Building Performance Evaluation

Final report

Domestic Buildings

Phase 2: In-use performance and post occupancy evaluation

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1 Introduction and overview

This report concludes a two year building performance evaluation (BPE) study of the Larch and Lime houses, a pioneering project in Wales consisting of two Passive House homes designed to act as prototypes for future social housing.

Bere:architects was commissioned after winning an open competition initiated and managed by the Building Research Establishment (BRE) in Wales. The competition was held at an exciting time in Wales, when very well informed and visionary political leadership was operating in strong synergy with an imaginative and energetic team of forward looking and knowledgeable people at the BRE in Wales. The BRE team held a rigorous interview process to ensure that the winning team also had the technical and collaborative expertise required. The competition was held in collaboration with the Blanau Gwent Council at Ebbw Vale who provided the land. The site was provided at the head of a large coal-mining valley, on high ground in an exposed position that was formerly the site of a large steel works. The extreme site was a deliberate choice. If a building could work according to Passive House requirements in such a location, it could work anywhere in the UK.

Construction of the winning designs was paid for by the Welsh Government with the assistance of European Union funding. The client was the executive partner and one of their construction teams acted as the main contractor.

The competition was called ‘Future Works’ and the objective was to build two prototypes for social housing that would meet the demanding Passive House standard at an affordable cost. The houses also had to achieve level 4 or 5 of the Code for Sustainable Homes.

The aim was to determine if housing with improved resilience, longevity, health benefits and sustainability could be built close to the same build cost as ordinary social housing if it was built to the same specification as the prototypes, on neighbouring sites at a larger scale. While some additional costs were to be expected, BRE Wales, the competition organisers wanted to investigate if spending a small amount of additional money at this stage would reap longer term benefits, both financial and social. One of the questions was how much money would be saved in the longer term through fuel and other savings, and so retained in the local Welsh economy rather than being spent on fuel imports?

Figure 1-1. Architect's 3D rendered image of the houses (street view)

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 Passive House Institute in Darmstadt, Germany, 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[1] 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;

[1] In the specific case of this project the competition brief demanded the use of a modified "extreme weather" file instead. See the following chapter.

- 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.

Figure 1-2. The Larch and Lime Passive Houses (backyard view)

The project consists of two Passive Houses: the Larch House and the Lime House. The primary objective of the Welsh Passive Houses projects was to achieve a comfortable and healthy home with low energy use that could be built at an affordable cost.

The houses were designed by bere:architects with mechanical and electrical services design by Alan Clarke, ventilation detailed design by Andrew Farr, structural engineering by Bob Johnson. Certification was completed in July 2010 (Larch House) and March 2011 (Lime house) by the BRE on behalf of the Passive House Institute, Darmstadt.

The Larch House has a total floor area of 99m^2. It is a three bedroom, two storey dwelling with large windows on its south elevation. It is clad in Welsh larch. The large south facing windows have external retractable venetian blinds providing the opportunity for summer shading to reduce any unwanted solar gains. The Lime House has a total floor area of 78m^2. It is a two bedroom, two storey house with conventionally sized windows. It is finished with

Welsh lime render. After a very fast track design process, the Larch House was the first of the two houses to be built, again a fast-track process from March to July 2010 in time for the opening of the Eisteddfod Festival, and the Lime House was built at a more leisurely pace due in part to the time required for the design of locally made Welsh windows, starting June 2010 and completing March 2011.

Both houses were designed to meet the Passive House standard, with very good insulation and airtightness, high performance glazing and a mechanical ventilation system with heat recovery. They also have locally manufactured solar water heaters on the roof – Larch House has a 4m^2 collector, while Lime House being smaller has 3.3m^2 – and locally made photovoltaic panels on the roof to generate electricity: 4.7kWp in Larch House, and 1.89kWp in Lime House.

Figure 1-3. Street view of the Larch House (left) and Lime House (right).

The two houses were designed with slight different approaches to Passive House, the Larch house complying with the annual Specific Space Heat Demand target of max 15kWh/m2 and the Lime house complying with the annual peak heat load demand of 10W/m2. These differences are explained in the following chapter.

The Larch House, has a design SAP rating of 101 – band A - and has achieved a Code of Sustainable Homes (CSH) Level 6. It is the UK's first Code 6, Zero Carbon Passive House. The Lime House was designed to have a SAP rating of 101 – band A – and a Code of Sustainable Homes Level 5. In reality, due to a communication error, the PV array from the design stage the Lime House fractionally missed compliance with CSH Level 5 – the SAP (2006) reached 99.1% instead of 100% needed to meet the CSH level 5. The houses were assessed under SAP 2006. It is thought that the houses would reach CSH level 5 if SAP 2009 was used, but this calculation has not been done.

Both houses were also designed to the Lifetime Homes standard, aiming for flexibility of use and adaption to changing needs of the occupants. They were constructed using natural materials where possible, for healthy indoor air quality, simple maintenance and possible reuse or recycling at the end of their lives.

Welsh manufacturers were sourced to demonstrate how Passive House homes can be produced using local products which support the local economy. The houses were made almost entirely with locally produced materials, including the structural frames (made locally with Welsh wood), the wall and roof claddings, the insulation, the renewables technologies, and in the case of the Lime House, the windows and doors too. See Appendix 1 for a material assessment list.

The construction timeline was extremely tight as the houses were to be opened to the public during the Eisteddfod Festival in July and August 2010. The Larch house was the first to be completed in July 2010, and was opened to visitors for educational visits for 18 months (originally 12 months was intended but it was extended due to the unexpectedly high public interest levels). The Lime house was under construction during the same period, allowing the visitors to follow its construction.

The client held a competition to select the tenants for the houses and they moved into their new homes in April 2012. This research project includes filmed interviews with the tenants that can be seen at **http://bere.co.uk/films**.

The Building Performance Evaluation research study

The research work was carried out in two phases and the present report follows on from the Phase 1 report, containing results and conclusions drawn from both Phase 1: Post occupancy and early occupation (January 2011 to July 2011) & Phase 2: In-Use Performance and Post Occupancy Evaluation Project (June 2012 to June 2014).

Phase 1 of the BPE study consisted of an analysis of the fabric performance of the building (chapter 3) and a testing and re-commissioning of the mechanical and electric systems installed in both houses (chapter 7).

Phase 2 consisted of the installation of comprehensive in-use performance monitoring equipment and the downloading and analysis of the data measured by this equipment for a period of two years (chapter 6). Phase 2 also included several post-occupancy workshops, interviews and surveys with the tenants to gather user feedback in the performance of the houses (chapter 5).

During both study phases a number of technical and design team walkthroughs took place to analyse and discuss the houses' equipment and performance (chapter 4). Finally at the conclusion of the BPE study phase 2 the design team carried out a number of interviews with the client, owner, contractor and other parties involved in the project in order to gather the different parties' perspective on the aims and achievements of the project and the whole process of construction, delivery and monitoring (chapter 9).

The key findings and messages for the client, owner and tenants as well as wider lessons taken from this Building Performance Evaluation study are summarized in chapters 10, 11 and 12.

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

Summary of findings

During phase 1 both houses were extensively analysed and tested in terms of fabric performance and systems commissioning. This is described in chapter 3, followed by a summary of the tests and their findings.

The co-heating test (Jenkins et al, 2011) found that the Larch house has a heat loss parameter of 62 ± 4 W/K for both ventilation and fabric losses and that Lime House's heat loss parameter was 45 ± 2 W/K (Siviour analysis in both cases, incorporating solar gains). Although these 'as built' figures were very slightly higher than the PHPP design predictions of a heat loss coefficient of 57.6 W/K for Larch house and 37.2W/K for Lime house they are both excellent results, confirming that both houses have indeed been built to the high standard that was intended. The tracer gas test (Jenkins et al, 2011) done at the same time also confirmed the blower door results, that both houses have exceptionally good envelope airtightness.

The fabric insulation of the houses was also analysed with a thermographic camera. The survey was carried out before sunlight had warmed any wall surfaces, with high internal temperatures and freezing external temperatures, and the results were excellent showing the surface temperature of the walls to be close to external temperature in freezing conditions, proving minimal heat loss through the fabric, as designed. However it highlighted a slight weak point around the plinth of each house where, to keep the structure as simple and cost-effective as possible, the insulation is at its thinnest. A subsequent three-dimensional thermal bridge analysis done by the design team and checked independently, confirmed that the thermal bridge was roughly as previously calculated at the design stage and wasn't therefore of any significance.

Throughout the construction and the monitoring period several airtightness tests were done, assessing the building's performance over roughly four years since the construction completion. The most recent test, done at the conclusion of the phase 2 of the BPE study, showed excellent airtightness results of 0.26 and 0.47m3/m2/hour, at 50 Pa (Larch and Lime house respectively).

Also during the BPE phase 2 an Indoor Air Quality analysis was carried out to measure and compare a range of indoor air quality parameters under normal conditions of building use. The report results were very satisfactory, showing all parameters to be better than acceptable levels according to international and UK-based guidelines.

During phase 2, after the houses became occupied, the BPE study had a stronger focus on the energy and environmental performance of the houses as well on occupancy evaluation. The methods and findings can be found in chapters 5 and 6.

The overall energy performance of the Larch and Lime houses over the two years BPE study is quite diverse due to some unexpected user behaviour but in spite of this, both houses have returned very low energy consumption. Larch house shows remarkable results with a two year combined space heating consumption of only 9.3kWh/m^2, well below the Passive House reference of 15kWh/m^2. On the other hand, the Lime house space heating consumption result was higher than the Passive House target with a two year combined result of

25.6kWh/m2. This was found to be due to the user's habit of leaving a bedroom window open in winter for extended periods of several hours each day. In spite of this habit, the energy consumption of the building is still considered low, and the result is useful in indicating that the impact of user behaviour, while significant, does not affect the status of a Passive House as an exceptionally low energy building. Neither house met the PHPP Primary Energy target of 120.0kWh/m^2 (primary energy includes conversion losses and transmission losses from the power station, which is very different to metered energy consumption). The average consumption for the Larch house was 158.0kWh/m^2 and for the Lime house was 189.0kWh/m^2 for the two years of monitoring. This was mainly due to very high socket loads from a large number of televisions running for extended periods, clothes driers and energy inefficient appliances (class A appliances are normally required for Passive House certification). However when the PV generated electricity that is exported to the grid is included the Net PHPP Primary Energy of the Larch House was 135.0kWh/m2 (two year average) and the Lime was 177.0kWh/m^2. The Larch PV system offset 71% of the overall CO2 emissions in the two years of the BPE study and the Lime PV system offset 33% (it's a smaller system). Net CO2 emissions of the Larch house were 9.4kg/m2 and of the Lime house were 24.0 kg/m^2 (two year average).

The Larch house had very low but not zero carbon performance during the monitoring period due to the unexpectedly high socket loads. This means that it did not meet the original performance criteria for level 6 of the Code for Sustainable Home (CSH). The Larch House did however meet CSH Level 5, with the PV system easily offsetting all emissions for heating, lighting and hot water. The Lime house was certified as CSH Level 4, although it has essentially a CSH Level 5 specification, and easily achieved its certification performance.

In terms of environmental performance, the houses have demonstrated to be extremely comfortable and very warm in winter with good indoor air quality and little energy consumption.

The external blinds in the Larch House were not fitted with the specified controls system. The simplistic control logic lowered and closed the blinds whenever sun shone on the control sensor and this caused various difficulties until the controls were disabled:

- during the heating season the building was unable to benefit from valuable external solar gains when the residents were not present to raise the blinds.

- Residents got into the habit of lifting the blinds whenever they were lowered and closed, and they continued to lift the blinds (rather than adjust louvre blade angles) in the summer because the closed blinds cut out light and views. This contributed to some summer overheating.
- To overcome the problem of the blinds lowering when this was not wanted, the power to the blinds was cut off for a while. Left like this, the blinds were not lowered at times when this was desirable, such as to shade the large windows in the summer.

Eventually the housing association arranged for a service visit from the blinds installer to remove the solar function which automatically lowered the blinds. Power could then be returned to the blinds and the occupants can now raise or lower the blinds as they wish, without the automatic controls changing their settings. In the final summer of monitoring, the residents reported being much happier about their summer comfort now that they are fully in control of the blinds.

Phase 2 of the BPE study was also focused in gathering in-depth feedback from the tenants. Occupancy feedback is crucial to understand the subtleties of the performance of the houses and is an important tool to continue to use in future projects. The design team, using the Soft Landings approach, did several walkthroughs, workshops and interviews with the occupants at critical seasonal times (following summer and winter seasons) to gather their views on the performance of each house. Four of these events have been captured in short films available for viewing on the bere:architects' website: **http://bere.co.uk/films**. Also a BUS methodology survey was carried out showing very good results for both houses that compare favourably with the benchmark. Both Larch and Lime residents have demonstrated high levels of satisfaction with their house's performance in energy and environmental conditions. All occupancy feedback is described in chapter 5.

It is important to note that the results from this BPE study of the Welsh Passive House prototypes should not be generalized as they are case study dependent. Although important findings and lessons have been derived from this study, only when the monitored performance of more Passive houses in the UK becomes available, can a generalized assessment of their performance be made.

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

2.1 Introduction

The Larch and Lime houses are located in Ebbw Vale, in Wales, on the site of the former steelworks "The Works". The whole site has benefitted from an extensive regeneration programme, including new facilities such as a school, a leisure centre and a hospital.

The competition brief was to provide two homes of less than $100m^2$ that would meet the Passive House standard, and comply with Code 4 or 5 of the Code for Sustainable Homes, as well as all the usual requirements for social housing, including limited construction costs.

The site is located in South Wales, 300 metres above sea level, at the top of a large valley. The site has particularly cold and overcast weather conditions with relatively little winter sun. Concern that the typical average weather data for this part of Wales would underestimate the houses' heating needs for the site made the BRE Wales, the competition organizers, demand that the PHPP design calculations would use a modified "*extreme once in 10 years*" weather data file, instead of the typical average weather data file.

Another competition requirement was to use locally produced products for the construction of the houses. Bere: architects chose to use timber as the main construction material as it is a renewable product and a widely available but under-used resource in Wales. The practice was able to draw from its experience with the Austrian carpentry company Kaufmann Zimmerei und Tischlerei who had contributed to the design of their Passive House in the London Borough of Camden which completed a few months earlier.

The design team had the vision that the houses could initiate the development of a new prosperous home-grown industry in Wales and proposed this in the study report "Integrated Strategies for the Welsh Timber Industry" (available for download at http://www.bere.co.uk/sites/default/files/research/Integrated-strategies-Welsh-Timber-Industry.pdf).

Going well beyond the competition requirements, but greatly encouraged by Nick Tune of BRE Wales who gathered a consortium of interested carpentry workshops to collaborate, the Lime house windows were made in Wales to a design developed by bere:architects and the window designer Bill Robertson. These were the UK's first Passive House certified windows. The aim was to demonstrate that UK manufacturers can achieve the same high standards as imported products, and to find out if they could be produced at a competitive price.

The ultimate objective, which was successfully demonstrated, was to show that very high performance buildings can be made, right now, using almost entirely UK produced (and in this case Welsh produced) materials, products and skills. If widely adopted, this approach has the potential to create major benefits for local people and the local economy:

a) Stimulation of local manufacturing.

b) Lower energy imports.

c) Better balance of payments.

d) Much greater resilience in the face of energy shortages.

e) Fewer health risks for the local population.

2.2 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

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

- Specific Space Heat Demand: maximum 15 kWh/m2

- Entire Specific Primary Energy Demand (includes transmission losses from power stations): maximum 120 kWh/m2

- Pressurization Test Result: maximum 0.6 h-1@50Pa

The energy consumption targets are absolute and cannot be offset by renewable energy. This is an important point because it is the only realistic way to close the winter gap between energy demand and renewable energy supply.

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 Passive House Institute 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.

2.3 Building design strategy

The competition requirement to use a modified extreme weather file determined the design approach as it made it more challenging to meet the low space heating requirements of the Passive House standard. The two houses were designed with the same fabric-first approach but using different design strategies to achieve the Passive House certification.

The houses are built using a closed panel timber frame system developed by bere:architects specifically to utilise the small-section local Welsh timbers and manufactured by a local Welsh factory, a timber frame manufacturer. Bere:architects timber framing design expertise had been learned from an 18 month knowledge-transfer exercise with the Austrian carpentry company Kaufmann Zimmerei und Tischlerei. Welsh timber is of smaller section than the timber available in Austria because the warm, damp climate of Wales makes the wood faster growing and less dense than the slow-growing mountain timber of Austria. The slower growing timbers of the Austrian climate have the advantage of being relatively strong so the trees can grow bigger than in Wales. However Welsh timber was required for the project as part of the strategy to avoid unnecessary imports.

The superstructure of the house was prefabricated off-site to ensure quality control and a draft free construction. The walls, floor slabs and roof elements are manufactured from UK sustainably grown timber (60% guaranteed from Welsh forests). The timber frame wall panels were insulated off site using 225mm thickness of locally produced mineral wool, and then clad internally with 100mm of natural wood fibre insulation and externally with 100mm rigid wood fibre board. This gives the walls a total of 425mm of insulation and a U-value of 0.095W/(m^2K). The roof, with 560mm mineral wool, has a U-value of 0.074W/(m^2K).

The made ground of the site was excavated to the required level and 480mm of XPS insulation was laid underneath a 250mm thick GGBS concrete slab. The super-insulated raft foundation has the ability to act as a buffer to retain warmth and a floating raft is resistant to any localised settlement of the ground. The final U-value is 0.076W/(m^2K).

Special are was taken with the air-tigthness detailing. Thermal bridging calculations were done to ensure significant junction details complied with the less than 0.01W/mK thermal bridge Passive House requirement.

Larch House

Larch House is 14m^2 bigger than Lime House. It has large south facing windows protected by external retractable blinds (occupying 55% of the south facade) to maximize the winter solar gains (Figure 2-2). PHPP software was used to determine the amount of glazing in all facades necessary to balance the heat losses and gains. The high quality Passive House certified windows are triple glazed and draught free with a tilt option to provide secure Summer time cross-ventilation. The large windows are a key feature of the house, providing a bright interior space and winter solar gains. They are however more costly than regular housing association windows and also due to the lack of local supplier they had to be imported from Germany.

Larch cladding is fitted on battens to the timber frame through the rigid wood fibre board creating a ventilated facade. The Larch cladding was specified to be fixed with a single stainless steel screw at regular intervals along its length. This is to enable the boards to naturally ‘cup’ without pulling the screws out of the battens as would happen with two screws. However this aspect of the house was not built as specified, and twin screws were used which may cause problems in the future if the boards cup and try to pull the screws out of their fixings.

The house is completed with a locally manufactured, reconstituted slate roof using over 60% recycled natural Welsh slate.

The PHPP final design had a specific heat demand result of 13kWh/(m^2a) , a specific primary energy demand result of 83kWh/(m^2a) and a peak heating load result of 11W/m^2 (see Figure 2-1 and Appendix 2)

Specific Demands with Reference to the Treated Floor Area				
Treated Floor Area:	86.7	m^2		
	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	**13**	**kWh/(m²a)**	**15 kWh/(m²a)**	**Yes**
Pressurization Test Result:	**0.2**	**h^{-1}**	0.6 h^{-1}	**Yes**
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	**83**	**kWh/(m²a)**	120 kWh/(m²a)	**Yes**
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	48	kWh/(m²a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	60	kWh/(m²a)		
Heating Load:	11	W/m²		
Frequency of Overheating:	6	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m²a)	15 kWh/(m²a)	
Cooling Load:	2	W/m²		

Figure 2-1. Larch house: Certified PHPP Spreadsheet – extract from the Verification page

Figure 2-2. South facade of the Larch House with large windows and retractable external blinds.

The internal layout of the house separates the social area at the ground floor and the private area in the first floor. The ground floor has an open plan kitchen with dining area, a living room with a study niche and an accessible bathroom. The first floor has three bedrooms and one bathroom (see Figure 2-3 and Figure 2-4).

Figure 2-3. Larch house images of the interior

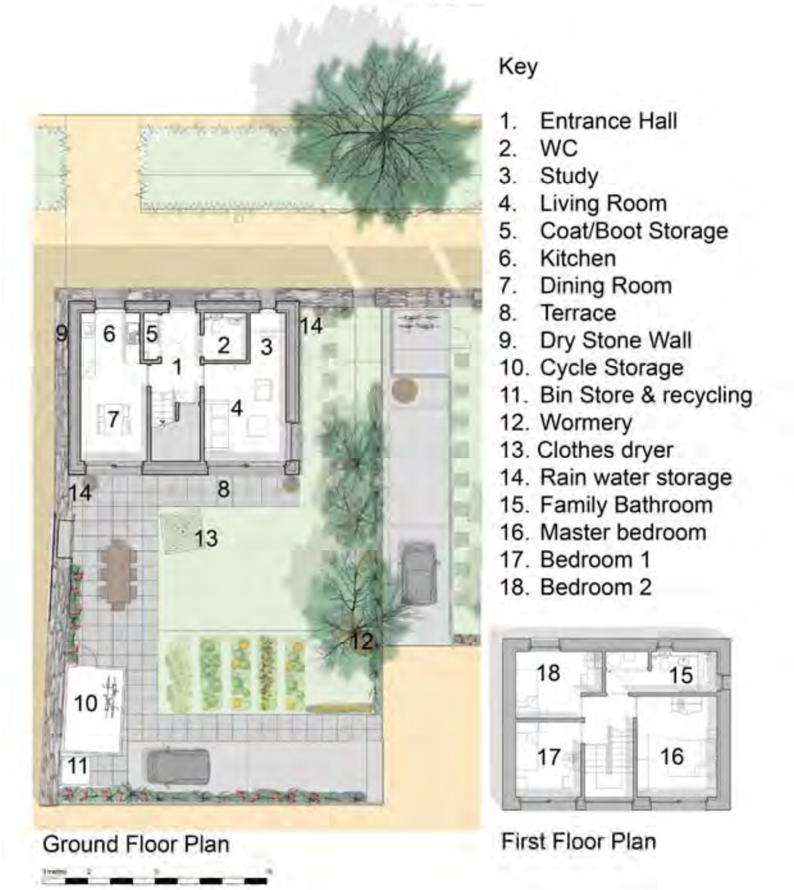


Figure 2-4. Larch House - floor plans

Lime house

To overcome the extra costs associated with the large windows of the Larch House, the Lime house was designed with a different strategy to achieve Passive House certification. Instead of using the Annual Heat Demand reference of 15kWh/(m^2a), the design is based on the Peak Heat Load. This is an alternative method that requires the building to use no more than 10W/m2 of heat on the coldest day according to the local weather data. In this case, using extreme weather data as specified in the competition brief, the 10W/m2 of heat must not be exceeded on the coldest day in a ten year period. This strategy makes solar gains less significant and internal gains more important and the design calculations allowed the team to reduce the amount of necessary glazing (to 20% of the south facade). With reduced risk of overheating due to the smaller windows, there was no need for external blinds (Figure 2-5).

Figure 2-5. Lime House - south facade with smaller windows than Larch House.

A design optimization graph produced by Robert McLeod (BRE Wales) and bere:architects summarizes the difference between the two strategies (Figure 2-6).

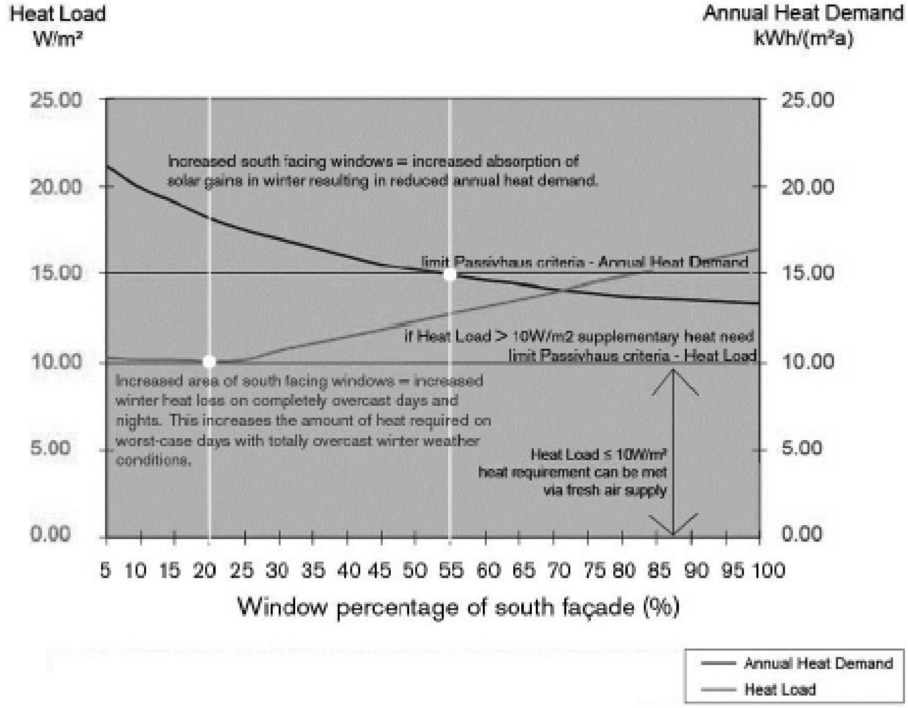


Figure 2-6. Design glazing optimization graph comparing the two Passive House design approaches based on Annual Heat Demand or Peak Heat Load.

The PHPP final design for the Lime house had a specific heat demand result of 17kWh/(m^{2}a) , a specific primary energy demand result of 87kWh/(m^{2}a) and a peak heating load result of 10W/m^2 (see Figure 2-7 and Appendix 2).

Specific Demands with Reference to the Treated Floor Area

Treated Floor Area:	69.1	m²			
	Applied:	Monthly Method		PH Certificate:	Fulfilled?
Specific Space Heat Demand:	17	kWh/(m²a)		15 kWh/(m²a)	No
Pressurization Test Result:	0.6	h⁻¹		0.6 h⁻¹	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	87	kWh/(m²a)		120 kWh/(m²a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	49	kWh/(m²a)			
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	75	kWh/(m²a)			
Heating Load:	10	W/m²			
Frequency of Overheating:	6	%	over	25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m²a)		15 kWh/(m²a)	
Cooling Load:	2	W/m²			

Figure 2-7. Lime House: Certified PHPP Spreadsheet – extract from the Verification page

The Lime House windows were manufactured in Wales by Custom Precision Joinery to designs developed by bere:architects with Bill Robertson (a Passive House window designer that bere:architects had worked with previously), Bayer Schreinerei (the Larch House window manufacturers), and the carpenters from Custom Precision Joinery. The developed windows were Passive House certified and the first UK-designed windows to be certified.

Figure 2-8. The Lime House windows being built at Custom Precision Joinery

Although smaller, the internal layout of the house follows a similar approach to the Larch House in so far as the social area is on the ground floor and the private area on the first floor. The ground floor has an open plan kitchen with dining and living area, and an accessible bathroom. The first floor has two bedrooms and a bathroom (Figure 2-9).

Figure 2-9. Lime house floor plans

The impact of the extreme weather file

The difference between the certification method based on annual heat demand or based on peak heat load is more pronounced given the use of the extreme weather file used. If normal weather data had been used there would be much less difference between the two approaches. This was confirmed by an experiment done by using a Manchester average weather data. The design calculations showed that certification could be obtained with a 33% glazing ratio in both houses and also reduced fabric specification (Figure 2-10) and there was virtually no difference between using the annual heat demand or peak heat load approach.

Figure 2-10. Larch and Lime House glazing ratio changes when using Manchester average weather data.

A further analysis was done to see the impact of the glazing changes and reduced specification with the extreme weather data. The revised design calculations showed that the peak heat load would increased to 11W/m^2, only a 1W/m^2 above the capacity of the air-side heating which in a 100m^2 is equivalent to just 100W.

Furthermore, a cost analysis done by Richard Whidborne, the project's quantity surveyor, compared the building costs of the Larch house with the Royal Institute of Chartered Surveyors database for a one-off detached house built in the previous 10 years. The results showed that the Larch house designed to extreme weather data specifications was 22% more expensive than typical low cost housing. But the Larch house revised specification for average weather data was only 9% more expensive than typical low cost housing. This would be due to reduced glazing area, no external blinds and reduced insulation specification.

In conclusion, with the benefit of hindsight, the design team considered that it would be simpler and more cost-effective to use the average local weather data rather than extreme weather data and allow for supplementary heating in the cold periods. The cost savings of using average weather data would also make the Passive House standard a more realistic strategy for social housing.

2.4 Building services strategy

Building services were designed by Alan Clarke with heat recovery ventilation (HRV) for all-year use, designed and commissioned by Andrew Farr from the Green Building Store. Both houses have fully opening windows for cleaning and a secure tilt action to encourage cross ventilation on both floors during the summer months. Additionally both houses have a solar thermal collector to provide hot water and a PV array to generate electricity.

Ventilation

Both houses have a Paul Focus 200 ventilation unit installed with the benefit of heat recovery fresh air supply and a VEAB hot water heating coil. The ventilation system is used to supply clean fresh air and extract used stale air and also to provide space heating in both houses. The heated air is carried in insulated ductwork to the bedrooms and the living room, plus the dining area in the Larch House. Air is extracted from the airing cupboard in the bathrooms and the kitchen area. Extract air returns to the heat exchanger and its heat is recovered in order to warm incoming air. A heater battery in the ductwork is connected to the hot water tank in the Lime House which is supplemented with solar energy, and directly to the boiler in the Larch House, and heats the supply air in case a higher temperature than that supplied from heat recovery is demanded. Duct terminals are manufactured by Lindab out of galvanised steel. In the kitchen, an extract grille was used that has a filter to protect the ducts from airborne fats and oils. All terminals are adjustable to achieve the required balancing and flow rates. Both houses have a simple boost button (separate from the main control panel) that accelerates the ventilation rate for a period of 30 minutes when required.Ductwork used is spiral wound galvanised metal ductwork and the Lindab connections, bends and tees are reliably sealed by means of their double rubber gaskets. Insulation of heated ducts is a combination of mineral fibre + foil throughout, except for vapour-proof Armaflex cellular foam insulation between the ventilation unit and the exterior of the house to avoid condensation on the short lengths of cold ductwork. Electric pre-heating protects the heat exchanger against frost using a Paul ISO unit with G4 prefilter and a Positive Thermal Coefficient of Resistance (PTC) electric element under control of an electronic thermostat to raise sub-zero intake air to a set point of -1°C. In the Larch House the ventilation unit is located in a cupboard by the entrance door with the intake and exhaust terminals facing the street (see Figure 2-11 for the ventilation diagram). In the Lime House the HRV unit is located in a cupboard off the kitchen under the staircase and the external terminals face the garden side (see Figure 2-13 for the ventilation diagram).

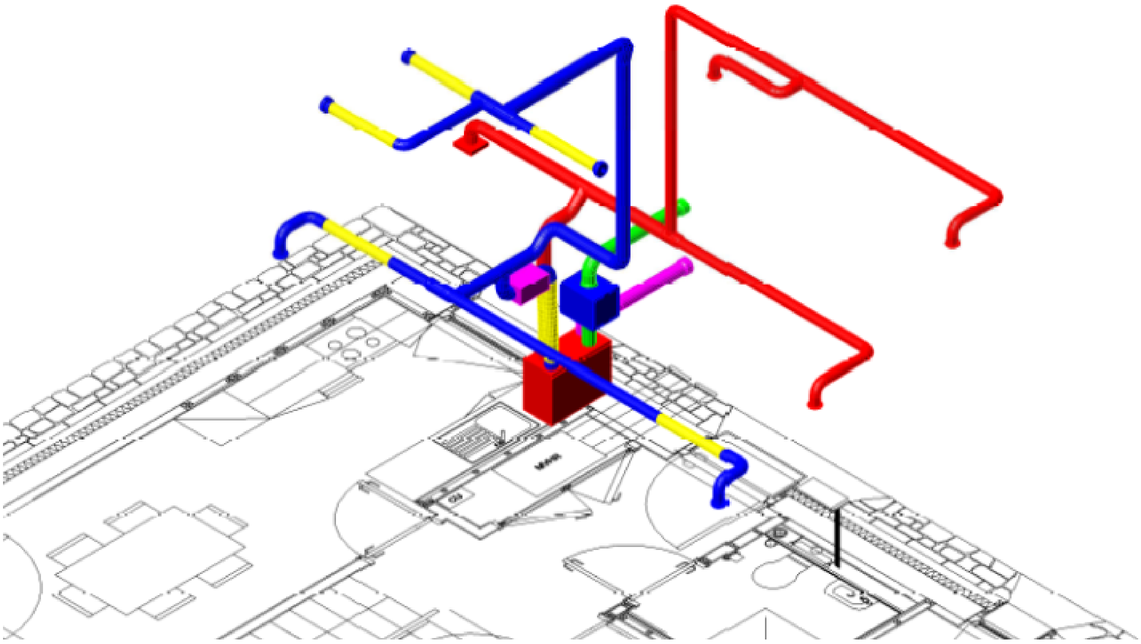


Figure 2-11. Heat recovery ventilation diagram designed by Green Building Store for Larch House


Figure 2-12. Ventilation system in the Larch House. A heater battery is installed directly above the ventilation unit (wrapped in silver foil) and this is supplied with hot water from the central heating boiler. The heater battery is on the left with foil covered insulation, the intake and exhaust ducts are on the right and insulated with vapour impermeable Armaflex insulation. The frost heater and pre-filter are in the black insulated box on the right.

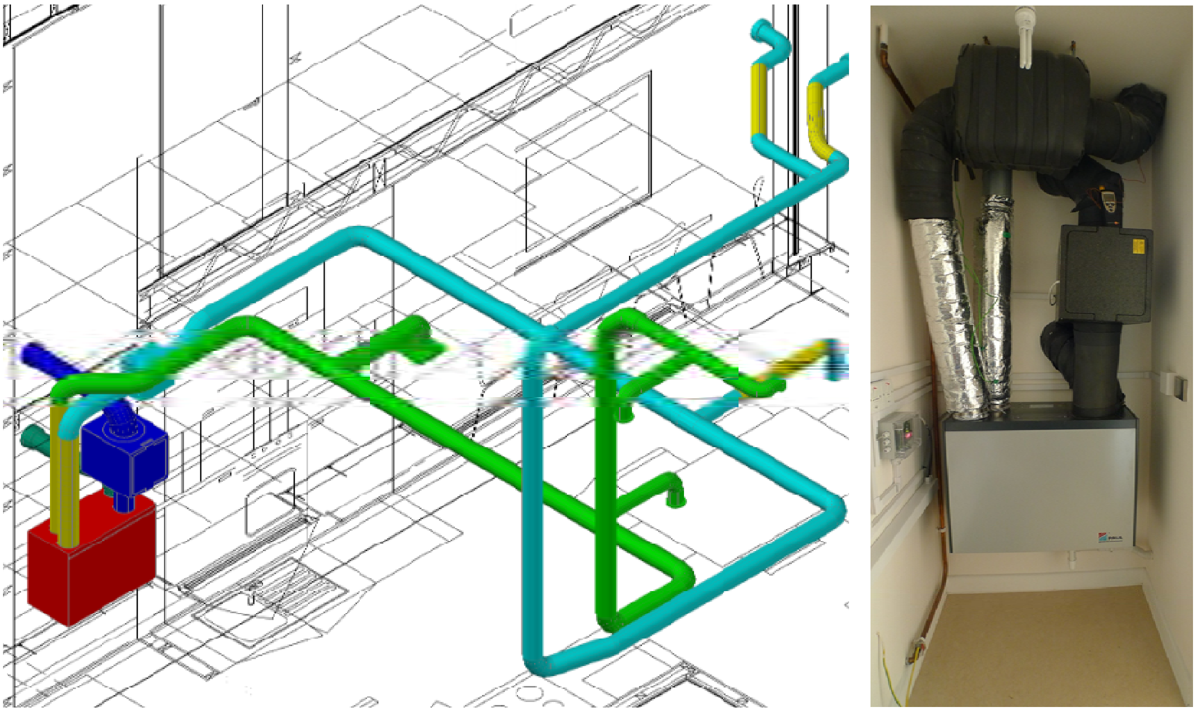


Figure 2-13. (left) Heat recovery ventilation diagram designed by Green Building Store for Lime House. (right) The frost heater is on the right, the silver ducting on the left contains silencers on supply and extract, and the heater battery is suspended from the ceiling. The control thermostat for the frost heater is on the wall on the left and the main MVHR controls on the right, with boost ventilation controls in the kitchen and outside the bathroom. These switch the MVHR to the highest flowrate for 15 mins.

Heating

In both houses the heating control is simply the room thermostat. The thermostat has an on/off button and up/down arrows to adjust temperature, which is displayed on an LCD screen. It was the expectation of the building services engineer Alan Clarke that "*this digital type of control will avoid the common misinterpretation of a rotary thermostat as a "tap" with the higher setting correlating to more power. Here power is very limited with air distribution heating so the use of constant set point, as opposed to running heating intermittently, is more important than usual*".

The boiler control has been set to supply water to the ventilation heater battery at a set temperature which is lower than the DHW set temperature to avoid scorching the air.

There is no need to interlock heating and ventilation controls because the Focus ventilation unit has no summer bypass. Interlocking was necessary with the early Paul Thermos units because the bypass could accidentally operate automatically during winter, so not recovering heat in the air extracted from the house, when high internal temperatures occurred in the winter, deliberately achieved through the use of heating. Newer Paul units with bypass have solved this problem, but the lower cost Focus units in the two Welsh prototype houses don't have a summer bypass and the risk outlined above does not occur.

In the Larch House there is additional heating by towel radiators (served by a hot water cylinder) and a small radiator is located in the airing cupboard for drying clothes. In practice the airing cupboard radiator has been found to be completely unnecessary. Supplementary heat from a towel radiator was considered necessary because despite meeting the Passive House target, the design peak heating load (11W/m^2) can't be met solely by the heat recovery ventilation system alone.

Thermostatic radiator valves (TRVs) are fitted to radiators to limit bathroom temperatures, as these heaters have excess capacity. The extra capacity may be absorbed when drying towels or other clothing, but it needs to be controlled to avoid overheating at other times.

The Lime House, because it was designed to meet the peak heating load of 10W/m^2 relies only on heating supplied via the ventilation system. Noting that the air heater battery uses copper tube it was decided to use the domestic hot water directly in the air heater, so that the hot water cylinder can be operated in the usual way, with stratification to optimise the solar thermal performance. A twin coil cylinder is used, with upper coil heated by the boiler and lower coil by the solar panel.

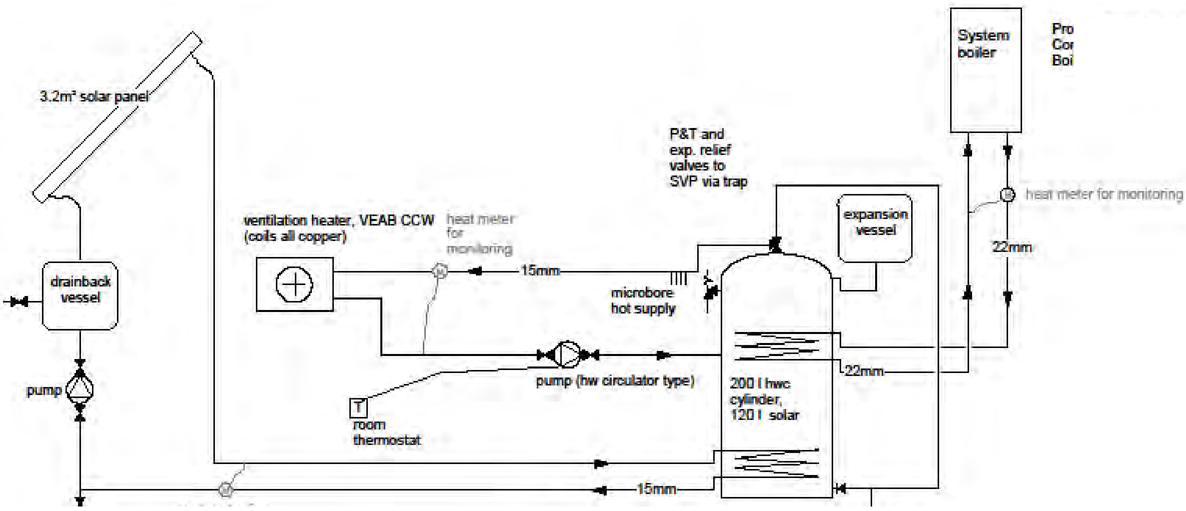


Figure 2-14. Lime House heating strategy diagram. Note that a change was made to the design as originally drawn above: the thermostatic mixer valve shown here fitted at the top of the cylinder, if set to protect occupants from scalding bathwater (below 40°C) would have prevented the circulation of sufficiently hot water for the heater battery, and was therefore removed during construction.

In the Lime House the cylinder coil temperatures are more critical than in the Larch House since it requires 100% air heating from water at standard DHW storage temperatures (around 55^{o}C). The larger capacity heater battery was fitted and this provides air at 49^{o}C for water flow and return temperatures at the heater of 53^{o}C/46^{o}C and cylinder set point of 55^{o}C.

Boiler controls are fitted but set to continuous DHW with cylinder temperature controlled via a boiler-connected temperature sensor. A standard high limit thermostat is included on the power supply to the 2-port valve, and the valve is controlled by the boiler to permit run-on as required.

Domestic Hot Water and Solar Thermal

Both Larch and Lime House have a Rehema Avanta 18s natural gas supplied boiler system installed. Each house also has solar thermal collectors installed in the roof (4m^2 in Larch and 3.3 m^2 in Lime). They were locally produced by Filsol, the only Welsh manufacturer of solar thermal panels. The 200 litres hot water cylinders are unvented copper cylinders specified with higher than normal levels of insulation at 100mm thick. There was some difficulty in that the terminals from the tanks were not ideal for insulating the pipes tightly against the tank, so there was some unwanted heat loss at these connections. The cylinder stores hot water from the solar water heater on the roof, provides hot water for taps, and hot water for the heating coil in the ventilation system.

The hot water distribution is via small-bore pipework, to minimise draw-off deadlegs. Basins, sinks and showers are fed with individual 10mm plastic pipework, which using an unvented system can provide around 7-8 l/m over distances of up to 10m. Flow rates are limited by restrictors for code for sustainable homes compliance and the pipework diameter has not reduced flows below those specified. Wait for hot water is minimal, only a few seconds. The bath uses 15mm pipework for faster bath filling considering that waiting for hot water is not important.

Pipework was specified to be mounted by means of brackets with long stems in order to enable the pipes to be thoroughly insulated. However the contractor used standard plastic clips throughout and did not observe minimum distances between pipes. As a result there are higher heat losses than designed from the airing cupboards. The solar systems in both houses have had several functioning problems since construction that are detailed in chapter 7.

Photovoltaic array

Each house has a PV array generating electricity that is either used directly in the houses or exported to the grid. The Larch House having a larger roof surface has a 4.7kWp system installed, while the Lime house has 1.89kWp system installed. The systems have so far worked well with the Larch House system offsetting an average of 71% of the dwelling CO_2 emissions in the two year monitoring period, while the Lime House system being smaller, has offset 56% of the dwelling CO_2 emissions.

Figure 2-15. PV array at the Larch House

2.5 Procurement, construction and delivery

The client wanted to use their standard design and build contract. In reality, the design was fully detailed by the design team as they and the client realised that this was the only way to achieve Passive House Certification. In addition, bere:architects provided on-site training, specially on the installation of airtightness membranes at crucial junctions like windows. Although this was an unusual arrangement that caused some difficulties, like the inability to issue instructions to rectify work that didn't comply with the specification, works on site were on the whole carried out satisfactorily. The client allowed most architects instructions to be processed, however when the wrong pipe clips were fitted, as described above, the instruction to replace them as designed was over ruled.

The timescales were very tight with both houses being delivered by the main contractor under 4-month building contracts, with their normal supply chain and sub-contractors, with the addition of a timber frame manufacturer, who were sub-contracted by the main contractor to deliver the fundamental timber frame. See chapter 9 for feedback from the client and contractor.

During construction there were a few problems that slightly compromised the performance of the houses. In the Lime House, the timber frame manufacturer changed the airtightness detail around the support detail for the first floor joists of the second frame that they built. This was only found after the building failed its first airtightness test. A compromise solution was proposed by the timber frame manufacturer and agreed with the client, but this resulted in a poorer air test result than the Larch House, although still a pass and still dramatically better than UK building regulations (the result was 0.35ach, or 0.34m3/m2h at 50Pa).

Figure 2-16. The Larch House under construction

Another site decision that affected the construction quality of the Lime House was the decision of the Timber Frame manufacturer to use different carpenters for each house. They used subcontracted carpenters for the Larch House. The architects spent a considerable amount of time giving window installation and air tightness training to what they believed to be the timber frame manufacturer’s own carpenters on the Larch House, only to find them dismissed for the Lime House project and replaced by a new team for the construction of the Lime House. Less training was given to the second team and the poorer air tightness of the Lime House is a direct result of this.

Other problems included the installation of the external lime render in the Lime house. As it was applied in sub-optimal weather conditions in the autumn, it cracked during the winter and was then repaired with the wrong products. Eventually to achieve a satisfactory appearance the building was painted.

There were some problems with the solar thermal system installation in the Lime House. The installer claimed the drainback could not be fitted in the cylinder cupboard so fitted it in the cold loft, converting the system to a pressurized one, but without the correct components. Eventually a new pump station and expansion vessel had to be fitted. The design team believes these problems were the origin of a continuous mal-functioning of the Lime house system. This is further discussed in chapter 7.

To help the new occupants understand the Passive House, the architects provided a user guide with information about how to use and manage the dwellings (see Appendix 10) which are to be permanently hung in the utility cupboards for reference. Also, several handover events were conducted following the 'Soft Landings' approach, with the design and technical team, the client , maintenance team and the tenants. These took place following the conclusion of the construction phase; and again later with the selected tenants and again a later one when the client's maintenance team changed (see chapters 4 and 5 for more details).

Figure 2-17. The Lime House nearing completion.

2.6 SAP assessment review

Due to the nature of the design project, which was aiming for Passive House Certification, the PHPP calculation tool was considered more relevant than SAP. The PHPP calculations were done by the design team and the SAP calculations were done by Brooks Devlin Associates, independent SAP advisors.

In design stage both houses aimed for a SAP rating of 101 – band A. Also Larch House aimed to achieve a Code of Sustainable Homes (CSH) Level 6 and Lime house CSH Level 5.

After construction, the 'as built' SAP revision concluded the Larch House to have a SAP rating of 112 and the Lime house of 97. On the CSH, Larch house was confirmed as Code Level 6 but Lime house failed to meet the Code Level 5 requirements and was considered Code Level 4. This was due to an on-site reduction of the PV array system from a design specified 2.0kWp to the installed 1.89kWp that brought the assessment to 99.1% improvement instead of 100% needed to meet CSH Level 5. It was unclear how this happened but the client was not willing to increase the PV system for compliance with Code 5. This was a frustrating outcome as the Lime House would have achieved Code Level 4 without any PV system and the design team felt this classification was misleading.

Interestingly, it should be noted that if the 'as-built' assessment had been done with the updated SAP 2009 the Lime house would have been considered Code Level 5. This is because SAP 2009 weighs more on the space heating element. However it was impossible to change the SAP version as it was determined under the Building Regulations that were in force at the time of construction.

See the 'as-built' SAP Assessment in Appendix 3.

At the conclusion of the BPE phase 2, in June 2014, Nick Devlin revisited the 'as-built' SAP calculations to compare the predicted thermal and electrical energy consumption with two years of measured data between April 2012 and April 2014 and fabric test results. For this the SAP calculations were adjusted to match the Heat Loss Coefficient to the values obtained in the co-heating test (see chapter 3.1) and the number of occupants was adjusted to real occupancy.

Following is a summary of the report (Devlin, 2014, submitted to TSB and in Appendix 4) findings:

- The measured weather data for the site illustrates the variability of annual weather patterns compared to the generic weather data used within SAP for space heating calculations. The SAP degree days (base 18) are 2,730 compared to measured values of 3,566 and 2,984 for Year 1 & Year 2 respectively. Although a somewhat over simplified statement, it can be proposed that one would expect the space heating requirements in Year 1 and Year 2 to therefore be greater compared to the standard SAP model.
- The co-heating test results demonstrate an approximate 12% (Larch) and 18% (Lime) greater heat loss from each of the dwellings compared to that predicted within the SAP calculation.
- SAP 2005 provided the option to include one thermal bridge (psi-value) for each junction. It is noted that the current (2012) version of SAP has been improved to allow multiple junctions to be included.
- The SAP default occupancy calculations underestimate the number of people living in each dwelling. The default calculation assumes 3.1 people in the Larch House and 2.5 in the Lime House compared to actual occupancy levels of 4 and 3 respectively.
- This is a fundamental issue as the occupancy assumptions inform the internal heat gains, domestic hot water consumption and electricity use. Each of these is used within the space heating demand calculation and therefore the correct occupancy level can have a measureable impact on the result. Notwithstanding this, an increase in the occupancy level would, within the SAP calculation, increase the internal gains and thus reduce the space heating demand.
- SAP calculations are based on a standard value for the internal temperature (a 2 zone model) and therefore cannot reflect the greater energy consumption arising from occupants adopting higher internal air temperatures.
- The predicted SAP space heating requirements have been recalculated to reflect the results of the co-heating and gas tracer tests. The predicted space heating requirements for the two houses are now reasonably similar. They are however significantly smaller than the monitored data as seen on the figure below.

Space Heating kWh/yr	SAP Original HLC	SAP Adjusted HLC	Measured Year 1	Measured Year 2
Larch House	715	805	1,105	475
Lime House	695	836	2,036	1,440

Figure 2-18. Space heating comparison

- For the Larch House, DHW consumption is 19% less than predicted within the SAP (adjusted occupancy) whilst it is 28% greater than predicted at the Lime House.
- In the Larch House, the actual electricity consumption is similar to that predicted by the SAP (assuming actual occupancy for appliances and cooking). In the Lime House, the actual electricity consumption is 15% lower than predicted (using actual occupancy).
- The ventilation system's electricity consumption is in both dwellings higher than predicted. Preliminary investigations indicate that this is probably related to the filters not being changed at appropriate interval periods. Where filters become blocked, the Paul Focus 200 automatically increases the fan speed to maintain the design air flow rate, thus increasing the fan electricity consumption.

In conclusion, whilst SAP remains a building regulations compliance tool and should not be relied upon to provide predictions of actual energy consumption, there remains merit in assessing the actual performance compared to the predicted. Ultimately, the revision of SAP to provide a more sound basis for energy prediction is desirable albeit that this might be at odds with its use for demonstrating compliance with the building regulations.

2.7 Conclusions and key findings for this section

- The design and construction of the two houses successfully delivered the competition brief using local contractors and manufacturers, albeit some construction problems slightly compromised the Lime House performance.
- The use of modified extreme weather data created a need for slightly more insulation than would otherwise have been specified, which slightly increased the construction cost of both houses. However it is arguable that if standard weather data had been used, it may have under-estimated the extreme microclimate of the location, high up in a valley with humid, overcast conditions prevailing for much of the year. This point highlights the significance of location, something ignored by UK Building Regulations,

which we understand is for political reasons, to make house building no more expensive in one area than another. This helps housebuilders but leaves many occupants in colder microclimates within the UK disadvantaged compared to those living in milder microclimates.

- The project was a good opportunity to test two different Passive House certification methods (averaged annual heating demand and peak heating load). Using the peak heating load allowed bere:architects to design the Lime House with a lower glazing ratio and no blinds, reducing construction costs.
- An experiment with the PHPP design calculations using an average weather data file, instead of the modified extreme weather file, demonstrated that the glazing ratio and insulation could be reduced, dropping the construction costs. It also showed that if average weather data is used, the two certification methods result in much less differentiation between designs than if worst case weather data is used.
- Testing the lower glazing ratio and insulation specifications of average weather data, when compared with the extreme weather data file, resulted in only a 1W/m2 increase in the heating load during an extreme weather event, the equivalent to just 100W in a 100m2 house. This seems to confirm that designs are financially optimised with average weather data for the particular local region of the UK, and the additional measures required to meet the requirements of extreme weather data for that region are not economically attractive.
- A cost analysis done by the quantity surveyor concluded that the Larch House built to the Passive House standard but using the lower specification required if using the average weather data applicable to a more typical lowland Wales location, resulted in a 9% uplift compared to typical low cost housing. This is very encouraging and would seem to make the Passive House standard an economically realistic option for private and social housing.
- The project successfully involved local manufacturers and suppliers in innovative ways by using Welsh timber for the frame construction and by producing the first Passive House certified UK window. The overall project was a good demonstration that UK manufacturers can upskill very quickly to achieve the same high standards as imported products. However it became clear from the window project that significant financial investment is needed to be able to achieve the efficiencies of German and

Austrian manufacturers who have spent decades developing competitive supply chains and manufacturing processes that out-compete, in terms of both cost and quality, a hand-made window made in Wales.

- The importance of closing the knowledge gap between design and construction teams is illustrated in this project. The Larch House benefitted from close guidance provided by the design team and resulted in a spectacular air-tightness result of 0.197ach @50pa. However the design team were unaware that they were training a subcontracted team of carpenters! When the timber frame manufacturer's own team replaced the subcontracted team on the second house, (the Lime House) there was initially an air tightness problem. After investigation and advice from the design team, the air tightness result was improved, sufficient for certification. The value of developing in-house advanced skills is emphasised by this incident.
- It is clear from this and other projects that to meet the ambitious targets 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, and with practice maintaining these new levels of quality will become easier and cheaper to do.
- Both Larch House and Lime House were delivered to an extremely high quality construction in a very short timescale. This was due to a very good site manager, the design team's very detailed drawings and on-site support and a shared vision and healthy relationship between the contractor, design team and client.
- The 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 until such time that the advanced construction skills necessary to build a very high performance building are embedded more widely in the construction industry.
- Great care must also be given to the installation of the mechanical and electrical systems as any fault can easily compromise the building's performance. Any ill-

conceived alterations to the systems after completion can damage the fabric and airtightness membrane, reducing the performance of the house.

- Comparison of the SAP ‘as-built’ assessment with the fabric test results and the two year monitoring data results, found that the SAP assessment was broadly over-optimistic about the performance of both houses. It was found to underestimate both dwellings’ real occupancy level, slightly under-estimate the fabric heat loss coefficient of both dwellings and greatly under-estimate the user space heating requirements of both dwellings. Overall electricity consumption of the Larch House was found to be close to the SAP assessment but in the Lime House SAP over-estimated consumption.

- SAP is widely used by designers as a prediction tool, and architectural press reports and RIBA awards applications use SAP results as a means of predicting the energy consumption of a building, since most designers have no other means to make predictions. However SAP is not intended to provide predictions of energy consumption. It is simply intended as an indication of compliance with building control requirements. The results of this research project provide further indication why SAP should not be relied upon to provide realistic predictions of space heating consumption in the hands of an average user (see also the sister study on the performance of the Camden Passive House in the same funded research programme) and should only be considered as a building regulations compliance tool. Greater awareness of this fact is desirable since most architects and other building professionals use SAP and quote SAP results to predict the energy use of their buildings without realising that this almost certainly creates a significance performance gap between design and actual building use.

- Ultimately, the revision of SAP to provide a more sound basis for energy prediction across the differing microclimates of the UK is desirable albeit that this might be at odds with its use for demonstrating compliance with a Building Regulations system that makes no attempt to achieve equal energy consumption in buildings across different parts of the UK due to its priority to require identical fabric requirements whatever the building’s location.

3 Fabric testing (methodology approach)

Several post-construction fabric tests were carried out in both the Larch House and Lime House. These were carried out mostly during the BPE phase 1, while the houses were vacant, but some were also carried out during the BPE phase 2. Fabric performance is an important factor in the performance success of any building including a Passive House building.

This chapter describes the procedures and key findings of the different tests, namely a co-heating and tracer gas test, a thermographic survey, a thermal bridging and fabric performance analysis, an in-situ U-value measurement and several airtightness tests.

3.1 Coheating and tracer gas test

The coheating 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^{o}C, and carefully monitoring the energy used to maintain this temperature, the heat being lost is calculated. The building is unoccupied during the test which normally lasts about two or three 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 fabric performs according to design.

A coheating test including a tracer gas test was carried out in the Larch and Lime houses in the first months of 2011 by a research team of the Welsh School of Architecture (WSA) - Jenkins et al, 2011 (Appendix 5)

The houses were heated to 25^{o}C using electric fan heaters and mixer fans, the HRV inlet and extract vents were sealed. For the test duration the internal temperature and RH and also the external weather conditions (temperature, wind speed, solar gains) were monitored. The research team then used the data to perform two analyses: a simple heat loss coefficient calculation (by dividing total energy by the hourly temperature difference) and a more sophisticated Siviour analysis, which incorporates the effect of the solar gains.

The results are summarised in Table 3-1 and the Siviour calculation is considered to be more reliable (Jenkins et al, 2011) because solar gains are taken into account. However it should be noted that in the Larch House at the time, the external sunshade blinds automatically closed when the sun came out, even in the winter months, so the simple HLC calculation may be the most appropriate one to use in the case of the Larch House.

Compared to design predictions the post-construction heat loss coefficient is remarkably close for both houses, although the Lime House result is slightly higher than predicted when using the Siviour HLC calculation.

Table 3-1. Coheating test results compared with design predictions

	Design predictions	Coheat test result - Simple HLC calculation	Coheat test result - Siviour HLC calculation
Larch house	57.6 W/K	60 ± 14 W/K	62 ± 4 W/K
Lime house	37.2 W/K	41 ± 8 W/K	45 ± 2 W/K

During the coheating test a tracer gas test was also carried out to measure the infiltration rate. The method involves monitoring the decay of the internal CO2 concentration following an injection of CO2 tracer gas. The tracer gas concentration was measured and recorded every minute for a period of 70 hours. The results demonstrated both houses to have exceptionally good envelope airtightness. In the Larch houses the tracer gas decay test infiltration rate result of 0.194 ACH^{-1} is close to the air pressure test value of 0.021 ACH^{-1} while in the Lime house the tracer gas decay test infiltration rate result of 0.0248 ACH^{-1} is lower than air pressure test value of 0.043 ACH^{-1}.

3.2 Thermographic survey

A thermographic survey is done using a thermal imager, a special camera that detects radiation in the infrared range of the electromagnetic spectrum and creates an image of that radiation. The amount of radiation emitted by an object increases with temperature, meaning that, through a thermal imager warm objects stand out against colder objects. In construction this type of survey is very useful to analyse the construction quality and detect cold bridges.

Both Larch House and Lime House were surveyed in February 2011 by bere:architects (see the report in Appendix 6). The survey was carried out at the same time as the co-heating test when the houses internal temperature was 25^{o}C. Externally the temperatures varied between 3 and 5^{o}C. This is a higher than normal temperature difference meaning the heat losses were expected to be exaggerated.

Larch house

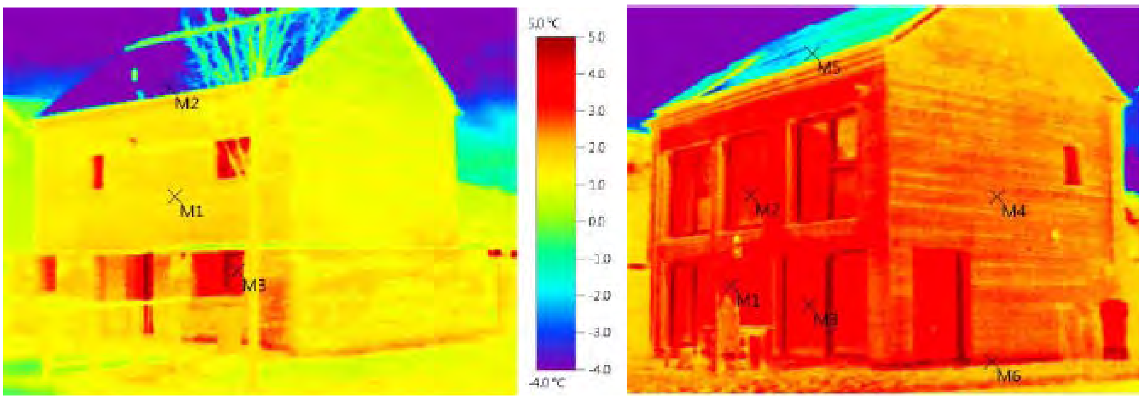


Figure 3-1. Larch House – Infrared image of the north and west facades (left) and south and east facades (right), neither view finding any heat loss through the walls. To be noted however is a thin line indicating slight heat loss around the house plinth (point M6). Note also that there is about 1°C temp difference between the south and north elevation, presumably due to solar gains – either residual from the day before, or already experienced by mid-morning on the day of testing.

The survey results were excellent showing the wall surface temperatures to be close or equal to the external temperature, a demonstration of minimal heat loss (see Figure 3-1). The camera detected a thin line of slight heat loss at plinth level which indicates that there is less insulation in this location. This was a deliberate design decision to keep the construction simple and economical and heat loss does not exceed design expectations as later confirmed with a three dimensional thermal bridge analysis (see chapter 3.3).

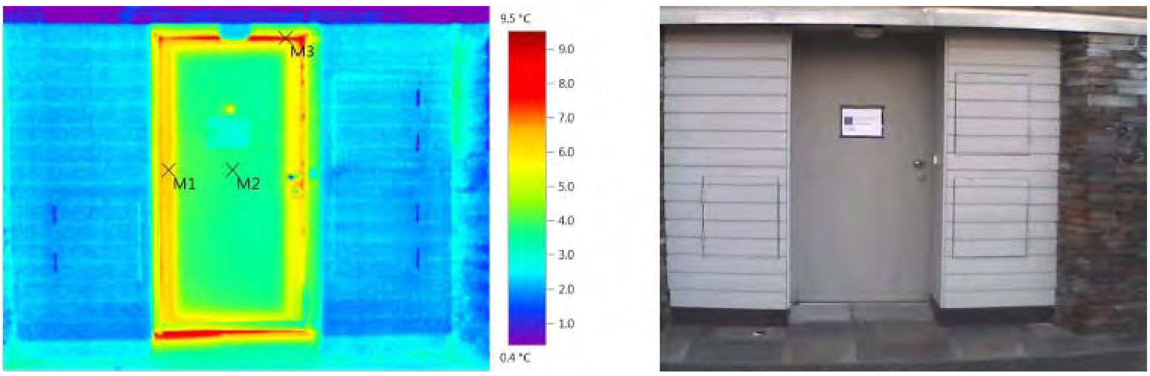


Figure 3-2. Larch House – Infrared image of the front door showing that it is relatively well insulated but there is some air leakage around the seals.

The survey of the front door detected that despite being insulated there is some air leakage around the seals. The front door was badly damaged on site after construction, prior to occupation, and despite the efforts of the design team it wasn't fully resolved. This issue is thoroughly discussed in chapter 8.

Lime house

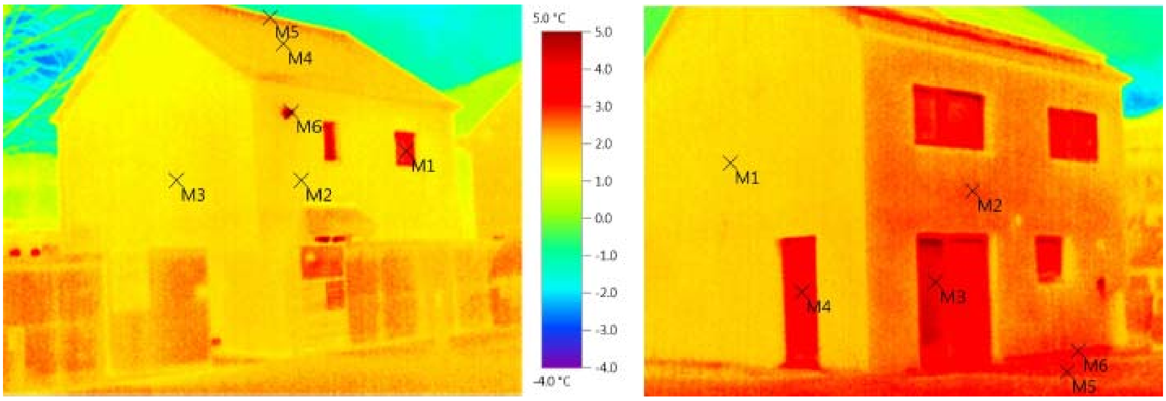


Figure 3-3. Lime House – infrared image of the north and east facade (left) and south and west facades (right) neither view finding any heat loss through the walls. It was noted however that the unheated loft is significantly warmer than the Larch House roof which suggested there could be a problem with the loft insulation which was subsequently investigated.

The Lime house survey results also found minimal heat loss though the walls (see Figure 3-3). However the roof finishes were found to be much warmer than the Larch House. This was not expected given the cold roof construction in both houses and led to an investigation of the loft insulation. Thermographic images taken inside revealed a problem with the loft insulation in the attic above (Figure 3-4).

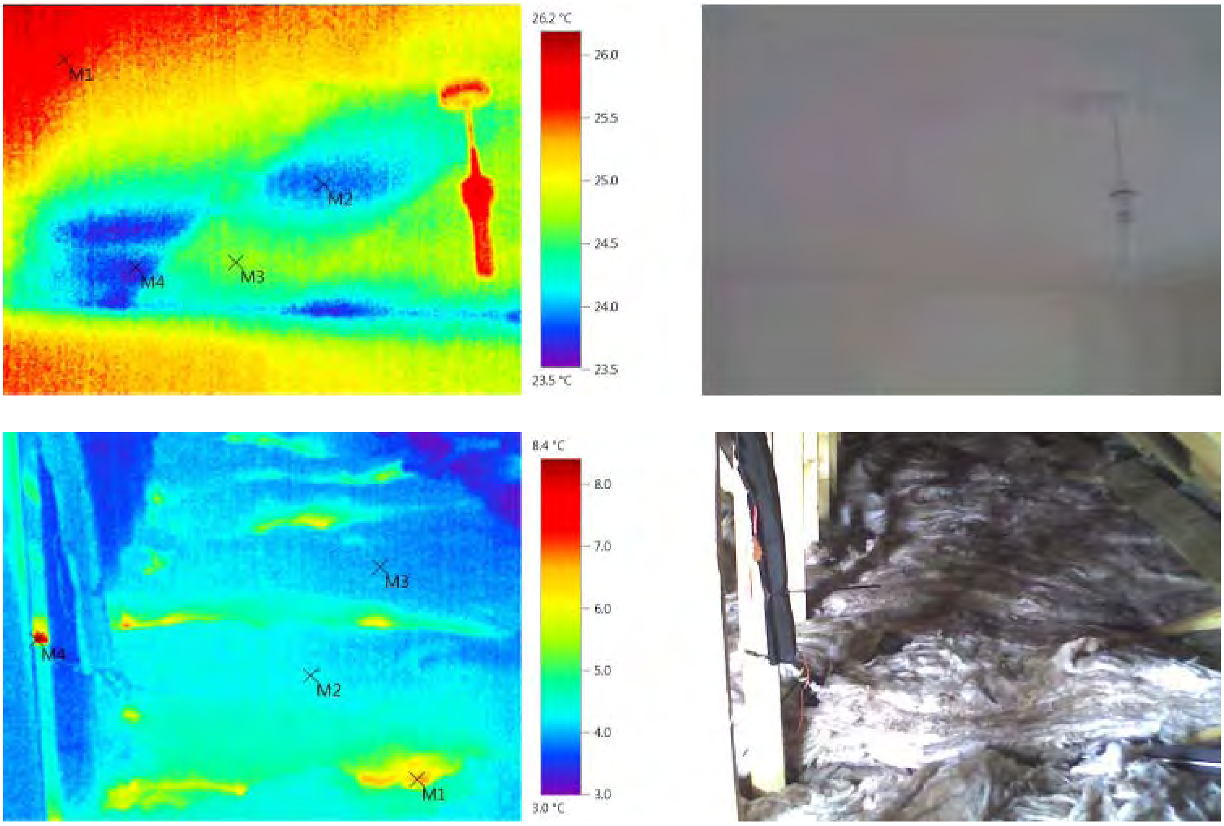


Figure 3-4. Lime House – infrared images of the bedroom ceiling (top) and loft insulation (bottom) showing that the insulation has been disturbed creating significant heat losses.

An investigation revealed that the insulation had been moved by the solar installer whilst making repairs to his faulty installation and had not been replaced, and where an attempt had been made to replace it, pipework was in places lifting the insulation from the loft floor resulting in thermal bypassing. Uninsulated solar pipework was also visible, reducing the potential to store energy from the solar panels (Figure 3-5).

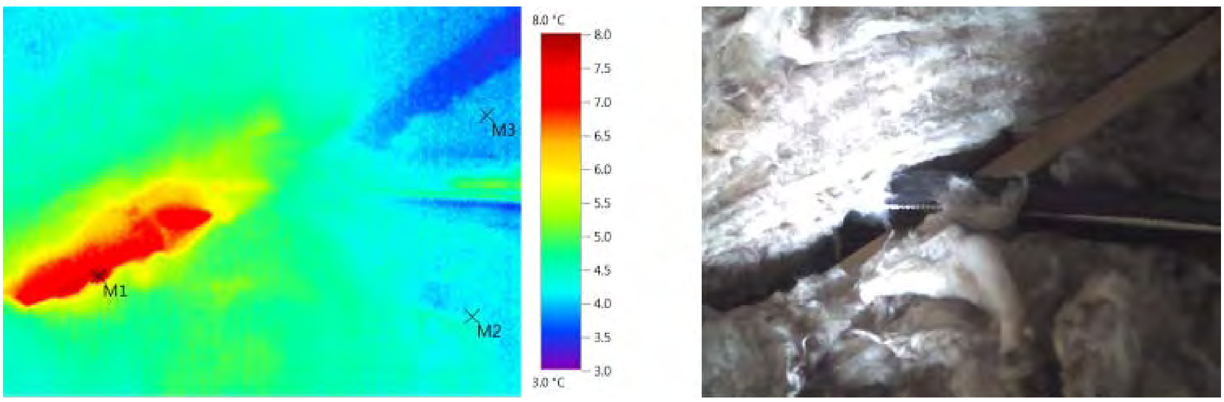


Figure 3-5. Lime House - infrared image of the solar pipework in the loft area.

In future projects this issue could be prevented by either:

1) Specifying a different type of insulation - If Warmcel insulation was used then this could have been simply raked over once the sub contractor had finished with the solar installation. However some other research indicates that Warmcel insulation may compress significantly over time, reducing its effectiveness.

2) The pipes could be threaded vertically and prominently through the insulation. This would make it easier for the roof insulation to be fitted snuggly around the pipe without risk of voids.

3) Including a maintenance access platform and making sure that all service penetrations are in a carefully controlled zone alongside the access platform.

3.3 Thermal bridging and fabric performance analysis

During the thermographic survey carried out in February 2011 a small increase in heat loss was detected around the plinth of the buildings. This prompted a check of the thermal bridge calculations previously carried out using Heat 2. Five key construction details were checked using three dimensional Therm 5.2 software, including the plinth connections, door thresholds and window sill and head details (see appendix 7).

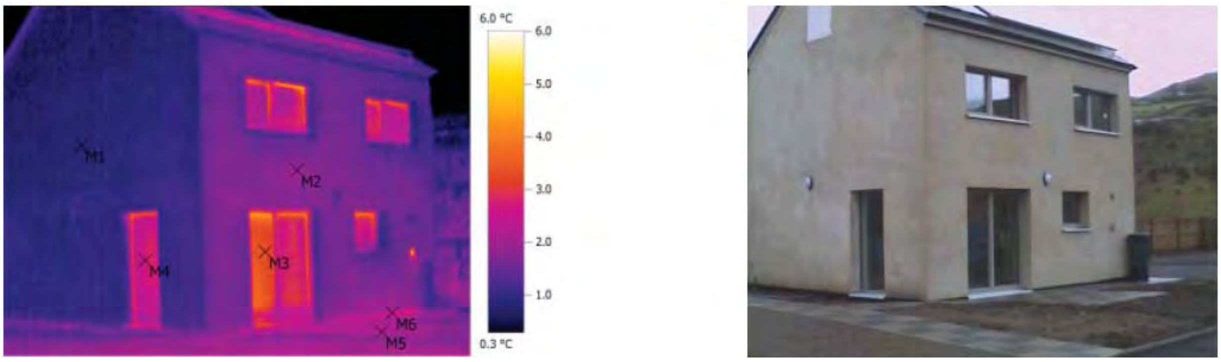


Figure 3-6. Thermal imaging of Lime House showing slight heat loss line along the building's plinth

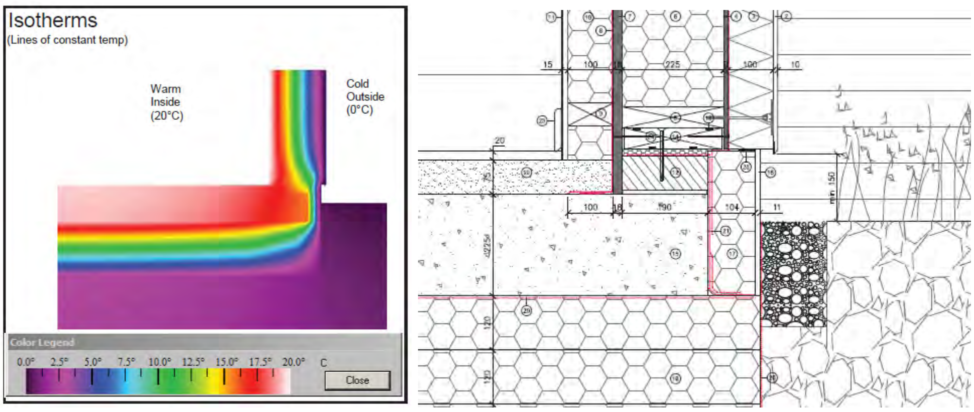


Figure 3-7. Therm 5.2 analysis of plinth construction detail.

In summary the thermal bridge values were all found to be as originally calculated and as entered into the PHPP upon which certification was based.

3.4 In-situ U-value measurement

The in-situ U-value measurement study aimed to determine if the quality of the construction fabric matched the design specification. For this purpose the research team of the WSA used heat flux sensors placed in walls of each house in places not exposed to direct sunlight. These devices measure the heat that flows through the object in which it is mounted.

Measurements were taken at 5 minute intervals and average daily for a period of 21 days for the Larch House and 14 days for the Lime House.

Figure 3-8. Heat flux sensor in the Larch House

The measured value of the thermal transmittance obtained in the Larch house was averaged around 0.12W/m^{2}K and in the Lime house was around 0.108W/m^{2}K against a design value of 0.095W/m^{2}K. The results for both houses show a good agreement between the design specifications and the in-situ measured values.

3.5 Airtightness tests

An airtightness test measures the air permeability of a building. Its results are a good indicator of the construction and sealing quality of the building fabric. A pressurised air change rate of 0.60ACH @50pa is also essential for Passive House certification.

In the Larch House and Lime House, several airtightness tests were carried out from the construction stage to the most recent one at the conclusion of the two year BPE monitoring study. All the tests were done by Gaia Aldas, using Passive House methods including averaging both pressurisation and depressurisation.

The tests were carried out by keeping all external doors and windows shut for the duration of testing (other than the door in which the test equipment was mounted). The plumbing services were sealed by water in traps and the ventilation system in each house was shut down and temporarily sealed by sealing over the external inlet and exhaust terminals and also the range of internal terminals in the various rooms. All internal doors were kept open to ensure the houses were tested as a single volume. Both pressurisation and depressurisation testing was carried out and the results averaged, as required by the Passive House Institute.

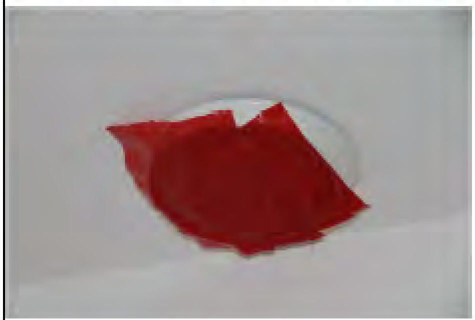
	
P3) External view of test equipment mounted in front doorway, Larch House; depressurisation	P4) Internal view of test equipment mounted in front doorway, Lime House; pressurisation test
	
P5) Bedroom supply terminal temporarily sealed for test, Larch House	P6) Bathroom extract terminal temporarily sealed for test, Lime House

Figure 3-9. Airtightness test equipment mounting and sealing of ventilation terminals

Larch house

Table 3-2 summarizes the different tests results for the Larch house, including the final acceptance test (used for Passive House certification) and the ones done during the BPE study, in comparison with the PHPP target. Find the acceptance test and the most recent test reports in appendix 8.

The Larch House results are very consistent over the four years since construction was completed. The most recent airtightness test found that the Larch House has a combined air change rate result of 0.25 ACH^{-1} @ 50Pa which is an impressive result, less than half the Passive House airtightness requirement of 0.60 ACH^{-1} @ 50Pa. The result is almost identical to the original test result and any difference could easily be explained by the quality of the taping of the equipment in the doorway, something found to be quite variable in practice.

Table 3-2. Summary results from airtightness tests in the Larch House

	PHPP target	Final (certification)	1st After completion	2nd After completion	BPE end of study
Date		19.07.2010	27.05.2011	16.07.2011	25.06.2014
Position of test equipm.	n/a	Equipment mounted in front door	Equipment mounted in window	Equipment mounted in front door	Equipment mounted in front door
Air change rate (ACH @ 50Pa)	0.6	0.23	0.61	0.26	0.25
Air permeability ($m^3/hr/m^2$ @ 50Pa)	n/a	0.24	0.63	0.26	0.26
Airflow @ 50Pa (m^3/hr)	n/a	65.07	170.3	71.3	70.8
Air flow exponent, n-value	$0.5 \leq n \leq 1.0$	0.76	0.70	0.82	0.83
Correlation coefficient r^2 value	R2 $\geq$ 0.98	0.998	0.993	0.994	0.995

It is important to discuss the substantial difference between the results of the tests with the equipment mounted in the front door and when it was mounted in a window. The latter methodology takes into consideration the airtightness around the front door which had several installation and maintenance problems. These problems are detailed in chapter 8 but in summary when the front door was installed, its threshold was not fitted correctly and began to jam during the first year, blocking the door. During the first year when the house was used for educational visits, this problem was not solved and in fact became worse by the building caretaker forcing the door to open and close. It eventually stopped closing and maintenance was called for repairs. However no adjustment to the door hinges or the threshold was done, instead the bottom of the three multi-point locking catches was removed to ensure the door could be locked while forced into a gentle bend. Gradually the forced closure of the door into a bend caused a permanent deformity. Nobody was prepared to take responsibility for the damage, or pay for its repair. In the end the design team sent its own carpenter to site to rout out the door and fit a metal tensioning device supplied by the German manufacturer to straighten the door. This solution was reasonably successful but was unable to fully restore the flatness of the door or fully repair its airtightness. As seen on the thermographic image on Figure 3-2 some leakage still occurs today

It is important to realise that the damage to the front door and the sequence of unfortunate events is highly unusual and no lessons can be drawn except that doors and windows should be fitted and commissioned by skilled craftsmen, taking particular care that any packing occurs only beneath the vertical members of the frame, and no packing is put beneath the threshold until it has been fixed perfectly flat. Doors require more skill to fit than windows due to the nature of the threshold detail and the fine tolerances that are necessary in an airtight level-threshold door. Doors are also prone to more intensive use than windows and part of the frame (the threshold) is effectively trodden upon daily.

In the light of these tests the Gaia Aldas technician concluded that their standard practice should be to carry out the acceptance tests with door fan equipment mounted in windows rather than door.

Nevertheless it should be noted that even with an imperfectly airtight door, if tested through a window, the Larch House test results would probably be considered acceptable with regard to Passive House certification.

Lime house

Table 3-3 summarizes the different tests results for the Lime House, including the final acceptance test (used for Passive House certification) and the ones done during the BPE study, in comparison with the PHPP target. Find the acceptance test and the most recent test reports in appendix 8.

The acceptance test results (used for Passive House certification) were not quite as good as the Larch House results. This is attributed to the change of construction team. While the design team helped to train the window installers for the Larch House, and monitored them closely on site, the learning was not carried over to the installers for Lime House because the timber frame subcontractor used different carpenters. To compound the problem, the contractors also changed the air tightness detail used for Lime House creating an air leakage problem at the junction between the ground and first floor. By the time this was discovered it was very costly to correct it and bere:architects had to accept a compromise repair and an inferior air test result, albeit still comfortably within the limits for Passive House certification.

Comparing all the results the Lime house shows some performance deterioration in the three and half years since construction was completed although some improvement since the last test done three years ago which may be due to replacement of a damaged front door in this case manufactured by a Welsh carpentry firm. Nevertheless, even with some deterioration, the most recent airtightness test showed a combined air change rate result of 0.48 ACH^{-1} @ 50Pa which is a remarkable result, better than the Passive House requirement of 0.60 ACH^{-1} @ 50Pa.

Table 3-3. Summary results from airtightness tests in the Lime House

	PHPP target	Final (certification)	1st After completion	2nd After completion	BPE end of study
Date		23.11.2010	27.05.2011	16.07.2011	25.06.2014
Position of test equipm.	n/a	Equipment mounted in front door	Equipment mounted in window	Equipment mounted in front door	Equipment mounted in front door
Air change rate (ACH @ 50Pa)	0.6	0.35	0.70	0.55	0.48
Air permeability (m3/hr/m2 @ 50Pa)	n/a	0.34	0.69	0.54	0.47
Airflow @ 50Pa (m3/hr)	n/a	73.8	147.5	116.3	94.6
Air flow exponent, n-value	$0.5 \leq n \leq 1.0$	0.82	0.68	0.65	0.76
Correlation coefficient r2 value	$R2 \geq 0.98$	0.996	0.997	0.997	0.998

An inspection done by the air tester in July 2011 reported a potential leakage in the first floor airing cupboard in the Lime House, where the potential for thermal shrinkage would be greatest. In the last test in June 2014 the same tester suggested that some of suspected leaks had been fixed although it is not known by whom.

As in the Larch House there is an important difference between the tests done with the equipment mounted in the door or window. Similarly to the Larch House, the Lime House front door (in this case manufactured by a Welsh carpentry firm) suffered some damage that compromised its airtightness. This is detailed in chapter 8 but after several complaints from the tenants of the drafty door, it was finally replaced early in 2014. The design team was not involved and has not yet been able to visit the site and check the new door or the quality of the installation.

3.6 Indoor air quality test

An indoor air quality (IAQ) test was carried out in both the Larch and Lime houses in March 2013 by Derrick Crump and Chris Walton from the Institute of Environment and Health from Cranfield University (submitted as part of the TSB BPE study - appendix 9).

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 for several hours prior to the visit. The parameters investigated were: measurements of volatile organic compounds (VOCs) and formaldehyde at two indoor locations as well as spot measurements of temperature, humidity, particulate matter (PM10) and carbon dioxide concentration. Passive samplers for nitrogen dioxide (NO2), sulphur dioxide (SO2) and radon were also placed in two rooms and outdoors for closure by residents and posting back. Some additional measurements outdoors would be undertaken for VOCs, NO2 and SO2.

Measurements were undertaken in the main living areas where tenants spend most of their time and some measurements were made outdoors as appropriate. The tenants had been asked not to carry out major cleaning, painting or other decorating activities during the day both prior to and during the period of investigation.

The report concluded that measurements of volatile organic compounds, including formaldehyde were within the range reported to occur in homes in England. International or UK-based guidelines for acceptable levels for the protection of the health of occupants exist for a relatively small number of the wide range of compounds commonly occurring in indoor air; these guidelines were not exceeded.

The concentration of one compound, decamethylcyclopentasiloxane (DMCPS) was notable because it dominated the VOC mixture present in both houses. The concentration was high in comparison to the majority of the homes included in the Indoor Air Quality Survey of England but there is no indoor air quality guideline for this substance which is not considered hazardous and is widely used in personal care products as well as in industrial manufacturing including construction products. The lack of a guideline value for its concentration in indoor air combined with the low amount of published information on human inhalation toxicity prevents an assessment of the potential risk to health, but the limited information available indicates DMCPS is of low toxicity.

Particulate PM10 and PM2.5 concentrations in the Passive House properties were similar or less than those outdoors. Formaldehyde (HCHO) levels were well below the World Health Organisation (WHO) and also the concentrations of nitrogen dioxide and sulphur dioxide were well below guideline values recommended by the WHO and indoor concentrations were similar to those outdoors.

Measurements of carbon dioxide, temperature and relative humidity were in the normal range for indoor environments. The residents did not report any problems with the indoor air quality to the research team.

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

3.7 Conclusions and key findings for this section

- The several fabric performance tests done in the Larch House and Lime House found both buildings to be performing very close to the design intentions.
- The co-heating test results were excellent and indicate very high quality construction in accordance with the design.
- The tracer gas test done at the same time as the co-heating test confirmed both houses to have exceptionally good envelope airtightness.
- The thermographic analysis confirmed a good fabric performance but also highlighted a problem in the loft of the Lime House where maintenance work disturbed insulation. To address the risk of disturbance of insulation by maintenance workers in future designs, it is suggested that a maintenance access platform should be provided in the loft to minimise the need to disturb loft insulation. Ideally all service penetrations should be in a carefully controlled zone alongside the access platform to avoid the need to step off the platform for any maintenance of the services installation.
- The in-situ U value measurement confirmed that the walls have been constructed with a thermal quality that closely matches the design specifications.
- The several airtightness tests done after completion until the end of the BPE study showed a minimal performance loss in the Larch House which is well within the bounds of measurement error (first and last tests of 0.23ACH@50pa and 0.25 ACH@50pa respectively) and a slightly bigger variation for the Lime house (from 0.35ACH@50Pa to 0.48ACH@50Pa). The most recent airtightness test results, done four and three and a half years after construction completion of the Larch and Lime houses respectively, are still remarkable results demonstrating an extraordinary

building performance, comfortably better than the Passive House requirement of 0.60ACH@50pa.

- There was a substantial difference in the results of the airtightness tests done with the equipment placed in the front door or mounted in a window. The worst results were with the equipment placed in the window which take into consideration the airtightness of the front door and highlighted the consequences of the several problems with the installation and maintenance of the front doors of both Larch and Lime houses (described in chapter 8). It should also be noted that even in the most unfavourable conditions, results were satisfactory. It is also important to note that the front door problems at the houses can be considered highly unusual and very particular to this project. No lessons can be drawn except that doors and windows should be fitted and commissioned by skilled craftsmen taking particular care to ensure the thresholds are fitted dead flat, and any problems should be addressed with speed.

- The IAQ study found the indoor environments of both the Larch House and the Lime House to be very healthy. The majority of the study parameters were within the UK and international guidelines, except for the concentration of DMCPS which was high in comparison to the majority of the homes included in the IAQ Survey of England, but the advice received is that DMCPS, widely used in cleaning products, has no known health problems.

4 Key findings from the design and delivery team walkthrough

4.1 Technical walkthrough

Immediately before the start of phase 2, on March 2012, a technical walkthrough took place with the architects' team, M&E consultant, a maintenance officer from the client, together with maintenance representatives including an M&E specialist, a decoration and general maintenance specialist and a glazing repair specialist.

The walkthrough was intended to give the maintenance team the confidence to look after the buildings by showing that they are not very much different to ordinary houses. The design team explained the commissioning strategy, discussed any technical problems that had arisen with the equipment and how best to avoid these in future. Filter replacement for the heat recovery unit was explained and the team answered any requests for more information. Finally the BPE programme was explained.

Figure 4-1. Justin Bere from bere:architects explaining why the pipe insulation needed to be improved.

Following this meeting a walkthrough with the new tenants took place:

4.2 Occupant walkthrough

Following the technical walkthrough, an occupant walkthrough was arranged with the new tenants, the client, the architect, the M&E consultant and the maintenance team as part of Soft Landings Stage 4: Initial Aftercare. This was an opportunity to introduce the two families to their new homes details and how to run them. Although they had looked around the houses during the public open days, this was the first time the tenants were able to consider their respective houses as their own new home.

The walkthrough included a building introduction with a discussion of the general design principles and how the houses differ from the type of housing the families had lived in the past. The Passive House concept and principles were also introduced followed by a tour of each house, introducing and explaining the control systems.

In this walkthrough the tenants were also introduced to the Technology Strategy Board BPE project, its goals and how it was hoped the findings would be used. The monitoring equipment had already been installed and the various sensors were explained. Finally the tenants had the procedures explained to them for dealing with any technical problems or concerns.

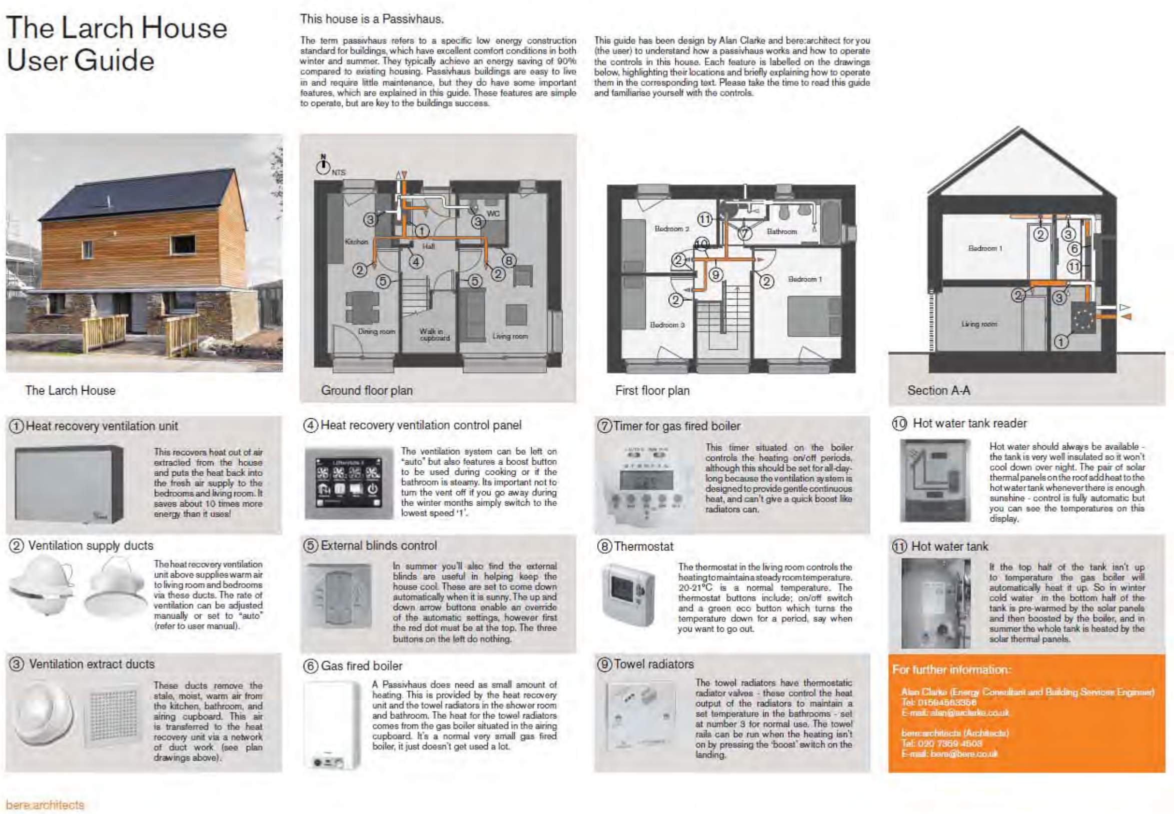


Figure 4-2. The Larch House user guide.

Bere:architects prepared a user guide panel (see Figure 4-2 and Appendix 10) providing detailed information about the systems employed in each house and how to operate them.

4.3 New maintenance team handover

In late 2013 a new maintenance team was appointed by the client to be in charge of the maintenance of the houses. Bere:architects prepared and delivered another presentation for the new team explaining the specification of the houses. This acted as a knowledge transfer initiative in line with the Soft Landings process Stage 5. The training session was recorded and a short film was produced with film director Carmen Zografou.

The film can be viewed here: http://www.youtube.com/watch?v=w09khx2jQz0&

Figure 4-3. Still image of the new maintenance team handover film

During the training session held by Justin Bere, director of bere:architects, the new maintenance team was introduced to the Passive House standard and how it was applied to the Larch and Lime houses. Important construction details of the walls and floor junctions were explained as well as the importance of the continuous airtightness layer and thermal bridge free construction. The new maintenance team was also briefed on the mechanical systems that had been installed, with some emphasis on the heat recovery ventilation (HRV) which was a new concept to the maintenance team. In the HRV system, the importance of frequent filter replacement (every six months) was highlighted.

Finally Justin Bere explained the ongoing monitoring project and some of the environmental performance results such as the steady internal temperatures and excellent relative humidity conditions.

The maintenance team was also provided with a pdf of the presentation, in electronic format, for future reference. This document included the design team contacts, including the M+E engineer and ventilation system designer.

Figure 4-4. Still image of the new maintenance team handover film

The maintenance team said that they found the project approach to be very interesting, even commenting "*why aren't all houses build like this?* They said they were surprised that the systems seemed to be hardly more complicated than a conventional dwelling.

4.4 Observations from the design and delivery team

The design team are agreed that the completed houses generally match their design intent. However there were a few disappointments:

4.4.1 There was disappointment that the specification for pipe clamps had been ignored, an error that severely compromised domestic hot water pipe insulation in both houses, resulting in excess heat loss during Summer months. Long-stemmed pipe clamps had been specified, with a preference for clamping over the outside of insulation, but the minimum requirement was to provide stems long enough for high quality split-insulation to be fitted without any gaps. By contrast, plastic pipe clips were installed and these prohibit the proper insulation of pipework. This is now a point which is repeatedly emphasised by the architects as a priority requirement on all new projects.

4.4.2 The solar thermal systems in both houses were faulty and the services consultant had to commission an independent report in order to try to convince the client and their main contractor of this fact. In the end it took more than two years for the Larch House solar thermal system to be rectified, but the solar thermal system in the Lime House has never worked up to the point of writing this report, over three years after completion. Part of the reason for this is that the original installer has gone into liquidation. The architects still believe that solar thermal systems are an excellent means of boosting the harvesting of solar energy to heat domestic hot water, but there are far too few competent installers. As a result of this experience, the architects on the whole now specify a single mechanical installation team for all their projects, although they realise that for competitive pricing they must find at least one other suitable team to offer main contractors.

4.4.3 Air filter changing on heat recovery ventilation systems is in fact much simpler to do than an annual boiler service or gas leakage check, and could easily be carried out at the same time by a suitably qualified plumber. It is a matter of some frustration that the client's maintenance team would not change filters routinely at the same time as the annual boiler maintenance and with the same operatives. Indeed, in spite of reassurances from the maintenance team in the maintenance team walkthroughs, they generally seemed unable to remember to change filters without a considerable amount of prompting from either the tenant or the architect. To act as a prompt, the authors of this report would like to see warning bleeps on ventilation systems similar to the battery-change warning sound in a smoke detector in order to prompt changing of filters, and another signal to warn if the system is switched off completely. It ought also to be possible to send a warning signal that could be picked up by a wifi receiver and transmitted to the building user's phone or to a receiver in a maintenance operatives' control centre. We would suggest that most tenants will be capable of changing their own filters, but would also like to see the introduction of filters mounted externally to the house in order to facilitate maintenance from contractors without the need to gain access internally to the property.

4.5 Conclusions and key findings for this section

- The walkthrough events were very useful to exchange feedback from all the people involved in the design and delivery of the houses. Everybody involved felt these events to be useful learning experiences.

- In the case of Passive Houses, where some new technologies are installed, the walkthrough events were very useful for the users to familiarize themselves with the technology with the benefit of expert guidance.

- The meetings with the maintenance team were also very important as they are the ones responsible for the day-to-day upkeep of the facilities and interaction with the tenants. They were particularly useful to demystify the maintenance requirements.
- There is a common problem across the UK of poor quality plumbing which seems to result from inadequate training, the absence of a high standard of professional examinations and the absence of a professional membership organisation to encourage, reward and uphold high standards and to discipline repeated failure to uphold proper plumbing standards. This problem affected the quality of the pipework installation and its insulation, and affected the quality of the solar thermal installation. Wherever possible it is the author's view that reliable plumbers should be named in a construction contract, even if this reduces competitiveness.
- Social housing maintenance teams need to be focused on being highly organised and professional in their approach to provide a satisfactory standard of maintenance and value for money for their employers.

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

After completion in July 2010, the Larch house was opened to visitors for educational visits for 18 months (the original intention was to open the houses for 12 months but this was extended due to an unexpectedly high level of public interest, both national and international). During this period, in March 2011, the Lime House was completed. The selection of the tenants was done by a competition which was concluded early in 2012. The occupants finally moved into the houses in April 2012.

The Larch House is occupied by a family of two parents and two young daughters and the Lime House is occupied by a young couple with a baby daughter (born shortly after they moved in).

All the occupancy evaluation studies were done during the BPE phase 2 as the houses were vacant during phase 1. During the first year the houses were used, the design team organized a series of workshops with the tenants following the Soft Landings approach. They were intended to gather initial feedback on the performance of the houses and also to assist the tenants with any questions or problems they might have been facing in relation to the performance of the houses or of the systems installed. At the end of the first year of occupancy the tenants were ask to contribute to a survey using the BUS methodology which allows the results to be compared to a domestic benchmark. Finally, at the end of two years of occupancy the tenants were interviewed again collecting further feedback on the performance of the houses.

5.1 Soft Landings workshops

During the first year of the BPE phase 2 a series of workshops were organized with the tenants as part of the Soft Landings approach. They were spread in two seasons, summer and winter, to gain a more comprehensive occupancy feedback. These workshops were filmed and can be seen on the ‘films’ page of the bere:architects website.

Summer workshop

The first workshops happened in July 2012, three months after the tenants had moved as part of Soft Landings stage 4: Initial Aftercare. The design and BPE team visited the new occupants of the Larch and Lime houses to find out how they were settling into their new homes and to collect feedback on the performance of their houses. The design team also spent some time with each family discussing how to get the best out of the low energy and health-providing features in their home.

Each visit to the houses was recorded both in a written report and a short film that can be seen at the 'films' page of the bere:architects website (http://www.bere.co.uk/films/larch-house-soft-landings-summer-workshop and http://www.bere.co.uk/films/lime-house-soft-landings-summer-workshop).

Figure 5-1. Still from the short film created from the summer workshop at the Larch House showing the difference between the clean and the dirty filters, July 2012 (authors bere:architects & Carmen Zografou)

<u>Larch House in Summer</u>

The Larch house tenants were delighted with their new home and said how they felt very happy and proud to have been selected to live in the house. The family said the house felt too warm at night sometimes, and rather than open windows, they used electric fans to create a cooling breeze in the childrens' rooms at night. When asked why they didn't open the windows they said that the children were afraid spiders would come in and preferred the windows to be closed the whole time. It also became apparent that they weren't using the blinds effectively to control daytime solar radiation as they felt the blinds obstructed the view and the house got too dark. The design team explained that the blinds needn't be left in the tilted closed position when lowered but could be opened into the horizontal position where they permitted views whilst creating shade from the sunshine. These were very interesting behaviour findings and the occupants responded thoughtfully to the advice they were given, continually learning and improving their operation of the blinds over the two year monitoring period. This is discussed further in Chapter 6: monitoring methods and findings. Also late in the monitoring study, insect screens were installed to see if the children benefitted from opening the windows at night.

During the workshop, the ventilation filters were replaced showing the tenants the collected dirt that had been prevented from entering the house (Figure 5-1). Involving the tenants on this procedure was important for them to understand how the ventilation system works and also the importance of demanding a replacement routine from the maintenance team to keep the system working in an optimized manner. Very dirty filters obstruct the passage of air and lead to increased fan energy use in order to maintain a constant air supply. Unfortunately, the filter replacing routine has been a continuous struggle in this project as detailed in chapter 7.

<u>Lime House in Summer</u>

The Lime House tenants were also pleased with their home which they said was always warm and comfortable. They had noticed a difference since when they moved in when the temperature was 17^{o}C (because it was vacant) and how it had acquired a comfortable base temperature. They were also pleased with the utilities bills they had recently received (£6 for gas and £14 for electricity) which were much lower than their previous home and much lower than that of relatives in similar-sized houses. Their surprise was all the greater as they had a small baby and they were using some appliances quite a lot, namely the washing machine (3 to 4 times a day) and the microwave and kettle more frequently to sterilize the baby bottles.

They reported to leave one or two windows always tilted open but still the temperature was constant and warm. They indicated that sometimes it felt too warm and they mentioned the desire to be able to lower the temperature to 18^{o}C. However they mentioned that they felt lucky because some relatives were still using heating in their homes during the summer months because their houses always felt cold and damp. They said they used the boost button for additional ventilation when cooking or having a house full of people. As in the Larch House, the ventilation system was explained and a lesson was given in changing the filters.

Winter workshop

After the first winter in the house, in March 2013, the design and the client's team returned to the Larch and Lime houses for a winter workshop as part of the Soft Landing Stage 5: Post Occupancy Evaluation, in order to discuss the occupants' experience of their first winter in the houses. The visit to each house was recorded in a short film that can be seen at bere:architects website (http://www.bere.co.uk/films/larch-house-soft-landings-winter-workshop and http://www.bere.co.uk/films/lime-house-soft-landings-winter-workshop)

<u>Larch House in Winter</u>

The tenants of the Larch House remained thrilled with how comfortable and warm they felt – a new experience in the winter months. The winter had been particularly harsh with lots of snow and the house had always felt warm, quite the opposite from family and friends that had struggled to stay warm during the cold months. They even reported that the heating control on the boiler had broken during Christmas and it had only been resolved in the New Year but they didn't miss the lack of heat or feel a change in their comfort levels.

The tenants also declared their utilities bill monthly direct debit to be about half of their previous address (winter £15/week electricity + £5/week gas compared to a previous bill of £30/week electricity + £12/week gas). However, they were still interested in driving their bills down more.

The key findings from the initial monitoring were also discussed. A relatively large electricity usage spike was detected in the early evening and it was confirmed that this related to daily cooker usage for a home-made hot family meal. It should also be noted that the cooker is the tenant's own appliance, and is not A rated. Compared with the UK national average for electricity usage, the consumption was high. However if the cooker consumption is normalised, electricity usage in the Larch House is very similar to the UK average (see Figure 5-2).

It is worth noting here that gas is commonly used for cooking appliances in the UK which will affect the average electricity use patterns compared to the Welsh houses which both have all-electric appliances. Second, the Larch House tenants seem to cook and eat together, in what used to be a common family tradition, more often than the average family in the UK today. Finally, the cooker/oven appliance used at Larch house is not A rated as normally required in a Passive House. It is standard procedure in UK social housing that tenants supply their own appliances and neither the client nor the design team were involved in their selection. In a building that is as energy efficient as a Passive House the choice of appliances is of greater significance than in a normal high energy building.

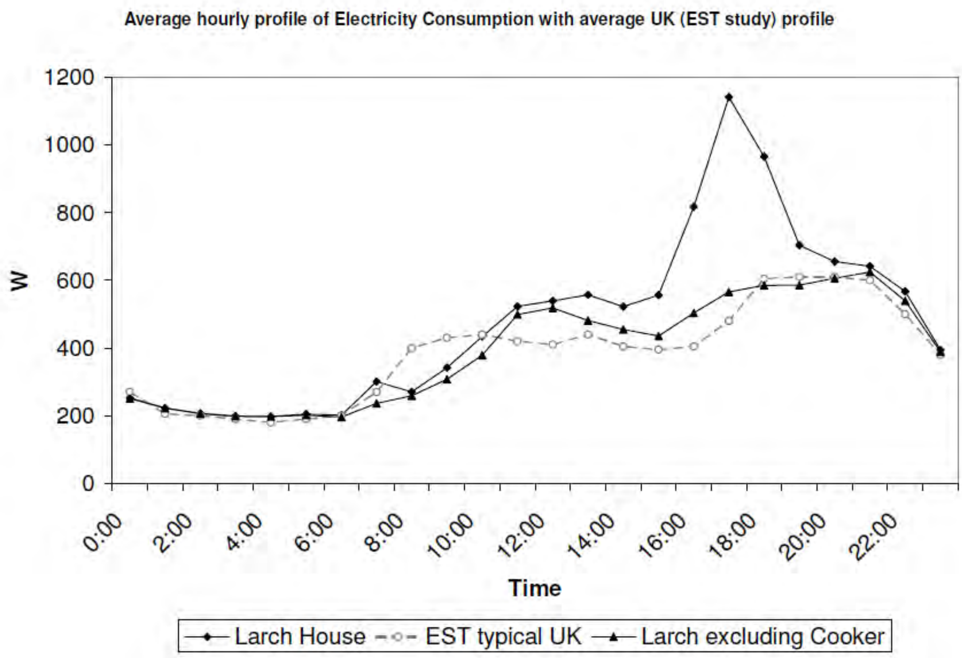


Figure 5-2. Larch House - Average hourly profile of electricity consumption with average UK (EST study) profile (graph by Dr. Ian Ridley)

Lime House in Winter

The tenants of the Lime House were also pleased with the performance of their house during their first winter and they were grateful for the lower energy bills.

The first monitoring results were discussed. They showed a higher heating consumption in the Lime House compared to the neighbouring Larch House and the design team tried to understand what might be causing it. It was noted that the striking plates of the front door lock had been damaged the previous autumn and as a result the front door would not close properly. This had not been repaired all winter, creating a cold air draft (see chapter 8 where the front door problems are detailed). This clearly increased the heat loss of the property, but the most important discovery from the workshop was finding that the tenants quite frequently leave the master bedroom window open during the night and sometimes during the day too (Figure 5-3). Discussion revealed that this was a parental habit passed on.

Figure 5-3. The Lime House showing the first floor bedroom and hallway windows tilted in the open position. Further investigation revealed that they were habitually left open almost constantly during the winter.

While in the summer this behaviour is welcomed to provide additional natural ventilation, in the winter the heat recovery ventilation system is set up to provide adequate rates of clean warm air. Opening the windows in the winter leads to higher energy consumption.

An analysis done by Dr. Ian Ridley (Ridley, 2013a) estimated that *"for each extra 0.1ach, an extra loss of 11W/K is added to the dwelling. The estimated heat loss of the house is approx. 73W/K compared to the design value of 45W/K. A co-heating test confirmed the heat loss of the dwelling to be close to the design value. If the bedroom window opening results in an extra 0.25 ach, this would account for the extra 30 W/k heat loss. This would also result in an extra space heating load of approx. 1500-2000 kWh."* Further monitoring findings are discussed in chapter 6.

A mix of reasons can cause this interesting behaviour. First the tenants seem to prefer lower temperatures and high rates of ventilation at night, but warmer temperatures in the evening before going to bed. They explained this is just what they are used to and the bills were so low anyway, that there was no great incentive to optimise performance.

It was noted that the simple heating controls don't have time control for the top-up heating, which means that there is no capacity to automatically lower the night time temperature in Winter. In a subsequent discussion, the M&E consultant suggested that a time control or a setback thermostat might be worth installing. The design team agreed to install a setback thermostat to automatically reduce the night time temperature in the house for the following winter and check the occupants' feedback. This was done in December 2013 and discussed in the second winter interview (see 5.4.)

5.2 BUS methodology

During phase 2, an official BUS methodology study was undertaken to assess the occupants' perspective of the building in operation. The BUS methodology is a standard survey procedure developed by Building Use Studies Ltd. and licensed to ARUP (amongst other companies) who performed the data analysis of the Welsh houses results (ref www.busmethodology.org.uk).

The study survey was posted to the tenants by bere:architects in June 2013 and returned in July 2013. All adult occupants completed the questionnaire giving us a total of 4 responses. Although this is a very small sample for a meaningful comparison with other residential building studies the results are still relevant to understand the occupants' levels of satisfaction with their home in a standard comparable procedure. The following results are from the two questionnaires.

The complete set of anonymous data tables can be found through the following link:
http://portal.busmethodology.org.uk/Upload/Analysis/2a1jsyrn.k4c/index.html

An additional explanation of the BUS methodology traffic light benchmark and slider graphs can be found in Appendix 11.

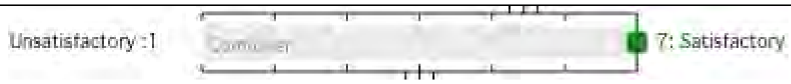
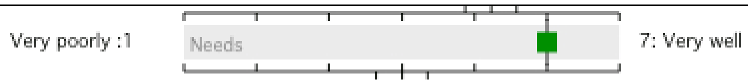
The BUS methodology indices provide an overview of the building performance and are compared with a limited number of domestic houses already in the BUS methodology database. As seen on Table 5-1, the Larch and Lime Passive Houses have very high levels of performance on the user Comfort, Satisfaction 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 (from Table 5-2). The value of both Larch and Lime houses is quite high, meaning that the occupants feel overall very comfortable and are willing to overlook some of their complaints on the house performance.

Table 5-1. BUS Indices

	Mean	Percentile	Scale
Summary	1.5	99	[-3 to +3]
Comfort	1.82	99	[-3 to +3]
Satisfaction	1.17	99	[-3 to +3]
Forgiveness	1.23	90	[-0.5 to +1.5]

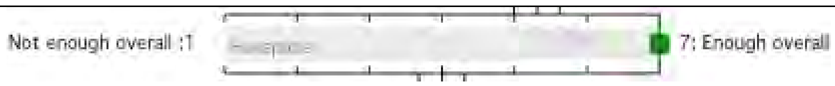
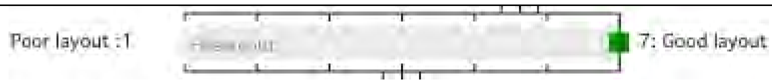
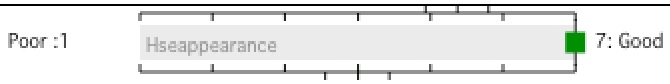
Table 5-2 shows the results for the variables that assess overall satisfaction. The Larch and Lime House residents rated their houses as comfortable, with satisfactory design and capable of supplying for their needs. They don't consider however their houses to make them feel more or less healthy. As example of things that work well for their needs, the tenants stated that they enjoy the layout of their house, the location and the [low] cost of the utility bills. Asked about the things they feel not to work so well, the tenants complained about small storage space in the kitchen, lack of a garage and that the house feels warm in the summer. The Lime House tenants complained about their front door being hard to lock and drafty, and that they had alerted *"the relevant people"* (this problem is detailed on chapter 8).

Table 5-2. Summary of BUS overall variables

Variable	Result	Percentile
Comfort: overall		99
Design		99
Health (perceived)		81
Needs		99

In the "residence overall" section respondents can rate several aspects of their homes (Table 5-3). The Larch and Lime Passive Houses achieved outstanding results with the occupants rating themselves as highly satisfied with their house in terms of space, layout ("*lovely open plan*"), location (*good*", "*fab*" , "*perfect for work and family"*) and appearance ("*perfect*", *"very nice*" and "*beautiful*") but are much less satisfied with the storage facilities, especially in the kitchen cupboards (*"not enough storage"*).

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

Variable	Result	Percentile
Space		99
Layout		99
Storage		39
Location		99
Appearance		99

To describe the thermal comfort of the houses, several variables are assessed in terms of air and temperature (Table 5-6Table 5-4 to Table 5-7Table 5-5). In general winter conditions are perceived to be more comfortable than the summer ones. Summer temperatures were noted to be on the warm range and less comfortable, below average. This section included comments such as *"we were always warm at winter"* but also *"summer nights are hot, could really do with 'fly blinds' so windows can be left open"* or *"hot in summer although we control it well with ventilations"*.

Although it should be noted that the survey was done in the summertime (which might influence the temperatures perception) these results make sense in the light of the occupancy behaviour discussed in the previous chapter and also the monitoring results presented and discussed in chapter 6.

Table 5-4. Temperature variables in winter

Temperature in winter: overall	Uncomfortable :1	7: Comfortable	69
Too hot :1	7: Too cold	Stable :1	7: Varies during day

Table 5-5. Temperature variables in summer

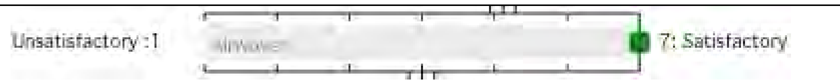
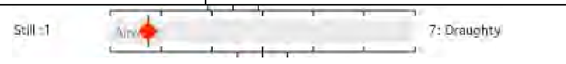
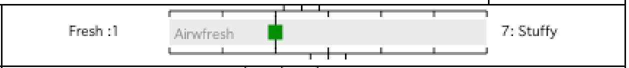
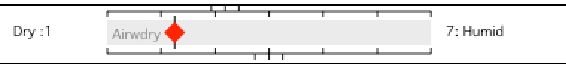
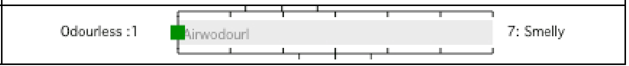
Variable	Result		Percentile
Temperature in summer: overall	Uncomfortable :1	7: Comfortable	8
Too hot :1	7: Too cold	Stable :1	7: Varies during day

Air was noted as odourless, fresh and slightly dry. 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 complained of air quality and the overall satisfaction is generally high, it is thought that this was intended as a positive comment.

Table 5-6. Summer air quality variables – the red mark on 'still-draughty' was a misunderstanding of the question – the response of 'still air' was intended to confirm that there are no unpleasant draughts.

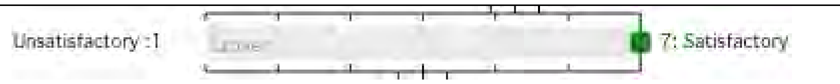
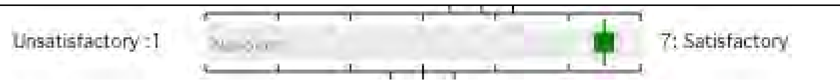
Variable	Result		Percentile
Air in summer: overall	Unsatisfactory :1	7: Satisfactory	35
Still :1	7: Draughty	Fresh :1	7: Stuffy
Dry :1	7: Humid	Odourless :1	7: Smelly

Table 5-7. Winter air quality variables – the red mark on 'still-draughty' 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
		
		

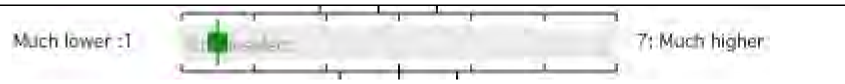
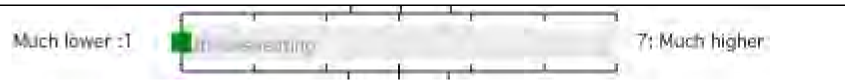
Lighting and noise (Table 5-8) were overall rated satisfactory. In the comments the Larch House tenants complimented the large windows but complained the electric blinds to seem occasionally too noisy.

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 previous accommodation except water which is considered to be roughly the same. Some of the comments include "*don't need to use much heating (...)*" or "*electricity bills much lower due to natural light*".

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

Variable	Result	Percentile
Utilities cost for electricity		10
Utilities cost for heating		10
Utilities cost for water		88

All respondents have said that living at the Passive Houses has changed their lifestyle, they are closer to work and also family and friends, enjoy the garden and bigger space and also the lower utility bills that enable them to save money.

Interestingly one of the comments – *"due to lower utility bills we are able to spend money on other things (i.e. our family, days out, etc.) which can only be a good thing"* – seem to indicate a form of rebound effect, when the potential savings from improved energy efficiency measures are being spent on other energy consuming activities, reducing the potential carbon savings.

Overall the Larch and Lime houses achieved a very good BUS methodology result that compares favourably with the benchmark. The BUS methodology survey was also able to highlight where, in the residents perspective, the houses have succeeded most (like the design features, warm winter temperatures, lower utility bills, general high comfort level) and where they have fallen short (slightly warm summer temperatures, not enough storage)

5.3 Post-occupation evaluation interview

In March 2014, following the second monitored winter the design team arranged for separated interviews with the tenants from each house to get their feedback on the comfort and performance of their house and to discuss the most recent monitoring results. The interviews were carried remotely through telephone conference and Skype. The following is a summary of the findings and the full report can be found in Appendix 12.

Larch House end of monitoring interview

The Larch House tenants were still very pleased with the house, which they felt had performed very well during the winter, keeping them warm and comfortable. The second winter results summarized in the quarterly monitoring report covering December 2013 to February 2014 showed a great reduction in the overall energy consumption, especially for heating. Discussing the reasons for these great results, the tenants said that the winter was milder but also they felt they had gained a much better knowledge of how to operate the system and to optimise it, keeping the thermostat at a temperature of 20^{o}C (lower than the previous winter). The reduction in energy consumption was consistent with a reduction in the utility bills. The electricity consumption still shows a usage spike in the early evening due to cooking but also due to the use of the TV and several game consoles, some of them recently acquired. The tenants also said the external blinds automatic function had at their request been disabled. This had been requested by the tenants due to the simplistic programming software in the blinds which, contrary to specification, were previously closing the blinds automatically when there was any sunshine, reducing the beneficial winter solar gains. Manual control of the blinds enabled the tenants to leave the blinds open in winter to enjoy the warming benefits of winter sunshine.

Another topic discussed was the insect mesh in the bedroom windows. In the previous summer the tenants reported that they were not opening the windows in the evening for night purging because their children were afraid of insects and spiders resulting in the house feeling uncomfortably warm. The design team installed insect mesh in the oldest child's bedroom window in December 2013 and this unexpectedly resulted in the child now keeping the window open quite a lot of the time during the winter months as well as the spring. Because of the advantages for summer ventilation the design team agreed to send more mesh for other windows which was done shortly after the interview.

The architects have offered to continue monitoring the houses for another year after the end of the monitoring period and the tenants have willingly agreed to this. It will be interesting to watch the impact of window opening on summer temperatures, but before next winter it will be sensible to discuss the energy consumption that will be associated with opening the bedroom window in the winter months.

Lime House end of monitoring interview

The Lime House tenants said they had felt *"nice and warm"* during the winter season although *"a bit cooler"* in comparison with the previous winter. The tenant also said that the first floor feels warmer than the ground floor and that the air quality is "*fine*". In comparison to the homes of friends or family, the tenants feel that the Lime House is "much warmer".

In the previous winter the tenants had the habit of opening the master bedroom window during the night increasing the energy losses and leading to higher energy consumption (see chapter 5.1). To try to change this behaviour the design team installed a new programmable thermostat that would allow the tenants to set a temperature reduction for the night time in winter. However the tenants are still using the manual operation only, turning the thermostat up in the evening and then down again before going to bed.

At the same time, the monitoring data analysis report found evidence that during the second winter the tenants were now closing the windows during the night. However visual observations as well as the temperature and CO2 profiles indicate that the tenants have switched their habit of opening a window in the Winter from night time opening to day time opening, before going to work; closing the window again when the first occupant returns home in the evening. They now leave a bedroom window and sometimes a ground floor window open on tilt mode during the day. This behaviour was confirmed by the tenant for comfort reasons "*so it's not so warm when we get in*", as *"the house gets very warm"*, especially if it's a sunny day.

On returning home in the evening after leaving one or two windows open all day, they sometimes find the house to be chilly and turn the thermostat up to compensate. Their regular heating routine is to turn the thermostat down before going to work, keeping the heating off all day, and turn the thermostat up again in the evening for two or three hours, usually at a set temperature of 21^{o}C, or higher if it is a cold day.

Through discussion with the tenants, it is believed that this behaviour is based on habits learned during upbringing where windows were opened to ventilate houses and clear damp and condensation. This is not necessary in a Passive House because the house is ventilated 24/7 by the heat recovery ventilation unit and there is no condensation due to the insulation and absence of cold bridges that cause condensation in ordinary houses.

The occupants' preferences to continue to leave windows open in Winter results in higher energy consumption as discussed in the following chapter 6. It is not clear if the tenants still don't understand how to get the best performance from their house, or whether they just prefer to hang on to old family habits, or whether they just like feeling a breeze of cold air which might signal that it is time to turn the heating on, just as it would traditionally signal that it is time to light an open fire and gather around it. It is recognised that there is a deep human instinct to gather around fires in the evening that stretches back over several million years of the latest phase of evolution of homo-sapiens as a social species.

The tenant has expressed openness to discuss behaviour change, with a particular interest in strategies to reduce energy use and bills. The design team have offered to prepare some written advice before the next winter and discuss this with the tenants. This is due to be done during November 2014, and the tenants have agreed to allow monitoring to continue so that we can share results of their behaviour change with them in the spring.

5.4 Conclusions and key findings for this section

- Occupant evaluation studies can provide great feedback for designers as it helps to identify the building problems and any design or construction faults. Additionally lessons from the building in use are valuable to inform future projects. The Soft Landings workshops and interviews have proved to be hugely relevant to discuss the performance of the houses with the users, providing great insights to how the users interact with their homes. Also the results from the BUS methodology study offered a good overview of the residents' perceptions on several aspects of performance. Moreover being a standard assessment it generated comparable results with benchmarks.

- Understanding the occupants' perception and relationship with the indoor environment is important as occupant behaviour can have a significant impact on energy consumption. In this matter the Welsh Passive Houses are a unique case study as they put side to side two houses of similar design and specification but with very different occupancy behaviour.

- The occupancy evaluation interviews were very important to contextualize the monitoring analysis findings. For example knowing the Larch House residents don't open the windows in the summer evenings for night purging or that they don't use the blinds in the most effective way can explain the summer overheating they mentioned. Also knowing the Lime House tenants window opening habit and heating routine provided some context to understand the higher energy consumption of the Lime House.

- Overall both families are very satisfied with the performance of their houses. The BUS methodology survey results were in general very good comparing favourably to the benchmark. The survey was also able to highlight where, in the residents perspective, the houses have succeeded most (they appreciate the houses' location, appearance, design and layout, comfortable winter temperatures, lower utility bills and general high comfort level) and where they have fell short (they complained about slightly warm summer temperatures and not enough storage space).

- Nevertheless the high Forgiveness Index result (a measure of tolerance of users with the building environmental performance) means the occupants feel generally very comfortable and are willing to overlook their complaints.

- The interviews indicated that there was an interest, particularly useful for the Lime House tenants, in written guidance notes that would help tenants to get even better performance out of their buildings next year. It is thought that a simple 'Energy Saving Guide', along the lines of our 'Welcome Guide' but much briefer, would be of use to tenants, and could become a standard offering of bere:architects.

6 Monitoring methods and findings

This section contains an analysis of the comprehensive in-use data that was collected from both the Larch House and the Lime House between May 2012 and April 2014 inclusive (see Appendix 18 Raw Data Archive). Air quality, thermal comfort, water usage and the monitored performance of both houses are studied during the first two years of occupation. The analysis was carried out by Dr Ian Ridley who started the work while still at UCL London, and completed it in his new position at RMIT Australia. The text in this chapter is mostly written by Dr Ridley, with additional commentary in italics.

Please note that when PHPP metrics are referred to in this report, the floor areas are calculated according to the Passive House methodology in which, conservatively, only usable living space is calculated. For example, staircases are not included and floor areas do not include the thickness of walls. When UK SAP and Code for Sustainable Homes metrics and CO2 emissions are calculated, gross internal areas are used, including staircases and external walls.

6.1 Monitoring System

A wireless data logging and monitoring system, compliant with the specification of the BPE programme and the UK Energy Saving Trust CE 298[2] protocol, was installed. Eltek of Cambridge were chosen as the manufacturer of the equipment because they were the only supplier that could be found that was able to take pulse outputs from electrical, hydraulic and air quality sensors and import the data into a single piece of software for comparison and analysis. All data is recorded at 5 minute intervals. 85 data channels were monitored over the 24 month period. Of the 17.8 million data points available for measurement, 17.1 million were successfully collected, giving a data capture rate of 96%.The details of the system are as follows:

[2] EST (2008) CE298 Monitoring energy and carbon performance in new homes. Energy Saving Trust. EST. UK: 2008. [cited 2012 Available from: **http://www.energysavingtrust.org.uk/business/Global-Data/Publications/Monitoring-energyand-carbon-performance-in-new-homes-CE298** (link no longer available)

- An on-site Weather Station measured Dry Bulb Temperature, Relative Humidity, Wind Speed and Direction, Global Solar Radiation, Atmospheric Pressure, Precipitation.
- Room Temperature and Relative Humidity were measured in the Living Room, Kitchen, Master Bedroom, Bathroom, and Second Bedroom (Larch only). Concentrations of CO2 were monitored in the Living Room and Master Bedroom.
- Utilities metering consists of Total Electricity, Total Gas, Total Water Consumption, with further detailed electricity sub metering on the following circuits: Sockets, Lights, Up Sockets, Down Lights, Cooker, Auxiliary Loads, Mechanical Ventilation and Heat Recovery (MVHR).
- Duct Temperatures are measured at the following positions in the MVHR system: Air Off heater, Duct Heater Flow, Duct Heater Return, MVHR Supply, MVHR Extract, MVHR Intake, Master bedroom Supply, Living Room Supply, and Kitchen Extract.
- Heat Meters were installed on the hydronic systems to measure the space heating supplied by the Heater Battery in the MVHR supply, the space heat supplied by the towel rails in the bathrooms (Larch only), the solar input to the hot water cylinder, Domestic Hot Water Consumption.

6.2 Summary of External Weather Conditions

The external climate was monitored by an on-site weather station which serves both the adjacent dwellings. Table 6-1 and Table 6-2 summarize the average monthly weather conditions during the monitored period.

In Year 1 degree days (base 18) [3]were 3566, 14% higher than the climate file used in the PHPP design calculation. The Year 1 average annual temperature was 7.9^{o}C, 1.5^{o}C, colder than the climate file used in the PHPP design calculation. Global Horizontal Solar radiation was 4.0% lower in year 1 than the PHPP design climate file, slightly higher in winter, but lower in summer. In Year 2 degree days (base 18) were 2985, 5% lower than the climate file

[3] *Degree days* is a measure of the difference between the baseline temperature and the actual outdoor temperature multiplied by the number of days. *"Base 18"* means the reference temperature is 18^{o}C. They can be either *heating* or *cooling* degree days, depending if they are the sum of the differences between outdoor and base temperature whenever the outside temperature falls *below* or *above* the base temperature, respectively. In this case, since most of the days, temperature is below the baseline they are heating degree days which are an indication of the energy demand for heating a building.

used in the PHPP design calculation. The Year 2 average annual temperature, 9.8°C, was 0.4°C, warmer than the PHPP design climate file. Onsite Global Solar radiation was 5.0% lower than the PHPP design climate file.

Table 6-1. Climatic conditions during Year 1

	Monitored			Meteonorm derived PHPP Weather file		
	T °C	Degree days (Base 18)	Global Horizontal Solar W/m²	T °C	Degree days (Base 18)	Global Horizontal Solar W/m²
May-12	11.2	218.0	280.8	13	155	231
June-12	12.3	172.0	164.7	14.6	102	260
July-12	13.9	135.0	224.2	16.6	42	244
August-12	14.9	101.0	132.4	17.8	6.2	200
September-12	11.7	189.0	189.0	14.5	105	140
October-12	8.6	277.0	94.5	8.7	288	58
November-12	5.8	351.0	52.8	5.9	363	29
December-12	3.0	404.7	38.1	2.7	459	19
January-13	2.9	419.0	*	2.2	490	24
February-13	1.9	454.0	*	2.8	441	37
March -13	2.0	485.0	105.0	4.4	422	69
April-13	6.0	360.0	147.0	9.5	255	176
	Average T°C	Annual Degree Days	Average W/m²	Average T°C	Annual Degree Days	Average Solar W/m²
	7.9	3566	127.5	9.4	3128.2	123.9

† Note Due to malfunction of on-site weather station in January and February of 2013, data was taken from Ebbw Vale weather station from Weather Underground. Solar data was unavailable for this period. (**http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=IWALESEB2**)

Table 6-2. Climatic conditions during Year 2

	Monitored			Meteonorm derived PHPP Weather file		
	T °C	Degree days (Base 18)	Global Horizontal Solar W/m^2	T °C	Degree days (Base 18)	Global Horizontal Solar W/m^2
May-13	9.20	260.00	190.00	13	155	231
June-13	12.70	158.40	206.00	14.6	102	260
July-13	17.8	53.7	246.0	16.6	42	244
August-16	15.3	90.3	162.0	17.8	6.2	200
September-13	12.5	150.0	169.0	14.5	105	140
October-13	11.7	178.0	53.4	8.7	288	58
November-13	5.9	357.0	37.8	5.9	363	29
December-13	6.1	366.9	19.3	2.7	459	19
January-14	5.2	394.8	20.2	2.2	490	24
February-14	5.1	357.0	43.8	2.8	441	37
March -14	6.7	349.7	116.6	4.4	422	69
April-14	9.0	269.0	144.0	9.5	255	176
	Average T°C	Annual Degree Days	Average W/m^2	Average T°C	Annual Degree Days	Average Solar W/m^2
	9.8	2984.8	117.3	9.4	3128.2	123.9

It should be noted that under the conditions of the design competition to build the houses, the PHPP weather file was designed to represent very severe weather conditions, that would occur once every ten years, rather than average weather conditions for the location. To put the performance of the dwellings in context of the weather conditions they were exposed to during the 2 year monitoring period, the first year winter was more severe than the PHPP design weather file, with a very severe winter. The second winter was warmer than the PHPP design weather file, and is more representative of the average weather conditions to be expected on site.

6.3 Primary Energy and Carbon Performance

The main energy and carbon performance metrics of the dwellings in year 1, year 2 and the two year average, are presented in Table 6-3, Table 6-4 and

Table 6-5.

The term 'Primary Energy' is new to most people in the UK, including most academics, and is often confused with metered energy use. In fact primary energy is typically 2.5 – 2.7 times *greater than metered energy use, depending on fuel type and region, because primary energy is the amount of energy input at source. A low carbon electricity supply will have a lower multiplication factor than a high carbon electricity supply.*

Table 6-3. Energy and Carbon Performance Year 1

Passive House Planning Package PHPP v 1.0 metrics kWhPrim/kWhFinal Gas 1.1 Grid Import Electricity 2.7 PV Electricity 0.7		
	Larch	Lime
Space Heat kWh/m^2	13.0 kWh/m^2	30.0 kWh/m^2
Primary Energy kWh/m^2	163 kWh/m^2	201.3 kWh/m^2
Final Energy kWh/m^2	98 kwh/m^2	138.9 kWh/m^2
Net Primary Energy kWh/m^2	141 kWh/m^2	190.1 kWh/m^2
Net Final Energy kWh/m^2	65 kWh/m^2	123.9 kWh/m^2
	Larch	Lime
CO_2 emission kg	3177 kg	2907 kg
CO_2 emission kg/m^2	32.9 kg/m^2	37.6 kg/m^2
Net CO_2 emission kg	1082kg	2060 kg
Net CO_2 emission kg/m^2	11.2 kg/m^2	26.8 kg/m^2

Table 6-4. Energy and Carbon Performance Year 2

Passive House Planning Package PHPP v 1.0 metrics kWhPrim/kWhFinal Gas 1.1 Grid Import Electricity 2.7 PV Electricity 0.7		
	Larch	Lime
Space Heat kWh/m^2	5.6 kWh/m^2	21.2 kWh/m^2
Primary Energy kWh/m^2	153 kWh/m^2	176.8 kWh/m^2
Final Energy kWh/m^2	91 kwh/m^2	119.1 kWh/m^2
Net Primary Energy kWh/m^2	128 kWh/m^2	163.6 kWh/m^2
Net Final Energy kWh/m^2	55 kWh/m^2	102.0 kWh/m^2
UK Standard Assessment Procedure SAP 2012 version 9.92 (May 2013) kWhPrim/kWhFinal — kg CO_2/kWh Gas 1.2 — 0.216 Grid Import Electricity 3.07 — 0.519 PV Electricity 3.07 — 0.519		
	Larch	Lime
CO_2 emission kg	3018 kg	2612 kg
CO_2 emission kg/m^2	31.1 kg/m^2	33.9 kg/m^2

Net CO_2 emission kg	743 kg	1632 kg
Net CO_2 emission kg/m^2	7.6 kg/m^2	21.2 kg/m^2

Table 6-5. Energy and Carbon Performance, Average Performance over the 2 years

Passive House Planning Package PHPP v 1.0 metrics kWhPrim/kWhFinal Gas 1.1 Grid Import Electricity 2.7 PV Electricity 0.7		
	Larch	Lime
Space Heat kWh/m^2	9.3 kWh/m^2	25.6 kWh/m^2
Primary Energy kWh/m^2	158.0 kWh/m^2	189.1 kWh/m^2
Final Energy kWh/m^2	94.5 kWh/m^2	129.0 kWh/m^2
Net Primary Energy kWh/m^2	134.5 kWh/m^2	176.9 kWh/m^2
Net Final Energy kWh/m^2	60.0 kWh/m^2	113.0 kWh/m^2
UK Standard Assessment Procedure SAP 2012 version 9.92 (May 2013) kWhPrim/kWhFinal kg CO_2/kWh Gas 1.2 0.216 Grid Import Electricity 3.07 0.519 PV Electricity 3.07 0.519		
	Larch	Lime
CO_2 emission kg	3098 kg	2760 kg
CO_2 emission kg/m^2	32.0 kg/m^2	35.8 kg/m^2
Net CO_2 emission kg	913 kg	1846 kg
Net CO_2 emission kg/m^2	9.4 kg/m^2	24.0 kg/m^2

Headline Summary of the Larch House:

The Larch house had a very good space heating performance, meeting the 15 kWh/m2 Passive House target for space heating demand during both year 1 and year 2, achieving 13.0 kWh/m2 in year 1 and 5.6 kWh/m2 in year 2, (9.3 kWh/m2 two year average). The Larch house did not however meet the PHPP Primary Energy target of 120 kWh/m2, with 163 kWh/m2 year 1 and 153 kWh/m2 in year 2, (158 kWh/m2 two year average).

When the PV generated electricity that is exported to the grid is included the Net PHPP Primary Energy of the Larch house was 141 kWh/m^2 in year 1, 128 kWh/m^2 in year 2, (135 kWh/m^2 two year average). The Larch PV system offset 66% of the dwelling CO_2 emissions in year 1, and 75% in year 2, (71% two year average). Net CO_2 emissions of the Larch house were 11.2 kg/m^2 in year 1, 7.6 kg/m^2 in year 2, (9.4 kg/m^2 two year average).

The Larch House had very low but not zero carbon performance during the monitoring period. It did not meet the original performance criteria for CSH Level 6. The Larch House did however meet Level 5 of the Code for Sustainable Homes, the PV system easily offset all emissions for heating, lighting and hot water.

Headline Summary of the Lime House:

The space heating performance of the Lime House was not as good as that of the Larch House, it did not meet the 15 kWh/m^2 Passive House target for space heating demand in both years achieving 30.0 kWh/m^2 in year 1, and 21.2 kWh/m2 in year 2, (25.6 kWh/m^2 two year average). *Reasons for this are discussed elsewhere. Section 6.4 includes a short discussion on the user winter habit of leaving the master bedroom window open at night and for much of the day. In spite of this, the heating demand of the house remains remarkably low; very much lower than a typical house in the region.*

The Lime House did not meet the Primary Energy target of 120 kWh/m^2 during both years, 201 kWh/m^2 in year 1, and 177 kWh/m^2 in year 2, (189 kWh/m^2 two year average). Allowing for the PV electricity exported to the grid the Net Primary Energy of the Lime House was190 kWh/m^2 in year 1 and 163 kWh/m^2 in year 2, (177 kWh/m^2 two year average). The 1.9kWpeak PV system offsets 29% of the dwelling CO_2 emissions in year 1 and 38% in year 2, (33% two year average).

Net CO_2 emissions of the Lime house were 26.8 kg/m^2 in year 1, 21.2 kg/m^2 in year 2 and 24.0 kg/m^2 averaged over the two years. The Lime House was certified as CSH level 4, although it has essentially a CSH level 5 specification. The combined CO_2 emissions for space heating, domestic hot water and lighting were 22.12 kg/m^2 in year 1, and 20.9 kg/m^2 in year 2, (21.1 kg/m^2 2 year average). The PV system offset 10.2 kg/m^2 in year 1, and 11.9 kg/m^2 in year 2, (11.8 kg/m^2 2 year average). The average net emissions for space heating, domestic hot water and lighting, including PV offset, of the Lime House were 9.3 kg/m^2, it did not therefore meet the required performance of a Level 5 of the Code for Sustainable Homes. The Lime house easily achieved CSH Level 4 performance with a normalised CO_2 emission reduction of 64%.

Table 6-6. Breakdown of Energy and Carbon Performance Year 1

	Larch		Lime	
	kWh	CO_2 Kg	kWh	CO_2 Kg
GAS Total	3721	804	6533	1411
Space Heat	1105	239	2038	440
Domestic Hot Water	825	178	1662	359
Distribution and Cylinder Losses	1420	307	2180	471
Boiler Loses	372	80	653	141
Electricity Total	4572	2373	2883	1496
Lights	250	130	96	50
MVHR	408	212	509	264
Cooking	735	381	77	40
Boiler and Pumps	247	128	326	169
Sockets	2,967	1540	1876	973
TOTAL		**3177**		**2907**
PV Offset	4035	2094	1632	847
Total - Offset		**1082**		**2060**

Table 6-7. Breakdown of Energy and Carbon Performance Year 2

	Larch		Lime	
	kWh	CO_2 Kg	kWh	CO_2 Kg
GAS Total	3359	726	5254	1135
Space Heat	475	103	1440	311
Domestic Hot Water	1800	389	1085	234
Distribution and Cylinder Losses	1948	421	2204	476
Boiler Loses	336	73	525	113
Electricity Total	4418	2293	2847	1478
Lights	240	124	95	50
MVHR	353	183	736	382
Cooking	585	304	114	59
Boiler and Pumps	203	106	315	164
Sockets	3,037	1576	1586	823
TOTAL		**3018**		**2612**
PV Offset	4385	2276	1889	980
Total - Offset		**743**		**1632**

Disappointingly during the first year of monitoring the solar thermal systems in both houses did not work at all (more details further in Chapter 7.5), leading to potential savings of over 1000kWh per year being lost. In the second year the solar system in Dwelling 1 (Larch House) worked reliably, contributing 1250 kWh to the cylinder, domestic hot water consumption in year 2 was 1800 kWh, resulting in a solar fraction of 68%. Substituting the measured solar radiation and external temperature into PHPP, a solar contribution to useful heat , under year 2 conditions, was predicted to be 1700 kWh, and the DHW heat demand 2493 kWh, with a solar fraction of 68%. In year 2 the solar system therefore produced 26% less useful heat than expected, but the solar fraction was equal to that predicted by PHPP due to the lower than expected DHW consumption.

Table 6-8. Breakdown of Energy and Carbon Performance, Average Performance over the 2 years

	Larch		Lime	
	kWh	CO_2 Kg	kWh	CO_2 Kg
GAS Total	3540	765	5894	1273
Space Heat	790	171	1739	376
Domestic Hot Water	1313	284	1374	297
Distribution and Cylinder Losses	1684	364	2192	473
Boiler Loses	354	76	589	127
Electricity Total	4495	2333	2865	1487
Lights	245	127	96	50
MVHR	380	197	623	323
Cooking	660	343	96	50
Boiler and Pumps	225	117	321	166
Sockets	3002	1558	1731	898
TOTAL		**3098**		**2760**
PV Offset	4210	2185	1761	914
Total - Offset		**743**		**1846**

The profile of gas, space heating, and domestic hot water use in the Larch House during the two winters are compared in Figure 6-1 to Figure 6-3. It can be seen that in year 2 the boiler was re programmed to switch off between mid-night and 6:30 am.

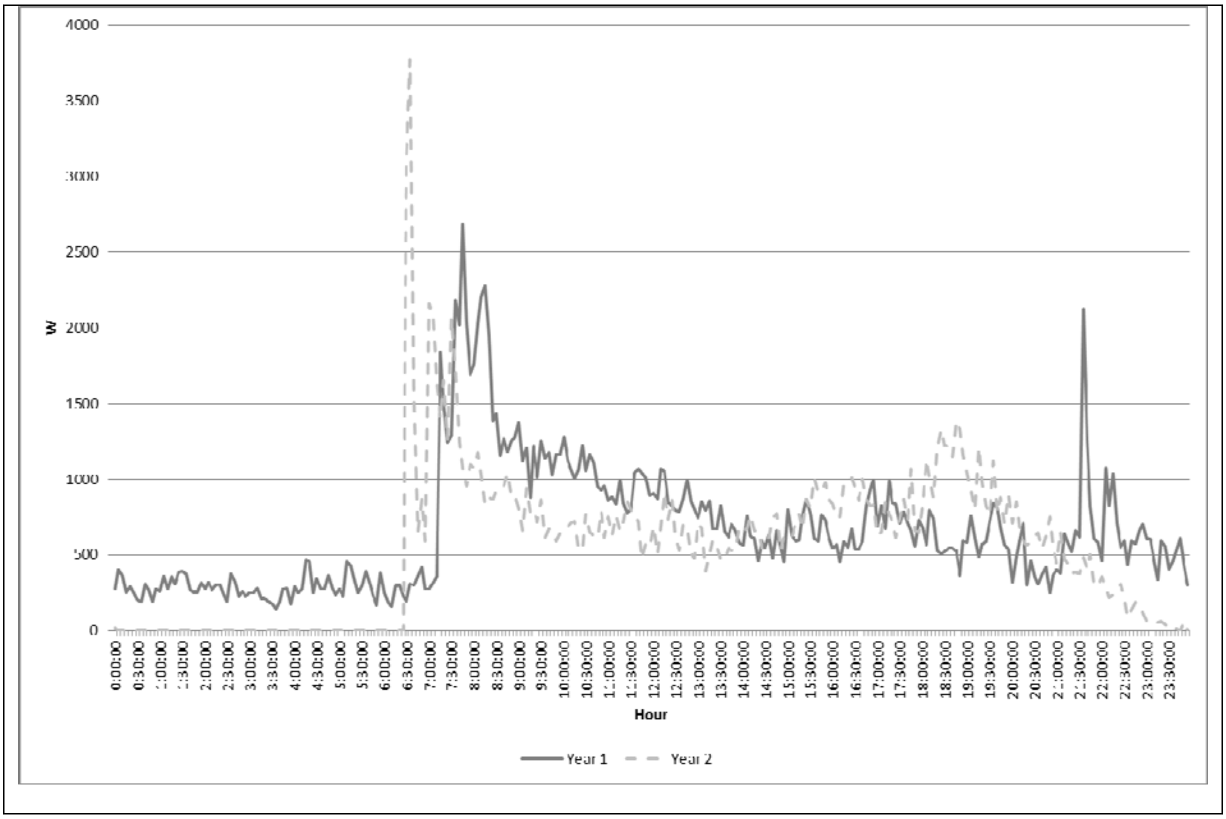


Figure 6-1. Average hourly profile of winter Gas power use: Larch House

This re programming is also seen in the space heating and domestic hot water consumption.

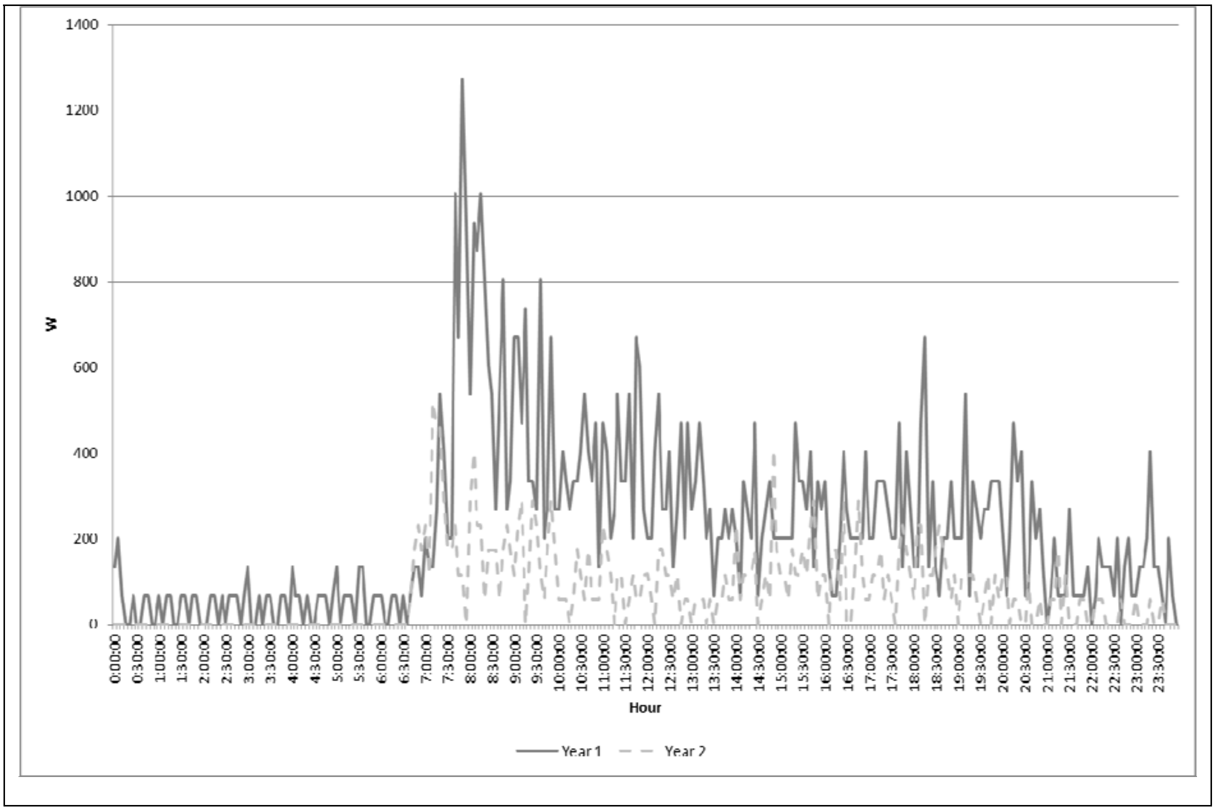


Figure 6-2. Average hourly profile of winter Space Heating power use: Larch House

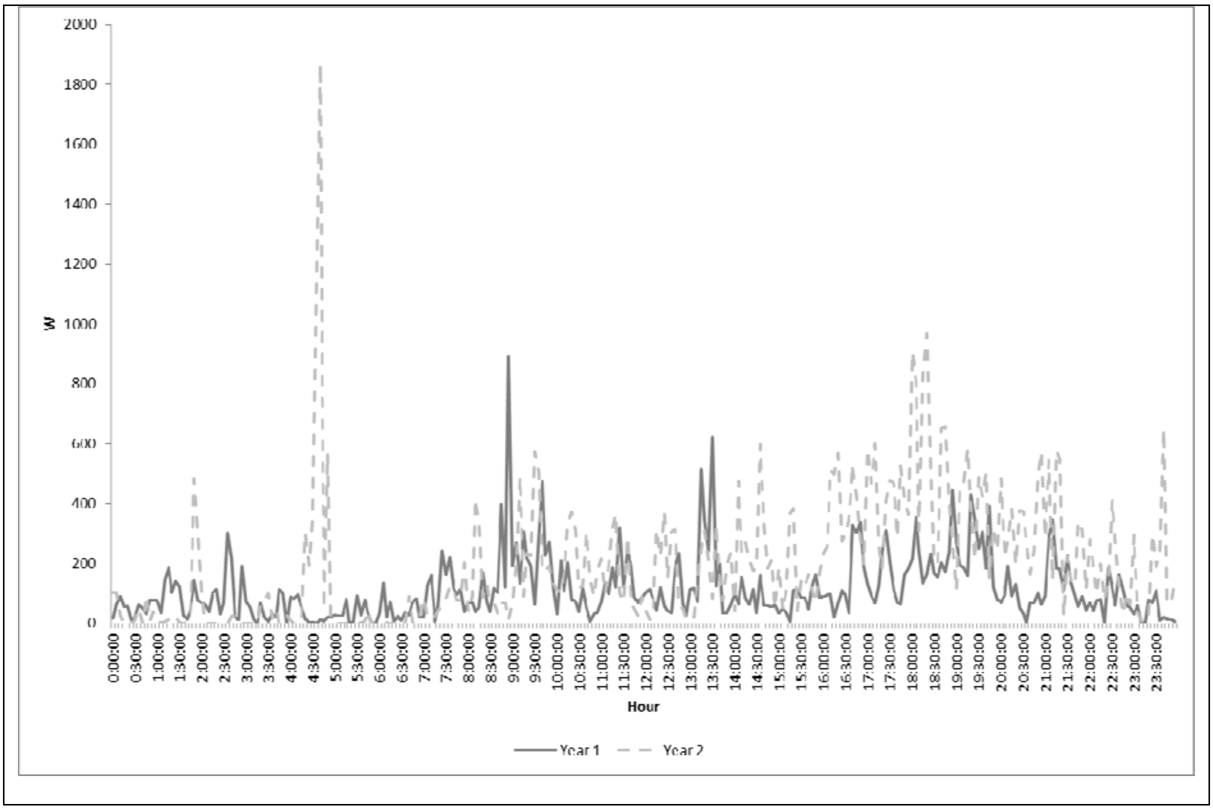


Figure 6-3. Average hourly profile of winter DHW power use: Larch House

Space heating in Larch is notably reduced in year 2 due to the milder external temperature.

Also it should be noted that shortly before the second winter of this monitoring study, the occupants of the Larch House reported that the housing association had complied with their request for the solar override on the external blinds to be disconnected, giving manual control of the blinds to the occupants. For the first time this allowed the house to benefit from winter solar gains when the occupants were out at work, whereas previously the blinds automatically lowered to shade the building even in winter when the solar gains should be allowed to enter the building.

The profile of gas, space heating, and domestic hot water use, in the Lime House during the two winters are compared in Figure 6-4 to Figure 6-6.

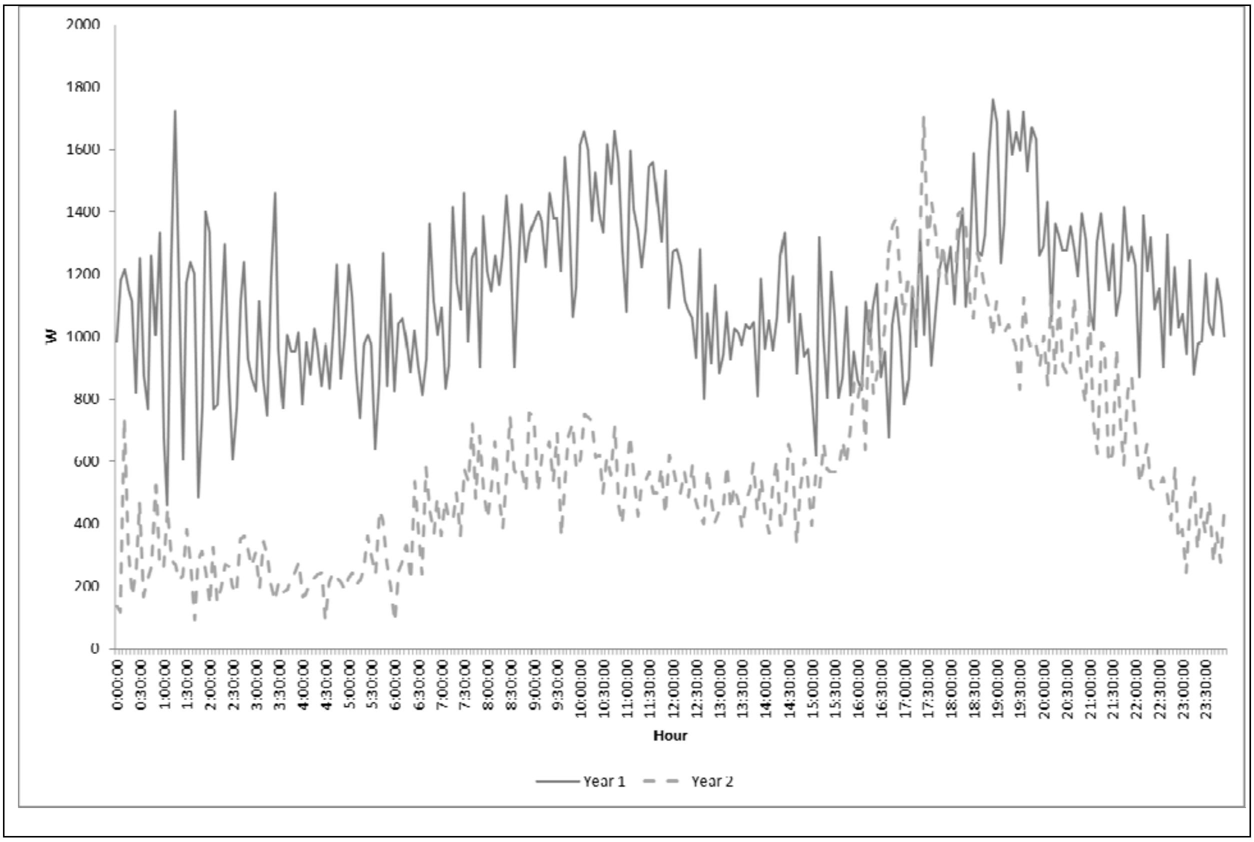


Figure 6-4. Average hourly profile of winter Gas power use: Lime House

In the Lime House a reduction in year 2 gas consumption is observed but the boiler continues to operate from midnight to 6 am. The boiler re programming seen in Larch House is not repeated in Lime House. However in Lime Housed domestic hot water use and space heating are reduced during the early hours of the morning in year 2. As noted in the occupant interview (Chapter 5.3), the tenants tend to turn the thermostat up in the evening when they return from work and turn them down again before going to bed. This is indicated also by the hourly profiles of gas and domestic hot water use, with spikes around 17:30 and 18:00 in the afternoon.

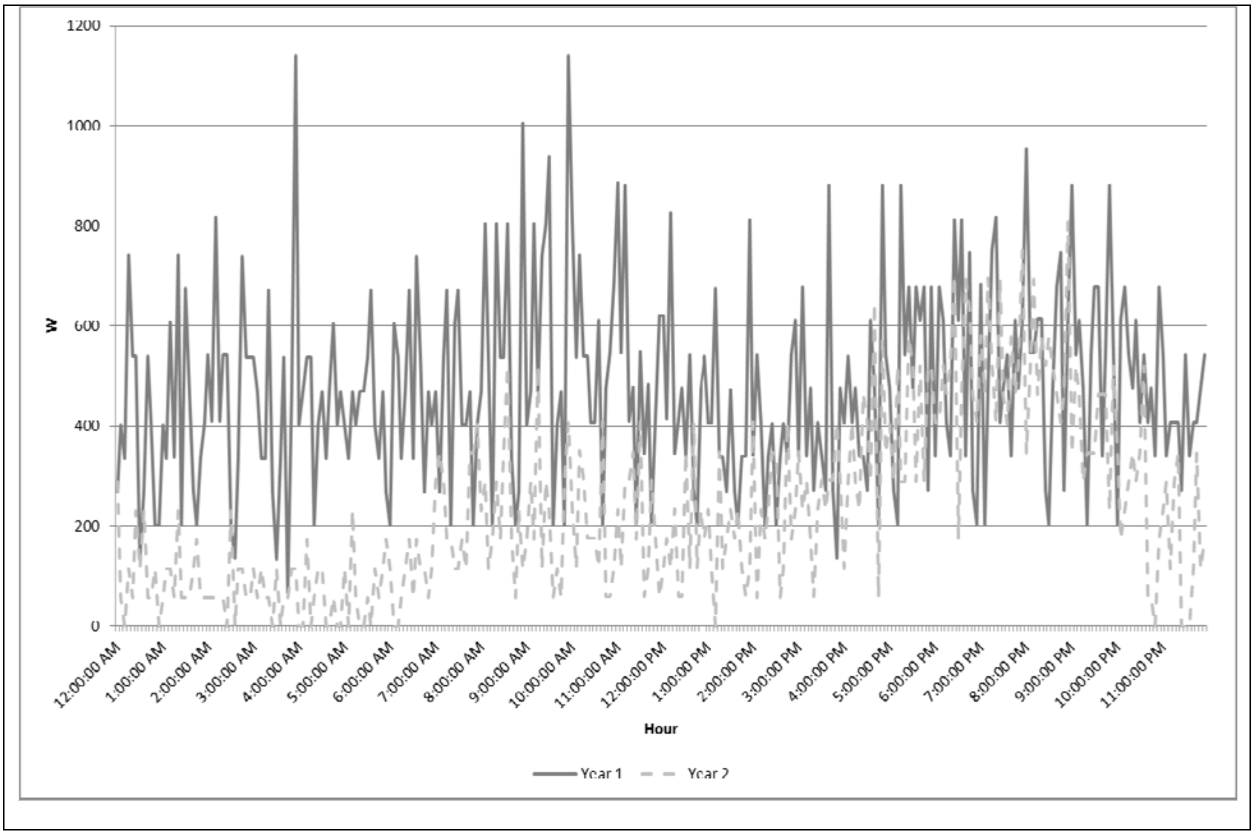


Figure 6-5. Average hourly profile of winter Space Heat power use: Lime House

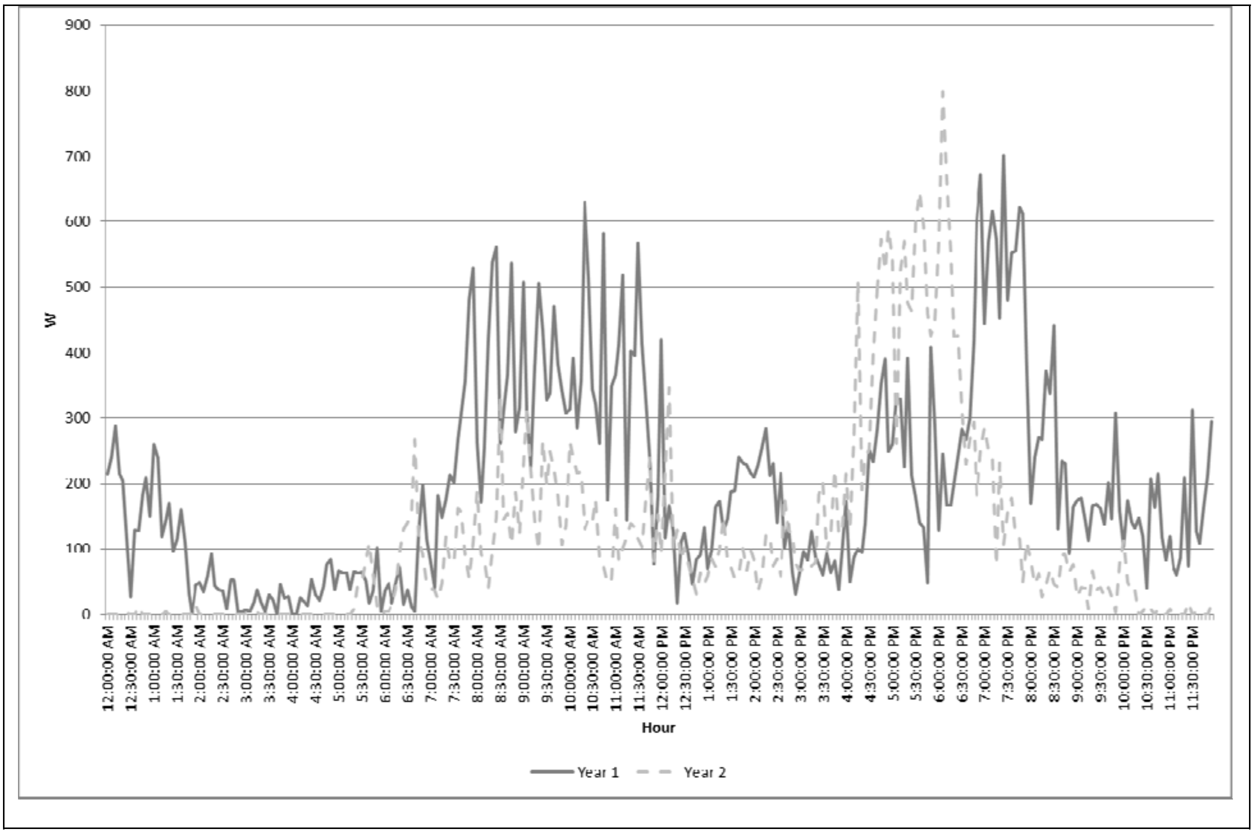


Figure 6-6. Average hourly profile of winter DHW power use: Lime House

6.4 Estimated in use Dwelling Heat Loss

Using data from both winters the daily rate of heat input to the dwellings was regressed against the daily internal – external temperature difference. The total heat input consisted of all gains from electricity consumption, occupancy gains, solar gains and space heating, gains from distribution and storage losses of the domestic hot water system but allowing for cold water feed and evaporation losses.

Solar gains are calculated using Eqtn. 1

Gsolar = 0.9 x Aw x S x g x FF x Z   Eqtn [1]

Where 0.9 is a factor representing the ratio of typical average transmittance to that at normal incidence

Aw is the area of an opening (a window or a glazed door), m^2

S is the solar flux on a surface, W/m^2

g is the total solar energy transmittance factor of the glazing at normal incidence

FF is the frame factor for windows and doors (fraction of opening that is glazed)

Z is the solar access factor

The winter time daily heat balance, that will be less accurate than the co heating test estimates a heat loss of 80 W/K in Larch House and 74 W/K in both dwellings. The higher in use heat loss especially in Lime House suggests the occupants are opening windows in winter.

Note: during the filmed winter interview of the occupants of the Lime House Dr Ridley's hypothesis was confirmed. The occupants of the Lime House discuss their occupancy habits on the film and told the interviewers that they prefer to leave windows open during the night in winter. (This film can be found on the bere:architects 'films page' of the ***www.bere.co.uk*** *website).*

The reasons for this were discussed with the occupants, a little inconclusively, and also separately by the design team. In the end an automatic setback thermostat was installed in the living room to reduce night time temperatures to see if this enabled the occupants to feel comfortable on winter nights with the windows closed. However the hoped-for change of user behaviour was not achieved and after the installation of the setback thermostat the occupants opened the windows during the day when they were at work and lowered the thermostat during this time. They then turned the temperature up quite high in the evenings, and off again before going to bed, at which point they opened the windows again. It is not clear yet if they misunderstood the meaning of 'setback thermostat', but from information gleaned in discussions with the tenants, the design team think that the occupants are repeating deeply ingrained parental habits. These habits may originate from purging smoke residues in a house with coal fires, or purging the air for other reasons in an old house. The occupants have agreed with the architects that monitoring may continue beyond the end of the monitoring period and the intention is to give the occupants of the Lime House an illustrated guide of how their use habits affect their bills, and how an alternative use pattern could save them more money.

It should be noted that even with a bedroom window open for long periods in the winter, day and night, the overall annual heat energy demand of the building remains very low compared to average UK usage.

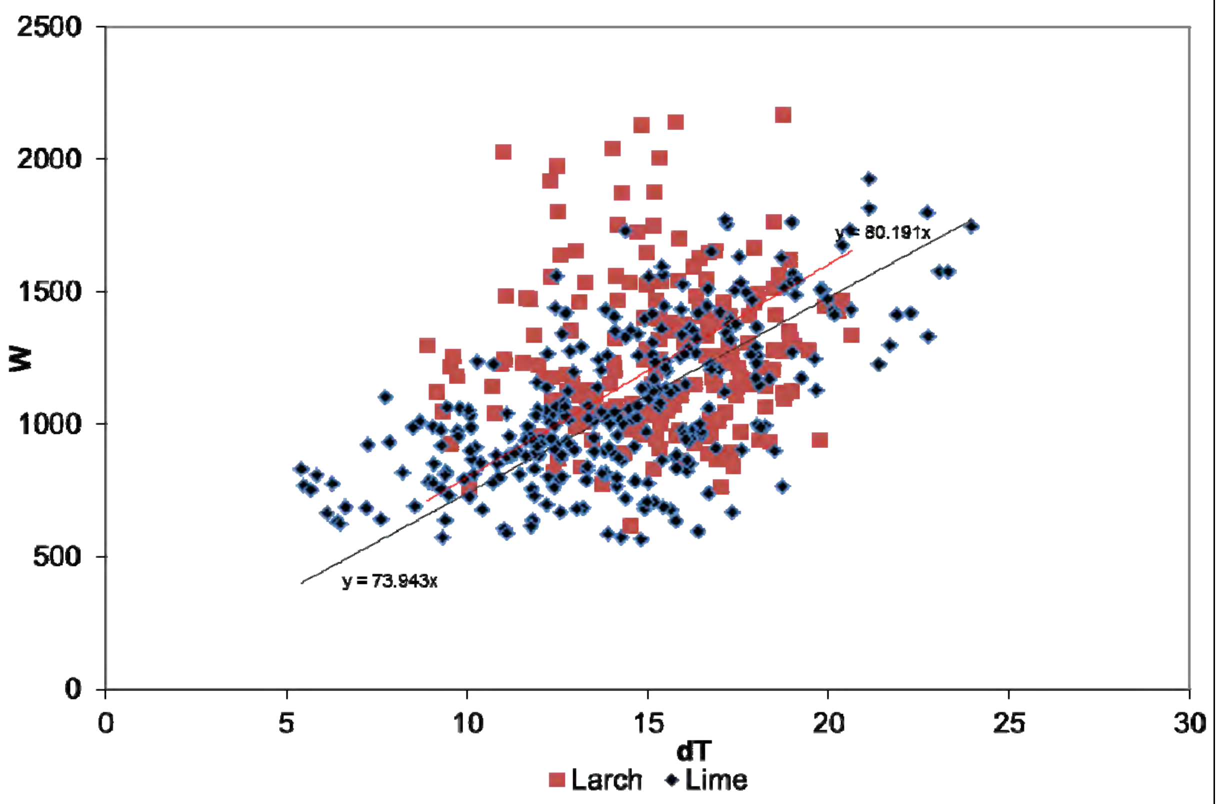


Figure 6-7. Heat loss of the two dwellings estimated from winter daily energy input.

6.5 Ventilation and Indoor Air Quality

The performance of the MVHR systems in each dwelling is summarised in Table 6-9 to Table 6-11. The thermal efficiency, calculated according to Passive House Institute "*Requirements and Testing Procedures for energetic and acoustical assessment of Passive House ventilation systems for certification as "Passive House suitable component"* [4], of the MVHR units in both dwellings were lower than the 92% manufacturer quoted values, but still above the Passive House minimum requirement of 75%. Similarly the energy consumption of the MVHR units was slightly higher than expected, In Larch energy consumption was 0.4 Wh/m3 - below the Passive House maximum of 0.45 Wh/m^3. In Lime energy consumption was 0.5 Wh/m^3 - above

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[4] Passive House Institute, Requirements and Testing Procedures for energetic and acoustical assessment of Passive House ventilation systems for certification as "Passive House suitable component", 2009

the Passive House maximum of 0.45 $Wh/m^{3.}$ The MVHR unit provide an average ventilation rate of 0.31 ach^{-1} in Larch and 0.38 ach^{-1} in Lime.

Relative humidity, vapour pressure excess and CO_2 concentrations are presented in Table 6-12 to Table 6-14. Relative humidity levels are compared to current ADF Building recommendations to avoid mould growth.

Both Dwellings have very good IAQ in terms of RH and CO_2 levels. On cold dry days internal RH will however fall below 30%. Vapour pressure excess is low and there is no risk of mould growth. In Larch the average winter ventilation rate provided by the MVHR unit is 0.31 ach^{-1}, and CO_2 concentrations exceed 1400ppm in the master bedroom of Larch for 13% of the 2 year monitoring period, the vapour pressure excess is also higher than in Lime. In Lime the average ventilation rate provided by the MVHR is higher at 0.37 ach^{-1}, bedroom CO_2 levels exceed 1400ppm by a negligible 0.1% over 2 years.

Table 6-9. Average MVHR Performance over the 2 year monitoring period

	Power W	Air Flow m^3/hr	Specific Fan Power W/l/s	Consumption Wh/m^3	Thermal Efficiency %	MVHR Ach-1
Larch	39.9	99.9	1.4	0.4	75.8	0.31
Lime	62.2	122.2	1.8	0.5	77.1	0.38

Note Air flow estimation is based on flow measured as a function of fan speed at time of commissioning.

Table 6-10. Monthly MVHR Performance Larch

	Power	Fan Speed	Air Flow	Air Flow	Specific Fan Power	Specific Consumption	Thermal Efficiency %	MVHR
	W		m3/hr	l/s	W/l/s	Wh/m3	%	Ach-1
May-12	39.8	1.3	99.6	27.7	1.4	0.4	76	0.31
Jun-12	39.4	1.3	99.4	27.6	1.4	0.4	73	0.31
Jul-12	42.6	1.4	102.6	28.5	1.5	0.41	76	0.32
Aug-12	59.7	2	119.7	33.2	1.8	0.5	80	0.37
Sep-12	57.4	1.9	117.4	32.6	1.8	0.49	84	0.36
Oct-12	61.1	2	121.1	33.6	1.8	0.5	82	0.37
Nov-12	52.2	1.7	112.2	31.2	1.7	0.5	78.4	0.35
Dec-12	36.2	1.2	96.2	26.7	1.4	0.4	77.8	0.30
Jan-13	39.2	1.3	99.2	27.6	1.4	0.4	70.8	0.31
Feb-13	41.4	1.4	101.4	28.2	1.5	0.4	74.3	0.31
Mar-13	36.0	1.2	96.0	26.7	1.4	0.4	75	0.30
Apr-13	36.5	1.2	96.5	26.8	1.4	0.4	78.2	0.30
May-13	28.4	0.9	88.4	24.6	1.2	0.3	77	0.27
Jun-13	27.7	0.9	87.7	24.4	1.1	0.3	74	0.27
Jul-13	24.0	0.8	84.0	23.3	1.0	0.3	69	0.26
Aug-13	30.8	1.0	90.8	25.2	1.2	0.3	70	0.28
Sep-13	23.0	0.8	83.0	23.1	1.0	0.3	76.8	0.26
Oct-13	27.2	0.9	87.2	24.2	1.1	0.3	76.3	0.27
Nov-13	27.2	0.9	87.2	24.2	1.1	0.3	81.6	0.27
Dec-13	45.8	1.5	105.8	29.4	1.6	0.4	75.6	0.33
Jan-14	38.6	1.3	98.6	27.4	1.4	0.4	73.4	0.30
Feb-14	43.7	1.5	103.7	28.8	1.5	0.4	72.4	0.32
Mar-14	42.5	1.4	102.5	28.5	1.5	0.4	73.4	0.32
Apr-14	57.1	1.9	117.1	32.5	1.8	0.5	74.4	0.36
Average	39.9	1.3	99.9	27.7	1.4	0.4	75.8	0.31

Note: the air flow is estimated (calculated) using the fan speed and the power consumption of the fan. When the MVHR units were commissioned, the measured the air flow was noted as a function of MVHR power consumption and fan speed. These measurements were used to estimate the air flow.

Table 6-11. Monthly MVHR Performance Lime

	Power	Fan Speed	Air Flow	Air Flow	Specific Fan Power	Specific Consumption	Thermal Efficiency %	MVHR
	W		m3/hr	l/s	W/l/s	Wh/m3	%	Ach-1
May-12	36.9	1.2	96.7	26.9	1.4	0.38	74.4	0.30
Jun-12	55.5	1.9	115.5	32.1	1.7	0.48	60	0.36
Jul-12	74.4	2.5	134.4	37.3	2	0.55	78.4	0.41
Aug-12	87.1	2.9	147.1	40.8	2.1	0.59	83.1	0.45
Sep-12	60.8	2	120.8	33.6	1.8	0.5	80	0.37
Oct-12	46.8	1.6	106.8	29.7	1.6	0.44	82	0.33
Nov-12	31	1.03	91	25.23	1.22	0.34	81	0.28
Dec-12	26	0.86	86	23.86	1.09	0.3	86.6	0.26
Jan-13	25	0.84	85	23.63	1.06	0.29	80.3	0.26
Feb-13	47.6	1.6	107.6	29.9	1.6	0.4	84	0.33
Mar-13	61.6	2.1	121.6	33.8	1.8	0.5	83	0.37
Apr-13	72.8	2.4	132.8	36.9	2	0.5	78.2	0.41
May-13	73.9	2.5	133.9	37.2	2.0	0.6	61	0.41
Jun-13	59.0	2.0	119.0	33.0	1.8	0.5	61	0.37
Jul-13	65.1	2.2	125.1	34.7	1.9	0.5	68	0.38
Aug-13	66.0	2.2	126.0	35.0	1.9	0.5	69	0.39
Sep-13	58.5	2.0	118.5	32.9	1.8	0.5	64.2	0.36
Oct-13	68.0	2.3	128.0	35.6	1.9	0.5	67	0.39
Nov-13	69.1	2.3	129.1	35.9	1.9	0.5	80	0.40
Dec-13	87.4	2.9	147.4	40.9	2.1	0.6	84.4	0.45
Jan-14	82.9	2.8	142.9	39.7	2.1	0.6	85.1	0.44
Feb-14	80.2	2.7	140.2	38.9	2.1	0.6	85.9	0.43
Mar-14	78.9	2.6	138.9	38.6	2.0	0.6	86.9	0.43
Apr-14	79.2	2.6	139.2	38.7	2.0	0.6	87.9	0.43
Average	62.2	2.1	122.2	34.0	1.8	0.5	77.1	0.38

Note: the air flow is estimated (calculated) using the fan speed and the power consumption of the fan. When the MVHR units were commissioned, the measured the air flow was noted as a function of MVHR power consumption and fan speed. These measurements were used to estimate the air flow.

Table 6-12. Relative Humidity, Vapour Pressure Excess and CO_2 concentrations Year 1

Relative Humidity	Larch			Lime		
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
% Hours <30%	24.5	24.5	22.8	9.4	9.4	16.9
% Hours >70%	0.0	0.0	0.0	0.0	0.0	0.2
30%> RH< 70%	75.5	75.5	77.2	90.6	90.6	82.9

Bregs ADF: Average RH	Larch			Lime		
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
Day >89%	PASS	PASS	PASS	PASS	PASS	PASS
Week > 79%	PASS	PASS	PASS	PASS	PASS	PASS
Month >70%	PASS	PASS	PASS	PASS	PASS	PASS
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
VP Excess Pa	239	343	381	213	258	259

Carbon Dioxide	Larch		Lime	
	Living Room	Master Bedroom	Living Room	Master Bedroom
% Hours <1000ppm	91%	64%	98.7%	88.7%
% Hours >1000ppm	9%	36%	1.3%	11.2%
% Hours >1400ppm	1%	10%	0%	0.1%

	Larch		Lime	
	Living Room	Master Bedroom	Living Room	Master Bedroom
Stan T@5 ^{o}C Ext	23.1	22.1	21.6	21.7
Stan RH @5^{o}C , 80% EXT	32.9	38.9	35.4	36.8

Table 6-13. Relative Humidity, Vapour Pressure Excess and CO_2 concentrations, year 2

Relative Humidity	Larch			Lime		
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
% Hours <30%	7.1	2.0	1.0	6.5	2.8	0.5
% Hours >70%	0	0.4	0.5	0.8	2.7	0.6
30%> RH< 70%	92.9	97.6	98.5	92.7	94.5	98.9
Bregs ADF: Average RH	Larch			Lime		
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
Day >89%	PASS	PASS	PASS	PASS	PASS	PASS
Week > 79%	PASS	PASS	PASS	PASS	PASS	PASS
Month >70%	PASS	PASS	PASS	PASS	PASS	PASS
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
VP Excess Pa	260	365	404	236	285	287

Carbon Dioxide	Larch		Lime	
	Living Room	Master Bedroom	Living Room	Master Bedroom
% Hours <1000ppm	79.0	61.7	98.8	89.0
% Hours >1000ppm	18.1	35.9	1.3	7.8
% Hours >1400ppm	0.7	15.7	0.2	0.0
	Larch		Lime	
	Living Room	Master Bedroom	Living Room	Master Bedroom
Stan T@5 °C Ext	22.6	21.4	20.1	21.3
Stan RH @5°C , 80% EXT	38.5	39.5	35.3	45.2

Table 6-14. Relative Humidity, Vapour Pressure Excess and CO_2 concentrations, Average

Relative Humidity	Larch			Lime		
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
% Hours <30%	15.8	13.25	11.9	7.95	6.1	8.7
% Hours >70%	0	0.2	0.25	0.4	1.35	0.4
30%> RH< 70%	84.2	86.55	87.85	91.65	92.55	90.9
Bregs ADF: Average RH	Larch			Lime		
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
Day >89%	PASS	PASS	PASS	PASS	PASS	PASS
Week > 79%	PASS	PASS	PASS	PASS	PASS	PASS
Month >70%	PASS	PASS	PASS	PASS	PASS	PASS
	Living Room	Master Bedroom	Up Bath	Living Room	Master Bedroom	Up Bath
VP Excess Pa	250	354	393	225	272	273

Carbon Dioxide	Larch		Lime	
	Living Room	Master Bedroom	Living Room	Master Bedroom
% Hours <1000ppm	85.0	62.9	98.8	88.9
% Hours >1000ppm	13.6	36.0	1.3	9.5
% Hours >1400ppm	0.9	12.9	0.1	0.1
	Larch		Lime	
	Living Room	Master Bedroom	Living Room	Master Bedroom
Stan T@5 °C Ext	22.9	21.8	20.9	21.5
Stan RH @5°C , 80% EXT	35.7	39.2	35.4	41.0

The average 24 hour profiles of RH and CO_2, in winter (averaged over the 2 years), in the two houses are presented in Figure 6-8 to Figure 6-11 . RH conditions in the living rooms of both houses are very stable.

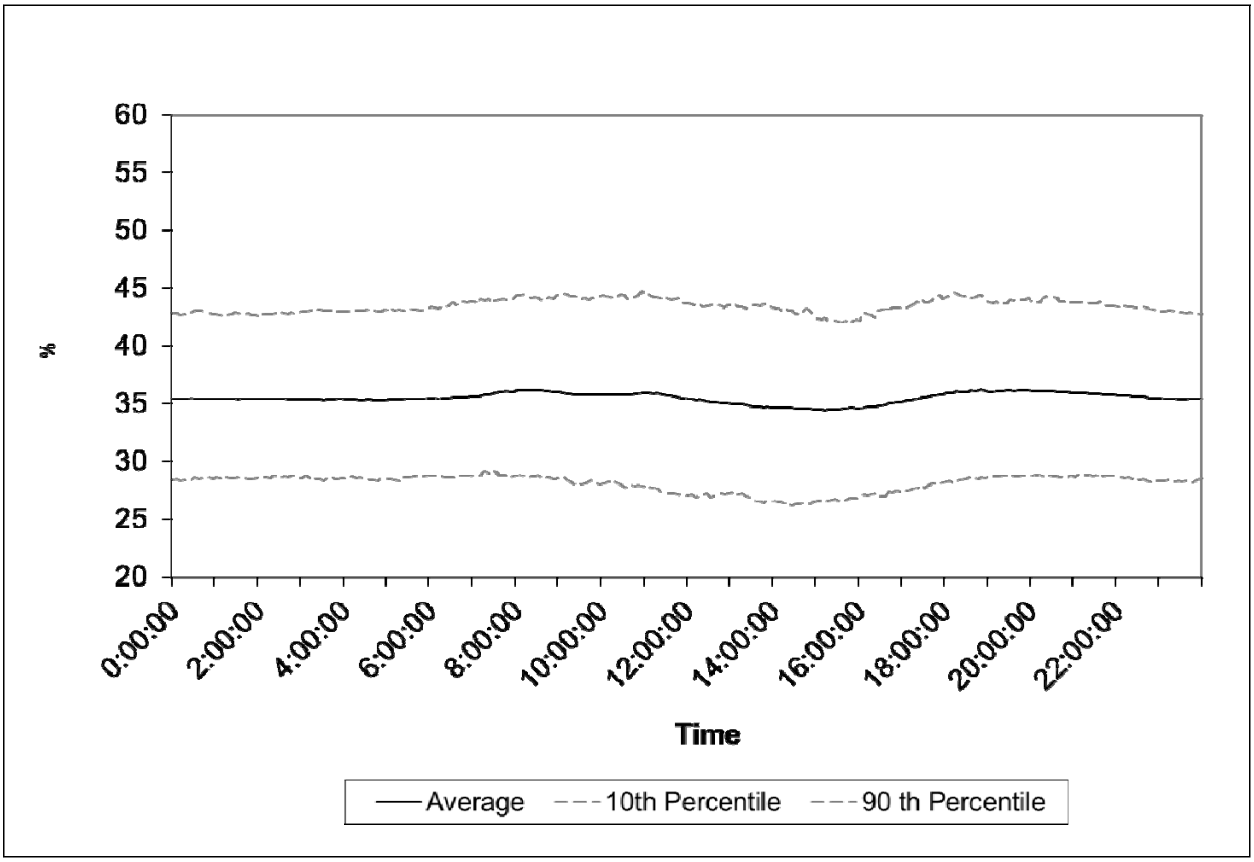


Figure 6-8. Hourly profile of living room winter RH: Larch House

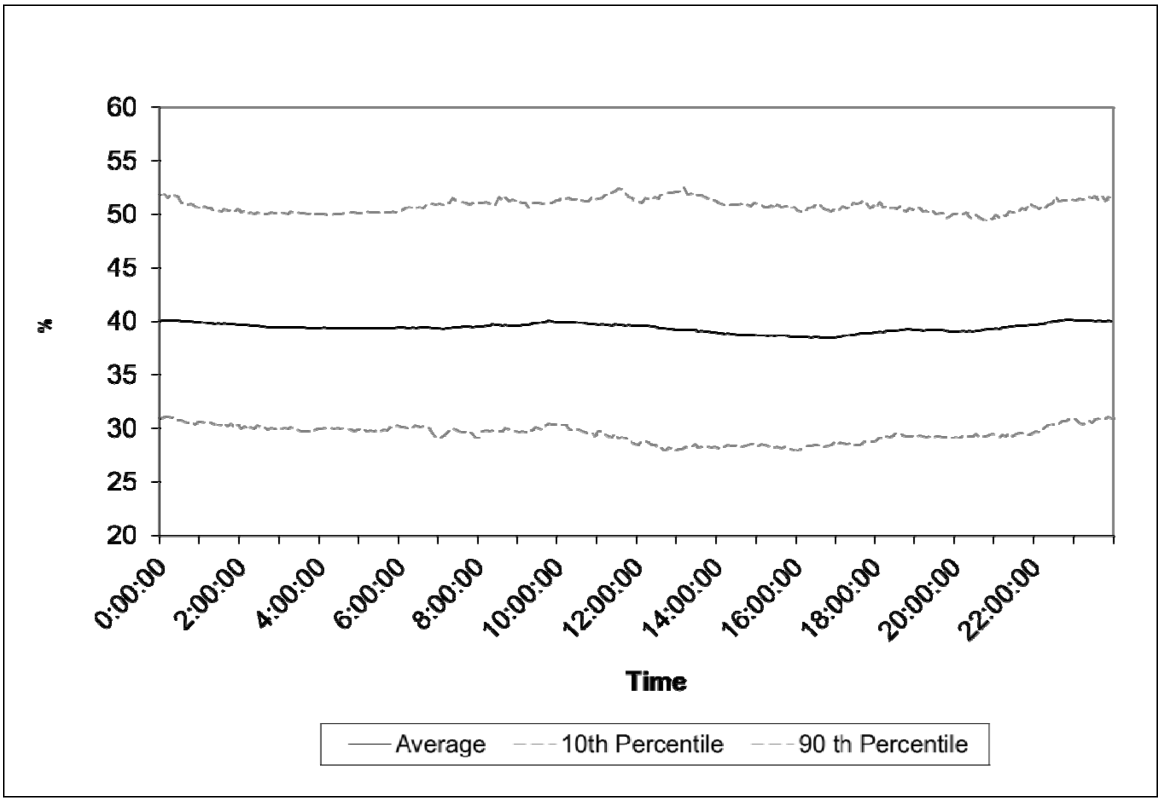


Figure 6-9. Hourly profile of living room winter RH: Lime House

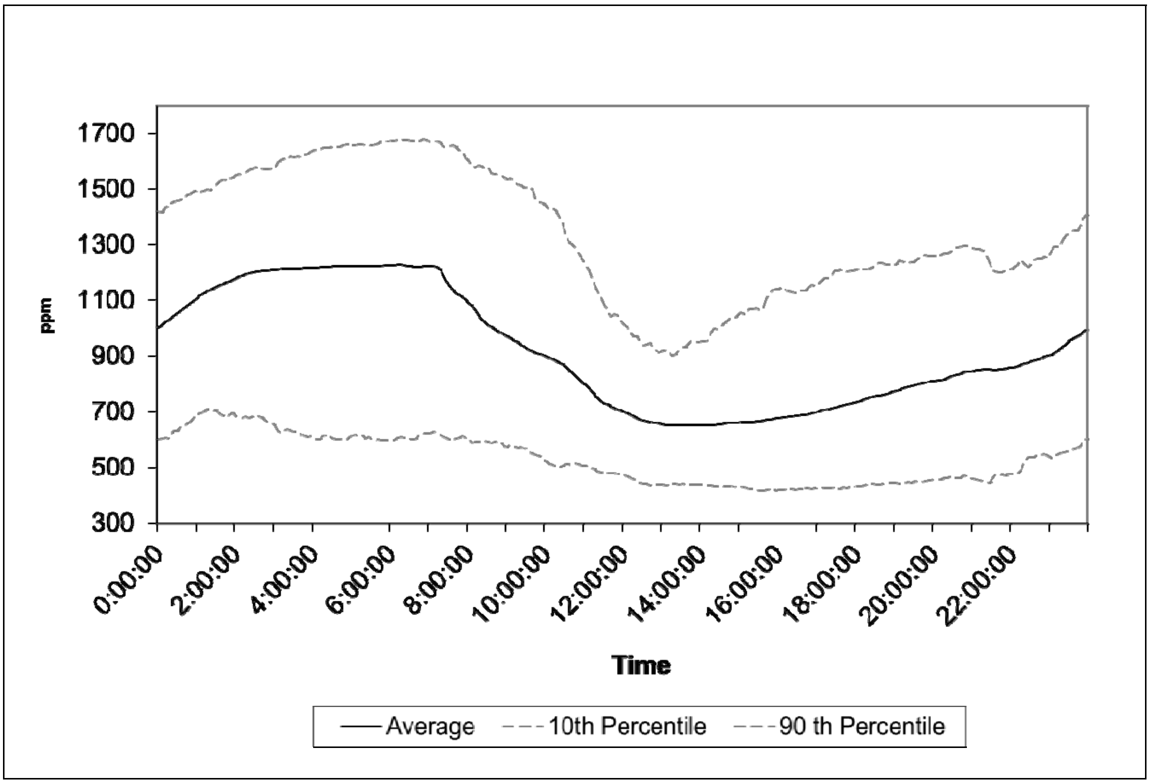


Figure 6-10. Hourly profile of bedroom winter CO_2: Larch House

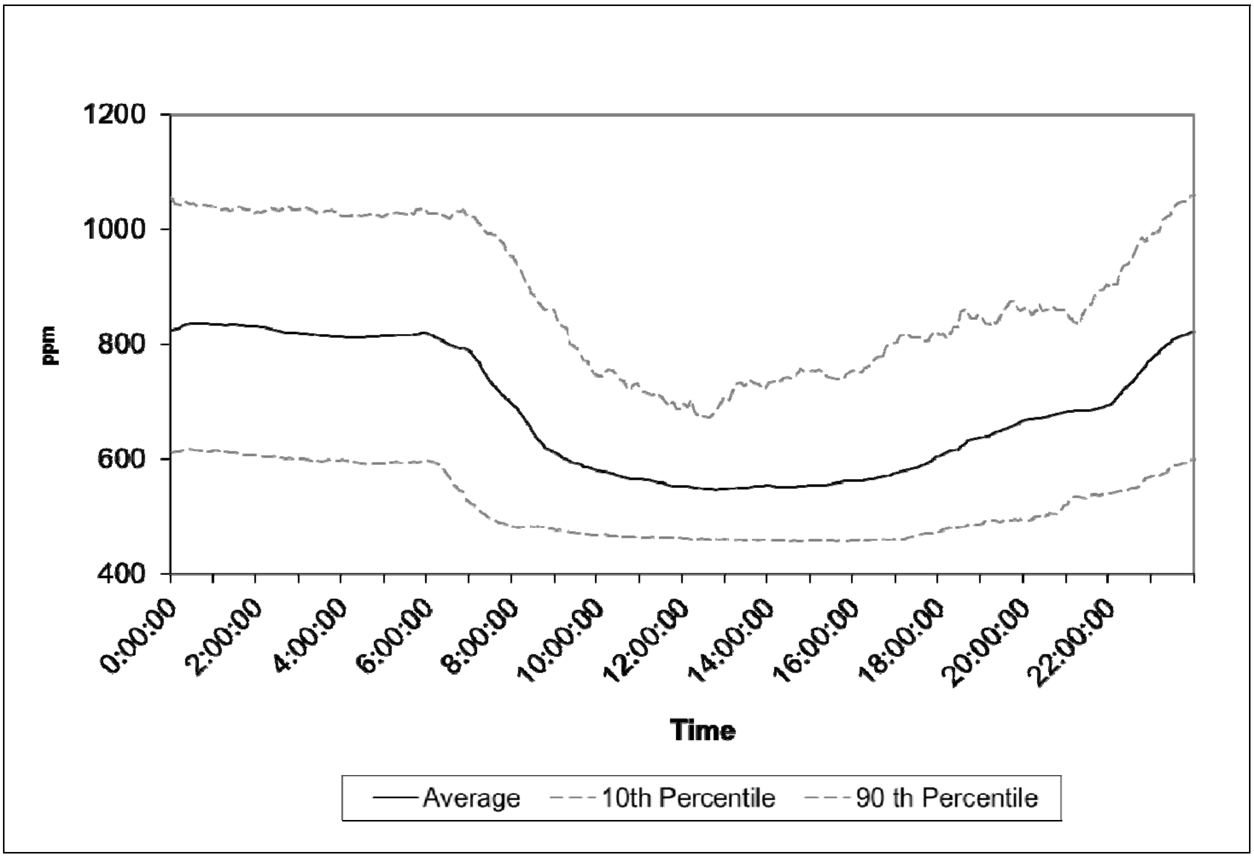


Figure 6-11. Hourly profile of bedroom winter CO_2: Lime House

6.6 Electricity Consumption

In Larch House internal gains from electricity consumption are high, 6 W/m2, total internal gains, including distribution and storage losses reach 8W/m2, much higher than the 2W/m2 used in the design calculation.

In Lime House internal gains from electricity consumption are also high, 4.9 W/m2, total internal gains, including distribution and storage losses reach 8W/m2, much higher than the 2W/m2 used in the design calculation.

The average hourly profile of electricity consumption in the two dwellings is given in Figure 6-12 and compared to those of the average UK dwelling. The high early evening peak in Larch House is due to high cooker use.

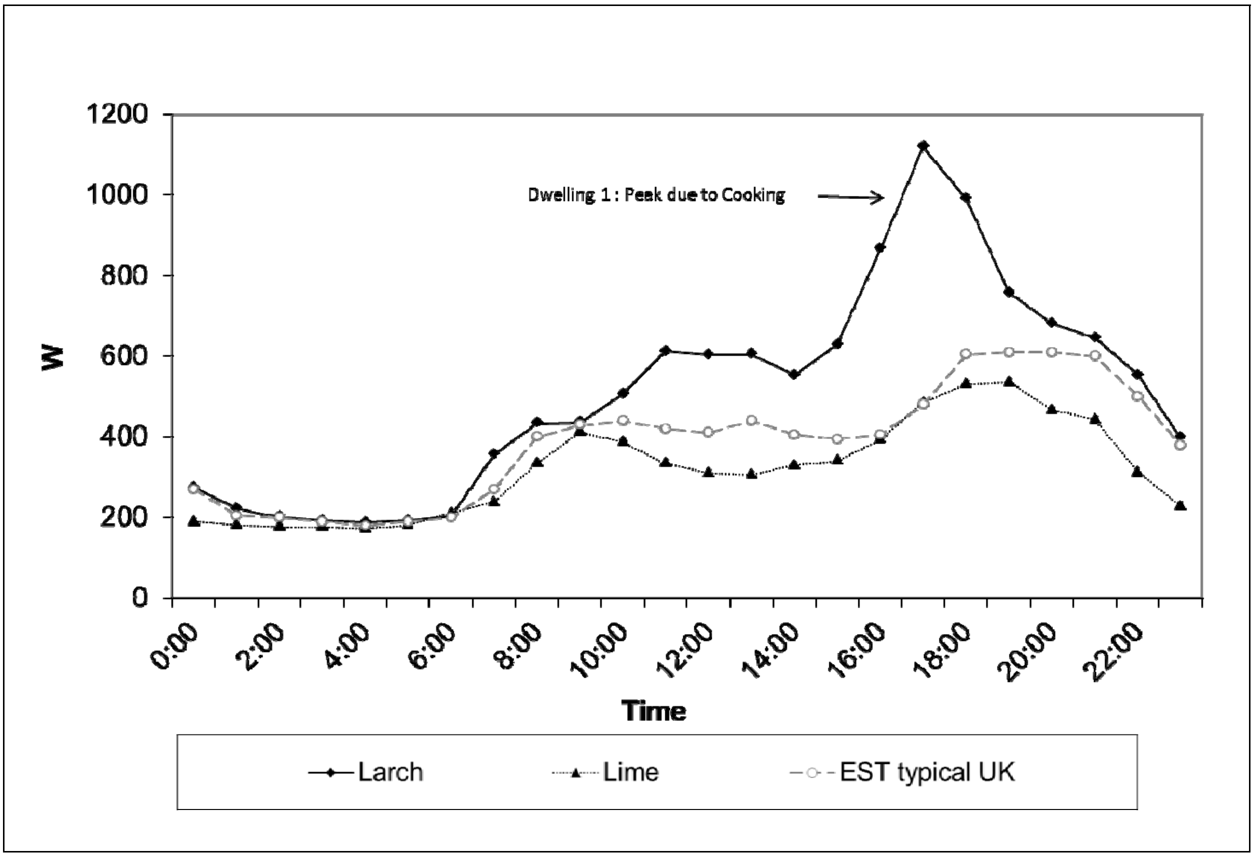


Figure 6-12. Hourly profile of average electricity consumption: Two year winter average

The PHPP predicted electricity consumption for Larch House and Lime House were 1682 kWh and 1269 kWh respectively. Measured total electricity consumption is 267% and 225% of the PHPP predicted in Larch and Lime respectively. In Larch, measured socket and cooking loads alone are 217% that of the total PHPP electricity consumption. Although not high by average UK standards, the electricity consumption of both houses is clearly excessive compared to Passive House philosophy and expectations.

It is a requirement that electrical appliances in a Passive House are A-rated for efficiency. However in rented accommodation in the UK it is customary for tenants to supply their own refrigerator, cooker, washing machine and other other household appliances. Tenant choice may be dictated by price rather than quality. This appears to be the case in both the Larch and the Lime House as non A-rated kitchen equipment was installed by both occupants, and in the Larch house the effect of this is magnified because the cooker is run for longer periods than usual.

Additionally Larch House occupants own a very large television that the occupants say is switched on from about 4pm until bedtime on most days, and the two children each have a *television in their bedroom, together with games consoles and i-pads. There are three games consoles in the house and all three are frequently in use at the same time.*

In the Lime House, a drier with a direct electric heater runs for extended periods each day to dry their young baby's clothes. This has been found elsewhere to be unnecessary in a Passive House since a portable clothes rack will completely dry clothes overnight, but old family habits die hard and air drying of clothes would not be successful without heat in most ordinary houses.

So a combination of user factors result in a higher electricity consumption than expected, although as stated by Dr Ridley above, the consumption is nevertheless not high by average UK standards.

The average hourly profiles of PV Generation, PV export, Electricity import and total electricity consumption, in both winter and summer in the 2 houses are presented in Figure 6-13 to Figure 6-16.

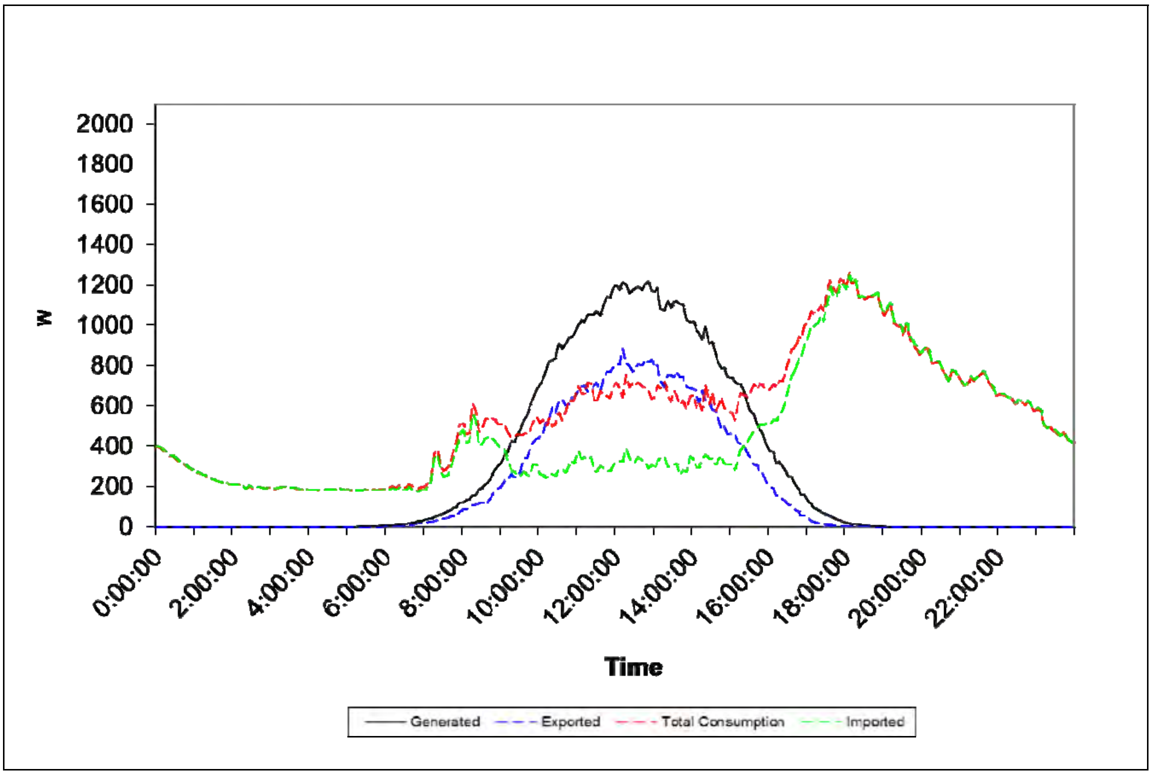


Figure 6-13. Hourly profile of PV Performance: Larch House, Winter

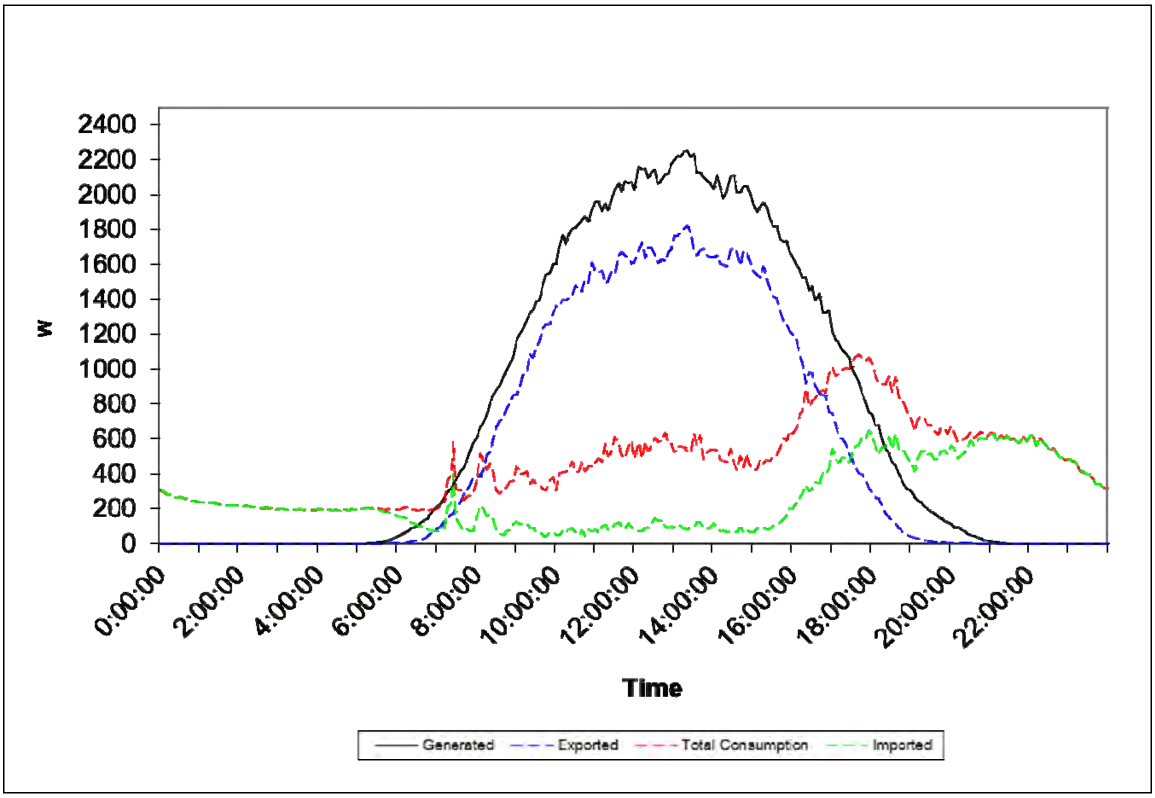


Figure 6-14. Hourly profile of PV Performance: Larch House Summer

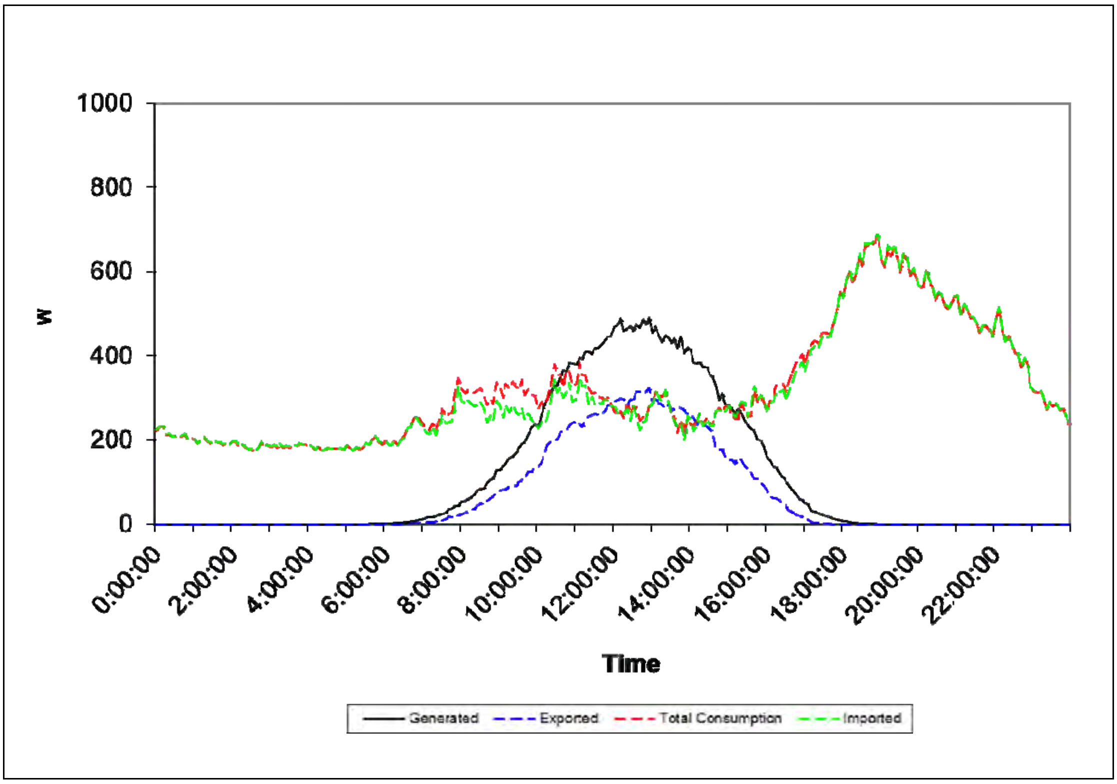


Figure 6-15. Hourly profile of PV Performance: Lime House Winter

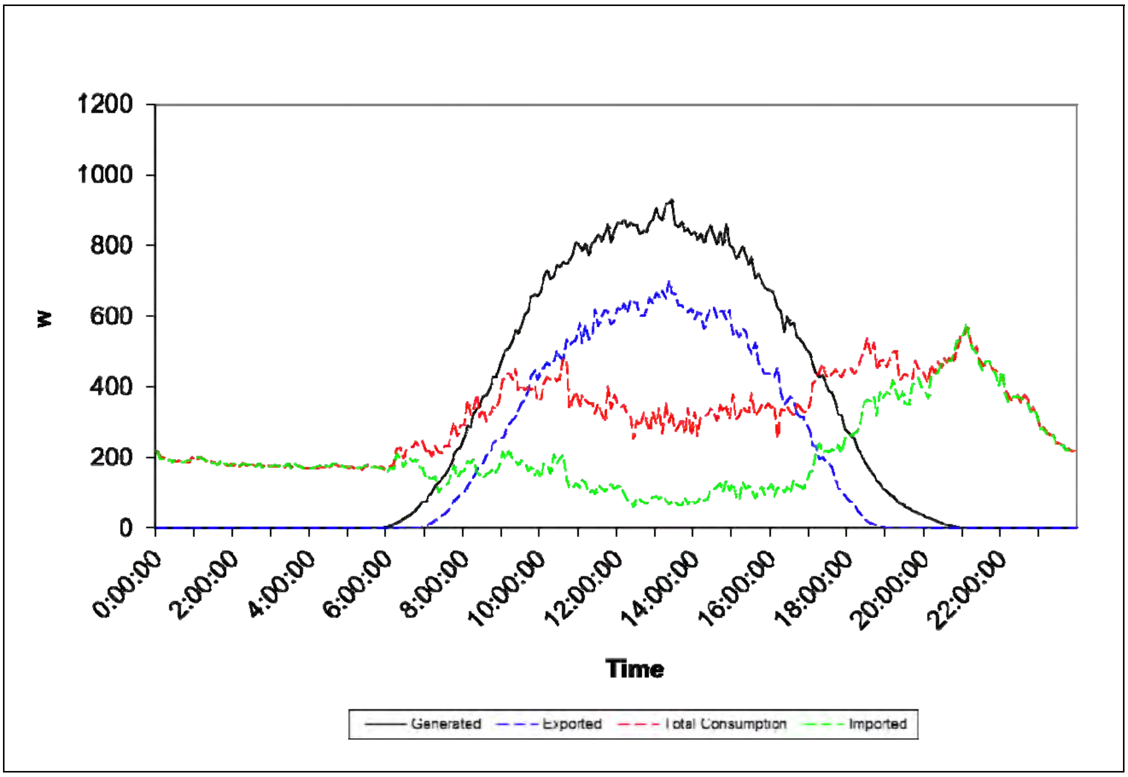


Figure 6-16. Hourly profile of PV Performance: Lime House Summer

The average annual yield of the 4.7 kW peak PV system in Larch House was 896 kWh/kW peak. The average annual yield of the 1.9 kW peak PV system in Lime was 926 kWh/kW peak.

6.7 Average Room Temperatures

The average winter and summer temperatures in the dwellings are presented in Table 6-15. In winter both dwellings were found to be comfortable. Although warm by average UK standards neither set of occupants grossly overheat their dwellings in winter, but winter living room temperatures in Larch House regularly exceed 24 °C.

Table 6-15. Average Room temperature and Relative Humidity

	Larch House				Lime House			
	Living Room °C	Master Bedroom °C	Living Room RH %	Master Bedroom RH %	Living Room °C	Master Bedroom °C	Living Room RH %	Master Bedroom RH %
Summer Average	24.8	23.7	41.7	47.0	21.5	20.8	47.4	55.1
Winter Average	22.9	21.8	35.7	42.5	20.9	21.0	39.2	40.9

The 24 hour profiles of living room temperature for the two houses, in winter and summer, averaged over the 2 year monitoring period are presented in Figure 6-17 to Figure 6-20. In Larch House the average daily minimum temperature in the living room was 21.5 ^{o}C, at 7 am, the 10th percentile daily minimum is 20.5 ^{o}C. The average daily maximum occurred at 9pm and was 24.3 ^{o}C.   The 90th percentile of winter daily maximum in Larch was over 25^{o}C. Lime House was cooler; the average daily minimum temperature in the living room was 19.8 ^{o}C, at 7 am, and the 10th percentile daily minimum was 17.7 ^{o}C. The average daily maximum occurred at 9pm was 22.0 ^{o}C. The 90th percentile of winter daily maximum in Lime House was 23.9^{o}C.

In summer the average living room temperature in Larch House ranged between 24 ^{o}C to 26^{o}C. The 10th percentile of the daily minimum was above 22 ^{o}C. The hottest part of the day in the living room was from midday to 6pm. Summer time over heating risk is examined in more detail in section 7.8.

Lime House was significantly cooler in summer than Larch House. In summer average living room temperatures in Lime House ranged between 20.5 ^{o}C to 22.5 ^{o}C. The 10th percentile of the daily minimum was above 18.5 ^{o}C. The hottest part of the day in the living room was in late afternoon at approximately 6pm.

Shortly before the second winter of this monitoring study, the occupants of the Larch House reported that the housing association had complied with their request for the solar override on the external blinds to be disconnected so that to shade the building, the blinds must be operated manually only. This gives the occupants complete control of when they choose to shade the building. Importantly to control Summer heat gains, it has now allowed them to lower the blinds and adjust the tilt angle to maintain shading while letting in plenty of light. Previously the blinds automatically lowered and raised many times a day in response to sun and clouds, and the simple controls lowered the blinds in the closed position, putting occupants in darkness when they came down. Rather than go through the slightly fiddly process of adjusting the tilt of the blinds many times a day, occupants previously tended to simply press the 'up' button to raise them again. Now that the blinds are manually operated, they can be lowered and adjusted until 'just right' in the knowledge that the settings won't be messed up next time the sun goes behind a cloud and the blinds are raised.

The occupants have agreed to allow the architects to continue monitoring the house for another year and it will be interesting to see if manual operation of the blinds enables occupants an easy and intuitive method of improving summer temperatures inside the house.

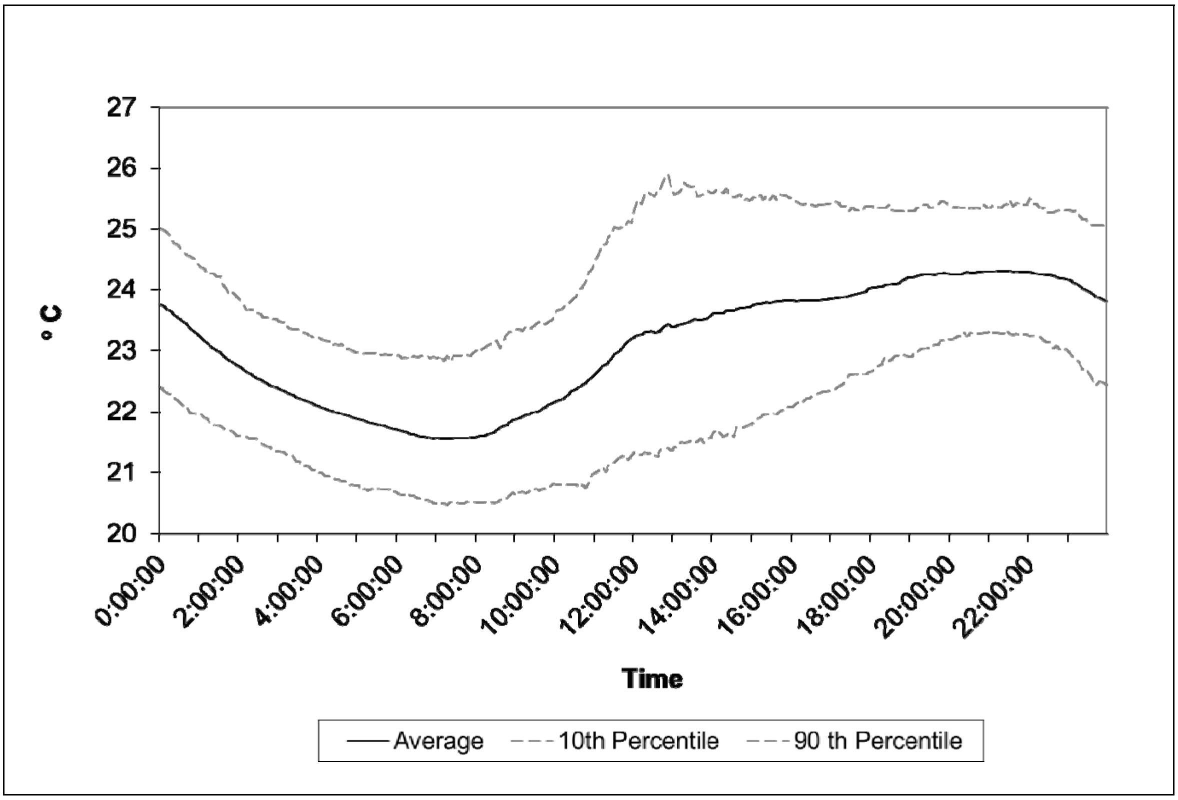


Figure 6-17. Winter Temperature Profile: Larch House

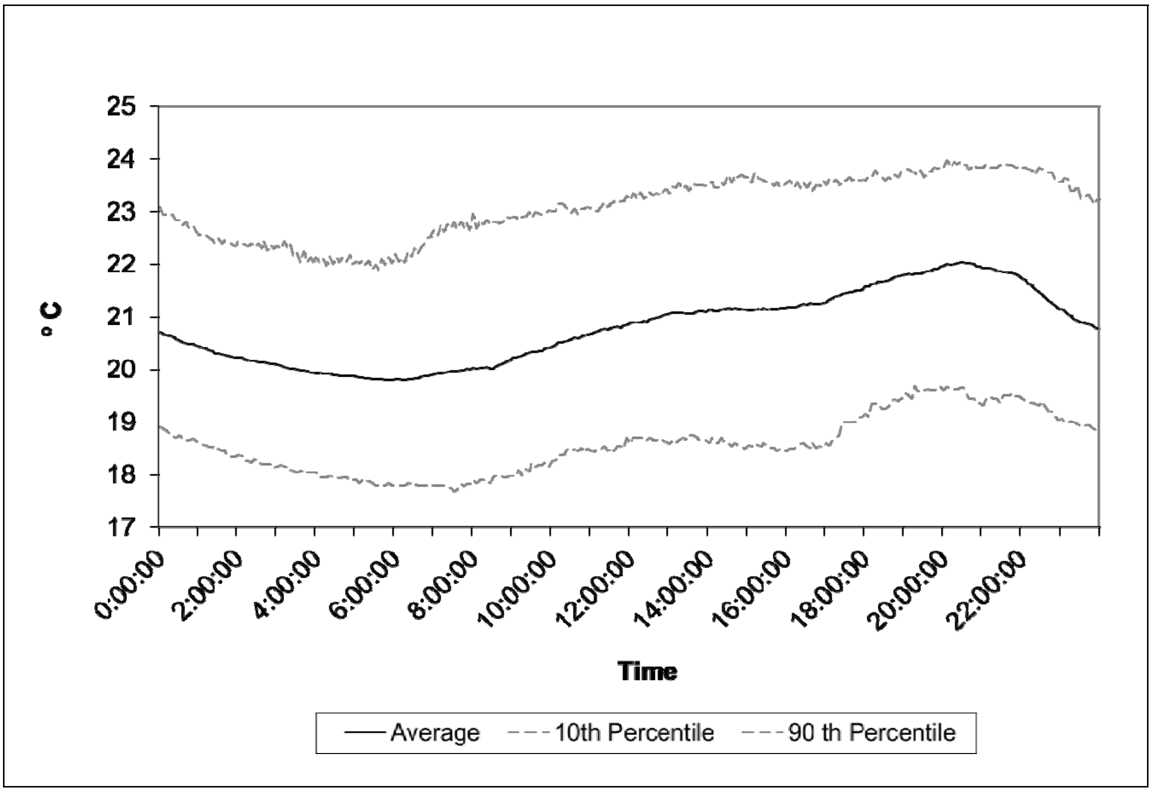


Figure 6-18. Winter Temperature Profile: Lime House

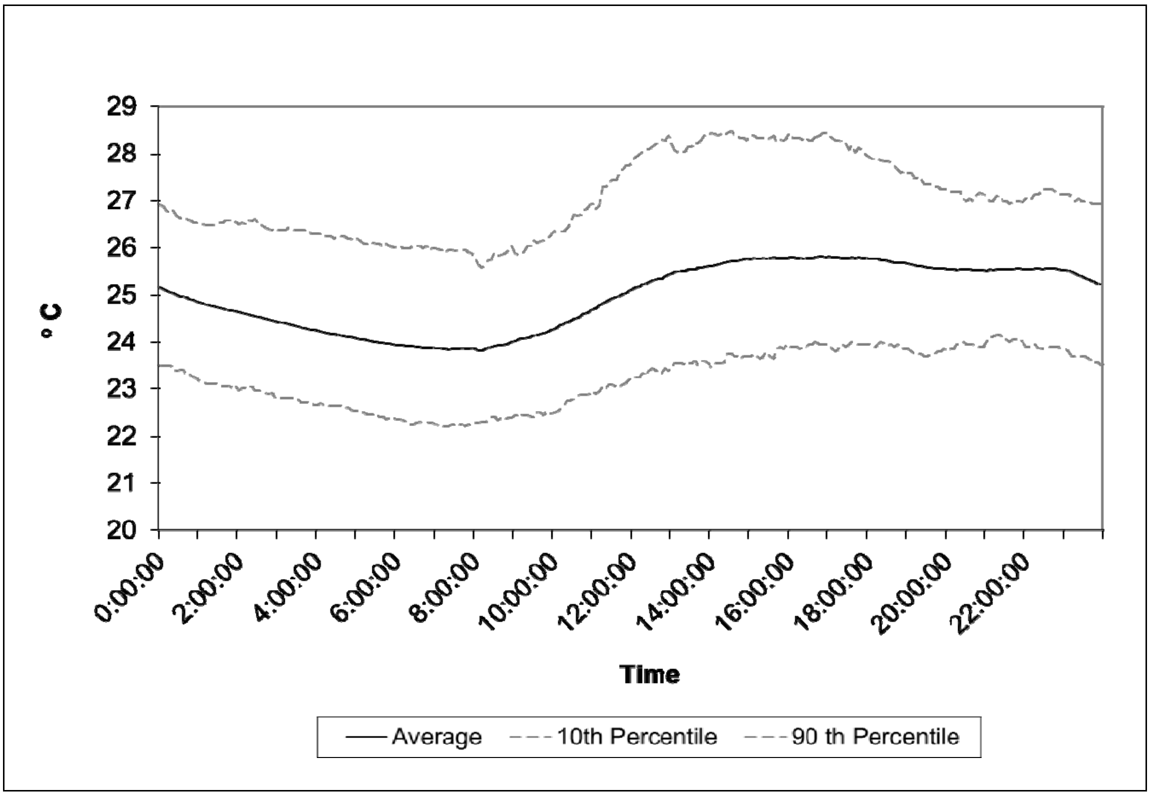


Figure 6-19. Summer Temperature Profile: Larch House

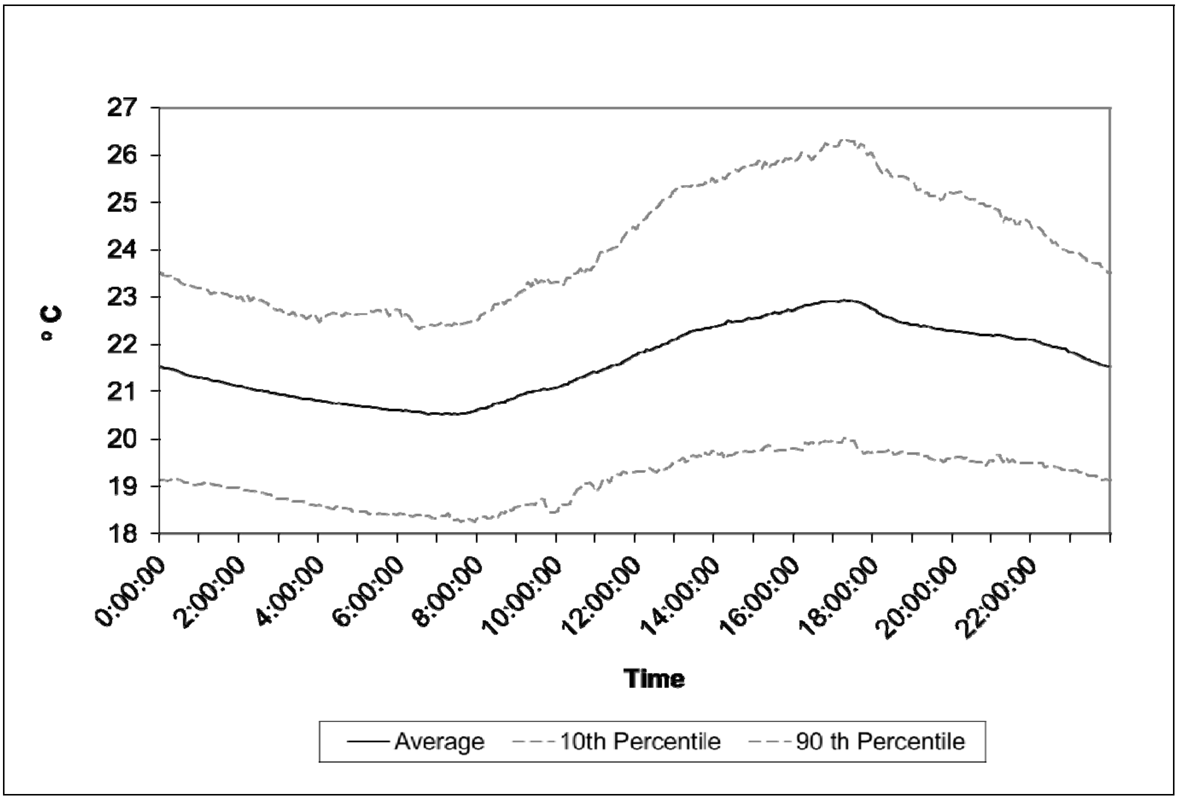


Figure 6-20. Summer Temperature Profile: Lime House

6.8 Comparison of Measured and Predicted Space Heating Performance

The measured monthly average external temperature and solar radiation and internal heat gains were substituted into the original PHPP calculations to predict the Monthly Space Heating Demand. Table 6-16 and Table 6-17 present the comparison of monitored space heating and normalised PHPP predicted space heating. In year 1 Larch House performs very well with the monitored space heating consumption of 13.0 kWh/m2 being below the normalised PHPP prediction of 15.5 kWh/m2. In year 2, the performance of Larch is again very good, 5.6 kWh/m2 compared to the normalised PHPP prediction of 4.9 kWh/m2. In year 1 the monitored space heating demand in the Lime is 30.3 kWh/m2, compared to the 16.5 kwh/m2 predicted by PHPP, in year 2 the monitored performance is 21.1 kwh/m2 compared to the predicted 4.8 kWh/m2.

Table 6-16. Comparison of Normalised PHPP prediction and monitored space heating , Year 1

	Larch		Lime	
	PHPP	MONITORED	PHPP	MONITORED
May	0	22	1	5
June	0	18	0	0
July	0	21	0	0
Aug	0	6	0	0
Sep	0	19	2	0
Oct	1	41	8	5
November	159	159	142	223
December	314	128	241	411
January	213	271	202	378
February	313	219	239	479
March	315	127	247	382
April	5	74	24	155
Annual Total kWh	1321	1105	1106	2036
Annual Total kWh/m^2	15.5	13.0	16.5	30.3

† Note January and February solar data was unavailable, data from the original weather file was used

Table 6-17. Comparison of Normalised PHPP prediction and monitored space heating , Year 2

	Larch		Lime	
	PHPP	MONITORED	PHPP	MONITORED
May	0	24	0	43
June	0	21	0	10.04
July	0	6	0	2
Aug	0	4	0	0
Sep	0	15	0	0
Oct	0	52	0	0
November	114.8	93	85.7	220
December	107.1	78	86.5	193
January	33.7	5	52.3	358
February	121.5	38	93.4	338
March	1.8	65	6.0	187
April	0.1	74	0.3	89
Annual Total kWh	379	475.0	324	1440
Annual Total kWh/m^2	4.9	5.6	4.8	21.2

The Co heating tests carried out in the post construction phase of the evaluation program had previously confirmed the fabric heat loss of the dwelling to be close to the design value. The in use estimated heat loss of the house is approx. 73 W/K compared to the design value of 45 W/K . Interviews with the occupants of Lime House revealed their preference to leave bedroom windows open at night during the winter. So the main cause of the under performance of the space heating consumption in Lime House is hypothesised to be due to the fact that occupants leave windows open for extended periods in winter.

This can be rationalised as follows:

If the bedroom window opening results in an extra 0.25 ach-1, this would account for the extra 30 W/k heat loss. This would also result in an extra space heating load of approx. 1500-2000 kWh. Window opening could easily account for the higher than expected space heating demand. Previous studies [50] have noted that some tenants of UK social housing open windows in winter in dwellings fitted with MVHR units. Dwelling 2 was certified via the 10W/m2 peak heating route, rather than the 15kwh/m2 annual method. The heat input of the space heating system regularly exceeded the 10 W/m2 peak target. In year 1 for 60% of the winter hours the system has 0 kWh heat output, 38% of the time the system output 15 W/m2, equivalent to 1kWh output in a 1 hour period in a 67m2 dwelling. The peak space heating output is 30W/m2, which occurs for 3% of the winter heating season.

For comparison with an average UK dwelling, if the specific space heating consumption of an average house is expected to be 100kWh/m2, this makes the Lime House year 1 performance, even with the master bedroom window open in winter, three times better than the consumption of the average UK dwelling and its year 2 performance five times better than the consumption of the average UK dwelling.

Lime House, with the master bedroom window open in Winter, performs favourably compared even to the design expectations of a CSH5 or CSH6 dwelling which would be expected to use, if performing as designed, a little less than 45 kWh/m2.

Summertime Overheating: **The summer time internal temperature performance of the dwellings is compared to CIBSE, PHPP and BS EN 15251 overheating metrics in Table 6-18 to**
Table 6-20.

Table 6-18. House Overheating Criteria Summary, Year 1

	Larch	Lime
CIBSE		
Living Room >28	0.9% < 1 % PASS	0.5% < 1% PASS
Bedroom >26	4.3% > 1 % FAIL	10.4% > 1 % FAIL
PHPP		
Living Room > 25	18.1% > 10% FAIL	19.1% > 10% FAIL
Bed Room >25	8.3 % < 10% PASS	16.1% > 10% FAIL
BS EN 15251		
% of time in Class 2 Comfort Range	73.3 %	95.6%
Criteria 1 Hours of Exceedence	431 Hours > 40 Hours FAIL	22 Hours < 40 PASS
Criteria 2 Days >10	25 Days FAIL	1 Day FAIL
Criteria 3 Hours > Tupp	45 Hours FAIL	0 Hours PASS

Table 6-19. House Overheating Criteria Summary, Year 2

	Larch	Lime
CIBSE		
Living Room >28	0.0% < 1 % PASS	0.0% < 1% PASS
Bedroom >26	12.5% > 1% FAIL	2.7% > 1% FAIL
PHPP		
Living Room > 25	51.7% > 10% FAIL	8.6% < 10% PASS
Bed Room >25	26.1% > 10% FAIL	6.2% < 10% PASS
BS EN 15251		
% of time in Class 2 Comfort Range	66.4 %	80.6%
Criteria 1 Hours of Exceedence	554 Hours > 40 Hours FAIL	37 Hours < 40 PASS
Criteria 2 Days >10	17 Days FAIL	0 Day PASS
Criteria 3 Hours > Tupp	27 Hours FAIL	0 Hours PASS

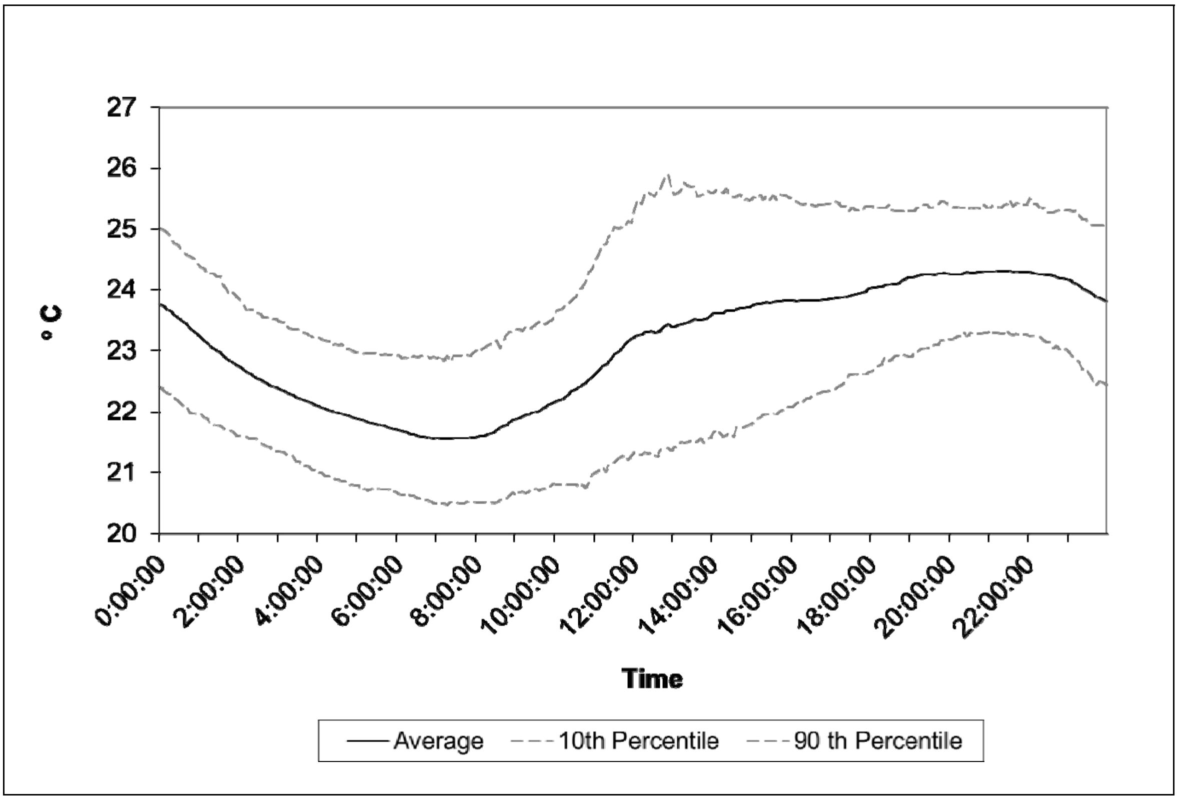
Table 6-20. House Overheating Criteria Summary, Average

	Larch	Lime
CIBSE		
Living Room >28	0.5% < 1 % PASS	0.3% < 1% PASS
Bedroom >26	8.4% > 1% FAIL	6.6% > 1% FAIL
PHPP		
Living Room > 25	34.9% > 10% FAIL	13.9% > 10% FAIL
Bed Room >25	17.2% > 10% FAIL	11.2% > 10% FAIL
BS EN 15251		
% of time in Class 2 Comfort Range	69.9 %	88.1%
Criteria 1 Hours of Exceedence	493 Hours > 40 Hours FAIL	30 Hours < 40 PASS
Criteria 2 Days >10	21 Days FAIL	1 Day FAIL
Criteria 3 Hours > Tupp	36 Hours FAIL	0 Hours PASS

In the summer of both year 1and year 2 Larch fails the CIBSE overheating criteria due to the number of hours the bedroom is above 26 ^{o}C. The PHPP criteria are passed in the bedroom in year 1 but fail in the living room in both years. In both year 1 and year 2 the BS EN 15251 criteria are not met as it fails all 3 Criteria. In year 1 Larch exceeds BS EN 15251, criteria 1 on 431 occasions, the average external temperature and global solar radiation at these times are 14.9 ^{o}C and 533 W/m^2. In year 1 Larch exceeds BS EN 15251, criteria 2, 25 times. In year 1 Larch exceeds BS EN 15251, criteria 3, 45 times. The mean difference between the summer living room temperature and the comfort temperature is 2.3 ^{o}C. In year 2 a similar performance is repeated with all 3 BS EN 15251 criteria exceeded, Criteria 1 554 hours, Criteria 2 17 days and criteria 3 27 hours.

The risk of summer overheating in Larch was found to be high but as previously noted, shortly before the second winter of this monitoring study, the occupants of the Larch House reported that the housing association had complied with their request for the solar override on the external blinds to be disconnected so that to shade the building, the blinds must be operated manually only. This gives the occupants complete control of when they choose to shade the building. Importantly to control Summer heat gains, it has now allowed them to lower the blinds and adjust the tilt angle to maintain shading while letting in plenty of light. Previously the blinds automatically lowered and raised many times a day in response to sun and clouds, putting occupants in darkness when they came down. Rather than go through the slightly fiddly process of adjusting the tilt of the blinds many times a day, occupants previously tended to simply press the 'up' button to raise them again. The occupants have agreed to allow the architects to continue monitoring the house for another year and it will be interesting to see if manual operation of the blinds improves summer temperatures inside the house.

Additionally it is noted elsewhere that occupants of the Larch House were not benefitting from the cooling benefits of the night time opening of bedroom windows. This was due to the family's fear of spiders and other insects. At the end of the monitoring period fly mesh was installed outside the window of bedroom 3 and the forthcoming year of monitoring will find whether this has benefitted the users.



In both year 1 and year 2, Lime House fails the CIBSE overheating criteria due to the number of hours the bedroom is above 26. In year 1 the PHPP criteria are failed due to the hours above 25 in both the living room and bedroom, however in year2 Lime House passes the PHPP criteria in both the living room and bedroom.

In year 1 The BS EN 15251 criteria are met as only Criteria 2 is failed. In year 2 all BS EN 15251 criteria are met. In year 1 Lime exceeds BS EN 15251, criteria 1 on 22 occasions. In year 1 Lime exceeds BS EN 15251, criteria 2 once. The mean difference between the summer living room temperature and the comfort temperature is -0.4 ^{o}C. . In year 2 Lime exceeds criteria 1, 2,and 3 , 37hours ,0 days and 0 hours respectively.

The risk of summer overheating in Lime House is low, and significantly lower than in Larch House during the test period. Larch House exceeds the BS EN 15251 criteria at lower external temperatures than Lime House. The distribution of the difference in the living room operative temperature and the comfort temperature as defined by BS EN 15251 are presented in Figure 6-21 for data the from both summers.

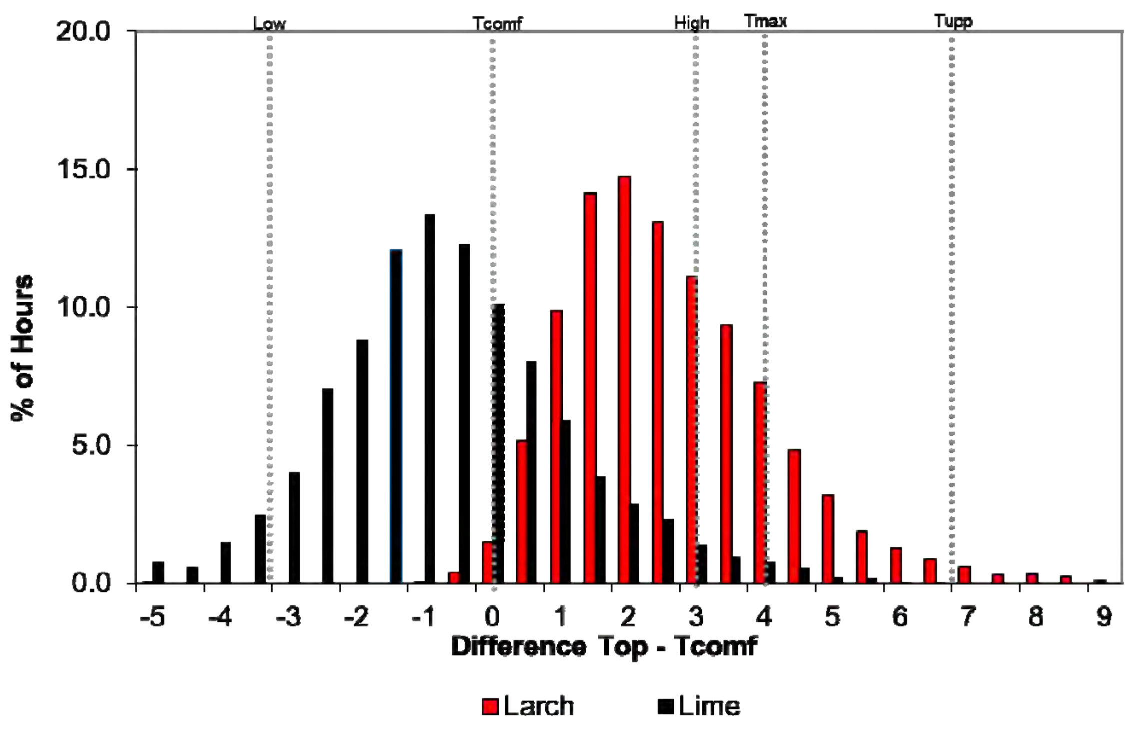


Figure 6-21. Distribution of the difference in living room operative temperature and summer comfort temperature

The difference between the summer performance of the two houses shown in fig 6-21 is thought to be due to:

- *Larch House user reaction to the automatic operation of the blinds. Larch House is fitted with external blinds on the south facing windows. These have slatted louvres that can be tilted by the occupants to allow natural daylight in and views out when the blinds are lowered on a sunny summer day. Interviews and discussion with the occupants after the first year of occupation revealed that they did not fully understand how to use the external blinds, or tilt the louvres. When the blinds were automatically lowered by the controls in the fully closed position, the occupants simply pressed the 'up' button to regain daylight even though this meant that the large windows were not benefitting from solar shading.*

- *The resistance to using natural ventilation in summer to achieve night time cooling in the Larch House due to spiders and other insects.*

Both these issues have now been addressed and will be watched in the third year of monitoring.

The blinds were adjusted to manual operation just before the last winter of the funded monitoring period. It remains to be seen if this helps summer temperatures during the next year of non-funded monitoring.

The occupants also reported that they did not like ventilating the bedrooms during summer by opening the windows as this allowed spiders to enter the bedrooms. It is hoped that after installing insect mesh outside the bedroom windows, better summer time performance will be achieved during the next year of monitoring.

It should also be noted that the heat recovery units installed in both houses do not have the benefit of a summer bypass. This means that the warmth from the outgoing air is recovered and put back into the incoming air in the summer months as well as winter. A system with a summer bypass, while costing a little more money, is now considered by the design team to be worthwhile unless it is certain that the occupants will fully understand and utilise night time purge ventilation.

6.9 Discussion

Space heating (Larch House): Larch House has a large area of south facing glazing which, even on a bright overcast winter day, helps to warm the house. In the first year of monitoring, with 3570 degree days, the house required 13kWh/m^2 of heat energy, which was even better than the 15kWh/m^2 Passive House design target. In the second year of monitoring the house again bettered the 15kWh/m2 Passive House target with a winter space heat requirement of only 5.6kWh/m2, for a year with 2985 degree days. These results represent an estimated 90-95% saving compared to a building designed to current UK Building Regulations.

Space heating (Lime House): Lime House had a space heating performance of 30 kWh/m^2, in year 1 and 21.2 kWh/m^2 in year 2, exceeding the expected requirement of 17 kWh/m^2. Lime House was certified via the 10W/m^2 peak heating route, rather than the 15kwh/m2 annual method and the heat input of the space heating system regularly exceeded the 10 W/m^2 peak target. The heating performance of Lime House is due to leaving bedroom windows open for extended periods in winter. In spite of this, the energy use found in the Lime House is significantly better than the design expectations of normal houses in the UK. Even with its master bedroom window open for extended hours in winter, the Lime House out-performs the design target of houses designed to the top level of the Code for Sustainable Homes which are designed to achieve heat requirements of no more than 45kWh/m2.

Summer comfort (both houses): The occupants of both houses were affected by some summer overheating. This was due to problems discussed in 6.8, namely:

- Less than expected summer night cooling from secure tilted-open bedroom windows due to the occupants' fear of spiders entering the house through open windows.
- Overriding the automatic operation of the external blinds in the Larch House which resulted in less than expected use of the available summer shading. This caused larger external heat gains than expected in the summer months.
- Poor quality pipework insulation which resulted in increased internal heat gains. In both houses, pipe fixings made of metal with long stems were specified to allow hot water supply pipes to be fully wrapped with insulation. However the plumber instead used common plastic pipe clips and poor quality pipe insulation. However these clips hold pipes too close to the walls and so make it impossible to fit the specified thick-walled insulation around the back of the pipework. Pipework installed in this way

loses more heat than expected, and although this would not be significant in an ordinary house, it is thought that the resulting internal heat gains may contribute to summer overheating.

- Greater use of televisions, games consoles and other appliances than expected. Gains from electrical appliances are 6.1 W/m^2 and 4.9 W/m^2 respectively in Larch House and Lime House, far exceeding the standard 2.1 W/m^2 assumed in the PHPP design calculations.
- Heat losses from using a 'C' rated oven daily for extended periods in the Larch House. The client's tenants are required to supply their own appliances such as ovens and hobs. 'A' rated appliances are mandatory in a Passive House, but neither house complies with this requirement. Apart from affecting primary energy consumption, use of a poorly insulated oven will inevitably lead to higher than designed internal heat gains which may contribute to Summer overheating.

A strategy to address summer overheating has been discussed with the Larch House tenants and was put in place towards the end of the second year of monitoring:

- Insect mesh has now been fitted to bedroom 3 (north facing) and supplied for the tenant to install in the two south facing windows to facilitate night time cooling.
- The blinds are now operated manually as discussed.
- The occupants have now bought an efficient portable halogen oven.

The impact of these adaptions will be tested in year 3 of monitoring (which will continue beyond the end of Technology Strategy Board funding), but it can already be reported that the portable halogen oven has reduced electricity consumption for cooking by 40% (see Figure 6.-22).

Our recommendations for future social housing designs would be:

- Use average weather data as recommended by PHI. If this is done, whether using Specific Heat Demand or Peak Heat Load as a certification factor, more moderately sized windows than in the Larch House will be found to suffice. More moderately sized windows will save capital costs (smaller windows are cheaper than large ones and if blinds aren't needed this will also save money).

- Insect mesh screens should be considered to encourage occupants to freely open windows on tilt on summer nights.
- Ensure that all parties commit to high standards of hot pipework insulation from the outset, and understand that the normal close-coupled pipe clips will not be allowed.
- Consider policies that might ensure the house is fitted with A-rated appliances.
- Provide guidance notes and one-to-one support to help the tenants get the best out of their house.

Our recommendation for privately owned housing of a similar design would be, in addition to the above:

- Where large windows are desired, use Warema or Hella external louvred blinds (as Larch House) but instead of basic radio controlled operation, it is essential to use a hard-wired intelligent controls system that can be programmed to let sun into the house during the winter when it is needed, and keep it out during the summer when it is not wanted. When the blinds are automatically lowered, the controls should also be set so that the blinds automatically tilt to allow views and daylight while keeping out any unwanted sun.

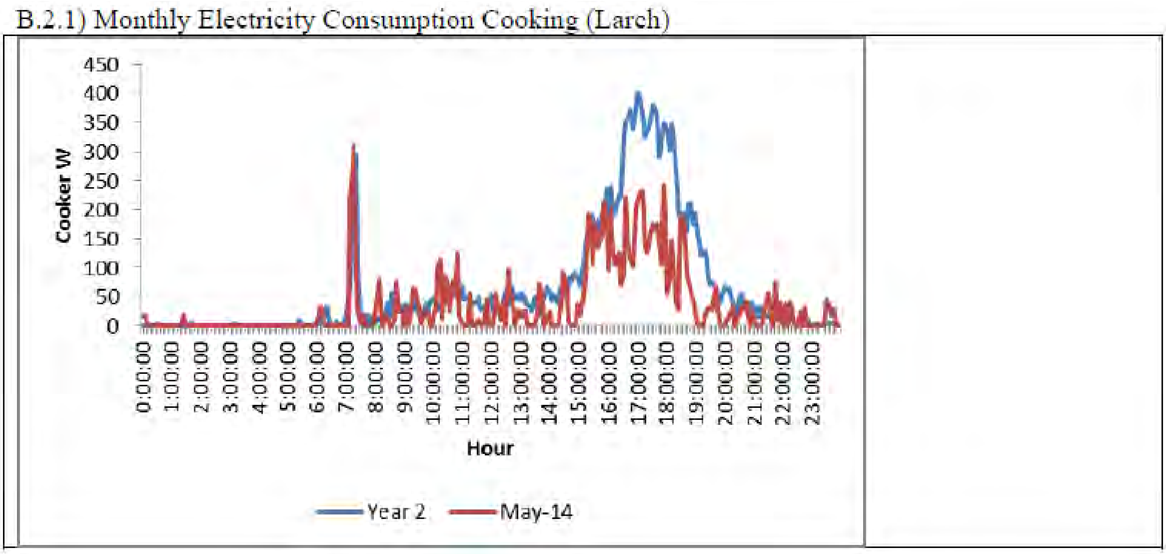


Figure 6-22. In May 2014 the occupants of the Larch House replaced the cooker with a new halogen oven, as a consequence the electricity consumption for cooking reduced by 40%. The profile of oven use remained the same, but the peak power use of the oven in the evening was significantly reduced.

Electricity use generally: Overall electricity consumption, though found to be average when compared to standard UK houses, was found to be high compared to PHPP design targets. Reasons include:

- Greater use of irregulated energy consumption than expected from televisions, games consoles and other tenant-owned appliances. Gains from electrical appliances are 6.1 W/m^2 and 4.9 W/m^2 respectively in Larch House and Lime House, far exceeding the standard 2.1 W/m^2 assumed in the PHPP design calculations. Occupant choice of appliances can form a significant percentage of the energy performance of a building that uses as little regulated energy as a Passive House.

- The occupants of Larch House were found to be atypical by UK standards in terms of the energy used for cooking, consuming over 700 Kwh annually where a typical family in the UK has been found to consume less than 100 kWh for cooking.

Primary Energy: Both dwellings exceed the 120 kWh/m^2 primary energy target for Passive Houses (primary energy includes transmission losses from power stations – a unit of energy which is much higher than metered energy consumption). The Primary Energy target was missed for the reasons stated above in the section on 'electricity use generally'. High socket loads have the following results:

- The primary energy target of the dwellings, 120 kWh/m^2,is difficult to achieve.

- The net zero energy and Code Level 6 target of Larch is difficult to achieve with a 4.7 kW peak PV system even though the PV system produces yields of over 850 kwh/kW peak, which is good best practice performance for systems in the UK.

Local weather data: Due to the pioneering nature of the project and the cautious requirements of the design brief, the dwellings were designed using a PHPP weather file based upon the worst of 10 years of local climate, rather than the average conditions that would normally be used for the PHPP weather file. The houses were intended as prototypes for Ebbw Vale and other similar exposed sites and in view of this the BRE decided that for the first two houses it would be wise to err on over-specification of the fabric of both houses for these two prototypes. The decision was influenced by some uncertainty about the precise local weather conditions used to create the weather data file; it was thought that in reality average local conditions might be more severe than the conditions upon which the average weather data file was based. The weather data results were as follows:

- The monitoring found that Larch House met the 15 kWh/m^2 space heating criteria even during the coldest winter/spring of the last 40 years, demonstrating that, as would be expected when using an extreme weather data file, Larch House met the standard Passive House space heating requirement in an exceptionally cold winter.

- During the milder second year of monitoring, which is more representative of average weather conditions, Larch House performed, as would be expected when using an extreme weather data file, better than the standard space heating requirement, requiring only 5.6 kWh/m2 for space heating.

- With careful design, construction and operation, net annual CO_2 emissions below10kg/m^2 can be achieved, even in locations with harsh climates with greater than 3000 heating degree days. The results of this research project indicate this is possible in UK social housing certified to the Passive House standard and fitted with 5kW peak PV systems. Net zero carbon performance may require larger PV systems or decreased appliance use.

Strategies to incentivise and enable occupant behaviour and appliance choices may be needed if Passive House primary energy targets and net zero energy performance targets are to be met.

“Behavioural” factors, such as summer ventilation and shading practices are crucial to the overheating risk.

Opening of bedroom windows in winter impacted on the space heating performance of Lime House. Behavioural or occupant choices in terms of appliance use impacted on the electricity and primary energy consumptions of both dwellings.

6.10 DomEARM analysis

During the BPE phase 2 there were two DomEARM analyses. DomEARM is an energy survey developed by Arup and stands for “Domestic Energy Audit and Reporting Method”. It is based on CIBSE TM22 but modified for domestic use. It has three levels of operation and is calibrated against CHESS benchmarks for energy uses. The first level provides basic energy meter reading data, the second level has sub-metering and circuit readings, while the third level provides an in-depth audit of all the energy consuming equipment in the home.

For both the Larch and Lime Houses a Level 3 analysis was done at the end of the first and second year of monitoring. For each house and each analysis a report was prepared and submitted to TSB. They can also be found in Appendix 13.

The Level 3 assessment shows a comparison of the annual energy performance, CO2 emissions and energy costs with benchmarks, namely a UK average, Part L compliant, CSH 4 and CSH 6. As seen from the following graphs the results from the Welsh houses are very impressive, with both houses performing in general more efficiently than the benchmarks.

From the graphs 6-23 & 6-24 it is striking that non-electric energy (eg gas and oil) represent, on average, by far the largest source of domestic energy consumption in the UK. Both the Larch and the Lime House gas consumption is roughly 80% lower than the UK average.

Domestic electricity consumption is much smaller than gas and oil consumption, however in both Larch and Lime Houses it is higher than the benchmarks mostly due to the fact that gas is not used in the kitchen, only being used for the boiler. Larch House has much higher cooking loads than average in the UK as previously discussed, and it is therefore unsurprising that electricity usage was roughly 50% higher than the UK average (Figure 6-24). Electricity consumption of the Lime House is roughly 15% higher than UK average (Figure 6-24).

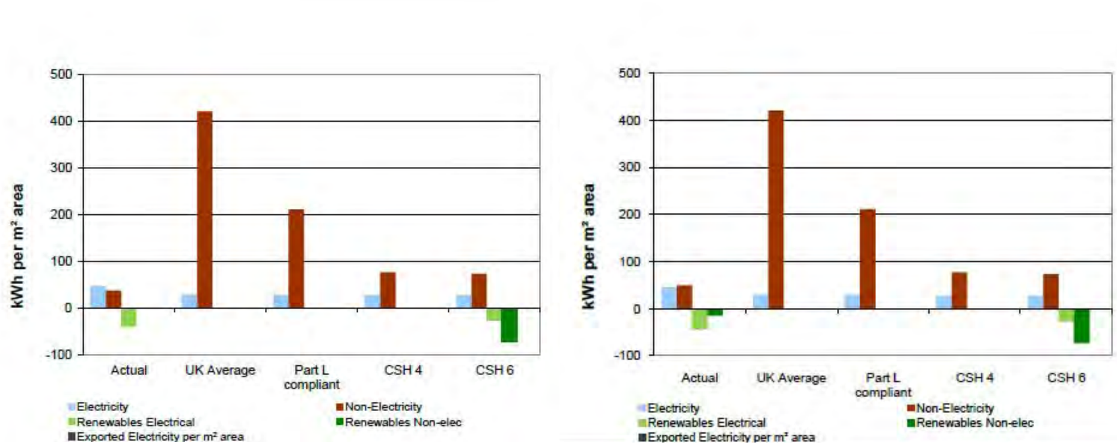


Figure 6-23. Larch House – Annual energy performance compared with benchmarks (first year on left, second year on right).

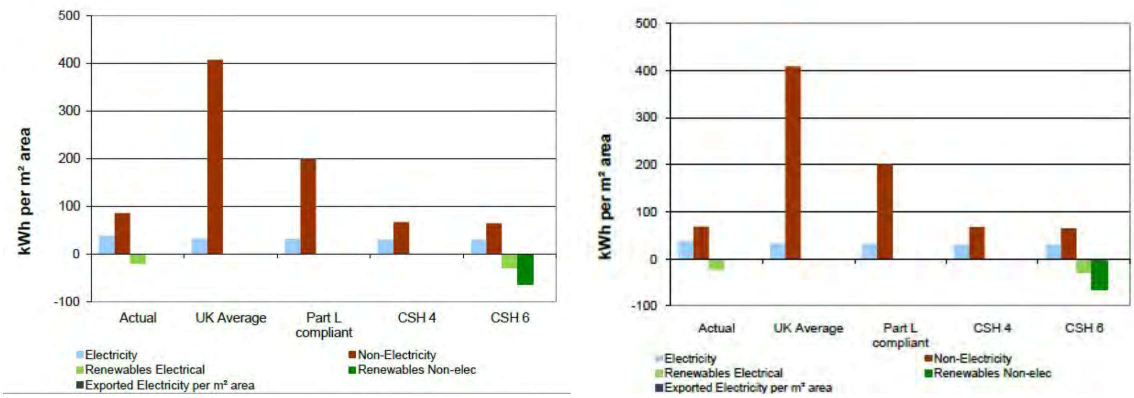


Figure 6-24. Lime House – Annual energy performance compared with benchmarks (first year on left, second year on right).

The annual CO2 emissions per m2 for both houses are dramatically lower than the UK average and still lower than the CSH levels (Lime house emissions improved in the second year).

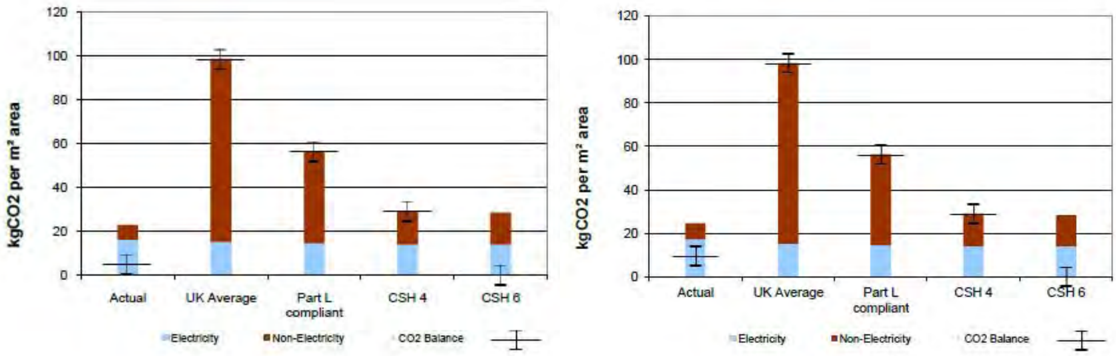


Figure 6-25. Larch House – Annual CO2 emissions per m2 compared with benchmarks (first year on left, second year on right)

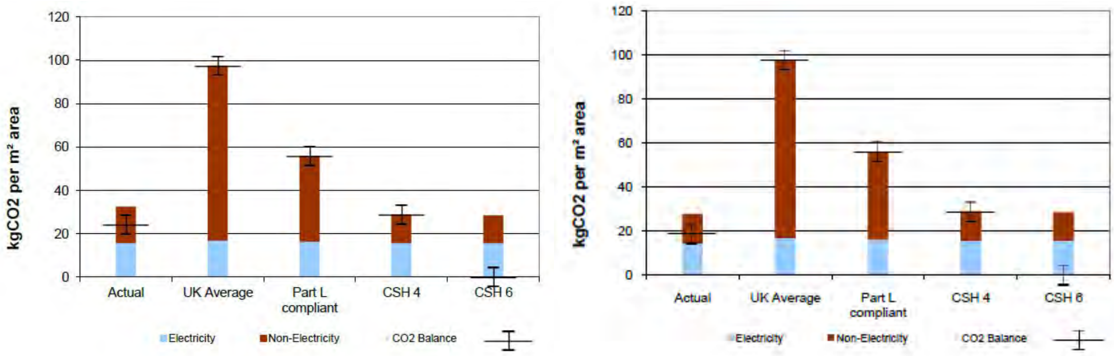


Figure 6-26. Lime House – Annual CO2 emissions per m2 compared with benchmarks (first year on left, second year on right)

Regarding energy cost, both houses spend less than the UK average and slightly more than CSH.

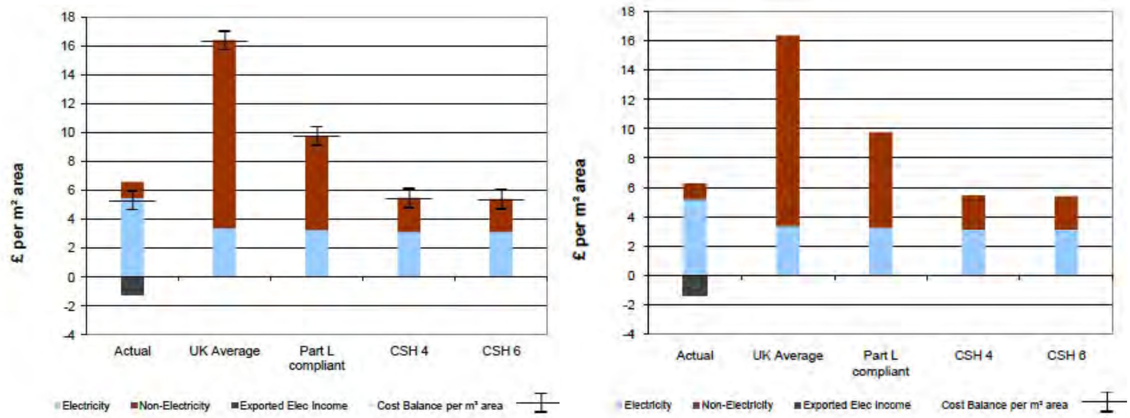


Figure 6-27. Larch House – Annual energy costs compared with benchmarks (first year on left, second year on right).

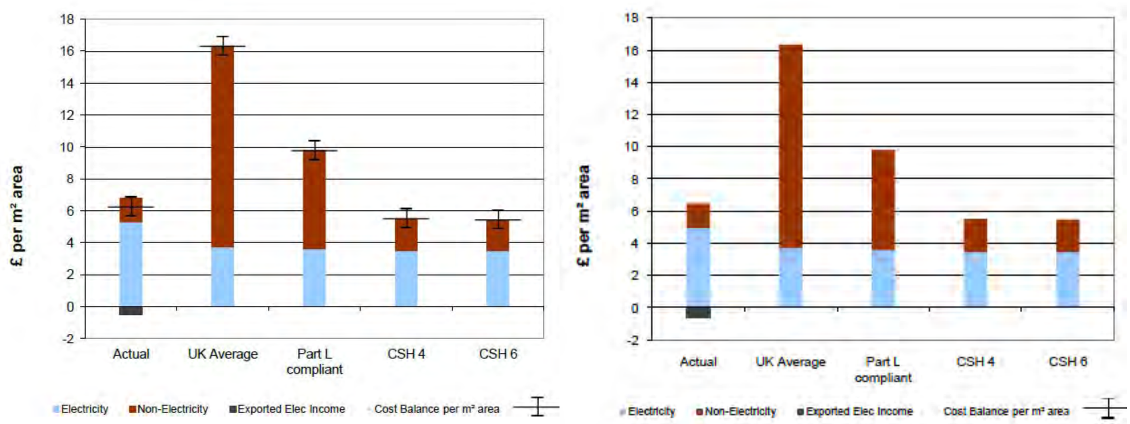


Figure 6-28. Lime House – Annual energy costs compared with benchmarks (first year on left, second year on right).

6.11 Conclusions and key findings for this section

- To be certified as a Passive House, a building should have at least A-rated kitchen and laundry appliances installed in them. However the housing association did not supply these appliances and residents were required to bring their own, which in both houses were not A-rated. As a result, the socket loads of both houses are much higher than expected, although they were found to be similar to UK average socket loads. The pattern of use of these appliances was also found to be a factor in the residents' higher than expected socket use. There is significant scope for the residents of both houses to reduce their electrical appliance consumption if they wish to do this, and a start has already been made in the Larch House by the use of a more efficient oven as shown in the graph in section 6.9 of this report.

- It is important to note that the occupants are very happy with their houses and with the very low energy bills that they enjoy, nevertheless in the ongoing monitoring of these two houses, which will be implemented outside the scope of Technology Strategy Board funding, it is the intended to see whether occupants can be helped to reduce their electrical socket use without compromising their enjoyment of the houses.

- Occupant patterns of use also affected summer time overheating in Larch House (section 6.8 of this report), which by the criteria of BS EN 15251 is considered severe. By estimating the summer time heat loss and the ventilation rate, Dr Ridley calculated that occupant behaviour in Larch House may have contributed to its overheating by not opening the bedroom windows at night in the summer months to achieve purge cooling. Again this is a matter that the occupants are keen to address. Insect mesh has already been installed outside one of the bedroom windows and it is due to be installed outside the others before the next heating season in order to see what benefits can be achieved by enabling the occupants to open the windows without fear of spiders and flying insects entering the house.

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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 houses include:

- A heat recovery ventilation system (HRV, commonly referred to as MVHR);
- Natural gas boiler;
- 200 litres hot water cylinder;
- Solar thermal collector (Larch 4m^2 / Lime 3.3m^2)
- A photovoltaic array system (Larch 4.7kWp / Lime 1.89kWp)

The ventilation system is a Paul Focus 200 heat recovery ventilation unit located in an entrance cupboard at the Larch House and in a cupboard off the kitchen at the Lime house with a quoted heat recovery efficiency of 91% and no summer bypass. The system is designed to provide a constant background ventilation rate of 120m^3/hr in both houses.

Space heating is provided via air by a 1kW (max output) heater battery (heat supplied by the hot water cylinder) in the supply air duct of the ventilation system. In the Larch House the heating is complemented with towel radiators in the bathrooms.

Domestic hot water is supplied by the 200l hot water cylinder. The cylinder stores hot water from the solar thermal collector and is supplied with supplementary heat by the gas boiler.

7.2 Heat recovery ventilation unit re-commissioning

The ventilation systems were originally commissioned in July 2010 after construction completion. This was done by Andrew Farr, the ventilation system designer from Green Building Store. A second commissioning report was carried out in June 2011 by Andrew Farr again, in preparation for the TSB BPE phase 2 report. Both reports have been submitted to the Technology Strategy Board and can be found in appendix 14 and 15.

In both houses the mesh grilles in the air intake louvres that are designed to catch large fragments of debris were found to be heavily blocked by insects and general dust from the adjacent construction site - Figure 7-1. The constant volume fans were found to be running noisily to compensate for the additional pressure loss from the blocked grilles. The mesh panels were not easily accessible for cleaning and since the internal filters were expected to be changed frequently, it was decided to remove the outer mesh panels to simplify maintenance (filter maintenance is discussed in 7.3).

Figure 7-1. Intake and exhaust mesh, showing accumulated debris from neighbouring construction site.

In both houses, due to the depth of the carpet and underlay that was fitted, the air transfer paths via door undercuts from bedrooms were found to be too small at <5mm giving rise to airflow speeds of >1.3 m/s. This exceeds the Passive House specification as it may lead to over-pressurisation of the external fabric of the room concerned, with an impact on infiltration heat loss.

Lime House

During commissioning, measurements of flow rate and power consumption were taken with both dirty and clean filters. Measurements were taken with dirty G4 filters and clean G4 and F8 filters. Unsurprisingly with the dirty G4 filters the pressure loss across the filters increased. The higher grade filtration F8 filters also increased the pressure loss across the filter because the ventilation unit has a 'constant volume flow' fan which compensates for the variation in resistance to air flow (pressure loss) with higher fan speed to maintain the constant air flow. This means that, even with infrequent maintenance, air quality will be maintained as far as possible but dirty filters will have an impact on the energy consumption of these units.

Tests were also done with different fan speeds (usually set according to occupancy rates: fan speed 1 for low occupancy; speed 2 for normal occupancy; speed 3 for increased occupancy). In the Lime House it was confirmed that fan speed 2 would provide the 'as designed' air flow in the supply and the extract valves.

Larch House

As in the Lime House, the internal air flow rates were similarly affected by the various filters used in testing. The results for the Larch House were in line with the Lime house results. The dirty G4 and higher gradation F8 filters lead to increased pressure loss in the filters and increased fan power consumption in about 5%. The flow rates were checked and found to be stable in all cases, indicating that the constant volume fans were working effectively.

Apparently there was more air measured internally than externally but the minimal difference could be explained due to the deviation of measuring techniques. Tests were also done with different fan speeds. Again fan speed 2 was found to provide the correct air flow as determined in the design stage.

7.3 Filter maintenance and HRV performance

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.

Heat recovery ventilation (HRV) units are relatively new to the UK but rapidly becoming more widely adopted. There has been 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 is to set minimum standards for training, design, installation and maintenance. In the Welsh Passive Houses the design team worked closely with the suppliers, consultants and installers to ensure the systems are working optimally. Moreover the design team carried out several workshops and interviews with the client, tenants and maintenance team (following the Soft Landings approach – refer to chapters 4 and 5) to ensure the knowledge was transferred to all involved with the buildings.

The HRV filters are a crucial element in the ventilation system performance. They ensure good indoor air quality by filtering the external air pollution and they ensure that the heat exchanger and ductwork are kept clean from dust particles. They are normally installed in the HRV unit, in the frost protection unit and in the kitchen extract valve. It is important to change them regularly (or clean them in the case of the kitchen extract valve) to optimise energy efficiency and comfort levels. 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.

During the monitoring period the filter maintenance was assured by the design and technical team on their frequent visits to the houses. After they were changed during the second commissioning report in June 2011 (detailed earlier), the filters were again replaced in November 2012 when Andrew Farr, the ventilation system designer, carried out a site visit. On that visit Andrew Farr changed both systems to a 'two-filter' system, removing the G4 filter inside the HRV unit and keeping only the single F8 filter in the ISO Frost Protection (intake) and the G4 filter on the exhaust. The next filter change was scheduled to be done by the client in six months' time or 1 year's time the latest in November 2013 but this wasn't done.

At the end of 2013 the design team held a knowledge transfer meeting with the new maintenance team company to explain the particularities of the Passive House standard construction, emphasizing the systems and maintenance requirements (as described in chapter 4.3). During this meeting the maintenance team were made aware that the filters hadn't been changed for one year, and that the usual interval for filter changing is six months. The maintenance team was to proceed with the filter change as soon as possible.

However, despite several contacts from the design team with the client and the maintenance team after the meeting, the HRV filters were not replaced until April 2014 in the Larch house (one year and half since the previous change) while in the Lime house, they hadn't been replaced at the time of writing of this report (July 2014, one year and seven months from the previous filter change in November 2012).

In June 2014 the design team did an analysis with the monitoring data to investigate the impact of the filter replacement in the electricity consumption of the HRV units in the two houses. It was assumed that the systems are set on fan speed 2 although there are no records of whether the tenants changed this setting. Also we must note the electricity consumption during winter includes the direct electric pre-heater consumption which will automatically operate in the event of frost.

Larch House

In the Larch House it was noticed that after the filter change in 2012 the electricity consumption of the unit decreased to approx. 20-30 kWh/month and started to increase after one year, around November 2013 when they should have been replaced, reaching 40kWh/month in April 2014. When they were changed the consumption dropped again to below 30kWh/month (Figure 7-2).

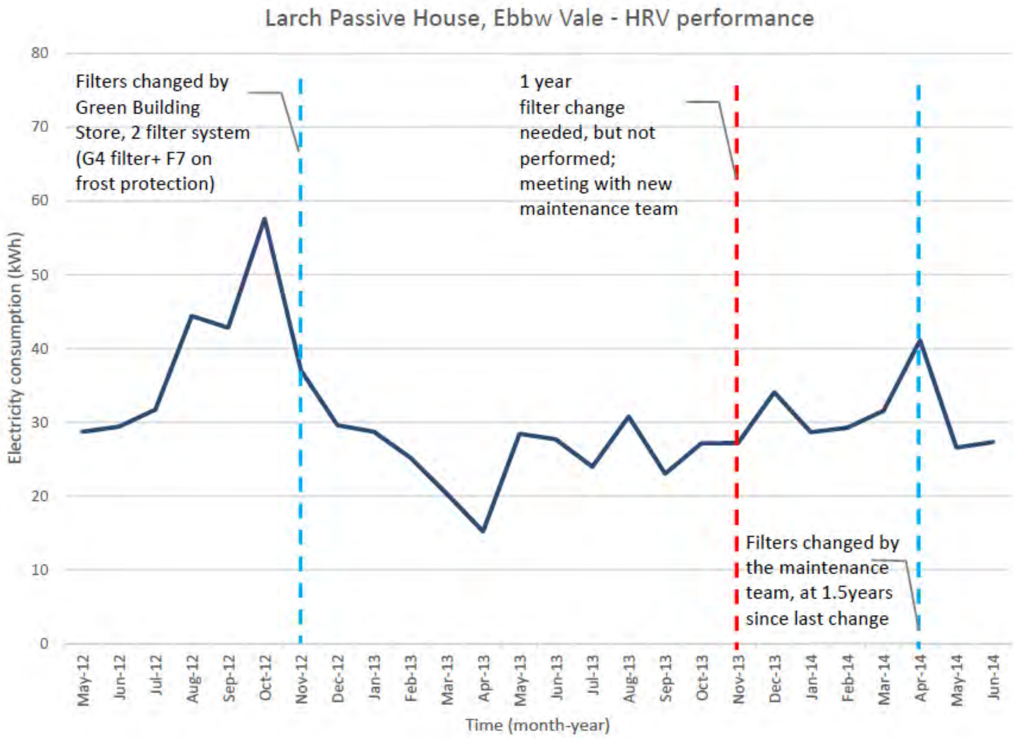


Figure 7-2. Larch House – HRV energy performance analysis

A close-up analysis of the monitored power wattages during the first week in April 2014 (before the filters were changed), compared with the first week in May 2014 (after the filters had been changed) and then a similar week in June 2014 showed that the power decreased from 45W in April to 39W in May and 37W in June 2014. During the re-commissioning of the HRV unit in June 2011 the fan speed 2 was found to correspond to 40W fan power. It was therefore deduced that the extra c. 5W can be apportioned to the filters being dirty, meaning an approx 10% variation (increase) of the fan power due to dirty filters.

Lime House

In the Lime house, when analysing the HRV energy performance, a more worrying phenomenon was detected (Figure 7-3). At the time of writing the report the filters had not been changed since November 2012. This is apparently due to the fact that the tenants are working and the maintenance team could not find a suitable date and time to visit the house. The electricity consumption seems to have increased constantly since March 2013, but, alarmingly, seems to be decreasing recently. According to the HRV supplier, this can be due to the fact that the fan may be cavitating due to the clogged filters, so the air resistance is decreased and the fan effort reduced. Unfortunately, this may damage the HRV unit. Celtic Horizons and the occupant have both been advised of this but neither party appears to care enough to organise a filter change.

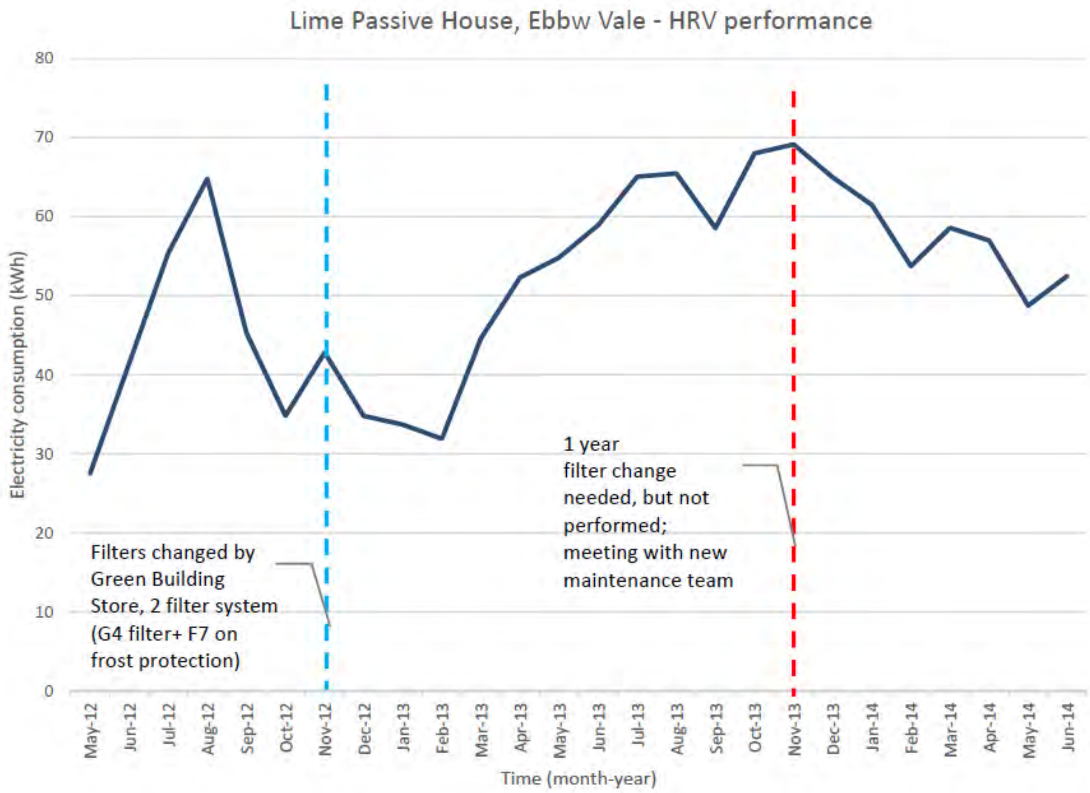


Figure 7-3. Lime House – HRV energy performance analysis

It is important to note that CO2 levels were found to be within the recommended range most of the time. Since the PAUL ventilation units have 'constant volume flow' fans, there is no negative consequence for the indoor air quality. With dirty filters the fan will work faster to compensate for the increase resistance to air flow (pressure loss) and maintain the constant air flow. The main concerns are (1) increase in energy consumption (2) damage to the equipment if the replacement is ignored for too long (over a year in this case).

7.4 Space heating and boiler

In both houses space heating is provided via the supply air by a 1kW (max output) heater battery (the heat is supplied direct from the boiler in the Larch House and by the hot water cylinder in the Lime House). In the Larch House the heating is supplemented with towel radiators in the bathrooms and the airing cupboard. Both these radiators have been found to be unnecessary. The Lime House relies only on heating supplied via the ventilation system.

In June 2011, Alan Clarke, the M+E engineer joined Andrew Farr on the re-commissioning of the mechanical systems.

Larch House

In the re-commissioning, Alan Clarke tested the boiler and it was seen that the boiler flow temperature rises steadily until the boiler ceases firing at 5°C above the boiler flow set point, and then cools again as the pump continues to run. The boiler cycles on this basis whilst there is demand for heating and there was no sign of the boiler temperature rising too fast or the boiler controls locking out.

Typical running temperatures to the air heater are 75°C flow (boiler set point) and 65°C return. It was intended to run at lower temperatures however the heating coil installed was smaller than originally specified. As the house was due to open for the Eisteddfod Festival, and the boiler temperature could be adjusted, it was decided to leave the system as built but to fit the larger coil (with lower water temperatures) in the second house to compare performance.

At these water temperatures the temperatures at the coil (measured externally on the copper pipe) were 68°C flow and 64°C return. The air temperature off the coil is 44°C. This rises slightly as the system temperature fluctuates, but has not been seen to exceed 50°C, the highest temperature normally advisable to avoid a smell of scorching in the air. The slight under capacity in the heating system is not expected to be an issue here as there is ample capacity in the towel radiators to make up for any shortfall in the air heating.

With off-coil temperature of 44°C the supply air temperatures were measured as follows:

Room	Supply air °C
Living	37
Dining	38
Bed 1	35
Bed 2	33
Bed 3	33

There appears to be significant duct heat loss, about 10°C in some cases, though no problem maintaining desired room temperatures in winter. It is probably beneficial that it is the bedrooms, with longer duct runs, that suffer the most heat loss.

In January 2013 Alan Clarke revisited the house to help solve a fault in the heating system. It was found that the hot water cylinder sensor had come out of its pocket meaning the boiler thought the water was only at 20°C and when the programmer was set to heating + hot water the boiler diverted to hot water only to try to heat the water to its set temperature. The tenants said that the house felt warm enough without the air heating and it seems the whole house was comfortably warmed during this period by the bathroom towel radiators. Alan Clarke refitted the sensor into the tank and this solved the problem.

Lime House

In the initial commissioning the airflow was set by Green Building Store to sensible levels for ventilation, putting 60% of the air into the bedrooms and 40% into the living room. Most of the extract is at ground floor level so some of the ventilation air from bedrooms is drawn through downstairs rooms, providing more fresh air when bedrooms are unoccupied. Although this is a good arrangement for fresh air supply, it proved less good for heating: during the first winter of operation (the year before occupation) room temperatures were typically 2°C higher upstairs than downstairs, so the ventilation was re-adjusted to provide 60% downstairs and 40% upstairs. After this change monitored supply air temperatures were higher downstairs than upstairs, successfully re-balancing the temperatures experienced across both floors.

Note that this commissioning was done before the houses became occupied. Now, after about two years of occupation we can evaluate if this re-adjustment proved successfully. Figure 7-4 shows the average monitored temperatures over the two years of the phase 2 of the BPE study. During this period the difference of temperatures between ground (Living room and kitchen) and first floor (bedrooms) was negligible, so the ventilation re-adjustment seems to have been a good idea.

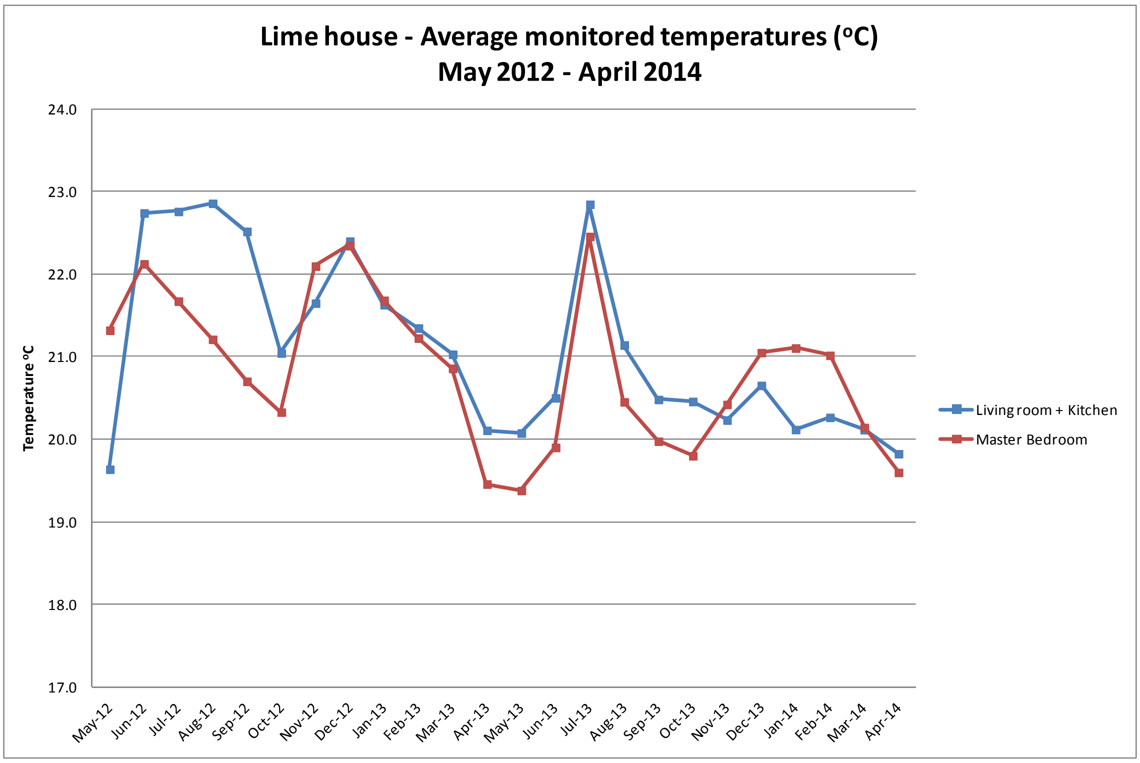


Figure 7-4. Average monitored temperatures in the Lime House over the two years of BPE study.

In early 2012, before the tenants moved in, the boilers in both houses stopped working due to pump failure. It was found out that the pumps had overheated and failed due to low water pressure. The mains water had been turned completely off by the contractor because its pressure was too high. The pumps were replaced and pressure reducing valves were fitted in the mains water supply to both houses and the boilers started working again.

7.5 Solar Thermal Unit

Each house has a locally manufactured Filsol flat plate solar thermal collector. The Larch House has a total of $4m^2$ and Lime 3.3m2 according to the size and expected occupancy of the houses.

The Larch House solar thermal system was designed to use a pressurised system but it was intended to use a drainback system in Lime house to compare operation and reliability of the alternative approach. However the installers felt there was not room for the drainback tank in the airing cupboard and fitted it in the loft of Lime House. Alan Clarke pointed out that this is inaccessible and not a frost free location, so not viable and the installer converted the system to a pressurised system.

The solar thermal systems in both houses had a number of problems from the outset that the installer seemed incapable of repairing and so a third party solar specialist, Llanisolar was commissioned to examine the systems. The principal finding was that the switch from drainback to pressurise in Lime house carried out without changing the pump station, leading to thermo-syphonic loss of heat from hot water tank to panels – this cannot happen with a drainback system but in a pressurised one a non-return valve is needed. The installer was asked to fit the correct type of pump station and expansion vessel, which has now been done. However at the time of installation of the monitoring equipment (October 2011) the system had lost pressure and the pump was unable to circulate fluid, and at the time of writing this report, the solar thermal system is still not working, three years after completion of the building.

The Llanisolar report also found that the return temperature sensors were not fitted by the contractor correctly – these are needed for kWh monitoring only so do not affect operation but did lead to odd readings on the public display panels. When installing the monitoring equipment these sensors were found to be fitted securely but to the flow pipework not the return, and had to be refitted to the correct pipes.

In the meanwhile the systems installer company Micaul Solar was dissolved and despite the best efforts from the design team to have the client and maintenance team to fix the problems with the Lime House solar thermal system, they still have not been solved.

An analysis done by Dr. Ian Ridley (2014) estimated a loss of 1000kWh/year of potential savings. For comparison, in the Larch House during the second year of the BPE study its solar system worked reliably contributing 1250kWh of heat energy to the cylinder.

Rob McLeod, former technical manager at BRE Wales, commented (see section 9.2):

"The energy not saved by the solar thermal system in Lime House is on a par to the total heating demand of the building. It is *of enormous significance, it's equivalent to the energy saved by going from building regulations to Passive House, which is lost because the installer has not done his work*. Microgeneration technologies need to be installed by MCS certified installers and these installers need to be reported if the systems are not working as intended – this finding needs to go back to the industry."

7.6 Photovoltaic (PV) system

Each house has PV array generating electricity that is either used directly in the houses if equipment is drawing energy, with the excess exported to the grid. The Larch House has a 4.7kWp system installed, while the Lime House has 1.89kWp system installed.

At design stage the Larch House had a much smaller system specified of 2.40kWp that was upgraded just before construction so that the house could meet the Code of Sustainable Homes Level 6.

In the Lime House the specified design system was 2kWp to achieve the Code of Sustainable Homes Level 5. However, for some reason, this failed to happen and a fractionally smaller system than required for Code 5 was installed. When this was found out, after completion, the client chose not to upgrade the system to the specified size and the Lime House was certified as Code Level 4, although it is effectively Code 5.

The PV systems have so far worked well with no technical problems. The monitored annual energy production results are presented in Table 7-1 in comparison with design prediction and SAP as built predictions.

Table 7-1. Photovoltaic system annual energy production design vs average 2 year monitored data

(kWh/year)	System designed	PHPP design predictions	SAP design predictions	System installed	SAP as built predictions	Monitored (av. 2 years)
Larch house	2.40 kWp	2584.00	1958.96	4.70 kWp	3834.56	4210.00
Lime house	2.00 kWp	2584.00	1636.80	1.89 kWp	1546.78	1761.00

Compared to design predictions the systems are performing better than expected. The Larch House has an average annual production of 4210kWh, a 9% increase from the SAP 'as-built' predictions and the Lime House has an average annual production of 1761kWh, 12% higher than SAP 'as-built' predictions. According to Dr. Ian Ridley's calculation the Larch House system offsets an average of 71% of the dwelling's CO_2 emissions in the two year monitoring period, while the Lime House system being smaller has offset 56% of the dwelling's CO_2 emissions.

7.7 Conclusions and key findings for this section

- 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 CO_2 savings.

- However, despite frequent prompts from the design team, there has been poor filter maintenance with very long intervals between filter changes. Although this situation doesn't reduce the amount of air supplied or affect the indoor air quality it leads to increased energy consumption and, more worryingly as in the Lime House, can potentially put the system at risk of damage. It is therefore important that client, tenants and maintenance teams are aware of the importance of keeping the systems properly maintained. All that is required is an annual filter change. Ideally a maintenance program should be established by the client and followed by the maintenance team. The trouble involved shouldn't be any different from maintaining a boiler.
- When designing a project with air heating only it is recommended to carefully consider the heat supply from the ventilation based on ventilation rates, duct heat loss, and room heat loss, plus desired room temperatures and considerations of buoyancy driven calculation between floors too.
- The solar thermal system in the Lime House was never fitted correctly and has never worked. This was due to installer errors. Neither the contractor nor the client, nor their maintenance team have, in three years, made a serious attempt to fix the problems. The fact that Micaul Solar, the solar installation company, was dissolved has not helped the situation.
- The PV system has been working reliably generating more energy than predicted.

8 Other technical issues

Other technical issues that have affected the houses' performance relate to external front door in both houses and the external blinds in the Larch house.

8.1 External front door problems

In both the Larch and Lime houses there were several although different problems with the front doors that have affected the performance of the houses.

Larch House

As with all windows and doors in the Larch House, the front door is a Passive House certified door designed and build by the German manufacturer Bayer Schreinerei.

Figure 8-1. The Larch House entrance facade

When the front door was installed, its threshold was not fitted correctly and during the year before occupation of the house, while being used by Blanau Gwent council and the BRE for educational visits, the threshold began to jam against the bottom of the door. It is also possible that the internal face of the door became excessively dry due to the house being unoccupied in its first year with the ventilation system working. If the outside of the door was at the same time excessively moist due to external winter weather conditions, it is hypothesised that this could have resulted in some additional pressure to deform the door in the same direction as the pressure from the sticking threshold. But whatever the cause, the door was forced and deformed and the multi-point locking became difficult to operate. For some time the door problem was not reported and so not looked at by the contractor. It was not until the door stopped closing altogether that the council manager of the building asked the contractor to carry out some maintenance. However the contractor did not adjust the door hinges or the threshold. Instead the contractor simply removed the bottom one of the three multi-point locking catches to allow the door to be locked while bent and while not closing against its seals. So the door continued to be forced into a bend to the point when it was permanently deformed and should have been replaced, since its airtightness had been severely compromised. Unfortunately there was no budget to replace the door and since no money was forthcoming even to pay for what were by now major repairs, the design team paid for its own carpenters to go to site in January 2011 to rout out the door and fit a metal tensioning device ordered from Germany to try to straighten the door (Figure 8-2).

Figure 8-2. Larch House front door being fixed by bere:architects' own carpenter in January 2011

Bere:architect's carpenter restored the door's functionality but it was so badly damaged by the users that even the insertion of the door straightening device couldn't fully restore its airtightness. As seen on the thermographic image on figure 8-3, some air leakage still occurs. This defect remains today.

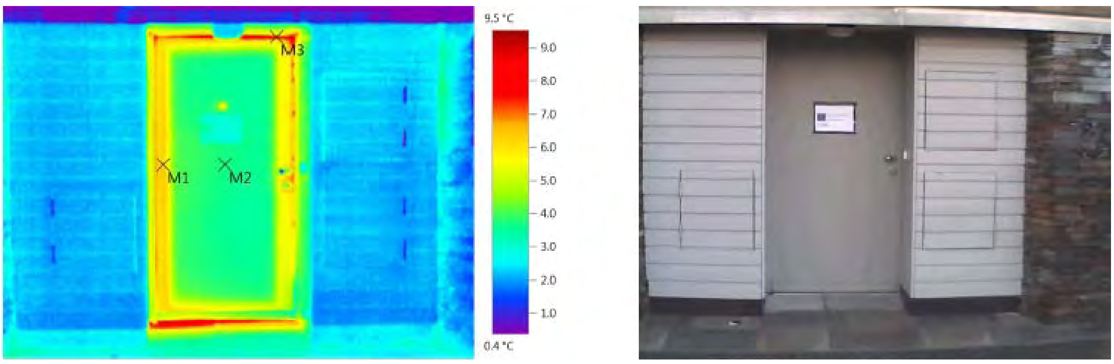


Figure 8-3. Thermographic image of the Larch House front door taken in February 2011, showing the result of damage caused by users who forced the door during the year before occupants moved in.

Lime House

The Lime House doors and windows were prototype doors made by Welsh company Custom Precision Joinery to designs developed by bere:architects with Bill Robertson (a Passive House window designer Bere:architects had worked with previously), Bayer Schreinerei (the Larch House windows manufacturers), and the carpenters from Custom Precision Joinery. The developed windows were Passive House certified and the first UK-designed windows to be certified.

Figure 8-4. The Lime House front facade

It is believed that the same phenomenon occurred in the Lime house but because the house was built at a later stage and less used for the education visits the damage was smaller. Still, thermographic images taken in January 2011 clearly showed air leakage (Figure 8-5). The door was repaired by Custom Precision Joinery in February 2011.

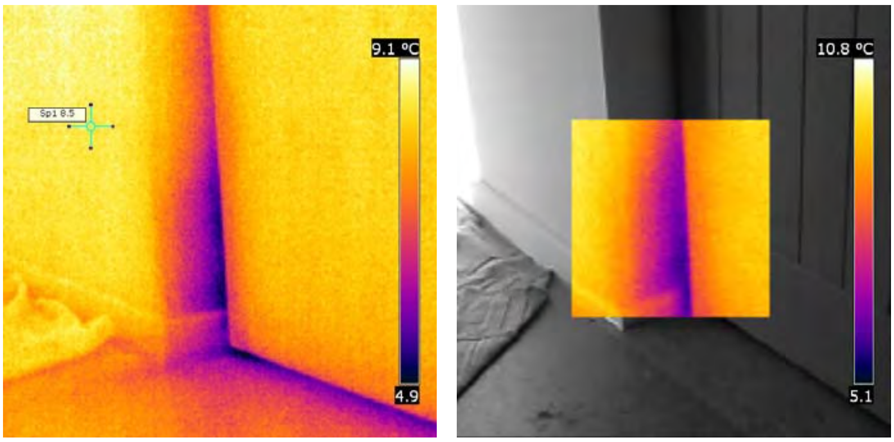


Figure 8-5. Thermographic image of the Lime house front door taken in January 2011

Later at the end of 2012 the new tenants complained about difficulties in closing the door. A visual inspection detected that the door seemed to have been forced open. Below the strike plate there was a mark suggesting a crowbar or other tool had been used to lever the door open and the wood of the door leaf was cracked adjacent the top door hinge, suggesting that excessive force has been used to close the door (**Error! Reference source not found.**). Thermographic images confirmed the door leakage (Figure 8-7). The architects suggested that this door simply needed some sympathetic maintenance by Custom Precision Joinery but the client, inexplicably decided the door damage was beyond repair, and ordered a replacement door.

Figure 8-6. Lime house front door damages in December 2012

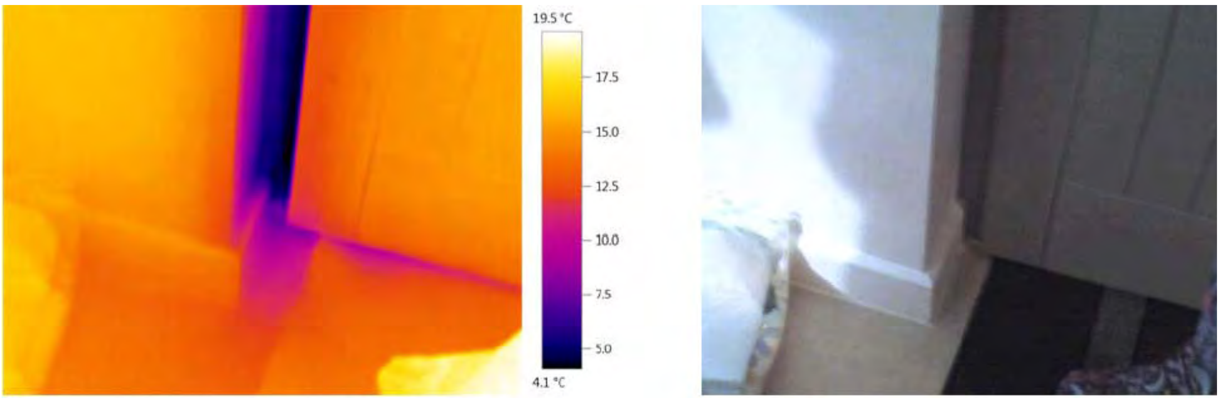


Figure 8-7. Thermographic image of the Lime house front door taken in March 2013

The damaged door was finally replaced early in 2014. The design team was not involved and has not yet been able to visit the site and check that the new door has been made to the original standard, with an insulated core, or been able to check the quality of the installation.

It should be noted that the air leakage from the doors was in both cases minimal compared to the air leakage from a normal door. The air leakage wasn't, for instance, severe enough to compromise the co-heating test results (see chapter 3.1). But because they were fitted in a Passive House their high performance is nevertheless important. A Passive House front door has to be finely toleranced in order to achieve a level access, whilst at the same time being completely draught free.

It is also relevant to note that the damage to the front doors and the sequence of unfortunate events is highly unusual and no lessons can be drawn except that doors and windows should be fitted and commissioned by skilled craftsmen and problems should be addressed with speed. Doors require more skill to fit than windows due to the nature of the threshold detail and they also are prone to more intensive use. Alternatively, to make installation easier by less skilled carpenters, level access doors could be ordered with a more robust threshold with a tough frame member beneath the threshold (eg 100x100 section timber). The architectural design will need to accommodate this.

8.2 Larch house external blinds

In the Larch house, external automatic blinds were fitted to the large south-west facing windows to reduce summer overheating and to provide more privacy. External shading devices such as retractable blinds and fixed overhangs and are the best solution to both avoid summer overheating and allow winter solar gains. Internal devices are not the most suitable option as it's more effective to control excess solar radiation before it hits the glass (after which it the radiation will already be inside warming the air.)

Figure 8-8. External blinds at the Larch House.

For safety and to avoid damage to the windows, the blinds were fitted with wind sensors making them retract when wind speed exceeds a reference value (set to about 26mph). Also to control summer overheating a solar sensor was installed to lower the blinds when there was sunshine was also installed to avoid relying exclusively on the occupants remembering to lower the blinds. Unfortunately, and surprisingly, the solar sensor does not differentiate between summer and winter sun as expected at the design stage.

In early August 2010, during the house opening week in Eisteddfod the blinds showed erratic behaviour in conditions where rapidly moving clouds brought the sun in and out and the electric supply to the blinds was cut not to disturb the visitors. Also it was found that when the blinds were lowered due to sunshine they would prevent the occupants using the back door so the solar control in the dining room window / back door was deactivated to prevent this situation. Feedback indicated that the controls may be too confusing for some social housing users. Later in the year the 8-channel controllers were replaced by simpler 1-channel controllers.

Contrary to specification, the blinds were provided with handsets controllers however if the users misplace a handset the replacement is not a simple procedure as re-programming of the new handset is required. The handsets have a fixed wall support and tenants were alerted to take extra care with them. A security cable was fitted to each handset to avoid the risk that they were misplaced.

In November 2011, whilst the houses were still vacant, the monitoring equipment for the BPE phase 2 was installed and the design team started following the performance of the houses closely. It was ascertained that the installed solar setting controls were activated by sunshine whether summer or winter. While this function is welcome in summer to keep out excessive solar radiation conducive to overheating it is unsuitable in the winter because the blinds do not allow solar gains when available and needed.

In January 2012 a test was done by disabling the blinds power and keeping them in the 'up position'. The subsequent decrease in boiler consumption confirmed that the blinds coming down in the winter was adversely affecting the performance of the building.

Several options were discussed such as installing a seasonal control unit that would deactivate the automation of the blinds in the winter but keep it in the summer or adding an internal temperature sensor, making the blinds come down only if the internal temperature was above a certain level. Unfortunately no simple and affordable solution could be found. In the end, the tenants said that they would prefer manual operation of the blinds.

It is always a matter of debate as to how much automation to include in a system. Simple automation is welcome so that the users have less to worry about, however if automation is in any way susceptible to poor maintenance then there is a risk of future problems and if automation acts in a counter-intuitive way it will upset occupants. Both these concerns should remain uppermost in designers' minds when choosing to automate systems.

During 2013 the tenants reported the blinds were mal-functioning a couple of times. In March a general power cut wiped out the settings, and the blinds were not retracting during windy conditions. Later in October the occupants reported the blinds were behaving erratically moving up and down with no apparent reason. Since visits from the UK distributors were expensive and never entirely successful, and since the blinds were also continuing to go down when there was sunshine in the winter, earlier this year it was decided to remove the automation setting and let the tenants control their blinds manually. The tenants have reported that they are very happy with the manual controls and that they now fully understand the purpose of the blinds and how to derive the greates benefits from them. Indeed there is late evidence reported earlier, that manual operation of the blinds is beginning to result in improved performance in both summer and winter conditions.

In Rob McLeod's interview, section 9.2. a reference is made to a 2013 academic paper that found that occupant interaction with solar blinds is primarily led by visual comfort and not thermal comfort, which can often lead to overheating.

There is evidence of a similar influence on early occupant interaction in the Larch House, as can be seen from occupant interviews in the Soft Landings films of the Larch House on the 'Films' page of the Bere:architects website.

It does not help that when blinds are lowered, they are in the closed position which is useful at night, but reinforces the notion that the blinds are provided for privacy reasons. If the blinds were instead lowered with louvres tilted in the open position, it is possible that this would help occupants understand that they are primarily a shading device, not a privacy device. It would be worth exploring with the blinds manufacturers, Hella and Warema, whether this is an optional commissioning choice that could be provided for future projects.

8.3 Conclusions and key findings for this section

- All Passive House construction requires skilled craftsmen and great attention to detail. The installation of front doors is particularly challenging due to the nature of the threshold detail that has to ensure a level access whilst ensuring airtightness.
- Further research is needed to determine if in damp climates the resulting extreme difference in humidity between the internal dry face of a Passive House front door and the external damp face of the door may result in deformation of a wooden door with an insulated core. If so, fully glazed doors may be more robust in damp climates.
- As with any other high performance equipment, commissioning and maintenance of a Passive House should be carried out by skilled and conscientious people.
- While passive solar gains are welcome in a Passive House during the winter, helping to reduce the heating demand, like an ordinary house, solar gains may be higher than needed in the summer. The manufacturer’s controls for external blinds were found to be problematic because (a) they didn’t differentiate between summer and winter conditions (b) they were not sophisticated enough to lower the blinds in the daytime open position, so rooms were plunged into darkness.
- The design team was disappointed with the quality of the support given both during design and at commissioning by the UK supplier / installer of the blinds.
- To minimise the complexity of automated blinds, the idea of a timed seasonal switch may be worth some investigation.
- In the case of the Larch House, the simplest solution was eventually introduced; manual operation by an informed user.
- In the long term, bearing in mind climate change and the expected increase in Summer temperatures, the smaller windows of the Lime House may be the best way forward for social housing and general market housing. Retractable external roller blinds can be installed relatively cheaply if required to control heat gains.
- When the blinds are lowered, the default with both Hella and Warema blinds is that they are lowered in the closed position which is useful at night, but reinforces the notion in users that the blinds are provided for privacy reasons as opposed to solar shading. If the blinds were instead lowered with louvres tilted in the open position, it

is possible that this would help occupants understand that they are primarily a shading device, not a privacy device. It would be worth exploring with the blinds manufacturers, Hella and Warema, whether this is an optional commissioning choice that could be provided in the future.

9 Feedback from the client, owner, contractor and other parts involved

At the end of the Building Performance Evaluation study the design team carried out a series of interviews with the main parties involved in the initiation, design, procurement or construction of the two prototype houses. The maintenance subcontractor team would not respond to repeated requests for an interview. The idea was to gather the different participants' perspectives on the project and the whole process of construction, delivery and the results of the monitoring of building performance.

The design team interviewed Nick Tune, the Director of BRE Wales (organiser of the competition); Rob McLeod, former technical manager at BRE Wales; Gareth Davies, the Head of Development (the client and owner); and Jeff Jones, the Technical Director of the main contractor.

The interview findings were compiled in a separate report submitted to the Technology Strategy Board and can be found in appendix 16. Following is a summary of the feedback.

9.1 Feedback from the competition organizer: BRE Wales

The competition was the brainchild of BRE Wales director, Nick Tune who is interviewed below. Through his efforts, key people at the very highest levels of Welsh government understood the need to build a demonstration project to explore the potential for delivering low or 'zero carbon' housing at an affordable price. As a result of Nick Tune's leadership, the Welsh Government agreed to fund the project with help from the European Union.

Nick Tune, director of the Building Research Establishment (BRE):

At the time, the Welsh Government's target was to achieve 'zero carbon' (as defined by the Code for Sustainable Homes level 6) in all new housing by 2011. Although there was some doubt as to whether this ambition was achievable by 2011, it was at least a strong and urgent commitment to a direction of travel.

The political leader of the Welsh Assembly (Jane Davidson) understood the vision that a pilot project was needed to find out if we could affordably achieve a very low energy house. The Passive House Standard was chosen for the project because Nick Tune was convinced (and remains so) that it was the best methodology to achieve the best space heating reductions.

It was decided to launch an open, international competition to build a three bedroom house and a separate competition for a two bedroom house. However the judges struggled to find two architects who could deliver a Passive House. Bere:architects were selected as they were "head and shoulders above everyone else". Nick Tune believes that now there is a huge increase in the number of practices that have the expertise to build a Passive House, including practices in Wales.

The main challenge was the tight timescale but everyone had a very positive attitude and pulled it together, although at the time the construction risk was a big worry.

It is Nick Tune's firm view that the project was a success. However the impact in Wales is still not as big as he wanted. During the period that the houses were open to the public, there were visitors from all over the world as far afield as China and Japan. But it is disappointing that the prototypes didn't result in more Passive Houses in Wales. This is because the financial crisis stalled all projects, and now there are different political drivers.

The original vision was to build out across the Ebbw Vale site at scale. While the one-off pilot projects were unaffordable, at scale it was clear that savings would have been possible. It was planned to take out the house builders' risk by offering the land at low prices to local builders and self-builders. However subsequently, due to house-builder lobbying, the local council were given political directive to sell the sites for the highest price that they could get. By this time Jane Davidson had retired from politics. Nick Tune feels that if she had still been leading the Welsh Assembly, she would have maintained the momentum of the vision.

Nevertheless industry in Wales was upskilled by the experience and the BRE and other partners involved also benefitted from the knowledge gained. An example of financial benefit to the Welsh economy is that Timber Frame manufacturer won a large project in Cornwall on the back of their experience in the project, and other partners have also benefitted.

Nick Tune believes the current climate discourages innovation. '*Getting rid of sustainability standards and trying to put them in building regulations will mean that we are taking a backwards step as many of the issues cannot be covered by building regulations and those that can will take many years to get them adopted. In the meantime there is nothing to drive sustainable housing. Big vision future thinking is now missing. However it will come back again, but it may be too late*'.

9.2 Feedback from the former technical manager at BRE Wales

Dr. Rob McLeod, former technical manager at BRE Wales:

Dr. Rob McLeod provided the lead technical support during the design stages of the project. He strongly supported and encouraged the use of timber for constructing the houses because it is a low cost renewable material that can be provided in abundance from the local economy. He also acted as a design mentor, checking and advising on the PHPP calculations and signing off the final PHPP worksheet. It was he who advised on the precautionary approach of using one-in-ten year peak load weather data in the PHPP and who suggested the alternative, and at the time new approach to using peak heat load as the determining factor in the Passive House certification of the Lime House.

Dr. Rob McLeod was interested to read the detailed findings of the two years of monitoring and the occupancy behaviour. Rob commented that the monitored performance data appears to have justified the use of more cautionary weather data in these pilot projects and that this precaution may have helped compensate for a degree of design prediction uncertainty as well as the documented ‘slippage’ during the build phase. He would like to carry out his own analysis of the data in due course to produce further research findings, particularly with regard to weather data and the resultant ‘as-built’ performance which are aspects of Passive House design that he is particularly interested in.

Nevertheless he believes the findings of the monitoring report are of great importance, but should be given greater context, making reference, for example, to research that he has previously published on weather data, overheating and future performance.

The overheating issues detected in the houses were discussed. Rob referred to a 2013 academic paper (McLeod et al., 2013) that found that occupant interaction with the blinds is primarily led by visual comfort and not thermal comfort, which can therefore undermine the use of blinds in the prevention of overheating.

Author’s note: There is considerable evidence of the same influence on early occupant interaction with external solar blinds in both the Larch House and the Mayville Community Centre, the latter being subject of another TSB funded research project currently nearing completion. It does not help that when blinds are lowered, they are in the closed position which is useful at night, but reinforces the notion that the blinds are provided for privacy reasons. If the blinds instead lowered with louvres tilted in the open position, it is possible *that this would help occupants understand that they are primarily a shading device, not a privacy device.*

The BPE study results of the Welsh houses also demonstrated how occupancy behaviour plays an important role in influencing whether the internal environmental conditions and energy consumption are as good as the design targets. In the Larch House tenants are not using summer night ventilation as expect in the design stage because of fear of spiders and insects (restricting cross ventilation and leading to overheating) while the Lime House tenants leave their windows open very often, regardless of whether it is winter, leading to higher than predicted energy consumption.

Climate phenomena like urban heat island and possible future climate change may also increase the overheating risk of buildings in the future, so Passive House design should investigate options to limit future summer cooling loads.

Rob McLeod was disappointed to hear about ongoing problems with the faulty solar system in the Lime House. The energy which is not being saved by that system is on a par to the total heating demand of the buildings. It is *'of enormous significance, it's equivalent to the energy saved by going from building regulations to Passive House, which is lost because the system designed was not correctly implemented by the installer during installation phase*.' Microgeneration technologies need to be installed by MCS certified installers and a register should be kept of systems which have been installed but are not working as intended– this finding needs to go back to the industry. It is also important to have seasonal commissioning to ensure the systems are working properly throughout the year.

Rob believes the knowledge from the Welsh Passive Houses project should be made available to the wider public to accelerate the learning and uptake of new technologies and new standards in Wales and across the UK. According to Rob, '*This TSB funded project has resulted in significant learning, knowledge transfer and innovation for all the parties involved*.' Further competitions and innovative design challenges would accelerate innovation and upskilling. Providing ongoing funding is critical for the continuation of this successful initiative.

9.3 Feedback from the building owner

Gareth Davies, former head of development

The client, the housing association, agreed to undertake the procurement of the two houses through their normal supply chain and to become the owner of the two houses at the end of the process. Their Head of Development, Gareth Davies, lead the client's involvement in the project.

Gareth Davies' overall view was that the process was interesting, fascinating and hard. It was hard due to the very tight construction timescale, hard because it was new and also hard because some people didn't seem to 'get it'. He sensed that most people who came to the Eisteddfod exhibition didn't seem to understand the principles of Passive House standard.

Gareth says still today, three or four years later a lot of people still don't appear to understand the principles of Passive House construction which he feels is strange because this is not particularly different to an ordinary building, just built to a higher standard.

Gareth Davies says he was pleased with the process but said if he could change anything, it would have been to be given more time so that the client could have gone to tender. The timescales were very short as the houses had to be ready for Eisteddfod but everyone felt a feeling of excitement and privilege to build for a major cultural event. All the awards and other spinoffs were tremendous.

The client would have liked to build more, building on what they learnt on the project, setting up local supply chains, so that after a few years the costs had been brought down. However the recession put a stop to funding and now Wales is "caught up" in a review of standards in Wales, led by Carl Sargent, Housing Minister. The London government is criticising the Welsh planning system for slow progress in approving housing schemes and the question is being asked whether very low energy buildings are compromising the supply of housing in Wales. The general funding stream is reduced now, and very different funding stream models have been introduced. The client feels able to easily meet the latest standards, and to continue to do so in the future if they move closer to Passive House.

The decision whether to adopt Passive House is not influenced by the need to compete against house builders. Most of the client's developments are delivered on a larger site in partnership with a house builder and built to the house builder's requirements. This restricts any ambition to achieve higher than normal quality. Build quality is normally no more than the minimum required by building regulations.

In terms of building maintenance, Gareth Davies mentioned there is a perception from the maintenance team that is a 'bit of a pain' but in reality there is not a lot of difference compared to standard houses.

Commenting on the faulty solar system in the Lime house (detailed in chapter 7.5) Gareth Davies regretted that the original installation subcontractor had gone into receivership before correcting their mistakes and said he would endeavour to discuss with the main contractor how to rectify this situation.

9.4 Feedback from the main contractor

Jeff Jones, technical director, main contractor

Jeff Jones is the company's Technical Director and he was in charge of the project construction.

The overall feedback is that it was a positive, beneficial experience in which a lot was learned although the delivery involved was hard work, due to the tight timescale.

The major challenges on site were related to the requirements of the Passive House construction, such as achieving the airtightness and the heat recovery ventilation installation which were both new technologies to the company. However the main contractor were glad the architect's team offered their support and expertise on site as the project would have been very difficult to deliver otherwise.

Jeff believed these pilot projects were intended to pave the way for scaling up, so that Passive House or extremely low energy concepts, would benefit from economy of scale. Unfortunately the recession stopped that and most housing associations opt for ordinary housing which only has to comply with the Code of Sustainable Homes Levels 3 or 4, so the main contractor found themselves competing with large house builders on projects where the highest sustainability is not on the priority list.

Legislation is needed to force the change towards better standards. The main contractor has not had the opportunity to apply the experience gained in subsequent Passive Houses projects in Wales. They have also been working mostly with masonry construction, which is still considered more cost effective than timber frame in the area, although timber frame is slowly becoming more competitive than it was before.

Jeff Jones says that his company has benefitted greatly for the learning experience on site, and this has given them an advantage in winning other high quality work. The major lessons learned were regarding the airtightness and avoiding thermal bridges. When specified by the designer on subsequent projects, they have been using special membranes for the installation of windows and they note the market of windows and airtightness membranes has evolved and there are now more cost effective options available. They have also passed on the knowledge gained on the Welsh Passive Houses by training other site managers and sub-contractors.

Jeff also mentioned that housing associations encourage a fabric first approach (combined with efficient ventilation and heating systems) and prefer not to install solar thermal or PV arrays, to reduce the investment and maintenance requirements. He nevertheless agreed that these systems are helpful to achieve a zero carbon goal.

Regarding the systems installed in the houses he found it difficult to explain the occupants the heat recovery ventilation concept and how it works.

9.5 Conclusions and key findings for this section

- All the parties involved have had a very positive learning experience which they have been able to take forward in new projects; even if the new projects have not been Passive Houses.
- Everyone shared a vision and indeed the expectation of taking off from the prototype houses to larger scale projects that would have allowed savings to be made to the build costs, so making Passive House projects more competitive. Unfortunately the economic recession stalled innovative projects and the momentum was lost. Today Wales has different political drivers that are less aware of the need to prioritise sustainability.
- The biggest difficulty on site was the tight timescale to deliver the houses. This was successfully overcome due to the energy and commitment of all parties involved in the project.
- The closely-knit design and construction team managed to easily deliver the airtightness requirement of the Passive House construction, and the contractor is appreciative of the time and support the architects team gave on site.
- The contractor is mostly doing less ambitious projects today but has been using the learning experience, namely on airtightness construction and how to avoid thermal bridges.
- All parties involved feel confident that the success of this project could be repeated at scale, and significant cost savings could be achieved at scale, now that they are all fully trained up by the learning experience of the project.

- All parties feel frustrated that recent government directives have resulted in a dumbing down of quality and sustainability, and look forward to the time where vision and ambition once again become the drivers of research and development towards economical methods of building to the highest standards, for the benefit of the economy and the people of Wales.

10 Summary of findings and key messages for the client, owner and occupier

A study using a database from the Ministry of Housing in the Netherlands found that although occupant characteristics and behaviour significantly affect energy use, building characteristics have a 10 times greater impact of the energy use in a dwelling.

10.1 Summary of main findings

Energy and Environmental performance conclusions

10.1.1 The design and construction of the two houses successfully delivered the competition brief using local contractors and manufacturers, although the contractor's failure to install a working solar thermal system on the Lime House somewhat compromised the Lime House performance and has created ongoing maintenance problems for the client. The cost to building owners of the mistakes made by poor quality mechanical services subcontractors is illustrated across other BPE research projects and is not unique to this project. To address this national problem, in future it is recommended that much greater emphasis is put on driving up standards of pipework installation, pipework insulation and improving the quality of workmanship of mechanical services contractors generally.

10.1.2 While the build cost of the project was higher than normal buildings, the rushed and non-competitive procurement process played a part, as well as the fact that these were one-off pilot houses without the benefit of development at scale, and on a site that required special measures to achieve the very low energy consumption and high comfort levels in spite of the extreme local climate. Considering all these factors, a cost analysis was carried out to consider future opportunities:

10.1.3 The cost analysis done by Richard Whidborne, the quantity surveyor, concluded that if, in order to compare with the cost of a minimum-standard building regulations house type, the Larch House was built to the Passive House standard but using the lower specification required using the average weather data applicable to a more typical lowland Wales location, then a 9% cost uplift over the minimum standard house would result. This is very encouraging because it is achieved without even tackling supply chain economies of scale and would seem to make the Passive House standard an economically realistic option for private and social housing.

10.1.4 The project successfully involved local manufacturers and suppliers in innovative ways by using Welsh timber for the frame construction and by producing the first Passive House certified UK window. The project was a good demonstration that Welsh manufacturers can upskill very quickly and with R&D support, could compete effectively on the European market.

10.1.5 The Larch House benefitted from close guidance provided by the design team as demonstrated by the spectacular air-tightness result of 0.197ach@50pa. Good knowledge transfer of new advanced building skills by the design team closed the knowledge gap between design and construction teams. The additional cost of employing knowledgeable architects to build new skills in the construction team is a price worth paying. However a long term strategy should be implemented to embed the knowledge within construction partners, so that in time less architectural guidance of the construction team is needed, bringing down costs.

10.1.6 The several fabric performance tests done in the Larch House and Lime House, including the excellent co-heating test results, found both buildings to be performing very close to the design intentions. This fact should be borne in mind when considering any of the minor occupancy-related difficulties.

10.1.7 The Indoor Air Quality study found the indoor environments of both the Larch House and the Lime House to be very healthy.

10.1.8 The client's maintenance teams have consistently failed to provide what the research team would consider to be the necessary quality of service. There seems to be a problem gaining access to properties to carry out maintenance, resulting in higher costs to maintenance teams and it is suggested that stronger incentives for tenants to cooperate with maintenance managers might be incorporated in tenancy agreements, at the same time as demanding improved communication strategies from maintenance organisations. Social housing maintenance teams need to be focused on being highly organised and professional in their approach to provide a satisfactory standard of maintenance and value for money for their employers.

10.1.9 With good design and commissioning protocols, as well as routine maintenance protocols, we believe that faultless heat recovery ventilation systems can be assured.

10.1.10 We recommend that high performance level threshold front doors are ordered with a robust frame section beneath the threshold (while also designing for level access) to minimise the risk of installer error.

10.1.11 Any system is only as good as its weakest link. The team believes that the resilience of both houses, 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.

10.1.12 Occupant-related conclusions

10.1.13 The results of the 2 year analysis indicate that the energy use and environmental performance of both buildings are excellent, showing that the impact of user behaviour on the performance of the building, even in the worst case, doesn't appear to undermine the low energy credentials of the building when compared to ordinary houses designed to the building regulations. The findings endorse the benefits of an approach 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.

10.1.14 Overall both families are very satisfied with the performance of their houses. The BUS methodology survey results were in general very good comparing favourably to the benchmark.

10.1.15 The high BUS study's high Forgiveness Index result (a measure of tolerance of users with the building environmental performance) means the occupants feel generally very comfortable and are willing to overlook any complaints.

10.1.16 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. In the Larch House, opportunities exist in the opening of blinds in winter to absorb solar energy and in closing of blinds in summer during the day and opening of windows in summer during the night to cool the fabric. In Lime House opportunities to save energy exist in winter by leaving windows closed during the day and night during the cold winter months, and by leaving the thermostat at its set winter temperature without daily manipulation that wastes energy.

10.1.17 The interviews indicated that there was an interest, particularly useful for the Lime House tenants, in written guidance notes that would help tenants to get even better performance out of their buildings next year. It is thought that a simple 'Energy Saving Guide', along the lines of our 'Welcome Guide' but much briefer, would be of use to tenants, and could become a standard offering of bere:architects. This would advise on how to best operate opening and closing of windows, and how to best operate blinds if fitted. The guide would be set up a series of clauses that would be deleted where appropriate. It is respectfully suggested that if this idea was also adopted by the client, this could make their occupants feel more closely supported by their landlord, and could bring the maintenance teams and occupants more 'on board' in recognising the benefits of mutual care and cooperation.

10.1.18 Clear energy and cost savings can be achieved by tenants who invest in A-rated appliances. It is understood that tenant normally bring their own appliances and cost saving requirements or lack of understanding of the benefits usually mean that these are not A-rated. There may be benefit in including advice in the above-mentioned 'Welcome Guide'. Perhaps even, a loan could be provided to upgrade to an A-rated appliance, paid back via a slight increase in rental payments for a year, which would to a degree be offset by energy savings?

10.1.19 We recommend incorporating retractable insect screens into bedroom windows of all future projects in order to encourage users to open their windows at night and benefit from summer night purge cooling.

10.1.20 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 in particular raised the awareness of the residents of the Larch House 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 Larch House 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 each analysis of the building's performance.

10.1.21 It was interesting to note how, perhaps due to very busy lives, the occupants of the Lime House failed to achieve the best performance from their house, by their wish to leave windows open all day in winter months.

10.1.22 While some people would inevitably suggest that this means the systems are too reliant on maintaining low ventilation heat losses, 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 left their windows open during the day, then the problem would have been more serious because a great deal more energy would have been needed to warm the house back up again in the evening.

10.1.23 However a lesson that the design team does draw from this experience is that there would be great benefit for all building types, whether ordinary or low energy, if equipment manufacturers were to develop cheap and effective smart warning mechanisms to minimise the risk of users inadvertently using building components sub-optimally. Such a warning should be easily and economically applicable to the opening habits of windows, with a simple red and green light providing the necessary guidance. 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.

10.1.24 One of the occupants comes from a family that has a history of suffering from lung problems. This occupant has noticed the benefits of living in a Passive House, corresponding with the fact that air humidity was found at all times to be in the range known to be optimal for minimising the level of airborne indoor pollutants that are known to aggravate asthmatic symptoms. This provides further support to the hypothesis that Passive House buildings provide health benefits for asthma sufferers.

10.2 Conclusions and key findings for this section

10.2.1 The design and construction of the two houses successfully delivered the competition brief.

10.2.2 Cost analysis concluded that there is a 9% cost uplift over a minimum standard house design in a lowland setting with less extreme weather.

10.2.3 The project demonstrated that Welsh manufacturers can upskill very quickly, creating short and long term benefits for the local economy.

10.2.4 The additional cost of employing knowledgeable architects to build new skills in the construction team is a price worth paying.

10.2.5 Closing the ‘Performance Gap’. The several fabric performance tests found that both buildings perform very close to the design intentions.

10.2.6 Indoor Air Quality was found to be excellent at all times.

10.2.7 There seems to be a problem gaining access to properties to carry out maintenance, irrespective of the design approach. Successfully addressing this problem would result in large financial savings, both short term and long term.

10.2.8 With good design and commissioning protocols, a faultless heat recovery ventilation system is assured.

10.2.9 Any system is only as good as its weakest link. Success is dependent on meeting not just some, but ALL the quality assurance requirements necessary for a certified Passive House.

10.2.10 The impact of user behaviour on the performance, even in the worst case, doesn't appear to undermine the low energy credentials of the buildings when compared to ordinary houses designed to the building regulations.

10.2.11 Both families are very satisfied with the performance of their houses.

10.2.12 Poorly designed controls can undermine performance. Simplicity helps.

10.2.13 Poor tenants who would most benefit from energy savings usually don't have the benefit of A-rated appliances.

10.2.14 Retractable insect screens should be fitted into bedroom windows to encourage users to open their windows at night in summer. The small additional cost is likely to deliver valuable productivity and health service savings.

10.2.15 There would be benefits if equipment manufacturers were to develop cheap and effective smart warning mechanisms to minimise the risk of users inadvertently using building components sub-optimally.

10.2.16 This study provides further support to the hypothesis that Passive House buildings provide health benefits for asthma sufferers.

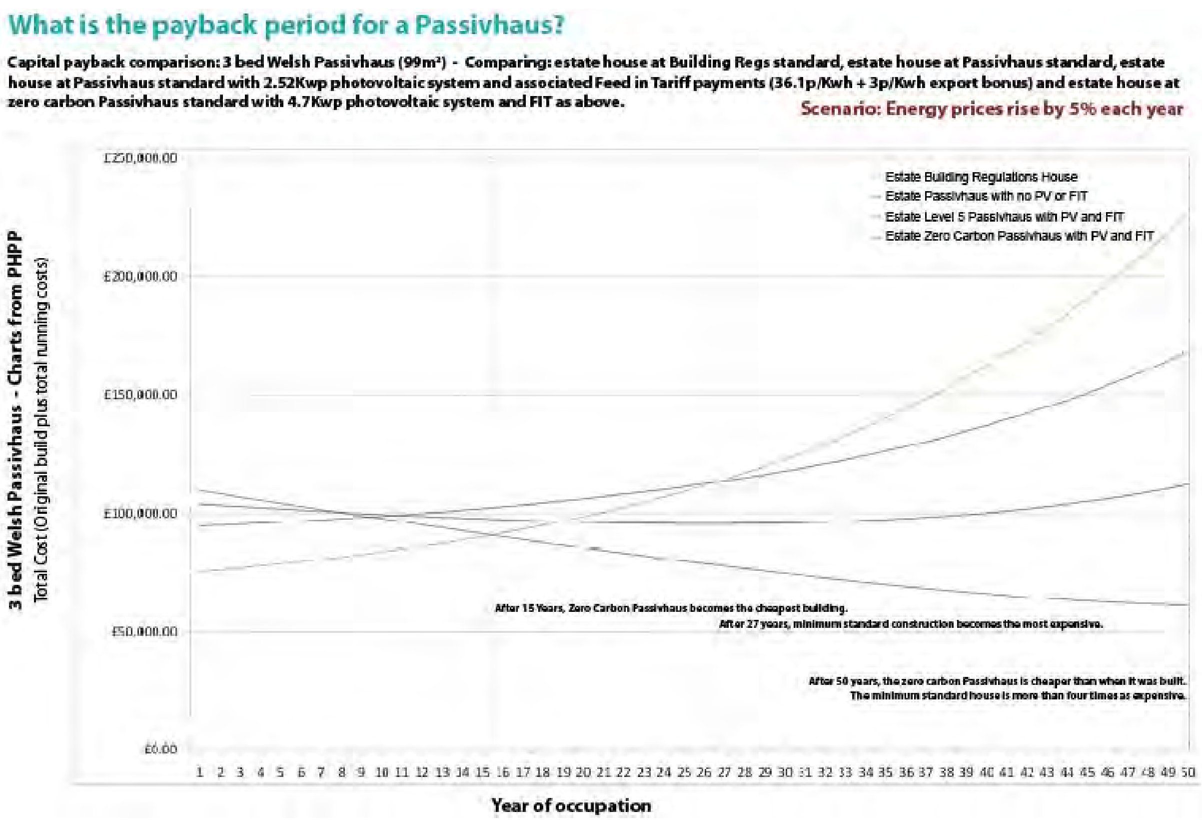
11 Wider Lessons

11.1 Lessons from the project

11.1.1 All parties involved feel confident that the success of this Passive House project could be repeated at scale, and significant cost savings could be achieved at scale.

11.1.2 Cost analysis concluded that there is a 9% cost uplift over a minimum standard house design in a lowland setting with less extreme weather. At scale and with practice, even this could be bettered.

11.1.3 The long term benefits for the national economy dwarf the modest additional costs as shown in this graph:



11.1.4 The carbon emission savings are equally significant, with global benefits.

11.1.5 The project demonstrated short and long term benefits for the local economy, including increased competitiveness.

11.1.6 Knowledgeable architects and well-trained contractors have a key role to play.

11.1.7 Passive House design was found to be a reliable way to close the 'Performance Gap'.

11.1.8 The impact of user behaviour did not adversely affect the low energy credentials of the buildings when compared to ordinary houses designed to the building regulations.

11.1.9 Passive House design delivers excellent indoor air quality and further support to the hypothesis that Passive House buildings provide health benefits for asthma sufferers.

11.1.10 Better building maintenance will save money, both short term and long term.

11.1.11 Any system is only as good as its weakest link. Success is dependent on meeting not just some, but ALL the quality assurance requirements necessary for a certified Passive House.

11.1.12 Users consistently show higher satisfaction with their houses than benchmarks. .

11.1.13 Retractable insect screens should be fitted into bedroom windows to encourage users to open their windows at night in summer. The small additional cost is likely to deliver valuable productivity and health service savings.

11.1.14 There would be benefits if equipment manufacturers were to develop cheap and effective smart warning mechanisms to minimise the risk of users inadvertently using building components sub-optimally.

12 Messages for other designers

12.1 Main messages

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

12.1.1 The Passive House Planning Package has been found to work very well in the UK context. No performance gap of any serious significance was found between PHPP u-values and actual u-values, or between predicted energy use and actual energy use under a co-heating test. User impacts did not undermine the benefits of building to the Passive House standard.

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

12.1.3 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.

12.1.4 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.

12.1.5 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.

12.1.6 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).

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

12.1.8 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.

12.1.9 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.

12.1.10 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.

12.1.11 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.

12.1.12 To achieve successful low energy buildings, overcome the 'Knowledge Gap' and overcome the 'Skills Gap'

12.1.13 Knowledge and skills gaps cause performance gaps.

12.1.14 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.

12.1.15 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.

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

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

12.1.18 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 retractable insect mesh screens outside bedroom windows or even a few dedicated summer night time cooling windows that open inwards with security louvres fitted externally and with concealed insect mesh.

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

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

12.1.21 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.

12.1.22 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.

12.1.23 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.

12.1.24 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.

12.1.25 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.

12.2 Dissemination

12.2.1 The findings of this BPE study may be relevant and helpful to several important stakeholders in the built environment:

12.2.2 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).

12.2.3 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.

12.2.4 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.

12.2.5 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.

12.2.6 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 RMIT on this project, and several papers and architectural magazines articles have detailed the performance of this 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.

12.2.7 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.

12.3 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. It is widely accepted 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.

- Similar and consistently strong results have been found in both of our other two Building Performance Evaluation studies of Passive House buildings (Camden Passive House and the Mildmay 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.

13 References

Crump, Derrick and Walton, Chris, 2013, *Assessment of Indoor Air Quality in Four Dwellings*, Institute of Environment and Health, Cranfield University.

Jenkins, H.; Jiang, S; Guerra-Santin, O.; Tweed, C.; 2011, *Coheating test Future Works, Ebbw Vale*, Welsh School of Architecture, Cardiff University

Ridley, Ian, 2012-2014, Quarterly Reports, RMIT

Ridley, Ian, 2013a, *Performance of the Larch and Lime Low Energy Houses, Performance Summary for the First Monitored Year of Occupation (March 2012 – April 2013)*, RMIT University.

14 Appendices

Technology Strategy Board guidance on section requirements:	The appendices are likely to include the following documents: • Details on commissioning of systems and technologies through appending of the document *BPE_Domestic_commissioning sheets.doc* • Initial energy consumption data and analysis (including demand profiles where available) • Further detail or attachment of anonymised documents • Additional photographs, drawings, and relevant schematics • Background relevant papers

Supporting documents:

14.1 List of Materials Assessment

14.2 PHPP Worksheets (Certification Issue)

14.3 As-built SAP Assessment

14.4 SAP comparison Report

14.5 Coheating and Tracer Gas Decay Report

14.6 Thermographic Survey

14.7 Thermal Bridging Analysis

14.8 Airtightness Reports

14.9 Indoor Air Quality Report

14.10 User Guide Poster

14.11 BUS methodology Study

14.12 Post-occupancy Evaluation Interview with the tenants

14.13 DomEARM Study

14.14 M+E Commissioning Report

14.15 MVHR Commissioning Report

14.16 End of BPE Study Feedback Report

14.17 Photographic Survey Report

14.18 Raw Data Archive