University of Strathclyde Engineering

Department of Mechanical and Aerospace Engineering

To analyse the operational performance of the mechanical systems incorporated into a Passive House located in Scotland.

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Graham Henry Date: 05/09/14

Abstract

This project assesses the operational performance of three individual mechanical systems incorporated into a passive house in order to achieve thermal comfort. A passive house is any building built to a specific, stringent set of building standards to promote an outstanding level of energy efficiency. The case study under investigation was the UK’s first affordable passive house and is located in Dunoon, Scotland.

The operational performance was assessed with regards to running costs, primary energy consumption, thermal supply/demand matching and the thermal comfort experienced by the occupants. Different objectives for each individual system were designed in order to meet this main project aim. These systems being: a solar thermal hot water (*STHW*) system, a mechanical ventilation heat recovery (*MVHR*) system and an air source heat pump (*ASHP*) system. A general methodology for monitoring, testing and analysis was developed for the project which can now be adapted to any other similar building and systems. A short period of telemetry monitoring and on-site testing of the equipment and passive house was carried out in conjunction with interviews with the main occupant and research into passive house design practice.

From this, it is shown that the original *Passive House Planning Package* (*PHPP*) design tools can lack accuracy. Secondly, the report outlines how the building is operating better now than when it was originally constructed and commissioned. From the analysis, recommendations to further improve the *STHW*, *MVHR* and *ASHP*’s operational performance have been outlined. An example being that the 97% predicted hot water contribution from solar thermal in June at the design stage is optimistic as the system presently achieves 43%. A change in control logic outlined has proven that this could realistically be raised to 71%. The *MVHR* unit is operating above the *PHPP* outlined temperature transfer efficiency minimum of 75% but below the manufacturer’s quoted 91%. The project highlights why the *ASHP* should never be used to meet cooling loads and operates at a high COP of 3.49 during testing in heating mode. This thesis is fundamentally a detailed examination of a lived-in passive house’s performance in contrast to design and manufacturer’s predictions.

Acknowledgements

I would like to take this opportunity to thank a number of people who have been involved in this project and provided guidance and assistance along the way. It was very much appreciated. Firstly, I would like to thank Dr. Jeremy Cockroft for acting as my thesis supervisor and initially providing me the opportunity to undertake this project. I would also like to thank his fellow colleagues at *ESRU*, Dr. Paul Strachan and Dr. Paul Tuohy who provided valuable information regarding the project and enhanced my knowledge of *Sustainable Engineerin*g throughout my masters course at the *University of Strathclyde*.

Furthermore, I must thank all the staff at the *Glasgow School of Ar*t with whom I collaborated on this project with. The time and resources they exerted on this project is what made it possible. A special mention goes to Dr. Filbert Musau and Janice Foster.

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1. Project Outline

1.1. Aim and Objectives

The aim of the project is to assess the operational performance of each individual system within a newly certified (2012) passive house located in Dunoon, Scotland. There are three mechanical thermal systems incorporated into the passive house's design and construction. These are a solar thermal hot water (*STHW*) system, a mechanical ventilation heat recovery (*MVHR*) system and an air-source heat pump (*ASHP*). This will be achieved through predominantly through on-site testing and non-invasive monitoring over a relatively short time period.

This operational performance relates to all aspects of performance, including: operational running costs, primary energy consumption, thermal supply/demand matching, internal thermal comfort and the occupant's experience with the systems and resulting living experience. This project consisted of a detailed monitoring process via data logging of multiple built environment conditions for a short period of 8 full days and a stringent system testing process. The focus of the project was predominantly the three mechanical systems installed into the house in order to provide the occupant with a comfortable living environment and in order to meet space heating, cooling, ventilation and hot water (*HW*) demands. Previous studies on the Dunoon passive house shall be scrutinised with the impacts of their recommendations and system improvements examined. Further faults shall be highlighted and recommendations to improve the overall performance of the house shall be made. The individual system objectives are outlined in further detail below;

Solar Thermal Hot Water System:

The *STHW* system as a whole is designed to meet 100% of the house's hot water demand, with the *Passive House Planning Package* (*PHPP*) for this specific home stating that 55% of the annual *HW* contribution will met by solar irradiance. It must be noted that this prediction most likely came from the independent design team as the *PHPP* does not typically make such predictions for *STHW* systems. The remaining 45% contribution is to be met via the supplementary electrically driven immersion heater within the thermal store. Numerous objectives for the *STHW* system were outlined in order to meet the overall project aim. These are as follows;

1. To analyse the current operational performance of the *STHW* system by comparing periods of high and low solar irradiance levels. The relationship between the immersion heater and solar thermal pump controls are to be assessed. To analyse and discuss all aspects of current performance and determine if the 55% design prediction is realistic on-site.

2. To examine and recommend new practical and ideal control logic to improve the current system's performance.

3. To analyse the current risk of legionella within the system and recommend risk prevention methods.

Mechanical Ventilation Heat Recovery System:

The *MVHR* system has been incorporated into the passive house design in order to aide in the meeting of space cooling and heating demands and provide sufficient fresh air to the occupants. Numerous objectives have been outlined in order to determine the systems current operational performance, with present flaws in design, commissioning and operation to be highlighted and recommendations made. These objectives are as follows;

1. To compare the system's thermal performance with that of the *PHPP* building design and manufacturer's quoted data.

2. To analyse the system's Coefficient of Performance (*COP*) and running costs.

3. To analyse the risk of the overheating within the passive house during summer operation.

4. To investigate the *MVHR*'s ability to aide in meeting the space heating and cooling demands and supply each room with the adequate level of fresh air.

Air Source Heat Pump

The *ASHP*'s main function within the Dunoon passive house is to meet the winter condition's space heating loads. It also incorporates a cooling function in summer but this is rarely required due to the operation of the *MVHR* system and manually assisted natural ventilation. Due to the function of the *ASHP* and climatic conditions during the project timeline, monitoring over a long period of time was not possible. Instead, testing of the equipment was performed. This testing was carried out in order to meet the following objectives;

1. To determine the operational *COP* of the *ASHP* in heating and cooling operation and compare this with the manufacturer's data and *PHPP* design criteria. This may be done under simulated environmental conditions.

2. To analyse the heat distribution and load matching ability of the system in conjunction with the operation of the *MVHR* system during both winter and summer environmental conditions.

2. Methodology

A project methodology was contrived with the intent of meeting the main project aim and multiple objectives outlined previously. A strategy of non-invasive monitoring of the passive house's mechanical systems and built environment was developed. Telemetry monitoring was going to be carried out for a period of between one and two weeks (resulted in 8 full days).

The project was limited to non-invasive monitoring techniques in order to reduce the impact to the occupants. They have tolerated numerous monitoring and tests in the past under this one strict condition. These techniques also helped minimise the project costs. The timescale itself was also limited. This was restricted to summer monitoring and testing. This had to be carried out at times of availability of the *Glasgow School of Art* (*GSA*) staff, homeowner and required electrician. The Masters course also had a strict project timeline.

The project was undertaken in collaboration with the *GSA*, whose *Mackintosh Environmental Research Unit* (*MEARU*) had a keen interest in the design and operation of Scotland's first certified passive house. The *GSA* contributed valuable time and resources such as additional monitoring equipment. The project was limited in location to the Dunoon passive house. This was due to a number of reasons. Firstly, the interesting and innovative design and operation made it an ideal test case. Secondly, follow-up monitoring and testing was required following the multiple previous studies undertaken on the site. Additionally, the homeowner was accommodating and it was within close proximity to the *GSA* and *University of Strathclyde*. However, it is important to note that this methodology may be adapted to other sites. The monitoring and tests outlined can easily be carried out on similar mechanical systems. Once the data has been successfully obtained, similar analysis may be performed in order to determine a building and accompanying systems operational performance.

2.1. Equipment

Eltek telemetry monitoring equipment was used to obtain the required data from the passive house. This system used a series of transmitters to record measurements from the mechanical systems and built environment and send them to a data receiver located within the house. This data was then stored for the project time period and obtained using a direct serial link with a laptop when the metering finished. A basic schematic of the process is shown below for clarity;

Figure 1: Eltek Monitoring Equipment. [Source: Eltek. (2014)]

The actual equipment set-up may be viewed from the images below;

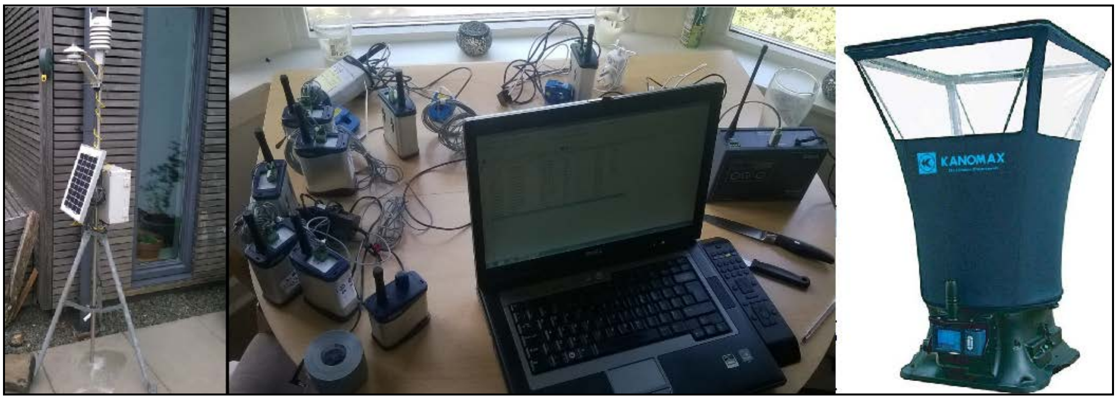

Figure 2: Dunoon Equipment. [Sources: www.calright.com]

2.2. Data Logging

This equipment, consisting of a weather station, temperature sensors, amp-meters and anemometer was used in conjunction with the *Eltek* software equipment was used to meet the project aim. For ease of examination, the monitoring set-up for each individual system has been tabulated as follows;

STHW System:

Location	Measurement	Unit
Outdoor Weather Station	External Temperature	°C
Outdoor Weather Station	External Solar Irradiation Level	W/m^2
STHW Store	Top of the Tank Temperature	°C
STHW Store	Cold Water Tank Feed Temperature	°C
STHW Store	Hot Water Tank Supply Temperature	°C
STHW Store	Solar System Water Flow Temperature	°C
STHW Store	Solar System Water Return Temperature	°C
Main Circuit Board	Solar Panel Controls and Pump Electrical Consumption	A
Main Circuit Board	Immersion Heater Electrical Consumption	A

Table 1: *STHW* Monitoring Set-up

MVHR System:

Location	Measurement	Unit
Outdoor Weather Station	External Temperature	°C
MVHR Unit	Supply to Grilles Temperature	°C
MVHR Unit	Extract from Grilles Temperature	°C
MVHR Unit	Exhaust Temperature	°C
MVHR Unit	Fresh Air Intake Temperature	°C
Living Room	Space Temperature	°C
Kitchen	Space Temperature	°C
Downstairs Hallway	Space Temperature	°C
Master Bedroom	Space Temperature	°C
Bedroom 2	Space Temperature	°C
Main Circuit Board	*MVHR* Electrical Consumption	A

Table 2: *MVHR* Monitoring Set-up

The anemometer was also used in order to obtain the operation volume flow rates of the *MVHR* unit. Both supply and extract rates of each room were measured instantaneously under test conditions.

ASHP System:

Location	Measurement	Unit
Outdoor Weather Station	External Temperature	°C
ASHP Unit	Supply Temperature x 2	°C
Living Room	Space Temperature	°C
Kitchen	Space Temperature	°C
Downstairs Hallway	Space Temperature	°C
Master Bedroom	Space Temperature	°C
Bedroom 2	Space Temperature	°C
MVHR Unit	Supply to Grilles Temperature	°C
MVHR Unit	Extract from Grilles Temperature	°C
Main Circuit Board	*ASHP* Electrical Consumption	A

Table 3: *ASHP* Monitoring Set-up

In addition to this, to meet the *ASHP* objectives the anemometer was to be used to measure the unit's volume flow rate of supply air under test conditions. Also, it must be noted that two *ASHP* supply temperatures were taken for accuracy as the manufacturer's guide indicated the impact the guide vanes have on heat distribution into the space. Hence, a mean temperature was used for purposes of accuracy.

For the monitoring period, a data logging interval of 5 minutes was set up for each individual piece of monitoring equipment. Monitoring for a 8 full days was achieved resulting in over 48,000 successful and relevant data entries.

2.3. Data Analysis

The *Eltek* equipment comes with a set of programmes (*DARCA*) for set-up, downloading and analysing the data obtained by the receiver. All of these programmes were used in detail apart from the *DARCA* analysis tool. Instead, it was decided to export the data into an *Excel* file. It was found this this gave more freedom to graphically and statistically analyse and display the data. Detailed analysis was performed in order to meet the project aim and objectives.

3. Background Research

3.1. Introduction to Passive House Construction

A passive house is any building built to a specific, stringent set of building standards to promote an outstanding level of energy efficiency. It is a voluntary construction standard. The building standards are outlined by the *Passivhaus Institut*, an independent research institute led by the renowned Dr. Wolfgang Feist. This is the only internationally recognised, performance based energy standards in the construction of passive house certified buildings. Studies indicate that passive house standards enable energy savings of up to 90% in comparison to existing, similar building types and over 75% compared to new builds built to satisfy current building regulations. [Passipedia. (2014)]

There are over 30,000 passive house constructions worldwide with more than 4,000 certified passive house experts [Passivhaus Trust (2014)]. In 2014, the world's first passive house supermarket has been certified in Hanover, Germany. This was built as part of a pioneering zero emission residential area known as '*zero: e park*'. In 2013, the world's first passive house office tower was certified by the institute, the '*RHW.2*' tower in Vienna, Austria. This incorporated a large photo-voltaic system combined with a tri-generation power system to meet the heating, cooling and electrical load in a highly energy efficient manner. Other innovative features included supplementary cooling in conjunction with a nearby canal, an intelligent building façade and waste heat recovery from the data centre. This level of innovation is not required for standard small-scale passive house building design but highlighting these showpiece cases indicates the potential within the construction industry.

Figure 3: Passive House Buildings.[Source: passivehouse.ca, farm6.staticflickr.com, wilderutopia.com]

Within the UK building industry, passive house construction uptake has been slow. By 2013, there were only 250 completed and certified passive house buildings in operation. Yet, in 2012 there were over 145,000 permanent dwellings completed by tenure. In 2013, that figure was over 135,000 [UK Government. (2014)]. Clearly, passive house construction is far from the norm. With the modification of the *European Building Directive* the path to zero-carbon buildings has been defined, with three aspects being the focus. Firstly, new buildings should have a high energy performance. Secondly, the remaining very low energy demand should be met using a significant share of renewable technologies. Thirdly, cost-optimal levels for minimum energy performance are requested [F.Ochs et al (2014)]. Passive houses meet the first two demands perfectly, yet cost effectiveness is still and issue with their construction. The UK government had a legal obligation to take this directive on-board, hence the announcement of a zero-carbon housing requirement for new builds by 2016. However, this policy has been watered down with regards to energy efficiency and consumption targets for buildings. This has been done through the addition of ‘A*llowable solutions*’ to building design into legislation whereby it is technically difficult to meet the performance criteria [J. Grant (2013)]. These exemptions are expected to be wide scale.

3.2. Passive House Design Criteria

The *Passivhaus Institut* (*PHI*) was conceived following the first passive house pilot project built in Darmstadt, Germany in 1990. This was a fully functioning family home. The *PHI*'s primary aim is to deliver energy efficient, comfortable and affordable buildings. In order to achieve *PHI* certification, all of the following building criteria must be met;

Passive House Criteria	Maximum Allowable Value	Units
Specific Heating Demand	15	kWh/m^2 per year
Specific Cooling Demand	15	kWh/m^2 per year
Specific Primary Energy Demand	120	kWh/m^2 per year
Summer Overheating	10% over 25°C	°C
External Envelope Opaque Component U-Value	0.15	W/m^2K
Glazing and Doors U-Value	0.8	W/m^2K
Airtightness	0.6 @ 50Pa	Ach^{-1}
MVHR Thermal Efficiency	≥75	%
Ventilation Electricity Demand	0.45	Wh/m^3

Table 4: Passive House Criteria

The *PHI* outlined five key principles for achieving the defined criteria. These are the following;

1) Building design should be free of thermal bridges where possible.
2) Superior glazing must be used in order to maximise the use of solar gains and natural daylight. They must also minimise heat losses.
3) A mechanical ventilation system must be incorporated with heat recovery.
4) High quality and quantities of thermal insulation must be included in building design.
5) The construction must be close to airtight. Controlling air changes to approximately $0.4Ach^{-1}$ is considered ideal.

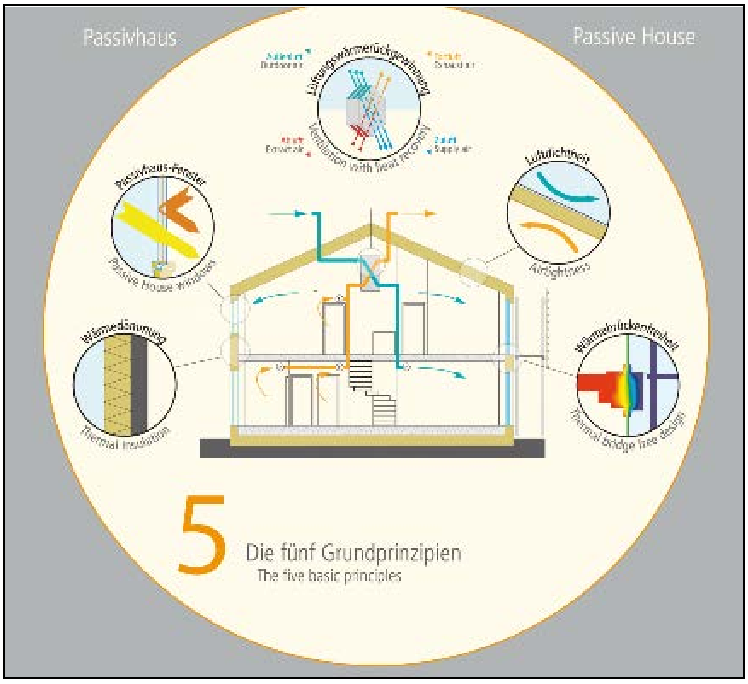

Figure 4: Passive House Design Diagram.[Source: Passipedia. (2014)]

To supplement these principles, the *PHI* recommends further intelligent design steps. These include making extensive use of intrinsic heat from internal sources such as waste heat from lighting and appliances. Active daylighting techniques along with ‘*smart*’ electric lighting are promoted. The *PHI* also recommends the integration of heat pumps, direct solar thermal and geothermal solar systems where energy and economically viable. It should be noted that these are not mandatory for certification. Once designed and constructed, the building must undergo a rigorous testing process prior to gaining the institute’s accreditation.

3.3. Passive House Planning Package

In order to aid with the design of passive house buildings, the *PHI* has developed independent software tools for dynamic building simulation. These determine the required design energy balances and planning process for passive house construction. The algorithms and corresponding software are constantly developed and upgraded based on the monitoring of existing buildings. These have been predominantly researched and developed by the culmination of the work done by Dr. Bo Adamson of Sweden and Dr. Wolfgang Feist of Germany who are leading experts in the specific field [W. Lamond (2011)]. The *PHI* offers the design tools as a package known as the *Passive House Planning Package* (*PHPP*). The Dunoon, Scotland house analysed in this project was designed using a unique *PHPP*.

Like all building modelling design tools, their accuracy from the design stage to actual building performance on site is varied. The accuracy of predictions and the capability of the construction industry to deliver those predictions is often largely an unknown science. Comparative studies between the *PHPP*, *SAP*, *BIM* and *IDEAS* methodologies to determine the correlation between them all and strength and weaknesses of the varied methods has been examined in detail in the past. To date, there is no unified way to predict a buildings performance with near perfect accuracy from the design phase to its built operation. The quantities of dynamic parameters determining a building’s services operations are vast. An example of one flaw with the *PHPP* design tool is that only single values are used for the monthly temperatures and hours of sunshine. The input values are just taken as monthly averages. Furthermore, the climate file location is often flawed, with only a small number of climate files available for the UK. For the Dunoon, Scotland passive house that this project centres on a climate file for Sheffield, England was used to generate the *PHPP*. This leads to a very generalised and inaccurate method of determining the buildings response to external environmental conditions and sizing of mechanical system. This issue is examined throughout this project.

3.4. Barriers to Passive House Expansion

Although zero-carbon new builds are being encouraged through government legislation, widespread passive housing growth has yet to happen. At present, the prominent current building trend is to radically reduce space heating through improved thermal performance [L.Georges et al (2012)]. This is largely done through increased level of insulation thickness and quality. The reduced heating demand is then met using highly efficient heating systems, typically via condensing gas boilers. The high level of additional investment required to meet the passive house criteria is often considered not to be the global economic *optimum* design strategy.

Studies undertaken by *Audenaert et al.(2008)* compared break even times for costs of passive houses and low energy conventional housing as alternatives to standard conventional housing. Their modelling, based on *Energy Performance Ratings*, indicated that low energy conventional housing broke even earliest. *Mahdavi and Doppelbauer (2010)* conducted a similar analysis based on actual monitored data resulting in the same conclusion. However, this study only used 5 months of data and was not fully transparent. Numerous European studies have established that low energy conventional housing represents an '*economic optimum*' [R. Galvin, (2014)]. Severe assumptions are required in order to make passive house construction compete in the market. Studies conclude that passive houses would require either significant financial incentives or a lower discount rate combined with a high increase in future fuel prices in order to compete and provide an *optimal* return on investment. However, passive house buildings offer inspiration and are landmarks in what can be achieved through low-carbon design even if they are at times just showpiece or marquee projects.

4. The Dunoon Passive House

The passive house at the centre of this study is one located in Dunoon, Scotland. Dunoon is situated on the Cowal Peninsula in the Argyll and Bute council. It sits on Firth of the Clyde to the west of Gourock, Scotland. This location ensures a maritime and temperature climate. This offers cool summers and mild winters. The average January minimum temperature is 1.8°C with the average July maximum being 18.5°C over a 20 year range. This must be considered ideal for passive house design. It is an exceptionally wet part of the UK.

Figure 5: Location of the passive House. [Source: Google Maps, e-architect.co.uk]

The passive house itself was completed in October 2010 by the construction company *Fyne Homes*. It is a two-storey, two-bedroom, semi-detached family home built as part of a development of 15 low energy homes for first time buyers. It was built on a council owned site as part of an affordable housing initiative. A single passive house was included by the architects as the project's showpiece. An additional 15% of funding for the passive house over the high efficiency conventional housing was required. It was the first certified passive house in Scotland. In 2011, the house won the '*First affordable Passivhaus for the UK*' award from the *Royal Institute of Architects* [Architecture & DesignScotland (2011)].

4.1. The Dunoon Passive House's Design

The Dunoon passive house became certified by the *PHI* in 2012, over one year after opening. All *PHI* design and operation criteria were met for the first time by a house located in Scotland, apart from the specific heating demand. This was marginally over yet was given an exemption due to the location and the fact that no mechanical cooling would be required due to the design of the *MVHR*. The total primary energy demand for the home was still far below the tolerated 120kWhrs/m^2 per year limit. To aide in ensuring this low level of demand, the house was fitted with low energy appliance such as the fridge and cooker and *LED* lighting. Two south facing and one north facing skylights were also integrated into the architectural design to provide daylight and additional manual ventilation if the occupant desired. It is also important to note that the location had no access to mains gas supply. This had a bearing on the selected mechanical systems and utilities. Some of the key criteria have been tabulated below;

Passive House Criteria	Maximum Allowable Value	Value for Dunoon Passive House	How Value was Determined	Units
Specific Heating Demand	15	21	*PHPP*	kWh/m^2 per year
Specific Cooling Demand	15	N/A	*PHPP*	kWh/m^2 per year
Summer Overheating	10% over 25°C	2.8% over 25°C	*PHPP*	°C
MVHR Thermal Efficiency	≥75	91	Rated	%
Ventilation Electricity Demand	0.45	0.31	Rated	Wh/m^3
Glazing U-value	0.8	0.8	Design	W/m^{2}K
U-Values Walls/Roof	0.15	0.094	Design	W/m^{2}K
U-Value Floor	0.15	0.15	Design	W/m^{2}K
Airtightness	0.60 @ 50Pa	≤0.41 @ 50Pa	Tested	Ach^{-1}

Table 5:Dunoon Passive House Criteria Comparison

In addition to the high standard of building fabric design and construction, the three mechanical systems had been integrated into the building design. The three systems are central to this study and their importance to the performance of the passive house is indicated in this chapter. A simple collection of systems is not sufficient to construct and operate a building as complex as a successful passive house. The integration as a whole is greater than the sum of the individual parts (*Feist and PHI, 2007*). The difficulties involved in integrating these systems are critical to this project, with the complexities and re-occurring issues involved highlighted throughout. Analysing whether or not the systems work in tandem is key.

4.2. STHW System

The *PHI* does not set out stringent guidelines on how *HW* demand should be met. Instead the institute just sets out broad energy targets for the entire building. The *PHI* just indicates that domestic *HW* generation and distribution should be achieved with '*minimal heat losses*'. However, meeting *HW* demand becomes increasingly important in passive house design over modern conventional housing. This is due to the extremely low space heating demand, the resultant of a high performance building envelope. The *HW* demand is a far greater proportion of the total heating demand than most other domestic constructions. The addition of a *STHW* system here may be viewed as an added energy efficient bonus as the design team initially predicted that 55% of the annual *HW* contribution would be met by the solar thermal system operation. The high energy yield from the *STHW* system was the primary reason it was incorporated into this passive houses design. Due to funding issues and the council's and UK government's aim to promote cost effective renewable energy systems, this was not just included without energy and cost analysis. Determining if this reasoning translates to on-site performance is an important aspect of this project.

The *STHW* system consists of a 200 litres thermal store, rooftop solar thermal collectors, electric immersion heater and accompanying pipework, pumps and controls. All components have been manufactured by *Velux*. There is 4.6m^2 of solar thermal rooftop panelling, with 6 x 0.9m^2 *Velux M08* collectors. In the northern hemisphere, south facing collectors obtain the maximum levels of solar irradiance. The Dunoon passive house has one side of its roof structure that is almost perfectly south facing. This ensures a high level of performance throughout full daylight hours. The images underneath indicate the panel installation;

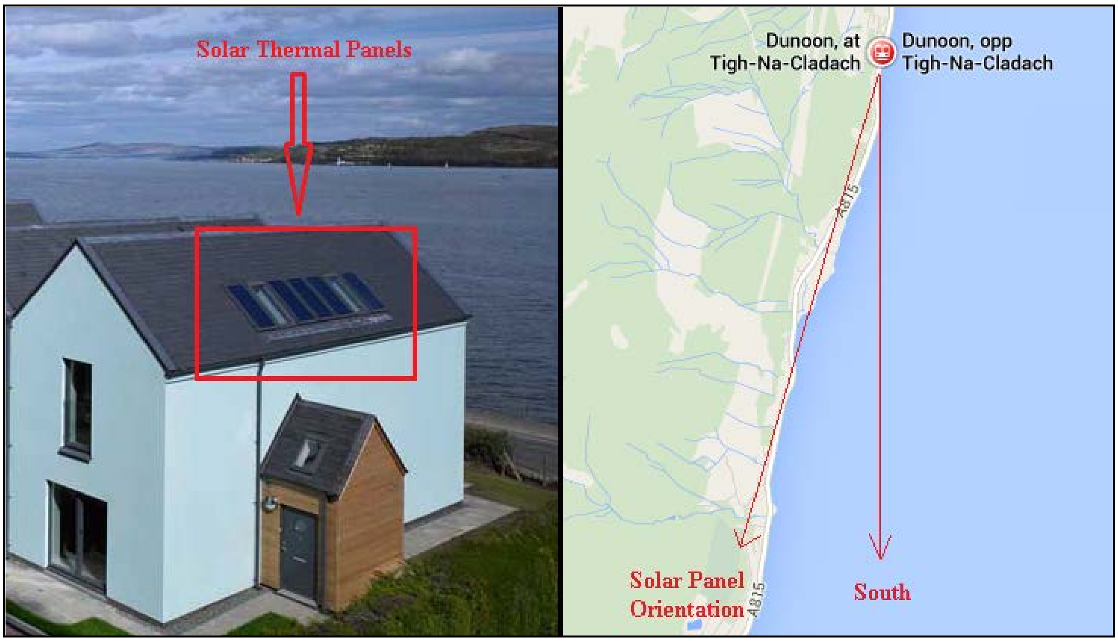

Figure 6: Solar Panel Installation. [Source: e-architect.co.uk, Google Maps]

A rough schematic of the system is shown below;

Symbol	Specification
S1	Collector sensor 1
S2	Store sensor
S3	Collector sensor 2
S4	Measuring sensor (optionally)
R1	Solar pump collector 1
R2	Solar pump collector 2

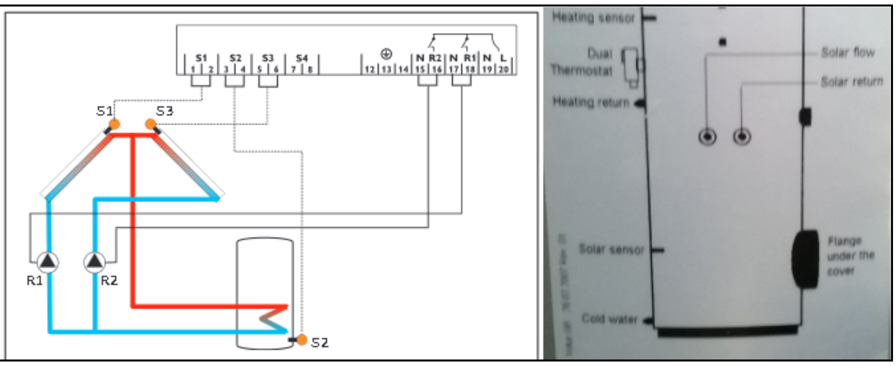

Figure 7: STHW Schematic and Photo

The *STHW* system operates on a solar heating circuit positioned in the lower half of the tank. This is supplemented by an electrically driven immersion heater in the top half of the tank. The immersion heater is time controlled by the occupant. At present, this is timed to operate from 07:00am until the top of the tank temperature rises to approximately 57°C (based on the studied logged data). The solar thermal control is programmed to operate based on the conditions experienced by one temperature sensor near the base of the tank and two temperature sensors placed on the solar thermal rooftop panelling. The control logic is set so that the solar pumps operate when the difference between the bottom of the tank and the solar panel temperature is greater than 6K. This value is recommended by the supplier based on trial data. There are two independently operating solar pumps, each one driving the circuit to different sections of panelling. If the controller reads that only one grouping of panels is 6K hotter than the bottom of the tank temperature then only that pump is operational. The control is very simple. Yet, as this project data and analysis will highlight, it is extremely problematic.

The system has been monitored and tested previously by the *Energy Systems Research Unit* (*ESRU*). Their conclusions and system recommendations led to the present control and immersion timings being put in place. This project shall prove that whilst these have improved the systems operation, they are far from producing an *optimum* performance.

It is also important to note that this system has been designed to run independently of all the other systems within the passive house. The *STHW* system does not include any heat recovery from the building or other mechanical systems and does not aid in meeting the buildings space heat demands. This certainly could have been an option to increase energy efficiency, especially given the high level of performance predicted in the *PHPP*. A heating coil from the *STHW* thermal store through the *MVHR* with summer bypass was not analysed prior to construction.

Prior to this project, when interviewed the main occupant indicated that she was not entirely happy with the system's operation. She pointed out that she had to become more aware of her consumption levels and patterns. Although this has resulted in a saving of energy and money, it is not ideal in terms of user-friendly operation as large volumes of high temperature *HW* are not readily available at all times.

4.3. MVHR System

The *MVHR* is central to the operation of the passive house in ensuring thermal comfort through adequate ventilation and the meeting of the space heating and cooling loads. The *PHI* sets out stringent guidelines for *MVHR* operational performance. All passive houses require a functioning *MVHR*. This is predominately due to the low air change rates with the buildings as a result of the high standard of air tight construction. Natural ventilation is limited in order to reduce space heating and cooling loads. As well as ensuring an adequate fresh air supply into the building for occupants, the *MVHR* compliments the main source of space heating and cooling in meeting thermal demands through two steps. Firstly, the *MVHR* recovers heat from the extract ducting system by heating or cooling the fresh air supply delivered to the building. Secondly, the *MVHR* circulates the heat around the building as required. Different levels of supply for different rooms are determined in the design phase and the system is commissioned accordingly. Due to the high performing building envelope, the *MVHR* is required to be operational 24 hours a day, all year round. For the Dunoon passive house, the *MVHR*'s main function besides ventilation is to assist with meeting the winter space heating loads. This is due to the climate in which the building is located. However, it also ensures the building does not over heat in summer.

For the Scottish passive house, a *PAUL: Focus 200 MVHR* has been installed. This is located along the south facing exterior wall. It has been rated to recover 91% of exhaust heat. The cited electrical demand is extremely low at 0.31Wh/m^3. This rated criterion is far better than the *PHI* requirements of ≥75% heat recovery and ≤0.45Wh/m^3. Hence why this exact unit type has been officially validated as a suitable passive house component by the *PHI*. According to the manufacturer's data, the *MVHR* is capable of achieving a ventilation supply temperature of ≥16.5° when the external temperature drops to -10°C. These results ensure it is an ideal selection for a building located in Scotland. The system is fully functional at extremely low temperatures as it is equipped with frost protection for external temperatures as low as -15°C. The *MVHR* is designed to deliver a volume flow rate ranging from 116 - 155m^3/h. The *PHPP* predicted this to be a good match based on the building's occupancy levels, air change rate and volume. This report will investigate whether or not that is truly the case.

The main occupant has expressed her happiness with the ventilation units operation in the past. She has been very satisfied with the level of thermal comfort in the summer time. However she has expressed concerns about thermal comfort during winter. Once again *ESRU* monitored and tested the *MVHR* system installed in the Dunoon passive house and made a number of conclusions and recommendations. This follow-up project will further scrutinise the system and highlight a number of flaws with its current operation.

A basic schematic of the system has been shown below;

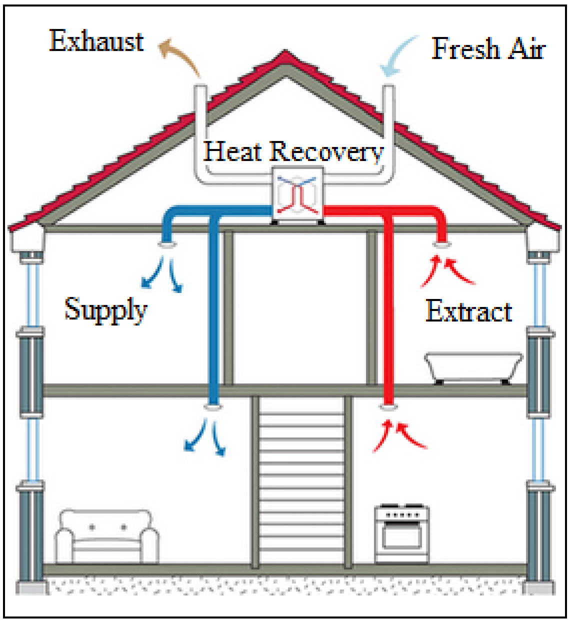

Figure 8: MVHR Schematic [Sources: www.thefueleffect.co.uk]

4.4. ASHP System

Heat pumps have the potential to reduce the costs, emissions and resource intensity of UK heating energy consumption. In *'Sustainable Energy – Without the Hot Air'*, David MacKay argues that a heat pump powered by electricity generated at centralised, highly efficient gas power stations represents a significantly smaller gas consumption than that of a condensing boiler. He puts forward the argument that all fossil-fuel driven heating should be replaced with heat pumps and that doing so in conjunction with advanced heating control systems and high performance building envelopes would reduce the primary energy use for heating by approximately 75%. It is this logic that makes heat pumps a common heating system installed in passive housing. However, these arguments are based on current the UK *Renewable Heat Incentives* being maintained and all heat pumps operating with a COP above 3.0. [M.E Baster (2011)]

The Dunoon passive house currently meets the building's heating demand via an air-source heat pump. It is manufactured by *Mitsubishi* and has a quoted *COP* of 4.0 in heating mode. It has a rated capacity of 4.0kW for heating and 3.5kW for cooling. It has been certified as an 'A' ranked energy efficient product. The heat pump is operated manually and on a timer set by the occupant. It is not used by the occupant as a space cooling device, mainly due to the building climatic location. Its sole purpose it to meet the winter space heating demand.

ASHP's are not typically designed to meet the full peak load of a building due to their low thermal capacity and low grade heat source yet the *PHPP* design determined that a single *ASHP* would be adequate to meet the home's space heating requirements. This was selected over a ground-source heat pump or electrical heating based on their cost and demand matching analysis. A high-efficiency gas powered condensing boiler system was not an option due to the lack of access to mains gas supply in the area.

Following the first winters operation, the heat pump was replaced with the current model. The unit was largely undersized to meet the peak heating load. Even since the replacement, the homeowner has described conditions in winter as '*too cold, with noticeable variations in temperature throughout the day and night*.' She stresses that a single *ASHP* is not sufficient for the house and that supplementary heating via the use of the fireplace is often necessary. It is also pointed out that the system is expensive to run and that heat does not distribute around the house evenly. These issues are examined within this project.

4.5. Previous Studies

Numerous studies on differing aspects of the Dunoon passive house's design and operation have been undertaken since its completion in 2010. These include studies performed by *ESRU* and *MEARU*. Numerous student projects have also been carried out in conjunction with these academic units. At present, *MEARU* is monitoring the entire circuit board for a one-year period in order to study electrical consumption and demand patterns. Other organisations such as *Architecture & DesignScotland* have produced reports on the project's construction and operations. The exemplar building has attracted much interest and attention from academic and private sector organisations.

This project may be seen as a follow up to a similar project performed by *ESRU* in 2011. However, this differs in numerous aspects as every system has either been fully replaced or the control systems completely altered since that study. Firstly, with regards the *STHW* system, the control strategy has changed. Additionally, this study is the first time that the system has been monitored whereby the solar thermal pumps, controls and immersion heater operation have been metered independently and accurately. The new *MVHR* unit has only been tested by *MEARU*. Only an air test has been performed as this is the first time that the thermal performance of the system has been scrutinised. Finally, the heat pump replacement has never been tested in detail before. This will be a first for this passive house. All recommendations and conclusions may be seen as independent from previous studies.

5. STHW System Analysis

The *STHW* system was analysed in a number of parts. Firstly, the system's operation on a day of low external solar irradiance was compared with the operation of a day of high operation. The days experiencing the lowest and highest mean solar irradiance during daylight hours was selected for analysis. These were the 25th and 29th of June respectively. Here, the *STHW* pump and supplementary immersion heater operation were compared, with respect to operation, controls and running costs.

Secondly, consecutive days of low and high solar irradiance were grouped together and analysed. This was important to gain a greater understanding of the systems operation, controls and running costs as it was found that each day had a knock on effect on the next. The percentage of supply being met by solar irradiance could then be compared with the design prediction of 97% in June for this specific passive house.

Once the control logic was understood and scrutinised, alternatives were suggested as a means of improving the system's performance with respect to energy consumption and cost.

Finally, the issue of legionella build-up and potential system hazards was analysed and discussed for the specific *STHW* system. Throughout the analysis, like all analysis within the scope of this project, user experience and comfort has been taken into account and discussed.

5.1. Previous Studies & Visual Inspection

ESRU: performed a detailed study of the system's operation in early 2011; one year after the building was opened. From this, they concluded that 40% annual contribution from solar irradiance would be a more realistic system target. They based this on a literary review and similar monitoring.

ESRU outlined how the system was controlled with one obvious flaw being that at times the water flowing to the panels was slightly warmer than the return water to the tank, indicating a net heat loss. This occurred when the tank stratification was such that the temperature difference of 6K between the bottom of the tank and the panel used to trigger the solar pump was not great enough.

Initially, *ESRU* discovered that the supplementary immersion heater was set to automatically operate 3 times per day, regardless of solar irradiance levels. This intermittent operation throughout the day was in order to maintain the tank at a very high temperature. The controls were reset to operate the electric heater twice a day in order to achieve an upper tank temperature of 60°C. *ESRU* indicated that no supplier could provide better system controls at a price deemed worthy. A part of this project was to determine whether or not these were the optimal control settings and if not, how could they be improved.

The *ESRU* research also highlighted the potential dangers of legionella yet did not propose any realistic solutions or go into details of the threat. They indicated that the water at the bottom of the tank may not reach a safe sterilisation temperature and that there was no de-stratification pump. This pump is common industry practice within these high risk systems. This area clearly need more attention, hence it has been analysed further using the logged temperature data.

A number of further issues were emphasised but not resolved or analysed in detail, these included the poor quality of insulation on the *STHW* system and the potential risk of space overheating during summer operation. These clear gaps in the previous study have been addressed within this project.

5.2. Day of Low external Solar Radiation

As outlined, the 25/06/2014 was investigated as a day of low solar irradiance in Dunoon, Glasgow. The installed weather station indicated a mean solar irradiance level of 62.2W/m^2 with a daily high of 142.9W/m^2. This is extremely low for summer conditions.

The key data logging variables relating to the operation of the *STHW* system have been plotted below for this day;

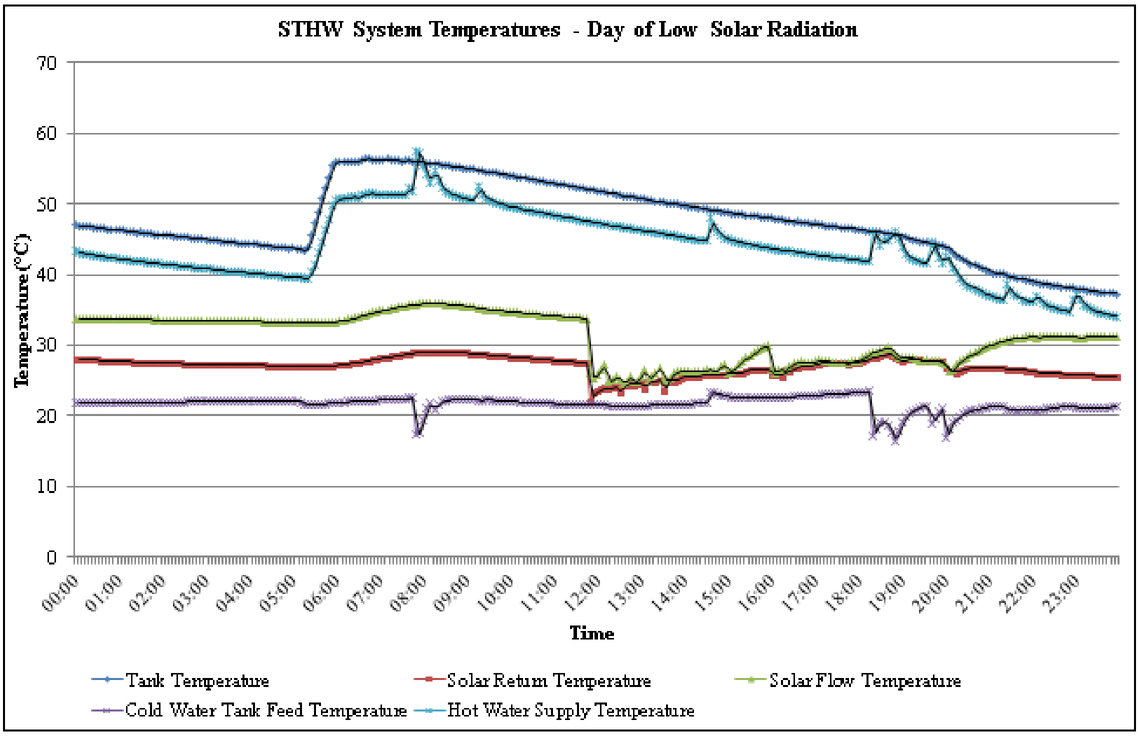

Figure 9: *STHW* Temperatures on Day of Low Solar Irradiance

At 00:00, the top of the tank temperature is 47.0°C. This is the resultant of continuous heat loss from the previous day's high of 52.0°C. The tank continues to lose energy until the timed immersion heater comes on. This operates for 60 minutes until the tank temperature is raised from 43.3°C to its daily high of 56.35°C. The solar pump is still in operation during this day and it has been concluded that it is highly ineffective. The top of the tank temperature drops 4K, from 56°C to 52°C in 3hrs 20mins in the morning when no equipment is operational, i.e. static heat losses. Yet in comparison, the top of the tank losses 4K, from 47°C to 43°C, when the solar pump is in operation in 3hrs 5mins even though there is a reduced thermal driving force. The pump controls are not effective here as there is a blatant waste of energy and money.

For these 24 hours, 0% of the *HW* supply is met by solar irradiance as the tank temperature never once increases once the solar thermal pump becomes operational. Heat losses are just amplified. Here Sol $_{Flow}$ > Sol $_{Return}$ temperature always. The programmed control of switching on the solar pumps when the bottom of that tank is 6K less than the solar panel temperature is flawed. The solar heating coil is located higher up the tank where temperatures are higher. Even for the 20mins during the day when solar irradiance is at an average high of 123W/m^2 the tank temperature drops by 0.1K. The ΔK between the solar flow and solar return ranges from 3.95K to 0.1K at its daily 'best'.

Another note to be taken from the above graph is that there is a high *HW* demand in the evening time. This clearly impacts on the top of the tank temperature as cold feed water enters the tank. However, the hot water supply temperature to the utilities is still adequate at 35°C. A hot shower typically requires water up to 41°C depending on the consumer but discharge temperatures of 35 - 46°C are cited as the acceptable range within UK domestic properties.

A graph has been plotted to indicate the operation of the *STHW* pump and supplementary electric heater on this day;

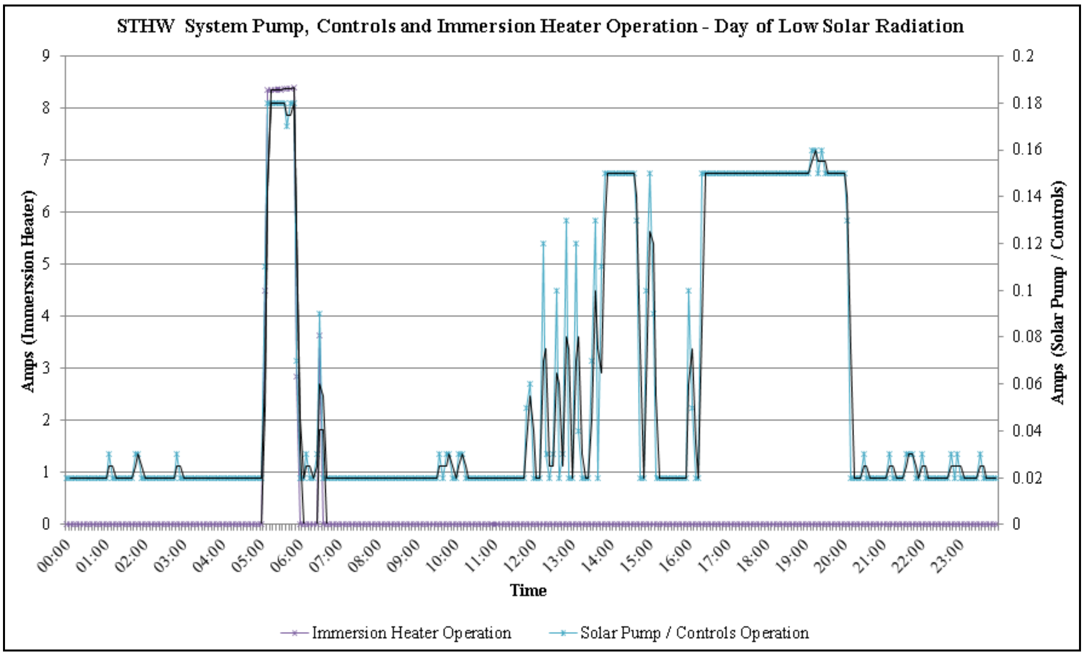

Figure 10: *STHW* Controls on day of Low Solar Irradiance

It is clear from the graph that the immersion heater is required for 60mins while the solar pump operates intermittently for a combined total of almost 6hrs throughout the day. The external environmental conditions have been shown below so controls can be discussed clearly;

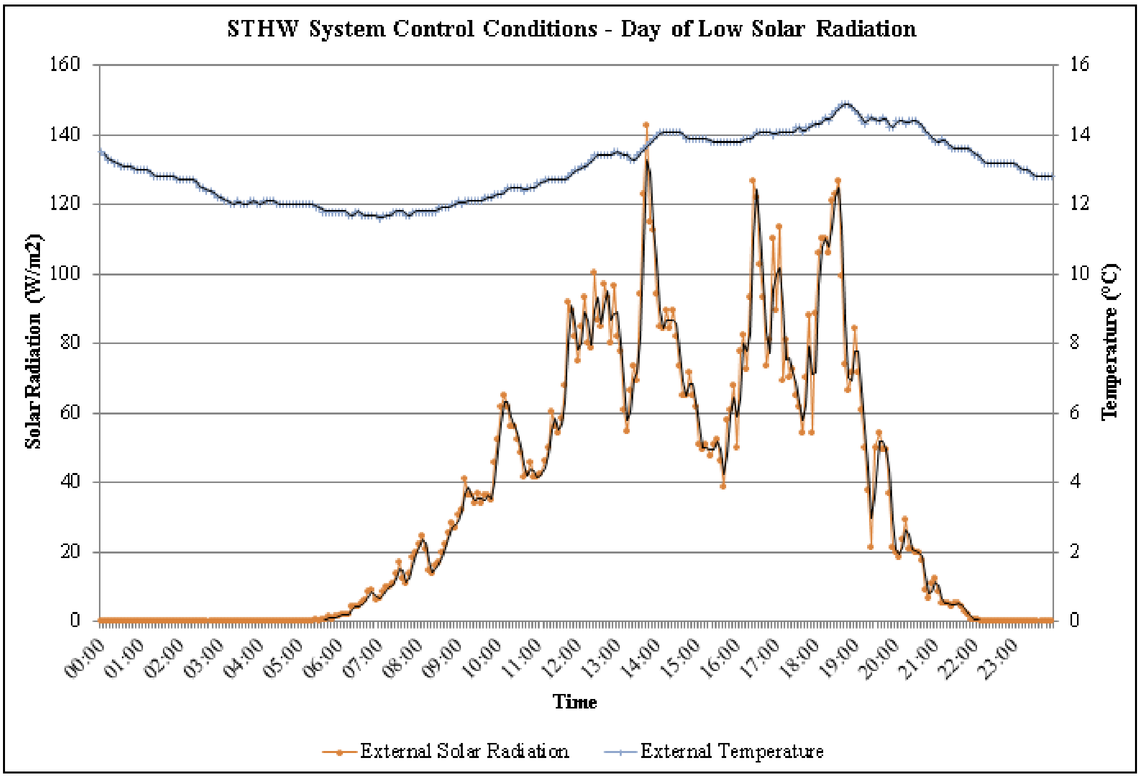

Figure 11: *Environmental Conditions* on day of Low Solar Irradiance

The flawed control logic ensures that the pump is constantly on between 16:20 and 20:05. Here, the solar circuit temperature is above the solar panel temperature as the solar radiation levels remain low, if varied. Clearly energy is being wasted.

Now it is important to examine how that relates to cost. A cost analysis for the day's operation has been performed. This is outlined below;

	Value:	Units:
Immersion Heating Average Current:	7.347	A
System Average Wattage:	1759.0	W
Operational Hours:	1.00	hrs
Kilowatt Hours:	1.76	kWhrs
Cost of the days Operation:	0.196	£
STHW Pump + Controls Average Current:	0.138	A
System Average Wattage:	28.3	W
Operation Hours:	5.92	hrs
kWhrs:	0.17	kWhrs
Cost of the days operation:	0.019	£
Total Cost of days Operation:	**0.214**	**£**

Table 6: Cost Analysis for Operation on Day of Low Solar Irradiance

[Note: The above calculations were performed using the amp-meter recordings. Conveniently, the immersion heater and the *STHW* pump and system controls were on individual electrical circuits in the house. The average wattage was calculated under the assumption that the circuits were single-phase 240V supply with a power factor close to unity. This assumption was made throughout the project.]

The *STHW* pump and controls contribute to 8.7% of the day's operational electricity costs. Although minor in relative terms, its sole function on this day was to enhance the systems heat losses. It's an unnecessary waste of energy and money. When isolating this day, it may be seen as a poor indicator when the *STHW* system is completely useless in June and is compensated using an electrically driven heat source. Ideally, a more efficient back-up source of heat when solar conditions are poor would be more economically and environmentally beneficial if the system is deemed not to meet the prediction of 55% contribution from solar thermal. No access to mains gas is clearly an issue.

5.3. Day of High external Solar Radiation

To analyse as day of high external solar radiation, the 29/06/2014 was investigated. The installed weather station indicated a mean solar irradiance level of 333.9W/m^2 with a daily high of 1188.0W/m^2. This is extremely high for summer conditions in Scotland. The daily mean is over 5.3 times that of the day analysed as low solar irradiance with the daily peak high being over 8 times higher. The substantial differences are ideal for comparison purposes.

The key data logging variables relating to the operation of the *STHW* system have been plotted below for this day. This has been displayed below;

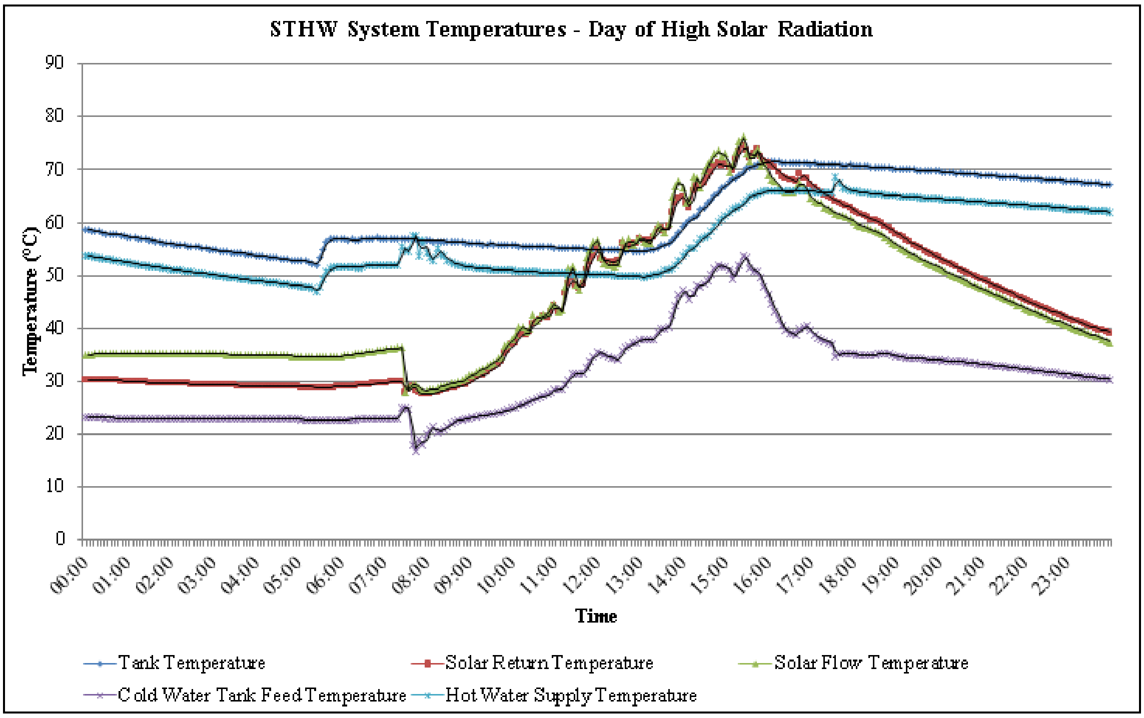

Figure 12: *STHW* Temperatures on Day of High Solar Irradiance

From the graph, we see that the top of the tank temperature is already at a high of 58.7°C at 00:00. This is due to the good solar conditions and *STHW* operation of the previous day, whereby the mean solar radiation levels stood at 337.7W/m^2, almost identical to the 24 hours under examination. This has a substantial bearing on the day's system operation. Here, the tank is sitting at a much higher temperature when the immersion heater is set to come on in the morning. It is at 52.0°C instead of the 43.3°C when the day of low solar irradiance was followed by a day the previous days equally poor levels and operation. This enabled the tank to reach its top of the tank set-point temperature of 57°C in less time (50mins), resulting in an energy saving of over 25%.

The solar pump becomes operational just after 07:30, coincidentally when a large volume of fresh cold feed water enters the tank. This is probably due to the occupant having an early morning shower. This results in a net cooling of the tank, over a time lag as natural circulation occurs within the water storage vessel.

At 07:30, the solar return temperature begins its operation at 28.45°C. This rises to a weekly peak of 73.45°C at 15:20 due to the ideal solar conditions and pump operation. This operation is an indication of the system working exactly how it is designed and results in the highest witnessed solar return temperatures into the tank. This results in the top of the tank temperature rising to a high of 71.45°C, instantly killing all legionella cells in the upper portion of the tank. A circulation pump would be required to ensure that all legionella bacteria are killed within the tank.

It should also be noted from the graph that the *HW* demand was high on this day. That can be seen by the level of fluctuation of the cold water feed temperature into the storage vessel. This has a substantial impact on lowering the tank temperature. Yet, it should also be noted how high the feed water temperature is, above 40°C at times. This is the highest witnessed throughout the monitoring process and helps reduced the heating load. It may be considered surprisingly high.

The simplistic control mechanism once again ensures that the solar thermal pump is operational up until 01:50 the following morning. This is despite the fact that solar radiation levels drop below 20W/m^2 after 19:00 and to 0W/m^2 after 22:00. It has little positive effect past 16:00. A resultant net energy loss has been witnessed past this time. The system operation has been graphed below;

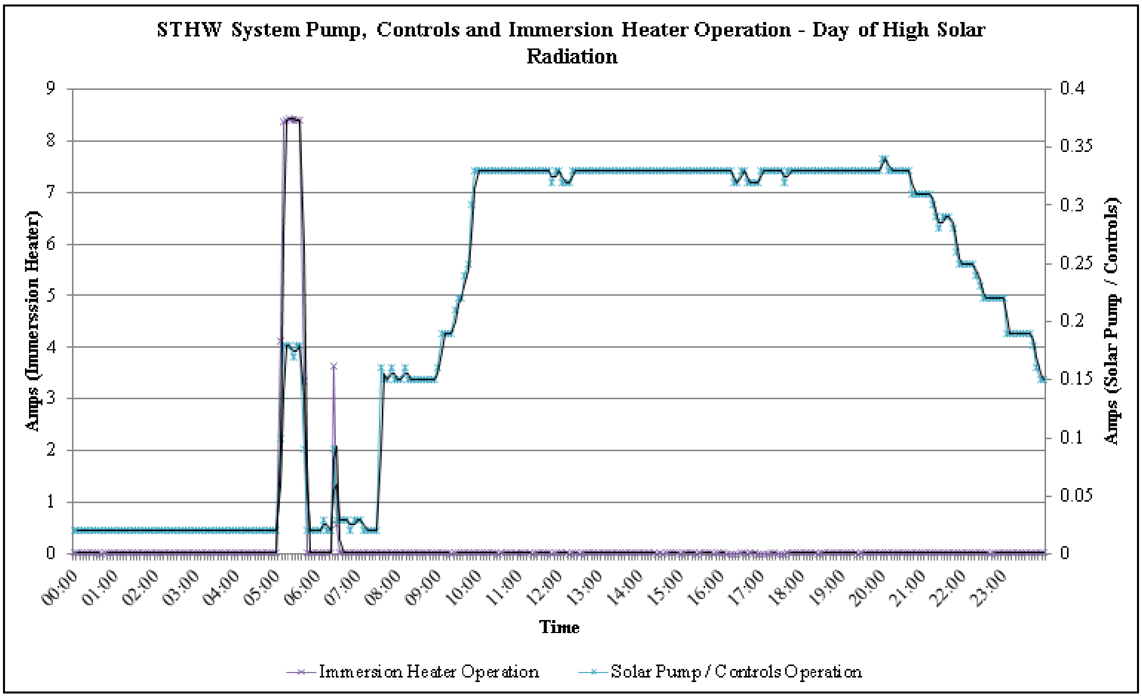

Figure 13: *STHW* Controls on day of Low High Irradiance

The corresponding external environmental conditions have been graphed below for visual purposes;

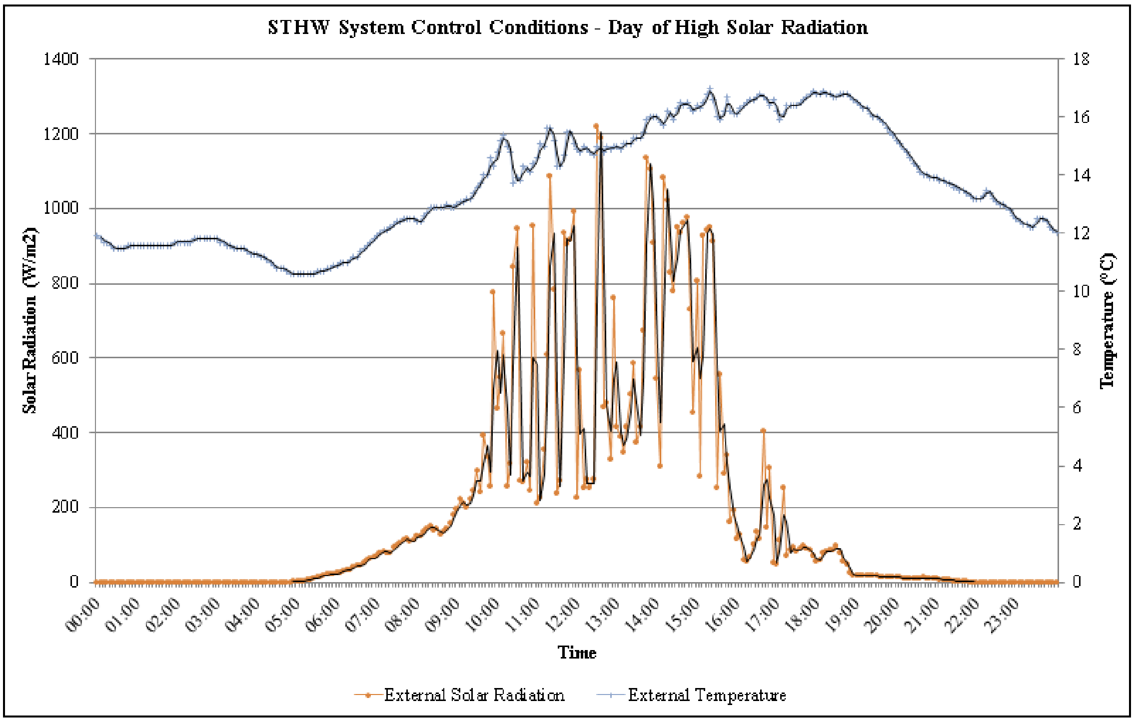

Figure 14 *Environmental Conditions* on day of High Solar Irradiance

There may be heat stored within the solar plate collectors from the high levels of radiation throughout the day; however this has dissipated well before 01:50 in the morning. A 6K temperature difference will still be evident resulting in the pumps driving the solar thermal circuits. Should the storage vessel contain a circulation pump, this method of control may be sufficient or at least more accurate. However, it does not.

Due to these conditions, it is clear from the graph that the solar flow and return temperatures drop drastically as operation continues into the evening/night. The top of the tank temperature and hot water supply temperature also gradually lowers. This is due to the *STHW* operation but also static heat losses over time due to the high thermal driving force.

An operational cost analysis of the immersion heater and *STHW* pump and controls has been performed. The results are tabulated as follows;

	Value:	Units:
Immersion Heating Average Current:	6.35	A
System Average Wattage:	1518.0	W
Operational Hours:	0.830	hrs
Kilowatt Hours:	1.27	kWhrs
Cost of the days Operation:	0.141	£

STHW Average Current:	0.29	A
System Average Wattage:	64.6	W
Operation Hours:	16.5	hrs
Kilowatt Hours:	1.07	kWhrs
Cost of the days Operation:	0.118	£

Total Cost of days Operation:	**0.259**	**£**

Table 7: Cost Analysis for Operation on Day of High Solar Irradiance

Realistically, should a more intelligent control system of been in place, solar thermal should have been able to meet 100% of the day's *HW* contribution. This may be said as the *HW* supply temperature sits at 48.1°C prior to the supplementary immersion heater beginning its operation and coincidentally prior to the occupant taking a shower. This is more than adequate for all domestic *HW* utilities. This would have resulted in a reduction of operational costs and primary energy usage by over 50%, even with the poorly controlled solar pump operation.

In comparison with the operational costs for the previously analysed day of low solar irradiance, some surprising conclusions may be drawn. The domestic *HW* system cost the homeowner less to run on the day of low solar irradiance. This is due to the inadequate controls. The immersion boost heating in the morning cost approximately 20% less when solar irradiance levels were high, however the solar pump and control operation led to an operational cost over 6 times as much.

Ideally, the controls would have resulted in the immersion heater being deemed dispensable and the *STHW* system being operation between 09:00 and 17:00 when external solar radiation levels would have produced a net gain in thermal energy within the storage vessel. This would have reduced the day's operational costs to £0.068. This level of control would have resulted in a 74% cost saving.

5.4. Comparison of Consecutive Days of Low and High Radiation Levels

As previously stated, system operational costs and performance is impacted by the previous day's external environmental conditions. The top of the tank temperature at the beginning of every day (00:00) has a direct bearing on the costs and energy consumption. Analysing consecutive days of low external solar irradiance gives a clearer picture of the systems operation, as these results will aide in drawing more concrete conclusion about the system and resulting energy consumption and controls. The same theory is applied to consecutive days of high external solar irradiance. Only two days of consecutively low levels of solar irradiance were monitored on site. These were the 25th and 26th of June. Meanwhile, three days of extremely high mean solar irradiance were witnessed. These being the 28th, 29th and 30th of June 2014. All of this data is also to be analysed with the design prediction of 97% HW contribution met by solar thermal in June for the Dunoon passive house in mind. The required variables logged for discussion have been tabulated below;

Date:	**25th**	**26th**	**27th**	**28th**	**29th**	**30th**
Tank Temperature prior to Immersion Heating:	43.6	34.4	37.7	49.2	52	63.9
Tank Temperature after Immersion Heating:	56.35	56.2	N/A	57.1	57.1	63.9
Mean daytime Solar Irradiance (08:00 – 21:00):	62.2	170.5	N/A	337.7	333.9	381.5

Table 8: Solar Irradiance and Tank Temperatures

Examining the consecutive days of low solar irradiance, it is clear that immersion heating is mandatory due to the top of the tank temperatures on the following days prior to supplementary heating. Even for the three days of high solar radiation, two out of three of the days require supplementary electric heating to raise the top of the tank to the set-point temperature of 57°C. Although guidelines outline that *HW* utility supply temperatures should be up to 41°C, from analysing the logged data it is clear that there is no way that solar thermal alone can maintain this temperature for the 8 days monitored.

From the data gathered, a running costs comparison has been performed for the consecutive days of low and high external solar irradiance. This has been tabulated below for ease of understanding;

	Low Solar Radiation	**High Solar Radiation**	**Units**
Average Solar Irradiance (08:00 - 21:00):	116.4	351.0	W/m^2
Immersion Heater Average Current:	7.21	5.45	A
Immersion Heater Average Wattage:	1730.4	1308.0	W
Immersion Heater Operational Time:	2.4	2.0	hrs
Immersion Heater Consumption:	4.188	2.616	kWhrs
Immersion Heater Operational Cost:	0.465	0.291	£
Immersion Heater Daily Average Operational Cost:	0.233	0.097	£
STHW Average Current:	0.21	0.27	A
STHW Average Wattage:	50.2	64.3	W
STHW Operational Time:	19.8	46.8	hrs
STHW Consumption:	0.995	3.006	kWhrs
STHW Operational Cost:	0.111	0.334	£
STHW Daily Average Operational Cost:	0.055	0.111	£
Overall Daily Average System Operation Running Costs:	0.288	0.208	£

Table 9: Cost Analysis for Operation on Consecutive Days

For the two consecutive days of low irradiance, over 75% of the electrical consumption is consumed by the supplementary immersion heater. Even during the ideal conditions of consecutive days of high solar irradiance the immersion heater consumes 47% of the total system's electricity. The controls must be deemed extremely poor as at long periods during the monitoring the conditions were evident to reduce this consumption substantially.

One fundamental flaw is operating the solar thermal pump when the solar return temperature is below the solar flow temperature. Both connections are level on the tank so it is clear that the pump should not be operational when this condition is being met. This happens with surprising frequency. Even for the 3 days of high solar radiation, the solar circuit is having either a zero or negative impact on the overall tank temperature for over 8% of its operational time due to the return temperature being lower than the flow temperature. This is an obvious waste of money and energy, contributing to avoidable heat losses.

Thankfully, when analysing consecutive day's operation, it has been found that the average daily running costs are reduced when solar conditions are superior. The solar pump running costs double on average but the immersion heater consumes approximately 60% less electrical energy. A 28% reduction in costs is seen.

5.5. Further Findings from Analysis of the Full Monitoring Period

In order to further analyse the test period as a whole, the following table has been developed;

Date	Average Solar Irradiance (08:00-21:00) (W/m^2)	Average Static Tank Losses per Hour (ΔK/hr)	Average Tank temperature Change during ST Pump Operation (Δ/hr)	Net Tank Temperature Change during ST Pump Operation (ΔK/hr)
25th	62.20	-0.55	-1.05	-0.50
26th	170.50	-1.15	-0.51	0.64
27th	283.10	-0.43	-0.29	0.14
28th	337.70	-1.26	0.44	1.70
29th	333.90	-0.63	0.59	1.22
30th	381.50	-0.71	0.77	1.48
1st	502.90	-0.58	-0.56	0.02
2nd	114.90	-0.48	-0.51	-0.03
Average:	273.34	-0.72	-0.14	**0.58**

Table 10: Tank Energy Gains and Losses due to Solar Thermal

Here, the average hourly temperature drop at the top of the tank has been calculated for the period of each individual day whereby the immersion heater and solar pumps are not in operation. This gives an average static loss per day, arising from the tank temperature itself and also the *HW* demand as *HW* supply is draw from the tank and cold water is fed in to supplement this. This varies greatly and is a good indicator of the thermal store’s energy losses per hour. Then, the average temperature change per hour due to the operation of the solar thermal circuits has been calculated. From this value, the static losses have been offset to give a guide as to the net temperature change per hour within the tank due to solar irradiance. This gives a good indicator as to what net energy gains the solar thermal circuits are achieving over each days operation.

In addition to this data, the temperature increases in the tank due the operation of the immersion heater are tabulated below;

Date	Immersion Heater (ΔK)
25th	13.0
26th	21.8
27th	18.7
28th	8.0
29th	5.1
30th	0.0
1st	0.0
2nd	4.4
Average:	8.9

Table 11: Tank Temperature Gains due to Immersion Heater

By studying and comparing these two tables, numerous conclusions can be drawn from the monitoring process. Firstly, from an energy perspective the solar thermal pump would have been better off for the entire day of both the 25th and 2nd. This backs-up the previous findings related to the 25th. The solar pumps operation is leading to increased energy losses. It is effectively costing money to make the system worse! This once again highlights the need for a better control system. From the table, the solar thermal pump is only achieving considerable net energy gains on 4 out of the 8 monitored days for late June / early July. Overall, there is a net temperature increase in tank temperature due to the solar thermal pump operation. Yet this comes at a considerable cost to the homeowner. The solar thermal circuits raise the tank temperature by an average of 0.58K per hour during the test period, at an electricity cost of 0.69p/hr or a 64p total.

Under the current controls and environmental conditions, the immersion heater raises the tank temperature an average of 8.9K per day. Meanwhile the solar thermal circuits raise it by an average of 6.6K a day. This has been calculated using the average temperature increase and the average pump running time. In terms on energy, this analysis gives an approximate estimate that only 43% of the *HW* supply is being met by solar irradiation.

[Note 1: This may in fact be meeting 100% of the *HW* demand but this is kind of irrelevant and a way to skew the performance to seem closer to the optimum. It would be pointless to meet 100% of the demand via solar thermal if the system is supplying 5 times this *HW* energy, varying between solar thermal and electrical heating.]

[Note 2: Precise energy balances relating to tank heat losses and gains due to the immersion heater, solar thermal pump, static losses and *HW* demand cannot be determined as an accurate mean tank temperature and the mass flow rates of the solar circuit, *HW* supply and cold water feed are unknown quantities. However, this temperature dependant method uses accurate data and gives a good understanding of the system’s operation over the monitored period.]

5.6. Control Recommendations

It is clear from the previous analysis that the *STHW* system lacks an adequate control system to achieve substantial costs saving and get close to the design condition of 97% of supply met by solar thermal for the month of June. Should the homeowner want to avoid investing in new and costly controls, a number of steps may be suggested. One solution may be to reduce the top of the tank set point temperature to ≈ 43°C and operate the system as currently doing so. It is clear from the monitored data that the occupant's peak *HW* demand occurs directly after the immersion heating operation. Therefore, 57°C is unnecessarily higher than the required 41°C for a hot shower and other utilities. As outlined later, the set point of 57°C is not adequate to prevent the threat of legionella throughout the tank anyway. From the data it is clear that the solar circuits can currently maintain a temperature of above 40°C for the majority of the days under monitoring. Should the occupant require a large *HW* demand or external conditions are substantially lower than average, manual boosting of the thermal store may be undertaken.

Furthermore, a logical control setting using the current control equipment would be to reduce the immersion set point temperature to 46°C (maximum recommended requirement for domestic *HW* utilities) and to alter the solar thermal pump to be set on a timer whilst using the current temperature sensor logic. The operation would remain the same but could only operate during times of potentially high solar irradiance. From the data logged, this would be more logical due to the flaws in the temperature difference method alone. A 09:00 to 17:00 daily summer setting for the solar thermal pump would save significant quantities of energy and money. For the days of consecutively high solar irradiance analysed previously, with this control logic, the immersion heater would not be required to operate and solar thermal would meet 100% of the *HW* demand. The average daily running costs would reduce from 20.8 pence to 6.8 pence. An achievable saving of 66% by simply switching the control logic in the summer months. Applying this logic to the entire 8 days monitored, gives the following results;

	Current Operation	New Control	Units:
Immersion Heating Average Current:	6.44	7.94	A
System Average Wattage:	1545.6	1905.6	W
Operational Hours:	6.44	2.30	hrs
Kilowatt Hours:	9.95	4.38	kWhrs
Cost of 8 days Operation:	1.106	0.487	£
STHW Average Current:	0.26	0.28	A
System Average Wattage:	62.4	68.2	W
Operation Hours:	91.58	51.25	hrs
Kilowatt Hours:	5.71	3.50	kWhrs
Cost of the 8 days ST Operation:	0.635	0.388	£
Total Cost of 8 days Operation:	1.742	0.876	£
Average cost of 1 days Operation:	**0.218**	**0.109**	**£**

Table 12: *STHW* Cost Comparison with new Control Logic

[Note: The 0.28A new current is taken as an average based on the pump performance during full operation between 09:00 – 17:00 of all monitored days. This is deemed to be a logical pump set point for comparison purposes if the temperature difference logic remains intact.]

This new and improved control logic would reduce the supplementary heating costs by over half and the solar thermal pump and control costs by over 35%. Not only would this half the average running cost for the monitored period, it would also reduce thermal losses from the tank as the solar pump would not operate beyond 17:00 on a daily basis whereby the solar return temperature is consistently below the solar flow temperature. This would provide sufficient *HW* to the household, at a likelihood of a slightly reduced acceptable mean supply temperature in some mornings but an overall higher mean.

Based on this monitoring and analysis, the design prediction of 97% *HW* contribution met by solar thermal for the Dunoon passive house in June seems either incredibly optimistic or a completely flawed design modelling process. From these results, the system currently achieves 36% of its *HW* contribution via solar thermal. Enhanced controls outlined would increase this closer to 50%. This is with regards electrical consumption. The 8 days monitored may be considered an accurate sample period for external environmental conditions and *HW* demand in the month of June. 97% supply contribution is not achievable, certainly using these controls.

Performing an energy analysis similar to the previous section, the following comparison between the current and recommended controls has been made;

Date	Current Net Tank Temperature Change during ST Pump Operation (ΔK/hr)	Average Tank temperature Change during Timed ST Pump Operation (Δ/hr)	Net Tank Temperature Change during Timed ST Pump Operation (ΔK/hr)	Net Tank Temperature Gain per Hour with New Control (ΔK/hr)
25th	-0.50	-0.88	-0.33	0.17
26th	0.64	-0.40	0.75	0.11
27th	0.14	-0.29	0.97	0.83
28th	1.70	1.28	2.54	0.84
29th	1.22	1.88	2.51	1.29
30th	1.48	1.38	2.09	0.61
1st	0.02	-0.56	0.02	0.00
2nd	-0.03	-0.51	-0.03	0.00
Average:	0.58	0.24	**1.07**	0.48

Table 13: Tank Energy Gains and Losses due to Solar Thermal with New Control Logic

The results from the immersion heating operation under the new control logic have also been tabulated;

Date	Immersion Heater (ΔK)	New Controls Immersion (ΔK)
25th	13.0	2.3
26th	21.8	11.6
27th	18.7	8.3
28th	8.0	0
29th	5.1	0
30th	0.0	0
1st	0.0	0
2nd	4.4	0
Average:	8.9	2.8

Table 14: Tank Temperature Gains due to Immersion Heater with new Control Logic

From this data, it is clear that the system's operation improves with regards thermal energy supply for every days monitoring apart from two which remain static. It is not only providing a monetary saving. The two days whereby the thermal store does not achieve a net temperature gain due to the new theoretical controls is due to the fact that the solar thermal pump never operates outside the new time limits anyway. This is due to the fact that the entire tank's temperature has risen considerably so that there is no longer a large enough temperature difference between the bottom of the tank and the solar panels to operate the pumps. This is the case even though solar conditions are strong during the evening.

With the new controls, the immersion heater would only be required to raise the top of the tank temperature by an average of 2.8K per day. Yet, the solar thermal would raise the tank by an average of 6.8K with static losses taken into consideration. This control system would sufficiently meet the occupant's current *HW* demand and would mean that over 71% of the contribution would come from solar thermal. This is a very simple means of improving the *STHW* system with respect to both thermal energy, primary energy consumption and running costs.

One other alternative would be to implement a solar power meter into the control logic whereby the solar pump only operates above a certain solar irradiance set point. This may be considered too costly, given the *GSA* accurate weather station cost £4,000 and a basic meter costs £100 without incorporating it into the control programme. The payback period may be far too high given the complexity for such a basic domestic system.

5.7. Threat posed by Legionella

The ideal temperature growth range for legionella is between 32 - 42°C. For this reason alone, *STHW* systems run a high risk of legionella concentrations growing above acceptable, safe limits. Legionella may be killed using temperature controlled methods. Almost 100% of legionella bacterium is killed instantly when water temperatures rise above 70°C. The same occurs when water is raised above 60°C for over 10 minutes or above 50°C for over 2 hours.

The immersion heater set-point of 57°C at the top of the tank will not instantly kill the bacteria, but will do over time and prevents its growth. Analysing the hot supply temperature is not completely accurate as the reading is taken at approximately 15 centimetres from the tank due to access issues, therefore suffering high pipework heat losses when the water is stagnant due to a lack of utility usage. A more accurate analysis has been performed by examining the top of the tank temperature, as the supply pipework connection is located near here. From the logged data, the top of the tank meets the outlined criteria at least once per day to kill over 99% of legionella bacteria. This is due to a combination of the low *HW* demand, immersion set-point temperature and solar thermal performance. However, this does not completely eliminate the risk to the occupants.

The *STHW* system has not been fitted with a circulation pump, instead relying solely on natural convection currents and disturbance from the several connections. The positioning of the electric immersion heater in the upper half of the tank also ensures that the bottom half of the tank relies heavily on the solar return connection to raise its temperature substantially. During the first 72 hours of monitored period, the solar return water only rises about 50°C for 2 hours 25 minutes. This is alarming considering that it is during June and the water is fed in half way up the tank. There is a high risk of dangerous levels of legionella bacteria concentrated at the bottom of the thermal store. Due to the low demand, *HW* supply connection at the top of the tank and top of the tank immersion heater set point temperature this may only become a health risk during exceptional circumstances. Yet this is still a risk and should be considered bad design practice. For example, this may occur should the occupant require an unusually large volume of *HW* for any given reason.

5.8. STHW System Conclusions

From the system analysis, some general conclusions have been made. These are as follows;

1) The 97% prediction of *HW* contribution met by solar is unattainable in practice. The initial design modelling of the system may be considered flawed. Currently the system meets 43% of its *HW* contribution via solar thermal operation. This equates to 36% of the system's running costs.

2) The solar thermal pump operation is saving the occupant money and energy. There is on average a 28% cost saving on days of high solar irradiance levels compared with days of low solar irradiance.

3) The control settings are extremely poor, resulting in high thermal losses and energy wastage. Should the operator switch the current control logic for the solar thermal pump to be time dependant as well as temperature driven in the summer and reduce the immersion heating set-point to an adequate level, running costs will reduce by 50%. Then the percentage solar contribution will rise to approximately 71%.

4) It is not possible to rule out the threat of legionella based on the *STHW* design and operation at present.

6. MVHR Analysis

The next mechanical system investigated and analysed with regards all aspects of performance was the passive house's *MVHR* system. Associated factors such as system running costs, primary energy consumption, thermal performance, internal comfort impact and occupant's user experience have all been scrutinised.

Firstly, thermal performance was investigated for the monitored period. This was achieved through the examination of the systems temperature transfer efficiency via the logging of the temperatures recorded in the supply, extract and fresh air ducts. Secondly, due to the timing of the project, issues relating to summer overheating risks within the building were studied using collected data. The effectiveness of the heat distribution was also evaluated.

A focus on the *MVHR*'s operation during '*winter*' conditions was attempted using the data logged for the coldest period tested. Here the heat distribution and overall system *COP* were analysed and discussed. Furthermore, an examination of the volume flow rates delivered to each room were tested and fresh air requirements and blockage due to ageing filter usage were determined.

6.1. Previous Studies & Visual Inspection

ESRU: In 2011, *ESRU* also produced a report based on their examination of the *MVHR*'s performance. The passive house was in its first full year of operation and had yet to be certified by the *PHI*. Hence, *ESRU* encountered some system teething problems.

Initially, the *MVHR* was positioned in the centre of the house, causing multiple problems relating to the long duct runs. Upon replacing it, the ceiling needed to be removed which uncovered extremely wet ducting and surrounding mineral wool insulation. When it was replaced, the *MVHR* was re-positioned to its present location, adjacent to an external wall. This decreased the required duct runs, solving numerous issues. The insulation was still deemed too thin however, only 19mm in thickness. It was not sealed to the ends of the ductwork, resulting in excessive thermal losses. Condensation was still deemed a risk however, as poor insulating material was also used. There were no air transfer openings under doorways, blocking the distribution of air and heat around the home. The occupant was also unclear about the system's operation and maintenance requirements. Following *ESRU*'s study, a list of recommendations to remedy these issues was sent to those responsible for the buildings construction and operation, *Fyne Homes*.

From inspection methods performed in this project, it was clear that numerous issues have been successfully addressed. The insulation around all ductwork has been replaced by high quality rubber-based insulation, 100mm in thickness as recommended by the system's supplier. Condensation risks have been minimalised if not erased. Air transfer openings have been applied to all doorways, ranging between 25 and 30mm. This eliminates the need to leave all doors open and is well above the recommended minimum of 15mm. The occupant has been informed about the *MVHR* operation and the need to change the filters at least twice per year.

6.2. Temperature Transfer Efficiency

The temperature transfer efficiency is a good indicator of how an *MVHR* unit is performing. It is calculated using the following formula;

$$\eta = \frac{T_{supply} - T_{fresh}}{T_{extract} - T_{fresh}}$$

According to the *Passive House Criteria* '*at least 75% of the heat from the exhaust air is transferred to the fresh air again by means of a heat exchanger*.' This is a fundamental requirement for all certified passive housing worldwide. Using the data logged supply, fresh air and extract temperature sensors in this monitoring project and understanding the operation of the *MVHR* unit, it was possible to calculate the operational temperature transfer efficiency. This has been tabulated below;

Day:	25th	26th	27th	28th	29th	30th	1st	2nd	Overall Average
Operational 'Temperature Transfer Efficiency' Average:	0.85	0.84	0.86	0.87	0.88	0.86	0.81	0.85	0.85

Table 15: MVHR Average Daily Temperature transfer Efficiency

From the data, it is clear that the system is performing as designed, with regards heat transfer efficiency. It is 10% above the *PHI* requirement for the test period. The system's operation becomes more important during winter operation as there is a greater temperature difference between the external and internal environment. The heating load is increased and the heat recovery from the *MVHR* becomes critical in limiting the demand placed on the building's *ASHP*. From the data, the 27th provides the coldest external conditions and the efficiency achieves an average value of 0.86. This must be seen as a positive result.

6.3. Thermal Comfort during Summer Operation

According to the *PHI* criteria, '*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.*' This is in conjunction with *CIBSE* guidelines which states that domestic internal environments should range between 21 - 25°C with relative humidity in the range of 30 – 70%. The entire test period has been analysed for overheating potential, disregarding the period for which the *ASHP* was tested. The results have been tabulated below;

Room:	Living	Bed 2	Master	Kitchen	Hall	House Average	Units
Frequency above 22°C:	25.76	20.33	81.06	54.94	31.01	42.62	%
Frequency above 25°C:	2.42	0.00	7.05	0.00	0.00	1.89	%
Average Temperature:	20.26	21.64	22.94	22.20	21.63	21.73	°C

Table 16: Room Space Temperatures

Overall, it is clear that the *MVHR* ensures that the passive house meets the *PHPP* and *CIBSE* design criteria for thermal comfort. Overheating is experienced, but within the limits deemed acceptable. The living room experiences overheating in the morning when solar irradiance is high. This is due to the room's orientation and high glazing percentage. However, this room is typically unoccupied apart from late in the evenings so this is not an issue. The room is comfortable when in use. The master bedroom is the only issue worth examining. This is by far the hottest space in the home. This space suffers overheating on days of high solar irradiance between 15:00 – 00:00 hrs. This is due to a number of factors including the west facing glazing, low *MVHR* supply volume flow rate (discussed later), occupancy heat gains and fewer external openings upstairs for manually controlled natural ventilation. The local midges problem also prevents manually controlled natural ventilation at night!

The day whereby overheating occurrence is highest has been graphed below;

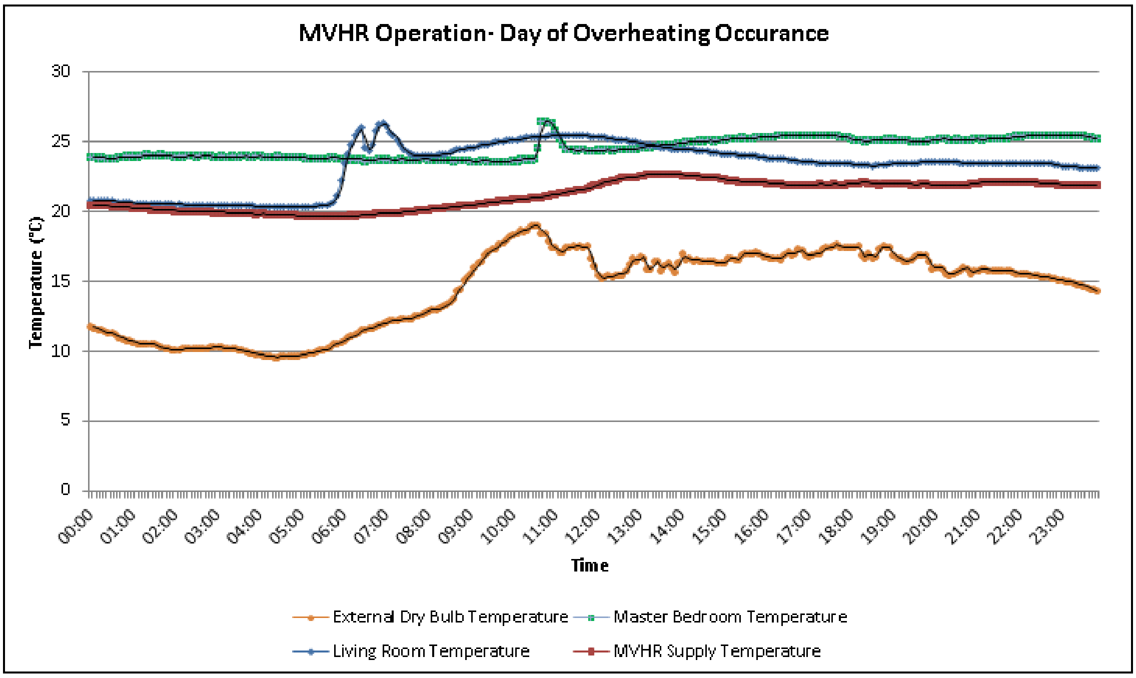

Figure 15: *MVHR* and Space Temperatures on Day of Frequent Overheating

On this day, the master bedroom experiences overheating for 37% of the time, with an average temperature of 24.55°C. This must be considered high. The living room experiences overheating for 15% of the time, with an average temperature of 23.27°C. Although this is not a major concern due to the relatively low frequency over the test period, this could have easily been eradicated with the implementation of an *MVHR* summer by-pass. From the data, this is not in use for this summer's operation. In Dunoon, additional control and equipment to operate summer by-pass operation should be considered an unnecessary cost and control complication, and the monitoring backs that up.

Overall, the 1.89% house average overheating for the test period is below the 2.8% *PHPP* summer prediction. The *MVHR* is operating well with respect to internal temperature. From the performed occupant's survey, the *MVHR* feedback has been extremely positive. A score of 7/7 was given for level of control, with the occupant claiming to have full ventilation control and '*very happy*' with the system's operation. The internal environment was described as '*still, fresh and odourless with no relative humidity issues*.' The summer temperature was judged to be perfect during both day and night.

6.4. Performance in Colder Conditions

As stated, the *MVHR* is of vital importance during winter operation. Its heat recovery is critical in maintaining an ambient living space. Monitoring the *MVHR*'s performance during winter external conditions was not possible during the time of this project. However, much can be taken from analysing the system's performance during the coldest 24 hours of data available. Here, the '*COP*' was analysed to determine the heating effect the *MVHR* unit was having on the home. Although *COP* is widely used for air-condition purposed, altering it here to indicate the cooling effect per input unit of electricity draws interesting performance information. The formula used is as follows;

$$\text{'}COP\text{'} = \frac{m \times C \times (T_{supply} - T_{outside})}{P_{fan}}$$

Using this formula and the data logged throughout the test period, the following graph could be plotted;

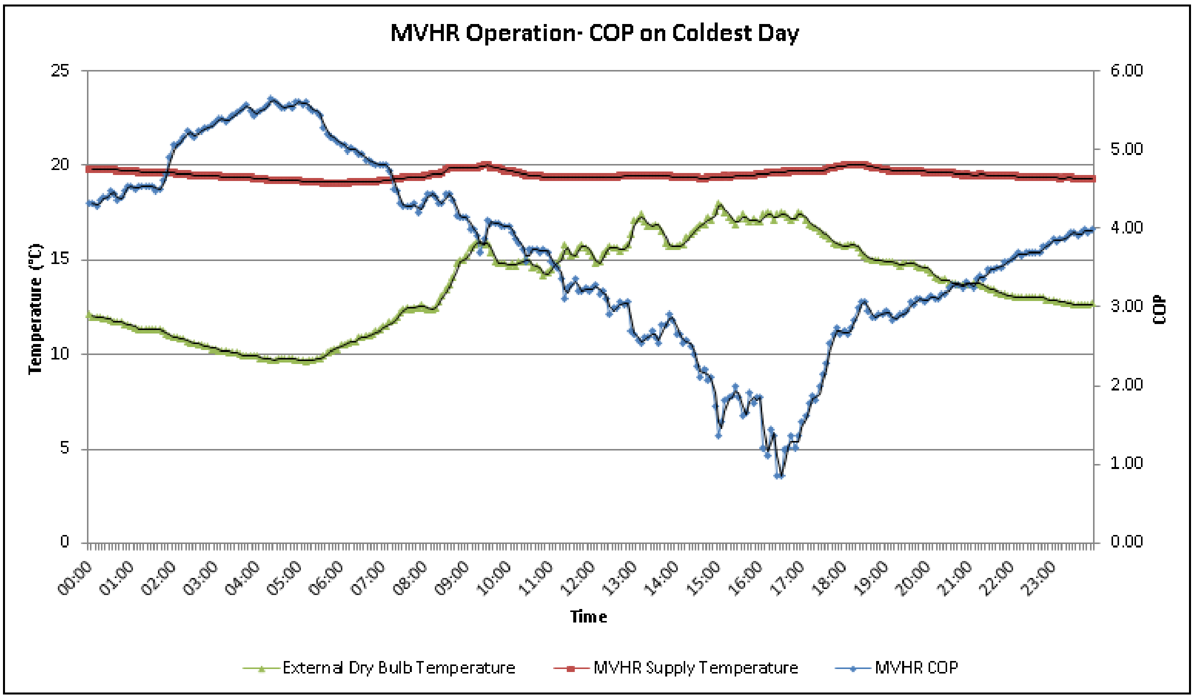

Figure 16: *MVHR* and External Temperatures on Coldest Day. Also, Corresponding COP.

Here, the temperature drops below 10°C for the only prolonged time within this test period. It is evident from the graph that the '*COP*' increases as external temperature drops. This is due to the greater driving force for thermal transfer with the *MVHR*'s heat exchanger with no increase in power input to drive the ventilation process. It is critical to note that the supply temperature to the rooms remains relatively constant, even at the lower external temperatures. This is due to the very high temperature transfer efficiency of the device. This is an extremely positive sign for winter operation. This has been guaranteed by the manufacturer and is holding up under intensely scrutinised monitoring. It would be ideal to perform this test under winter conditions below 0°C. This is another indication that summer by-pass operation would just complicate the systems operation in Scotland. Although it's the depths of summer, the *MVHR* is maintaining an ideal internal ambient temperature. Full fresh air supply with summer by-pass would reduce the internal temperature below the desired 20°C ideal minimum recommendations.

Issues regarding thermal comfort in the winter have been highlighted by the homeowner. However, these shall be discussed in the *ASHP* analysis.

6.5. Running Costs

Apart from winter operation, the *MVHR* runs on a constant basis on '*Setting 2*'. This has been verified with the homeowner. From the monitored data, the summer running costs could be calculated with relative ease. Calculating the annual running costs was not possible as this would require roughly estimating the period of time the *MVHR* operates on '*Setting 3*'. This is highly variable, dependant on user preference and external conditions yielding little conclusions. The operational current would also be an estimate based on the manufacturer's data. This is often optimistic, as is quantified under idealistic test conditions. However, the summer running costs calculated from the actual metered data have been outlined below;

	Value	Units
MVHR Average Current:	0.14	A
System Average Wattage:	34.0	W
Operational hours per Week:	168.0	Hrs
kWhrs per Week:	5.71	kWhrs
Cost of Weekly Operation:	0.635	£
Cost of Summer Operation:	8.254	£

Table 17: MVHR Running Costs

Due to the stringent air-tightness guidelines for passive house design, requiring air changes below $0.6Ach^{-1}$, the constant operation of the *MVHR* system is mandatory to provide sufficient volumes of fresh air to the occupants. The low wattage recorded on the low setting resulted in a low running cost. £8.25 for the entire three months of summer must be considered cheap as the system provides both ventilation and maintains thermal comfort.

6.6. Commissioning/Maintenance issues:

A basic system performance test was undertaken on site by *GSA*. An anemometer was used to measure the volume flow rates of all supply and extract ducts within the passive house under '*normal*' (Fan Setting 2) and '*boost*' (Fan Setting 3) operation. The system was also tested with clean filters and with a 50% cardboard occlusion to simulate dirty filter operation. Due to timing limitations, these test results were taken from *GSA* for the purpose of this project. The data was verified on site by taking spot measurements. The results have been tabulated as follows;

Extract:	Clean Filter			50% Occlusion		
	Setting 2	Setting 3	Variation	Setting 2	Setting 3	Variation
Room	(l/s)	(l/s)	(%)	(l/s)	(l/s)	(%)
Kitchen:	8.00	13.40	0.60	7.20	13.60	0.53
Hallway:	3.30	5.40	0.61	3.10	5.30	0.58
Downstairs WC:	4.70	6.40	0.73	3.10	5.30	0.58
Bathroom:	5.50	9.30	0.59	5.60	8.70	0.64
Total:	21.50	34.50	0.62	19.00	32.90	0.58
Total (m^3/hr):	77.40	124.20	0.62	68.40	118.44	0.58
Design Flow Rate (m^3/hr):	85.00	131.00	0.65	85.00	131.00	0.65
% Leakage/Losses:	8.94	5.19		19.53	9.59	

Supply:	Clean Filter			50% Occlusion		
	Setting 2	Setting 3	Variation	Setting 2	Setting 3	Variation
Room	(l/s)	(l/s)	(%)	(l/s)	(l/s)	(%)
Living Room:	4.50	5.60	0.80	4.50	6.10	0.74
Master Bedroom:	8.10	12.50	0.65	7.50	12.30	0.61
Bedroom 2:	8.10	11.60	0.70	7.30	11.30	0.65
Total:	20.70	29.70	0.70	19.30	29.70	0.65
Total (m^3/hr):	74.52	106.92	0.70	69.48	106.92	0.65
Design Flow Rate (m^3/hr):	85.00	131.00	0.65	85.00	131.00	0.65
% Leakage/Losses:	12.33	18.39		18.26	18.39	
Supply:Extract	0.96	0.86		1.02	0.90	

Table 18: MVHR Volume Flow Rate Test Results

The supply:extract ratio is very important in ensuring a high level of heat transfer in the *MVHR*'s heat exchanger and maintain the thermal efficiency above the *PHI* requirement of 75%. 0.96 calculated here during normal operation is very good. This improves as the filters become blocked. 0.86 under boost conditions is quite a drop off. This is alarming as the *MVHR*'s performance gains greater importance under this setting in winter operation. There will be a greater level of heat transfer as the ratio decreases but the volume flow rate of hot air supplied to the rooms will be significantly lower. Overall, the losses witnessed are to be expected due to duct leakage and a drop in fan performance over time. These losses stand at 9% for the extract and 12% for supply under normal operation. Upon system inspection, the standard of installation must be deemed of very high quality since the *MVHR* unit replacement and system upgrades have been made.

Under monitored summer conditions, the system operation must be deemed successful. However under winter operation when the fan operates in ‘*Boost*’ mode, the system becomes more unbalanced, favouring depressurisation. This results in higher running costs and additional wear on the fan units. The supply volume low rate is over 18% lower than the manufacturer’s catalogue. This has a large bearing on heating distribution in winter and reducing the load on the *HP*. Performance drops even further as static pressure rises within the ductwork under occlusion testing. The importance of clean filters has been stressed to the occupant, especially in winter.

Fresh air supply is another worrying factor highlighted in the test results. *CIBSE* recommends a minimum of 8l/s of fresh air per person in domestic dwellings. The total delivery of 20.7l/s under ‘*normal*’ *MVHR* operation and 19.3l/s when the filters become clogged is unsatisfactory for a house designed for 3 to 4 inhabitants. A minimum fresh air supply of 32l/s was expected. The fresh air supply to the living room is inadequate for even one person. This has a bearing on thermal comfort and health.

6.7. MVHR System Conclusions

From the system analysis, some general conclusions have been made. These are as follows;

1) The *PHI* criteria regarding the *MVHR*'s operating efficiency is being met successfully, with an average temperature transfer efficiency of 85%.

2) The *MVHR* is providing a high level of thermal comfort and is preventing over-heating in the summer effectively. This too is in line with *PHI* criteria.

3) The system's operation should be considered cost effective and very user friendly.

4) The *MVHR* is not supplying sufficient and healthy levels of fresh air to the home.

5) From the monitored data, the system will encounter problems during winter operation when it is required to assist the heat pump in meeting the space heating load and distribute the heat around the house. This shall be discussed further in the next section of this report.

7. ASHP Analysis

The third and final mechanical system investigated and analysed in relation to various aspects of performance is the passive house's *ASHP*. Firstly, the *ASHP* was tested under '*winter*' operation. Here the achieved *COP* and distribution of heat around the home has been scrutinised with the potential to achieving thermal comfort discussed. A similar test was performed for the *ASHP* operating in cooling mode. These tests were performed in tandem with the functioning *MVHR*.

Unlike the previous tests and data logging, numerous problems were encountered when evaluating the system's operation during both summer and winter external environmental conditions. Firstly, the external conditions themselves were not ideal with the homeowner undertaking the heating test when the external temperature was above 10°C and the cooling test when the external temperature was below 20°C. Furthermore, the homeowner executed the test with the *MVHR* set on the '*normal*' fan setting and not '*boost*' and had the *ASHP* operating on its lowest volume flow rate setting. Unfortunately the installation of the monitoring equipment and testing had to be non-invasive, therefore one could not perform detailed, time consuming tests on the day of installation or removal. It is important to highlight this at the beginning of the analysis to provide clarity and context to the discussion ahead. Although not a definitive testing procedure, it is felt that some valuable conclusions can be drawn from the test data obtained.

7.1. Previous Studies

ESRU: In conjunction with their testing of the *STHW* and *MVHR* systems, *ESRU* included some notes on the passive house's *ASHP* in their 2011 study, following a year one monitoring process. They highlighted the issue of the required defrost operation during extreme winter conditions. This occurred when the outdoor unit drop below 6°C for prolonged periods of time, negatively impacting the systems *COP* and reducing the energy delivered to the home as heating operation ceased during these periods. The manufacturer was contacted regarding this issue yet could not provide any insight or data relating to the affected performance. In this test, temperatures did not drop low enough to test performance incorporating defrost operation. Since the *ESRU* monitoring and report, the *ASHP* has been replaced by a larger and upgraded model due to inadequate winter operation.

With regards the house's *PHPP*, an annual *COP* of 2.50 had been specified. This was based on the manufacturer's '*Seasonal COP*' for the original system. It is clear that the *PHPP* design tools contain flaws as the system was undersized. Another point to note is that the *PHPP* does not specify predicted modelling performance data at low external temperatures. This is critical for operation in Scotland.

7.2. Heating Operation Testing

[Note: Following the administration of test instructions to the homeowner, it was discovered that it was not possible to relate the variable operational currents powering the *ASHP* to a precise mass flow rate. The mass flow rate of air could not be measured during the test for reasons outlined in the previous section. Instead, for the purpose of relative accuracy and to not deem the monitoring and testing invalid, the manufacturer's guidelines for the *ASHP* setting under test conditions was used to obtain an operating current and delivered mass flow rate. From this, analysis could begin as the *COP*, running costs and heat distribution under test conditions could be calculated.]

Although this project occurred during the summer period, it was possible to simulate a test period whereby the *ASHP* would be required to meet a high heating load. This was achieved by requesting that the homeowner undertook an *ASHP* test when the external temperature dropped to its lowest at night and altered the internal temperature set-point to its absolute maximum. This resulting ΔK ensured that an unattainable heating load would be present and that the *ASHP* would operate at its maximum for the corresponding volume flow rate set point. The test lasted one full hour. From the data logged during the monitoring process and test, the *COP* could be calculated using the following formula;

$$COP = \frac{m \times C \times (T_{sink} - T_{source})}{P_{fan}}$$

From this equation and data, the following graph could be plotted;

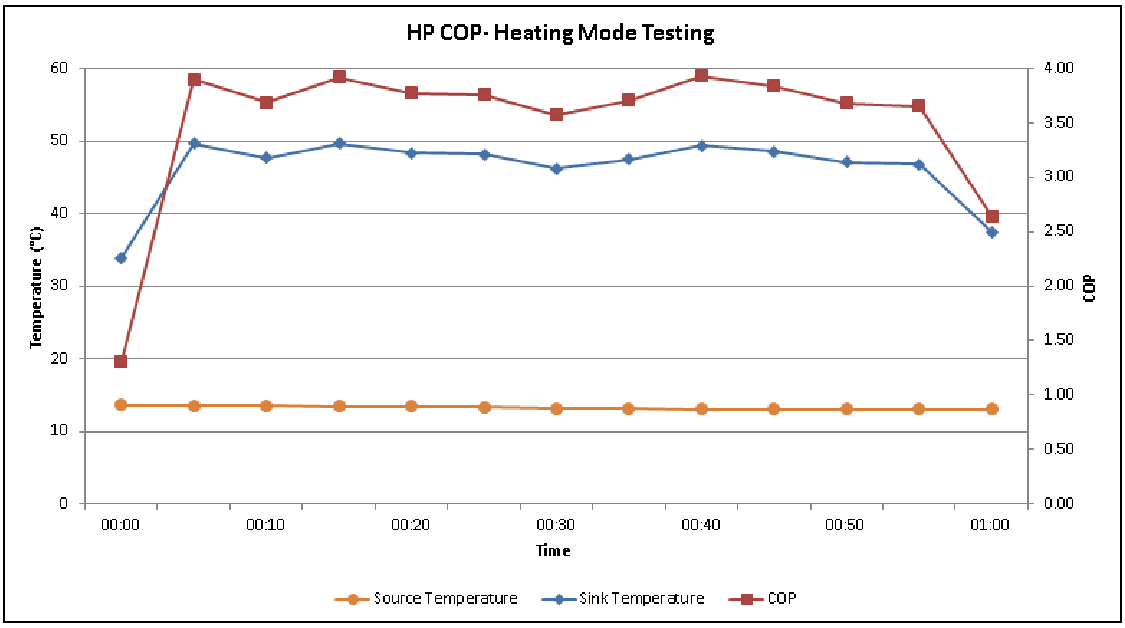

Figure 17: *ASHP* Temperatures and Corresponding COP during Heating Test

The manufacturer's data indicates that the maximum achievable *COP* is within the range 3.93 – 4.00. This is under stringent test conditions where the source temperature is 7.0°C and the internal temperature is 20.0°C. During the on-site test, conditions have been similar to this with an average source temperature of 13.2°C and an average internal temperature at the sink of 20.8°C. Therefore, even though it was the middle of summer, a realistic *ASHP* test was achievable to test the manufacturer's data. The *COP* averaged 3.49. This must be considered high, with over 3 units of heat being delivered for every 1 unit of electricity consumed. Modern heat pumps typically achieve a *COP* in the range of 2 – 4. The sink temperature rises to almost 50°C under test conditions, delivering an average of 2.6kW throughout the test.

$$Q_h = m \times C \times (T_{sink} - T_{hallway}) = 0.1074 \times 1005 \times (46.2 - 22.0) = 2612W$$

The unit is rated at 4.0kW. From previous tests and background research it is evident that the *COP* is not as good under '*real*' Scottish winter conditions. The quoted test conditions are not what are to be expected on-site in winter. Ideally, testing below ≈ 5°C would have taken place.

The heat distribution around the home has been plotted below. The graph shown is from the start of the test until two hours after the test, as there is a time lag in heat distribution around the house. This is one of the key functions of the *MVHR*'s operation when working in conjunction with the *ASHP* as the *ASHP* only delivers heat into the ground floor hallway.

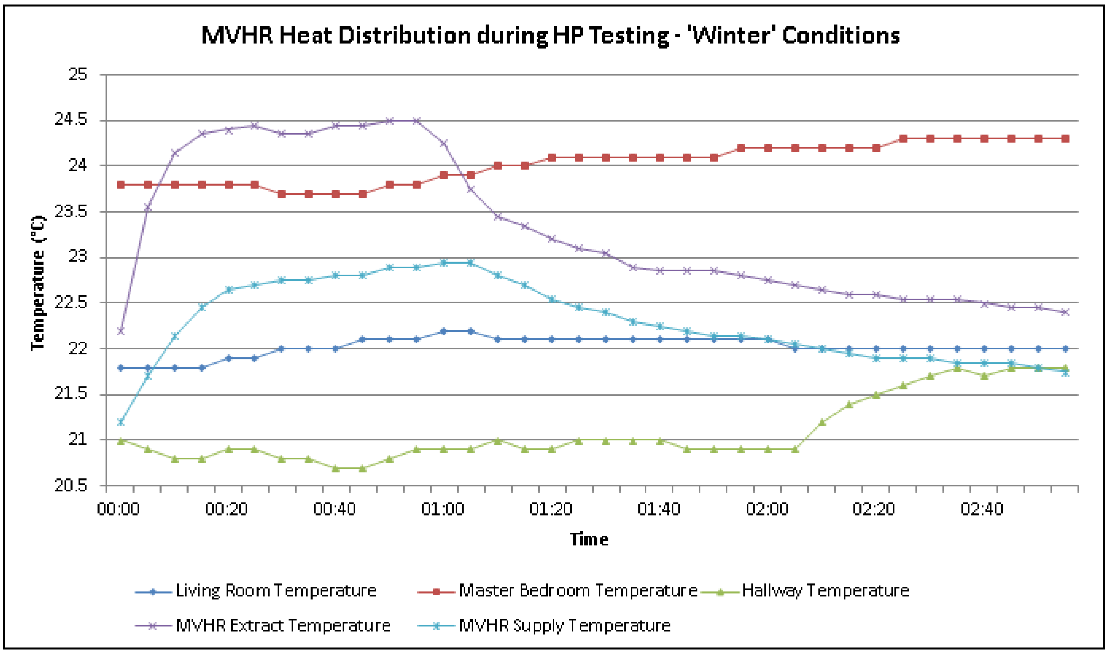

Figure 18: *MVHR Heat* Distribution during Heating Test

From the graph, it is clear that all three rooms have a net rise in temperature from the beginning of the test to the two hours after the test is complete. The master bedroom and hallway temperature both rise by approximately 1°C. The different time lags for temperature rise are interesting as the supply volume flow rates, room dimensions and sensor positioning is unique for each space. Overall, the temperature rise is not dramatic. However, it must be highlighted that the delivered volume flow rate by the *MVHR* is extremely low due to the '*normal*' fan setting. More importantly, the sharp rise in *MVHR* duct temperatures during the test period indicate the impact the test has on the system. Both the supply and return duct temperatures rise by approximately 2K and fall sharply following the completion of the test. This indicates the important function of the *MVHR* in action during simulated winter operation. Ideally, the *MVHR* and *ASHP* fan settings would have been maximised for testing purposes.

7.3. Cooling Operation Testing

The same methodology has been applied to the summer operation test method and analysis. Here the *ASHP* maximum design *COP* is outlined as 1.02 by the manufacturers' catalogue. This has been attained under test conditions of a 35°C source temperature and an internal temperature set point of 27°C. Realistically, these conditions would never be met in Scotland. This *ASHP* has not been primarily designed for cooling operation. The poor quoted *COP* indicates this as the on-site performance will yield less than one unit of cooling energy for every one unit of electrical input regardless of the operating conditions. However, it is interesting to test the actual performance against the manufacturer's literature.

The homeowner could only perform the test when the source temperature averaged 16°C and the internal temperature was 22.3°C. This is typical for Scotland. This was at mid-day when solar irradiance and the external temperature were at their daily maximums. The internal temperature set-point was reduced to its absolute minimum in order to simulate the maximum available cooling load to ensure that the *ASHP* would operate at its maximum output for the specific fan speed setting. The *COP* formula used to analyse the systems performance was as follows;

$$COP = \frac{m \times C \times (T_{sink} - T_{source})}{P_{fan}}$$

From this, along with the monitored data, the following graph could be plotted for the test period;

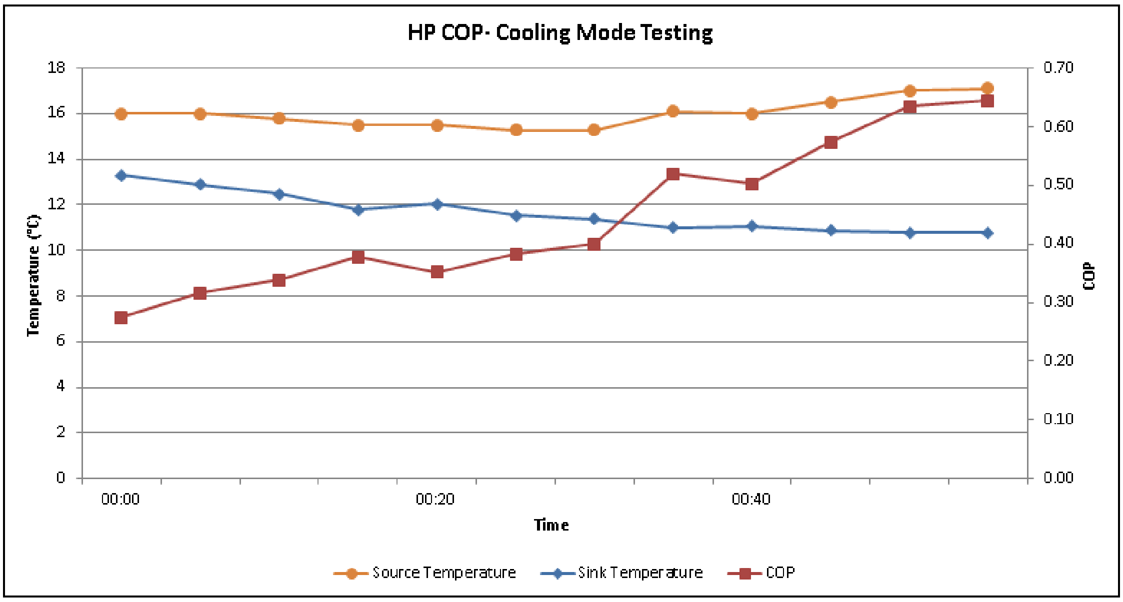

Figure 19: *ASHP* Temperatures and Corresponding COP during Cooling Test

[Note: The *Energy Efficiency Ratio* (*EER*) is often cited as the way to express the efficiency of a heat pump but this is directly proportional to the *COP*, hence it has been disregarded. It effectively makes *ASHP*'s operating in cooling mode seem more energy efficient than they are. (*EER* = 3.41 x *COP*)]

The *COP* rises to a maximum of 0.65 when the source and sink temperature difference reaches is maximum. This is due to the rising external (sink) temperature, creating a greater thermal driving force for mechanical cooling. The *COP* average sits at 0.45 yielding less than half a unit of cooling delivered for every single unit of electricity consumed by the heat pump. Luckily the heat pump is only required for heating purposes as this would be a highly inefficient method of cooling the passive house. This highlights the importance of the *MVHR*'s operation to minimise overheating during the summer months.

The average cooling load delivered into the house during the test period made minimal impact on the internal temperatures. The average cooling effect on the hallway was as follows;

$$Q_c = m \times C \times (T_{hallway} – T_{sink}) = 0.1074 \times 1005 \times (22.3 – 11.7) = 1144W$$

Upon studying the monitored data, the hallway dropped by 0.5K over the course of the test but the other rooms in the house remained relatively unchanged with no noticeable cooling effect. The mechanical cooling delivered was not great enough to impact the *MVHR* duct temperatures. This was not aided by the low fan setting of the ventilation unit itself as supply and extracts volume flow rates to and from the rooms was very low. This test did not occur under ideal test conditions.

[Note: Due to the limited testing and altered logged operational current for accuracy purposes, outlined previously, system running costs could not be calculated in detail. This would be an entirely different project analysing space heating load profiles and user control settings for heating and cooling over a designated period. From the data, it was simple to determine that the *ASHP* cost 11.6p to run the heat pump for the hour at which '*winter*' conditions were tested.]

7.4. ASHP System Conclusions

From the system analysis, although the testing and monitoring of the *ASHP* was not ideal some general conclusions can be made. These are as follows;

1) The *ASHP* achieved high *COP* results under testing in simulated ‘winter’ conditions and the *MVHR* effectively distributed the heat around the home. The signs were good for real winter operation. However, this is inconclusive as testing could not take place during extremely low external temperatures and resulting high space heating loads.

2) The *ASHP* should not be used to provide mechanical cooling. It performs poorly, resulting in high costs and energy consumption. Natural ventilation and *MVHR* operation are sufficient for preventing overheating and maintaining thermal comfort.

8. Project Conclusions

This project has highlighted some fundamental system design and operational flaws that still need to be addressed to optimise the building's performance. Firstly, the *STHW* system currently achieves 43% of its *HW* contribution via solar thermal, far below the design team prediction of 97% for June operation. This report has indicated how simply switching the control logic can raise this contribution to approximately 71%. It has also been shown how the threat of legionella has not been completely eradicated all year round. On a positive note, the system's current operation costs the occupant 28% less on average when solar irradiance levels are high when compared to days of poor solar conditions. The solar thermal circuit is saving the homeowner money and energy.

Secondly, the *MVHR* system meets the *PHI* criteria by recovering heat with an average monitored temperature transfer efficiency of 85% consuming a low level of electricity. Whilst the system prevents overheating of the passive house by meeting the building's cooling load all year round, it does not provide the adequate volumes of fresh air supply should the building be occupied for the designed level of three or four people. At present that is not an issue. Furthermore, the low volume flow rates mean that heat is not distributed sufficiently during winter operation to meet the building's high heating load. This was highlighted during the testing of the *ASHP* and contact with the homeowner. The *ASHP* testing may be deemed inconclusive. However it was concluded that it should never be used as a cooling device and that issues would be experienced when attempting to successfully meet the peak heating load. Testing did indicate that the heat pump can achieve an average COP of 3.49 in heating mode.

Overall, the report may be viewed as detailed follow-up to previous case-studies and system changes with a lot of positives discovered with regards the building's operational performance. The home is now operating far better than originally constructed and commissioned in 2011. Incorporating the system suggestions within this report shall further enhance the performance of the UK's first affordable passive house.

As a general conclusion from this study, it is difficult to envisage a widespread roll-out of passive house expansion across the UK. The concept requires substantial additional investment of costs and resources in the planning and construction phases leading to poor economic payback times when compared to conventional homes built to high construction standards. However, the Dunoon passive house is a marquee project operating at an extremely high performance with regards energy. The building has been constructed to meet the *PHI* design criteria and has been successfully certified. This study has highlighted the mechanical systems and building envelope's ability to work in conjunction to achieve a high level of thermal comfort and occupant satisfaction for the majority of the year.

9. Possible Further Work

As outlined in this report, the methodology used to examine the performance of the passive house may be adapted to any other building and set of similar thermal mechanical systems. The testing and monitoring methods are not case specific. This report and analysis could easily be modified for a new *STHW* system incorporated into a school in France per say.

With regards this specific test site, further work to enhance this analysis may be performed. A number of suggestions have been outlined below;

STHW:

1. To calculate the monthly and annual *HW* contribution from solar thermal energy. This would require test data for other seasons of the year. Adapting this test data to achieve this was considered but extrapolating the 8 day testing period for one full year would be deemed pointlessly inaccurate. Also, the detailed building and system modelling would have had to be the sole aim of the project. This was not the case.

2. To implement the new recommended control logic and monitor and analyse the system improvements with regards primary energy consumption, running costs and *HW* supply.

ASHP:

1. A focus on the *ASHP*'s operation in winter would be beneficial. Testing the system in conjunction with the *MVHR* both operating at their winter volume flow rate set-points to meet peak heating loads would help the homeowner who has had trouble with the system since the opening of the house. This would further highlight the *PHPP* design flaws.

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