Plummerswood House

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

InnovateUK project number	450072
Project author	Gaia Research
Report date	2015
[1]InnovateUK Evaluator	Tim Sharpe (Contact via www.bpe-specialists.org.uk)

No of dwellings	**Location**	**Type**	**Constructed**
Single	Scottish Borders	Detached dwelling	2011
Area	**Construction form**	**Space heating target**	**Certification level**
346 m^2	Timber	15 kWh/m^2 p.a.	Passivhaus

Background to evaluation

This report describes the monitoring and performance of Plummerswood House undertaken by Gaia Research in collaboration with Gaia Architects and Arup Scotland over a two-year period. It was the first house to be constructed in Scotland to the PassivHaus Standard using off-site, glue-less mass timber technique, Brettstapel. The air tightness target was < 0.6 m^3 (m^2.h) @ 50 Pa. Post-construction air tightness tests confirmed air permeability of 0.49 - 0.50 m^3 (m^2.h) @ 50 Pa. A retest undertaken towards the end of the monitoring confirmed an air permeability of 0.69 m^3 (m^2.h) @ 50 Pa.

Design energy assessment	**In-use energy assessment**	**Sub-system breakdown**
Yes	Yes	Yes

Plummerswood was designed to achieve PassivHaus certification. MVHR provides ventilationand space heating supplemented by a woodstove and a downstairs bathroom towel rail. The aim was to use the mechanical systems as supplements to natural systems, rather than as replacements for them. In 2012 the total metered consumption was 10,181 kWh. In 2013 when the building was run in an optimised condition consumption was 8,699 kWh. The energy consumption of the MVHR heating element in year 1 was 2199 kWh or 6.4 kWh/m^2 p.a. Consumption fell in year two to 2092 kWh or 6.0 kWh/m^2 p.a. despite more severe weather conditions. An estimated 6,400 kWh (18.5 kWh/m^2) was generated by the wood-burning stove each year, providing 74% of the total heating demand. Primary energy demand was 47.9 kWh/m^2 p.a. (TFA).

Occupant survey type	**Survey sample**	**Structured interview**
Bus (domestic)	N/A	N/A

The property performed well when assessed for perceived air quality, with the survey results showing the property to be of the fresh against the BUS benchmark comparison. The survey respondents noted the property as being still rather than draughty. The results for summer were similar to that for winter.

NOTE: All appendices were redacted by Innovate UK prior to publication. These may be available from Gaia Research on application.

Contents

Executive Summary

General

- This report describes the monitoring and performance of Plummerswood House undertaken by Gaia Research in collaboration with Gaia Architects and Arup Scotland over a two-year period (January 2012 to December 2013).
- The comprehensive monitoring programme appraises technical and human aspects of the design development, handover and operation of the building in line with protocols prescribed by Technology Strategy Board (TSB).
- The monitoring equipment was as prescribed by the TSB to meet its protocols.
- The monitored project is a 346m^2 PassiveHaus certified eco-house, in the Scottish Borders, designed on Howard Liddell's ***Ecominimalist*** principals.
- The project fitted within Gaia Group's overall approach to innovation in support of sustainable development of the built environment which involves research, design, evaluation & feedback, dissemination, training and capacity building.
- The house was completed in Autumn 2011 and won the 2012 Scottish Homes Award for Architectural Excellence (small projects) and a Scottish Borders Council Award.
- It brings together the internationally recognised PassivHaus Standard specification with Gaia's integral and groundbreaking approach to a healthy indoor climate.
- The process addresses issues including resource effectiveness, toxicity cycles, indoor climate, human factors in environmental control, sustainable forestry, manufacturing, local economic development and place making.

Pioneering Brettstapel

- It is the first house to be constructed in Scotland to the PassivHaus Standard using the innovative off site glue-less mass timber technique known as Brettstapel**.**
- It is the 2nd demonstration project by Gaia aiming to promote UK manufacture of Brettstapel. The 1st being Acharacle School.
- Both evolved as demonstration projects as no UK manufacturer of Brettstapel could be found.
- Both had superstructures prefabricated in Austria and shipped to site.
- The superstructure for Plummerswood was constructed on site in six weeks, in the midst of the winter of 2010, on foundations built by local builders.
- An estimated 16,000 kg CO_2 was emitted through transportation, which compares well with sequestration of 243,000 kg CO_2 in the main timber elements.
- Both projects were designed to address understanding of comfort in a low carbon society by providing for, and then evaluating, human factors in environmental control.
- Acharacle School was designed as a Factor 10 building - that is requiring $^1/_{10}{}^{th}$ of the heating needs of a building regulations building. It was designed for natural ventilation with the classroom ventilation automatically controlled according to CO_2 concentration and temperature, with manual override to allow for human preferences.
- Plummerswood was designed to achieve PassivHaus certification, and MVHR provides ventilation and space heating supplemented by a wood stove and a downstairs bathroom towel rail.

Passive Ecological Design

- The aim was to use the mechanical systems as supplements to natural systems, rather than as replacements for them. It was intended to be an active house responding to human factors, rather than a passive house responding to a regulated norm. This places the project at the forefront of examining and optimising passive design.
- Passive design techniques included:-
  - ✓ PassivHaus standard thermal & air-tightness standards to minimise heating demand.
  - ✓ Air tightness target of less than 0.6 $m^3/hr/m^2$ @ 50Pa or 0.46 ac/h^{-1}.
  - ✓ Design of solar orientation, overhangs & shading to optimise inter-seasonal heat gains.
  - ✓ Design of a natural ventilation stack and cross ventilation design strategy to contribute to minimising the requirement for MVHR.
  - ✓ A daylighting strategy to minimise requirement for artificial lighting.
  - ✓ Attention to minimising other power loads.
- Gaia has a long history of involvement in healthy indoor climate, optimized material specification, ventilation and moisture management. All the building materials were vetted against Gaia's strict non-toxic and hygroscopic standards.
  - ✓ Special attention was paid to avoidance of synthetic and heavily processed materials and those with polluting impacts on indoor climate and waste streams.
  - ✓ The insulation is made from low-grade wood fibres bonded by tree resin.
  - ✓ The building fabric is vapour-permeable, which allows any excess moisture to pass through it to the outside surface without affecting how well it insulates.
  - ✓ Much of the internal finish comprises of untreated timber, which offers a large hygroscopic surface area.
  - ✓ Areas that could be subjected to high levels of indoor moisture, e.g. bathrooms, kitchen and wet room, have clay board and clay plaster ceilings.

Monitoring & Outputs

- The monitoring team set out to investigate specific aspects of the design. This included:
  a) Review of research developments & practical activity in UK Brettstapel manufacture.
  b) Comparison of MVHR and NV operation.
  c) Thermal and moisture buffering of exposed timber and the effect on indoor climate.
- Gaia's intention was to contribute to knowledge in the developing area of passive design by experimenting with the MVHR to compare performance under mechanical and natural ventilation regimes and to ensure that building operation was fully optimised in relation to energy, comfort and indoor environmental requirements.
- Post construction air tightness tests confirmed air permeability of 0.49/0.50 $m^3/h.m^2$ @50Pa equivalent to air leakage rates (ALR) of 0.37/0.38 h^{-1}@50Pa respectively. Within the design target of 0.6 h^{-1}@50Pa. This followed remedial work to polyurethane seals above many of the windows that were not fully expanded due to the very cold temperatures. A further test at the outset of the monitoring identified air permeability of 0.59 $m^3/h.m^2$ @50Pa equivalent an ALR of 0.42 h^{-1}@50Pa. It was noted that leakage is greater with the building pressurized, which was thought to be due to the high level windows opening slightly under pressure. A further test undertaken towards the end of the monitoring period confirmed an air permeability of 0.69 $m^3/h.m^2$ @50Pa equivalent to an ALR of 0.49 h^{-1}@50Pa

- The thermal imaging report is comprehensive. Areas of specific concern were identified and anomolies investigated.
- A heat flux test was undertaken.
- The clients have provided a short video: **The clients story.**
- A summary presentation has been prepared so that participating organisations can provide feedback to their own organisations and beyond.
- A final report is available along with the task reports prepared throughout the two year period. These fully describe the Design Construction and Handover Processes.
- The gathered data is available.

Occupant surveys

- Plummerswood scores highest amongst comparable buildings for humidity in winter
- The property performs particularly well for humidity, freshness and odour in summer .
- The performance overall is at the top of the data range of comparable buildings.

Key Findings – Internal Environment

- The building benefits from thermal mass.
- The building exhibits evidence of hygroscopic mass. The internal relative humidity is stable without the swings in the outside air moisture content. In summer the relative humidity is in the range of 50% - 60% representing ideal conditions.
- The winter variation in humidity is less than that in summer, which is expected with the building closed and mechanically ventilated.
- From October to December 2012 the dining room temperature cycles daily from around 17^0C to 22^0C. The MVHR system set point is 17^0C and solar gains and loads from people, lighting and cooking increase the temperature during the daytime.
- During the same period the bedroom temperature is more stable than the dining room.
- The relative humidity is in the range 40 to 55%. It has a spike twice daily consistent with the owners using the shower at around 10:30 in the morning and again in the evening.
- There is no appreciable difference between occupied and unoccupied period.
- Under higher than normal temperatures the passive approach maintains comfortable conditions and does not overheat.

Key findings - Energy Monitoring

- The Domestic Energy Assessment and Reporting Method (DomEARM) was used for the reporting of the metered data collected from January 2012 to December 2013.
- Two assessments covers
    a. 2012 where the building was run as per the O&M instructions and the total metered consumption was 10,181kWhrs
    b. 2013 when the building was run in “optimised” operation it was 8,699kWhrs.
- The reduced energy consumption from very good levels at the onset of the study to extremely low levels was largely due to refinements in operation and increasing the proportion of time that the building is operated in passive mode.
- The MVHR consumption is substantial but the system draws next to no power from May to October. The energy consumption of the heating element in Year 1 was 2199kWh or 6.4kWh/m^2 at a cost of approximately £266/annum. The consumption fell in year two to 2092kWh or 6.0 kWh/m^2 despite more severe weather conditions.

- An estimated 6,400kWhr (18.5 kWh/m^2) was generated by the wood-burning stove each year, providing 74% of the total heating.
- Around 1930 kWhrs was generated by solar thermal reducing electricity consumption for hot water by around 50% in the spring and summer months.
- A bio disk draws a continual load equal of 2kWh per day.
- Energy demand for small power equipment in the building such as computers, TV, IT system, fridge etc. is around 6kWh per day.
- The lighting energy consumption reduces significantly from winter to summer consistent with the occupants taking care to only use artificial lighting when necessary.
- Plummerswood uses less energy/m^2, emits less CO_2/m^2 and costs less to run /m^2 than a Code for Sustainable Homes Level 6 (CSH6) building.
- It generates less than 25% of the renewable energy of a CSH6 house but requires less than 50% of the energy overall.
- It uses 6.4 and 6.0 kWh/m^2 of metered heating of treated floor/yr for 2012 an 2013 respectively compared to the design objective of 15kWhr/m^2 with the remainder from biomass.
- The Primary Energy Demand, the total energy used for all domestic applications inclusive of biomass (heating, hot water and domestic electricity) does not exceed 47.9 kWh/m^2 of treated floor area per year compared to the design objective of 120 kWh/m^2.

Modelled - Solar Gains

- The model demonstrates the efficacy of the external blinds to the living room and confirms that the fixed overhang of the south facing patio windows obviates the need for blinds. This validates the passive solar design.
- In the spring/summer period the effect of the overhang means that the temperatures with and without the blinds are similar.
- The modelling indicates that beneficial solar heat gain potentially reduces the heating demand by 35%. Without external blinds the anticipated annual heating demand would be 94kWh. With external blinds the annual heating demand increases to 143kWh.
- The external blinds could block beneficial passive solar heat in winter. Manual control of the living room and master bedroom blinds is critical to exploiting solar heat to the maximum. More advanced control could potentially identify solar ingress and internal temperatures to determine whether automatic opening or closing would be beneficial.

Modelled Solar Hot Water System

- The controller does not measure water flow rate and so it is not possible to establish reliable heat yield data. To assess the efficacy of the solar thermal system we used the winter period electric heating element sub-metered data (13.3kWh) and applied this across the year (4855kWh). The measured annual energy consumption of the element - 2457kWh gives us the solar thermal yield - 2400 kWh - approximately 50% of the use.

Modelled - Comparison of MVHR & Natural Ventilation

- MVHR treats a house as a single zone. Varying occupancy profiles are not recognised. So it uses more energy than strictly required through over ventilation of unoccupied or under occupied spaces or results in poor air quality in occupied rooms.

- It was predicted at the beginning of the project that the frost coil in the MVHR would consume a significant proportion of the MVHR energy and hence that MVHR does not theoretically offer an energy saving. Essentially a simpler mostly passive approach would have similar energy consumption. As the MVHR has significant capital and life cycle cost and maintenance implications this was considered an important consideration.
- The performance has been optimized by the occupants only using the MVHR when they feel they need to.
- As the client operates the MVHR in the winter and cannot easily disable the frost coil a further opportunity for optimisation is unavailable.
- It has been suggested that MVHR should be able to operate without the need of frost coil protection otherwise it doesn't appear to meet the standards for PassivHaus.
- However it should be noted that turning off MVHR systems, once installed, or only using them part time, could cause indoor climate problems if this results in a reduction in maintenance and leads to a build up of insects, particles etc. in air channels.
- A major issue appears to be a need to better understand the benefits of MVHR over NV in a variety of conditions, taking account of the MVHR design including frost protection, climate, client needs, requirements and aspirations and client intervention.

Ventilation tests

- The CO_2 concentration in the bedroom follows a daily profile swinging from 500ppm up to 1000ppm. It is normal practice for the bedroom door to be left open at night allowing for circulation of air to the rest of the house and the CO_2 in the bedroom is maintained at around 700 ppm. Measurements indicates that CO_2 level are in part controlled by the buffer effect of the volume of the other rooms in the house.
- The increase in CO_2 with the MVHR switched off overnight and the door and windows to the master bedroom suite closed compares very well with the predicted increase and suggests that the space is highly sealed. It identifies that some form of ventilation above infiltration would be essential to maintain suitable conditions in the bedroom.
- With the MVHR set at the recommended speed for night use (ventilation rate of $28m^3$/hr or 8 litres/s) and the door and windows to the master bedroom suite closed, the CO_2 concentration increases from 700ppm to 1400 ppm, again closely matching the prediction. The use of the low speed setting is therefore contingent on the occupants having the door to the rest of the house open to allow for air circulation into the bigger volume of the house as is their normal pattern.
- The temperature did not drift out of a comfortable range for any of the tests.
- With the MVHR off and the window opened to replicate trickle ventilation control, CO_2 control is very effective. It performs better than the MVHR. This could be a significant energy saving as the MVHR otherwise ventilates the whole volume overnight.
- Trickle vents are sealed up during an airtightness test as they're deemed to be 'designed ventilation' (like extract fans and other mechanical ventilation outlets/inlets) so in principal it would be possible to specify windows with optional trickle vent in a passive house and provide greater flexibility and reduced MVHR use for users.
- Openness to the house volume is an important aspect but may not suit all lifestyles.
- Further experimentation would be required to optimise and control the size of the trickle ventilation openings.

Key Findings – Operation and Management

- The water consumption is 83% lower than that of benchmark buildings. However, the building is off-grid and there is a localised energy penalty incurred to treat the borehole water and sewage. The bio disk is a substantial proportion of the overall electrical load. A review of sewage options would be undertaken on future projects to determine the best solution in the context with the aim to create improved efficiency without undermining environmental health or the local environment.
- Power failure occurred during the first year of occupation and, as the generator does not support ovens and the hob, the owners used gas fired camping stoves. This did not introduce a risk as the MVHR remained operational, however it may be an issue in other circumstances where occupants are not used to house that is airtight and there is a potential lack of air for combustion. In these circumstances occupants will need to be advised to open windows and to install Carbon Monoxide sensors.
- The operation and maintenance manuals recommend replacement of the filters for the MVHR system every 90 days at a cost of approximately £50 per quarter. These were found to be clean after 90 days and changing them an unnecessary expense.
- MVHR filters could be a significant element of the overall running cost and there is no mechanism to check whether the filters need replacing and thereby to optimise the change period. The manufacturer of the MVHR unit is as yet unable to provide better feedback on filter condition through for example pressure gauges.
- Unpleasant odours in the utility room resulted from the piping of the pressure relief on the domestic hot water cylinder. The plumber did not install the system with discharge to outside, as is the norm, as they were concerned about compromising the integrity of the air tightness. With Brettstapel construction all services penetrations of the envelope need to be designed before manufacture/construction. This takes a lot of time and attention to detail. In most cases at Plummerswood this was done properly but there was a failing in the utility room. This was remedied.
- The client control of blinds, lighting is a significant element in energy reduction supporting the original design concept of incorporating human factors.
- Access is good for filter replacement except the ceiling extract in the kitchen area.
- The occupiers have modified their cooking habits and do not cook greasy food in order to overcome problems this would introduce with the induction hob.
- Some lamps will be difficult to replace such as above the main first floor link bridge.
- The occupiers noted that two external rain-cladding panels are lighter in colour than the other panels as they needed to be replaced following a dispute between the blind installer and the main contractor. This was in regard to the installation of one of the external blinds and damage that occurred.
- The standby generator has worked well.
- The occupants would like to know why the bio-disc was not put onto the back-up power. The bio-disc goes into alarm and the occupants are not sure if the quality of the water from the borehole is compromised.
- The occupiers would have liked to have two levels of manuals. They feel that they would have benefitted from a simplified user guide that covered the basics.
- The occupiers were not too sure of the procedure for highlighting problems and how they are to get resolved. They were not sure how long it should take for faults to be rectified and would have welcomed more feedback on progress.

Solar Hot Water System

- The M&E consultant considered a range of LZC technologies. The clients influenced the decision with a preference for solar thermal and a retrospective analysis confirmed this as a valid decision.
- The installation was flawed, responsibilities blurred and the installers were not registered with the RHI Scheme which compounded the problems.
- The lack of performance of the solar thermal panels was a source of frustration. At the outset of the project it was apparent that the solar hot water heating system circulation pump operated only intermittently and there was no hot water yield from the system. The monitoring team identified that the control sensor was located incorrectly at the bottom inlet of the panels when it should have been located at the top outlet. The fix was relatively straightforward.
- The error resulted in 6 months of increased energy consumption. A key lesson learned from this study is that this type of error is easily possible in the construction of domestic properties, which rely on installations from local plumbers who are unlikely to have installed this type of technology previously.
- More scrutiny of any proposed installation would be undertaken in future projects to ensure adequate skills and registration were addressed.

Lighting Control System

- The lighting control system is unnecessarily costly and complex for a domestic installation and requires bespoke software to operate. It appears that the services engineers successfully lobbied that a property at the upper end of the market would be expected to have such a system. However, the occupiers are aware of the need to keep the lighting switched off when not necessary and a simple system would have been sufficient for their needs.
- During spring/summer 2013 it became apparent that parts of the lighting control system was behaving randomly with lights failing to respond to switching. The monitoring team arranged for the manufacturer to attend site and review the installation. The lighting was re-programmed and a booster installed. The system now functions correctly.
- Defects in the installation and lack of attention from service providers meant that without specialist input it might have been very difficult to resolve and potentially a health and safety risk.
- There are no outstanding technical issues apparent and the occupants appear to be very happy with the building and its responsiveness to their dwelling patterns.
- Snagging did take a long time in part due to the reluctance of some suppliers of skills and services to return to or visit the site. This is not an uncommon problem in the industry especially where projects are small and remote. .
- The monitoring project was a significant benefit in enabling the technical issues to be resolved including the lighting and the solar panels.

Summary of Overall successes and failures

- The building provides a good case study because it intentionally set out to fulfil the PassivHaus specification using MVHR complimented with opening windows and human controls. This allowed comparisons of energy consumption and internal environmental conditions in MVHR mode with the house closed up but progressively reducing the ventilation rate and in natural ventilation mode with the MVHR off.

- Disadvantages of MVHR include lack of zonal control and inability to direct air to where it is needed. The experiments on the MVHR – with willing occupants - were a useful contribution to the knowledge on these issues. The energy consumption can be controlled by attention to detail and it is clear that the management of the MVHR is a significant contribution to delivering energy efficiencies.
- This project has been particularly successful due to the engagement of the owners and the warm relationship between the clients, the architects and the monitoring team.
- The building appears to largely meet its design objectives.
- It provides an exemplar of off-site Brettstapel PassivHaus certified construction.
- The clients have a multi-award winning building that demonstrates very best practice in terms of a passive approach. The thermal insulation, thermal mass and air-tightness performance minimise heating demand and hygroscopic mass minimises humidity fluctuations and improves indoor climate. Theday lighting has been carefully designed to minimise requirement for artificial lighting and the solar orientation, natural ventilation and shading has also been designed to optimise heat gains. All of this was undertaken with an awareness of the desirability and benefits of personal control.
- The occupants have provided a short but thorough overview of the management issues from their perspective and the latent issues since occupation.
- The occupants expressed some disquiet at the lack of response from some professionals at and following handover, which was not fully comprehensive. However, they were also aware that the handover was complicated due to a death in the design team and were naturally prepared to exhibit patience in this regard.
- Whilst the written documentation provided was substantial and has proven useful for the client/ occupant in dealing with teething problems in the building's occupation, they would have benefited from having the documentation explained at the point of handover. In terms of the physical handover process, the combining of the technical handover/commissioning with the client handover meant there was no opportunity for interactive demonstrations/ training for the occupants and as a result they have had to learn how to operate some aspects of the building themselves.
- Requests from the clients for better handover information and a protocol for logging and addressing outstanding issues is noted for future projects.
- Following an initial settling in period, the clients have expressed satisfaction with the building and the control of the various systems.
- The building has proven to be robust and stable in terms of internal environmental conditions and benchmark energy consumption. Satisfactory internal environmental conditions are achieved and consistently maintained at a stable level.
- The internal temperature is consistent with the client requirements and the relative humidity is in line with best-practice values.
- There is enthusiasm to pursue local Brettsatpel manufacture in the UK but this is likely to put Gaia in the role of catalyst rather than in developing a business opportunity.
- Arup Scotland intends to develop the techniques of modelling hygroscopic mass as part of their overall modelling capability.
- The messages in this report are being disseminated through a range of media including professional, sector and academic conferences.

- The BPE process undermined much of the delight of research through over bureaucratisation, poor briefing, badly prepared, poorly drafted, documentation and impenetrable software.

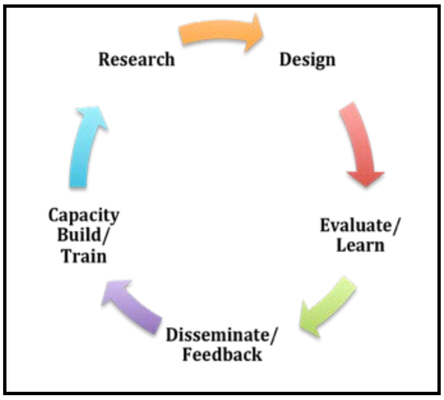
1 Introduction and overview

1.1 The Building Project

Gaia Architects was commissioned to design a dwelling on a site overlooking the River Tweed in the Scottish Borders.[1] The brief included a requirement for the dwelling to last at least 100 years and to take account of the requirements of future generations of the family. Gaia aimed to maintain its reputation for innovation and to push the boundaries of sustainable housing by pioneering an exemplar passive eco-house.

Picture 1. Plummerswood House

Evolution of the commission fitted within **Gaia Group's** overall approach to innovation involving research, design, evaluation & feedback, dissemination, training and capacity building.[2] The process addresses issues including resource effectiveness, toxicity cycles, indoor climate, human factors in environmental control, sustainable forestry and place making.



Picture 2. Gaia Life Cycle Approach to Innovation

Plummerswood is designed on ecological design principles, based on Howard Liddell's ***Ecominimalist*** [3] approach, to create a healthy, comfortable, energy efficient home. The aim was to use mechanical systems only in so far as they were necessary and to ensure that they were a supplement to natural systems, rather than a replacement for them. This places the project at the forefront of examining and optimising passive design.

The design team comprised of Gaia Architects, Ralph Ogg & Partners (Quantity Surveyor), Harley Haddow LLP (Structural) and Fulcrum Consulting (M&E) subsequently taken over by Mott MacDonald. The prefabricated superstructure was constructed on site to a six-week timetable, in the midst of the winter of 2010, on foundations built by local builders. The fit out was also by a local builder. The fixed furnishings resulted from design collaboration between Gaia Architects and Real Wood Studios.

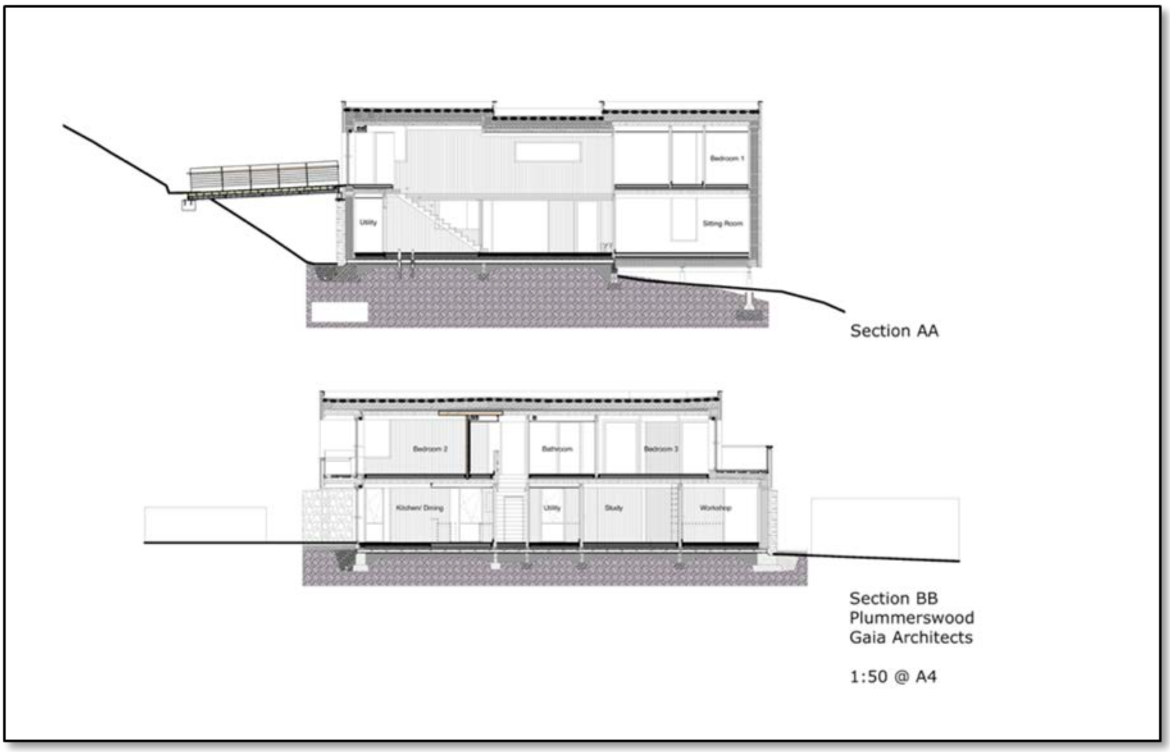
Picture 3. Construction December 2010

---

[1] Known as Plummers Knowe throughout the building process and changed to Plummerswood on occupation.
[2] www.gaiagroup.org
[3] Liddell H.L. (2007) *Ecominimalism the anti-dote to eco-bling* RIBA Publishing

The 346m^2 house was completed in Autumn 2011 and won the Scottish Homes Award for Architectural Excellence (small projects) in 2012 and a Scottish Borders Council Award.

Picture 4. Floor Plans



Picture 5. Elevations

1.2 Fundamental principles

1.2.1 Innovation for sustainable forestry, manufacturing, local economy & skills

The house combines the internationally recognised PassivHaus Standard specification with Gaia's integral and groundbreaking approach to a healthy indoor climate.[4] It is the first house to be constructed in Scotland to the PassivHaus Standard using an innovative off site glue-less mass timber technique known as Brettstapel**.**[5]

The use of Brettstapel has its roots in a research project undertaken by Gaia Architects and Gaia Research, along with Finnish and Norwegian partners (1997 - 2000). This work investigated the potential to add value to timber in rural communities in the European Northern periphery**.**[6] This led to an initiative by **Gaia Group** (2002) to promote UK manufacture of Brettstapel, which saw the design of **Acharacle School** by Gaia Architects (2007).[7] The intention was that Plummerswood build on the experience of Acharacle.

Both evolved as demonstration projects as no UK manufacturer of Brettstapel could be found. Both had superstructures prefabricated in Austria and shipped to site. The design team very much preferred to use Scottish timber and manufacturing capability, however it was felt that demonstration projects to illustrate the innovative potential of the technique would be invaluable. They considered the impact of transportation from Austria and a value of 16,000 kg CO_2 was estimated as emitted. This compared well with the sequestration of 243,000 kg CO_2 in the main timber elements (Brettstapel structural panels, insulation, sheathing boards and cladding).

Picture 6. Austrian Prefabrication Factory

Both projects were also designed to address contemporary understanding of comfort in a low carbon society by providing for, and then seeking to evaluate, human factors in environmental control.[8]

1.2.2 Passive Design

Acharacle School was designed to a Passive Standard – at that time understood as a Factor 10 building - that is requiring $^{1}/_{10}$th of the heating needs of a building regulations building.[9] [10]

---

[4] http://www.passivhaus.org.uk
[5] http://www.brettstapel.org.uk
[6] http://www.gaiagroup.org/Research/RI/PAS/roundpole/
[7] http://www.gaiagroup.org/?project_id=26
[8] Shove E., et al *Comfort in a lower carbon society* Building Research & Information Volume 33, Issue 1, January 2005, pages 32-40 http://www.tandfonline.com/doi/full/10.1080/09613210802079322#.UwN9SxbjOCs
[9] http://passipedia.passiv.de/passipedia_en/basics/what_is_a_passive_house
[10] http://en.wikipedia.org/wiki/Factor_10

However, in line with Gaia's ecominimalist philosophy it was designed for natural ventilation rather than mechanical ventilation with heat recovery (MVHR). The classroom ventilation was automatically controlled according to CO_2 concentration and temperature, with manual override to allow for human preferences in environmental control.

Plummerswood on the other hand was designed to incorporate MVHR, and to achieve PassivHaus certification.[11] The MVHR provides ventilation and space heating supplemented by the wood stove and a downstairs bathroom towel rail. Gaia's design intention was to contribute to knowledge in this important developing area of passive design by experimenting with the MVHR to compare performance under mechanical and natural ventilation regimes in order to ensure that the building operation was fully optimised in relation to energy, comfort and indoor environmental requirements.

Passive House requirements

A building considered a Passive House,must meet the following criteria:

1. The **Space Heating Energy Demand** is not to exceed 15 kWh/m^2 of net living space (treated floor area) per year or 10 W/m^2 peak demand.
In climates where active cooling is needed, the **Space Cooling Energy Demand** roughly matches the heat demand, with a small allowance for dehumidification.

2. The **Primary Energy Demand,** the total energy used for all applications (heating, hot water & electricity) must not exceed 120 kWh /m^2 of treated floor area per year.

3. In terms of **Airtightness**, a maximum of 0.6 air changes/hr at 50 Pascals (ACH50), verified with an onsite pressure test (in both pressurized and depressurized states).

4. Thermal **comfort** must be met for all living areas during winter as well as in summer, with not more than 10% of the hours in a given year over 25°C.

The above criteria are achieved through intelligent design and implementation of thermal bridge free design, superior windows, ventilation with heat recovery, quality insulation and airtight construction.[12]

- U-values for opaque elements (walls, ground floor, roof): max. 0.15 W/(m^{2}K)
- U-values for windows (total for frame and glazing): max. 0.8 W/(m^{2}K)
- Construction free of thermal bridging, Psi max.= 0.01 W/(mK)

Passive House buildings are planned, optimised and verified with the Passive House Planning Package (PHPP).

1.2.3 Optimised form fabric & control to minimise capital & running cost

The passive design techniques included:-

- PassivHaus certification standard thermal & air-tightness performance to minimise heating demand (0.6 m^3/hr/m^2 @ 50Pa or 0.46 ac/h^{-1}).
- Design of solar orientation & shading to optimise inter-seasonal heat gains.

[11] At the time of writing we are unclear whether MVHR is an absolute requirement of compliance for accreditation to the PassivHaus standard, and if so the geographical and other boundary conditions that apply. We hope that this research will contribute to developing debate.

[12] Note that there are discrepancies in the way that different energy assessment methods calculate energy consumption. The PHPP specifically excludes areas such as those with headroom less than 2m (eg below stairs) and areas covered with fixed furniture such as bookshelves, stoves etc. (297m^2) SAP takes all of the space between wall surfaces as having equal value (373m^2). DomEARM is based on treated floor area (346m^2).

- Design of a natural ventilation stack and cross ventilation design strategy to contribute to minimising the requirement for MVHR.
- Careful design of daylighting strategy to minimise requirement for artificial lighting.
- Attention to minimising other power loads.

Supplementary heating is limited to a wood-burning stove (HWAM Vivaldi 3.5 kW) supplied from their own regenerating woodland and a towel rail in the downstairs bathroom (500W Zehnder, Fassane Spa Electric). The control mechanism on the downstairs bathroom towel rail is a factory fitted Timerprog immersion heater.

1.2.4 Use of healthy materials

Gaia has a long history of involvement in healthy indoor climate, optimized material specification, ventilation and moisture management at all stages of the innovation life cycle.[13] [14] [15] All the building materials were vetted against Gaia's strict non-toxic and hygroscopic standards in order to contribute to this objective. Special attention was paid to the avoidance of synthetic and heavily processed materials and those with polluting impacts on indoor climate and on waste streams. The insulation is made from low-grade wood fibres bonded by tree resin. The building fabric is vapour-permeable, which allows any excess moisture to pass through it to the outside surface without affecting how well it insulates.

1.2.5 Hygroscopic mass to minimise RH fluctuations & improve indoor climate

Gaia Architects' standard healthy internal environments specification aims to use materials to assist in buffering moisture and thereby contributing to maintain comfortable and healthy humidity levels in a building.[16] Much of the internal finish comprises of untreated timber, which offers a large hygroscopic surface area, though not as much as the end grain of timber. Also areas of the house that could be subjected to high levels of indoor moisture, e.g. bathrooms, kitchen and wet room, have clay board and clay plaster ceilings.

1.2.6 Human factors in environmental control

The architects were keen that Plummerswood was responsive to user needs, requirements and aspirations for personal control, i.e. an active house responding to human factors, rather than a passive house responding to a regulated norm.[17] This should not be confused with the international Active House or "Smarthouse" which is technology and electronic controls driven.

---

[13] http://www.gaiagroup.org/index.php/project/view_details/21/
http://www.gaiagroup.org/Research/RI/LowAllergyHousing/Final_ALAH_GN_compressed.pdf
[14] http://www.gaiagroup.org/include/pdf/publications/dynamic%20insulation%20web.pdf
[15] http://www.architectsjournal.co.uk/home/a-heated-exchange/183628.article
[16] DTU (2005) *Moisture Buffering of Building Materials* Department of Civil Engineering Technical University of Denmark Report BYG·DTU R-126.
[17] See Norwegian "Aktiv Hus" http://www.aktiv-hus.no

1.3 The Monitoring Project

This report describes the monitoring and performance of Plummerswood undertaken by Gaia Research in collaboration with Gaia Architects and Arup Scotland over a two-year period (January 2012 to December 2013).

The comprehensive monitoring programme appraises technical and human aspects of the design development, handover and operation of the building in line with protocols of soft and hard monitoring prescribed by Technology Strategy Board (TSB). Requirements for reporting on these issues are clearly laid out in the proforma of this report. The monitoring equipment was as prescribed by the TSB to meet its protocols.

In addition the monitoring team set out to investigate specific aspects of the design. Gaia promote passive design as an approach that can often be financially justified by significantly reducing the amount of building services required to balance capital costs whilst also delivering savings on running costs. Throughout this study we have sought to pursue and enhance innovation specific to sustainable building design. This included:

a) Review of research developments and practical activity in UK Brettstapel manufacture.[18]
b) Comparison of MVHR and NV operation in terms of the impact on energy consumption and indoor air quality
c) Thermal and moisture buffering of exposed timber and the effect on indoor climate and how this information can contribute to Arup environmental modelling capability.

Participants

- Gaia Architects provided support to Gaia Research in respect of the project history, design intent and design progression.
- Arup Scotland, who were not involved in the design, undertook data gathering and data analysis as well as some of the physical testing.
- RMP, GAIA ALDAS and Jennings ALDAS undertook airtightness testing. Bill Bordass acted as an independent reviewer at key stages of the project.
- The occupants, Ian & Anne Nimmo, were fully engaged in the monitoring process, kept a diary to assist in the performance analysis, and carried out experiments under the instructions of the monitoring team. They made comment through the required feedback mechanisms. They also provided a short video: **The clients story.**[19]

A presentation has been prepared to summarise the monitoring so that participating organisations can provide feedback to their own organisations and beyond to a wider audience.

---

[18] Appendix 1. Updated Review of research developments and practical activity in UK Brettstapel manufacture
[19] http://www.youtube.com/watch?v=-3qk5HpQIcU

1.4 Key findings - Energy Monitoring Results

1.4.1 Domestic Energy Assessment and Reporting Method [20]

The Domestic Energy Assessment and Reporting Method (DomEARM) was used for the reporting of the metered data collected from January 2012 to December 2013.

Two assessments were undertaken. One covers the 2012 period where the building was being run as per the O&M instructions. A second covers 2013 when the building was being run in "optimised" operation.

Summary of the main data inputs and the methodology

Total: - The total consumption comprises of the total of the mini-meters plus the assumed consumption for the bio-disc and non-metered equipment to allow there to be consistency with the sub-metered data requirements of the level 3 assessment. In summary, the total consumption for 2012 was 10,181kWhrs, and for 2013 it was 8,699kWhrs.

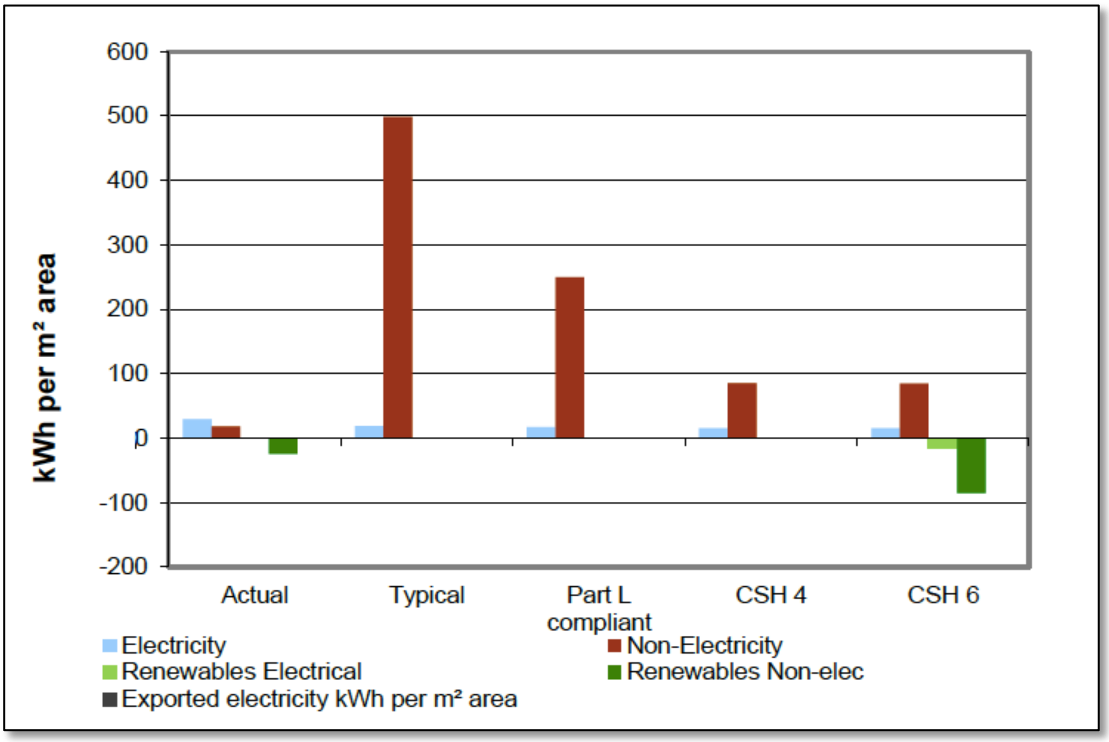
Electricity Unit Rate: - The cost of electricity per kWh is consistent for both assessments and based on the unit rate of 12.09p/kWh provided by the client in December 2012. As the standing charge is time dependent and not usage dependent this has been excluded from the cost of electricity section.

Biomass Consumption: - The owners reported starting to use their wood-burning stove on 13 October 2012. They measured the mass of the timber at around 10kg per day and the moisture content at around 15 to 20%. This is relatively low moisture content and the calorific value is likely to be high. For the purpose of this appraisal we have used a value of 4000kWh/ tonne for the energy associated. Therefore 40kWh/day of biofuel is combusted.

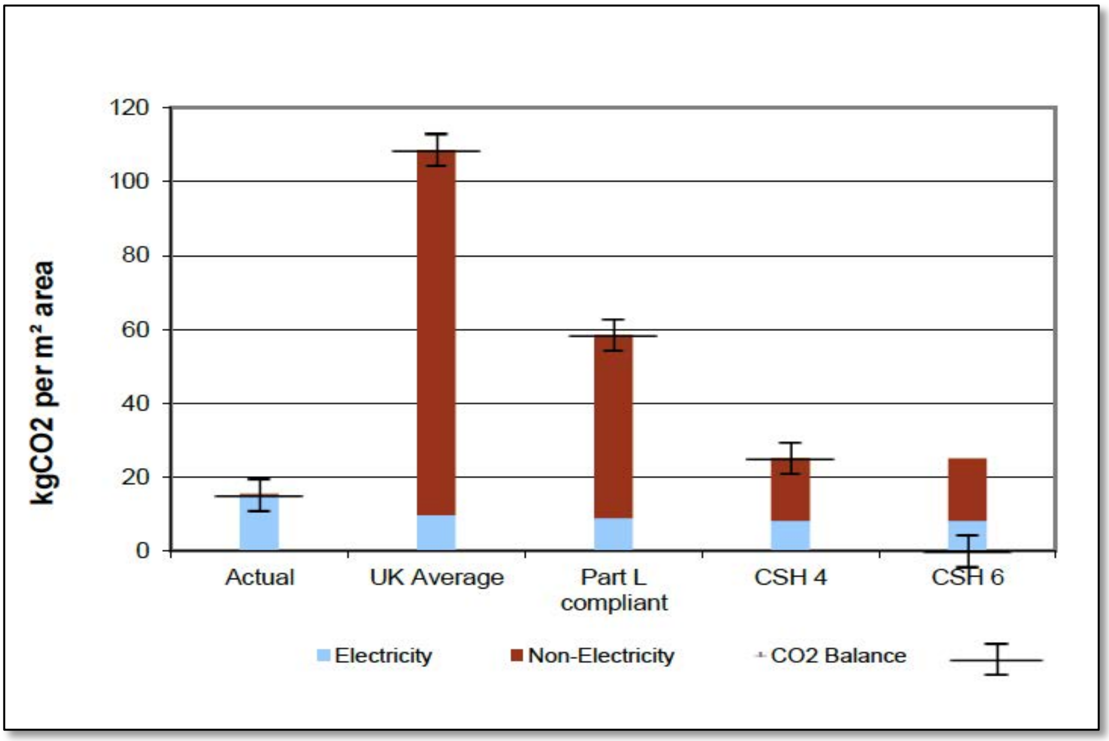
The occupant diary indicated that biofuel was combusted for 19 days in October, 30 in November and 31 in December. A total of 3200kWh generated over 3 winter months. The occupants' diary confirms no use of the stove during April to September and so for the purpose of the DomEARM a value of 6,400kWhs is applied to the full winter in 2012, providing 74% of the total heating. The MVHR elements consumed around 2,199kWhs. The DomEARM spreadsheet identifies the log stove as the primary system. The same estimated biomass consumption is used for 2013.

Solar Hot Water Generation: - Solar generation is estimated from the sub-metered data. In the winter, when the solar hot water yield is negligible the hot water element typically consumes around 13.3kWhrs per day. The yield is therefore 13.3 x 366 (leap year 2012) = 4868kWhrs minus the HW element actual consumption (2929kWhrs in 2012) = 1927 kWhrs.

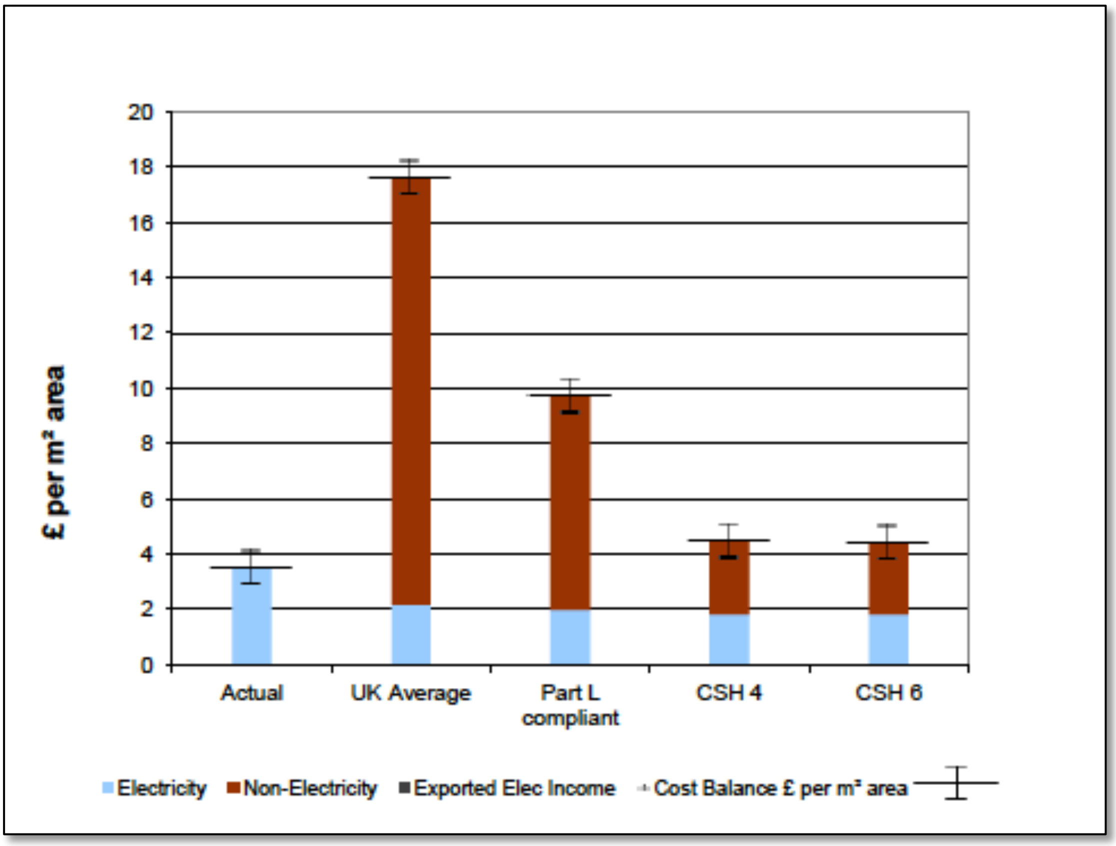
[20] Appendix 2: Results of the DOMEARM 2012/13



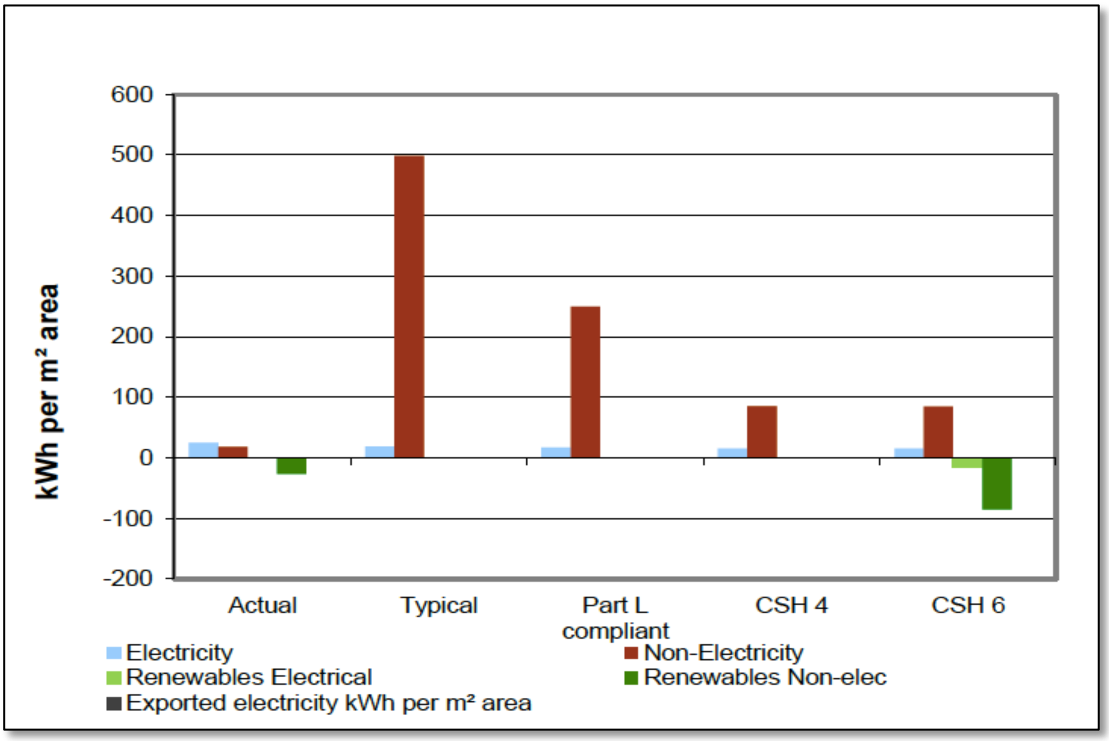
Graph 1. Energy Comparison 2012



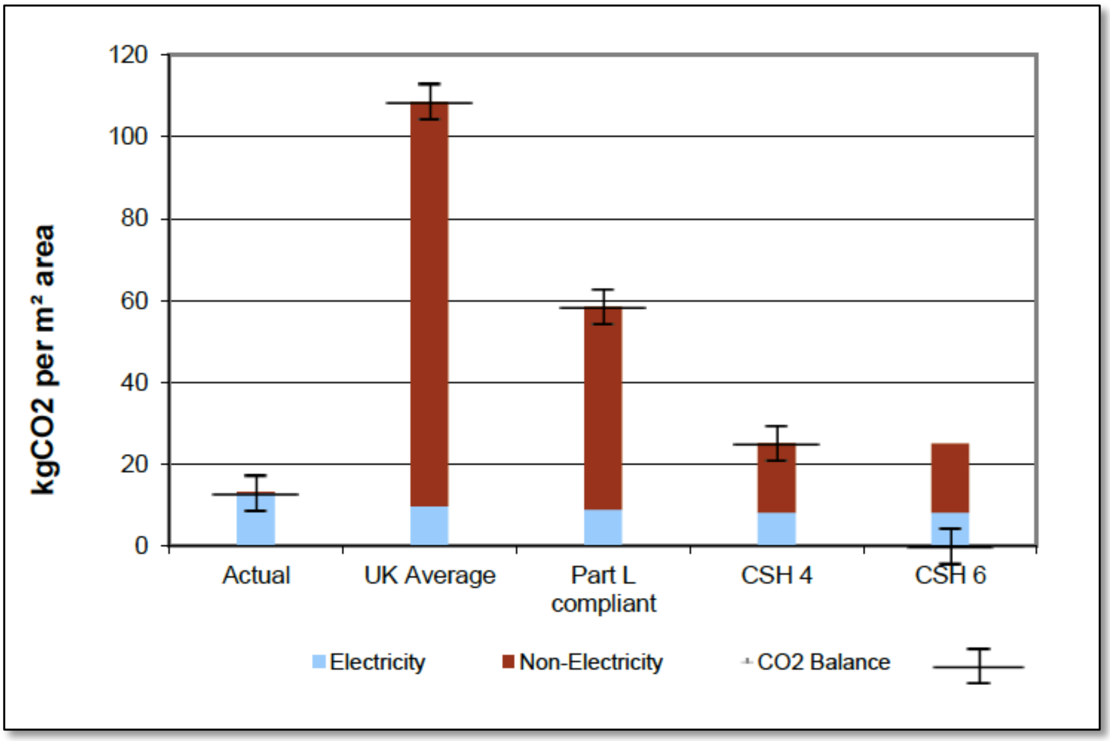
Graph 2. CO_2 Comparison 2012



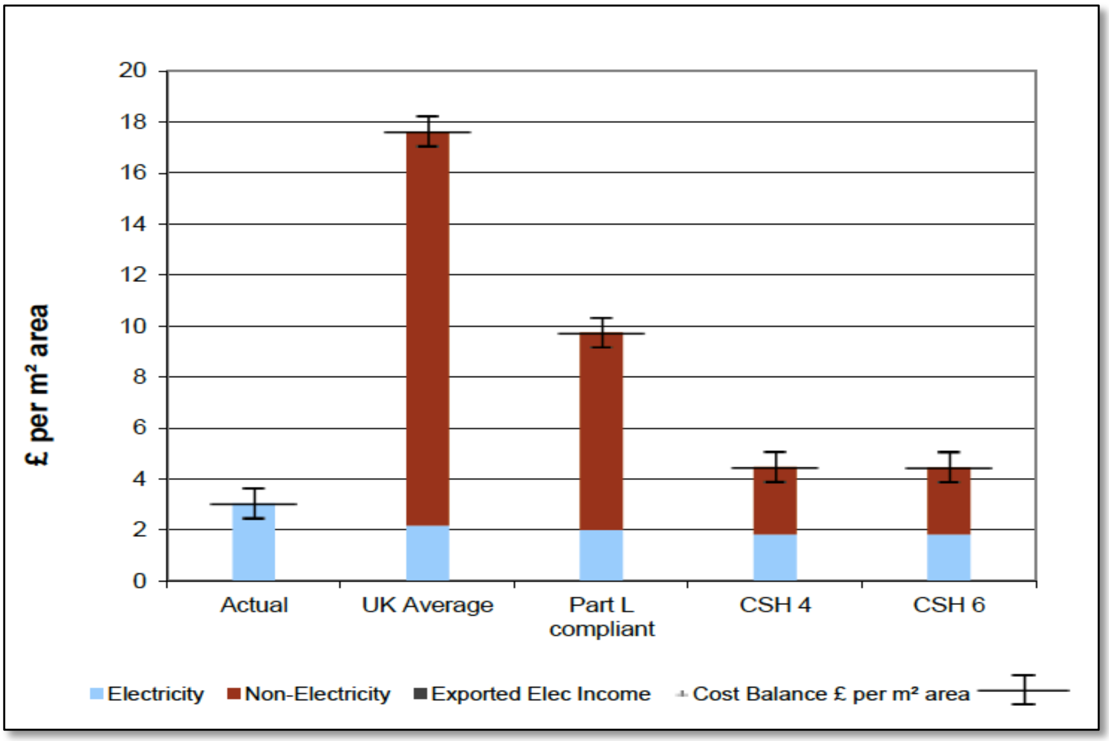
Graph 3. Cost Comparison 2012



Graph 4. Energy Comparison 2013



Graph 5. CO_2 Comparison 2013



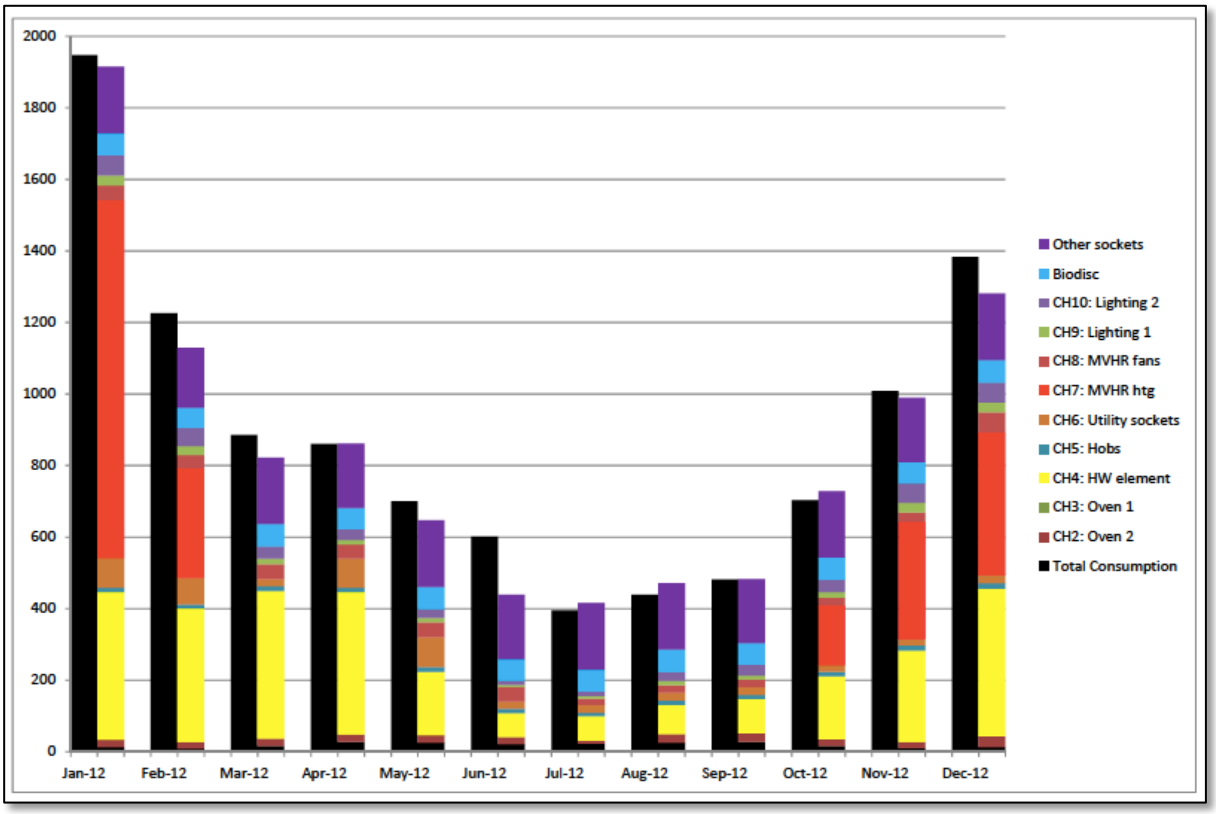
Graph 6. Cost Comparison 2013

1.4.2 Metered Data

Black columns are the total electricity consumption from the utility bills. The multi-coloured columns are the breakdown for the 10 sub-meters. The main energy consumers are: -

Yellow: DHW production;
Red: MVHR heating element;
Blue: Bio disk (shortfall assumption);[21]
Purple: Small power (shortfall assumption);

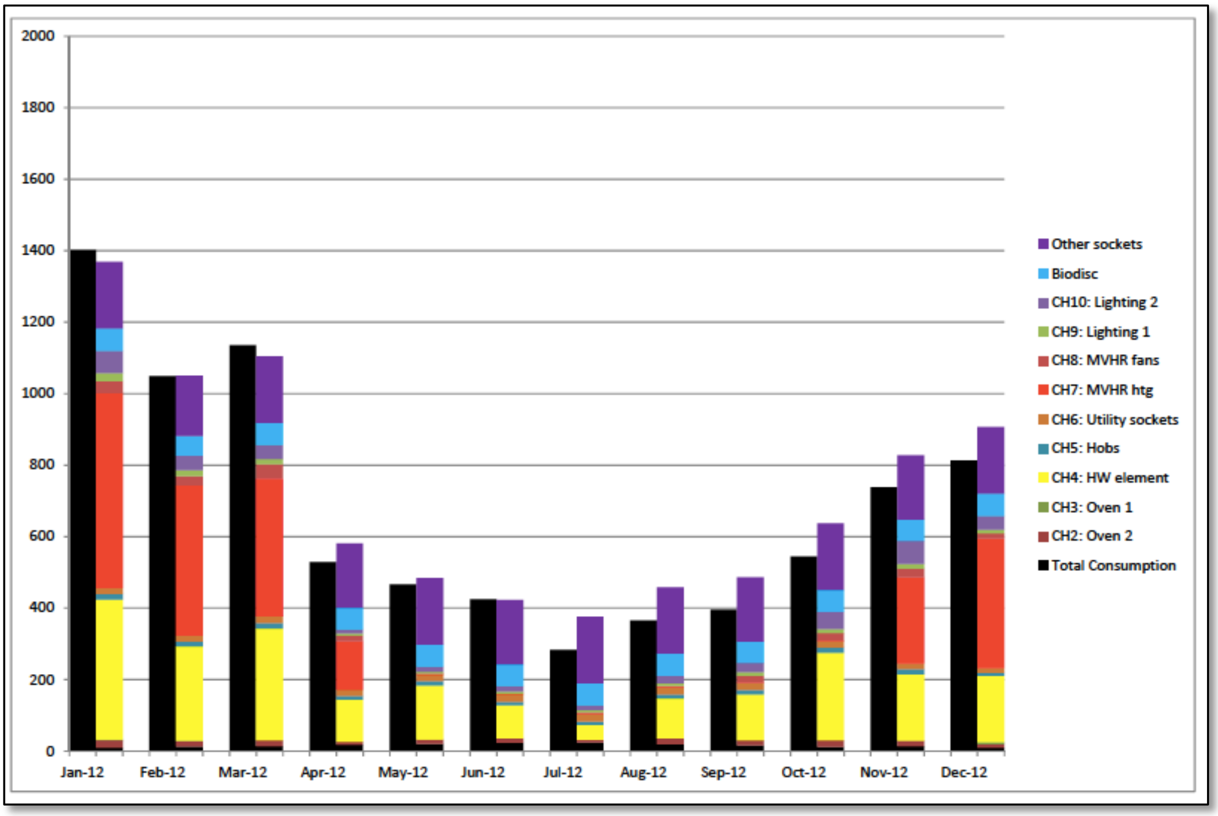
Other sub-metered elements are noted in the legend below.



Graph 7a: Sub-Metered Data – Monthly – 2012

---

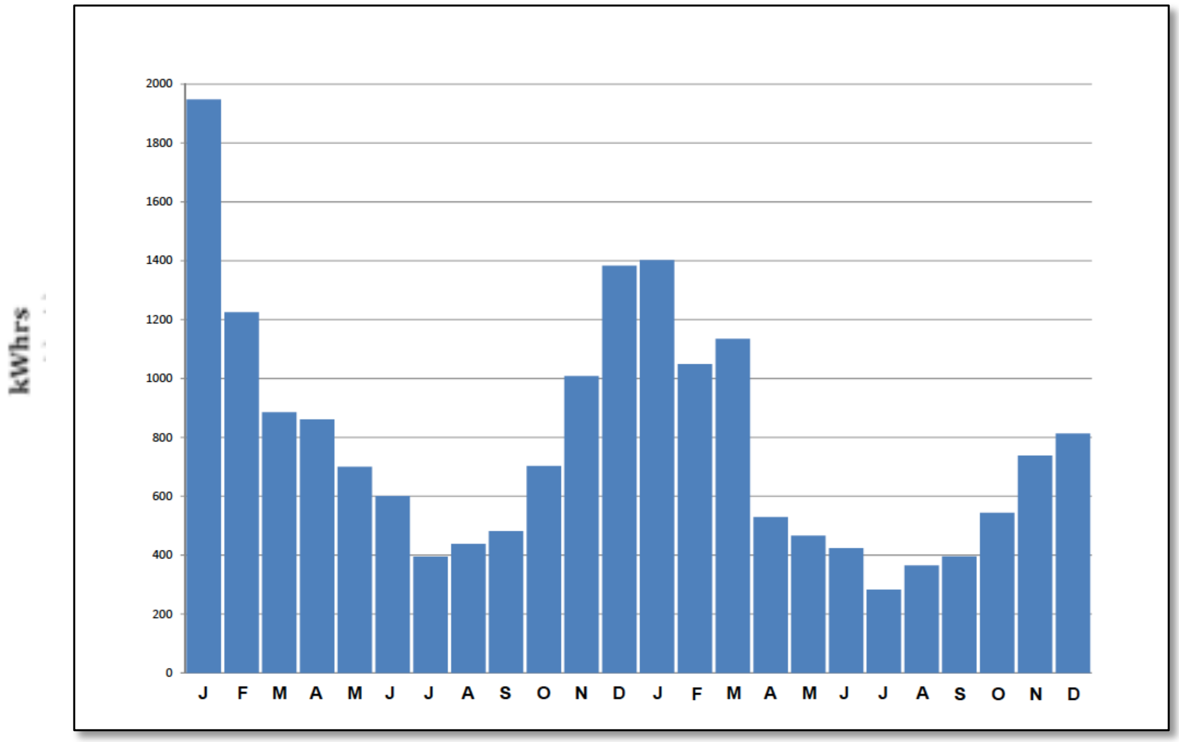
[21] A BioDisk is a packaged sewage treatment plant for domestic dwellings without access to mains drainage. It uses rotating biological contactor technology. It is often used for locations where discharge is to sub-surface irrigation, or to a suitable watercourse where approved by the Regulator, and where a septic tank will not meet the required standards.



Graph 7b: Sub-Metered Data – Monthly – 2013

Items of particular note are:

- The MVHR consumption is substantial but the system draws next to no power from May to October. The energy consumption of the heating element in Year 1 was 2199kWh or 6.4kWh/m^2 at a cost of approximately £266/annum. The consumption fell in year two to 2092kWh or 6.0 kWh/m^2 despite more severe weather conditions.
- BIomass consumption accounts for a further 18.5 kWh/m^2 in years 2012 and 2013 respectively.
- The solar hot water system reduces the electricity consumption for hot water production by around 50% in the spring and summer months when compared with winter.
- Energy demand for small power equipment in the building such as computers, TV, IT system, fridge etc. is around 6kWh per day.
- The bio disk draws a continual load equal of 2kWh per day



Graph 8: Total Energy Consumption 2012 -2013

The monitoring team have been able to help to reduce energy consumption from very good levels at the onset of the study to extremely low consumption for regulated loads. This is largely due to refinements in operation and increasing the proportion of time that the building is operated in passive mode. See Appendix 3 for an analysis of energy consumption against degree-days for January - March 2012 and January - March 2013.[22]

1.4.3 Outcome

Plummerswood uses less energy/m^2, emits less CO_2/m^2 and costs less to run /m^2 than a Code for Sustainable Homes Level 6 building. It generates less than 25% of the renewable energy of a CSH6 house but requires less than 50% of the energy overall.

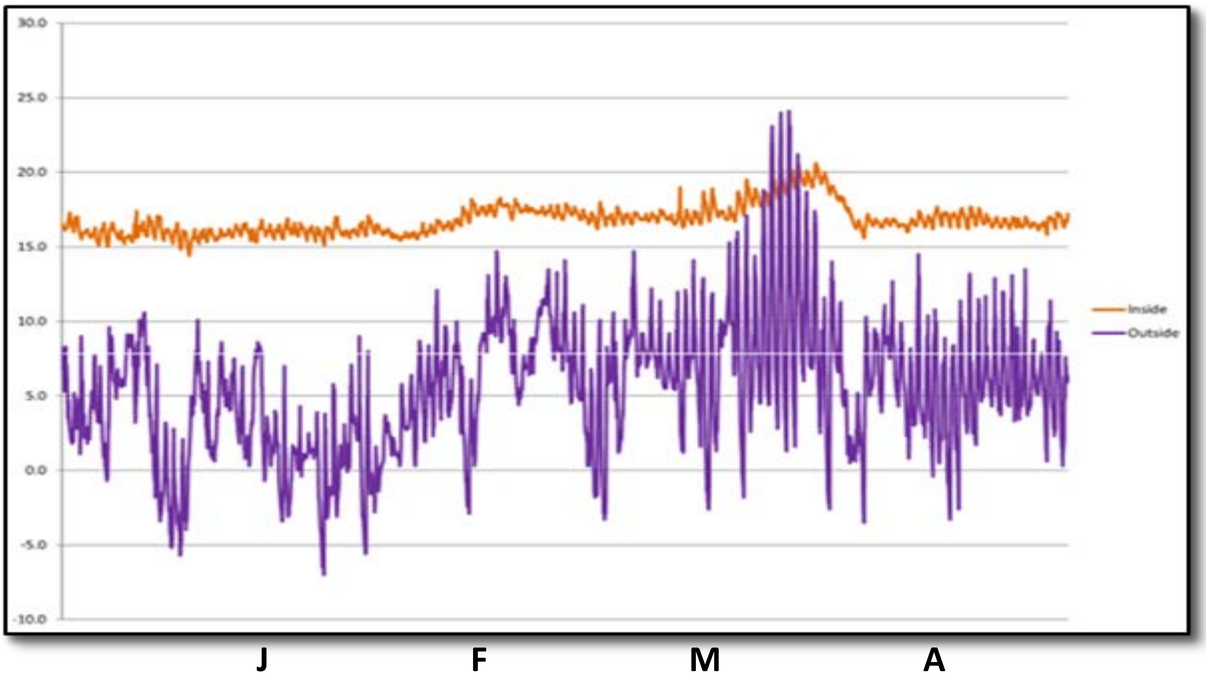
Compared to the design objective of 15kwhr/m2 **for heating of treated floor area per year** or 10 W/m^2 peak demand. It uses 6.4 and 6.0 kWh/m^2 for years 2012 an 2013 respectively with the remainder from biomass.

The Primary Energy Demand, the total energy used for all domestic applications inclusive of biomass (heating, hot water and domestic electricity) does not exceed 47.9 kWh/m^2 of **treated** floor area per year compared to the design objective of 120 kWh/m^2.

[22] Appendix 3: Quarter report 5 Section 2.3.2 Improvement in Energy Use

1.5 Key Findings – Internal Environment

1.5.1 Assessment of Thermal Mass - January to April 2012



Graph 9: Temperature Profile Dining Room - January to April 2012

A review of the temperature being achieved internally compared to the external temperature was undertaken to assess how the building is performing against the theoretical heat losses for the period January to April 2012.[23] During most of this time the building was operating using the MVHR. Notably during a warm period in March the internal temperature remains comfortable suggesting that the building benefits from thermal mass.

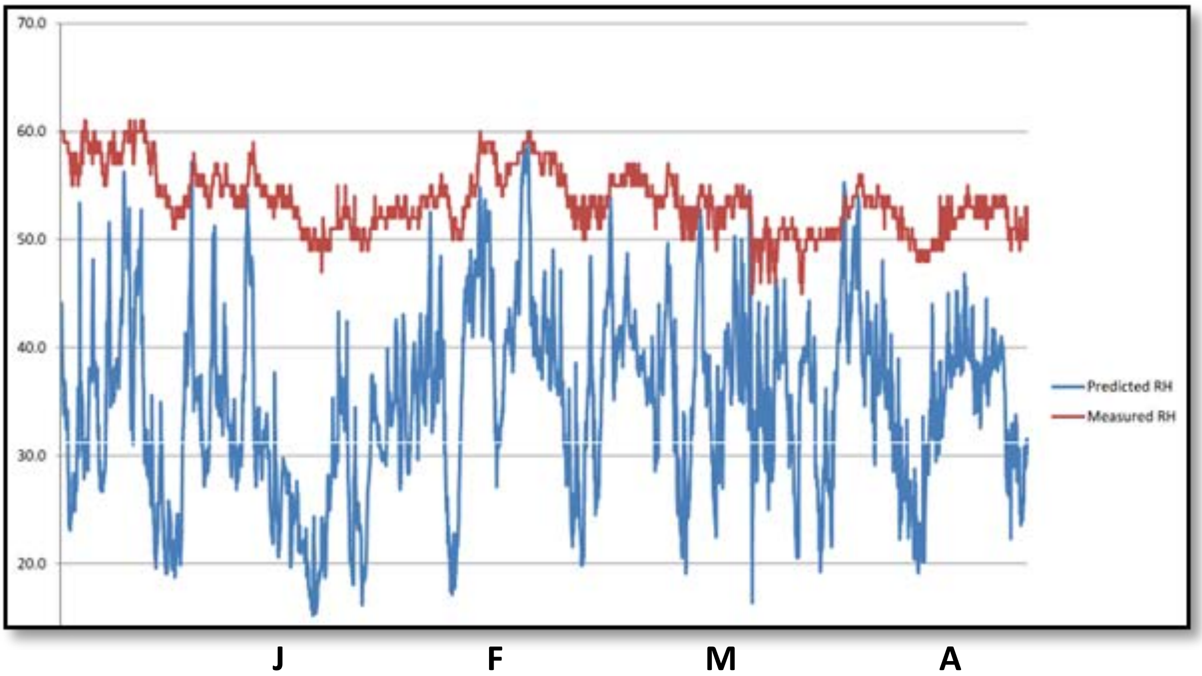
1.5.2 Assessment of Moisture Mass - January to April 2012 [24]

A review was undertaken to test the efficacy of the hygroscopic materials that make up the internal surfaces. These materials are intended to allow moisture to be absorbed during periods of high RH and readmitted to the room air during periods of low RH. The outcome should be stable RH inside relative to fluctuating external conditions. The internal and external moisture content were compared to assess the difference between them.

The red line represents the RH inside. The blue line is the actual measured external relative humidity that has been transposed along the straight horizontal line on the psychometric chart to the internal temperature as if undergoing a sensible heating process. The graph indicates that there must be some effect on the internal environment that is adding moisture to the air during these months.

---

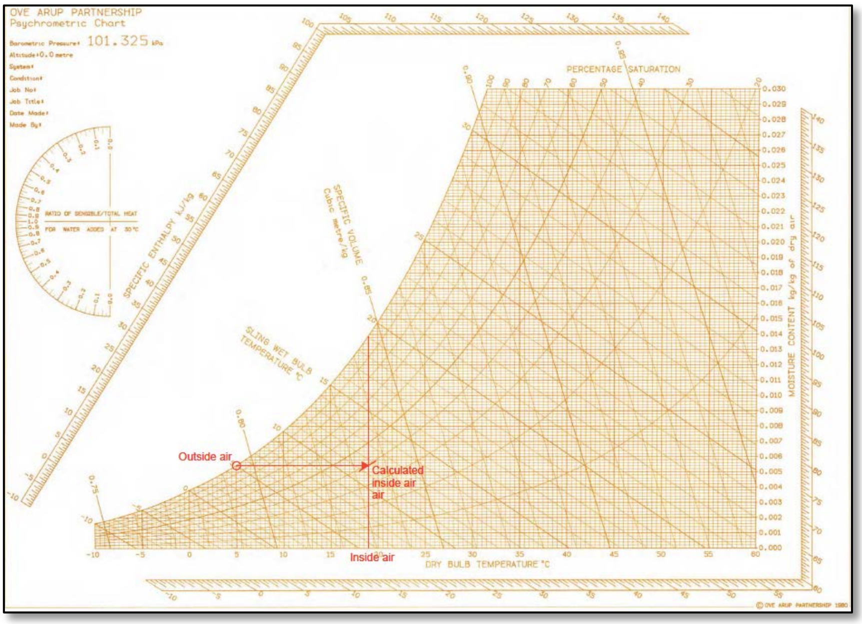
[23] Appendix 4: Environmental Reports – Task Report 17
[24] Appendix 4: Environmental Reports - Task Report 16 and Quarter Report 4



Graph 10: RH Profile Dining Room - January to April 2012

The measured internal relative humidity is very consistent during the monitored period and does not have the swings shown in the outside air moisture content. The relative humidity is in the range of 50% - 60% representing ideal conditions.

During the latter period of March a very warm spell of weather was experienced and the MVHR system was switched off and the house naturally ventilated. This may account for the marginally wider swings in internal relative humidity.

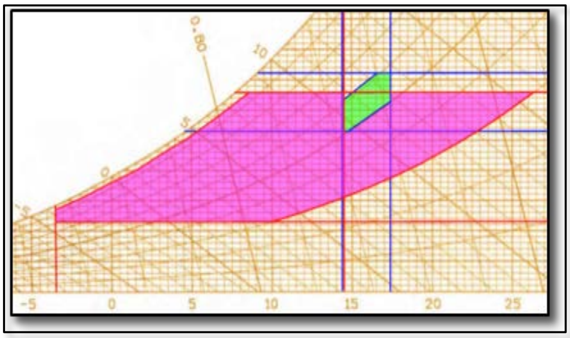


Picture 7: Sensible Heating of External Air[25]

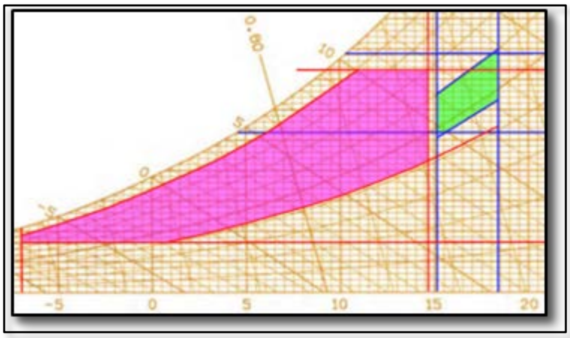
25 Appendix 4 – Environmental Monitoring Quarter Report 4 contains monthly graphs

The moisture attenuating properties of the construction materials were further reviewed using psychometric charts for each month on which we have drawn a summary of the collected data for external climate and internal conditions.[26] In each graph the purple shaded zone represents the range of external climate conditions experienced throughout the month. The green shaded zone represents the range of the internal conditions for the same period. This therefore represents the envelope of the absolute max/mins.

The data shows the external conditions have a much greater range of moisture content as compared to the internal conditions. In winter the internal moisture content is consistently greater than the external moisture content and has very little change.

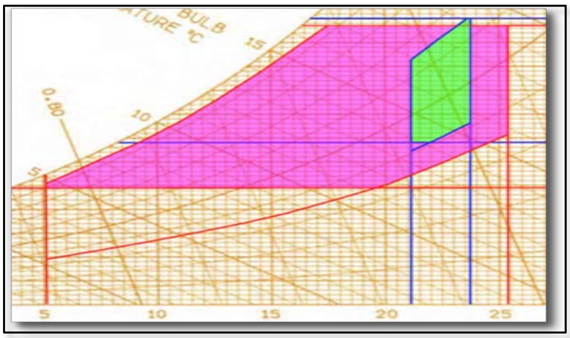


Graph 11: Psychometric Range: Jan 2012

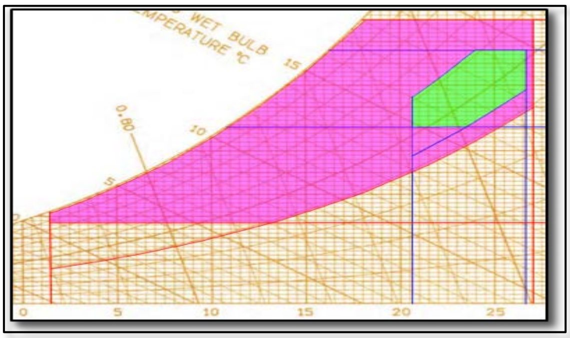


Graph 12: Psychometric Range: Feb 2012

In summer the green shaded zone has moisture content between the extremities of the purple zone. The differences in the range of moisture content inside to outside are not as large in the summer period as in winter. We would anticipate that this derives from the house being naturally ventilated in this period. The ventilation through the building would be much greater in the summer.



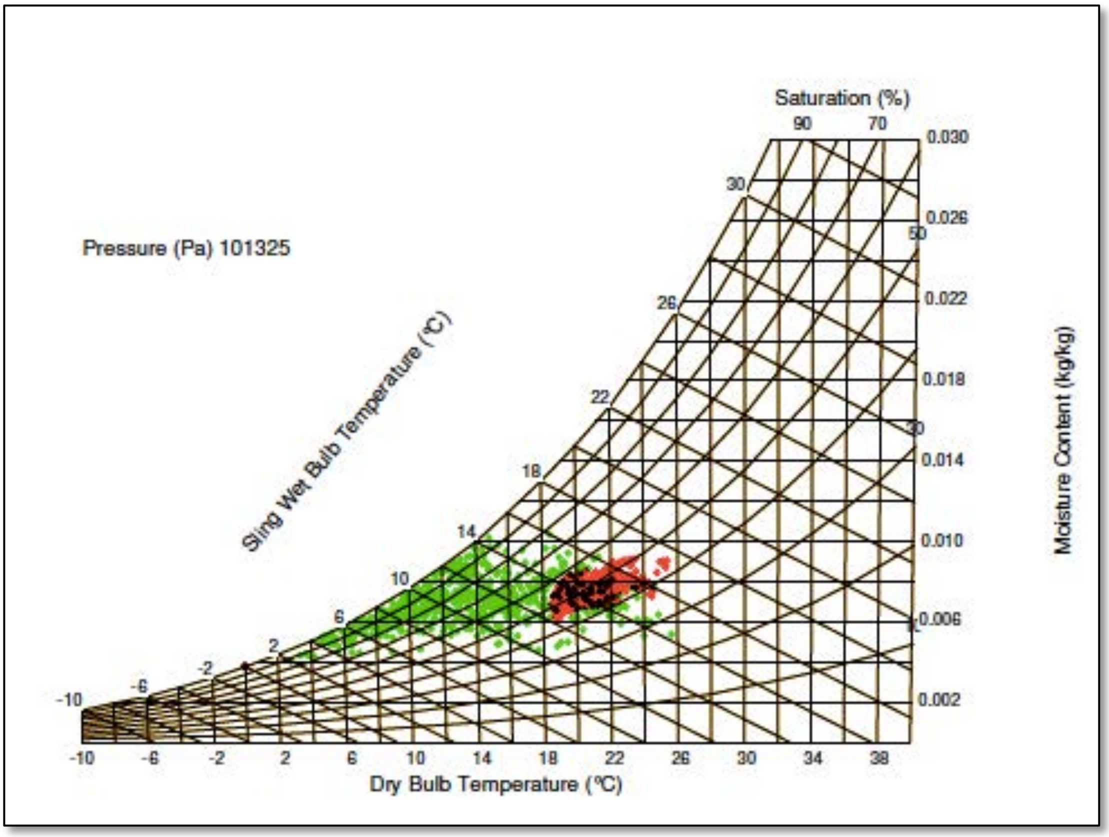
Graph 13: Psychometric Range: July 2012



Graph 14: Psychometric Range: August 2012

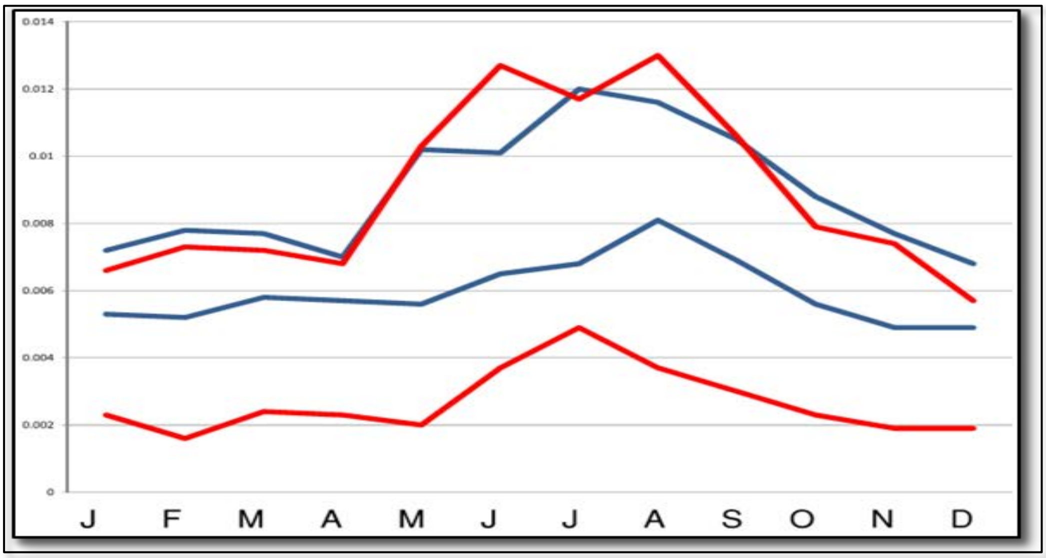
In the graph below the internal and external conditions for a sample month - June 2013 - are overlaid to show the distribution and frequency of each occurrence. This identifies that peaks and troughs are rare.

[26] Appendix 4– Environmental Reports - Quarter Report 4



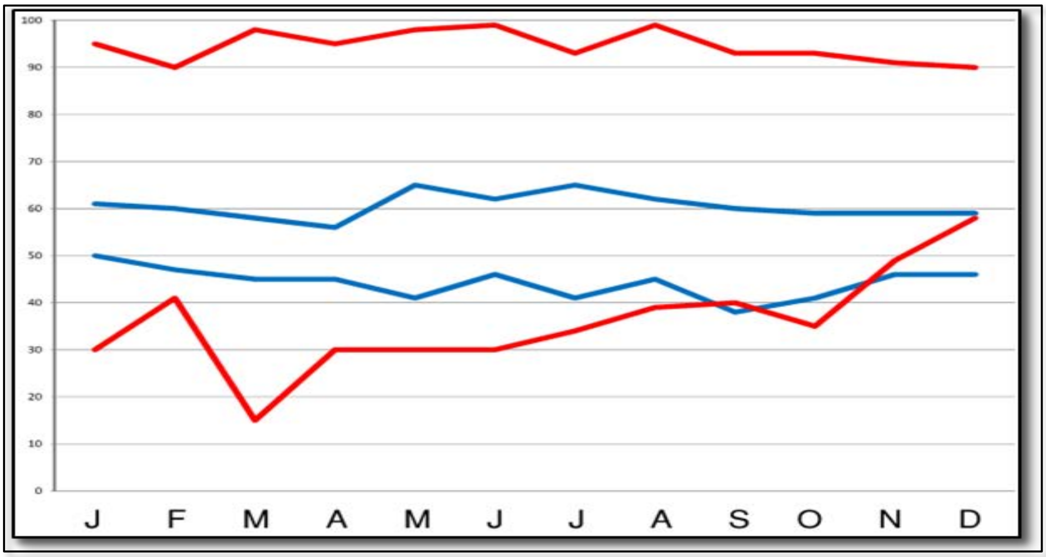
Graph 15: Distribution of Internal and External Conditions June 2013

Below we compared internal humidity (absolute then relative) for inside to outside during 2012. [27] The red lines represent the extremes in humidity outside. The blue lines are inside.



Graph 16: Extremes of Absolute Humidity 2012 - red lines outside, blue lines inside.

27 Appendix 4: Environmental Reports - Quarter Report 4



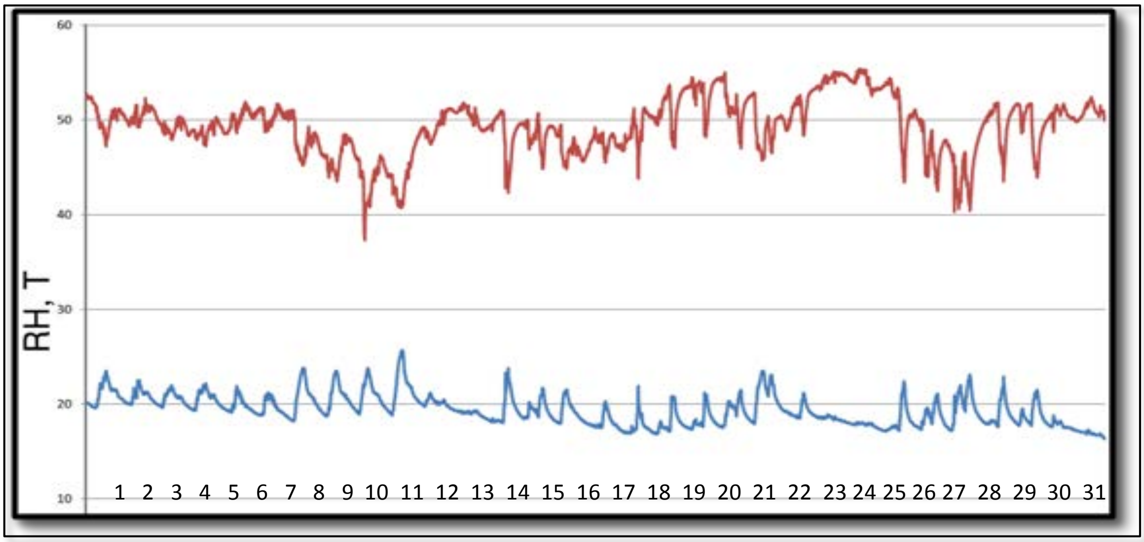
Graph 17: Extremes of <u>Relative</u> Humidity 2012 - red lines outside, blue lines inside.

The graphs demonstrate stability in internal relative humidity - ranging from 45% to 65% - compared with the wider extremes outdoors. The winter variation in humidity is less than that in summer, which is expected with the building closed and mechanically ventilated.

1.5.3 Assessment of Stability [28]

Temperature & Relative Humidity -October to December 2012

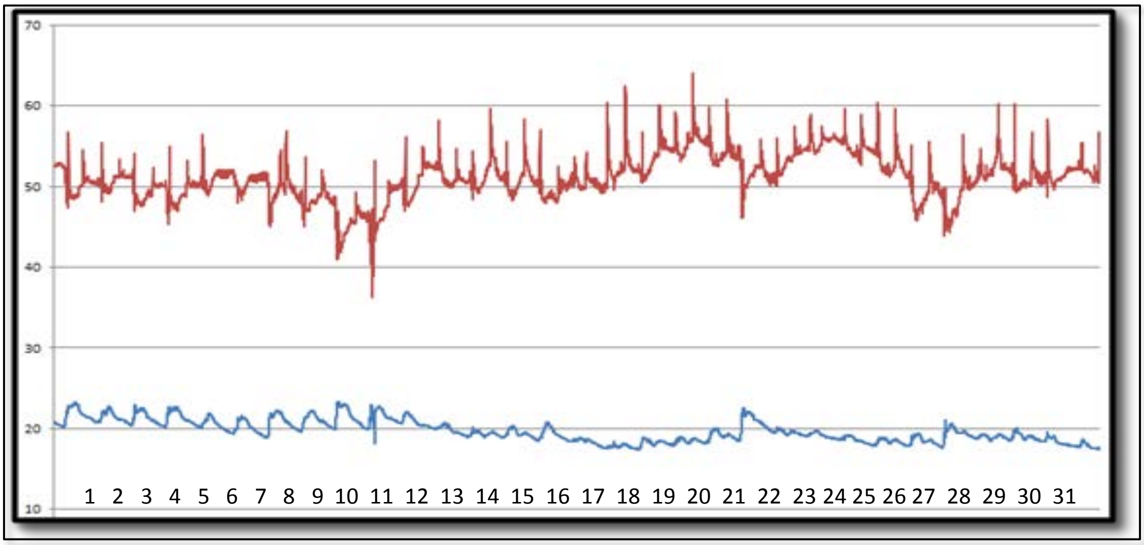
a) Dining Room RH and Temperature



Graph 18: Dining Room RH and Temp– October 2012

From October to December 2012 the dining room temperature cycles daily from around 17^0C to 22^0C. The MVHR system set point is 17^0C and solar gains and loads from people, lighting and cooking increase the temperature during the daytime. The relative humidity is in the range 40 to 55%. Spikes in temperature occur with coincident drops in RH.

b) Master Bedroom RH and Temperature



Graph 19: Master Bedroom RH and Temp– October 2012

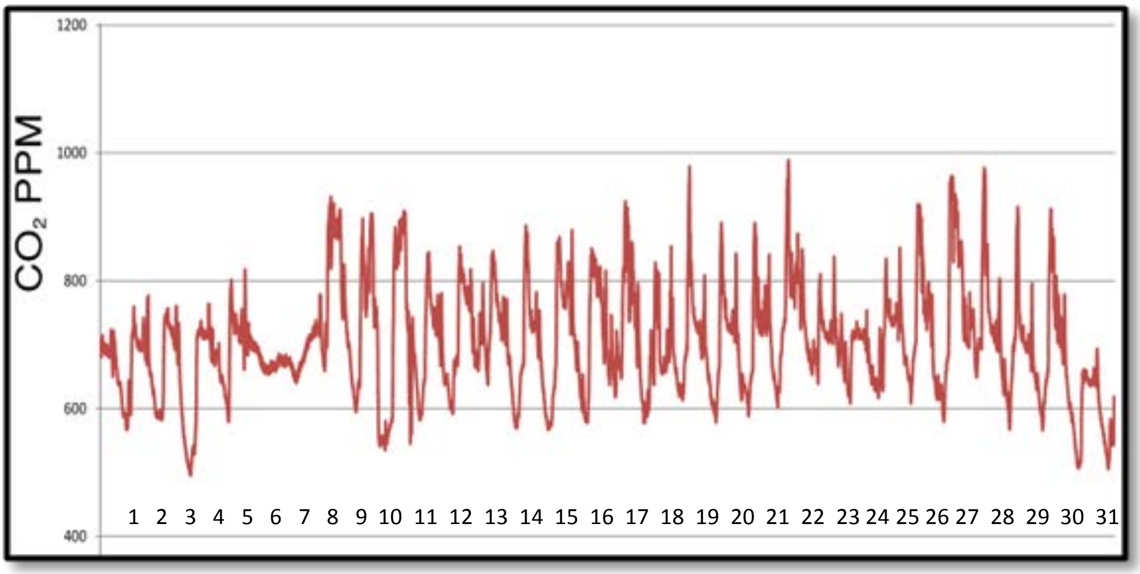
---

[28] Appendix 4 – Environmental Reports - Quarter Report 4

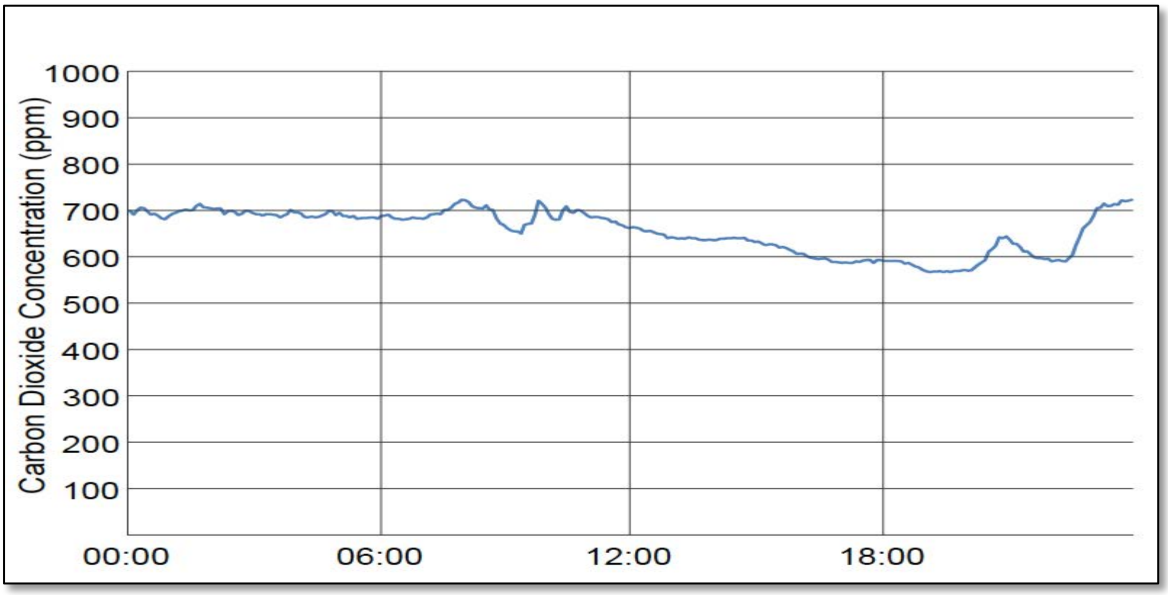
During the same period the bedroom is more stable than the dining room in temperature. The relative humidity has a spike twice daily. This is consistent with the reported bathing of the owners who use the shower at around 10:30 in the morning and again in the evening.

1.5.4 Assessment of Carbon Dioxide Levels - October to December 2012[29]

During this period the MVHR was generally set at low speed but the door between the master bedroom and the main house was left open, allowing the air to circulate between the bedroom and the rest of the house. The CO_2 concentration in the bedroom follows a daily profile swinging from 500ppm up to 1000ppm.



Graph 20a: Bedroom CO_2 Concentration– October 2012



Graph 20b: Bedroom CO_2 Concentration– Sample Day 1st October 2012

29 Appendix 4: Environmental Reports - Quarter Report 4

The profile for November was similar with an occasion where the CO_2 concentration rose to around 1400ppm. The CO_2 concentration rose above 1000ppm more frequently in December.

Using the methodology in CIBSE AM10 for the reservoir effect and assuming an 8hour occupied period in say the master bedroom (2 people) the final CO_2 concentration would be 1340ppmv if the system were to operate in normal mode. If the system were to operate at reduced mode the CO_2 concentration would increase to 1720ppmv.[30] Therefore the CO_2 was absorbed into the volume of the whole house.

Measurements taken at other times of year with the MVHR system off, indicates there is no adverse impact on the concentration of CO_2 in the bedroom, which indicates that the CO_2 level is in part controlled by the buffer effect of the volume of the other rooms in the house.

1.5.5 Assessment of MVHR Operation - Summertime

As part of the review of the internal conditions a study of the operation of the MVHR was undertaken in August - September 2012. This examined the internal conditions under MVHR and natural ventilation conditions.[31]

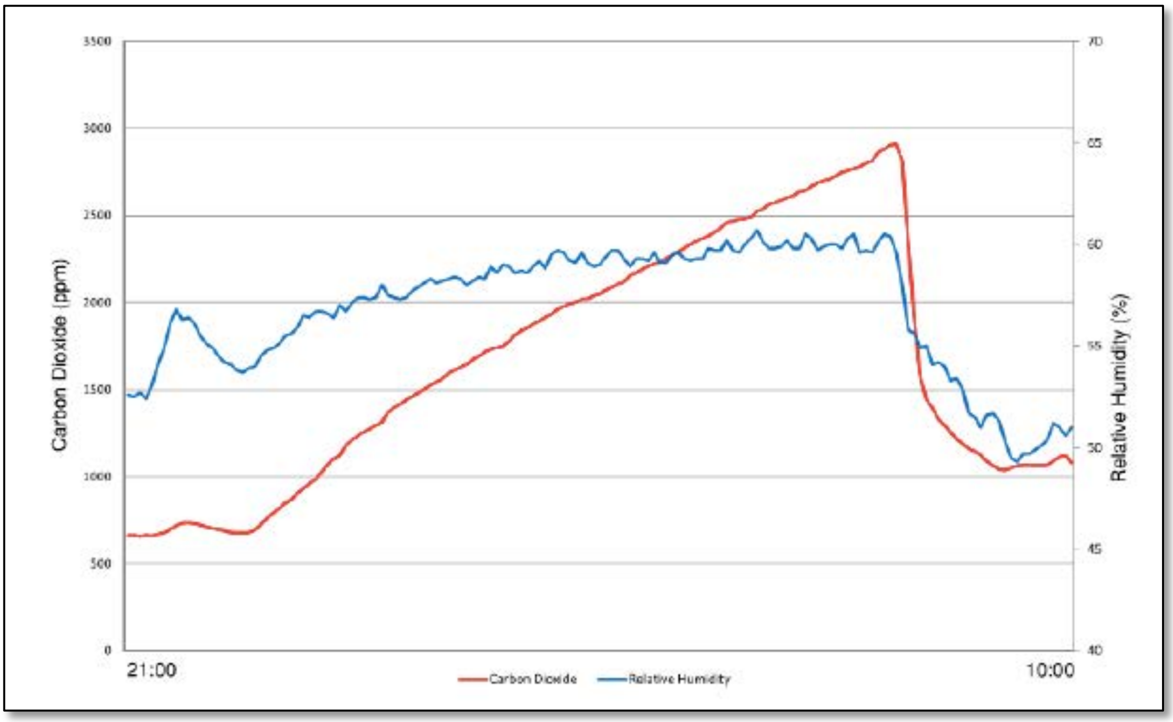
Over the course of 4 days and nights we asked the occupants to undertake a range of activities. The experiments were focused on the master bedroom, as we are able to monitor conditions with a known occupancy. The activities were recorded in the occupants' diary.

Note it is normal practice for the bedroom door to be left open at night allowing for circulation of air to the rest of the house and the CO_2 in the bedroom is maintained at around 700 ppm, but during these experiments it was kept closed.

<u>Test 1: MVHR Off and room sealed</u>

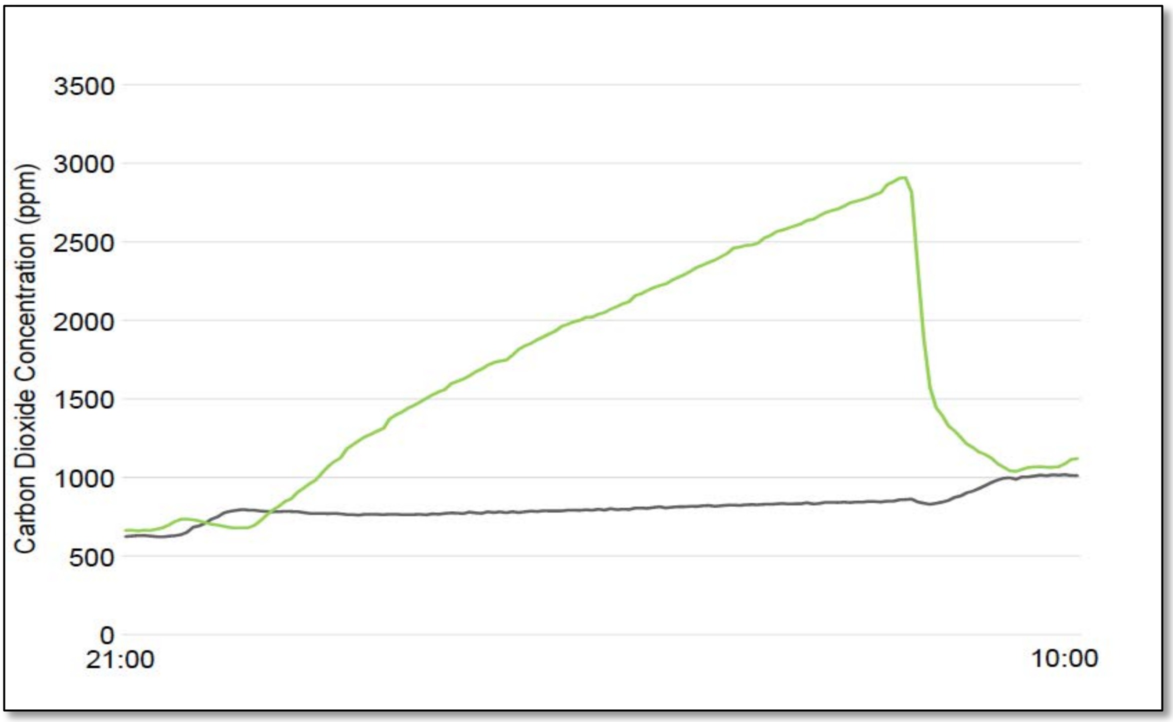
The First test took place on Thursday night. The MVHR was switched off and the door and windows to the master bedroom suite closed. The conditions in the space would therefore be maintained only by air leakage through the building envelope and around the bedroom door. Due to the very high air tightness it was anticipated that the concentration of CO_2 would increase and that the rate of increase would be linear.

[30] Appendix 5 – Review of Systems - Task Report 13
[31] Appendix 4 – Q3 Environmental Monitoring Report.



Graph 21a): Bedroom CO_2 concentration and RH with MVHR Off – Room sealed

The master bedroom CO_2 concentration is shown as the red trace with the RH in blue.



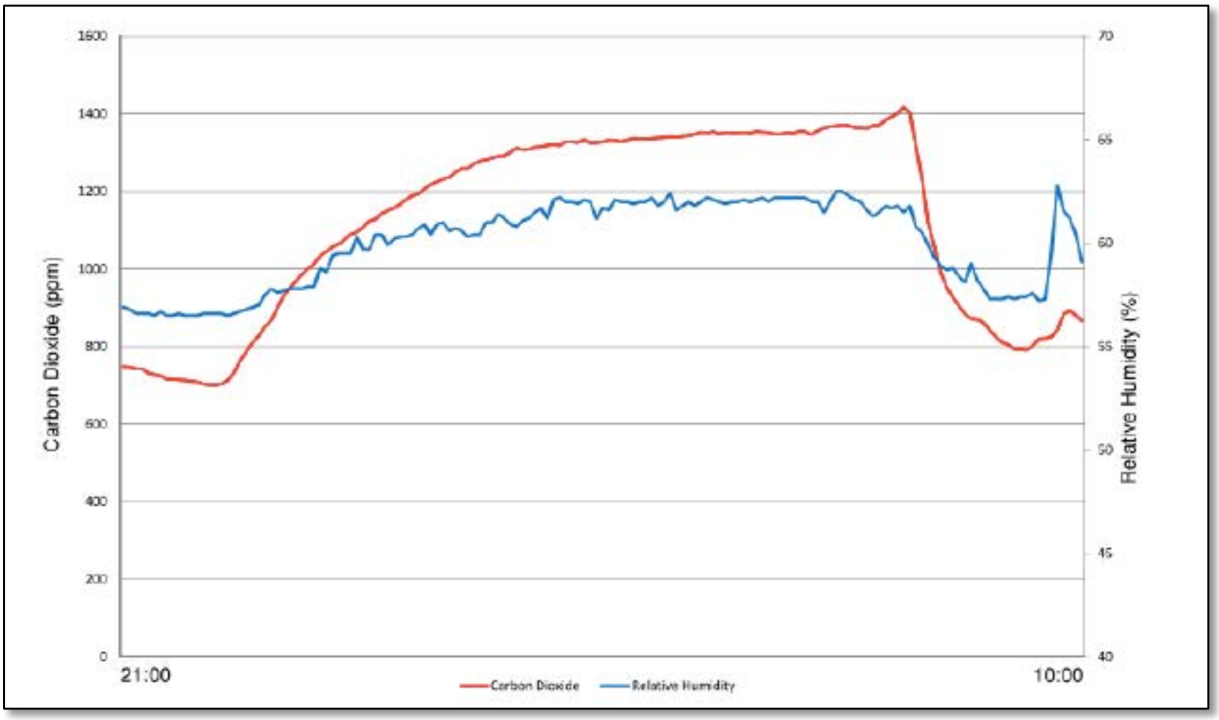
Graph 21b): Bedroom & Kitchen CO_2 concentration with MVHR Off

For comparison the bedroom CO_2 concentration with the door sealed overnight (green) is also shown alongside the dining room (black trace).

Assuming the CIBSE AM10 release rate of CO_2 - $5.56x10^{-6}$ m^3/s - for occupants with sedentary activity - we would anticipate the increase in CO_2 would be in the order of 3200ppm over 9 hours. This compares very well with the measured increase from 680ppm to 2800ppm over this time and suggests that the space is highly sealed. Some infiltration is occurring creating a drop of 400 ppm for the measured CO_2 compared to the predicted. Clearly some form of ventilation above infiltration would be essential to maintain suitable conditions in the bedroom. Over the same period the Relative humidity increased from around 55 to 60%.

Test 2: MVHR at Low Speed Setting

The MVHR at Plummerswood allows the occupants to vary the ventilation rate through a touch control panel. The design ventilation rates are identified in Task Report 21.[32] The O&M documentation recommends Speed setting 1 for night use equivalent to a ventilation rate of $28m^3/hr$ or 8 litres/s. Using the same emission rate as above of $5.56x10^{-6}$ m^3/s - for occupants with sedentary activity – we predicted that the CO_2 concentration would increase to a steady state of 808ppm above the baseline starting point if the infiltration adjustment of the previous test without the MVHR on is applied.



Graph 22: Bedroom CO_2 and RH with MVHR On at Recommended Speed – Room sealed

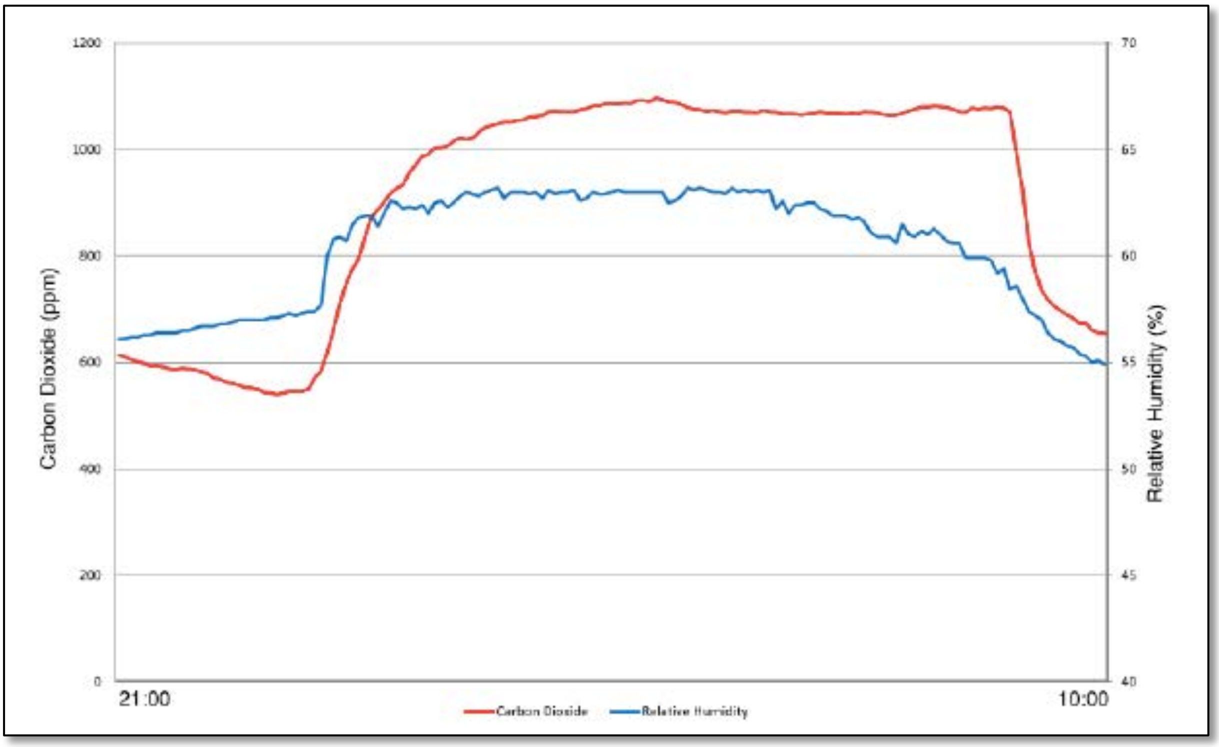
The CO_2 concentration increases from 700ppm to 1400 ppm, which closely matches the prediction. CIBSE guidance suggests that CO_2 concentration is ideally kept to an upper limit of 1000ppm. The use of the low speed setting would therefore be contingent on the occupants having the door to the rest of the house open to allow for air circulation into the

32 Appendix 4. Environmental Monitoring Qr Report 3

bigger volume of the house as is their normal pattern. Over the same period the Relative humidity again increased by around 5%.

Test 3: Trickle Ventilation Simulation

For this test the MVHR is off and the window is opened by a small amount to replicate trickle ventilation. The master bedroom CO_2 concentration is shown as the red trace.. It was very difficult to predict how the CO_2 concentration might react for this test. The measured values are shown below.



Graph 23: Bedroom CO_2 and RH with Trickle Ventilation Simulated - Summertime

The use of natural ventilation as the means to control CO_2 is very effective in this test and performs better than the MVHR. As the MVHR ventilates the whole volume overnight, if a trickle ventilation strategy could be applied instead this might be a significant energy saving.

As trickle vents are sealed up during an airtightness test as they're deemed to be 'designed ventilation' (like extract fans and other mechanical ventilation outlets/inlets) so in principal it would be possible to specify windows with optional trickle vent in a passive house and provide greater flexibility and reduced MVHR use for users.

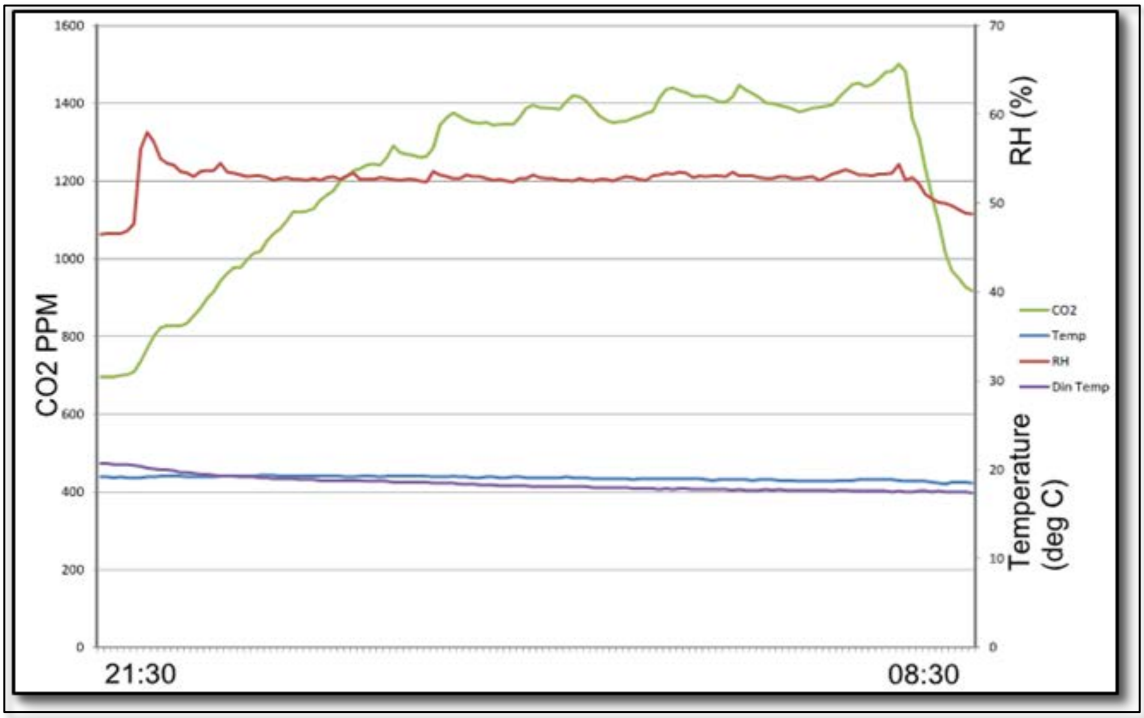
The temperature did not drift out of a comfortable range for any of the tests. [33]

[33] Appendix 4: Qr Report 3 Section 2.4

1.5.6 Trickle Ventilation Simulation - Wintertime[34]

A further study of the operation of the MVHR was undertaken on three occasion in February / March 2013.

The occupants switched off the MVHR system and simulated natural ventilation through trickle ventilation overnight by leaving the bedroom window ajar. It is normal practice for the bedroom door to be open but during these experiments it was kept closed.



Graph 24: Environmental Conditions during 1st winter trickle ventilation test

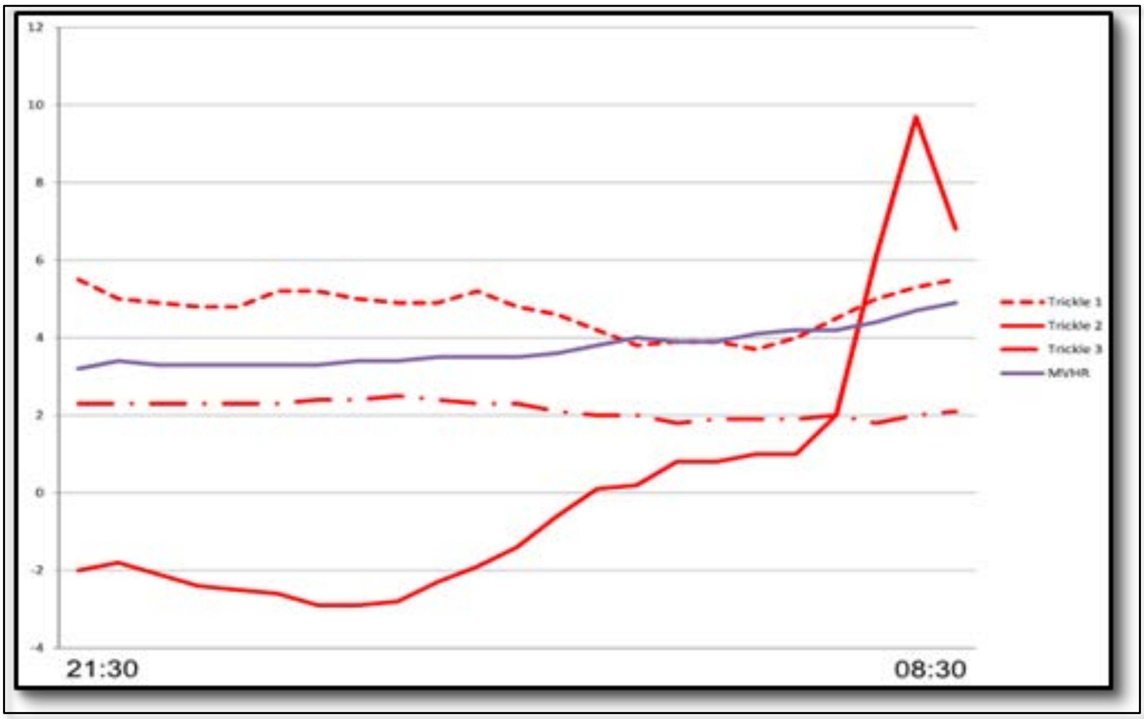
From the diary the owners kept during the monitoring we understand that a shower was taken at around 10:00 at night. A sample night indicates: -

- An uplift in RH from around 50% to 60% when the shower is in use. The RH drops quickly and stabilises at around 53%.
- CO_2 rose from 700 to 1500ppm.
- Temperature drop off was slight from around 20^{o}C to 18^{o}C in the Bedroom and Dining Room.

The results from two subsequent nights are very similar to those described for the first.

The external temperature during the three tests during the experiments provides a reasonable representation of winter conditions. See graph below.

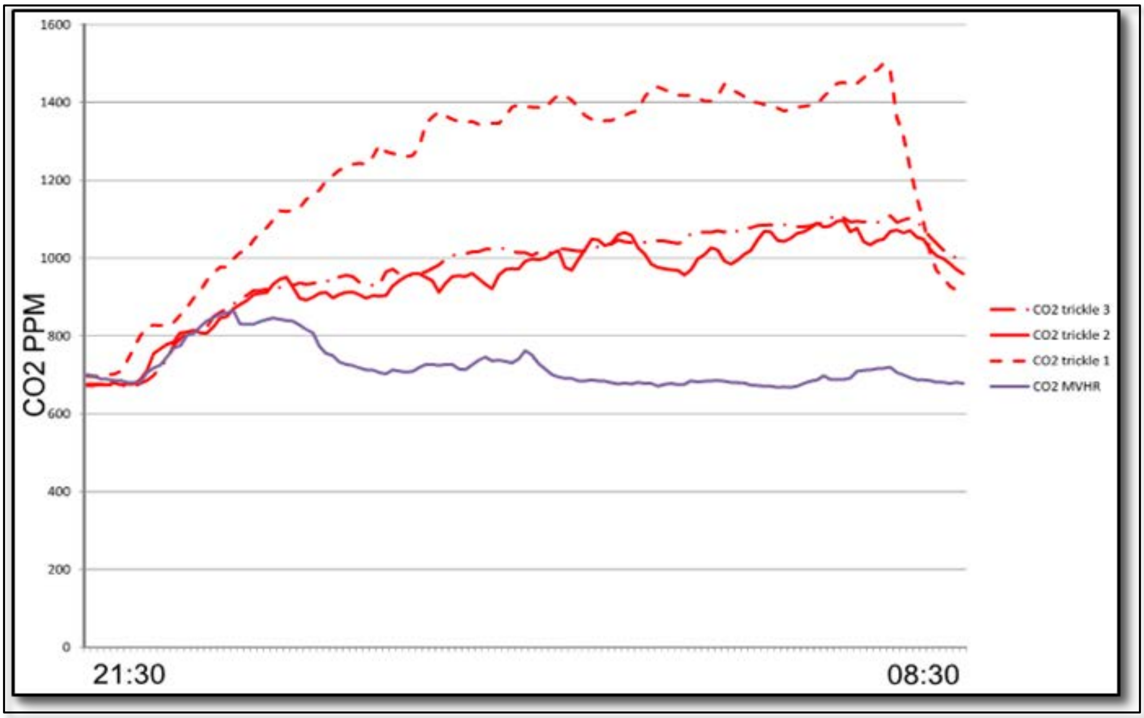
[34] Appendix 3: Quarter Report 5. Section 3



Graph 25: External Temperatures during winter trickle ventilation tests

Impact on CO_2 Concentration of Trickle Ventilation approach

Comparing the concentration of CO_2 in the bedroom using the MVHR with three consecutive nights using the trickle ventilation test indicates that trickle ventilation could adequately control the CO_2 concentration.



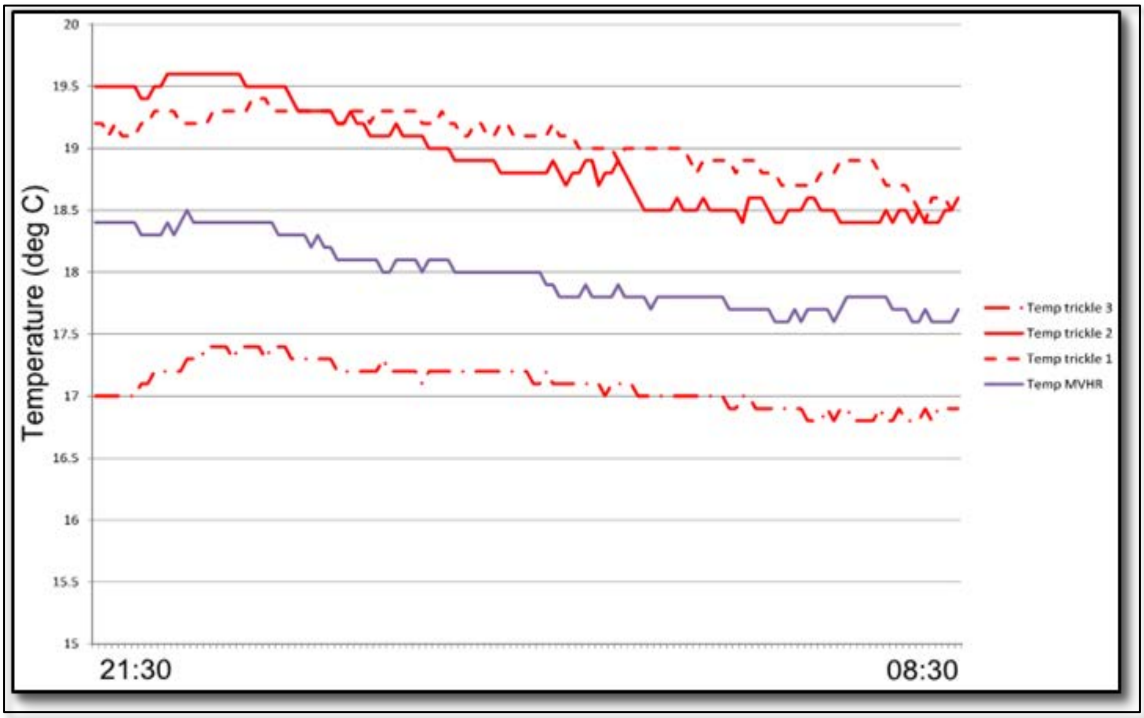
Graph 26: CO_2 Concentration during winter trickle ventilation test

The CO_2 concentration was consistently higher in trickle ventilation mode as compared with the MVHR, however the period with the MVHR on also involved the door between the bedroom and the rest of the house being open and the CO_2 being buffered by the whole house volume. The openness to the house volume is clearly an important aspect but may not be suitable for all lifestyles. Further experimentation would be required to optimise and control the size of the trickle ventilation openings.

Impact on Temperature of Trickle Ventilation approach

With the MVHR off there is no heating available. Therefore the bedroom temperature is only maintained by the residual heat in the building fabric and the heat produced by the occupants. The temperature with the trickle ventilation only was comparable with that with the MVHR operating. It can be concluded that the heat generated by the occupants is adequate to maintain comfortable conditions. It is also possible that the moisture uptake in the materials will also have an impact here because energy is released when water goes from vapour in the indoor air to liquid in the materials and opposite during the daytime when the materials dry out and it helps to reduce the effect of solar ingress.

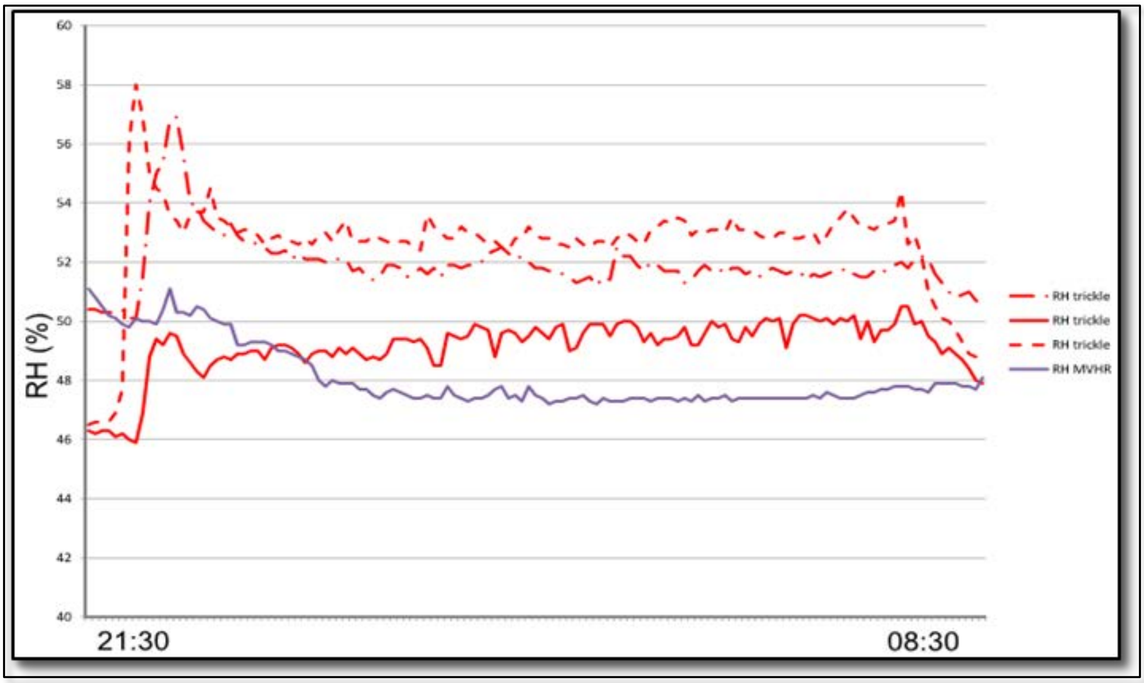
The internal temperature for the coldest outdoor temperature, experiment 3 from 8 to 9 March was the lowest but still reasonable.



Graph 27: Bedroom Temperature during winter trickle ventilation test

__Impact on Relative Humidity of Trickle Ventilation in the bedroom__

The relative humidity performed better for the trickle ventilation than for the MVHR.



Graph 28. Bedroom RH during winter trickle ventilation test

1.5.7 Examination of an Unoccupied Period[35]

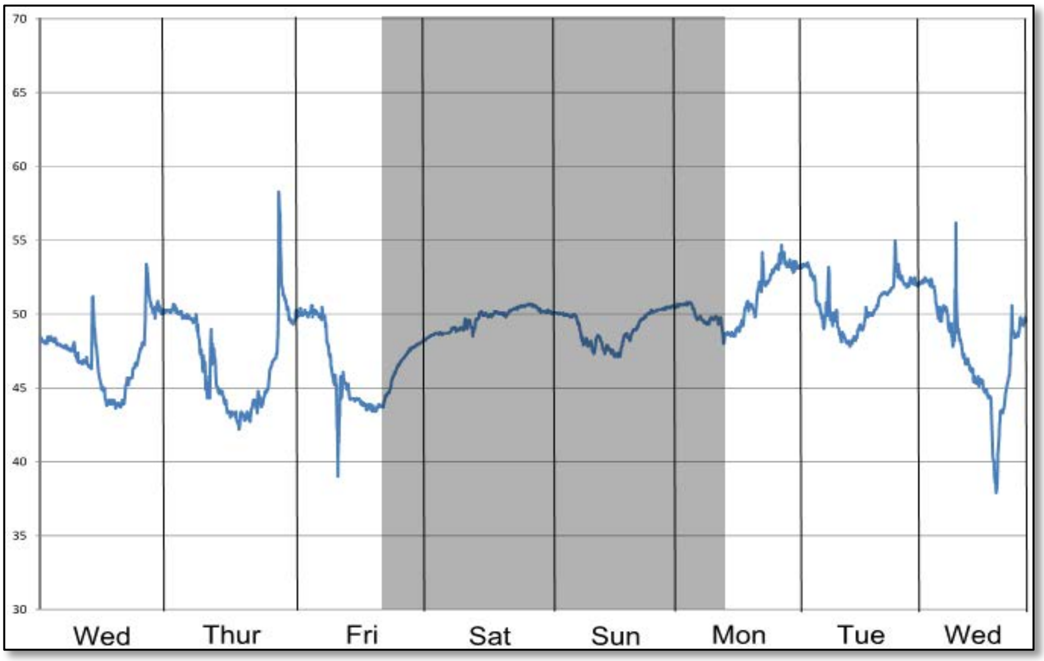
The environmental data from 15 to 22 May 2013 was reviewed in order to capture a period when the occupants were away (evening Friday 17 May - Monday 20 May) and the immediate period before and after. The issues we have considered include:

- Is there an impact on the relative humidity in the property?
- Is there a significant drop-off in carbon dioxide?
- Does the daytime temperature reflect human intervention in the occupied period?

__Relative Humidity__

The most likely room to exhibit a difference in RH between the occupied and the unoccupied period would be the master bedroom and ensuite. The unoccupied period is shaded. The occupancy period has a noisier RH trace but there is no appreciable difference. This is further evidence that the hygroscopic properties of the building construction counteract moisture-creating activity of the occupants.

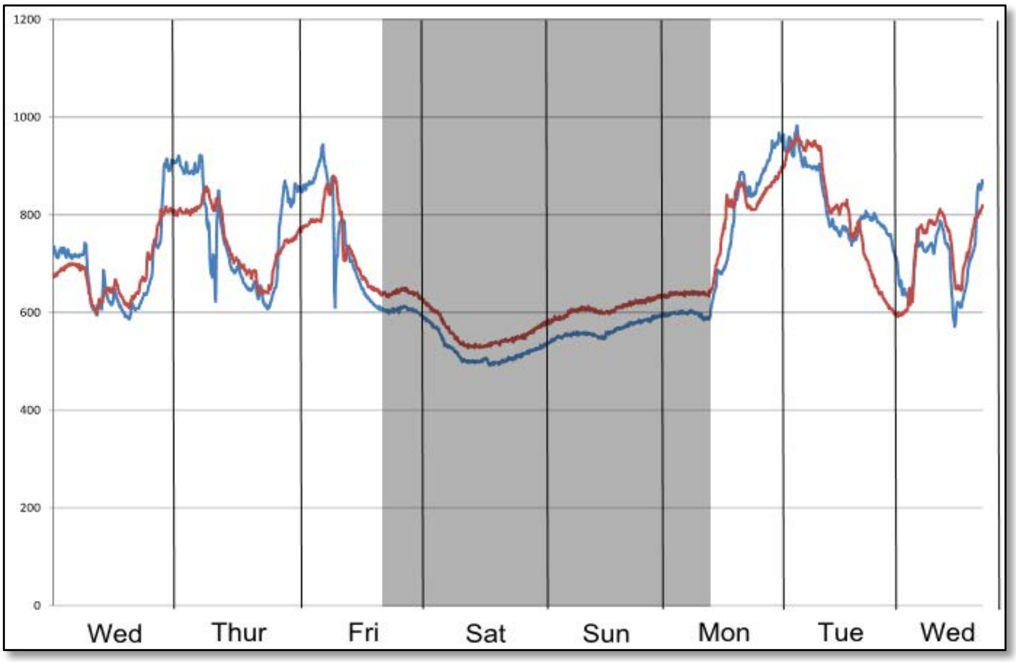
[35] Appendix 3: Environmental Monitoring Q6. Section 3



Graph 29: Bedroom RH during occupied and unoccupied periods

Carbon Dioxide

The CO_2 concentration in the master bedroom ensuite (red) and the dining room/kitchen (blue) are shown for the same period. The MVHR is off and the slight upward drift in CO_2 concentration during the unoccupied period is unexplained but may be due to slight instability in the monitoring equipment or equalisation of CO_2 throughout the house.

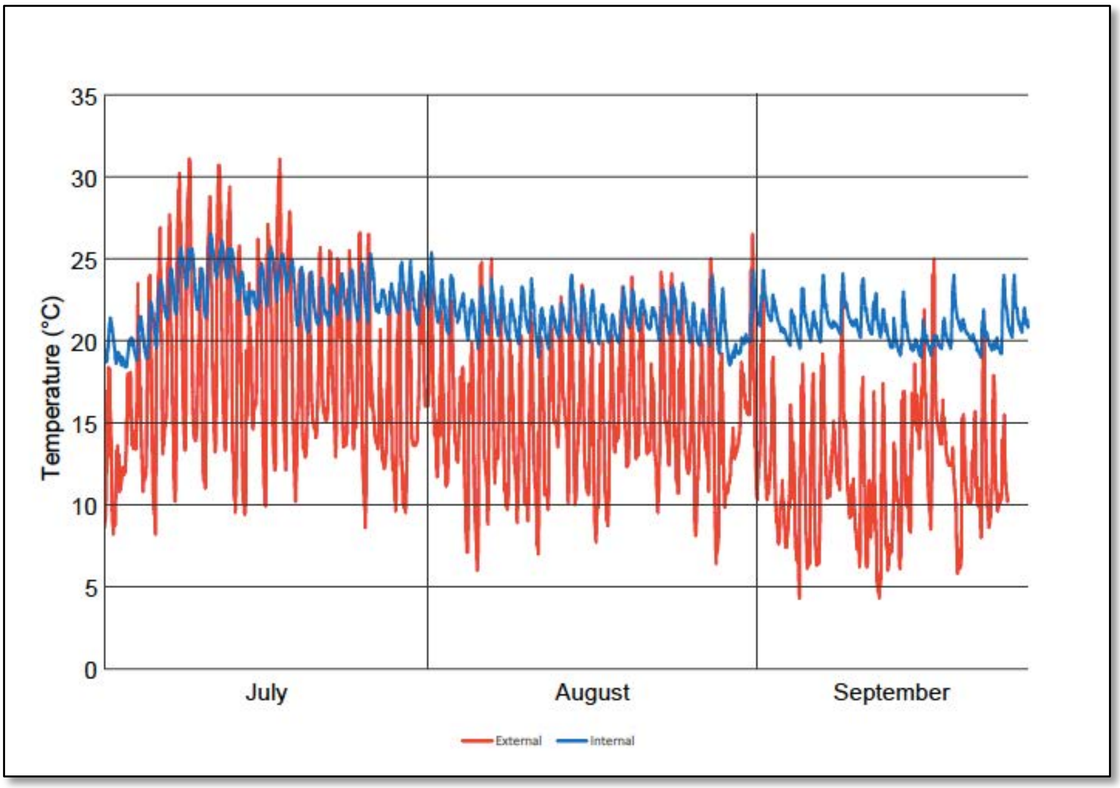


Graph 30: Bedroom and Dining Room CO_2 during occupied and unoccupied periods

There is no appreciable difference in conditions between occupied and unoccupied period.

1.5.8 Assessment of Overheating Risk- July to September 2013 [36]

The MVHR heating was off throughout this monitoring period. The results shown here for the Dining Room are therefore with the house in fully passive mode, attenuated by manual operation of the windows. The bedroom operated in a similar manner- occasionally with higher temperatures. The bedroom is more exposed to east and south, as it does not have overhangs. It does have external blinds.



Graph 31: Temperature – July to September 2013

During this period the external temperature was particularly warm on occasions. This temperature range is greater than would typically be expected for Scotland summer conditions and therefore acts as a good test to how Plummerswood operates in potentially overheating conditions.

From the data provided it is possible to conclude that the passive approach maintains comfortable conditions in peak summer conditions and does not overheat, exhibiting use of thermal and moisture mass.

---

[36] Appendix 3: Environmental Monitoring Q7 section 4.2

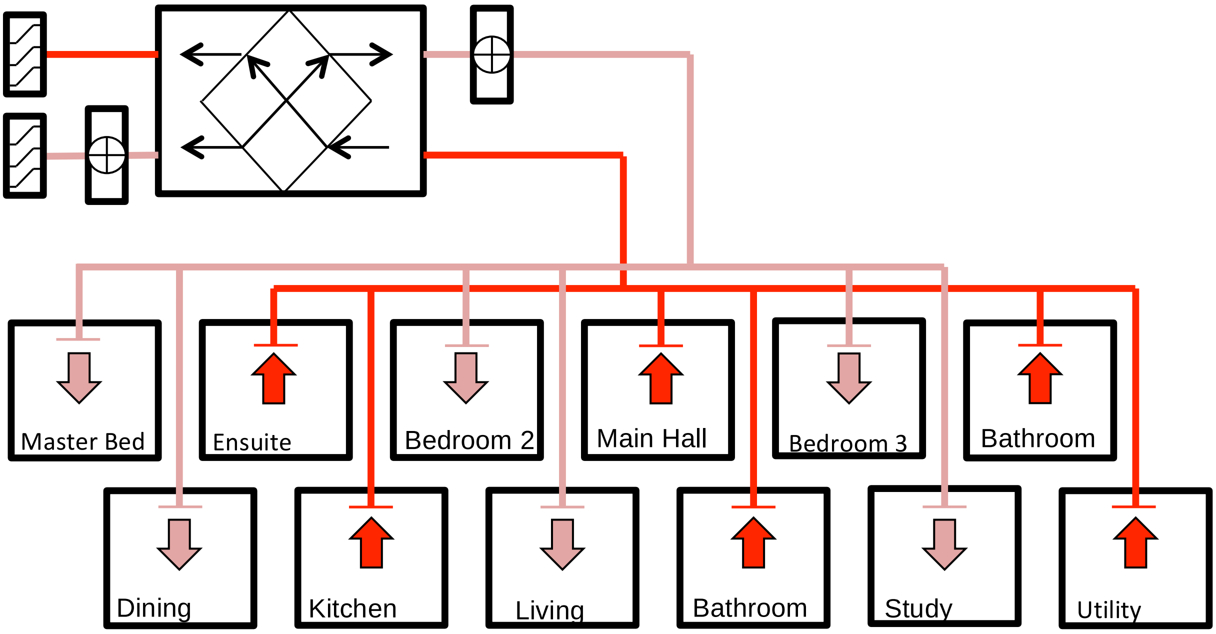
1.6 Modelling

1.6.1 Energy Comparison of MVHR & Natural Ventilation[37]

The MVHR generally serves air to the occupied spaces of the house such as the living room, dining room, study, bedrooms etc. Air is extracted from wet and sanitary type spaces such as toilets, bathrooms and the kitchen.

The system is designed to deal with the following considerations:

- · Control of temperature by providing space heating;
- · Control of moisture by providing minimum background ventilation;
- · Control of odours;
- · Limiting the build up of carbon dioxide by ventilating with 100% outside air.



Picture 8. MVHR Configuration

The MVHR incorporates electrical resistance pre-heating and main heater batteries. The reheat battery is 2kW but the size of the frost battery is not identified in the manuals.

A criticism of the MVHR system is that it treats the whole house as a single zone and does not recognise that the house has varying occupancy profiles over the course of the day and night. The consequence is that the system consumes more energy than is strictly required through over ventilation of unoccupied or under occupied spaces or alternatively results in poor air quality in occupied rooms.

---

[37] Appendix 5 – Review of Systems Task Report 13 Review of MVHR Operation and Comparison with Natural Ventilation

The energy consumption in MVHR and natural ventilation modes has been estimated. The proportions of energy consumption for ventilation and space heating compared to a trickle ventilation strategy are as follows.

	MVHR		NV
	Ventilation (kwh)	Heating (kWh)	Alternate (kWh)
Frost Coil	371		0
Loss at Heat Exchanger	416		0
Space Heating		7,625	7,625
Fan	372		8 + 123
Bathroom Extract Heating	0		283
Demand Ventilation Heating	0		714
Total	1,159	7,625	8,753
		8,784	8,753

Table 1: Estimated Energy Consumption in MVHR & Natural Mode

Based on the assumptions fully detailed in Task Report 13, it was established at the beginning of the project that the MVHR system does not theoretically offer an energy saving and that a simpler mostly passive approach would have similar energy consumption to the use of MVHR. Essentially the frost coil in the MVHR was predicted to consume a significant proportion of the MVHR energy. As the MVHR has significant capital and life cycle cost and maintenance implications this was considered an important finding.

The enrgy consumption of the MVHR has been significantly lower as the occupants have only used the MVHR when they feel they need to if they are for example

- Showering or cooking;
- They need to heat the house.

The actual energy consumption of the MVHR over the two years is
2012: Fan 413 Heating: 2199
2013: Fan 202 Heating: 2092

In addition an estimated 6,400 kwhrs of biomass has been used/annum.

As the client operates the MVHR in the winter and cannot easily disable the frost coil a further opportunity for optimisation is unavailable. It has been suggested that MVHR should be able to operate without the need of frost coil protection otherwise it doesn't appear to meet the standards for PassivHaus.[38]

However it should be noted that turning off MVHR systems, once installed, or only using them part time, could cause indoor climate problems in the long run if this results in a reduction in maintenance and leads to a build up of insects, particles etc. in air channels.

[38] Arup Correspondence 9th April 2014

1.6.2 Modelled Solar Gains[39]

Task Report 15 models aspects of solar energy.

- The anticipated impact of solar control on summertime thermal comfort in the dining room with and without external blinds.
- The predicted reduction in heating energy due to operation of the blinds.

In the spring/summer period the effect of the fixed overhang of the south facing patio windows means that the temperatures modelled with and without the blinds are similar and confirms that the kitchen did not require blinds. In this period the natural ventilation would be used to maintain the room temperature and the MVHR heating would be off.

The model also demonstrates the efficacy of the external blinds to the living room in reducing overheating. The modelling indicates that beneficial solar heat gain potentially reduces the heating demand by 35%.

However in autumn and winter the external blinds could block potentially beneficial passive solar heat as the control currently is only based on potential solar ingress. Without external blinds the anticipated annual heating demand would be 94kWh. With external blinds the annual heating demand increases to 143kWh. The manual control of the external blinds on the living room and master bedroom is critical to exploiting this heat to the maximum.

This validates both the solar design and the emphasis on human control. More advanced control could potentially link solar ingress and internal temperatures in order to determine whether automatic opening or closing would be beneficial. This functionality is not currently available.

1.6.3 Modelled Solar Hot Water System

The solar water heating system includes a controller, which has an output of heat yield from the system. The control module calculates the heat yield based on the temperature difference between the water entering and leaving the panel. The controller does not measure water flow rate however and uses an assumed flow rate. This limitation in the system means that it is not possible to establish reliable heat yield data.

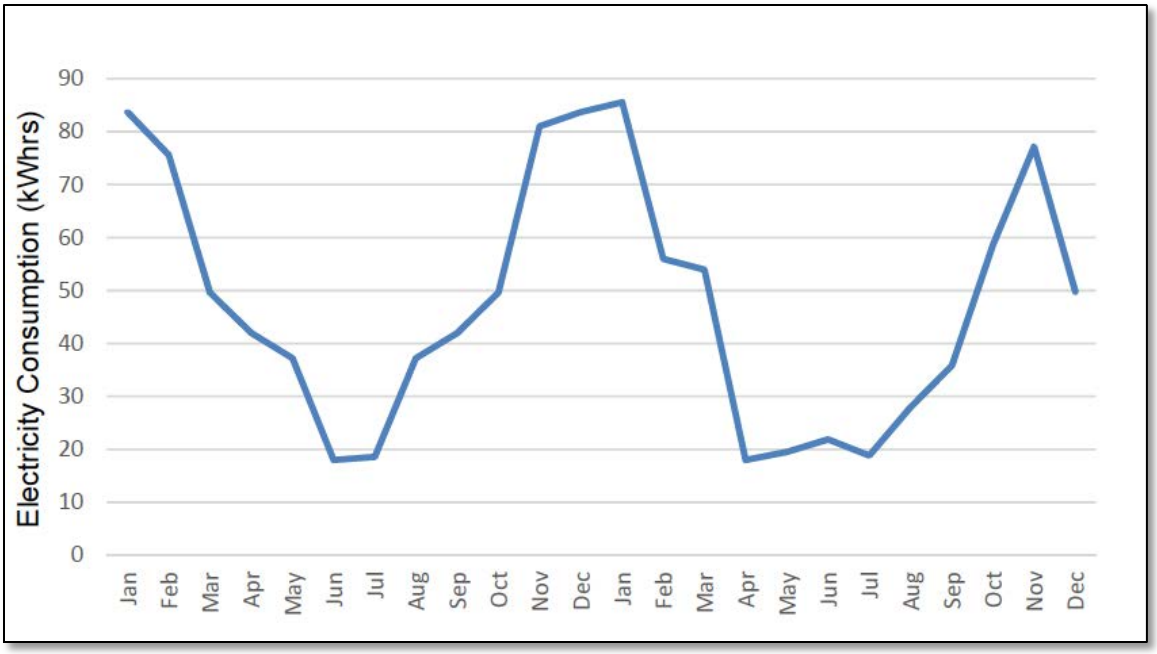
To assess the efficacy of the solar thermal system we used a winter period electric heating element sub-metered data and applied this across the year. The average daily consumption by the electric heating element is 13.3kWh or 4855kWh/annum. We then used the measured annual energy consumption of the element - 2457kWh - to arrive at the solar thermal yield of 2400 kWh or approximately 50% of the use.

---

[39] Appendix 5: Review of Systems Task Report 15:- review of Solar Energy Impact on Building

1.7 Lighting[40]

The energy consumption of the lighting system over the monitoring period is summarised below. As expected the lighting energy consumption reduces from the winter period to the summer period consistent with the occupants taking care to only use artificial lighting when necessary.



Graph 32: Lighting energy consumption

1.8 Water Consumption

The normal water consumption for a private dwelling of the size of Plummerswood is 300 litres/day. The water consumption is 83% of this value during the monitoring period.

[40] Appendix 5 – Review of Systems Task Report 12b:- review of Lighting and Daylighting Specification. Calculation of Daylight Factors

1.9 Key Findings – Operation and management

Over the course of the fourth monitoring quarter some operational issues were identified by the owners. We have summarised these below.

1.9.1 Operation of Building during Mains Electricity Failure

Due to the location of the building in a remote rural setting there is a susceptibility to mains power failure. This was considered in the design of the electrical services and a mobile standby generator was provided located in the ground floor workshop. The electrical services distribution includes a split between essential and non-essential supplies with the following essential supplies capable of being backed up by the generator:

- Power outlets in the kitchen
- Some lighting circuits on the ground floor
- Power outlets in the living room and study
- The borehole pump
- The security system

Power failure occurred on a few occasions during the first year of occupation and, as the generator does not support ovens and the hob, the owners used gas fired camping stoves. This did not introduce a risk as the MVHR remained operational, however it may be an issue in other circumstances where occupants are not used to house that is airtight and there is a potential lack of air for combustion. In these circumstances occupants will need to be advised to open windows and to install Carbon Monoxide sensors.

1.9.2 MVHR Filter Change

The owners followed the operation and maintenance manuals recommendations for the frequency of replacement of filters for the MVHR system. The manuals suggest filter replacement every 90 days at a cost of approximately £50 per quarter. These were found to be clean after 90 days and changing them was deemed to be an unnecessary expense.

There is no mechanism to check whether the filters are dirty and it may be that filters in many installations are being replaced prematurely. Others may not be being changed at all. The monitoring team enquired of the MVHR manufacturer regarding the possibility of retrofitting pressure gauges across the filters to provide better indication of how dirty they are. The manufacturer reported that the fans change speed automatically to compensate for dirty filters, which increases energy use. They cannot as yet provide functionality of a digital output that could then indicate the condition of the filters or trigger an alarm at a certain fan speed.

1.9.3 Odours in Utility Room

The owners reported unpleasant odours in the utility room. This appears to result from the piping of the pressure relief on the domestic hot water cylinder to a drain connected to the bio-disc. This connection had not been provided with a water trap. This was remedied.

It would appear as if the plumber did not install the system with discharge to outside, as is the norm, as they were concerned about compromising the integrity of the air tightness. With Brettstapel construction all services penetrations of the envelope need to be designed before manufacture/construction. This takes a lot of time and attention to detail. In most cases at Plummerswood this was done properly but clearly there was a failing in the utility room.

1.9.4 Solar Hot Water System

The lack of performance of the solar thermal panels due to poor installation has been a source of frustration. At the outset of the project it was apparent that the solar hot water heating system circulation pump operated only intermittently and there was no hot water yield from the system. The monitoring team identified that the control sensor was located incorrectly at the bottom inlet of the panels when it should have been located at the top outlet. The fix was relatively straightforward.

1.9.5 Blinds

The design principle was to use clear insulated glass to allow solar gain when required for passive heating. External blinds were installed to reduce solar heat gain in summer and reduce the risk of overheating. The blinds have automatic control, which would close the blinds when the solar radiation exceeds a particular value. This automatic function is potentially useful in summer, however in winter it could reduce the passive heating effect. The owners have taken over manual control of the blinds in order to maximise the useful gains and to minimise overheating.

1.9.6 Plug sockets

The lack of plug sockets in the central area of the house is a cause of frustration.

1.9.7 Lighting Control System

During spring/summer 2013 it became apparent that parts of the lighting control system was behaving randomly with lights failing to respond to switching. The monitoring team arranged for the manufacturer to attend site to review the installation and the lighting was re-programmed and a booster installed. After this the system has functioned correctly.

The control system is costly and complex for a domestic installation to allow for scene setting and it requires bespoke software to operate. When the software encounters problems there is potentially a very expensive service call from the equipment supplier. An alternative is that the manufacturer could have remote access to the system to reduce the costs of call outs. The owners were understandably concerned about providing this continuous access. The reason for the selection is unclear but it appears that the services engineers successfully lobbied that a property at the upper end of the market would be expected to have such a system. However it seems as though a simple standard system would have been sufficient for their needs.

1.9.8 Client Comments at 18/09/2013

The clients provided a detailed narrative as to issues that occurred during the first two years of occupancy.

Overview of how user friendly the buildings & systems (lights, MVHR, windows, blinds, solar, spaces) have been.

We have been pleased with how easy the building has been to run. The MVHR system is straightforward to operate, the lowest 'occupied' setting suiting us well. The filters are easy to change, but are quite costly so we're keen to find ways of extending their operational lives.

The hot water booster is a boon, because during the summer we switch the regular time-clock off and use the booster instead as required. The pump that circulates instant hot water to the remoter taps is also a good idea.

Fortunately we have Ethernet connections from our router to all the main rooms: the walls of the house rapidly attenuate the router's wireless signal. It's a shame there isn't a similar system for mobile phones and DAB radio, because most of the house is a 'not spot' as far as they're concerned.

The lights are working properly (for now!); we shied away from Philips' fancy control system for them and do find that some of the low-energy bulbs produce a harsh cold light. We haven't needed to use the automatic controllers for the external blinds, preferring to operate them manually as required. When we opened the windows over the summer we realized how few insects etc. we'd had inside the house up to that time!

Latent Issues

Lights

The Philips dynalites in the en suite bathroom and the kitchen continued to misbehave through to September 2013. Very occasionally the lights came on when they should (but then didn't go off again as they should). So we discounted the bulbs as faulty.

The upstairs ones (en suite bathroom and corridor) started playing up first, perhaps in May. The kitchen lights began to misbehave a month after that. Very occasionally the lights in the bathroom and kitchen did come on (one time in forty perhaps). Then we had to turn them off using the 'all lights off' switch in the vestibule, because the 'off' switches in the rooms themselves didn't do the trick.

We reached a point where we were getting rather anxious about the lights (or, to be more accurate, lack of them). The nights were drawing in and still more of the system behaves oddly. In addition we were concerned about a 'flashing light' phenomenon in the lounge.

Despite endless correspondence in pursuit of a solution the vast inertia on the part of the services engineers and the lighting installers appalled us. Thankfully the rest of the design and monitoring team, once they were alerted to the problem, were able to have a direct influence. The problem appears to have been the requirement for a booster in the system. A temporary one was promptly installed and subsequently a permanent one. Since then everything has been working as it should. We remain unclear as to whether the booster should have been specified but was not in which case a specification issue or whether it was specified but not installed in which case a workmanship issue. Without any feedback from Mott MacDonald we assume this will not be made clear. Philips paid for the remedial work.

We also received feedback on the 'flashing light' phenomenon in the lounge which we were informed was caused by an incompatibility between the Dynalite system and low-energy bulbs - it disappeared when 60W filament bulbs were substituted for the low-energy ones. We were told that the system is perfectly safe electrically. The solution seems to be that we carry on as we are (which is fine as far as we're concerned). However, it seems daft to us (if true) that the Dynalite system isn't designed to work with low energy bulbs and we understand that the information has been passed to Philips.

Door to workshop

We became concerned in the summer that the rear door to the workshop had become stuck. It transpired that a screw holding one of the fittings at the bottom of the door had come out and was catching in the corresponding fitting in the frame. We were provided with a temporary fix while he ordered a new fitting for the door. It's turning out to be quite an expensive operation, but Thomas Froehlich of Ecowin impressed us with his service - phoning us regularly with updates on the progress. Philips could learn a lesson from him.

Leaking shower

During the winter we noted a problem with the shower drainage.

When the upstairs shower was in use water sometimes came through into the utility room. We suspected that if one isn't careful the water from the shower runs out over the tiles and on to the wooden part of the floor. It can then make its way down between the floorboards to the utility room.

The builders sealed all suspected water paths from screw fixings to doorstop, and shower accessory fittings. This was followed with application of Sealant in the shower in the upstairs bathroom. Subsequent long showers have shown no evidence of leaks and rubber strips have been used to form a slight ridge and prevent overspill.

Solar panels

The snagging of this took a very very long time with difficulty in determining who would take responsibility for the system. Mott MacDonald simply blamed the installers and were unresponsive to our calls for the problems to be resolved. We understand the issues are well documented in the TSB reporting up to June.

Thankfully an investigation showed that some of the pipes had been wrongly connected. The system seems to have been operating well since mid summer and has not overheated since we raised the switch-off temperature from 60^{o}C to 65^{o}C. There is a (newish) small leak in the solar system. We propose to deal directly with Ecofitter and pay the bills direct.

Plug sockets

As time has gone on we have started to notice that the lack of sockets in the solar space is a bit of a constraint. We have to run extension leads from the living room or kitchen.

Fire Retardant

The use of fire retardant in the main solar space has always been a concern as it stains what is otherwise a lovely wood finish. However we believe that the colour is toning down as time progresses.

High Level Windows

In the summer we made the mistake of leaving the high level windows open when we were out. An unusually heavy storm ensued and we had water ingress into the main solar space. It also corroded the burglar alarm that was positioned at high level and this needed to be replaced. We now close the windows when we leave the house.

MVHR operation

To assist the monitoring team in their analysis we had the MVHR switched off from May until September and opened selected windows instead. This worked fine as far as we're concerned, the main downside being we had flies, moths etc. in the house for the first time! The standard windows are not designed to be left open, in that there is no catch system to stop them from swinging. (This isn't a great problem because they're quite heavy and so have a fair bit of inertia.) [41]
An allied point is that the house remained at a comfortably temperature during the long hot spell in July. We had been warned that our problem might be overheating in summer rather than freezing in winter.

Green Roof

The hot spell turned the green roof brown – we were a bit slow in getting round to watering it. We had enough water pressure to use a hose pipe connected to our outside tap.

Stove

A slight gap has appeared at a joint in the flue. This has been sealed using fire cement but as the fire has not yet been used it is unclear whether this has worked.

Other Outstanding Issues

Tiling - We still need the tiler to finish off some grouting but we will deal directly with him and pay the bills direct

Energy /Water Benchmarks - We look forward to receiving the energy and water consumption figures against UK benchmarks in due course.

Final completion. - Unsure if this is resolved: - "We require an up-to-date Energy Performance Certificate as part of the paperwork required re the Renewable Heat Incentive. He indicated this is something we would get when the house is finally signed off. Is he correct?"

The extent to which the building meets or otherwise our original aspirations. See http://www.youtube.com/watch?v=yVfTu_Vza4w

[41] The windows are designed without trickle vents.

1.10 Overall successes and failures.

In general this project has been particularly successful in no small part due to the engagement of the owners. They have been amenable to the various experiments the team have undertaken during the monitoring period and have recognised areas where they could operate the house more efficiently.

The occupants provided a short but thorough overview of the management issues from their perspective and the latent issues since occupation. The monitoring project was a significant benefit in enabling the technical issues to be resolved including the lighting and the solar panels. The experiments on the MVHR were a useful contribution to the knowledge on these issues.

The building performance appears to meet its design objectives. The clients have a multi-award winning building that demonstrates very best practice in terms of a passive approach. The thermal insulation, thermal mass and air-tightness performance minimise heating demand and hygroscopic mass minimises humidity fluctuations and improves indoor climate. The daylighting has been carefully designed to minimise requirement for artificial lighting and the solar orientation, natural ventilation and shading has been designed to optimise heat gains. All of this was undertaken with an awareness of the desirability and benefits of personal control.

The building has proven to be robust and stable in terms of internal environmental conditions and benchmark energy consumption. Satisfactory internal environmental conditions are achieved and consistently maintained at a stable level. The internal temperature is consistent with the client requirements and the relative humidity is in line with best-practice values.

The clients are clearly very happy with the building and are clear about the control of the various systems. They have expressed their satisfaction through video and through presentation of a diary to the principal architect. They have continued to operate the building as passively as practicable.

Total Energy Consumption
Through this study we have been able to help in the reduction in energy consumption from very good levels at the onset of the study to extremely low consumption for regulated loads. This has been mostly due to the operation of the building in passive mode, i.e. utilising body heat and other incidental gains for passive heating.

The building uses 6.4 and 6.0 kWh/m^2 of metered energy for years 2012 and 2013 respectively compared to the design objective of less than 15kwhr/m^2. This is less energy/m^2, less CO_2/m^2 and less cost to run/m^2 than a Code for Sustainable Homes Level 6 (CSH6) building. It generates less than 25% of the renewable energy of a CSH6 house but requires less than 50% of the energy overall. The total energy used for all domestic applications inclusive of biomass, heating, hot water and domestic electricity, does not exceed 47.9 kWh/m^2 of treated floor area per year compared to the design objective of less than 120 kWh/m^2.

2012												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CH1: SHW	12	8	16	27	25	21	22	25	27	16	9	12
CH2: Oven 2	21	19	21	21	21	21	9	25	24	19	18	31
CH3: Oven 1	0	0	0	0	0	0	0	0	0	0	0	0
CH4: HW element	412	372	412	399	178	66	68	81	96	177	255	412
CH5: Hobs	13	12	13	13	13	13	9	12	12	12	15	16
CH6: Utility sockets	83	75	21	80	83	20	22	22	21	19	18	22
CH7: MVHR htg	1000	305	0	0	0	0	0	0	0	167	327	400
CH8: MVHR fans	42	38	42	41	42	41	19	22	21	22	27	56
CH9: Lighting 1	28	25	16	12	12	6	6	12	12	16	27	28
CH10: Lighting 2	56	50	34	30	25	12	12	25	30	34	54	56
Biodisc	62	56	62	60	62	60	62	62	60	62	60	62
Other sockets	186	168	186	180	186	180	186	186	180	186	180	186
10181	**1915**	**1129**	**822**	**862**	**646**	**439**	**415**	**471**	**483**	**729**	**990**	**1280**
2013												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CH1: SHW	9	13	14	18	20	22	24	19	16	12	14	9
CH2: Oven 2	22	15	17	8	12	13	8	17	14	19	16	10
CH3: Oven 1	2	1	0	0	0	0	0	0	0	0	0	6
CH4: HW element	391	263	312	118	151	93	42	112	128	245	185	185
CH5: Hobs	16	13	16	10	13	10	9	11	12	14	14	9
CH6: Utility sockets	18	18	18	18	18	21	21	21	19	19	16	14
CH7: MVHR htg	545	419	385	135	1	1	1	1	1	1	241	361
CH8: MVHR fans	33	27	41	17	1	0	3	2	19	21	24	14
CH9: Lighting 1	23	16	15	6	6	6	6	7	10	11	13	11
CH10: Lighting 2	63	40	39	12	14	16	13	21	26	47	64	39
Biodisc	62	56	62	60	62	60	62	62	60	62	60	62
Other sockets	186	168	186	180	186	180	186	186	180	186	180	186
8699	**1368**	**1050**	**1104**	**581**	**484**	**422**	**376**	**458**	**486**	**637**	**828**	**906**

Table 2: Energy consumption

CO_2 Buffering by House Volume

Plummerswood has particularly low air permeability. The MVHR system treats the whole house as a single zone and does not recognise that the house has varying occupancy profiles over the course of the day. The result, potentially, would be either too much energy consumption through over ventilation or poor air quality in particular rooms. Through this study we have seen the potential for use of localised trickle ventilation and the benefit of opening up the volume of the house by leaving doors open between occupied rooms and non-occupied rooms. This approach has significant potential benefits if applied in the early design stages.

Defect in Solar Hot Water Heating Control

The error resulted in 6 months of increased energy consumption. A key lesson learned from this study is that this type of error is easily possible in the construction of domestic properties, which rely on installations from local plumbers who are unlikely to have installed this type of technology previously.

Defect in Lighting

The lighting control system is unnecessarily complex for a domestic installation and combined with defects in the installation or specification and lack of attention from service providers meant that without specialist input it might have been very difficult to resolve and potentially a health and safety risk.

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

2.1 Inception

Plummerswood is a three-bedroom private house located to the south east of Cardrona in the Scottish Borders. It is located on the side of steeply sloping hill with the fall off in levels from west to east. The surrounding area is Forestry Commission Scotland (FCS) land.

The clients, Ian and Anne Nimmo, initially approached Gaia Architects and two other architectural practices in regard to providing them with a house on a hillside site they were purchasing from FCS. They had at that point obtained outline planning permission for conversion and extension of a bothy on the site. The clients selected Gaia Architects, after interviewing all three practices, and only then requested a fee bid. This was accepted and thus the commission for the project was let. At an early stage Gaia Architects put together a green specification for the house, which embraced high standards across a range of environmental factors.[42]

2.2 Design Team

The clients were open to being advised as to the best way forwards. Following discussions on forms of procurement it was agreed that the route would be a traditional method using the RIAS/RIBA Plan of Work procedures. They asked Gaia Architects to recommend a design team.

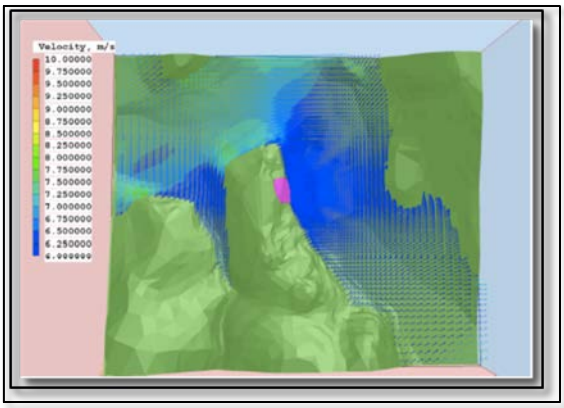
Gaia Architects readily proposed a Quantity Surveyor (QS), Ralph Ogg & Partners with whom they had worked closely on ecological design projects for 30 years. They also proposed an Edinburgh based structural engineering firm, Harley Haddow LLP, with whom they had an established relationship. Mechanical serving provision had long been a cause for concern for Gaia and after much consideration they proposed Fulcrum Consulting M&E with whom they were working on a local project, (subsequently taken over by Mott MacDonald).

2.3 Site Acquisition

Gaia Architects was appointed before the point of sale between the client and FCS and it was decided that a full site assessment was an appropriate starting point. Originally consideration had been to locate the house lower down the site such that it would be sheltered.

[42] Appendix 6: Design Progression: Report on Drivers for Commitment to Sustainability, and Consultants' Roles in achieving this – Gaia Architects December 2006

2.4 Early Modelling Involvement



Picture 9. Wind Analysis

The architects commissioned the M&E consultant to compare the benefit to day lighting and improved views against the additional heat loss that might result from a more exposed position. Computational Fluid Dynamics (CFD) and overshadowing analysis was undertaken. The results of the study were in a report entitled "*Wind and Shadow Analyses*"[43]

The report suggests that: -

(a) There would be a significant increase in wind speed for the more exposed location.
(b) The site does not suffer from overshadowing to an extent that would detrimentally affect the daylighting.

Picture 10. The Site

The key recommendations that resulted were

- That the house would be more appropriately sited at a higher level than the bothy;
- That a larger site area would enable the clients to benefit from the commanding range of views not available from the bothy site and impact more favourably on the interface between themselves and the edge of the major neighbouring forest.

This resulted in the clients negotiating a slightly larger site with FCS quite happy to accede to this request.

2.5 Brief [44]

Following the site assessment Gaia Architects developed the brief for the site to include the schedule of accommodation and the key spatial design aspects (room functions, relationships of rooms and relative sizes) and the key aspects of the sustainability agenda.

The sustainability aspects of the brief embraced the passive standard specification but also focussed on the specification of materials that were environmentally friendly and would also assist in providing a healthy indoor climate addressing both potential chemical and biological risks. The client signed off the brief and Stage C scheme design began (2006).

---

[43] Appendix 6: Design Progression - *Wind and Shadow Analyses* – Fulcrum Consulting 9th Feb 2007
[44] Appendix 6: Design Progression - Task report 6c – Realisation Process from Inception to Initial Occupation covers the nature of the design process, interface with the supply chain and how performance information was used

2.6 Design Development

Stage C was focussed, in the first instance, on locating the building on the site taking into account the aspect, prospect, site slope, access, orientation and construction feasibility. The client was keen to take time to get a design they were totally happy with and meetings took place with the family (at that time including two young adults). There was no pressure to rush towards the next stage.

2.7 Planning Permission

Gaia Architects had established a good relationship with the local planners after working with them on Visitor Facilities at nearby Glentress. The use of a massing and site context that made reference to hill forts in the area- but used timber rather than stone as the primary building material – was an approach that Gaia Architects anticipated they would be open to. The historical and geographical context was similar to Glentress and, as the Design Statements incorporated references to these, the planners were happy with the proposals.

A prominent location for the building was proposed using building materials that tone down to silvery timber grey, with the forest backdrop. All the neighbours were pre-consulted and there were no objections to the submitted designs.

2.8 Study Tours

It became clear as the design developed that the client had an interest in seeing other work of Gaia Architects, as well as buildings of interest and relevance to the emerging design. Site visits were made to Gaia Architects projects throughout Scotland (2007). At the time that key decisions were being made about the form and construction of the house the Acharacle Primary School had recently been determined as a Brettstapel construction.

The clients were invited to participate in a Study Tour to Austria to see a number of exemplar houses and other Brettstapel buildings in Vorarlberg, south west Austria.

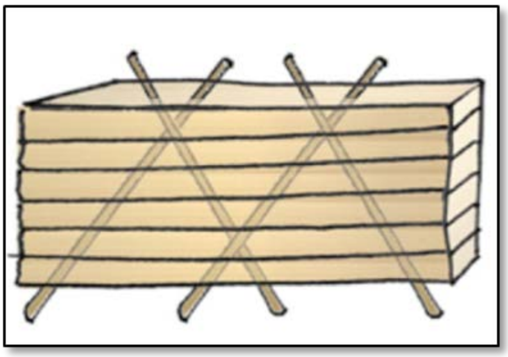
Ludesch Town Centre Building

This building made a huge impact and the clients decided that there were features of this and of other buildings they would like to emulate. They also decided on a Brettstapel construction aware that the superstructure would be prefabricated to very precise tolerances and would arrive with a guaranteed PassivHaus standard and in the knowledge that Gaia Architects was building up experience in this construction method (and its procurement) at Acharacle.

Picture 11: Ludesch Town Centre – constructed from Brettstapel

2.9 The Brettstapel System

Brettstapel is fabricated entirely from untreated softwood timber posts connected with hardwood timber dowels. It has no glues or nails. The hardwood dowels have moisture content lower than that of the posts. Over time the dowels expand to achieve moisture equilibrium thus ‘locking’ the posts together and creating a structural load-bearing system. The dowels are a development of an original nailing concept, providing greater flexibility. Diagonal cross dowelling (DiagonalDubelholz) is a late development from the dowelling concept resulting in additional stability.



Picture 12(a) Principle of DiagonalDubbelholz

Picture 12(b) Panel with acoustic finish

This simple construction method uses low-grade timber that would otherwise be unsuitable for use in construction, to form load-bearing solid timber wall, floor and roof panels. It locks in vast amounts of carbon dioxide.[45] The exclusion of glue (which is a component of other solid timber systems) means a healthier indoor air quality can be achieved. The lack of a need for any other treatments minimises the risk from harmful toxins.

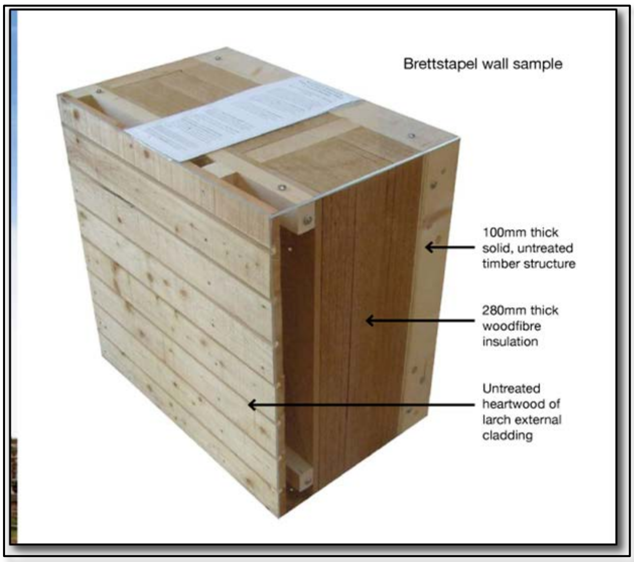
Benefits of Brettstapel

Embodied Carbon
Thermal mass (760 kJ/m^3.K);
Low Thermal Conductivity
Breathable construction;
Designed Airtightness;
Good acoustics (approximately 54db reduction dependent on thickness);
Healthy Indoor environment (no harmful compounds; hygroscopic finish for moisture stability);
Good Spans (Panel 80-370mm thick can span 3-15 m);
Off site Prefabrication;
Fire Resistance (120mm panel has a 60 minute rating).

[45] Trees retain the carbon portion of the CO_2 molecule to build their structures, and exhale most of the oxygen. The atomic weight for carbon is 12, for oxygen is 16, and so for CO_2 is 44 (12 + 2x16). One kg of carbon storage therefore represents removal of 44/12, or 3.67 kg of CO_2. The organic component of wood is 50% of the total, the rest is mostly O (45-50%) and H (5%) so Carbon dioxide sequestration is 1.8 kg of CO_2 per 1kg of dry timber)

2.10 Detail design – Fabric

The design of Plummerswood then evolved to meet the PassivHaus Certification standard (see page 4) using Brettstapel solid timber panels to form the superstructure.



The system includes approximately 80mm of solid timber on the inner surface of a wall. Outside of this is a sheathing board that forms the primary air tightness layer. Then approximately 280mm of wood fibre insulation. An air gap and rain screen completes the construction.

Picture 13. Brettstapel Wall System

At Plummerswood the timber external rain screen is typically applied at first floor level and significant portions of the ground floor. Portions of the external wall at ground floor level include natural stone wall that act as the rain screen.

Picture 14: Timber & stone rainscreen cladding

The house was designed through extensive dialogue with the clients to fully exploit the views available from the site, resulting in a simple, L-shaped layout across two storeys, with the intersection forming the double-height entrance.

Picture 15. The house benefits from extensive views

The landscape was generally open during the design and construction phase. Replanting of trees was undertaken as a part of the construction works. As these trees mature they are providing additional shelter to the south and west of the building.

The specification for the external envelope is provided below:

External Walls
25mm timber or 300mm stone cladding
80mm ventilated airgap
280mm woodfibre insulation
16mm sheathing & air tightness board (NOT TO BE BREACHED)
80mm thick Brettstapel wall elements
Fermacell board with 3mm plaster and decoration in some locations

Ground Floor with Slate on Concrete Slab
40mm slate on adhesive on
12.5mm Fermacell on
18mm sarking on
80x50mm battens @ 400mm c/cs on
140x50mm battens @ 400mm c/cs with
1 x 80mm and 1 x 140mm layers woodfibre insulation between battens on
Bituminous membrane on 150mm concrete slab on
25mm sand blinding & min 150mm Type 1

Ground Floor with Timber Floor on Battens on Concrete Slab
22mm solid timber flooring on
2 x 140x50mm timber battens & counter battens @ 400mm c/cs with
2 x 140mm woodfibre insulation between and laid on
Bituminous membrane on 150mm concrete slab on
25mm sand blinding & min 150mm Type 1

Flat Roof:
Extensive turf roof buildup
1.2mm thick single ply membrane
360mm rigid woodfibre insulation
Vapour barrier (by Sohm)
19mm sheathing board (by Sohm)
Timber firring pieces to create fall, infilled with soft insulation (by Sohm)
Over 180mm dd solid timber panel (by Sohm)

Surface Materials
The surface materials and estimated emissivity are as follows:

- Flooring (slate): 0.67 to 0.80;
- Flooring (solid timber): 0.91;
- Walls (internal surface and painted): 0.96;
- Walls (internal, exposed Brettstapel): 0.89;
- Glass: 0.93.

2.11 Detailed Design -Mechanical Services

The design of the mechanical systems was intended to be *"as simple as possible but no simpler".* The M&E consultant was appointed in the latter period of 2007. The Stage C design report includes a description of the services.[46] Numerous options were considered during the design process and some of these key issues are summarised below.

2.11.1 Heating System Selection

An early aspiration for the project was that it would achieve the PassivHaus standard and require very little heating.

The client wished to have a wood burning stove and consideration was given to a stove incorporating a water heating heat exchanger that would then provide heating to the rest of the house. As the combustion chamber of the stove would be required to be ventilated directly to outside, undermining the air tightness requirements, and for aesthetic reasons this option proved unworkable.

A MVHR system was considered for the provision of heating and winter ventilation for the house. A study was undertaken to assess whether a "self heating" approach was possible to allow the heat from occupants and internal processes to provide the heating without the need for supplementary heating. The MVHR would incorporate a heat exchanger at 80% heat recovery potential but no reheat battery. The results of the study were presented in a report entitled "*Winter Temperatures*".[47]

The modelling identified that the conditions in the house in winter conditions would be unacceptably cold using the "self heating" approach. A modification was made with a 1kW reheating element added.[48] This resulted in internal temperatures in the range 13 to 17^{0}C with an external temperature of 4^{0}C. This was approved for the design to progress.

2.11.2 Low and Zero Carbon Technologies (LZC)

The M&E consultant considered the following LZC technologies:

- MVHR (see above);
- Wood burning stove;
- Solar water heating;
- Photo voltaic (PV) panels.

Of these the MVHR, wood burning stove and solar water heating were incorporated into the design. The decision to use solar thermal was partially client driven. They had a solar water installation on their property in Edinburgh and were happy with the performance.

---

[46] Appendix 6: Design Progression Stage C design report was issued on 12 March 2008, Fulcrum Consulting
[47] Appendix 6: Design Progression. *Winter Temperatures*", Fulcrum Consulting 10th Feb 2009
[48] The system installed had a 2kW element

At the time the design process was taking place, 2007/2008, renewable heat incentives (RHI) and feed in tariffs (FIT) were not available and hence did not impact on the financial aspect of decision making. The solar water heating system is still progressing through the approval process for the RHI scheme.

The potential for PV was retrospectively considered by the monitoring team and confirmed the choice of solar thermal as a valid decision.

The averaged electricity consumption for Plummerswood is around 9,400 kWh. The area of photovoltaic panels required to offset this consumption and make Plummerswood net Carbon neutral was estimated. Three PV types were considered and the results are summarised below:

Technology	Yield ($kWh/m^2/yr$)	Approximate Cost (£/m^2)	Required Area for 100% Offset (m^2)	Total Cost
Thin Film	47	356	200	£71,300
Polycrystalline	71	480	132	£63,600
Monocrystalline	106	520	89	£46,200

This showed that it would be impracticable because of the area required and the overly expensive installation costs to offset all of the electricity usage with PV panels

2.11.3 Utilities

Electrical Supply

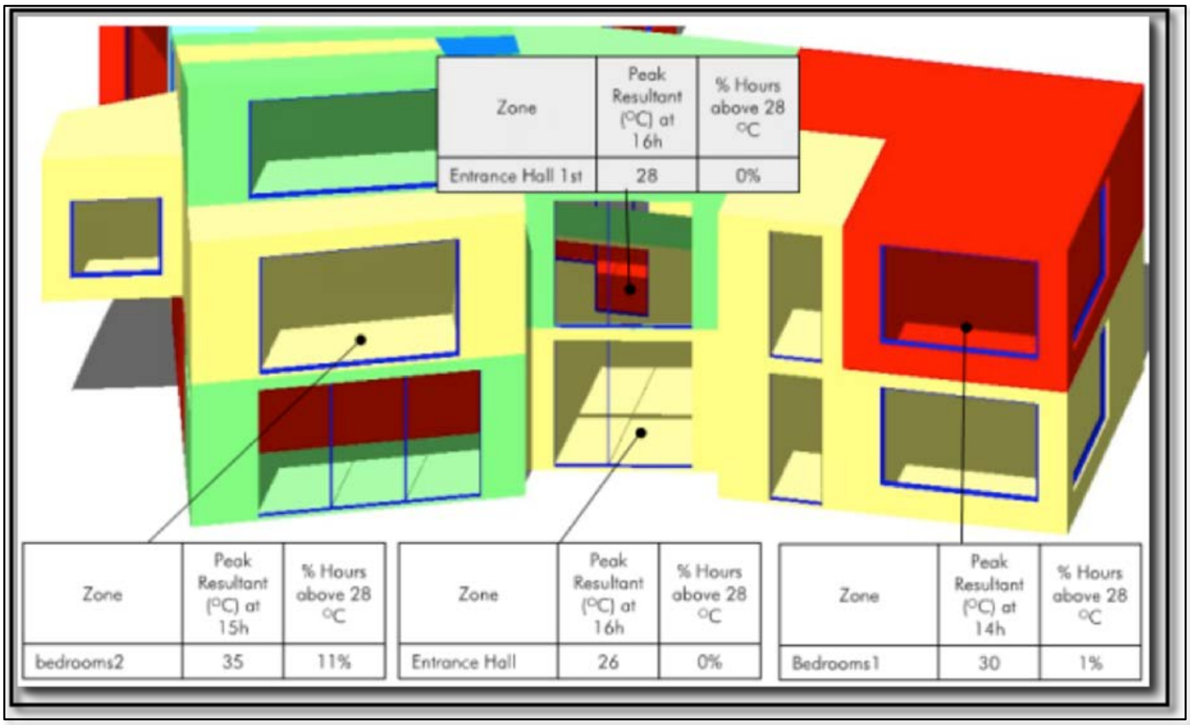
The site was purchased from FCS as a "serviced site" with sufficient electrical capacity in the utility company infrastructure to serve a new house without the need for reinforcement. As the design progressed it became apparent that planning permission was in process for a further two private properties in the vicinity of the site and there was insufficient electrical capacity in the existing utility company infrastructure. The cost for infrastructure upgrade was shared between the three properties.

In addition to the utility electrical supply, a mobile generator located in the ground floor workshop area, adjacent to the study, provides standby electrical power. This supports some key services in areas of the house which it was agreed would be used in the event of a power failure - power outlets in the kitchen, living room and study, some ground floor lighting circuits the cold water borehole pump, and security system.

Water Supply

A mains water supply was available for the house in the vicinity of the site boundary. It became clear that there was insufficient pressure in the utility company mains to be able to deliver water to the proposed position of the house on the top of the hill. A private borehole water supply was proposed and designed by the project civil engineer and installed by a specialist contractor who had provided a system for a neighbouring property. The borehole system incorporated a bio-disc. This proved to have significant energy implications.

2.11.4 Summertime Temperature Control



Picture 16. Modelled Summer Temperatures

The design intent was for the MVHR system to be used for winter conditions with temperature control in summer controlled through natural ventilation. Thermal analysis was presented by the M&E consultant in a report entitled "*Summer Overheating Analysis*".[49]

South facing rooms were considered and two options were explored. With the windows closed and the MVHR providing background ventilation, the modelling indicated significant overheating. A natural ventilation approach was modelled and resulted in a significant improvement but the south-facing bedroom showed signs of overheating. As the design developed further, overhangs, vertical external shading and external operable blinds were incorporated to reduce the risk of overheating.

2.11.5 Lighting Control System

An expensive and potentially complex lighting control system - Phillips Dynalite - was specified with the design intent that it was to be configured for simple operation. The installation or specification led to some problems as described elsewhere. The selection of the system appears to have been based on perception that a bespoke property of the nature of Plummerswood would be expected to have a sophisticated control system. However it seems as though a simple standard system would have been sufficient for the occupants needs.

[49] Appendix 6: Design Progression "*Summer Overheating Analysis*" – Fulcrum Consulting

2.12 Coordination with Subcontractors

Previous study tours (2004/05) had identified DiagonalDubelholz (a patented method of double diagonal doweling of Brettstapel units) as the most stable and highest quality version of the system. Gaia Architects had developed confidence in the Sohm Holzbautechnik Company from Austria (Sohm), who held the patent, and were at that time erecting the superstructure for the Acharacle School.

The decision to use Brettstapel meant that the project needed an appropriate procurement route. The process of procurement chosen was a traditional contract with the client with Specification and Drawings. A Bill of Quantities was provided for the tendering process. The four members of the design team were separately appointed. There was one major caveat, the superstructure was a nomination to Sohm.

The unusual aspect of the use of mass timber as the superstructure led to a two-stage process. A first stage enabling contract to arrange the site earth movement, drainage infrastructure, the formation of a new access road to the house, the major excavations for the house foundations and also to secure the bothy building. This was followed by the superstructure contract stage 2.1 to complete the foundations and erect the superstructure and then the fit-out stage 2.2.

Previous experience at Acharacle meant that Gaia Architects was well prepared for the areas of concern arising between the various responsibilities. Significant effort was committed to ensuring minimum risk to the client, where responsibilities overlapped. The main contractor Tender was issued to four contractors - mutually agreed between the Design Team and the Clients. The successful main contractor Rodger (Builders) Ltd is a relatively local and small to medium sized contractor.

Other than the superstructure there were two other nominated subcontractors. Real Wood Studios were responsible for providing all the internal screens, cupboards, doors and bookcases. Ashley Ann Kitchens did the kitchen fit out. For logistical reasons the completion of the external stone walling was taken out of the main contract at a late stage, and let separately.

2.13 Building Warrant

Early discussions were held with the Building Control Department to ensure that they were fully aware of the intended method of construction so that any major concerns could be dealt with at the outset.

The use of timber inside and out is a difficult issue in the UK. Gaia Architects experience of working with timber over 30 years, and the ability to quote precedents within the Scottish Building Standards, meant that concerns were resolved without too much additional work. The key issue was around the fire protection of the double height lobby area against surface spread of flame. The specification of a previously used (water-based) fire retardant was agreed as acceptable.

The Planning Permission and the Building Warrant were signed off by March 2012. The latter followed a short delay to allow some earth moulding on an external staircase.

2.14 Production information and Second Study Tour

With the design firming up in both form and construction negotiations with Sohm commenced. The detailed production information drawings were undertaken between Sohm and Gaia Architects with expert consultancy - in the form of pre-vetting architects drawings to Sohm - via Walter Unterrainer.

2.15 Enabling Works

The Stage 1 contract began at the end of 2009 and involved fencing, road making and infrastructure installation. The whole process was arranged in order to meet the delivery of the first consignment of prefabricated elements.

The client and members of the design team travelled to Vorarlberg to see the elements being constructed and to ensure that all the integrated services runs within the walls were incorporated.

2.16 Site Works - Superstructure

The first consignment of elements arrived in October 2010 together with the Austrian carpenters to assemble it. The ambition was to have the superstructure completed before the Christmas holidays. Gaia Architects knew that the Austrian attitude to Health and Safety was more relaxed than in the UK and a watch had to be kept on compliance.

When construction work was brought to a halt throughout Scotland, due to snow and long periods of freezing temperatures, the Austrians simply carried on, as the conditions were normal for them at that time of year. By working long hours and through weekends the super-structure was completed and airtightness tested by the 22nd December 2010 – a six-week process – as agreed.

Picture 17. Winter Construction

An airtightness test confirmed that the required performance target had been met.[50] The erection of the superstructure was appraised by the team as exemplary with no delays or outstanding issues to resolve. As with the Acharacle School – the subcontractor for the superstructure guaranteed PassivHaus standard as part of their delivery package – and the first air-tightness test was an endorsement of the construction quality.

---

[50] Appendix 7: Fabric Testing - RMP Airtightness Test December 2010

2.17 Site Works - Finishes

In December 2010 the building was handed back to the main contractor for completion. This comprised first fix services, first fix fit out, external works (including a bridge to the first floor), flooring and cladding. All the cladding and flooring timber was European larch, oak and ash felled, milled and supplied locally. The floor was constructed using a Gaia Architects detail with nail-free fixings (screwed battens holding loose boards in place).

Picture 18: Nail-free flooring screw-fixed battens holding loose boards

The painterwork and surface treatments were left to the very end of the contract so as to avoid dust. This proved a challenge as local bespoke joinery subcontractor selected by the client and nominated for the handcrafted doors and screens and cupboards was somewhat overwhelmed by the scale of works and took significantly longer than was programmed.

The client commitment to quality of the internal finishes, rather than speed, meant that the project was delivered a number of weeks late. A similar set of circumstances arose with the stonemason for the project, with the effect that the external walls (non-essential to the handover of the house as a working entity) were also removed from the main contract and carried on as a one-off cost. These were completed three months after practical completion.

2.18 Completion

Practical completion was achieved in November 2011 and a provisional certificate of occupation issued subject to a small itemised list of outstanding items. A number of related to external areas (e.g. wheelchair access to the front door.)

At this point it was impossible to test the doors and internal spaces as some of the screens were still missing and one external screen was awaiting replacement, which took 6 weeks.

A decision was made to co-ordinate the practical completion date with the handover, initiation and commissioning date so that all consultants and appropriate sub-contractors were on site at once, and that everything could be resolved with all present.

2.19 PassivHaus Certification

With the completion of the project at handover the PassivHaus certification was requested. The process had begun at the beginning of the project – as required by the certification rules. Gaia Architects carried an assessor in-house but the final certification needed to be done externally. Mott Macdonald carried out the PHPP calculations and BRE did the final check and verification of the data and issued the certificate.

2.20 Commissioning and Handover

The handover date was determined by a combination of elements. The clients were wishing to take up residence and the Building Control Department was prepared to allow entry with only a small numbers of items outstanding.

The formal handover of keys came at the point where critical Building Control issues (notably fire doors and compartmentation) could be signed off. This involved some temporary screening prior to tempered glass being permanently installed.

All the technical systems were handed over.[51] Caveats existed over the MVHR, which was to be commissioned once the joiner-work was completed to avoid getting dust into the system. The solar system appeared to be working. The lighting systems were operational with the exception of a faulty switch in the library.

2.21 Construction Process/Programme

Design Stage

The original programme provided for a design period from March 2010 to July 2010. The superstructure manufacturer/contractor, Sohm, was engaged during the design process. This allowed a number of design activities to take place as follows:

- Sub-structure design based on Sohm foundation design drawing;
- Review of structural loading calculations by the project Structural Engineer;
- Billing;
- Engagement of the superstructure manufacturer/contractor in the Stage G design process suits the Brettstapel construction, which requires exact co-ordination of issues such as the positioning of services in the superstructure.

Building regulations approval documents also had to be prepared for the building warrant to be obtained in good time for the start on site.

Tendering Stage

Tendering was programmed for four weeks during August 2010. A three-week period was allowed for review of the tender returns and acceptance.

---

[51] Appendix 8: Design and Handover Information containing the Building User Manual and EPC was created by Gaia Architects 2011

Construction Period
The construction period includes three key phases.
Stage 1 – Mobilisation and Site Works
Eight weeks was allowed for in the programme for mobilisation, site set up and sub-structure works. With the form of construction utilised it is important that the substructure works including below ground services are complete in time for the arrival of the pre-fabricated superstructure elements.
Stage 2 – Superstructure
The construction of the superstructure was programmed for November and December 2010. The superstructure erection process was programmed for eight weeks, commencing immediately after the completion of Stage 1. This was a very cold period in Scotland with the temperature consistently below $0^{o}C$ throughout the period.
Stage 3 - Fit Out, Landscaping and Commissioning
The fit-out period was programmed to commence five weeks into the superstructure fabrication. This suggests a phased process to the construction. The total period allowed was 12 weeks. A commissioning period of two weeks was allocated with handover following immediately after completion of commissioning.

2.22 Post Occupancy Evaluation

Gaia Architects were keen to see that the building performance was optimised to the satisfaction of the client, and to learn as much as possible from the design and procurement process in line with the innovation cycle philosophy. They were supportive of the application for funding to TSB and maintained involvement with the project until this was cut short by the tragic death of the principal of Gaia Architects in February 2013.

The client is very co-operative and very prepared to engage with the process. The client project log has been maintained throughout the project as a physical diary.

2.23 Review of Tender, Procurement & Construction process

Nomination
Once the client had chosen a Brettstapel construction it was inevitable that the building would be procured from Middle Europe. There were at this time no manufacturers of Brettstapel in the UK despite Gaia having sought to engender this for 15 years. Indeed a primary motivation in building firstly the Acharacle School and then Plummerswood using this technique was the opportunity to showcase the technique in the UK and create interest in manufacturing potential. When it was decided that the client wanted to procure diagonal dowelled system, it could only be Sohm (who have a patent on it).

There are risks with nomination, which include failure to deliver on time and a claim from the main contractor for delay. Having worked with Sohm previously Gaia was confident that this would not be a problem and so it transpired. The primary benefit was to obtain a guaranteed quality for a fixed price.

Construction
The construction proceeded as agreed and anticipated despite extremely harsh weather conditions on a remote and difficult to access site. The superstructure was provided to a PassivHaus brief and so no performance issues such as air leakage or cold bridges were anticipated, and none were subsequently identified.

Actual Programme
Overall the project progressed very slowly for a small project with the client taking a close interest in all the details. This was particularly telling at fit-out and is evident in the finish quality. The modelling and study tours fed into the design as they were intended to, with no significant changes occurring to the brief other than in an ordered progression of the concept.

Delays during the fabrication of the superstructure added around two months to the project. However, once on site, the mass timber superstructure manufacturer/contractor met the duration for erecting programmed. This was despite the very cold conditions experienced at that time. A significant extension to the construction programme occurred for the fit-out and this impacted on subsequent trades (such as painting).

The construction stage for the project completed in the latter half of 2011. The commissioning certificate for the MVHR system is dated September 2011. This is around five months after the Stage G programmed completion.

Snagging
There is an issue with dealing with any snagging issues from a distance – especially small items. With these outsourced to UK based companies, working to Sohm's instructions – the risks were minimised.

There was a long-standing problem with a UK based company who disputed their responsibility for a fault – declaring it to be main contractor abuse rather than an intrinsic manufacture problem. This was eventually resolved technically using a local company.

2.24 Review Of Standard Assessment Procedure (SAP)[52]

The monitoring team reviewed the original SAP calculations and the "Original SAP Score" is compared against a "Revised SAP Score". The aim was to identify any discrepancies between the design and SAP and whether the design accurately reflected in the SAP calculations and describe where these discrepancies lie.

The main discrepancies from the original SAP calculations to the completed design are:

- Thermal bridging factor incorrect
- Incorrect area of solar panels
- Incorrect electricity tariff used

[52] Appendix 9 SAP Review Task Report 6a – and appendix SAP Calculation Review includes the updated SAP

Minor discrepancies that also have a slight affect on the overall score include:

- Wall areas
- Floor areas[53]
- Proportion of space that is living area

This is summarised in the table below:

	Initial SAP Calculation	Reviewed SAP Calculation
TER (kg/m^2/year)	26.14	26.41
DER (kg/m^2/year)	15.02	13.79
EI	84	84.57
Current Score	81	76

Table 3: SAP Comparison

The new SAP worksheet is more reflective of the constructed building. The overall CO_2 emission decreases from 15.02 to 13.79 kg/m^2/yr. The main factor influencing this was the incorrect value for thermal bridging. The SAP rating was adjusted using the correct electrical tariff and went from 81(B) to 76(C). The environmental impact went from 84(B) to 84.57(B).

	Energy (kWh/year)		Emissions (kg/year)	
	Original	Revised	Original	Revised
Main heating	5140	4122	2169	1739
Secondary heating – Wood burning stove	879	702	22000	17061
Water heating	2846	3605	1201	1524
Space and water heating			3370	3278
Electricity for pumps and fans	1360	1360	574	574
Energy for lighting	1545	1545	652	652
Total CO_2 emissions			4618	4504

Table 4: SAP Comparison of Energy Consumption

2.25 Conclusion & Recommendations

The clients are very satisfied that the design meets their brief as identified in video footage and in written feedback. The architectural design team are satisfied that the project meets their aspirations for an exemplar building. BRE have confirmed that the design meets the PassivHaus standard. The award of the Scottish House of the Year, and numerous other awards provide a level of external evaluation of the design.

There were no major concerns regarding the design targets, operation or performance of the building. The programme was largely on track apart from additional time in meeting artisan finish quality, which the client was eager to allow.

[53] The SAP calculations use floor areas different from both the DomEarm and the PHPP

3. Fabric testing (methodology approach)

3.1 Air Tightness Testing

3.1.1 Methodology / Approach

The air tightness of a building can be presented as air changes per hour (h^{-1}). It is calculated by multiplying the air permeability by the surface area then dividing by the building volume.

Plummerswood was designed to PassivHaus standard and therefore had to achieve a rating of less than or equal to 0.6 ac/hr @ 50Pa. It was tested at the end of the construction period to ensure that it met the requirement. It was then tested as part of the TSB process to verify the original test. This test also included a survey to identify leakage sites. It was tested again approximately 15 months later to examine the extent of any movement or deterioration.

3.1.2 Air tightness testing for certification

The airtightness test undertaken in December 2010 by RMP as part of the design and construction process conformed to the requirements of The Air Tightness Testing and Measurement Association Technical Standard 1 (ATTMA TS1) 'Measuring Air Permeability of Building Envelopes' (2007). The air tightness was determined by positively and then negatively pressurising the building envelope using a fan.

The internal pressure measurement tube was located in the centre of the dwelling, and the external pressure measurement tube positioned to achieve external conditions, approximately 2m from the building façade.

Temporary seals were applied to the active part of ventilation openings that cannot be manually closed (e.g. toilet extract fans, cooker extractors). All external doors and windows were closed with the exception of the opening where the blower door is fitted.

Measurements of the air flow rate and corresponding indoor and outdoor pressure difference were used to create a building leakage curve over a range of fan flows. Before and after the measurements, recordings were made of the static pressure, the barometric pressure and the internal and external air temperatures. Airflow rates were adjusted accordingly and the air tightness then calculated at a reference pressure of 50 Pa.

This confirmed an air permeability of 0.74 $m^3/h.m^2$ @50Pa equivalent to an air leakage rate of 0.56 h^{-1}@50Pa within the design target of 0.6 h^{-1}@50Pa. The investigation highlighted that the expanding polyurethane seals above many of the windows were not fully expanded due to the very cold temperatures. Subsequent to the test additional remedial works was undertaken to improve these seals and two retests identified reduced air permeability to 0.49 and 0.50 $m^3/h.m^2$ @50Pa equivalent to air leakage rates of 0.37 and 0.38 h^{-1}@50Pa respectively.

Table 3: Test result summary						
Test No. D-5483-RRM-RGM	Appendix No:	Design Air Leakage Rate (h^{-1}@50Pa)	Measured Air Leakage Rate (h^{-1}@50Pa)	Measured Air Permeability ($m^3/(h.m^2)$@50Pa)	Correlation Co-efficient ($r^2 > 0.98$)	Air flow exponent ($0.5 < n < 1$)
-02	2	≤0.6	0.38	0.50	0.99938	0.786
-03	3	≤0.6	0.37	0.49	0.99878	0.743

Table 5: Certification Air Test Result Summary

3.1.3 Repeat Air Leakage testing [54]

Repeat air leakage testing was carried out on the 3rd February 2012, approximately one year after completion of the dwelling, using a Retrotec 3300HP Blower Unit, mounted in the side door of the house. Testing was carried out in accordance with the requirements of BS EN 13829 and the BINDT Quality Procedure, in conformance with the ATTMA TSL1 standard (2010), Method B.

All external doors and windows, other than that where the test equipment was mounted, were shut for the duration of testing, and internal doors were kept open to ensure the building acted as a single volume. No trickle vents were fitted in the dwelling. Other test preparations included checking that plumbing and waste traps were charged with water and temporarily sealing of the heat recovery ventilation including sealing all the distribution and extract terminals in the various rooms. This was carried out because it proved impractical to seal the ventilation ducts immediately on the warm side of the heat exchanger, as would have been ideal. The photographs below and overleaf illustrate some of the key features of the air tightness test preparation and equipment set-up:

Picture 19: Supply terminal in lounge temporarily sealed for duration of testing

Picture 20: Extract terminal in bathroom temporarily sealed for duration of testing

[54] Appendix 7: Fabric Testing - Gaia ALDAS Airtightness report February 2012

Picture 21: Test equipment mounted in side door

Picture 22: Hit-and-Miss vent closed for duration of testing

Picture 23: Supply terminal in bedroom temporarily sealed for duration of testing

Airflow @ 50 Pa:		**411.5 m³/hr**
Air Permeability Rate @ 50 Pa:		**0.59 m³/(hr.m²)**
Air Change Rate @ 50 Pa:		**0.42 ACH^{-1}**
	Correlation of results, R^2:	**0.999**
	Slope, n:	**0.70**
	Intercept, C_{env}:	**28.45 m³/(hr.Pa^n)**
Test Parameters:		
	Envelope Area, A_E:	**692 m^2**
	Volume, V:	**970 m^3**
	Env. Calc Prepared by:	**Paul Jennings, GAIA Aldas**

Table 6: First Monitoring Air Test Result Summary

This identified an air permeability of 0.59 $m^3/h.m^2$ @50Pa equivalent to an air leakage rate of 0.42 h^{-1}@50Pa, which meets the PassivHaus target for newbuild dwellings (a maximum Air Change Rate of 0.6 ACH-1 @ 50 Pa) by a substantial margin.

It was noted that both Air Change Rate and Air Permeability values are significantly worse when the building is pressurized, which was thought to be due to the high level windows opening slightly under pressure, reducing the effectiveness of the draught seals. A leakage testing survey was undertaken to identify any potential remediation requirements. The outcomes are noted in the report.

A further airtightness test was undertaken towards the end of the monitoring period in August 2013 using the same procedure as above. This confirmed an air permeability of 0.69 $m^3/h.m^2$ @50Pa equivalent to an air leakage rate of 0.49 within the design target of 0.6 h^{-1}@50Pa.[55]

Airflow @ 50 Pa:		474.5 m^3/hr
Air Permeability Rate @ 50 Pa:		0.69 $m^3/(hr.m^2)$
Air Change Rate @ 50 Pa:		0.49 ACH^{-1}
	Correlation of results, R^2:	0.999
	Slope, n:	0.73
	Intercept, C_{env}:	27.6 $m^3/(hr.Pa^n)$
Test Parameters:		
	Envelope Area, A_E:	692 m^2
	Volume, V:	970 m^3
	Env. Calc. Prepared by:	Paul Jennings

Table 7: Second Monitoring Air Test Result Summary

A review of the differences between the tests is provided in Appendix 7[56]

3.2 Thermography

3.2.1 Introduction

This infrared thermography followed the procedure "*Requirements for infra-red thermography surveys"* as described in the TSB Guidance for Project Execution document (Draft version 5 – June 2001). The survey was conducted on 3 February 2012 between 08:00 and 09:15 using a Flir T250 s/n 40 2000 390 thermal imaging camera

The purpose of infrared thermography is to identify irregularities in the thermal properties of the components constituting the external envelope of a building. These irregularities would be highlighted by temperature variations over the surface of the structure. Irregularities might include insulation defects, moisture content and/or leakage.

The principle of the test is to:

- Determine the surface temperature distribution over a part of a building envelope;
- Ascertain whether the surface temperature distribution is "abnormal";
- Identify the type and extent of any defect.

It is important that a survey is undertaken under specific conditions so that the results are not skewed by factors such as solar radiation, surface dampness or differing surface emissivities. The first chapter of the thermography report provides evidence that the

---

[55] Appendix 7: Fabric Testing – Jennings ALDAS - August 2013
[56] Appendix 7: Fabric Testing - Discrepancies in Air Leakage tests

requirements for conducting the survey have been met and summarises the results of the survey using the methodology for presenting the information described in BS EN 13187: 1999.[57]

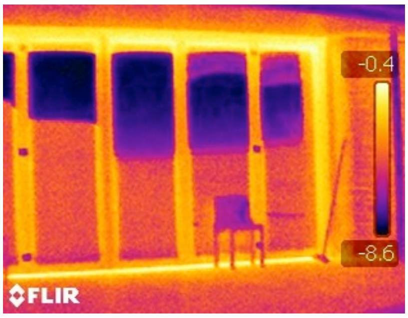
It was a very still day with wind speed less than 1m/s throughout the survey. With the extremely low air speed immediately prior to and during the survey the difference in air pressure over the leeward and windward sides of the building would be minimal. All surfaces of the house were dry and there was no rainfall during the survey.

The thermal imaging report is comprehensive. A sample of the results are presented below in accordance with BS EN 13187: 1999 as a series of thermograms, alongside conventional photographic records of the same views. Areas of specific concern are identified and labelled and related to text based account of the investigation of these anomalies.

External Surfaces

Kitchen/Dining Room Windows

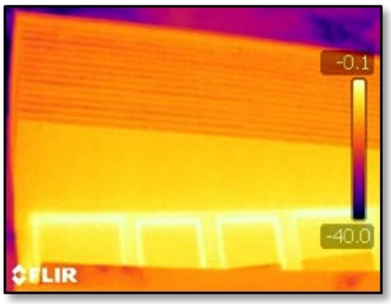
Air Leakage: Possible minor at head and base of door
Thermal Bridge: Minor at window frame as expected
Missing Insulation: No evidence

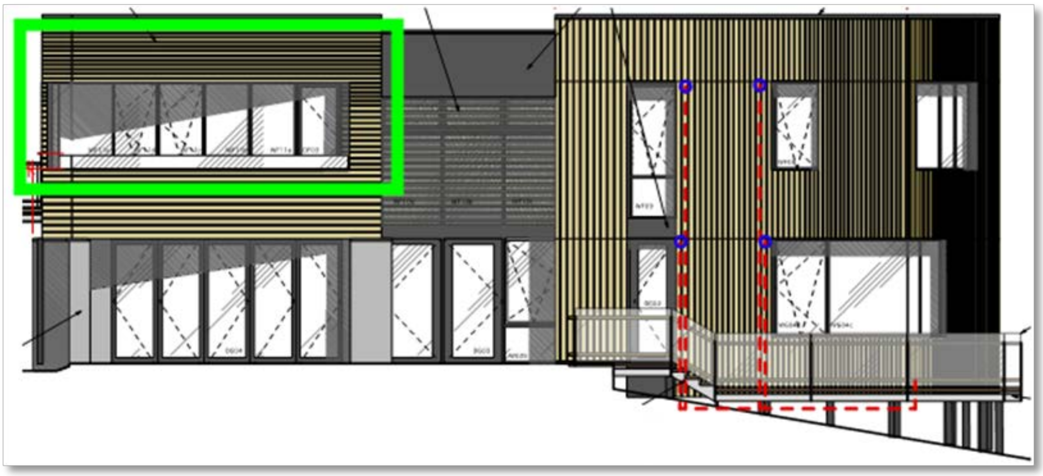


[57] Appendix 7: Fabric Testing -Thermography test

First Floor Bedroom Windows

Air Leakage: No evidence
Thermal Bridge: Minor at window frame as expected
Missing Insulation: No evidence



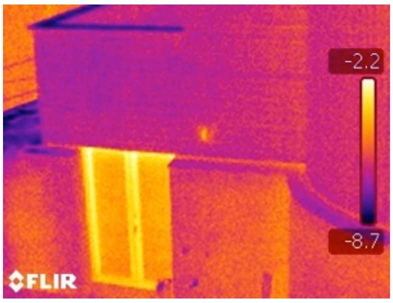


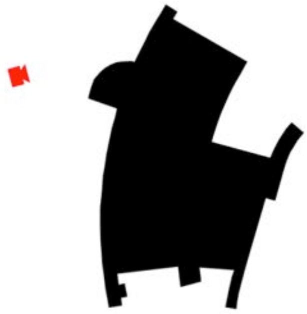
First Floor External Bridge Link Access (West)

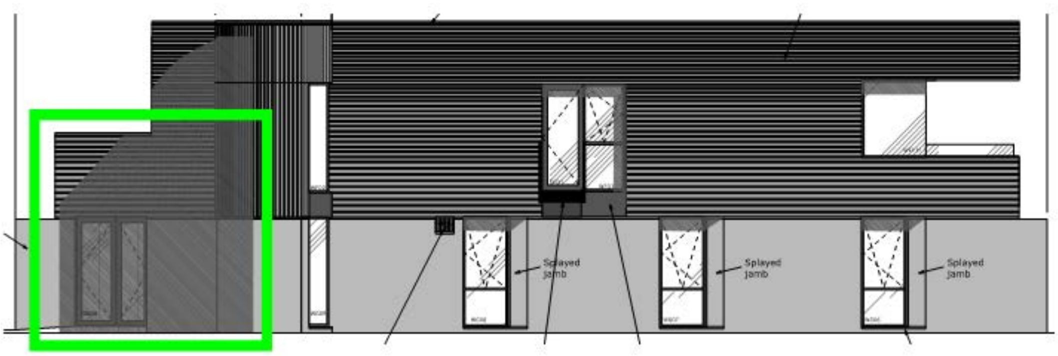
Air Leakage: Possible breaching of the air tightness layer for the installation of the wiring associated with the security alarm. More likely to be a heat source within the security alarm fitment.

Thermal Bridge: Minor at window frame as expected

Missing Insulation: No evidence



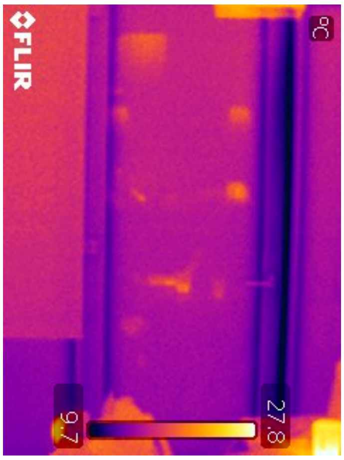


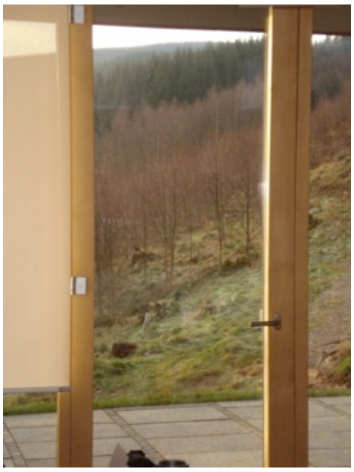
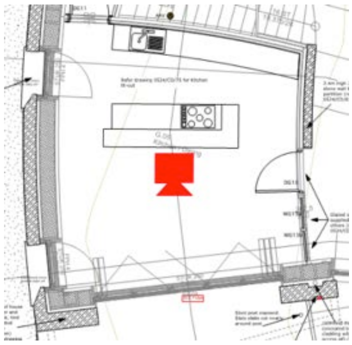


Internal Surfaces

<u>Dining Room Windows</u>

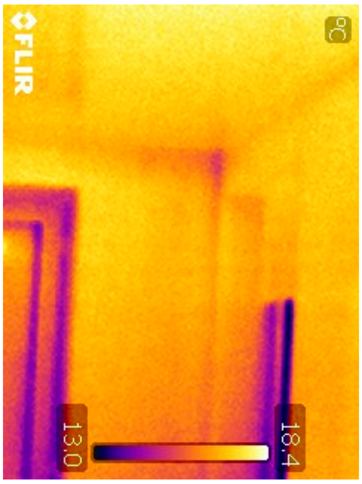
Air Leakage: No evidence
Thermal Bridge: Minor at window frame as expected
Missing Insulation: No evidence

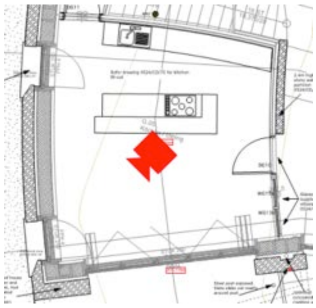


<u>Dining Room South West Corner</u>

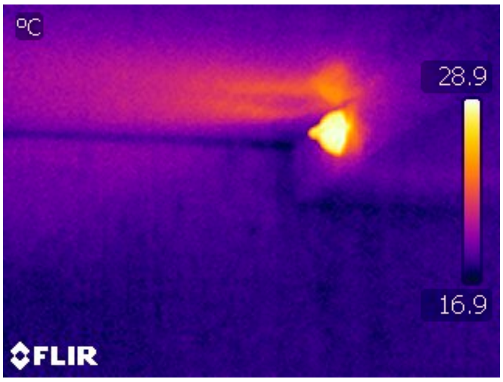
Air Leakage: No evidence
Thermal Bridge: Minor at window frame as expected
Missing Insulation: No evidence

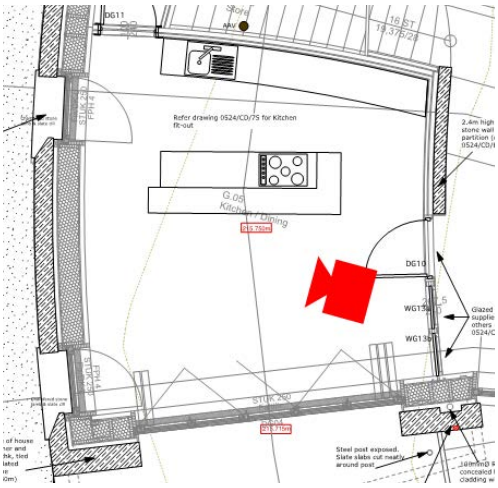


Kitchen Bulkhead

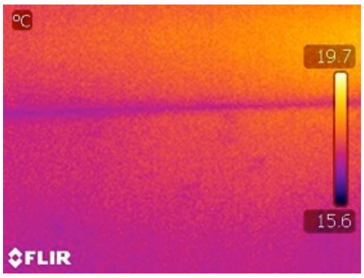
Air Leakage: No evidence
Thermal Bridge: Minor at window frame as expected
Missing Insulation: No evidence
Heat from supply air diffuser as a part of MVHR and air plume on ceiling identifiable.

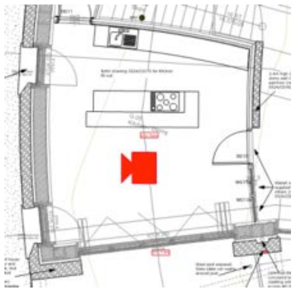




Kitchen Wall/Ceiling Junction

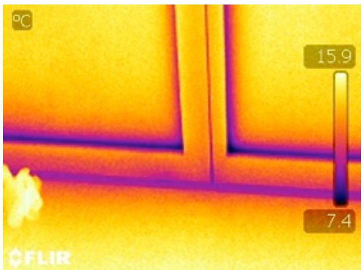
Air Leakage: No evidence
Thermal Bridge: No evidence
Missing Insulation: No evidence
Air plume on ceiling identifiable from supply air diffuser as a part of MVHR.

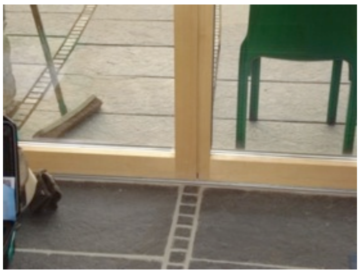
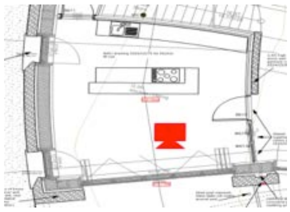


Bottom of Dining Room Doors

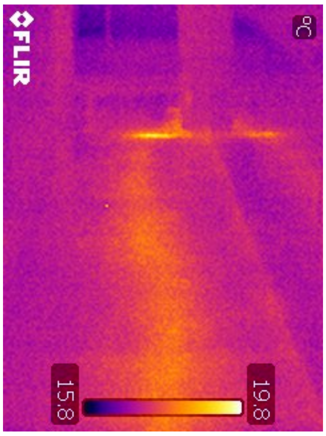
Air Leakage: Minor at base of door
Thermal Bridge: Minor at window frame as expected
Missing Insulation: No evidence

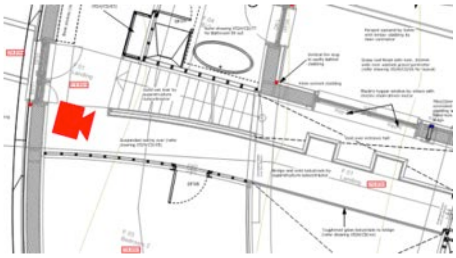


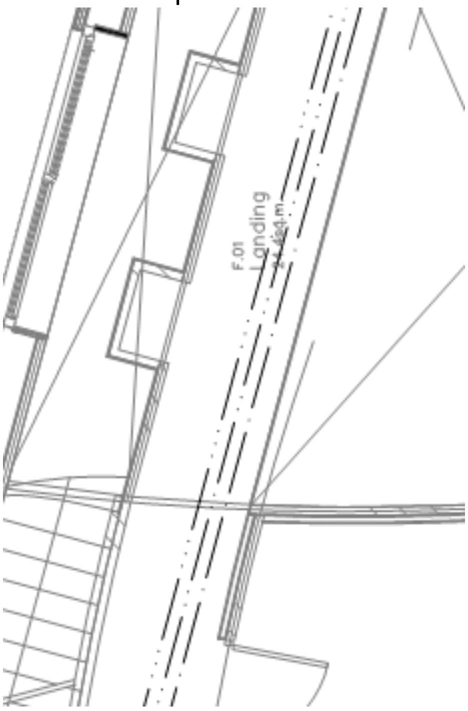
First Floor Corridor

Air Leakage: No evidence
Thermal Bridge: No evidence
Missing Insulation: No evidence





Domestic hot water pipework distributes in floor construction in the first floor corridor. See extract from M&E consultant's drawings below and also photograph taken during the construction period.



3.2.2 Summary of Thermographic Survey Findings

The building was identified as performing exceptionally well in terms of air tightness and thermal integrity and meeting the required standards. The result of the air tightness testing is an average Air Change Rate of 0.42 ACH^{-1} @ 50 Pa which meets the PassivHaus target for newbuild dwellings by a substantial margin.

The airtightness testing process provided opportunity to undertake a specific leakage inspection prior to the actual test, and particularly whilst the building was depressurised. This allowed additional improvements to be addressed. The photographs below and on the following pages show the leakage sites that were identified during the testing process.

It was noted that both Air Change Rate and Air Permeability values are significantly worse when the building is pressurized, which might perhaps be due to the high level windows opening slightly under pressure, reducing the effectiveness of the draughtseals.

Picture 24: Leakage between spotlight fittings and adjacent plasterboard ceiling

Picture 25: Leakage between ventilation terminals & adjacent plaster board ceilings and walls

Picture 26: Leakage at side of window cill in upstairs bedroom

Picture 27: Substantial low level leakage at hinge side of balcony doors in two bedrooms, Doors DF.02 & DF.03

Picture 28: Substantial leakage through base of wood-burning stove in living room

Picture 29: Leakage around external air supply to rear of wood-burning stove in living room

Picture 30: Leakage fire cement ineffective at junction between wood-burning stove & chimney

Picture 31: Leakage at window head along wall to jamb interface

Picture 32: Leakage along back edge of ventilation terminal

Picture 33: Leakage at edge of tiling in downstairs bathroom. Some leakage at side of the window

3.3 Heat Flux Test

The monitoring programme also allowed for an in-situ heat flux test to examine the U-Values of the external wall and ground floor in this domestic building. Four HFP01 Heat Flux plates / sensors were used.

Two heat flux plates were attached to the inside of the north facing external wall located in the Workshop space on the ground floor. The sensors were held in place with tape and were located approximately one metre above the ground and spaced approximately one metre apart. The sensors were connected to an Eltek Squirrel 1000 Series data logger, which logged readings from the sensors every ten minutes.

Another two heat flux plates were attached to the floor in the same room approximately one metre apart in the same way to take heat flux measurements of the ground floor construction. These were attached to the same data logger and transmitted readings every ten minutes. The data logger recorded readings from the 17th December 2013 until the 5th January 2014. The internal temperature for this space was also recorded during this time as well as the external temperature in the same location.

To calculate the U-Value of each construction the readings from the temperature sensors and the heat flux sensors needed to be converted. The heat flux sensors log readings in mV and for each test, for the wall and the floor. Two readings logged every ten minutes were averaged to give one reading per interval. The mV average reading was then converted into uV by multiplying by 1000. This uV reading was then dived by the Sensitivity (uV/W^{-2}) of the heat flux sensors, which is fixed for each sensor. This then gave a heat flux in W per m^2 for each set of sensors. The U-value of each construction is then given for every ten minutes by dividing heat flux (W/m^2) by the temperature difference (ºC) of the internal and external temperatures. This gave a U-Value for every ten minute interval, which was then averaged over the duration of the test to give the results below:

- Average U-Value of External Wall = 0.14
- Average U-Value of Ground Floor = 0.3

Comment on the results

The wall appears to perform well and the floor less so. The reason for this is unclear. There appears to be nothing in the floor construction that might cause account for the result. The calculated U-value in these locations are: wall 0.094 and floor 0.119 and there is no evidence of changes in exposure of the external surface that would have any bearing (the floor being sheltered). [58] There is the same amount of insulation overall in both elements (340mm), though slightly less between the base of the partition and external surface on the floor detail, than there is between the intermediate floor and the external surface on the wall detail because the floor cassette is only 280mm deep, with the remaining insulation above the base of the partition. In both instances the airtightness layer is in the same

[58] The floor U-value sheet gives the best breakdown of the floor construction in that area, since the description on the drawing is incomplete (refers only to a pre-fab timber cassette under the gravel).

relative position (inside face of main timber cassette), and on both occasions fitted by Sohm.

The reason for peaks and troughs is unclear. The wall readings seem to be particularly peaky with changes of a factor of 10 within 20 minutes. The floor measurements do not exhibit the same sharp peaks.

The accuracy may have been affected by the internal temperature, which varied from 16.4 to 14.3^0C, and is cooler than the optimum for the test. The external temperature was also not especially cold during the test. The maximum external temperature was 9.8^0C, and the minimum 0.4^0C meaning that the temperature difference stayed between 5.1 and 15.7^0C, again not optimum.

The fixing method of tape rather than paste may have also affected the results. The use of paste was avoided due to concerns about selected damage to the internal surfaces.

Another reason for the variation may be concerned with local movement and draughts although these are minimal at Plummerswood. Further comparison with tests taken in other buildings may help to resolve this issue, once these are published.

3.4 Conclusions & Key Findings

The data indicates that this is very well performing building in thermal and air tightness terms.

There are some surprising though not hugely significant detailing lapses such as leaks around door hinges and uncovered keyholes. In the interests of research into the Brettstapel technique, we recommend a further air tightness at a later date although in energy terms the client should have little concern.

4 Key findings from the design & delivery team walkthrough

4.1 Introduction

This section summarises the key findings from the Semi-Structured Interviews and Walkthrough undertaken in April 2012 with the M&E Consultant, Mott MacDonald Fulcrum using the *"Guidance on conducting handover process, semi-structured interviews and walkthroughs"* as required by TSB.[59] The aim is to explore the degree to which the design intent has been followed through in terms of delivery and subsequent adoption by the occupants. This aspect of the interview captured key decisions made and the reasoning behind the final design of the services.

The walkthrough identified a number of changes from the final design to the completed building. An interview with the project architect sought to clarify the reasons for changes. The walkthrough also identified lapses in finish quality. These are identified in Section 4.4.

4.2 Review of Design Process – Services

4.2.1 Issues arising

- The solar hot water heating system did not operate correctly until appraised by the POE process when the faults were identified and rectified.
- The occupiers are able to control the MVHR.
- The occupiers have replaced filters according to the instructions.
- Access is good for filter replacement except the ceiling extract in the kitchen area.
- The occupiers have modified their cooking habits and will not cook greasy food in order to overcome problems this would introduce with the induction hob.
- The controls for the lighting are perceived as being overly complex and inconsistent. It appears that a simple standard system would have been sufficient for their needs.
- The control for the lighting in the study does not work, despite replacement.
- The artificial lighting in some parts of the house is perceived as being "harsh".
- Some lamps will be difficult to replace such as above the main first floor link bridge.
- The occupiers noted that two external rain-cladding panels are lighter in colour than the other panels as they needed to be replaced following a dispute between the blind installer and the main contractor. This was in regard to the installation of one of the external blinds and damage that occurred.
- The standby generator has worked well.
- The occupants do not know why the bio-disc was not put onto the back-up power. The bio-disc goes into alarm and the occupants are not sure if the quality of the water from the borehole is compromised.
- In the winter period the occupants welcome the beneficial solar heat gain and they set the control of the external shades to manual. They revert to automatic control in summer.

[59] Appendix 10: Initial Review Task Report 7a

- The occupiers would have liked to have two levels of manuals. They feel that they would have benefitted from a simplified user guide that covered the basics.
- The occupiers were not too sure of the procedure for highlighting problems and how they are to get resolved. They were not sure how long it should take for faults to be rectified and would welcome more feedback on progress.
- The occupiers were interested to understand the main sources of electrical consumption and whether they could amend their behaviour to reduce this.
- Problems encountered are being dealt with in order to ensure minimum waste and optimum efficiency.
- The occupiers have been keeping a log of issues relating to the installation including: -
    - On which days the wood burning stove was used
    - The amount of wood burned per week
    - Days on which the MVHR was used for temperature control
    - Window opening pattern I.e. we're some or all of the windows opened on a particular day for keeping the house cool/ventilated
    - Occupancy patterns i.e. we're they away from the house for a period of more than a day or two
    - Any significant period in which guests are staying
    - When trades attend to remedy defects

4.3 As Built changes

This section summarises the following items:
- Examination of the dwelling for construction quality,
- Identification of areas where the 'as built' seems to differ from the 'as designed'
- A review of the explanation behind the changes.
- A Construction Quality Review undertaken on 27 March 2012, in the presence of the occupants.

A full review of the billing and as built drawing packages identified the following key differences between the final design and the completed building.
- Flooring to kitchen area and terrace out side kitchen changed from timber to slate
- Insulation/ floor build up altered
- External blinds added in to design
- Living Room stove location altered from north facing wall to south facing wall
- External landscaping to front of dwelling altered
- Wooden hand rail added to internal bridge balustrade
- Glass external balustrades (to the bridge and decking) changed to painted steel
- Rooflight removed from atrium space (above internal bridge).

4.3.1 Interview with Project Architect [60]

The Project Architect gave the following explanation for the changes:

[60] Appendix 10: Initial Review Task Report 6b Construction Review

- **Why was the flooring to the kitchen area and terrace outside the kitchen changed from timber to slate?**

This was a mutual client & Design Team decision, to change to more robust flooring to suit kitchen location and ease of cleaning when doors open and moving regularly between inside and outside. Cost implication was approx. +£25/m2.

- **Why was the floor build up to the slate floor altered (from 40mm slate on 20mm adhesive on 22mm ply, as per billing drawings, to 40mm slate on 12.5mm Fermacell on 18mm sarking, as per the as built spec)?**

It was changed to eliminate the use of plywood internally. There was no cost implication of doing so.

- **Why were external blinds added in to design?**

The blinds are required to minimise the risk of overheating to less than 10%, in order to achieve PassivHaus certification. This was the result of by feedback from the M&E Consultants, Mott MacDonald, who had run the house in PHPP and TAS and identified a risk of overheating. The window sizes were also reduced slightly as a result of this modelling.

- **Why was the living Room stove location altered from north facing wall to south facing wall?**

This was a mutual client/Design Team decision on the basis that the location on the north wall didn't suit possible furniture layouts. The new position also means that occupants can enjoy the view while also facing the stove.

- **Why was the external landscaping to front of dwelling altered?**

The external landscaping to the front altered to suit the actual landscape, as the topographical survey wasn't very accurate.

- **Why was a wooden handrail added to internal bridge balustrade?**

This was a client request, for ease of use.

- **Why was the external glass balustrade (to bridge and decking) removed?**

The balustrade was altered from glass to painted steel to save money.

- ***Why was the rooflight removed from the atrium space (above internal bridge)?***

Originally, a long rooflight over the internal bridge was shown, however it was removed to save money and reduce heat loss (as a result of PHPP/TAS feedback).

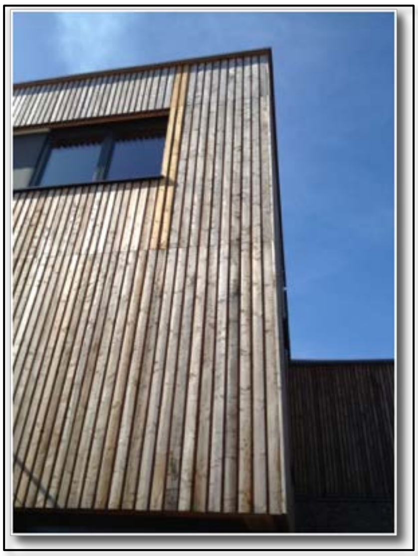
4.4 Quality Review[61]

The following items were noted as falling short of the general high standard of detailing and construction within the building. The items were identified and recorded during the site visit on 27th March 2012. Since that time these issues have largely been resolved.

Approach road
The finish to external hard surface in front of the house leads to dirt is being brought in with visitors. The occupant is intending to re-surface the approach road.

Kitchen sliding door
The mechanism appears to be damaged and there have been issues with water leakage below the door.

Cladding adjacent to damaged blind
Cladding to the right of the window was removed to allow access to remove damaged blind however the cladding boards were then lost and the replacements are the incorrect size and differentially weathered.



Caithness slate to outside terrace
The slate to the external terrace has not been grouted and is collecting debris and is hard to clean.

[61] Appendix 10: Initial Review Task Report 6b Construction Review

Roof Drains

There was evidence of staining resulting from the overflow from the balcony discharging down the stone wall, onto the paving below. The occupants also had good reason to be disappointed with the appearance of the overflow, which was a late addition to deal with water pooling on one of the balconies. Remedial work was undertaken to provide a more attractive finish combining a rain chain and slate sculpture.

Balcony Fall to Drain

There is standing water underneath the decking on both balconies. The flat roofs forming the balconies do not appear to fall correctly towards the drain.

Exposed Brettstapel finish

The occupants are disappointed that the exposed Brettstapel has been discoloured in the atrium space, due to the application of a fire retardant treatment, which appears unsuitable for use on sanded surfaces. The application of the treatment ceased after this space due to the discolouration issue so does not affect any of the other rooms. The discolouration has since lightened significantly and the client has stated that they are now happy with the finished appearance.

Slate to Dining Room / kitchen floor

The occupant has raised a concern that the slate used in the dining room is not easy to clean. The slate is not sealed and the occupant has reported that foods with a fat content such as biscuit and breadcrumbs leave a mark on the floor that requires cleaning, rather than simply sweeping up. The occupiers have put down carpet tiles to ease the cleaning requirement.

Conclusion and Key Findings

The occupiers like the passive nature of the property. They note that the two technical systems in the property, the solar hot water heating and the lighting controls, are the two systems that they are having trouble with.

4.5 Dwelling Operation and Usage Patterns

4.5.1 Domestic Hot Water System

The control for the domestic hot water return pump is a relatively simple time clock.

The solar hot water heating system did not operate correctly for a considerable time. A concern was raised during the early monitoring period that the system might be piped incorrectly. Issues experienced include:

- The circulation pump between the cylinder and the panels not turning on;
- A leak in the pipework;
- Concern regarding potentially wasteful operation of the electric heating elements;
- A plastic drum collects the discharge from the safety valve.

The situation was not helped by there being no DHWS schematic available. The circulation pump was replaced but still failed to work correctly. Water circulated for a few seconds when the pump was enabled but then flow ceased (according to the flow indicator). The domestic hot water return system pump did not operate. The time clock did not start the pump. There was a fused connection unit (FCU) in the vicinity of the pump but it was unclear what this served. The manufacturer attended site but was not able to resolve the problem and could not provide a definitive answer as to the cause. The system was switched off due to concerns that it would otherwise overheat.

The occupants did not receive a satisfactory explanation as to how the system should be piped, how it operates and the cause of the problem they experienced. The occupiers referred to nobody being aware that the controller had a slot for an SD card for data downloading and cited this as further evidence that nobody knows how the system is intended to operate. The controller was installed in a location that makes it fiddly to put the SD card in and take it out again.

It also transpired that the system was not installed by an accredited Renewable Heat Incentive scheme installer and this raised concerns that the clients will not eligible for the financial returns when the system issues are resolved.

The issues with the DHW have since been resolved, the pump is working, and the piping issues to the cylinder have been resolved. As yet there is still no RHI accreditation.

4.5.2 Mechanical Ventilation Heat Recovery (MVHR)[62]

The occupiers are happy with their ability to control the MVHR and appeared to be self-taught from the O&M manuals. They programmed the speed function using the diagrams in the manual. They have not received instruction as to the impact of this on indoor air quality however did demonstrate outline knowledge of why they should do this. They also demonstrated an understanding of how the boost function - controlled through wall switches in the kitchen and in the bathrooms - work and why they should use it. They had acquired sets of replacement filters and had replaced the set that were provided at handover using the countdown clock on the controller as a guide. Access is good for filter replacement except that the occupiers cannot change the filter on the ceiling extract in the kitchen area. On visual inspection of the replaced dirty filters, the main sources of contamination appear to be flies. There was no obvious sign of dust from construction activities.

At the time of the walkthrough the manuals did not include the testing and commissioning records. An update of the manuals was proposed.

4.5.3 Grease Extract System at Induction Hob

The occupiers demonstrated the operation of the grease extract system provided for the induction hob. The system appears to extract successfully during cooking however there is concern about the location of the discharge air into the cupboard below the hob. The hob manufacturer informed the occupiers that this discharge would adversely affect the induction hob. As a result the occupiers have modified their eating habits to exclude greasy food.

4.5.4 Artificial Lighting Controls[63]

The controls for the lighting are perceived as being overly complex and inconsistent. The controllers are generally of the same design but operate in different ways. In some cases the “off” switch does not turn the lights off. The numbered “on” switch has to be used to switch the lights off!

The control for the lighting in the study did not work. After replacement it worked intermittently for a while but then stopped working again. It became abundantly clear that the system was faulty and not fit for purpose. The occupiers are aware of the need to keep the lighting switched off when not necessary and it seems as though a simple standard system would have been sufficient for their needs. The lighting was re-programmed and a booster installed and is now functioning.

---

[62] Appendix 10: Initial Review Task Report 12a comprises a review of the MVHR System Controls
[63] Appendix 5: Review of Systems -Task Report 12b comprises a review of the Lighting, Daylighting specification and calculation of Daylight Factors

Artificial Lighting Effect

The artificial lighting in some parts of the house is perceived as being “harsh”. Where this is the case they are typically not used and freestanding lamps are used instead. An example of this is in the living room

Lamp Replacement

Some lamps will be difficult to replace. The occupier has been advised that lamps should last for twenty years and so maybe this is not an issue. An area where lamps will be particularly difficult or hazardous to replace will be above the main first floor link bridge.

4.5.5 Exterior Blinds

At the time of the walkthrough there was a dispute regarding the installation of one of the external blinds for the master bedroom. The dispute was between the blind installer and the main contractor and related to damage incurred during the installation process. The absence of the blind means that direct sunlight is entering the bedroom early in the morning (5:00).

In the winter period the occupants welcome the beneficial solar heat gain. In order to achieve this they set the control of the external shades to manual. Now that the summer season is being entered the occupants intend to revert to automatic control.

The occupiers noted that two external rain cladding panels were removed from the cladding because of the issue with the blind. These panels were left in the garage of the property amongst what looked like construction waste and subsequently found their way into the wood burning stove. A temporary fix was provided with panels lighter in colour than neighbouring panels as they have not had the same time to age. The panels are also not as wide as the other adjacent boards and need to be replaced. The issue has been resolved with the assistance of a local blind installer.

4.5.6 Emergency Power

The property has been provided with back-up power through a standby generator, which worked well during two power cuts. The occupants do not know why the bio disc was not put onto the back-up power. The bio disc goes into alarm and the occupants are not sure if the quality of the water from the borehole is compromised.

4.5.7 Water Consumption

At the time of the walkthrough a water meter was due to be installed as a part of the monitoring equipment. It should be noted that the building has its own private water supply and is also not connected to the public sewerage system. It is not connected to the mains. And the council tax charge for the property will be reduced by approximately £900 per year. The private water supply is subject to annual testing for quality. This costs around £130.

4.6 Manuals and Correct Use of the Dwelling

The occupiers would have liked to have two levels of manuals. They feel that they would have benefited from a simplified user guide that covers the basics. Also they were unsure of the procedure for highlighting problems and how they are to get resolved. They are not sure how long it should take for faults to be rectified and would welcome more feedback on progress.

At the time of the walkthrough the faults and snagging issues experienced had not adversely affected the ability to live and enjoy the house. The lighting control issues they were dealing with through trial and error. The absence of lighting in the study was an annoyance but did not hinder the use of the space. The issue with the lighting became more difficult later on. The occupants were able to generate hot water but were concerned about the inefficiency and energy waste associated with the faulty solar panel installation.

5. Evaluation of guidance offered to the occupants and the physical handover process

5.1 Written Documentation

A bespoke written Building User Manual was created by Gaia Architects, in addition to O&M manuals produced by the services consultants, Mott MacDonald and handed over to the client after the commissioning that occurred in September 2011. [64]

The O&M manuals cover the following:

MVHR system; Bio-disk system; Wood burning stove; Drainage; Paint systems; Roof gullies and downpipes; Parapet flashings; Internal and external blinds; External cladding; Internal bridge and bedroom 2 glass; Bathrooms; Louvre; Floor and wall tiling.

They also have two other Manuals.

1. Plumbing: Rehau pipework; Andrews water heaters; Thermostatic mixing valves; Flow regulating valves; Thermostatic circulation valves.
2. Electrics: Switchgear; Wiring accessories; Light fittings; Philips Dynalite; Towel rails; Smoke detectors; Intruder alarm; Test results and circuit charts.

The client provided the following feedback on the O&M manuals in March 2014 -

> *"We don't recall anyone's formally running through its contents etc., though we were suffering from severe information overload at the time and could well have forgotten. We have referred to it since handover, especially the sections on the MVHR, the Bio disk, the stove, paint and tiling. The Operation and Maintenance Manual is quite easy to follow. We do however feel that we lack crucial information, notably on the operation/maintenance of the doors and windows (Sohm), on the construction/maintenance of the roof (IKO), and on the borehole/pump/filter (Holequest). "*

Gaia Research has reviewed The Building User Manual, also produced for the client at the handover stage, and note the following:

> The manual forms a clear guide to operation and maintenance of the major building components, and also the reasoning behind the choice of system/ materials. Looking critically at the usefulness and accessibility of the Building User Manual, it is generally very clear and logically set out - with sections covering; the basic principles behind the design decisions; contact details for suppliers/ consultants/ contractors; services; and PassivHaus information.

With very few exceptions (some final U value information is missing) the manual is comprehensive and has good relevance both now and in the future since it provides basic

[64] Appendix 8: Design and Handover Information containing the Building User Manual and EPC was created by Gaia Architects 2011

details on ongoing maintenance, as well as information on the operation of the system/ component throughout an annual cycle (particularly relevant to the heating/ ventilation section, where the system's operation varies through the year).

If anything, there is too much background information at the start of each section, before the technical/ maintenance information for the system/ component/ material is covered. This may be useful on certain sections, particularly in the future, where maintenance/ renewal of a system/ component/ material could compromise the operation of the building/ comfort of the user.

One example of this would be paint or plaster finishes, whereby it is essential that the "breathability" of the fabric is maintained in order to control moisture within the building and therefore it is crucial that the occupant doesn't compromise this with the application an incorrect paint/ plaster finish.

In addition, the contents page would benefit from being more comprehensive, such that specific sections of the manual (such as the section on artificial lighting) could be found easily, without first having to turn to the start of the "Services" section and having to leaf through to the correct sub-section.

The "services" section of the manual refers frequently to the O&M Manuals, copies of which are also in the occupants' possession, and relevant drawings are referenced for clarity.

5.2 Physical Handover Process

Due to extenuating circumstances[65], only one walkthrough was carried out, combining both the commissioning/ design team walk through with handover of the building to the client. Due to the fact that the building was not 100% complete at the date of this walkthrough, whilst practically complete from a contractual perspective, not all systems/ components were demonstrated during the walkthrough.

The M&E consultants noted that the following systems were demonstrated to the client on 20/09/11:

- Cold Water System
- Window Actuation
- Electrical Blinds
- Lighting Control
- Ventilation

Gaia Architects noted that the following systems from their specification were also demonstrated to the client on 20/09/11:

- External blinds
- Window actuators
- Timber louvers

[65] The project Mechanical Services Engineer died in an accident in late 2011.

- Door locks
- Windows
- How to remove debris from gutter outlets
- Man safe (roof fall arrest) system
- Klargester controls and alarm system

These systems were noted for demonstration at a later date, though there is no record of their subsequent formal demonstration occurring.

- Internal blinds
- Wood burning stove
- Sanitary ware
- W/C's
- Showers
- Baths
- Sinks
- Electric towel rails
- Accessing plumbing - hatches etc.

Due to the doubling up of the walkthrough, there may be some repetition of information between this section of the report, and section 4.

In addition to the main walkthrough, a semi-structured interview and walkthrough with the client was conducted in March 2012 to determine how well the building was operating and how well the occupants were coping with managing the systems within the dwelling. Since this largely concerns M&E components and systems, there is also some overlap with section 4, whereby the commissioning and handover of the same systems/components is discussed.

The client / occupant has provided the following feedback on the walkthrough and the general handover process -

> *"We definitely felt the process was rushed. There were of course extenuating circumstances for this. We didn't discover for some time that the doors and windows are designed to open by tilting inwards on a horizontal hinge as well as a vertical one. We were left with several questions for example, when the external door for the workshop developed a fault we didn't at first know whom to contact."*

In terms of the provision of a maintenance schedule, one wasn't provided and the client stated that they wished it had, and were intending to create their own, to bring all maintenance information together in one place.

In terms of aftercare / repairs the client made the following comments:

> *"Aftercare has been mixed. Arthur Hancock of Rodger Builders did well by us. On the other hand we had protracted problems with the lights (Philips) and the solar hot water system (Baxi). There was no formal system for logging problems. Response to maintenance issues has been reactive, except where we have a contract (Bio disk)."*

And in terms of predicted against real energy efficiency, the client stated that:

"The only guidance we were given on predicted energy use came as part of Baxi's simulation of the performance of the solar panels for heating our domestic hot water. The comparison between the simulated and actual data is as follows:

Source of heat	*Simulation (one year)*	*Actual (1/3/2013-28/2/2014)*
Heating element (kWh)	1265	2180
Solar energy from panels (kWh)	2114	2765
Total (kWh)	3379	4945

We seem to have been using about 70% more electricity than predicted by the simulation, even though our actual needs were as specified (one bath and one shower a day). The solar panels also appear to have generated more heat than predicted, although we aren't confident about the accuracy of the amount. (It depends, for example, on which fluid is in the system. We believe ours is Tyfocor.)"

5.3 Summary of findings and main conclusions

Extenuating circumstances meant that the handover process was not fully comprehensive. Whilst the written documentation provided was substantial and has proven useful for the client/ occupant in dealing with teething problems in the building's occupation, they would have benefited from having the documentation explained at the point of handover.

In terms of the physical handover process, combining the technical handover/commissioning with the client handover meant there was no opportunity for interactive demonstrations/ training for the occupants and as a result they have had to learn how to operate some aspects of the building themselves.

Problems with the solar water heating and lighting that required ongoing attention were particularly frustrating and ultimately their resolution was largely due to problem solving by the monitoring team.

Generally the approach to snagging and maintenance, and co-ordination of this, has been good on the part of the main contractor but less so from specialist mechanical and electrical suppliers.

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

6.1 Summary[66]

Winter Performance
In terms of humidity, Plummerswood scores the best amongst the comparable reference buildings. The property performs well when assessed for being either fresh or stuffy with the survey results showing the property to be of the freshest of the properties in the comparison. The property is also noted as being still rather than draughty. It may be the case that the basis of the question for Still/Draughty may not have been fully understood by the occupants. It is often the case there are occasionally unexpected results for individual questions during the assessment.

Summer Performance
The results for summer are similar to that in winter. The property performs particularly well for humidity, freshness and odour. As with winter, there is an anomaly in the results for the question relating to still/draughty.

Overall
The performance overall is at the top of the data range of comparable buildings.

6.2 Conclusions and key findings for this section

It is clear from the survey results that the building performs well from a comfort point of view. As Gaia take indoor environmental issues very seriously and have been involved in research and development of low allergy buildings and the use of hygroscopic and non-toxic materials this is to be anticipated. There is no perceived requirement for a different approach.

---

[66] Appendix 11 – BUS Survey

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

This section is covered by Appendix 12[67] which is a review undertaken into the following items:

- Review of systems specification;
- Review of maintenance requirements;
- Review of Installation and commissioning;
- Review of snagging items and latent defects;
- Review control strategy, existing metering, sub-metering and communications provision;

We have highlighted those issues that we considered worthy of further investigation.

The approach to conditioning the spaces was ‘eco-minimalist’. I.e., to make the building fabric as thermally optimised as possible and thereby to use mechanical services as supplements to mechanical systems rather than as replacements for them. The operational strategy for all the systems was to minimise the use of active systems to that necessary for a comfortable and healthy environment by passive means supplemented by solar blinds and opening windows that had automatic control with manual override and a wood burning stove, solar thermal.

The resulting minimal systems specification strategy appears to be justified with the following proviso’s:-

- The lighting control system is overcomplicated for the current occupants needs, and whether it is justified will be unknown until point of sale. This became clear at the commissioning stage but the clients were able to operate it. Significant problems did not arise until some time later. Changing some of the lamps may prove awkward.
- More care should have been taken with the appointment of the solar thermal installers and the fact that the installation fell short of the required standard should have been identified at commissioning.
- The Biodisk uses considerable energy, which is partly due to its remote location. An option appraisal, which took into account running costs would have ben useful.
- In retrospect it appears as if provision of trickle ventilation in addition to or instead of the MVHR might have been a viable option, although the clients are happy with the MVHR operating in minimalist mode and it remains unclear as to whether this would meet PassivHaus standard specification. In respect of maintenance the filters are a significant cost and better diagnostics are required to optimise their replacement.

Since they took residence there has been an ongoing dialogue between the occupants, the architects and the monitoring team. The clients have been very keen to ensure the house performs optimally, and willing to 'experiment' to achieve this. They provided a short but thorough overview of the management issues from their perspective and the latent issues

[67] Appendix 12: Task Report 4. Maintenance, Commissioning and Energy Use Review

since occupation. This has enabled an induction process to occur in respect of the building systems that has allowed the energy consumption to be reduced from very good levels at the onset of the study to extremely low consumption for regulated loads. This has been mostly due to the operation of the building in passive mode, i.e. utilising body heat and other incidental gains for passive heating.

The monitoring process and client feedback to the architects has highlighted weaknesses and opportunities for improving pre and post handover processes. Unfortunately the engineers for the project were not engaged in this process.

Snagging did take a long time in part due to the reluctance of some suppliers of skills and services to return to or visit the site. This is not an uncommon problem in the industry especially where projects are small and remote.

The clients have expressed some disquiet at the lack of response from some professionals at and following handover. However, they were also aware that the handover was complicated due to a death in the design team and were naturally prepared to exhibit patience in this regard. Notwithstanding this, requests from the clients for better handover information and a protocol for logging and addressing outstanding issues is well made and noted for future projects. Following an initial settling in period, the clients have expressed satisfaction with the building and the control of the various systems.

Other aspects are covered elsewhere in this and supplementary reports.

8 Other technical issues

8.1 Introduction

The building provides a good case study because it intentionally set out to fulfil the PassivHaus specification using MVHR complimented with opening windows and human controls.

This allowed comparisons of energy consumption and internal environmental conditions in MVHR mode with the house closed up but progressively reducing the ventilation rate and in natural ventilation mode with the MVHR off unless heating was required.

It provides an exemplar of off-site Brettstapel PassivHaus certified construction, which makes it innovative in numerous mutually reinforcing aspects.

The monitoring identified

- Excellent energy performance
- Good internal conditions
- Evidence of thermal and hygroscopic mass
- Few thermal bridges
- A minor degradation in airtightness at the end of the TSB period
- No problems with, or mention of, the Workshop, which doesn't have a direct air supply or any form of heating, being too cold
- No issues of airtightness on the curved bays in the Study or back bedroom despite this being the first time Sohm had done such a tight curve in Brettstapel
- Energy consumption from the bio-disk

8.2 Conclusion

All of the issues are described in other sections of the report and have been adequately resolved. There are no outstanding technical issues apparent and the occupants appear to be very happy with the building and its responsiveness to their dwelling patterns.

9. Key messages for the client, owner and occupier

9.1 Introduction

This section is intended to investigate the main findings and draw out the key messages for communication to the client / developer and the building owner / occupier. Specifically required are: a summary of points raised in discussion with team members; recommendations for improving pre and post handover processes; a summary of lessons learned: things to do, things to avoid, and things requiring further attention/study.

The clients are also the developers, the current owners and the occupiers. They are highly unlikely to develop another building. The value of recommendations to the client on "*pre and post handover processes; a summary of lessons learned: things to do, things to avoid, and things requiring further attention/study"* appears therefore to be of limited value to them. These matters appear to have a greater relevance to the design and delivery team and the wider industry.

9.2 Lessons learned

MVHR

The building uses much less energy than typical domestic developments. The most significant energy consumers of the building are electric resistance heating by the MVHR and hot water heating.

Disadvantages of MVHR include the lack of zonal control and inability to direct air to where it is needed depending upon the activities being undertaken. Plummerswood has particularly low air permeability. The MVHR system treats the whole house as a single zone and does not recognise that the house has varying occupancy profiles over the course of the day. The inevitable outcome is either too much energy consumption through over ventilation of under occupied rooms or poor air quality in particular rooms.

The experiments on the MVHR – with willing occupants - were a useful contribution to the knowledge on these issues. The energy consumption can be controlled by attention to detail and it is clear that the management of the MVHR is a significant contribution to delivering energy efficiencies.

It would appear from the tests undertaken that a similar energy and indoor air quality performance could be achieved using trickle ventilation, good quality passive design of fabric, heating and ventilation in combination with sensible operation. Through the study we have also seen the benefit of CO_2 Buffering by house volume, which involves opening up the volume of the house by leaving doors open between occupied rooms and non-occupied rooms. This approach, applied in the early design stages, offers significant potential benefits in houses if it is suitable to lifestyles and in larger buildings in particular provided that sound attenuation can be addressed.

They bring into question the current tendency towards mandatory requirement of MVHR in PassivHaus certified properties when occupants might be willing to have alternative forms of heating such as woodburning stoves or small wet or electric systems with local control. Given the rapid development of passive house certification with its dependence on MVHR which is expensive in energy and space and could also give rise to sources of pollution this would benefit from further investigation.

MVHR filters could be a significant element of the overall running cost and as of the date of writing no system is available to allow for notification of when filters need changing and thereby optimise the change period. This has been raised with the suppliers.

Controls
The lighting control system is unnecessarily complex for a domestic installation and combined with defects in the installation and lack of attention from service providers meant that without specialist input it might have been very difficult to resolve and potentially a health and safety risk. Future projects would seek to avoid this complexity unless specifically sought by the clients.

The client control of blinds, lighting is a significant element in energy reduction supporting the original design concept of incorporating human factors unless more advanced feedback controls are developed that incorporate internal temperature optimisation with potential solar gains.

Solar Technology
The solar hot water system reduces the electricity consumption for hot water production by around 50% in the spring and summer months when compared with winter. The installation was flawed, responsibilities blurred and the installers were not registered with the RHI Scheme which compounded the problems. The error resulted in 6 months of increased energy consumption. A key lesson learned from this study is that this type of error is easily possible in the construction of domestic properties, which rely on installations from local plumbers who are unlikely to have installed this type of technology previously. More scrutiny of any proposed installation would be undertaken in future projects to ensure adequate skills and registration were addressed.

Water Consumption
The water consumption is substantially lower than that of benchmark buildings. However, the building is off-grid and there is a localised energy penalty incurred to treat the borehole water and sewage. The bio disk is a substantial proportion of the overall electrical load. A review of sewage options would be undertaken on future projects to determine the best solution in the context with the aim to create improved efficiency without undermining environmental health or the local environment.

10. Wider Lessons

10.1 Introduction

This section is intended to summarise the wider lessons for the industry, including, but not limited to clients, other developers, funders, insurance bodies, skills and training groups, construction team, designers and supply chain members to improve their future approaches to this kind of development. It is intended to provide a detailed insight in to the emerging lessons. This section is also intended to include consideration of costs. It should cover potential improvements to the design process and improvements in the construction process.

The section should also cover lessons that have been learned that will benefit the participants' businesses in terms of innovation, efficiency or increased opportunities and how these lessons will be disseminated.

.

10.2 Emerging Lessons

Fabric First

The monitoring has demonstrated the robustness of the 'fabric first strategy' in terms of internal conditions and also energy efficiency.

The house is designed to optimise form and fabric control to minimise capital and running costs of mechanical services. Aspects of the approach have been examined.

(a) The house is orientated to have the main occupied spaces generally facing south and adequate and appropriately designed shading to optimise heat gains. We have demonstrated the efficacy of the shading provided by the balcony above the dining area and the external shading in terms of summer comfort and passive winter heating especially when properly managed by the occupants.

(b) The house is designed to allow for natural ventilation – with attention to cross ventilation and stack ventilation in all the major rooms - and we have identified that this approach is adequate for much of the year in part because it can be complimented by the thermal and moisture mass in the building and by a strategy of using the whole house as a CO_2 sink. Further research could be undertaken to determine whether this approach in combination with designed and appropriately operated trickle ventilation might be adequate for a passive building to operate without the requirement for MVHR.

(c) The house is designed to incorporate hygroscopic mass to minimise humidity fluctuations & improve indoor climate. We have demonstrated the efficacy of this approach in providing ideal humidity conditions.

(d) The house is designed to minimise requirement of artificial lighting. We have demonstrated the efficacy of the approach in a situation where the owners are diligent in not using electricity unnecessarily and hence the lighting energy consumption is small.

(e) The biggest problems with the project revolved around the solar hot water system and the lighting systems. In addition the energy consumption of the MVHR was a cause for concern. This tends to reinforce the original aspiration to make the building as passive as possible and with as few technical systems as possible.

i. Solar thermal energy was designed in to contribute to the DHW demand. We have identified that it contributes around 50% of the demand and also shown that comparable contribution from pv's would be unreasonably expensive.
ii. The solar hot water system was wrongly installed by a company not registered for the RHI. The response of some consultants was slow and responsibilities blurred. This led to problems with the panels overheating but under-performing in terms of hot water delivery. Ultimately the problem with the installation was identified by the monitoring team and resolved by them. The RHI issue remains unresolved.
iii. The lighting system did fail and eventually the monitoring team undertook to appraise and fix the fault, which proved to be a design rather than a commissioning fault.

In many respects the problems that did occur were slow to resolve because of the rural location of the building and the reluctance of the various bodies to travel to it.

Cost

In respect of costs the major issue appears to be a need to better understand the benefits of MVHR over NV in a variety of conditions, taking account of the MVHR design including frost protection, climate, client needs, requirements and aspirations and client intervention.
The building intentionally set out to achieve PassivHaus certification with the use of a MVHR system complimented with opening windows. This allowed comparisons of energy consumption and internal environmental conditions in MVHR mode with the house closed up but progressively reducing the ventilation rate and in natural ventilation mode with the MVHR off unless heating was required.

The monitoring of Plummerswood bring into question the extent to which MVHR offers an optimised approach to building design in respect of cost and environmental impact. It indicates that the use of MVHR can differ little from that for trickle ventilation and given the cost of installation and management implications this is an important finding. It may well be possible to consider cost saving of leaving out the MVHR in some circumstances especially where as at Plummerswood there is no off gassing from the internal materials. In other respects quality was a driver for the project and the client was not willing to sacrifice this.

Brettstapel

The project provides an exemplar of off-site Brettstapel PassivHaus certified construction and offers opportunity to embed learning and build capacity for design/construction and manufacturing of mass timber. The design team preferred option was to utilise local timber however the use of Austrian timber and manufacturing in order to demonstrate the technique was shown to have no significant detrimental effect in terms of total carbon sequestration.

The use of Brettstapel at Acharacle Primary School in 2009 and Plummerswood in 2010 was based on a number of factors, including ecological impact, known non-toxicity, hygrothermal performance, acoustic performance, speed of erection, embodied energy and sequestration of carbon dioxide. Since their construction there appears to be have been limited interest in

the development of this form of construction in the UK compared to other European countries in the same time period.
The benefits it offers of intrinsic high fabric standard, rapid construction times and healthy indoor climate seem to be less attractive to the market than in other countries.

For further details of potential benefits refer to **http://www.brettstapel.org.uk** and **www.brettstapel.org**.

Only one building has been built from UK sourced Brettstapel since Plummerswood. This is an extension to a visitor centre in north Wales designed by Archetype Architects and built by a local contractor from Welsh timber. The project used Brettstapel for floor, wall and roof panels with timber sourced from and processed within 50 miles of the site. The contractor for this project, Williams Homes, Bala, is very keen to use this type of construction on other projects.

Napier University, through their Wood Products Innovation Gateway ('WoodPIG') programme (which ran from 2011-2014) have had small samples of Brettstapel manufactured from Scottish timber, which have been subjected to both fire and structural trials. The purpose of these has been to determine the suitability, and develop understanding of, Scottish timber for use in Brettstapel. As Brettstapel is a composite structural element that does not rely on any individual component having a particular degree of strength, the trials have (perhaps unsurprisingly) concluded that Scottish timber is suitable for use in Brettstapel.

Napier University have worked with a small number of Scottish businesses to fabricate these Brettstapel test panels including Makar (based near Inverness) and Living Solutions (based in Cowdenbeath, Fife). Both businesses used basic agricultural engineering technology to create jigs into which lamellae could be clamped, holes drilled and dowels inserted. Despite this work there are currently no businesses in Scotland commercially manufacturing Brettstapel.

Another business, InWood, based in Lewes, Sussex, have also begun to commercially fabricate Brettstapel from Corsican Pine grown locally to their factory.

As part of the WoodPIG project Napier initiated a 'Brettstapel Research Network' in 2011; a group of people from across the UK with interest in, and experience of, designing and building with Brettstapel made from home-grown timber. This included architects, engineers, wood scientists and builders. Unfortunately it does not seem to have had any real impact on bringing Brettstapel to a commercial market in the UK, least of all the UK. (Neither Williams Homes nor InWood were part of the Network.)

Despite both Plummerswood and the school at Acharacle both winning various architectural, technical and wood-related awards there is a clear lack of marketing and promotion of Brettstapel as a construction product in the UK, which undoubtedly goes some way to explaining the apparent dearth in the use of this material.

Specifically in relation to the house at Plummerswood the use of Brettstapel met the client's requirements for a house with: a lifespan equivalent to the Victorian stone house from which they were moving; a very healthy indoor environment; very low running costs and a feeling of solidity rarely found in new construction.

The supplier of the Brettstapel, Sohm Holzbautechnik GesmbH from Austria, also took responsibility for erecting the prefabricated, pre-insulated wall, floor and roof panels; their previous experience of building Brettstapel buildings to achieve the PassivHaus standard of energy efficiency giving both client and architects confidence in their abilities.

The use of Brettstapel allowed for an off site construction process that was suitable for current and future needs and could provide a basis of local manufacturing and development The only issues that arose from the use of Brettstapel were due to minor confusion and breakdowns in communications due to the language barrier. There was very little that needed be done to improve the process.

Benefit to participants

Participation in the monitoring was limited to the project clients, architects and Quantity Surveyor in part due to the untimely death of the project engineer. However, the involvement of an independent engineer in the monitoring of the design and delivery of the building has been advantageous in providing an independent view.

The period of monitoring has been a difficult one for the lead partner, Gaia Research, and at this stage it is unclear what benefit to future business can be realised. Avenues have been investigated for Brettstapel projects and there is enthusiasm to pursue local manufacture in Scotland but this is likely to put Gaia in the role of catalyst rather than in developing a business opportunity.

Arup Scotland intend to develop the techniques of modelling hygroscopic mass as part of their overall modelling capability.

Dissemination

The messages in this report will be disseminated through a range of media including professional, sector and academic conferences.

10.3 Conclusion

In conclusion, a highly successful project largely due to the healthy and warm relationship between the clients, the architects and the monitoring team.

The building meets its objectives and the monitoring and attitude of the monitoring were important in enabling problems to be resolved. The BPE process was very tiresome and undermined much of the delight of research through over bureaucratisation, poor briefing, badly prepared, poorly drafted, documentation and impenetrable software. Much of which appears still unresolved. Being granted the contract The guidance on drafting sections 7, 8, 9 and 10 of this report exemplify the source of frustration.

List of Images

List of Graphs

List of Tables

11. Appendices

Study Requirements Mapping

The mandatory requirements of the study are included in this final report and its appendices.

Tasks	Final Report Section	Appendices
Design and Construction Audit, drawings and SAP calculation review	Section 2 & 4	Appendix 9
qualitative semi-structured interviews and walkthroughs with occupants	Section 4	Appendix 10
qualitative semi-structured interviews and walkthough with the design team to explore design intentions compared with final performance	Section 4	Appendix 10
photographic survey	throughout	Appendix 7
Fabric testing	Section 3	Appendix 7
Thermography	3.2	Appendix 7e
In situ u-value measurement	3.3	Appendix 7f
Air permeability testing at the beginning of the monitoring period and towards the end of the monitoring period	3.1	Appendix 7b & c & d
Occupant satisfaction		
Evaluation of handover process and guidance provided to occupants	Section 5	Appendix 8 & 10
Occupant BUS survey using standardised housing questionnaire	Section 6	Appendix 11
Review of Systems design and Implementation including installation and commissioning checks of all services and systems	Section 7	Appendix 5 & 12
Comparison of Predicted Performance with actual performance and interpretation of findings	throughout	Appendix 2, 3,4 & throughout

Appendix 1: Updated Review of Research developments and Practical Activity in UK Brettstapel Manufacture

Appendix 2: Results of the DOMEARM 2012/13

Appendix 3: Environmental Monitoring

- Quarter 5 Report: Section 2.3.2 Improvement in Energy Use
- Quarter 6 Report: Section 3
- Quarter 7 Report: Section 4.2

Appendix 4: Environmental Reports

Quarter Report 3
Quarter Report 4
Task Report 16: Hygroscopic mass
Task Report 17: Temperatures
Task Report 40: Moisture Buffering

Appendix 5: Review of Systems

- Task Report 13: Review of MVHR Operation and Comparison with Natural Ventilation
- Task Report 15: Review of Solar Energy Impact on Building
- Task Report 12b: Review of Lighting and Daylighting Specification. Calculation of Daylight Factors

Appendix 6: Design Progression

- 6a. Report on Drivers for Commitment to Sustainability, and Consultants' Roles in achieving this – Gaia Architects December 2006
- 6b. *Wind and Shadow Analyses* – Fulcrum Consulting - 9th Feb 2007
- 6c. Task report 6c – Realisation Process from Inception to Initial Occupation
- 6d. Stage C Design Report - Engineering Services
- 6e. *Winter Temperatures* - Fulcrum Consulting 10th Feb 2009
- 6f. *Summer Overheating Analysis* – Fulcrum Consulting

Appendix 7 Fabric Testing

- 7a. RMP Airtightness Test Report December 2010
- 7b. Gaia ALDAS Airtightness Test Report February 2012
- 7c. Jennings ALDAS Airtightness Test Report - August 2013
- 7d. Discrepancies in Air Leakage tests
- 7e. Thermal Imaging Report
- 7f. Heat flux Test

Appendix 8. Design and Handover Information containing the Building User Manual and EPC - Gaia Architects 2011

Appendix 9 SAP Review

Task Report 6a Design & Constr Audit
SAP Calculation Review and updated SAP

Appendix 10. Initial Review

- Task Report 7a Interview with Client
- Task Report 6b Construction Review
- Task Report 12a MVHR System Controls
- Task Report 7b. Review of supply chain, specification and contractual issues

Appendix 11. BUS Survey

Appendix 12. Task Report 4. Maintenance, Commissioning and Energy Use Review