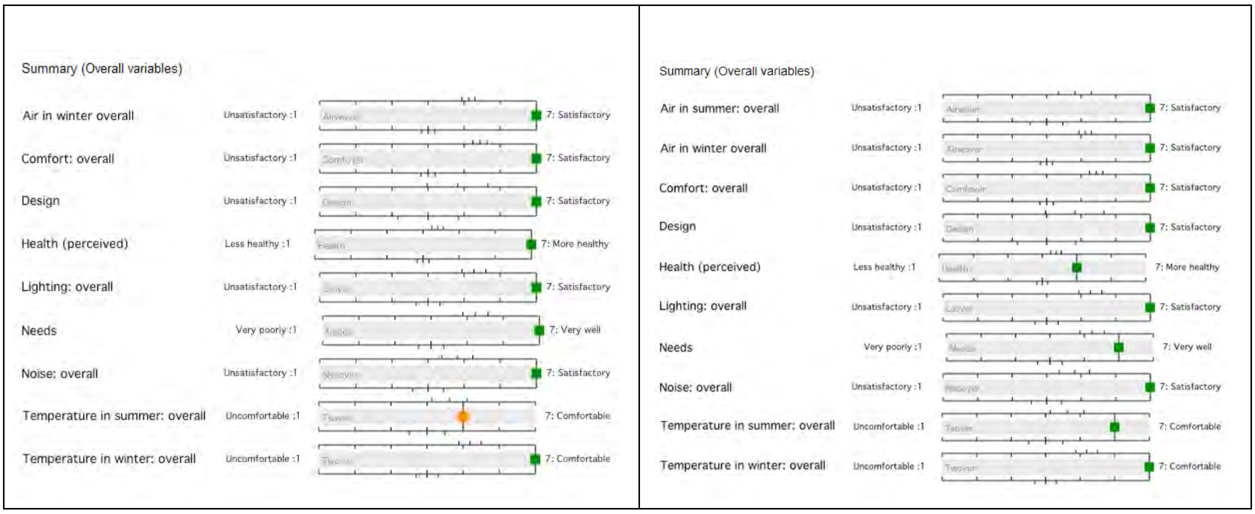
Variable	Result	Percentile
Utilities cost for electricity		32
Utilities cost for heating		10
Utilities cost for water		10

The Camden Passive House achieved an outstandingly good BUS methodology performance, and while it is hard to compare the results with the benchmark because there is just a single respondent, it appears that the house compares very favourably with other homes.

The anonymous data tables can be found in Appendix 8 and through the following link: **http://portal.busmethodology.org.uk/Upload/Analysis/y3ejjnmo.5my/index.html**

Below is a comparison of the overall results for the Phase 2 BUS methodology (June 2013) with the Phase 1 BUS methodology (July 2011) and. There are minimal differences in the results with the most recent survey showing an improved result for ‘Temperature in summer’ and a lower score for ‘Needs’ and ‘Health (perceived)’.

Table 5-10. Summary results comparison between BUS July 2011 (left) and BUS June 2013 (right)



5.2 Window Use Studies

Two studies were carried out of occupant patterns of window use during Phase 2 of the BPE study (see Appendix 9). The purpose of these studies was to determine whether the occupants were actively using the windows to optimise indoor conditions in the warmer months, and whether they felt the need for additional fresh air in the winter months. Residents were asked to report their daily window opening habits for a period of one week. They were asked to include information about which windows were used, to what extent they were opened (fully, half open or tilted) and the duration of the period of opening.

The first window use study was completed during one week in late May 2012. In the selected week external daily temperatures were regularly reaching 25^{o}C and night temperatures were dropping below 15^{o}C. Results of the survey indicated that no night purge ventilation was used (apart from one occasion in the dining room), bedroom windows were not left open at night, living room windows were the ones mostly used in the evening, occasionally in combination with dining room windows to achieve cross-ventilation, and the windows were always closed when the house was not occupied.

The second study was undertaken in early December. During the selected week external temperatures averaged 3.6^{o}C, with temperatures frequently dropping below 0^{o}C. The occupants responded that windows were not opened at all during the winter months. The occupants appear to understand the benefits of using the heat recovery ventilation during the winter.

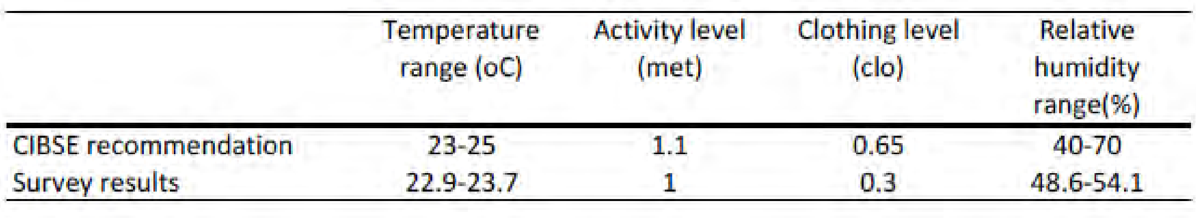
5.3 Post-occupation Evaluation interview

Following the first ‘Window Use Analysis Study’ in May 2012, a comfort survey and semi-structured interview were carried out in June 2012 by a researcher from University College London in order to investigate the association between occupant experience and different environmental factors (see appendix 10).

Using a separate set of data loggers, (HOBO data-loggers), the indoor temperature and relative humidity were monitored during the interview to evaluate the occupants’ satisfaction with the building and perception of indoor environmental factors (indoor air quality, acoustic comfort, thermal comfort and lighting).

Occupants were found to be generally satisfied with the internal conditions of their home and building systems. Three issues were raised namely the low lighting level in the spare bedroom (the client’s own electrician incorrectly wired the LED lighting in this room but the owner insisted on accepting this defect), some overheating issues in the summer (the residents reported the use of an electric fan in the bedroom instead of opening the windows in tilt-turn position for night purge due to security reasons) and the privacy of the first floor living space. The residents reported the external blinds to be mal-functioning - eventually found to be due to another wiring fault. For privacy reasons, the occupants were found to be keeping the internal blinds in the living room down during hours of daylight, while at the same time using electric lighting in the living room – this issue had been sensed by the design team when detecting a higher level of energy consumption for lighting on the monitored data. The external blinds were subsequently fixed. No issues were raised regarding indoor air quality and acoustic comfort.

During the survey indoor thermal conditions were monitored, as mentioned above, and internal conditions were found to be close to the CIBSE Guide A recommended comfort criteria for living rooms. The occupant was asked to rate his comfort level which he described as ‘neutral’. According to the results of the predictive model set in ISO 7730 he would be expected to be feeling 'cool' at this temperature in the Summer, but his description taken to mean that he was feeling comfortable.



	Temperature range (oC)	Activity level (met)	Clothing level (clo)	Relative humidity range(%)
CIBSE recommendation	23-25	1.1	0.65	40-70
Survey results	22.9-23.7	1	0.3	48.6-54.1

Figure 5-1. Recommended summer comfort criteria and survey results (Gautier, 2012)

In summary, the purpose of the study was to investigate how the occupants used the home and their level of satisfaction with the buildings systems. It was concluded that the occupants were very satisfied with the house.

5.4 Conclusions and key findings for this section

1. Occupant evaluation studies can provide great feedback for designers as it as it helps to identify the building problems or design/construction faults. Learning from the building in use can provide valuable lessons that inform future projects. The three different studies undertaken gave a good insight to the way the residents interact with their home. The BUS results provided a good insight to user perceptions and being a standard assessment generated comparable results with benchmarks. The window opening study, although short, indicates where occupant habits vary from expectations. Finally the more in-depth semi-structured interview provided useful feedback from the residents, particularly as it was obtained by an independent UCL researcher free from any design preconceptions.

2. Understanding the occupants' perception and relationship with the building's indoor environment is important as occupant behaviour can have a significant impact on energy consumption. The research found that some occupant behaviour patterns are slightly sub-optimal yet no performance gap has been found between designed and actual energy use or comfort.

3. The occupants are very satisfied with overall performance of the house. They appreciate the modern design, layout and space and storage available. They are happy with temperatures and thermal comfort, especially in winter. In the summer there is an indication of higher than ideal temperatures but it was noted that the occupants were content and they are not using the option of summer night purge ventilation.

4. The occupants expressed some concerns about privacy of the bedroom and living room. These concerns seem to make them overuse the blinds, reducing the solar gains in winter.

5. The final interviews, conducted 2 years after completion, indicate that the occupants remain very happy with their house and completely satisfied by the way it is performing.

6 Monitoring methods and findings

6.1 Monitoring methods

The wireless data logging and monitoring system at the Camden Passive House was designed, specified and monitored by Dr Ian Ridley, at University College London. Equipment was supplied by Eltek Limited and Bere Architects managed its installation. Eltek commissioned and tested the system. The installation took place in July 2011 by electricians and plumbers involved in the construction of the house. Data is recorded at 5 minute intervals and downloaded remotely via modem on a weekly basis using Darca Plus software. The same program was used to set up the system transmitters and the logger's channels. It also monitors and graphs the data on screen in real time, and stores the data for analysis and printout. Furthermore data is exported to a spread sheet for analysis and archiving and checked for sensor dropouts and to identify general maintenance and reliability issues.

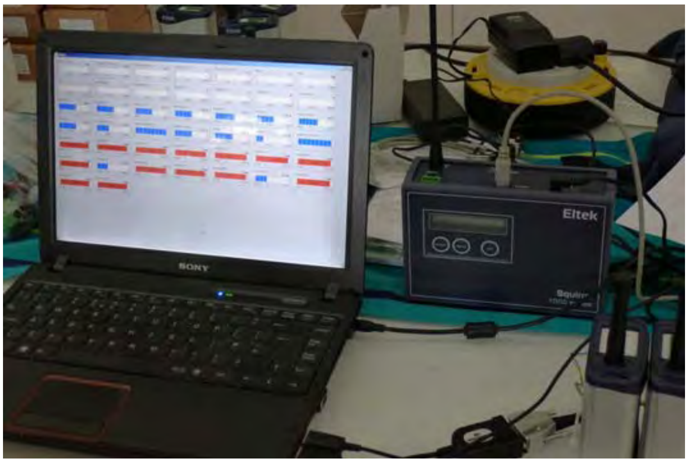


Figure 6-1. Eltek setting of the monitoring devices

A very wide range of monitoring devices was specified (refer to monitoring user guide in Appendix 12).

The monitoring system includes:

1. an external weather station (measuring dry bulb temperature, relative humidity, wind speed and direction, global solar radiation, atmosphericpressure, precipitation);
2. total water used;
3. total gas used;
4. total electricity used;
5. 11no. electrical circuits are sub-metered (ground floor lights, first floor lights, ground floor sockets, first floor sockets, utility room sockets, kitchen sockets, hob, oven, heat recovery ventilation unit, blinds, boiler);

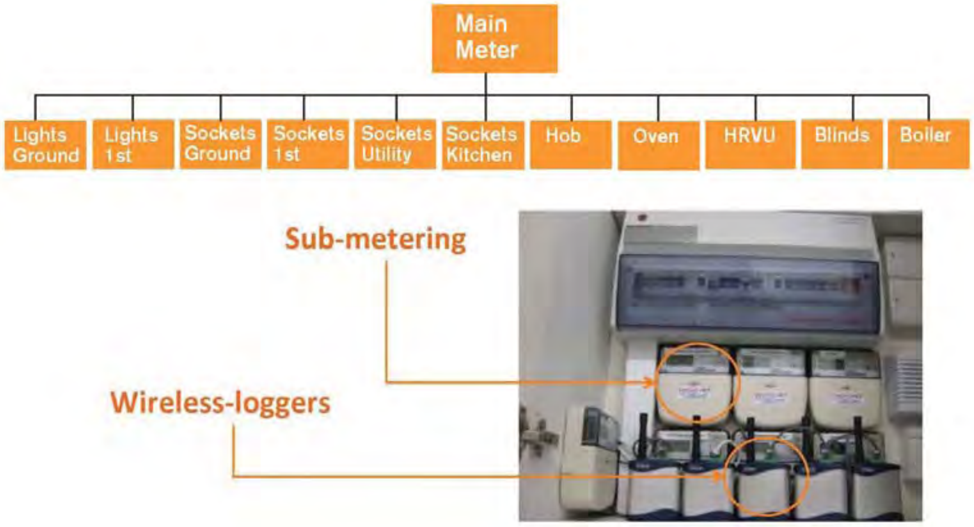


Figure 6-2. Electrical sub-meters are fitted with wireless transmitters to connect them to the data logger and transmitter.

6. 9no. duct temperature meters in the HRV system (measuring air off heater, duct heater flow, duct heater return, hrv supply, hrv extract, hrv intake, master bedroom supply, living room supply, and kitchen extract);
7. 3no. temperature and relative humidity meters (measurements from the kitchen, en-suite bathroom and guest bedroom);
8. 2no. temperature, relative humidity and CO2 meters (measurements from the living room and master bedroom);
9. 4no. heat meters (measurements of domestic hot water consumption, the solar input to the hot water cylinder, the space heating supplied by the towel rails and by the heater battery in the air supply)

Monitoring log

Throughout the duration of the BPE study a monitoring log was kept, describing relevant activities which might have an impact on the monitoring data, from systems re-commissioning and faults fixing, to occupant behaviour or occupancy data. This was crucial to keep the monitoring and data analysis team informed of any interventions; putting the analysis of monitoring data into context and enabling accurate interpretation of results.

6.2 Monitoring results

Monitored data spanned from October 2011 to September 2013 covering two years. Detailed monitoring reports were produced by bere:architects and submitted to the Technology Strategy Board on a quarterly basis, giving a detailed analysis of the building's performance for the two year period. Table 6-1 details the seasonal monitored periods.

Table 6-1. Monitoring periods detailed

Winter 1	October 2011-December 2012 / January 2012-March 2012 (quarters 1 & 2)
Summer 1	April 2012-June 2012 / July 2012-September 2012 (quarters 3 & 4)
Winter 2	October 2012-December 2013 / January 2013-March 2013 (quarters 5 & 6)
Summer 2 & Winter 3	April 2013-June 2013 / July 2013-September 2013 (quarters 7 & 8) Note: the 8th quarter was voluntarily extended to include a third winter of monitoring in order to provide increased veracity to the performance results (see fig 6.6).

6.3 Energy performance

The total energy consumption for the Camden Passive House was 6518kWh or 64.5kWh/m^2 in the first monitored year (October 2011 to September 2012) and 6697kWh or 66.3kWh/m^2 in the second year (October 2012 to September 2013). These numbers make the Camden Passive House one of the lowest energy dwellings monitored in the UK. Other similar UK projects with comparable energy consumption are BedZed 90kWh/m^2, The Long House with 80kWh/m^2, One Brighton with 72kWh/m2, and Princedale Road with 63kWh/m^2 (Ridley et al, 2011).

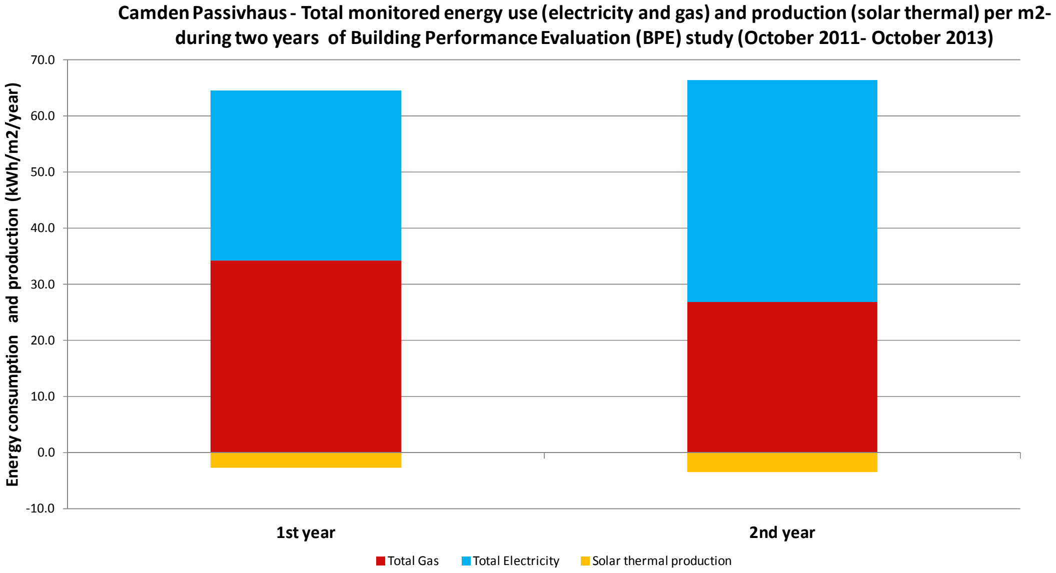


Figure 6-3. Total monitored energy use (electricity and gas) and production (solar thermal) per m2/year

In the first year 47% of energy consumption was due to electricity for all uses including unregulated uses (30.3kWh/m2), and 53% was due to gas for hot water and heating (34.2kWh/m2), while in the second year the division was 60% electricity and 40% gas (39.5kWh/m2 and 26.8kWh/m2 respectively).

The annual primary energy demand was 119kWh/m2 on the first year, slightly below the 120kWh/m2 *Passive House* target. But for the second year the primary energy demand was 136kWh/m2, a 12% increase. This is because, despite a rise in the total energy consumption of only 3%, there was a 30% increase in the electricity consumption and a 22% reduction in the gas consumption.

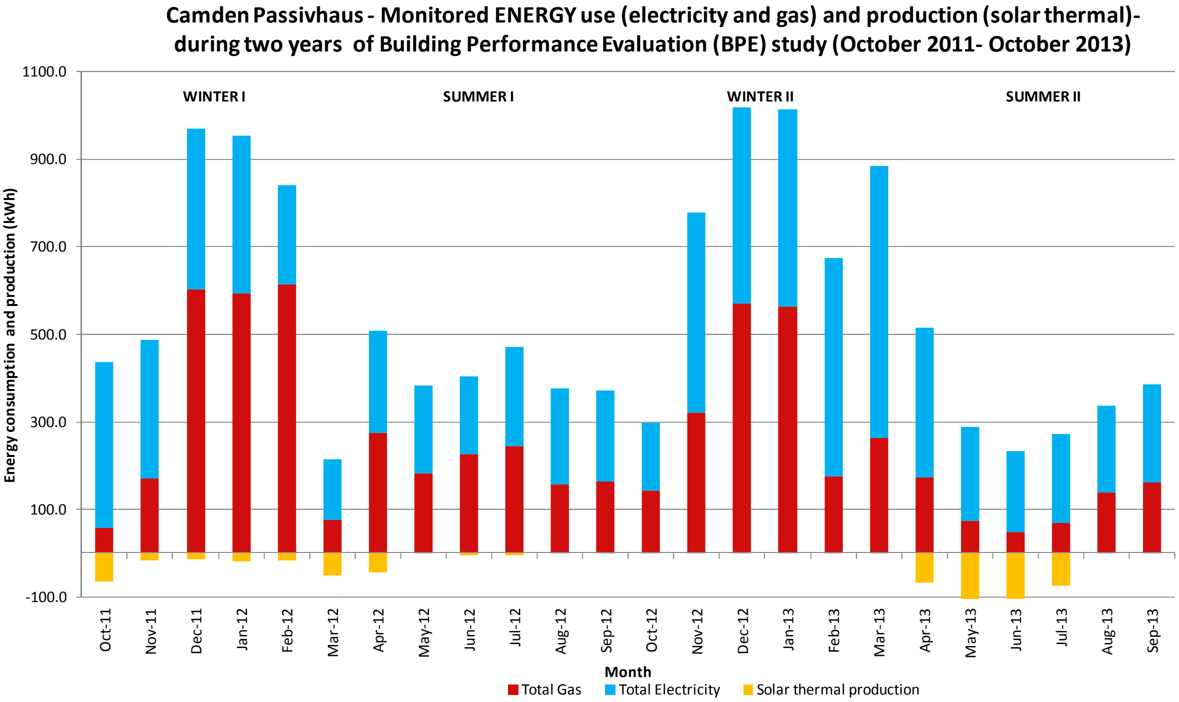


Figure 6-4a. Monitored energy use (electricity and gas) and production (solar thermal) for two years.

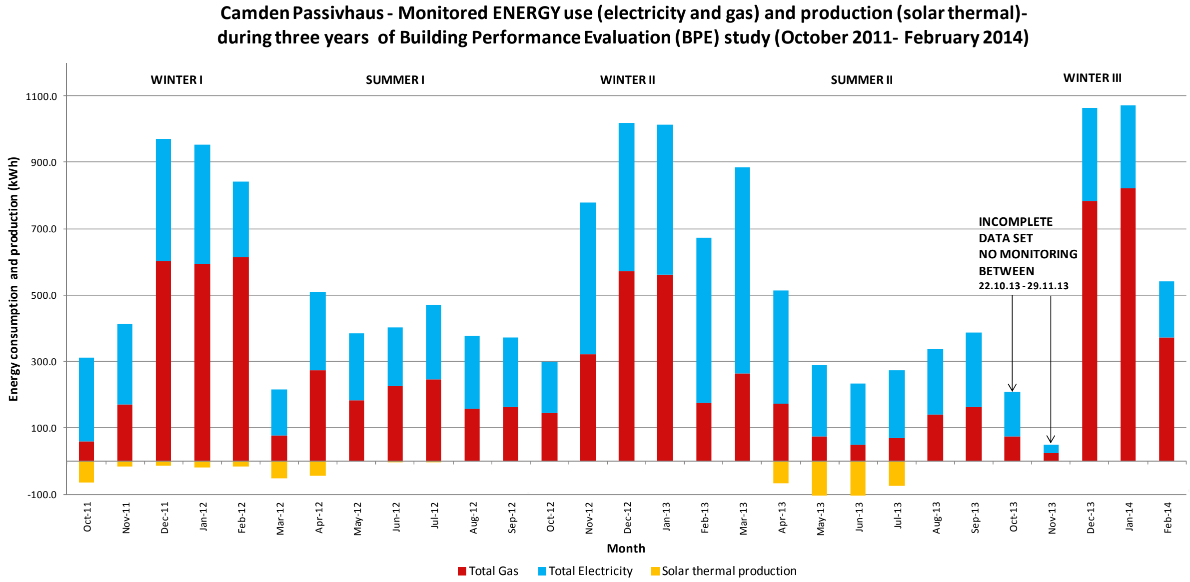


Figure 6-4b. Monitored energy use (electricity and gas) and production (solar thermal) extended to cover a third winter.

Figure 6-4a shows the monthly figures for the energy consumption over the two years of funded monitoring, and figure 6-4b shows monitoring extended to cover a third winter, until February 2014.

As expected, more energy was found to be consumed in winter than in summer due to colder temperatures and shorter hours of daylight in winter. This overview of energy consumption will now focus on how energy use was apportioned between electricity and gas and on understanding the reasons behind the results.

The first winter shows a higher consumption of gas than electricity, while the second one a higher consumption of electricity than gas. As explained below, the second winter's results may have been an anomaly; a theory supported by results derived from extending the study to cover a third winter.

Table 6.3 indicates that February and March 2013 were the coldest months of the year but gas consumption dropped during February while electricity consumption remained fairly static, rising slightly. CO2 readings suggest that the occupants were away from February 3rd to 10th inclusive; and Figure 6-11 shows a significant drop in water consumption during February 2013, consistent with the occupants being on holiday. However this alone would not appear to explain the monitored readings. The gas consumption is reduced by a greater amount than would be explained by a week's holiday away from home in one of the coldest months of the year, and it is odd that the electricity consumption didn't also reduce at the same time since socket and lighting use form a significant proportion of overall use (figure 6-5a&b) and would be expected to reduce to some extent when the occupants are absent.

We know from occupant interviews that they had some trouble with the gas boiler around this time and Professor Ian Ridley' interpretation is as follows:

"My interpretation is that in Feb 13 and March 13 the MVHR heating and towel rails were not used due to a programming problem with the boiler. The boiler was still "working" as there was still gas consumption, but this was reduced compared to normal "winter" use. I think the boiler was in just DHW (domestic hot water) mode. During Feb and March 13 electricity use rose due to electric heaters, but this is less obvious in Feb due to the occupants being away for 1 week."

Both February and March 2013 show a high level of energy consumption at the sockets levels. A correlation was found between the energy consumption in kitchen sockets and the increase in internal temperature. In April, as the external temperatures rose, the electrical socket loads started to decrease but it seems that electric heaters were still in use during April. From May 2013 onwards, the socket loads showed a marked decrease.

It was hypothesised at the time that the reason for the use of electric radiators may have been that the boiler heater valve might have been mal-functioning. However after a visit to check this, it was confirmed that the unusual readings were the result of a programming issue.

It seems likely that before the occupants went on holiday at the start of February the heating was switched off at the boiler which was left on DHW-only (see fig 6-10a which shows that gas heating usage suddenly disappears from the graph in February and March 2013 when one would have expected otherwise from the graph curves, considering these were the coldest months of that winter). When the occupants returned from holiday, the boiler was not switched back to combined DHW-and-Heating, but left on DHW-only. To deal with the resultant drop in indoor temperatures, and forgetting that they had switched the heating off, the occupants used portable electric radiators to increase indoor temperatures to their preferred level of approximately 23 degrees.

In **Error! Reference source not found.** we extended the monitoring period to a third winter (end of February 2014) in order to check that with correct boiler settings, the electricity socket usage would return to a more regular pattern in the winter of 2013/14. Reassuringly, the graph shows that this was the case.

6.3.2 Analysis of in-use electricity consumption

Total electricity consumption for the Camden Passive House was 3063kWh or 30.3kWh/m2 in the first year of monitoring and 3994kWh or 39.5kWh/m2 in the second year which represented a 30% growth of electricity consumption due, in part or entirely, to the user error explained in the previous section. The first year was a little below the median household electrical consumption in the UK which is 3,300kWh (OFGEM, January 2011) or 3,200kWh (OFGEM, July 2013), while the second year is a little higher than the median. With occupancy of two people, the electricity consumption per capita was 1532kWh and 1997kWh in the first and second monitored years respectively.

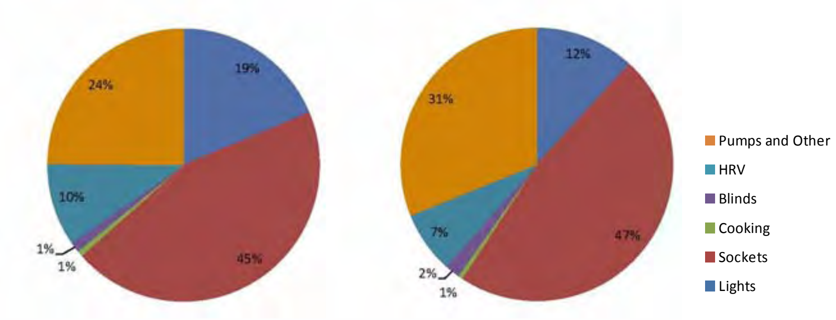


Figure 6-5a. Pie charts apportioning monitored electricity consumption. Left: First year (Oct 11 – Sep 12). Right: Second year (Oct 12 – Sep 13). Note: 'Parasitic' refers to the sum of solar, boiler and pumps

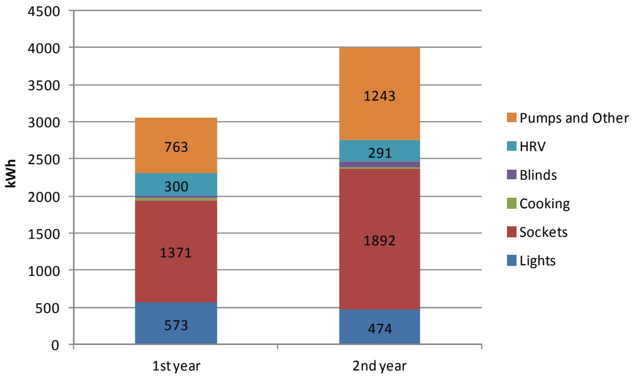


Figure 6-5b. Bar charts quantifying monitored electricity consumption. Left: First year (Oct 11 – Sep 12). Right: Second year (Oct 12 – Sep 13).

Figure 6-5a & 6-5b illustrate the electricity consumption by end use. In general almost half of the electricity was used by occupants' miscellaneous equipment plugged into power sockets. The ventilation accounts for just 7-10% of the total.

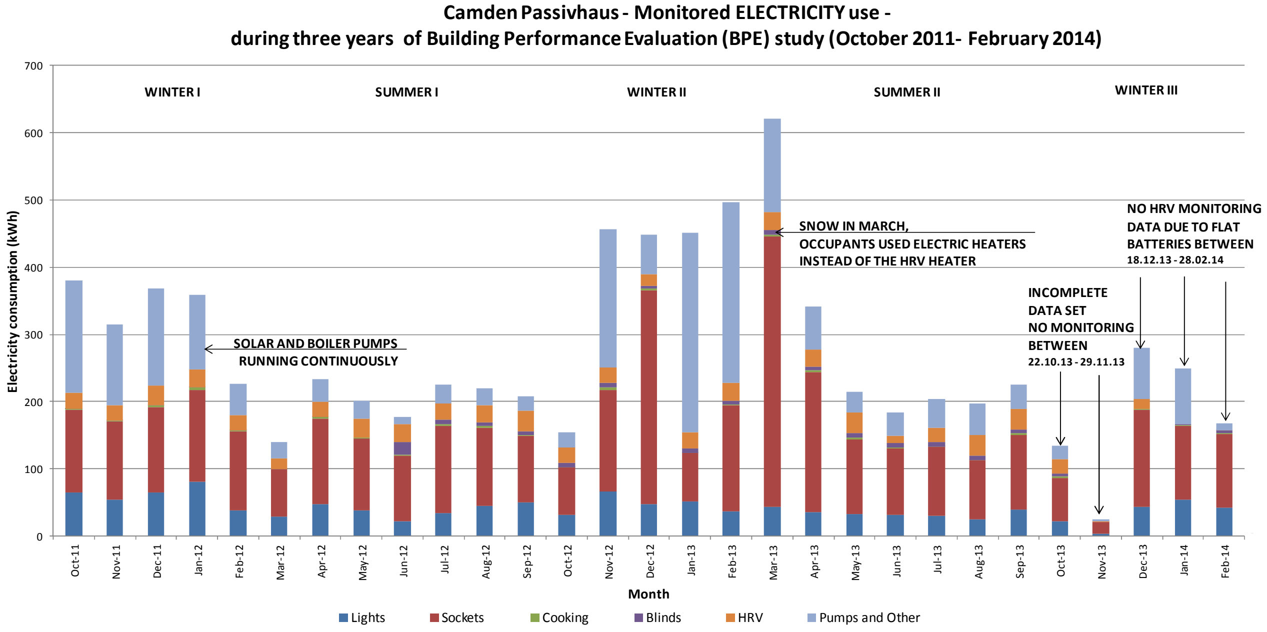


Figure 6-6. Monthly Monitored Electricity Consumption (kWh) - extended to include third winter (Oct 11 – Feb 14)

Table 6-2. Monthly Average Electricity Monitored Consumption (kWh) (Oct 11 – Sep 13)

	Electricity (kWh)						
	Lights	Sockets	Cooking	Blinds	HRV	Pumps and Other	Total Electricity
Oct-11	64	122	0	0	24	163	**372.9**
Nov-11	58	121	1	0	24	127	**330.3**
Dec-11	66	126	3	0	28	145	**368.8**
Jan-12	81	137	4	0	26	112	**359.6**
Feb-12	38	117	1	0	23	47	**227.2**
Mar-12	29	71	0	0	16	23	**139.5**
Apr-12	47	128	3	0	23	33	**233.6**
May-12	38	107	2	0	28	26	**200.8**
Jun-12	23	97	1	18	27	11	**177.6**
Jul-12	34	130	3	6	24	28	**225.0**
Aug-12	45	116	2	6	26	24	**219.4**
Sep-12	50	99	1	6	30	22	**208.5**
Oct-12	31	71	1	6	23	22	**154.3**
Nov-12	67	151	4	6	23	206	**456.6**
Dec-12	47	318	4	4	17	58	**448.0**
Jan-13	51	72	1	6	24	297	**451.0**
Feb-13	37	158	1	6	26	269	**497.2**
Mar-13	44	402	3	6	27	139	**621.1**
Apr-13	36	208	2	6	24	64	**341.2**
May-13	33	112	2	6	31	30	**214.8**
Jun-13	32	99	1	6	11	33	**183.3**
Jul-13	30	102	0	6	22	43	**204.3**
Aug-13	25	88	1	6	30	47	**197.3**
Sep-13	40	111	2	6	31	35	**224.8**
TOTAL	**1046**	**3263**	**43**	**108**	**591**	**2006**	**7057.1**

By looking at the monthly data desegregation of the electricity use (Figure 6-6 and Table 6-2) it is possible to more fully understand the impact of an initial wiring error; a later user programming error described in 6.3; and occupancy behaviour on the overall consumption of the building.

During the first months of the monitoring project excessive electricity consumption was detected for the solar and boiler pumps and also the lights (compared to PHPP design calculations). After a technical visit it was found that the solar pumps were running continuously due to a plumber's faulty wiring of the solar pump. After solving the system faults the pump energy consumption reduced greatly (February 2012). However further investigation of the monitored data showed that the occupants were also leaving the lights on during hours of daylight.

The second winter shows higher electricity consumption than the first winter, due to increased energy use from power sockets. Electricity consumption during October 2012 was relatively low compared to other months, mostly because the occupants were away between 5th and 21st of October (inclusive). Table 6-3 shows that: it was a colder winter than usual, particularly towards the end of the winter with temperatures averaging 3~4°C in February and March 2013 (it snowed in March). When the occupants returned from holiday electricity consumption was higher than usual due to the use of portable electric heaters since the boiler was set on DHW only as discussed in 6.3 above.

The period November 2012 to March 2013 show some fluctuations between electrical socket use and electrical pump energy use (fig 6-6). This can be explained as follows (see also previous section 6.3): The boiler was set to DHW-only, so when the ventilation system's thermostat called for heat, the boiler was unable to provide it because the heating was switched off, nevertheless the ventilation system called for the pumps to run for extended periods to try to deliver the heat that was called for. However, once portable electric radiators were switched on, indoor temperatures rose until the point at which the ventilation thermostat was satisfied, at which point, with no call for heat, the pumps were switched off. This explains why, when socket loads were high, pump loads were low and visa-versa when socket loads were low, pump loads were high.

In spite of fluctuating proportions of gas and electricity used during the winter of 2012-2013, it is interesting to note from figure 6-4 that the overall energy use (combined gas and electric energy use) during December and January of 2012-2013 was similar to the previous year. There was higher consumption in March 2013 than the previous March which may have been due to the unusually cold temperatures that prevailed in March 2013 (average 3.4°C) compared to the sudden and unusually high temperatures in March 2012 (average 9.8 °C, warmer than April 2012, 8.1 °C). Monthly average temperatures can be seen in Table 6-4.

The monitoring period was extended to a third winter (2013-2014) in order to see if, with the boiler controls set correctly to dhw-and-heating, the portable electric radiator use of the previous winter would re-occur.

The third winter of 2013-2014 was generally milder than the previous winter as evidenced by figure 6-13. However the same graph shows internal temperatures were a little higher than the previous winter, averaging approximately 23°C in the living room in December 2013 and January 2014.

Overall energy use for the winter of 2013-2014 was very similar to the previous two years (see figure 6-4) but significantly less electricity was used than the previous winter, and correspondingly more gas was used.

Throughout the Phase 2 study, energy consumption for lighting was higher than PHPP design predictions. The design team noted that in spite of large glazed areas and good natural lighting potential, artificial lighting was often used during the hours of daylight.

Conversations and interviews with the occupants revealed that they put a high priority on privacy. Most of their windows face the street and they have a tendency to keep the blinds fully closed during the daytime, resulting in increased lighting consumption (Figure 6-7).

It has been pointed out to the occupants that by angling the blinds upwards, privacy from the street could be achieved while allowing daylight to enter. However the suggestion has not been adopted and it is not clear why not, but it may be useful here to speculate on habits evident in the parents' home and that may therefore have been deeply ingrained during upbringing.

By reference to the photo below (Figure 6-6), the street elevation of the family home in which one of the occupants was brought up maintains a high degree of privacy from passers-by by means of the painted wooden blinds which appear to be mostly kept at least partly closed during hours of daylight.

This suggests that parental habits may have been picked up and continued with regard to usage of blinds. The street elevation of the parents' house is north facing so the habit of keeping the blinds closed does not result in loss of sunlight. However at the Camden Passive House, with its South-facing street elevation, closing the street-facing blinds in winter reduces an important source of free energy.

Figure 6-6. Painted timber blinds inside the street-facing windows provide privacy in the parents' family home.

Figure 6-7. The occupants of the Passive House say south-facing blinds to the living spaces (that are all street-facing) are kept closed during the day in order to maintain privacy – they are kept closed during the winter months more than expected at the design stage. However tilting the blinds slightly upwards to allow sunlight to enter the house would solve the privacy concerns while also allowing the benefits of solar gain in winter.

6.3.3 Analysis of in-use gas consumption

Total gas consumption for the Camden Passive House was 3455kWh or 34.2kWh/m2 in the first year of monitoring and 2704kWh or 26.8kWh/m2 in the second year which represented a 22% reduction. The size of the reduction in the second year may be an anomaly as explained in section 6.3.

With occupancy of two people, the gas consumption per capita was 1727kWh and 1352kWh in the first and second monitored year respectively. These figures are much lower than typical average annual domestic gas consumption currently used in the UK which is 20,500kWh (OFGEM, 2012).

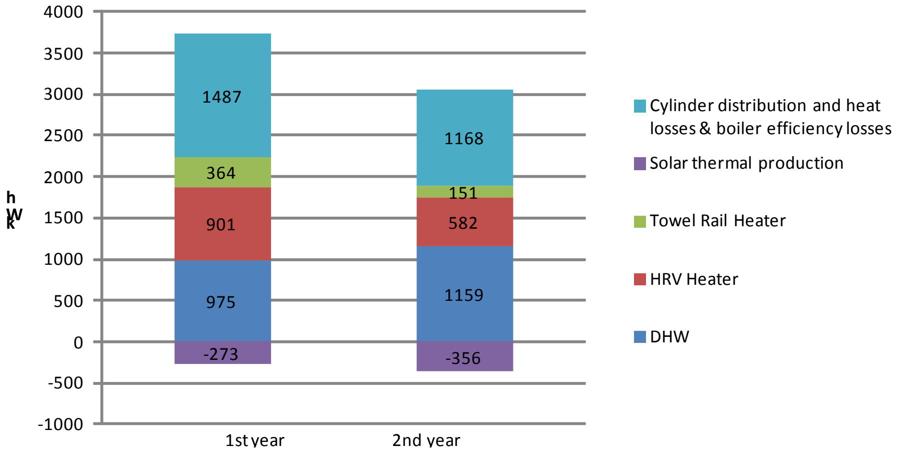


Figure 6-8. Monitored Gas Consumption Breakdown by End Use. Left: First year (Oct 11 – Sep 12). Right: Second year (Oct 12 – Sep 13).

Figure 6-8 illustrates the gas consumption breakdown by end use. About a quarter of the energy is used for domestic hot water (DHW) while a slightly smaller figure corresponds to the HRV heater. DHW consumption increased in the second year.

In the first winter gas consumption was a little higher than expected - this was related to a boiler and solar pumps system fault. Solar thermal production was affected by a series of technical problems which greatly reduced the expected savings. It can be seen that a large proportion of the consumption is allocated to losses on distribution, storage and efficiency. These losses were 1487kWh or 15kWh/m2 in the first monitored year and 1168kWh or 12kWh/m2 in the second one – which is in line with the 10kWh/m2 figure of DHW heat losses, recorded in other UK low energy dwellings (Clarke and Grant 2010).

March 2012 was warmer than April 2012 with higher insolation resulting in lower gas consumption. It is to be expected that gas consumption would drop as summer approached. However in June and July 2012 consumption increased! When the design team discussed this with the occupants they confirmed that the heating was still being used despite the summer temperatures and use of windows. As the occupants generally enjoy warmer temperatures they didn't feel the need to turn off the heating or turn down the thermostat!

Table 6-3. Winter 2012/13 compared to average weather data

Winter 2012/13

The 2012/13 winter was 14% colder than standard London Test Reference Years (TRY) file, but December was average. March 2013 was very cold.

The winter and spring of 2012/13 was more severe than the design calculation weather data. Exmination of the British Met office data suggests the spring of 2012/2013 was the coldest in 40 years. The mean temperature over the UK for the winter was 3.3 °C which is 0.4 °C below the long term average. December was equal to the long term average for the month, January was 0.4 °C below, February was 0.9 °C below and at average of 2.8 °C was the coldest month of the season. In Spring mean temperatures over the UK were well below the long term average during both March and April. March was dominated by easterlies and was particularly cold in the second half of the month, resulting in one of the coldest March months in the historic series. March was the coldest month in the 2012-13 winter, the first time this has occurred since 1975. The cold spell continued into early April. For a comparison the degree days in London for May 2012 to April 2013 were 2966, compared to the TRY average of 2476, 19% higher.

	Degree Days Winter 2012/13	TRY Degree Days
Nov-12	315	280
Dec-12	368	366
Jan-13	401	365
Feb-13	408	328
Mar-13	424	337

In October 2012 the occupants were away for over two weeks, resulting in lower gas consumption. However the significant drop in monitored gas consumption in February 2013 is explained in section 6.3, and clearly shows the HRV heater was not used at this time, in spite of a very cold spell of weather even though the boiler continued to provide domestic hot water (DHW). The boiler was switched to DHW only when the occupants went on holiday. When they returned, they forgot to turn the heating back on, and instead used electric heaters.

Looking at the monthly data desegregation (Figure 6-10a&b and Table 6-4) it is possible to understand the impact of system faults and occupancy behaviour on the overall consumption.

In the second winter it is thought the boiler was set to DHW only as explained in the previous section. Occupants returned from a holiday in February 2013 to a colder house than they were used to (and external temperatures close to 0^{o}C). Not realising that the colder indoor temperatures were due to the heating being switched off at the boiler, the occupants used portable electric radiators. However gas was used to heat DHW as normal.

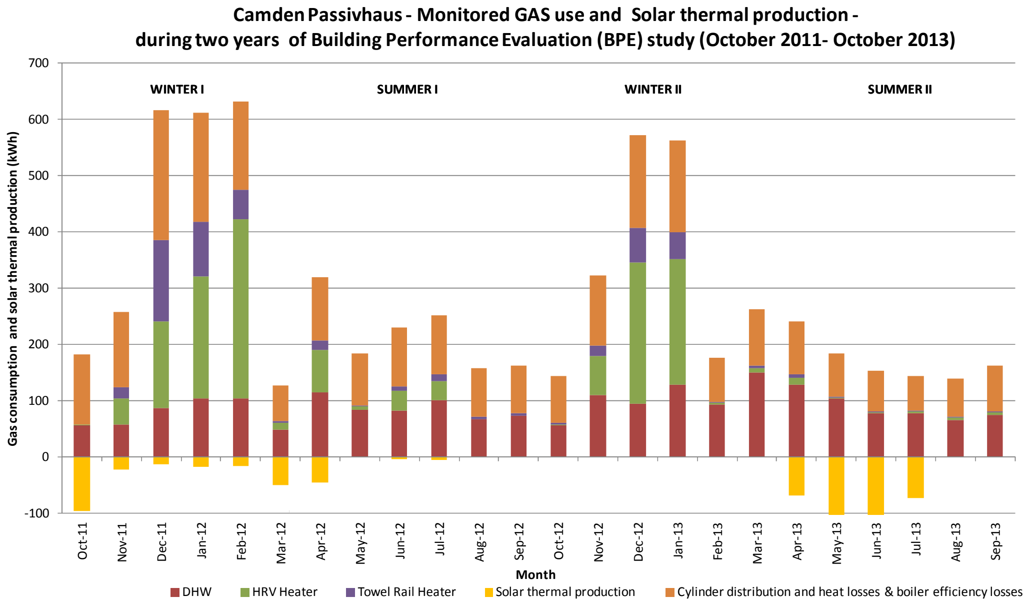


Figure 6-9a. Monthly Average Gas Monitored Consumption and Solar Thermal Production (Oct 11 – Sept 13)

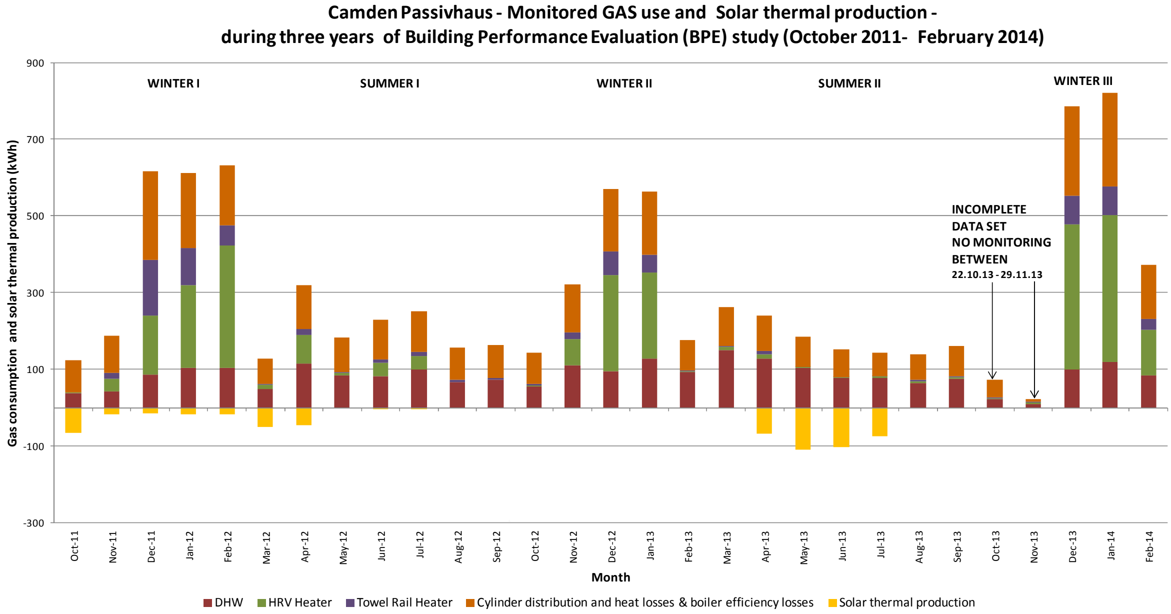


Figure 6-10b. Monthly Average Gas Monitored Consumption and Solar Thermal Production extended for a third winter (Oct 11 – Feb 14)

Table 6-4. Monthly Gas, Space Heating and Domestic Hot Water Monitored Consumption (kWh)

	Gas (kWh)					
	Total Gas	DHW	HRV Heater	Towel Rail Heater	Solar thermal production	Cylinder distribution and heat losses &
Oct-11	**85.6**	56	1	0	96	124
Nov-11	**233.6**	57.3	46.4	20.5	23.2	133
Dec-11	**601.5**	87.0	153.0	145.0	14.0	230
Jan-12	**593.8**	103.0	217.0	97.0	18.0	195
Feb-12	**614.0**	104.0	318.0	53.0	17.0	156
Mar-12	**76.2**	48.0	12.0	3.0	51.0	64
Apr-12	**274.8**	114.0	76.0	16.0	45.0	114
May-12	**183.2**	84.0	6.0	2.0	0.0	91
Jun-12	**225.8**	82.0	36.0	7.0	4.0	105
Jul-12	**245.8**	100.0	35.0	11.0	5.0	105
Aug-12	**157.5**	67.0	0.0	5.0	0.0	86
Sep-12	**162.8**	73.0	0.0	5.0	0.0	85
Oct-12	**144.1**	56.0	1.0	4.0	0.0	83
Nov-12	**321.6**	110.0	69.0	18.0	0.0	125
Dec-12	**571.0**	94.0	252.0	61.0	0.0	164
Jan-13	**562.6**	129.0	223.0	47.0	0.0	164
Feb-13	**175.7**	93.0	3.0	2.0	0.0	78
Mar-13	**262.7**	150.0	8.0	4.0	0.0	101
Apr-13	**173.0**	128.0	12.0	7.0	68.0	94
May-13	**74.1**	103.0	2.0	1.0	110.0	78
Jun-13	**49.2**	78.0	1.0	1.0	104.0	73
Jul-13	**69.2**	78.0	3.0	1.0	74.0	61
Aug-13	**138.9**	65.0	4.0	3.0	0.0	67
Sep-13	**161.5**	75.0	4.0	2.0	0.0	80
TOTAL	**6158.1**	**2134.4**	**1482.8**	**515.5**	**629.1**	**2654.6**

The second summer showed much lower monitored gas consumption than the first summer. It is clear from the graph on Figure 6-10 that this is related to the fact that the solar thermal system was operating correctly in the second summer, making a significant contribution to the production of domestic hot water. In general however the system has been found repeatedly not working during the Phase 2 study period due to poor installation work (as discussed in chapter 7) resulting in less substantial kWh and CO_2 savings than expected. This is the result of poor quality installation work by the client's own plumber who operated outside the terms of the building contract and under direct instruction of the client.

Figure 6-11 which shows a slight but steady increase in water consumption during the monitored period and figure 6-9 shows an increase in domestic hot water use during the same period. Increased DHW consumption will have affected gas consumption during the first two years of occupancy.

6.3.4 Analysis of in-use water consumption

Total water consumption for Camden Passive House was 66,695 litres in the first year of monitoring and 77,262 litres on the second year which represented a 15% increase.

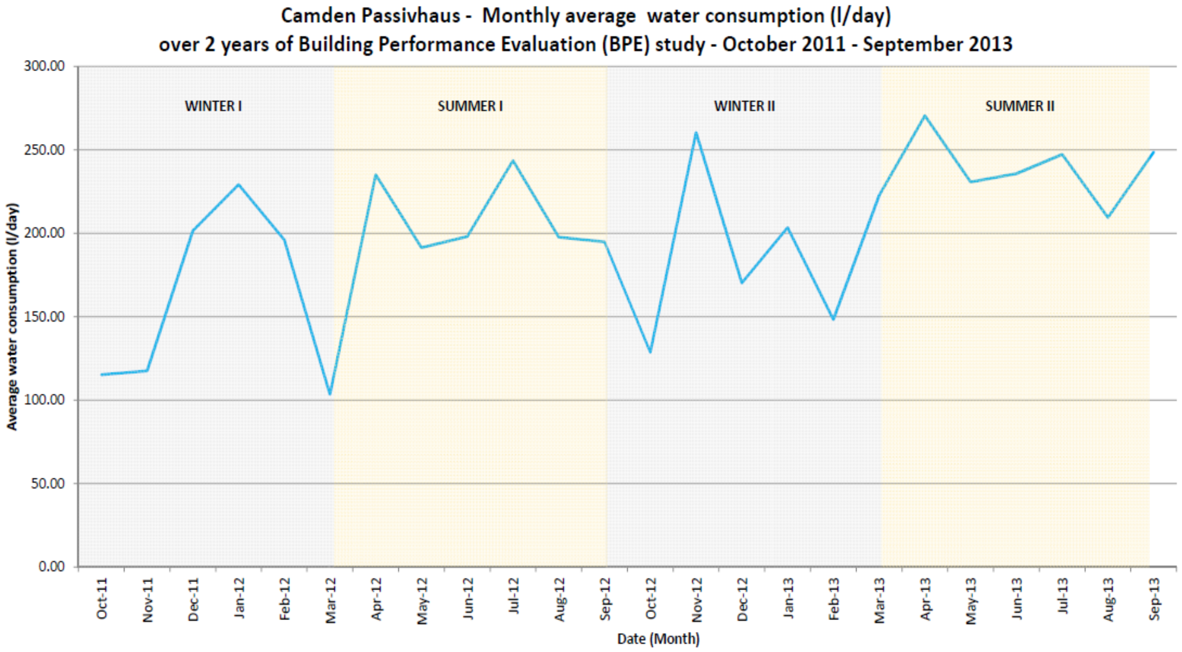


Figure 6-10. Monthly Average Water Monitored Consumption (Oct 11 – Sep 13)

The average daily consumption was 185l/day and 215l/day in the first and second monitored year respectively. With occupancy of two people, the average water consumption is about 99l/person/day which is lower than the typical average annual domestic water consumption of 150 l/person/day currently in the UK (DEFRA, 2008), although this is explained by the fact that the occupants both went to work during the monitoring period, so some of their daily water consumption happened elsewhere.

Figure 6-10 shows the monitored monthly average water consumption. The least water was used in March 2012 with an average of 103l/day and the most water was used in April 2013 with an average of 270l/day.

The graph below (Figure 6-11) shows the water consumption profile during a week in June 2013.

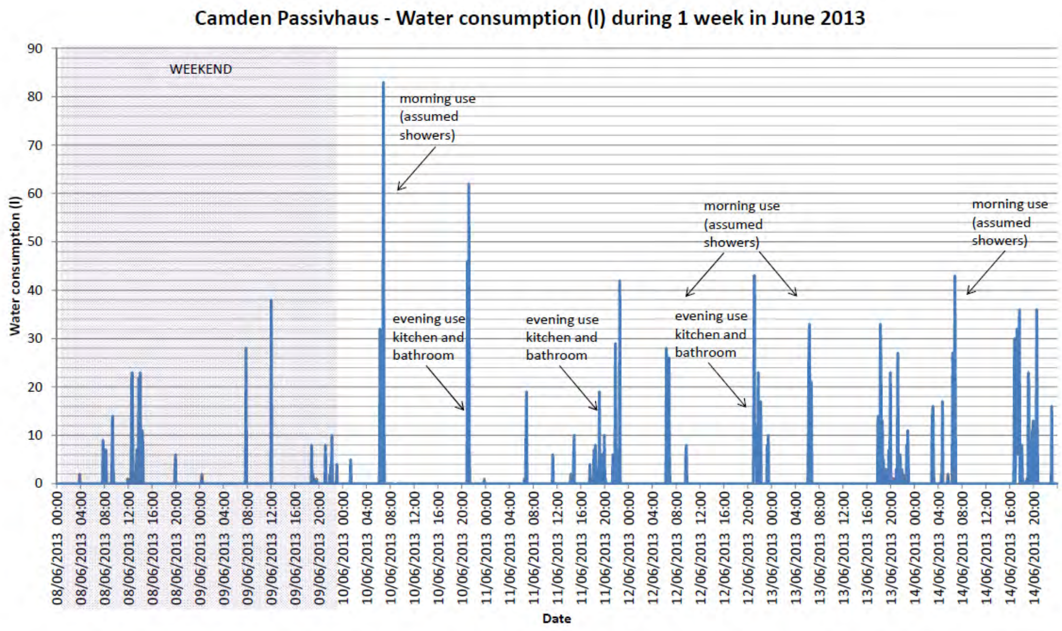


Figure 6-11. Water consumption profile during a one week in June 2013.

6.4 Comfort (Indoor temperature, RH and CO_2 performance)

6.4.1 Indoor temperature and relative humidity

External and internal environmental conditions were monitored. Results across the two years of the study show very stable indoor temperatures averaging 20~23°C in winter and 22~24°C in summer for the living spaces on the first floor and 18.5~20°C in winter and 20~22°C in summer for the bedrooms on the ground floor.

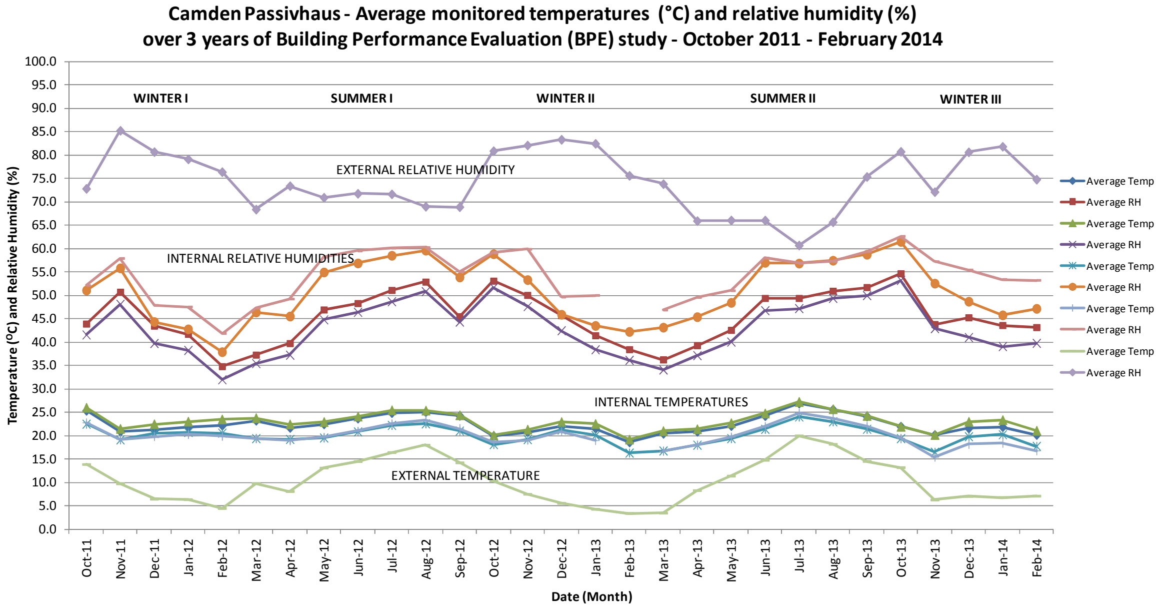


Figure 6-12. Averaged Monitored Internal and External Temperatures and Relative Humidity (Oct 11 – Feb 14)

The temperature difference between the living spaces and bedrooms is typical for these two different space types in ordinary UK houses, at least in the Winter months, but in the Camden Passive House this is attributed to the higher solar exposure of the first floor due to the fact that the main bedroom's external sun-shade blinds are kept closed during the day in the winter.

Throughout the monitored period, average relative humidity values remained within the optimal recommended range between 30% and 60%. Dr. Ian Ridley (Ridley et al, 2012) calculated the average vapour pressure excess in the living room, master bedroom and kitchen to be 292Pa, 328Pa and 283Pa respectively. Occasional evening peaks at 500Pa occur in the living room and kitchen but are in the 90th percentile of occurrence. Dr. Ian Ridley concludes that *"the relative humidity and CO2 concentrations in the living room and bedroom indicate good IAQ and appropriate ventilation rates."*

Table 6-5. Monthly Average Internal and External Conditions and Seasonal Averages (Oct 11 – Sep 13)

	Average temperatures (*C) and RH (%) and CO2 levels (ppm)											
	Living room			Kitchen		Bedroom2		Bedroom1			External	
	Average Temp	Average RH	Average CO2	Average Temp	Average RH	Average Temp	Average RH	Average Temp	Average RH	Average CO2	Average Temp	Average RH
Oct-11	25.3	43.9	616.5	26.0	41.5	22.5	51.0	22.8	52.1	686.2	13.9	72.8
Nov-11	20.9	50.7	698.3	21.5	48.1	19.1	55.8	19.2	57.9	762.4	9.7	85.2
Dec-11	21.2	43.4	712.3	22.4	39.7	20.5	44.3	19.8	47.9	743.1	6.4	80.6
Jan-12	21.7	41.7	739.6	23.0	38.3	20.7	42.7	20.3	47.5	808.1	6.3	79.1
Feb-12	22.1	34.8	669.3	23.5	32.0	20.6	37.9	19.9	41.9	687.2	4.5	76.3
Mar-12	23.2	37.2	622.0	23.8	35.4	19.4	46.4	19.4	47.3	646.6	9.8	68.3
Apr-12	21.7	39.7	734.5	22.4	37.2	19.2	45.5	18.9	49.2	758.2	8.1	73.3
May-12	22.4	46.9	648.5	22.9	44.8	19.5	54.9	19.7	58.2	741.2	13.1	70.9
Jun-12	23.6	48.3	668.9	24.1	46.4	20.8	56.8	21.0	59.5	742.1	14.5	71.7
Jul-12	24.8	51.1	662.8	25.4	48.7	22.2	58.5	22.5	60.1	707.8	16.4	71.6
Aug-12	25.0	52.9	656.1	25.4	50.8	22.5	59.6	23.3	60.2	749.7	18.0	68.9
Sep-12	24.2	45.5	660.7	24.4	44.3	21.0	53.8	21.5	55.0	709.5	14.2	68.9
Oct-12	19.9	53.0	670.2	20.0	51.7	18.1	58.8	18.6	59.1	620.8	10.3	80.8
Nov-12	20.8	50.0	765.6	21.3	47.6	19.2	53.3	19.1	59.9	809.3	7.5	82.0
Dec-12	21.9	45.7	955.9	22.9	42.5	21.2	45.9	20.8	49.6	941.3	5.6	83.3
Jan-13	21.5	41.4	758.0	22.5	38.4	20.0	43.5	19.0	50.0	854.8	4.3	82.4
Feb-13	18.6	38.4	685.2	19.2	36.1	16.3	42.2				3.4	75.6
Mar-13	20.4	36.2	712.9	21.0	34.1	16.8	43.1	16.7	46.9	738.1	3.4	73.8
Apr-13	20.9	39.3	726.3	21.4	37.1	18.0	45.4	18.0	49.6	780.2	8.3	65.9
May-13	22.1	42.5	690.1	22.7	40.0	19.4	48.4	19.7	51.0	718.1	11.4	66.0
Jun-13	24.2	49.4	1506.2	24.8	46.7	21.4	57.0	22.0	58.0	1740.8	14.8	66.0
Jul-13	26.9	49.3	688.7	27.2	47.2	24.0	56.8	24.8	56.8	786.6	20.0	60.7
Aug-13	25.6	50.9	700.1	25.7	49.4	23.0	57.4	23.7	57.2	696.1	18.2	65.6
Sep-13	24.1	51.7	755.0	24.2	49.9	21.4	58.7	22.0	59.4	767.1	14.5	75.3
Winter 1 average	22.4	41.9	676.3	23.4	39.2	20.5	46.4	20.2	49.1	722.3	8.4	77.1
Summer 1 average	23.6	47.4	671.9	24.1	45.4	20.9	54.9	21.2	57.0	734.7	14.0	70.9
Winter 2 average	20.5	44.1	758.0	21.2	41.7	18.6	47.8	18.8	53.1	792.9	5.8	79.6
Summer 2 avergae	23.9	47.2	844.4	24.3	45.1	21.2	53.9	21.7	55.3	914.8	14.5	66.6

Figure 6-13Figure 6-15. Monthly Average CO2 ppm Monitored Concentration (Oct 11 – Feb 14).In all three respects, the Camden Passive House was found to provide a very stable performance. Details of typical patterns of monthly and daily CO2 concentrations are shown in figs 6-14 & 6-15.

In February 2013 the occupants went on holiday and turned the boiler setting to DHW, effectively turning the supplementary heating off. At night external temperatures dropped to around 0°C but after 5 days without any heat input, the internal temperature of the house remained comfortable, only dropping to 17^{o}C despite the close to freezing outside.

This experience has highlighted the excellent thermal performance of the fabric of the house in extreme winter conditions.

Table 6-6. Summer time overheating % of hours over 25^{o}C and 28^{o}C (Summer year 1 left and Summer year 2 right)

	Living room		Kitchen		Bedroom 2		Bedroom 1	
	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C
Apr-12	0%	0%	1%	0%	0%	0%	0%	0%
May-12	23%	1%	25%	3%	0%	0%	0%	0%
Jun-12	14%	1%	23%	2%	2%	0%	1%	0%
Jul-12	35%	6%	51%	8%	7%	0%	8%	0%
Aug-12	45%	3%	55%	4%	0%	0%	8%	0%
Sep-12	27%	3%	27%	3%	0%	0%	0%	0%
Average	24%	2%	31%	3%	1%	0%	3%	0%

	Living room		Kitchen		Bedroom 2		Bedroom 1	
	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C
Apr-13	1%	0%	2%	0%	0%	0%	0%	0%
May-13	3%	0%	10%	0%	0%	0%	0%	0%
Jun-13	28%	0%	42%	1%	0%	0%	2%	0%
Jul-13	83%	29%	83%	36%	27%	0%	47%	0%
Aug-13	72%	2%	73%	2%	0%	0%	4%	0%
Sep-13	16%	5%	23%	5%	1%	0%	6%	0%
Average	34%	6%	39%	7%	5%	0%	10%	0%

Some summer overheating was observed in the first floor living spaces and also in the main bedroom (table 6-6), although as noted previously, occupants reported enjoying higher indoor temperatures in summer as well as in winter, so did not fully utilise the external shading and did not use any night time purge-ventilation.

The window use study referred to in chapter 5 gave an insight into the reasons for the higher indoor summer temperatures: the occupants stating that even during very warm weather no night purge ventilation was used.

In May 2012, when the occupants were contacted after concern that they might be experiencing overheating, they stated that they were enjoying the warmer temperatures. They also stated that they enjoyed the soundproofing and security of the triple glazed windows when they are closed at night.

In the later POE interview in June 2012 (see chapter 5) the residents reported feeling unsafe if the windows were tilted open at night, despite the fact that they tilt inwards at the top to offer the best security from intruders and rodents. Significantly, in the same interview the residents reported that the external blinds were not working properly for some months, so the only means to control solar radiation was by means of the internal blinds which are less effective for solar control (perhaps circa 40% reduction in heat gain) resulting in higher internal temperatures.

6.4.2 Indoor CO_2 levels

CO2 concentrations were monitored in the main bedroom and the living space on the first floor. Figure 6-14 and Table 6-5 show the monthly data desegregated. On average CO2 levels were good; around 600~700ppm in the living room and 1200~1300ppm in the bedroom at night.

CO2 concentrations in outdoor air typically range from 300 to 500 ppm. Thus indoor CO2 concentrations of 1000 to 1200 ppm in spaces housing sedentary people is an indicator that a substantial majority of visitors entering the space will be satisfied with respect to human bioeffluents (body odour). CO2 at very high concentrations (e.g. greater than 5000 ppm) can pose a health risk. (Refer to Appendix B, Summary of Selected Air Quality Guidelines in ASHRAE Standard 62.1-2010, "Ventilation for Acceptable Indoor Air Quality".)

The CIBSE recommended range of CO2 is vague for domestic applications. But the average range quoted between IDA1 and 3 (BS EN 13779) is 700ppm to 1200ppm. More simply, CIBSE Guide B suggests a range between 800 and 1000ppm, and this is still regarded as the norm. Up to 1500 is a suggested upper limit for short-term peaks, although as quoted above, much higher concentrations are needed to pose a health risk.

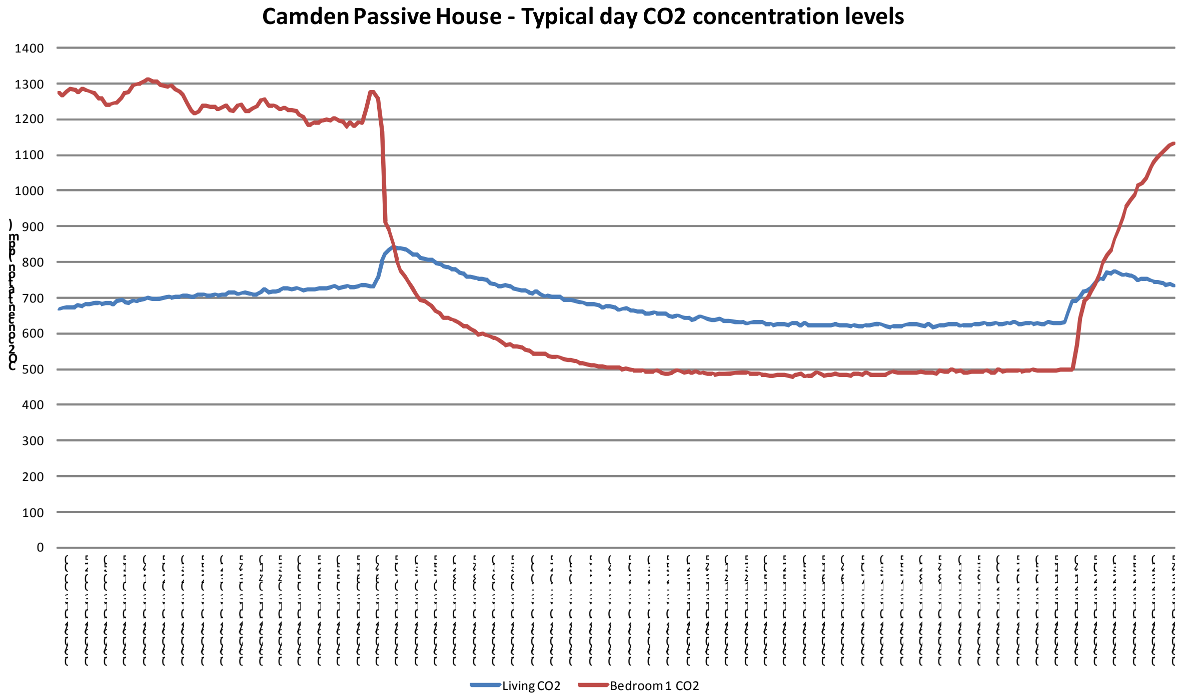


Figure 6-14. CO2 concentration levels for a typical day

However in June 2013 there was an incident with the ventilation system, in which the system was accidentally left switched off following an airtightness test for this report. This affected the indoor air quality resulting in abnormal levels of CO2 in the air. It was not until 22 days later, when analysing the monitored data that the team noticed that the ventilation system had not been turned on again after the air tightness test. This was immediately remedied but for 22 days the house didn’t have a functioning ventilation system. Although unintentional, the data that was collected during this period provided a unique opportunity to examine the benefits of a well-designed ventilation system in passive houses.

Lack of proper ventilation affected the indoor air quality resulting in higher concentrations of CO2 levels. In Figure 6-13 the increase in CO2 levels after the system was shut down is clearly visible. The occupants reported that they did not realise that the ventilation was switched off, which is surprising, and did not feel a need to open the windows, even though it was summer. When the ventilation system was switched on again, CO2 concentration returned to normal levels.

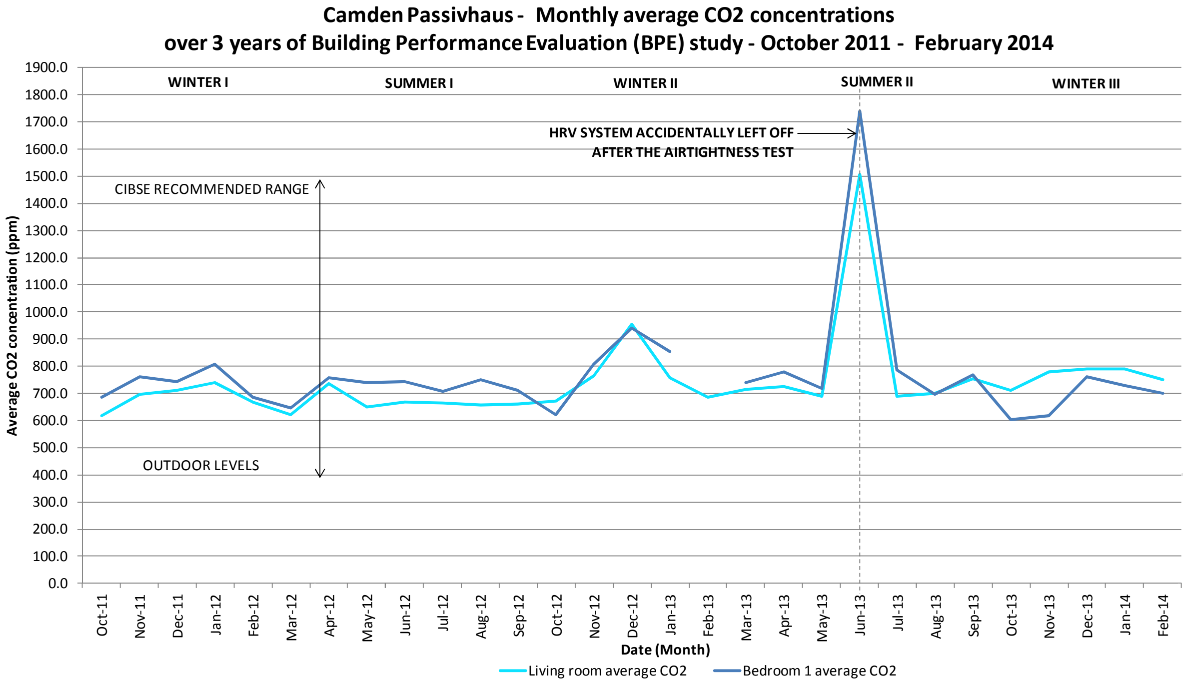


Figure 6-15. Monthly Average CO2 ppm Monitored Concentration (Oct 11 – Feb 14).

These findings demonstrate that an energy efficient draught-free house without a ventilation system, but reliant only on window ventilation to maintain fresh air, may suffer from routinely high CO2 levels in winter since occupants may not notice that the air feels stuffy or realise that CO2 levels are elevated.

In the living room of the Passive House, before the ventilation system was turned off CO2 levels were optimally low, ranging between 600ppm and 1000ppm (with occasional spikes at 1200ppm) with an average of 664ppm. However, during the time the system was off, the average concentration rose to 1955ppm with the highest values extrapolated to reach peaks a little above 5000ppm which is the logger monitoring limit. In the bedroom, before the system was turned off, CO2 levels ranged between 450 and 1200 (with occasional spikes above 1500ppm) while during the time the system was off, the average rose to 2352ppm with values also extrapolated to reach a little over 5000ppm, the data logger limit.

Though with the ventilation system switched off for an extended period these high concentration levels of CO2 are not dangerous for the occupants' health, they do indicate that without a functioning ventilation system, unless windows are opened from time to time, lack of proper ventilation can lead to CO2 levels up to 5000-6000ppm. CO2 is used as an indicator gas. We know that at 1000ppm other pollutants (potentially more dangerous, eg VOCs) are usually kept within safe levels of concentration. However at higher CO2 levels other pollutants such as VOCs would also be likely to increase.

The three week shut-down of the ventilation system had less impact on the temperature and RH levels than would probably have been the case if it had happened in winter. For example in the living room there was little change of the average temperatures from 23.6ºC to 24.5ºC and in the kitchen from 24.2ºC to 25.1ºC. The living room average RH increased from 41.9% in the period before the system was off to 53.3% (still optimal) and the kitchen average RH varied from 39.7% to 50.5% (total average 46.7%).

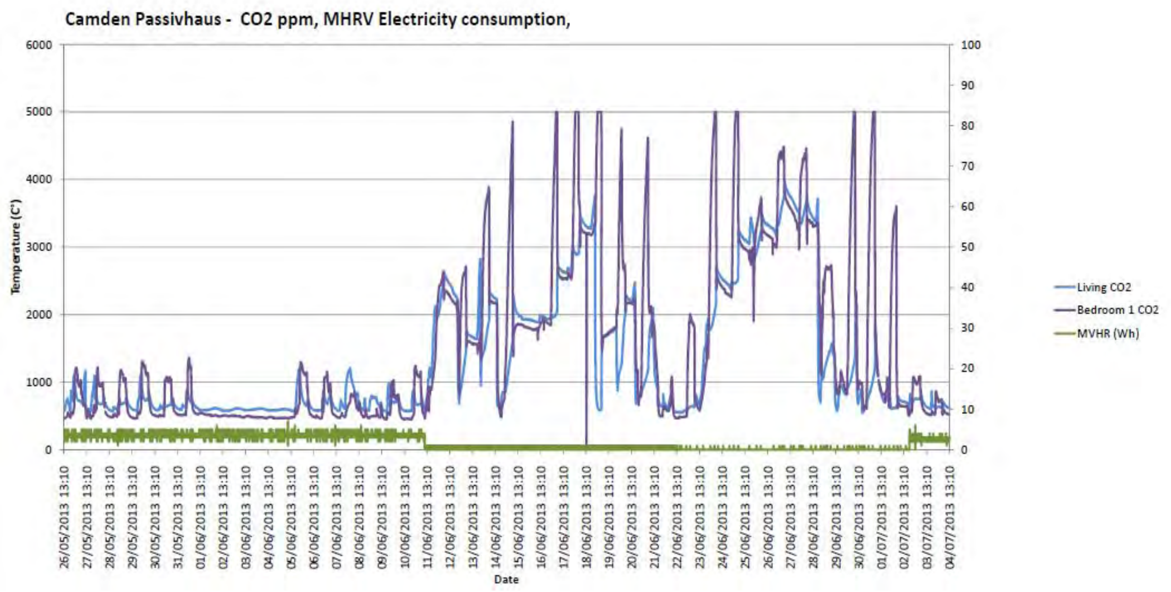
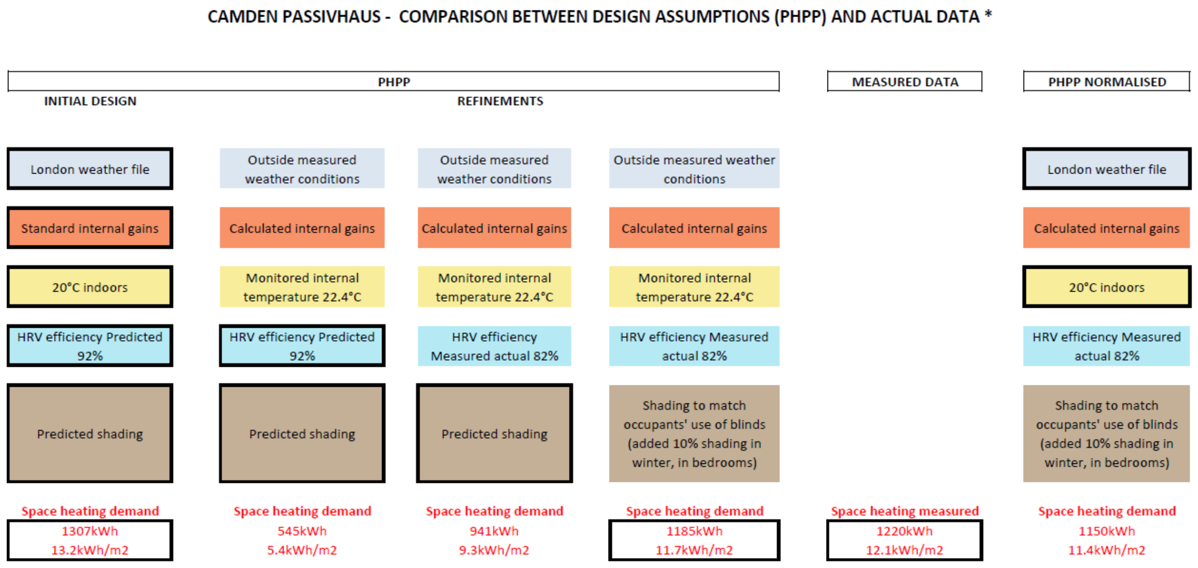


Figure 6-13. CO2 concentration when the ventilation unit was switched off in June and July 2013 and with windows kept closed even during hours of occupation at night. Electricity consumption of the heat recovery ventilation unit is shown in green at the bottom of the graph, demarcating the period during which it was switched off. The rapid reductions in CO2 levels suggests that the building may been occaionally purged by opening windows.

6.5 Comparison with PHPP predictions

A refined comparison was performed between the Passive House Planning Package (PHPP) software predictions and the measured data, in order to enable an accurate parallel to be drawn. The standard London weather data and typical internal heat gains and temperatures assumed initially at design stage were replaced with the actual recorded weather conditions and heat gains data in the PHPP software, as well as the actual measured HRV efficiency, and the actual shading pattern (use of the blinds) was also replicated. The impact of each element on the space heating demand was analysed and compared with the measured space heating output.



CAMDEN PASSIVHAUS - COMPARISON BETWEEN DESIGN ASSUMPTIONS (PHPP) AND ACTUAL DATA *

PHPP				MEASURED DATA	PHPP NORMALISED
INITIAL DESIGN	REFINEMENTS				
London weather file	Outside measured weather conditions	Outside measured weather conditions	Outside measured weather conditions		London weather file
Standard internal gains	Calculated internal gains	Calculated internal gains	Calculated internal gains		Calculated internal gains
20°C indoors	Monitored internal temperature 22.4°C	Monitored internal temperature 22.4°C	Monitored internal temperature 22.4°C		20°C indoors
HRV efficiency Predicted 92%	HRV efficiency Predicted 92%	HRV efficiency Measured actual 82%	HRV efficiency Measured actual 82%		HRV efficiency Measured actual 82%
Predicted shading	Predicted shading	Predicted shading	Shading to match occupants' use of blinds (added 10% shading in winter, in bedrooms)		Shading to match occupants' use of blinds (added 10% shading in winter, in bedrooms)
Space heating demand 1307kWh 13.2kWh/m2	Space heating demand 545kWh 5.4kWh/m2	Space heating demand 941kWh 9.3kWh/m2	Space heating demand 1185kWh 11.7kWh/m2	Space heating measured 1220kWh 12.1kWh/m2	Space heating demand 1150kWh 11.4kWh/m2

*- Data analysis source: Ridley, I, 2012, 'The monitored performance of the first new London dwelling certified to the Passive House standard'

Figure 6-14. Comparison between design assumptions (PHPP) and actual monitored data.

The comparison showed that the space heating energy consumption in the building (12.1 kWh/m2) is very accurately predicted being just slightly better (lower) than the initial PHPP design assumption (13.2 kWh/m2), and it is just slightly higher than the PHPP prediction made using the actual data for weather conditions, internal gains, internal temperatures, HRV measured efficiency and use of the shading devices (11.7kWh/m2).

Also, a normalised predicted space heating consumption was calculated, using typical weather data, typical 20ºC temperature, the actual measured internal gains, actual calculated HRV efficiency, and actual use of blinds in the winter, which resulted in a space heating demand of 11.4 kWh/m2, again a very accurate prediction resulted, just slightly lower than the actual measured figure.

The comparison with PHPP predictions is remarkably good. It can reasonably be claimed that with regard to specific heat energy, the performance gap between design predictions and actual use has been reduced to a negligible level at the Camden Passive House. The indications are that the Passive House Planning Package can be a very accurate means of calculating specific heat energy usage.

6.6 Conclusions and key findings for this section

1. There are still a limited number of passive houses in the UK making it difficult to compare the Camden results with a benchmark. However an overall result of 64.5kWh/m2 in the first monitored year and 66.3kWh/m2 in the second year make the Camden Passive House one of the lowest energy dwellings monitored in the UK. (The BedZed development consumed approximately 90 kWh/m2, The Long House 80 kWh/m2, The Bioregional One Brighton apartments have a median energy consumption of 72 kWh/m2.)

2. The monitoring data provided abundant and reassuring information on how the house performed over three heating seasons, as well as two summers. The data enabled the

monitoring team to perform an in depth study of the building including a comparison between the PHPP design assumptions using the standard climatic data file, and the actual in use data for weather, internal gains, and systems' performance.

3. The Camden Passive House has, in use, effectively closed the performance gap between design and actual performance in use.
4. The measured space heating demand is in close agreement with the designed performance predicted by the PHPP software.
5. These results were achieved while maintaining warm, comfortable and healthy winter conditions with an average winter living room temperature of 22.4 degrees C
6. The extra shading added by the use of blinds in the bedrooms during the winter probably increases space heating consumption but the negative impact is less serious than one might have expected.
7. The data logging and monitoring system was found to be robust.
8. Monitoring and data analysis were crucial to identify problems with the systems installed and allowed a better understanding of how the services work. Frequent data analysis allowed the team to identify mechanical and electrical installation problems which otherwise might have been difficult to spot, and to check whether the solutions adopted were effective. The results emphasise the crucial importance of simple, easily understood and maintained designs and the importance of employing or partnering with only the most reliable, high quality mechanical and electrical contractors and independent commissioning experts.
9. Comparing monitored data with occupant surveys, interviews and informal conversations provided a great insight to how occupants perceive the thermal environment, interact with the controls and use the space.
10. Overall, the design team has learned a great deal about how the systems work in practice, and gained reassurance from the results. However most buildings don't have access to funding for this level of monitoring and we are drawing upon what we have learnt to try to ensure that we can be confident that our future projects perform equally well. One outcome is that we now have a more integrated environmental and architectural design capacity. In particular we have formed a strong and experienced collaborative mechanical design team, installation team and commissioning team to form an integrated design and procurement process that is intended to overcome what we perceive to be one of the weakest links in modern housing procurement. It is currently intended that the team will work together on future projects in order to provide optimum reliability, quality assurance and ease of maintenance.
11. The monitoring skills and insights that the design team have obtained from their TSB-funded BPE projects, the specialist staff employed and the contacts made and developed mean that

Building Performance Evaluation will continue to be deeply engrained in the processes of the practice. The lessons learned will continue to be developed in the form of decision making protocols and embedded ever more deeply in the practice and disseminated to the wider construction industry wherever there is interest.

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

7.1 Systems installed - introduction

The mechanical systems installed in the house include:

- a heat recovery ventilation system (HRV, or commonly referred to as MVHR)
- a compact energy tower consisting of a small boiler with an integrated solar hot water tank and with connection to a tiny air-heater battery
- a vacuum tube solar thermal panel
- whole house water filtration
- a water softener for non-potable water
- an underground rainwater-harvesting tank which provides water for irrigating the green roofs and garden.

The ventilation system is a Paul Thermos 200 heat recovery ventilation unit located in a lightly insulated enclosure in the bike shed attached to the building, with a quoted heat recovery efficiency of 92%. The system is designed to provide a constant background ventilation rate of 130m3/hr (36l/s), 0.48 ach-1.

Space heating is provided via the air, by a 1kW (max output) heater battery in the supply air duct of the ventilation system, capable of supplying warm air at 55 deg C and complemented by heated towel radiators in the bathrooms connected to the small boiler.

A Viessman Vitodens 343 F compact energy tower system, comprising of a condensing gas boiler, integrated 200 litre hot water cylinder with direct solar thermal connection supplies heat to the heater battery and for domestic hot water. A south facing 3m2 Vitosol 200, evacuated tube solar collector is installed horizontally on the flat roof.

Throughout Phase 2 of the project, quarterly monitoring reports compared monitoring data to the PHPP design assumptions and correlated it with a monitoring log to investigate the energy performance of the building. This allowed the lead researcher and team to check that elements were performing as designed, and to identify problems as described in the sections to follow and also in the previous *Chapter 6. Monitoring Methods and Findings*.

The analysis of the monitoring data indicated that while overall the gas consumption was almost exactly the same as the PHPP design assumptions, the electricity consumption was slightly higher and the majority of electricity usage was found to be used for plug loads (unregulated energy).

Regarding the use of artificial light and natural daylight, the team found that the blinds were not used for shading during the summer as much as predicted, and more than expected during the winter, for privacy reasons, leading to an increased use of artificial lighting during day time.

The main systems employed in the house, their operational strategies and any problems encountered during Phase 2 of the BPE study are presented below.

7.2 Heat recovery ventilation unit

As described in the Final Report prepared for Phase 1 of the study, the mechanical ventilation system was re-commissioned in June 2011 by the supplier who also updated the filter on the air intake to an F8 one, which is pollen-grade, having a finer mesh than the previous one. This change was made in accordance with the most up to date recommendations from the Passivhaus Institut.

The ventilation system runs all year round to provide the background ventilation needed for living spaces bathrooms and the kitchen, but in the summer the heat recovery unit is by-passed to avoid warming the incoming air with heat recovered from the outgoing air. During commissioning he ventilation rate for each room was carefully set in accordance with normal building regulation hygiene rates but this can be increased for short periods if desired, by using a ‘boost button’ outside the bathroom. This facility was provided in case the occupants need a way of achieving rapid de-misting of mirrors after a shower. After a pre-selected period the ventilation automatically reverts to the normal setting. Additionally the occupants are free to open the windows, which they do in summer or during parties. It was found that they do this to a limited amount. This was reported during the ‘*Occupant windows use study’* performed during Phase 2 of the BPE project. The night purge ventilation strategy was reportedly used less than expected by the occupants because they do not feel safe with a window open in the bedroom due to its location on the ground floor, even though the windows are secured when tilted. As the occupants mentioned during the *Building User Survey (BUS)* the privacy issues and security issues will be addressed once a new evergreen and impenetrable Berberis thorn hedge matures on the front elevation.

The occupants reported that they found the ventilation system to be quiet and they had no complaints about it.

The heating function is provided via the heater battery, helped by a towel radiator in each bathroom. The system is configured so that when the HRV heater is on, both towel radiators switch on at the same time. The two radiators can also be switched on by means of a timed demand button when heating is not otherwise called for. It was found during a site visit that the towel rail in the guest bathroom was not working properly and could not be switched on independently of the heater battery. This was due to faulty workmanship by the client’s own plumber. The client decided not to ask the plumber to correct this fault.

The average monthly energy consumption of the HRV system is 23kWh, corresponding to an average power consumption of 36 W. A comparison with the measured flow rates as a function of fan speed and electricity consumption showed that an average fan speed between 2 and 3 was used, with a volume flow of approximately 114 m3/hr. The HRV system was set up to deliver 130m3/hr, or 36 l/s, which is an air change rate of 0.48 ach-1.

The average measured thermal efficiency, _HR, eff ,of the MVHR during the winter heating season, based on an average air supply of 32 l/s, was 82%, compared to the designed and certified value of 92%. It is not known if this is due to its location outside the Passive House envelope. For passivhaus certification P_{el} should be less than 0.45 Wh/m3 and $\eta_{HR, eff}$ should be greater than 75%, hence although the measured heat recovery efficiency performance is slightly worse than expected it still meets passivhaus standards.

7.3 Boiler and Solar Thermal Unit

The boiler is a compact unit with an integral solar cylinder and a solar control unit for the domestic hot water. The cylinder also feeds the HRV heater battery and as previously mentioned the two towel radiators in bathrooms. The radiators have variable choice demand switches to avoid them being left on for longer than two hours at a time.

During Phase 2 of the BPE study, several problems were identified through monitoring and solved by the design team working close with the M&E consultant (Alan Clarke) and installers on site:

- At the beginning of the monitoring period, the electrical consumption of the boiler was found to be higher than expected. This was found to be due to two pumps running continuously: the solar pump and the heater battery pump, even when the boiler was switched to hot water only. It seems that the plumber might have been aware of his wiring mistake because the heater battery valve was found to be turned down to constrict flow into it. The problem with the pumps resulted from a fault in the wiring which was subsequently fixed.
- In November 2012 the boiler stopped working. The PCB connection board needed replacing. This may have been damaged by the plumber’s earlier wiring fault.
- Throughout the Phase 2 study period, the solar thermal system was found repeatedly not working due to air in the system. There were several interventions to remove the air, followed by brief periods when the system would be running until air would build up in the system again. An expert Viessman specialist plumber was subsequently employed to check the system and he identified that a de-aeration valve was missing at the top of the system. This was installed and the system appears to have worked satisfactorily from that point..

The monitoring data showed during the last winter that the electricity consumption at the beginning of 2013 was higher than expected and the team found out that the occupants were using electric heaters. The monitoring data indicated that the boiler had been turned off for the winter holiday, and it appears they forgot to turn it back on when they returned, using electric radiators instead, until they were prompted by the design team. At first the team wondered if the valve between the boiler and the ventilation system heater battery was faulty, but subsequent checks found it to be running properly.

A detailed description of the interventions to the systems in the house was done by the design team in the '*Review of interventions report'* submitted to the TSB.

7.4 Long life filter

Passive House buildings are well known for their high insulation and airtightness qualities. They also need to be properly ventilated (following the well-known academic expression 'build tight, ventilate right'). The design team's experience is that a heat recovery mechanical ventilation system, which can be combined with natural ventilation during the summer, is an excellent and reliable solution for ensuring occupants automatically receive sufficient hygiene ventilation during the winter months.

There has been widespread concern about the effect upon performance of poor quality design, installation, commissioning, and failure to replace clogged up filters. It is true that any mechanical system from a simple boiler or other household appliance to a more complicated machine such as a motor car will underperform or fail if poorly designed, assembled or maintained. The usual answer in is to set minimum standards for training, design, installation and maintenance.

The design and commissioning team have not experienced problems so far with the installation and commissioning of the ventilation systems in any of their projects, and this research project has found that the ventilation system generally works faultlessly at the Camden house. We suggest the conclusion that the methods employed in the design, installation, commissioning and maintenance of Passive House ventilation units provides very effective quality assurance which could provide significant benefits if adopted across the house-building industry.

To provide longer filter maintenance intervals, the team have decided to try to develop a long-life filter. The design also includes a means of improving the accessibility of the intake filter so that it could be changed from outside the building under a service contract.

Given the typically high levels of dust and diesel emission particulates found in the air of UK towns and cities, the manufacturer's own filters (installed within ventilation units) typically need to be changed every 6 months but this may vary depending on the quality of the outdoor air. In social housing it is normal to arrange maintenance visits to inspect boilers every 12 months but gaining access can be difficult. So in order to make the changing of filters easier than boiler maintenance, Bere Architects came up with an innovative idea for a *Long Life Filter* which is a deep bag-filter in the air intake. This has been designed to allow longer maintenance intervals (one to two years) and to allow changing from the street by a maintenance engineer through an access grille.

The team sourced a prototype bag filter and installed it in the Camden Passive House at the end of September 2012, as an experiment on how the long life filter would perform over 1 year. Currently it has been in place for 18 months and a recent test with a Magnahelic gauge indicated that the pressure loss across the filter now necessitates a change. Ideally before changing the filter, measurements will be taken at each of the air supply and extract terminals to determine whether the air movements remain satisfactory in a relatively clogged-up 18 month old filter. It would also be good to check the filter for bacterial content.

This experiment is being performed outside of the scope of the TSB BPE project funding, however the team will analyse and disseminate the results of their research.

7.5 Conclusions and key findings for this section

- Forming a tightly integrated design team, architect and M&E consultant used this project to develop their future approach to designing robust, economical and easily maintained mechanical and electrical systems.
- Post-completion, the monitoring data and the logged information helped the same design team to identify problems and gain a better understanding of how their designs performed.
- The BPE research project has helped demonstrate the advantages of an intelligently designed, quality-assured approach.
- The merits of keeping designs simple, robust and above all intuitive were evident at all stages from design to user operation. Designers often forget that building users tend to be dis-interested in abstract building or system concepts. The purpose of any technology, and its method of operation, should either be crystal clear to building users, or should be robustly automated with simple, standard devices (<u>not</u> specially programmed building management systems).
- Even where user controls are as simple as turning on or off a boiler or a ventilation system, it is clear from this research that such basic user errors may happen. As a result, we are convinced that where the simplest manual control systems are selected in preference to automation, attention is needed to develop cheap and simple warning devices such as prominent red or green lights to indicate if a piece of equipment is switched off or on incorrectly. Further research and development in this field is, we believe, required.
- The data that was collected over the two year research project showed how the occupants interacted with the controls and how they used the house. The lessons learnt by the design team have provided vital lessons to fuel on-going consideration and future research aimed at achieving the most successful balance between user control and automation in future projects.
- Heat recovery ventilation, being a relatively new technology in the UK, was designed, installed and commissioned with great care and scrutiny by the team who also specified the design and commissioning services of a leading expert in ventilation. As a result, the ventilation system was found to be faultless in design, installation, commissioning and use,

with ventilation rates close to design targets, delivering a well-ventilated indoor environment (low VOCs and particulates concentrations), alongside energy and CO2 savings.

- Ironically, the established technology of simple domestic hot water and solar plumbing systems, whilst also designed with great care, were executed by the client's own plumber who was not answerable to the contract administrator's instructions. The faults that resulted from his workmanship were discovered and corrected during the first year of operation.
- The potential of even basic plumbing workmanship faults, if not found, to seriously undermine a building's performance was a salutary lesson. The sustained and combined efforts of the architect, services engineer and academic researcher were time consuming and costly but they were necessary in order to find the electrical and plumbing installation faults that would have been so easily avoided by a better quality site operative.
- The deep bag filter tested by the design team requires changing less often than standard filters.
- Air quality testing found low indoor levels of PM10 and PM2.5 particulates, up to 4 times better than the parents' Victorian house (comparing bedrooms), and 3 times lower than the external levels on the day of the measurements, suggesting that the HRV system may improve indoor air quality by delivering filtered fresh air.
- Although the failure of the HRV ventilation system or a boiler in a Passive House does not pose a serious health risk (over the 22 days when the system was not working there were spikes of approx. 5000ppm and natural ventilation is always available for the occupants, even in an 'air tight' house), it would be recommended that a battery or mains operated warning signal is embedded in systems, so that the occupier is aware when the boiler or ventilation system is not on (by accident or malfunctioning).

7.6 Conclusions and recommendations for other projects:

A. Knowledge gaps are the main cause of performance gaps.

B. Avoid the knowledge-gap between design and implementation of mechanical and electrical services systems. Hone highly skilled, closely cooperative design, installation and commissioning teams.

C. Specify trusted, trained specialist sub-contractors. Relying on the contractor or client to provide suitably qualified specialists is a lottery with the odds stacked against you.

D. Avoid the knowledge-gap between designer and user by using Soft Landings techniques including clear and carefully thought out user guides that carefully explain your design logic. If you cannot easily explain your logic, systems may be too complicated to be used effectively.

E. Systems should not be overly-complicated or rely on bespoke control systems. The design team is averse to using Building Management Systems and found that they could use manufacturer's standard controls with one piece of equipment leading another in the controls hierarchy.

F. Heat losses through pipes can be significant. Always allow ample space for insulation around pipes, and ideally the brackets holding the pipes should wrap around the insulation as well.

G. Rigorous and objective sub-meter and overall monitoring and a good Soft Landings approach are crucial to finding and fixing problems which may only become apparent post-completion. We would strongly recommend that these become compulsory parts of the design and construction process, supported by an appropriate Government policy which holds designers and developers jointly and properly to account for the success or failure of their designs. Only once design teams and developers are made to accept full responsibility for the performance gap in use of their buildings will they put serious effort into adopting systems and processes that avoid the performance gap in the first place.

H. If a designer's systems produce regular performance gaps in the hands of average users, don't blame the users; investigate your own design and procurement systems and fix them.

I. Anticipating potential problems is an important part of the creative design process.

J. Refining processes and incrementally improving designs are the real secrets of successful performance.

8 Key messages for the client, owner and occupier

8.1 Summary of main findings, key messages to the client and occupier

The client accepted the Passive House approach from stage D. While the client recognised the local authority planning and commercial benefits of having the house certified, he was not persuaded that Passive House certification would, even in the longer term, increase the market value of his building and therefore was not persuaded to commit any more money than he would normally spend on building a new house. However he was not averse to obtaining additional quality assurance for workmanship or improved durability of the building as a result of the certification process. The changes in the brief, from a speculative development to a private home for the client's daughter, mid-way through the construction contract, resulted in a series of changes to the project. However, it was very good that the team was clear from quite early about the client's agreement for the project to be Passive House certified, since the overall building form and glazing ratio could be optimised for cost effectiveness by means of stage C & D studies using the PHPP software (see http://bere.co.uk/research/using-the-passive-house-planning-package-as-an-early-stage-design-tool).

The conclusions of the Phase 1 report listed several key messages for the client:

- Management of the build process - not to mix a main contractor-driven approach, more formal, with a less formal one of employing trades people direct and giving individual instructions.

- Whilst the very low energy consumption findings and the affirmations of occupant comfort are both endorsements of the design approach taken, these factors can be further influenced by the occupants. Opportunities exist in the opening of blinds in winter to absorb solar energy and the opening of windows at night in summer to cool the fabric. (Such strategies were not adopted very much by the users who tended towards high appliance use and artificial lighting used during the day time.)

During the Phase 2 monitoring, it became apparent that some opportunities were not being adopted, while others were.

The main user-related findings in the 2nd Phase of the BPE study were:

1. The occupants are using more energy than necessary for artificial lighting. They enjoy higher indoor temperatures than anticipated or is generally considered necessary (winter indoor temperatures often 24^{0}C compared to 20^{0}C anticipated). The way the blinds are used is not helping prevent overheating in the summer in the living room and also increases the demand for space heating in the winter in the bedrooms. However in spite of sub-optimal user habits, the overall yearly energy consumption is still very close to the design prediction, which was targeting a very low consumption that is very much more ambitious than the current Building Regulation requirements. It is hoped that when the privacy and security issues are addressed

(growing an impenetrable evergreen Berberis hedge in front of the bedroom), the performance of the building will be improved (the external blinds at least might be kept up for longer periods of time in the winter, allowing the building to take advantage of solar gains which can be used by a Passive House even on a bright overcast winter's day, and the building will need less artificial lighting when the blinds are open during the day).

2. Although in the beginning the occupants (the client's daughter and her partner) were somewhat reticent about the research project, in time it helped them become more engaged with how the systems work, and we are grateful that this helped them become more supportive and interested in the monitoring activities and the performance tests (airtightness, co-heating tests, etc), which could be perceived as intrusions on their privacy.
3. Apart from the user guide prepared for the occupants, the design team organised several meetings and interviews with them; part of a detailed post-completion Soft Landings approach. Their informal feedback during Phase 2, as well as their comments attached to the second BUS survey (submitted to TSB and described in this report in Chapter 5), indicate that they have understood how the systems are meant to work, from heating via the air to cooling by night purging.

8.2 Occupant-related conclusions and lessons learnt

The key lessons learnt by the team can be summarised as follows:

1. The results of the 2 year analysis indicate that the energy use and environmental performance of the building are excellent, showing that the impact of user behaviour on the performance of the building is minimal when the design is based on a comprehensively calculated fabric-first Passive House approach with robust details including very good insulation, a draft free envelope and construction that is free of thermal bridges.
2. Reporting back to the occupants on how the building performed kept them interested and tolerant of the monitoring activities. The feedback from the design team raised their awareness about how they were benefitting from the free gift of natural energy from the sun in winter and how to best hold on to internal heat gains too, and how to use cool night time weather conditions, if they wished to, in the summer months. The occupants also became more aware of their own energy use and were pleased to see how economical they had become in the house when they saw an analysis of the building's performance.
3. It was interesting to note how, perhaps due to very busy lives, on three occasions the young occupants overlooked problems that the design team would have expected them to notice and remedy:
    a. When they went on a winter holiday they switched their heating system off and when they returned from holiday, they did not switch it back on but instead used a portable electric radiator.

   b. When the air tester forgot to switch the ventilation system back on, the occupants appeared not to notice until alerted by the research team three weeks later.
   c. When a portable remote control switch, the only form of control for the 1st floor blinds stopped working, they did not get this fixed until prompted by the monitoring team.

   While some people would inevitably suggest that this means the systems are too reliant on technology, we would refute such criticism. The fact is that the building systems have been found to be resilient and intuitive and hardly any more demanding to the users than an ordinary building. If this had been an average UK building where the occupants forgot to turn their boiler back on after a holiday, then the problem would have been more serious because at least ten times as many electric radiators would have been needed (see domEARM benchmarking appendix - assessment based on total building heat load requirements). Further, if the occupants were concerned about deterioration in air quality for the period in which the air tester had left the ventilation switched off, then the same solution as in an ordinary house remained available, that of simply opening the windows.

   However a lesson that the design team does draw from this project is that there would be great benefit for <u>all</u> building types, whether ordinary or low energy, if equipment manufacturers were to develop cheap and effective warning mechanisms to minimise the risk of users inadvertently leaving useful equipment switched off. This is already available in some advanced solar thermal systems and the architects intend to adopt new industry-standard monitoring and warning techniques for solar thermal systems in future projects. The topic of semi-automation while maintaining simplicity, is one that Bere Architects would like to explore further in their domestic and non-domestic projects. This is a topic that would benefit from future TSB funded research.

4. One of the occupants suffers severely from asthma, having at one point been hospitalised for this as a child. Air humidity found at all times in the Camden Passive House is in the range known to be optimal for minimising the level of airborne indoor pollutants that are known to aggravate asthmatic symptoms. While the occupant does not yet feel confident to cease taking anti-inflammatory drugs, symptoms were noticeably absent during the monitoring period until the final air test at the end of the research period pressurised the building by pumping large volumes of outside air into the building. We understand that this event was followed by a period where the occupant suffered from asthmatic discomfort. This provides support to the hypothesis that this building type provides benefits to asthma sufferers.

5. The designers recognise that they were not perhaps resistant enough to the idea of using the client's own plumber and electrician for the project (suggested by the client on cost grounds). This experience has made the architects forge a strong relationship with a specialist mechanical installer for future projects, and the architects are exploring the possibility of the same arrangement for electrical installation work too.

6. For future projects, simply keeping in touch with the occupants post-completion (even if only annually), and having access to their bills or to modern internet-connected equipment can help monitor and quickly identify problems with systems and also can help the occupants learn from findings and understand the building systems better.
7. As previously mentioned, explicit support from the client is invaluable for achieving the Passive House standard and certification.
8. Any system is only as good as its weakest link. The team believes that the resilience of this building, even when user habits were unexpected or sub-optimal with respect to achieving the best performance, has been dependent on meeting the full, holistic, quality assurance requirements necessary for a certified Passive House.

9 Wider Lessons

9.1 Lessons from the project

9.1.1. PHPP & SAP (From Section 2):

9.1.2. The Passive House Planning Package (PHPP) is a technical design tool designed to enable an architect to predict the energy use and occupant comfort conditions of a building. PHPP acts as a method of calculating the best fabric and services specification to achieve any given size, shape or orientation of a building in a specific location using precise local weather data.

9.1.3. The Standard Assessment Procedure (SAP) is the methodology mandated by the Department of Energy & Climate Change (DECC) to benchmark the CO2 emissions, based upon standardised data for the purpose of Building Regulations compliance. In practice it is used to assess and compare the energy and environmental performance of dwellings.

9.1.4. PHPP Performance Gap (all sections):

9.1.5. To achieve accurate design predictions, a fundamental requirement is that PHPP needs to be capable of closely predicting the thermal performance of building components. Tests carried out and reported in Phase 1 found that PHPP successfully provided accurate building heat loss predictions; accurately calculated fabric u-values and subsequent monitoring in use found that the PHPP also accurately predicted indoor comfort and in-use energy consumption. No performance gap of any significance was found between PHPP u-values and actual u-values, nor between predicted energy use and actual energy use.

9.1.6. The SAP Performance Gap (from Section 2):

9.1.7. By contrast to the accuracy of the PHPP predictions found throughout this report, SAP calculations predicted less than half the measured consumption of the building, indicating that SAP should not be used to predict levels of energy consumption. Where SAP is used to predict energy consumption, this may be a key factor in creating the ‘performance gap’ that is so common in the UK construction industry.

9.1.8. The research team found numerous defects in the SAP methodology which lead to the SAP performance gap. These included the following:

9.1.9. SAP is less rigorous than PHPP in accounting for thermal bridging resulting from poor quality fabric detailing and construction.

9.1.10. SAP is less rigorous than PHPP in taking account of heat loss due to air infiltration from leaky fabric.

9.1.11. SAP uses inaccurate ‘standardised’ weather data. The purpose of this is to make a ‘level playing field’ for building costs across the country. However it does not reflect the fact that it costs more money to achieve the same level of performance in the north of England than in the south.

9.1.12. SAP assumes higher internal heat gains than are usually found in a Passive House with its energy efficient lighting and appliances.

9.1.13. SAP is less rigorous than PHPP in assessing solar energy, an important factor in many low energy buildings.

9.1.14. The successful heating method used in the Camden Passivhaus is not even recognised as an option in SAP.

9.1.15. SAP’s defective Energy Ratings (from Section 2):

9.1.16. SAP gave an energy rating of only 88 or ‘B’ to the Camden Passive House; but this a house that performs, by design and in practice, better than the requirements of the 2016 zero carbon compliance standard and has been found to close the performance gap between predicted and actual energy use.

9.1.17. A future for SAP? (from Section 2):

9.1.18. SAP and PHPP are very different tools. The study confirmed the well-known and widely accepted view that SAP is not suitable for accurate energy consumption calculations. PHPP was found to be more detailed and ideally suited to accurately calculate energy consumption for low energy houses.

9.1.19. Overcoming the Knowledge Gap (from Section 2):

9.1.20. The project was delivered by a design team and a main contractor that had not previously delivered a Passive House. Yet it was a success. There are important lessons to be derived from this.

9.1.21. The architect and services engineer had both developed their knowledge by attending the International Passive House conference for several years previously. Two representatives of the contractor, Dominic Danner and Jon Seaman had also attended an International Passive House conference where they met Justin Bere, the principal director of Bere Architects.

9.1.22. This was Bere Architect’s second timber frame building. The first utilised cross laminated timber construction, and was relatively simple to design. This building was to use a more sophisticated timber stud construction to enable thinner walls to be constructed on the valuable London site, and to save natural resources and construction costs. To assist in bridging any remaining knowledge gap, Bere Architects employed an Austrian draughtsman with a diploma in timber construction; the eldest son of the owner of an Austrian timber frame company.

9.1.23. Overcoming the Construction Skills Gap (from Section 2):

9.1.24. To meet the ambitions of Passive House design, construction teams must commit to much higher levels of construction quality than is the current norm in the UK. A successful Passive House requires a meticulous and careful contractor. To give the best chance of success, the contractor should employ an expert ‘air tightness champion’ to maintain quality control on site. Dominic Danner (9.1.21) has gone on to provide this crucial service on other Passive House projects in the UK.

9.1.25. Only under rare conditions is a Design and Build contract considered suitable at this point for delivering a Passive House project in the UK because in 2014 there remain very few - if any - UK contractors with the necessary Passive House design skills to lead a successful Passive House project. A traditional form of contract administrated by an architect with Passive House expertise is normally essential.

9.1.26. If the main contractor employs the services of a subcontractor with specialist expertise in Passive House to work alongside a directly employed main contractor labour force, this is a proven way to embed skills within a traditional UK construction team that is prepared to embrace modern and high quality methods of construction.

9.1.27. Quality Control (from Section 2):

9.1.28. Any system is only as good as its weakest link. The team believes that the resilience of this building, even when user habits were unexpected or sub-optimal with respect to achieving the best performance, has been dependent on meeting the full, holistic, quality assurance requirements necessary for a certified Passive House.

9.1.29. There were some problems with the work of the plumber and the electrician on this project, both of whom were employed by the client outside the terms of the building contract. The architect was hampered in maintaining quality control with respect to these trades.

9.1.30. It is our view that a contract which does not enable the architect to have complete control over the quality of workmanship on site should be avoided, whether Passive House or not, but especially if high standards of workmanship are required for successful delivery of the project objectives. For similar reasons, ‘Contractor design and build’ contracts are not considered to be a good modus operandi where the largest proportion of the advanced construction knowledge lies with the architect.

9.1.31. Contract administration (from Section 2):

9.1.32. Even with a good contractor it is clear that a knowledgeable Passive House architect is required to guide the process successfully through to completing a contract on site. The traditional role of managing a construction contract is insufficient to deliver a successful Passive House and a more 'hands-on' approach is needed from an architect who is expert in advanced construction skills.

9.1.33. Airtightness (from Section 2):

9.1.34. Air tight construction minimises infiltration heat loss and contributes to comfortable, draught-free spaces. During interviews, the occupants have said how much they appreciate the comfort conditions of the house and draught free construction was found to be an important factor in achieving this comfort.

9.1.35. The resilience of this building has in part depended on meeting the Passive House airtightness requirement of 0.6ACH @50pa pressure. Draught-free construction is an important factor necessary to achieve the comfort, healthiness, performance and resilience of a certified Passive House. The results of the monitoring of this building illustrate that air tight construction, which is crucial for comfort (it avoids cold draughts) and crucial to minimise infiltration heat losses in winter, when matched by an appropriately designed, installed and commissioned heat recovery ventilation system has provided a vital contribution to this building's comfort and in-use performance.

9.1.36. Good airtightness depends upon design. The line of air tightness must be strategically designed and clearly demarcated (see http://bere.co.uk/research/airtightness-report-a-practical-guide)

9.1.37. Good airtightness also depends upon careful attention to build quality combined with some easily understood air tightness techniques. These techniques are not difficult to achieve if the correct materials are used and care is taken by all operatives, led by managers who are knowledgeable about advanced construction processes. (see http://bere.co.uk/research/airtightness-report-a-practical-guide)

9.1.38. Ventilation design (from Section 2):

9.1.39. While Part F of the Building Regulations requires good ventilation rates, there is a loophole in that the Building Regulations do not require that the ventilation rate of every room in a dwelling is individually calculated and commissioned. This allows ordinary houses to be built with inadequate ventilation in some spaces, and allows faulty ductwork to go unnoticed. It is a requirement of the Passive House certification process that all rooms must be individually commissioned to meet requirements and overall intake and exhaust figures must be compared to check for defective ductwork. Expert commissioning is needed. Andrew Farr of the Green Building Store provided the necessary expertise in ventilation system commissioning on this project.

9.1.40. A well-installed and commissioned heat recovery ventilation system, combined with a good airtightness result, played an essential role in the energy and CO2 savings and in delivering a comfortable environment with optimal relative humidity and CO2 levels. The building was also found to have very low levels of harmful particulates. In this project the ventilation also successfully delivered sufficient heat via a tiny 1kw heater battery, eliminating the expense of a traditional wet heating system.

9.1.41. Ventilation performance (from Section 2):

9.1.42. The indoor air quality tests conducted as part of this research project found that the quality of the air was better than in a conventional house located on the same street, and the levels of particulates in the fresh air inside the Passive House were lower than in the outside air, indicating the benefits of filtered fresh air using an F8 pollen filter.

9.1.43. The house remained habitable even when the ventilation system was accidentally turned off for three weeks, indicating that in the event of a systems failure or power cut, the occupants are not at risk if the windows remain closed, and if they wish, they can open the windows for ventilation.

9.1.44. Fabric tests (from Section 3):

9.1.45. A comprehensive range of fabric tests were carried out on the building, including two co-heating tests, heat flux measurements, a thermographic survey, a tracer gas air infiltration test and a fourth air-tightness blower door test. Under co-heating and under heat flux testing the building actually performed slightly better than the designs predicted.

9.1.46. All fabric tests resulted in impressive results that underscore the accuracy of the Passive House Planning Package (PHPP) as a design tool that closes the performance gap between design and actual use.

9.1.47. Co-heating test (from Section 3.3):

9.1.48. The conclusion of the UCL report on the 2nd co-heating test states: “the indication is that the Camden Passive House is one of only a few co-heating tested dwellings in the UK that meets its design intent. This is a positive reflection on the design and the build quality of the house and is especially encouraging considering the low heat loss that was targeted there.”

9.1.49. Window performance (from Section 3.2 & 4.2):

9.1.50. Tilt and turn multi-point window locking mechanisms have been common throughout Europe for many years, where people of all ages are generally familiar with the mechanisms since childhood. At the same time, in the UK relatively crude and basic latching mechanisms are still the norm. We had previously noticed rough treatment of tilt and turn windows on other projects.

9.1.51. The large windows at the Camden Passive House are tilt and slide. This requires a particular knack to operate and we provided verbal and wall-mounted instructions. In spite of this, the very high quality stainless steel mechanisms by the well-known Swiss manufacturer Roto have been broken by rough treatment on two occasions. The force required to break the mechanisms is substantial. It is our view that the benefits and risks of tilt-and-slide windows must be explained to clients and an assessment made of their ability or interest in looking after the windows, or the risks posed by staff and visitors. While multi-point locking mechanisms are essential for performance, tilting hinges are not necessary so if in doubt, simpler hinged mechanisms should be specified.

9.1.52. Summer night time purge cooling by means of natural ventilation is on this project and other subsequent projects not practiced correctly due to fears about factors such as security or insects. These concerns could be addressed in future projects by shielding secure night time natural ventilation through opening windows or hatches using fixed metal louvres, and by the provision of insect mesh over dedicated vents.

9.1.53. Air testing methodology (from Section 3.2):

9.1.54. The equipment and methodology for carrying out the air testing of very draught-free buildings should be improved and more rigorously recorded in order to ensure greater accuracy and reliability of testing. Detailed recommendations are given in Section 3.5.

9.1.55. Occupant surveys (from Section 5):

9.1.56. The Camden Passive House achieved an outstandingly good user rating as recorded in the BUS study, and while it is hard to compare the results with the benchmark because there is just a single respondent, it appears that the house compares very favourably with other homes.

9.1.57. The occupants are very satisfied with overall performance of the house. They appreciate the modern design, layout and space and storage available. They are happy with temperatures and thermal comfort, especially in winter. In the summer there is an indication of higher than ideal temperatures but it was noted that the occupants were content and did not feel the need to use summer night purge ventilation.

9.1.58. Monitoring (from Sections 6 & 7):

9.1.59. There are still a very limited number of passive houses in the UK making it difficult to compare the Camden results with a benchmark. However according to Dr Ian Ridley, lead researcher on this project, an overall result of 61.1kWh/m2 in the first monitored year and 64.1 kWh/m2 in the second year make the Camden Passive House one of the lowest energy dwellings ever monitored in the UK.

9.1.60. In Dr Ian Ridley's recently published research paper: 'The Monitored Performance of the first new London dwelling certified to the Passive House standard', published in 'Energy and Buildings', Dr Ridley's states:

9.1.61. "The total gas and electricity consumption of the house in the first year of monitoring was 6576 kWh, or 65.1 kWh/m2 per annum. The Camden Passive House is therefore one of the lowest energy dwellings ever monitored in the UK. The BedZed development consumed approximately 90 kWh/m2, The Long House 80 kWh/m2, The Bioregional One Brighton apartments have a median energy consumption of 72 kWh/m2. Only the Princedale Road retrofit dwelling with a total energy consumption of 62.5 kWh/m2 is less than the Camden passive House."

9.1.62. This result is all the more remarkable due to the fact that this is the only detached dwelling in the above comparison.

9.1.63. The measured space heating demand is in close agreement with the designed performance predicted by the PHPP software.

9.1.64. The BPE research project has helped demonstrate the advantages of an intelligently designed, quality-assured approach.

9.1.65. Installation and commissioning checks (from Section 7):

9.1.66. There are strong merits in keeping designs simple, robust and above all intuitive. The purpose of any technology, and its method of operation, should either be crystal clear to building users, or should be robustly automated with simple, standard devices (not specially programmed building management systems).

9.1.67. There is a need to develop cheap and simple warning devices such as prominent red or green lights to warn if equipment is switched off or on incorrectly. Further research and development in this field is, we believe, required.

9.1.68. Heat losses through pipes can be significant. Always allow ample space for insulation around pipes, and ideally the brackets holding the pipes should wrap around the insulation as well.

9.1.69. The data that was collected over the two year research project showed how the occupants interacted with the controls and how they used the house. Further research will be aimed at achieving the most successful balance between user control and automation in future projects.

9.1.70. The ventilation system was found to be faultless in design, installation, commissioning and use, with ventilation rates close to design targets, delivering a well-ventilated indoor environment (low VOCs and particulates concentrations), alongside energy and $CO2$ savings.

9.1.71. The deep bag filter tested by the design team requires changing less often than standard filters and should be taken to the marketplace assuming the remaining tests are successful.

9.1.72. Air quality testing found low indoor levels of PM10 and PM2.5 particulates, up to 4 times better than the parents' Victorian house (comparing bedrooms), and 3 times lower than the external levels on the day of the measurements, suggesting that the HRV system may improve indoor air quality by delivering filtered fresh air.

9.1.73. Knowledge and skills gaps cause performance gaps.

9.1.74. Avoid the knowledge-gap between design and implementation of mechanical and electrical services systems. Hone highly skilled, closely cooperative design, installation and commissioning teams.

9.1.75. Specify trusted, trained specialist sub-contractors. Relying on the contractor or client to provide suitably qualified specialists is a lottery with the odds stacked against you.

9.1.76. Avoid the knowledge-gap between designer and user by using Soft Landings techniques including clear and carefully thought out user guides that carefully explain your design logic. If you cannot easily explain your logic, systems may be too complicated to be used effectively.

9.1.77. Systems should not be overly-complicated or rely on bespoke control systems. Avoid Building Management Systems. Use manufacturer's standard controls. Only use equipment that is designed to work cooperatively with other equipment in a very clear and simple manner using un-modified product manufacturers' standard controls.

9.1.78. If design systems produce regular performance gaps in the hands of average users, don't blame the users; investigate the design and procurement systems.

9.1.79. Anticipating potential problems is an important part of the creative design process.

9.1.80. Refining processes and incrementally improving designs are the real secrets of successful performance. The excitement of a novel design quickly wears out when systems don't work properly.

9.2 Messages for other designers

The main messages the team would like to convey to other designers are:

9.2.1. The Passive House Planning Package has been found to work very well in the UK context. No performance gap of any significance was found between PHPP u-values and actual u-values, or between predicted energy use and actual energy use.

9.2.2. Heat recovery ventilation systems perform very well in both in terms of energy use and indoor air quality when installed and commissioned properly.

9.2.3. Good fabric design (good insulation, triple glazing, draft free detailing, no thermal bridges) and quality control on site will help a project deliver the predicted energy savings, while minimising the impact of unexpected patterns of use. The Passive House Planning Package (PHPP) together with other software for calculating thermal bridges (Heat 2 or Therm) are available to help designers in their work, as well as more and more Passive House specialised consultancies.

9.2.4. The airtightness is the most challenging element to achieve on site, in order to attain the rigorous Passive House standard. The team found that it is important to have an explicit and rational line of airtightness drawn on plans (red line) from the design stage. Also, it is essential to have a dedicated Passive House/airtightness champion on site doing inductions for all the trades and subcontractors and checking the quality of the work done on site.

9.2.5. It is key for the architect to take an active role on site and to transfer knowledge to the site team, making sure the contractors know what they are expected to do and what the key requirements are in order to deliver low energy buildings.

9.2.6. There are strong merits in keeping designs simple, robust and above all intuitive. The purpose of any technology, and its method of operation, should either be crystal clear to building users, or should be robustly automated with simple, standard devices (we recommend avoiding specially programmed building management systems).

9.2.7. A good soft landings approach is essential to make sure the occupants learn to use new or innovative systems.

9.2.8. Provide easy access for maintenance. Consider automated reminders about maintenance intervals, filter changing etc or advise owners to set up maintenance agreements just as they might do with a boiler. When a technology becomes more main-stream, the commissioning and maintenance will no longer pose problems.

9.2.9. Don’t use SAP to predict your energy use if you want to close the performance gap. SAP calculations were found to significantly under-estimate energy use in this project – by a factor of two.

9.2.10. SAP energy ratings cannot be relied upon to provide worthwhile outputs. This building is SAP rated as ‘B’ even though Dr Ridley found it to be the most energy efficient detached dwelling so far monitored in the UK, and its performance comfortably exceeds the government’s future ‘zero carbon’ standard.

9.2.11. It is recommended that design teams develop a more integrated environmental and architectural design capacity, in particular seeking to form a strong and experienced collaborative mechanical design team, installation team and commissioning team to form an integrated design and procurement process that is intended to overcome what we perceive to be one of the weakest links in modern housing procurement – environmental services.

9.2.12. Building Performance Evaluation should be essential work of all design practices. The lessons learned can be developed in the form of decision making protocols and embedded in the practice knowledge base and design processes.

9.2.13. To achieve successful low energy buildings, overcome the ‘Knowledge Gap’ (see 9.1.19) and overcome the ‘Skills Gap’ (see section 9.1.23)

9.2.14. Knowledge and skills gaps cause performance gaps.

9.2.15. Grow your skills. Assert your skills. Detailed suggestions are provided in this report and in the previous section (eg 9.1.32, 9.1.35). A successful project needs skilled quality control leadership at all stages from design to completion to post occupancy support. Knowledgeable designers are best placed to provide this leadership.

9.2.16. Be aware of the difficulty that many people in the UK have with advanced European window mechanisms. Explore reducing functionality with your window supplier, ideally with the option to add back functionality in the future by means of a simple adjustment lever in the edge of the frame, not dissimilar to the way a child lock in a car is adjusted.

9.2.17. Systems should not be overly-complicated or rely on bespoke control systems. Avoid Building Management Systems. Use manufacturer’s standard controls.

9.2.18. If design systems produce regular performance gaps in the hands of average users, don’t blame the users; investigate the design and procurement systems.

9.2.19. Security and insects are recurrent themes that seem to put people off night time purge cooling. So whether you are building a passive house or not, consider providing a few dedicated summer night time cooling windows that open inwards with security louvres fitted externally and concealed insect mesh. Even consider automation of these, but ensure the automation control is robust so that it can never open during the heating season and that mechanisms have a manual override.

9.2.20. Consider forming a strong and experienced collaborative mechanical design team, installation team and commissioning team to form an integrated design and procurement process.

9.2.21. It is advisable to keep to the manufacturer's standard controls rather than try bespoke control systems.

9.2.22. Where manual controls are used, integrate simple warning lights. Like a good car driver, take a defensive stance: assume that if there's scope to make an error, people will do so.

9.2.23. Anticipate problems. Refine processes. Incremental improvement is the real secret of success. (think of the steady incremental technical improvements to the VW Golf over many years for example). Avoid novelty for novelty's sake.

9.2.24. Automation of some functions may be advantageous but be cautious and make sure the system remains robust, easily understood and maintained and that you provide a manual override facility.

9.2.25. Create specification templates to standardise enhanced specifications. For example, Heat losses through pipes can be significant. Specify ample space for insulation around pipes, and ideally specify pipe brackets that wrap around the insulation as well.

9.2.26. Monitoring data can help identify faults and check the performance of the building, both in terms of fabric and systems. It is worthwhile promoting this as a must-have for all new buildings.

9.3 Dissemination

The findings of this BPE study are relevant and could be very helpful to several important stakeholders in the built environment:

- Other design teams (architects and M&E consultants). The design team will continue to disseminate the results of this BPE study via presentations, lectures and conferences aimed at architects and consultants interested in low energy buildings, performance in use, and closing the gap between design and the actual performance of the buildings. The team frequently shares their design experience in events such as: RIBA talks, Ecobuild, Passive House Conferences (UK and International), AECB conferences, Carbon Buzz website, articles in architecture and construction oriented journals (Architects Journal, BSRIA magazine, RIBA Journal, etc).

- Contractors: the design team worked closely on site with the contractors and sub-contractors, disseminating information about how to use Passive House techniques, and frequently perform training sessions on airtightness and windows installation.

- Manufacturers and suppliers: the design team kept in touch and gave feedback to the main systems' manufacturers, receiving advice when the systems happened to be malfunctioning.

- Clients and occupants, through regular feedback regarding the energy use of the building based on the monitoring data. Also, the team frequently participates in housing associations events, explaining their design approach and how that can be translated on to larger scale developments.

- Academics and students, who are analysing the data and producing reports which stand as evidence to how low energy buildings are performing. The team has worked with UCL and RMIT on this project, and several papers and architectural magazines articles have detailed the performance of this first London certified Passive House project. The team also intends to continue to present their BPE projects and the findings of the studies to students in architecture and built environment in major UK universities, through talks and site visits.

- The wider public, via the design team's website, blog and on their research and films pages online, and also by engaging with the local communities, organising tours and talks.

9.4 Conclusions and key findings for this section

Our objective in applying for funding from the Technology Strategy Board for Building Performance Evaluation studies of our first four Passive House building types was to establish objectively if the new direction that the practice had been taking since around 2000 was indeed a worthwhile direction; if the results matched our design intentions, and if we could really achieve the deep energy savings and carbon reductions that we were aiming for and that sceptics told us were unachievable. Most rational people accept that achieving these savings is an environmental imperative and one of the most important challenges mankind has ever faced. In view of the need for transparency and veracity, we wanted the results verified by the involvement of leading academic researchers and evaluators.

The results of two years' research on all four buildings have established beyond any reasonable doubt that the Passive House methodology works and is readily applicable in the UK. It has great potential to enhance people's comfort and health prospects, while simultaneously reducing their overall energy consumption eight or ten-fold, especially in the winter months when the gap between energy demand (for heating and lighting) and renewable energy supply is most problematic.

Far from being unaffordable, the energy savings found by this research have the potential to save the UK much more money than expenditure over a period of just 50 years due to the modest capital outlay compared to 'business as usual'. Buildings which save 80-90% of the energy used by UK average buildings have the potential, if they become the norm, to make large savings in fossil fuels and expensive new power stations.

Furthermore the results of this research prove that these benefits can be achieved by well-trained British construction teams at their first attempt. The essential air-tightness requirements are easily met or exceeded by well-trained and diligent teams. At the first attempt, installing windows, vapour control layers and heat recovery ventilation can be a success if either the architect or the contractor is knowledgeable and is prepared to take a hands-on approach.

The research team found that the total yearly gas and electricity consumption of the Camden Passive House (61.6kWh/m2/1st year, October 2011 to Sept 2012, and 64.1kWh/m2 in the second monitored year, Oct 2012 to Sept 2013) indicates this is one of the lowest energy dwellings monitored in the UK. Other similar UK projects with comparable energy consumption are BedZed 90kWh/m2, The Long House with 80kWh/m2, One Brighton with 72kWh/m2, Princedale Road with 63kWh/m2. Of all these buildings the Camden Passive House is the only freestanding building. All the other buildings with comparable results have the advantage of shared party walls which may transmit no heat loss at all where temperatures are similar either side of the wall.

Similar and consistently strong results have been found in both of our other two Building Performance Evaluation studies of Passive House buildings (Larch & Lime houses in Ebbw Vale, Wales and the Mayville Community Centre in London). The results indicate that Passive House buildings will consistently achieve exemplary low heat loss levels, and that Passive House design appears to be robust enough to achieve low overall energy consumption even with unexpected occupant behaviour.

These BPE studies found that the Passive House Planning Package (PHPP) is a good design tool. In spite of being a steady-state tool, it manages to anticipate accurately the energy performance of domestic and non-domestic buildings.

It is hoped that the knowledge gathered in Bere Architects' three Technology Strategy Board BPE studies will encourage a step change in the way buildings are designed and built, so that extremely low energy buildings with excellent comfort evolve from being 'prototypes' to becoming the 'norm' in the UK built environment.

10 References

1. References

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1.10. Stamp, Samuel and Ridley, Ian, 2011, *Co-heating test of* [address omitted], *Passivhaus,* The Bartlett School of Graduate Studies, University College of London.

11 Appendices

Supporting documents:

11.1.1. SAP Assessment

11.1.2. Comparison of Post Occupancy Monitoring and SAP Energy Predictions

11.1.3. PHPP Worksheets (Certification issue)

11.1.4. Thermal bridge report

11.1.5. Thermal imaging report

11.1.6. Co-heating test report

11.1.7. User Guide

11.1.8. BUS Survey

11.1.9. Window use surveys

11.1.10. Post occupation evaluation interview

11.1.11. Indoor air quality test

11.1.12. Monitoring Guide

11.1.13. DomEARM energy assessment and reporting study

11.1.14. Photographic Survey Report