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PASSIVHAUS SUMMER OVERHEATING:

THE DEVELOPMENT OF AN EFFECTIVE NATURAL VENTILATION SYSTEM

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ABSTRACT

Concern regarding overheating potential has been growing in the UK as buildings are being built to higher standards like Passivhaus. Lack of window operation due to noise and security implications specifically at night, alongside higher expected temperatures in the future can only add to this concern. Furthermore the quality of incoming fresh air through windows in Passivhaus dwellings could be lower compared to filtered air in MVHR systems. The aim of this research is to investigate the possibility of overheating in reference Passivhaus dwellings and consequently, to examine and propose a remedial natural ventilation strategy and system for the non-winter period. The internal temperatures, indoor CO_2 levels alongside frequency and duration of window openings were recorded using data loggers and sensors. A dynamic thermal model was created in DesignBuilder using data from the original PHPP model and further amended by results from monitoring, creating a base case model. A specific natural ventilation system was modelled using the base case model to increase efficiency and effectiveness of natural ventilation. The proposed system was also tested for the winter period in terms of airtightness and thermal bridging as well as forecasted future climate data. The proposed system increases natural ventilation rates compared to the original design, thereby reducing summer overheating for current and future climate by around 20%. Passivhaus designers can benefit from this system for new building designs or for refurbishment of existing Passivhaus building stock that could encounter overheating in the future. The system can be tested in the PHPP calculation allowing the elimination of all window operations during the cooling season.

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NOMENCLATURE AND SYMBOLS

Symbol	Description	Units
ach	Air Change per Hour	-
CO_2	Carbon Dioxide	ppm
f_{Rsi}	surface temperature	°C
K	Temperature in degrees Kelvin	K
n_{50}	Passivhaus airtightness	-
Pa	Pascal	-
P_H	Heating Load	W/m^2
P_K	Cooling Load	W/m^2
PMV	Predicted Mean Vote	-
PPD	Predicted Percentage Dissatisfied	%
Psi	Psi-Value, linear thermal bridging coefficient	W/mK
Q_G	Total Heat Gain	kWh/m^2
q_H	Specific annual heat demand	kWh/m^2
Q_H	Annual Heating Demand	$kWh/(m^2a)$
Q_K	Sensible useful cooling demand	$15kWh/m^2$
Q_L	Total Heat Loss	kWh/m^2
rH_i	indoor air humidity	%
R_{si}	Internal heat transfer resistance	m^2K/W
T_{comf}	Thermal comfort	°C
T_{om}	Monthly mean outdoor temperature	°C
T_{rm}	Exponentially weighted running mean of the daily mean outdoor air temperature	°C
TFA	Treated Floor Area	m^2

$\mathbf{U}$	U-Value, thermal transmittance coefficient	W/m^{2}K
$\mathbf{V_v}$	Net volume	M^3
$\mathbf{W_p}$	Primary Energy Demand	kWh/(m^{2}a)
$\mathbf{\Theta_{si}}$	Minimum Average Surface Temperature	°C
$\mathbf{\Theta_{op}}$	Average Operative Room Temperature	°C

ACRONYMS AND ABBREVIATIONS

BRE	Building Research Establishment
CFD	Computational Fluid Dynamics
CSH	Code for Sustainable Homes
DSM	Dynamic simulation model
DTM	Dynamic Thermal Model
ET	Effective Temperature
GHG	Greenhouse Gas
IAQ	Indoor Air Quality
IES	Integrated Environmental Solutions
IPCC	Intergovernmental Panel of Climate Change
MVHR	Mechanical Ventilation with Heat Recovery
PHI	Passivhaus Institute
PHPP	Passivhaus Planning Package
PV	Photovoltaic
RH	Relative Humidity
SBEM	Simplified Building Energy Model
SET	Standard Effective Temperature
UHI	Urban Heat Island

CHAPTER 1. INTRODUCTION

1.1. AN OVERVIEW

In recent years the need for low emission buildings has become widely recognised by Governments and end users due to the increasing greenhouse gas (GHG) emissions which have led to change in climate (Roaf et al., 2005). The latest UK Government response to climate change was to pass a bill on the 28th of October 2008 to cut CO_2 emissions to 80% (Figure 1-1) from 1990 levels by 2050 (HMSO, 2008). Furthermore as buildings account for around 50% of the overall GHG emissions (Figure 1-2) (Roaf et al., 2005), the importance of designing and constructing to higher building standards can be appreciated. This is further emphasised by the Intergovernmental Panel on Climate Change (IPCC) estimating 40% reduction in CO_2 emissions by 2030 due to more efficient building constructions (Schnieders, 2009).

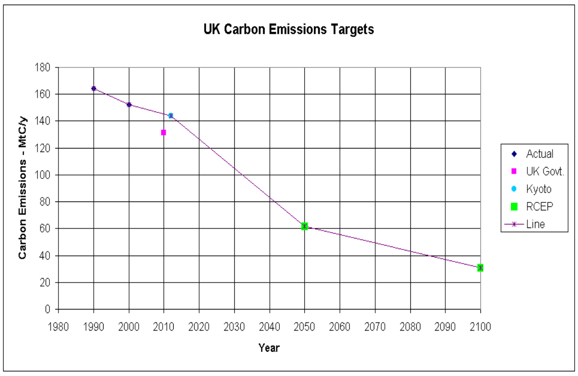


Figure 1-1- Graph showing the UK government CO_2 reduction target (source: Rajat Gupta 2008)

Traditionally the need for heating in the UK is higher than cooling demand especially for residential dwellings owing to the more moderate climate which has led to an increase in insulation and higher airtightness requirements in building standards such as the UK's Code for Sustainable Homes and the adoption of the German standard of Passivhaus. Moreover the reduction in CO_2 emissions would be most effective in moderate climates when targeting the heating requirements leading to subsequent problems and possible summer overheating (Hopfe & McLeod, 2015).

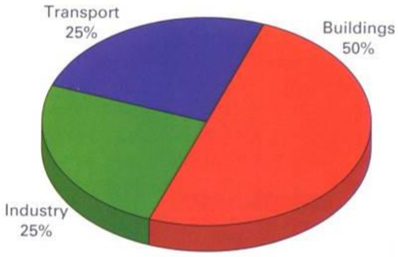


Figure 1-2- Percentage of fossil fuel use in developed countries (source: (Roaf et al., 2005) **P.4)**

Passivhaus requires a minimum airtightness level of 0.6 ac/h (air change per hour) at 50Pa (Pascal), for the liveable area defined as treated floor area (TFA). The airtightness requirement combined with a high level of insulation and elimination of cold bridging, to say the least, will achieve a maximum space heating and cooling demand of 15kWh/m^2 (Passive-On, n.d.). Furthermore building to Passivhaus standard will not only provide a high level of comfort for the occupants but also will help to reduce the energy requirements for the heating and cooling, by **90%** compared to the typical building stock and by **75%** compared to current standards in Germany (Figure 1-3) which can be very similar to the UK dwellings (Passive House Institute, n.d.).

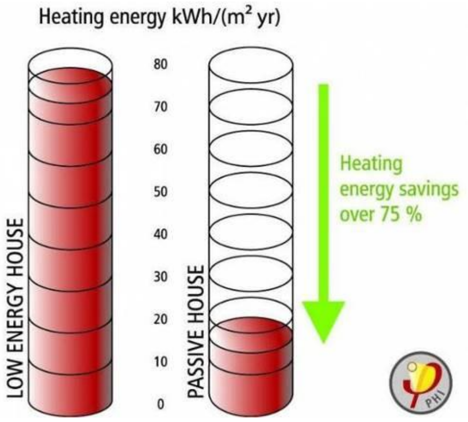


Figure 1-3- Passivhaus heating energy reduction in comparison to current standard (source: (Passive House Institute, n.d.)**)**

Passivhaus was developed by Wolfgang Feist around 24 years ago (Cotterell & Dadeby, 2012) and has rapidly grown across Europe, specifically Western Europe. Today more than 50,000 buildings have been built to the Passivhaus standard (IG Passivhaus, 2013) and it is becoming more widely used and recognised around the world. It has gone as far as some local authorities demanding the Passivhaus standard as part of the requirements to achieve a better and higher building standard. As such in **Frankfurt** from 6 September 2007, the magistrate is asking all new buildings belonging to the city administration to be constructed to Passivhaus standard and in **Freiburg** the Passivhaus standard was made mandatory for all new residential buildings from 2011 (International Passive House Association, n.d.).

Passivhaus is still a fairly new approach in the UK and because the first Passivhaus was only certified in 2010, there have been limited opportunities for carrying out post occupancy evaluation (POE) and monitoring. However there have still been some concerns regarding overheating in summer months in Passivhaus buildings due to their very airtight envelope and high level of insulation. Across Europe and recently in the UK there has been detailed monitoring and studying carried out in this area and this has highlighted the potential of overheating in Passivhaus buildings like Camden Passive House in London (Ridley et al., 2013) (McLeod et al., 2013). However in comparison, some of the studies carried out by Passivhaus Institute (PHI) has shown higher occupant satisfaction during the summer (McLeod et al., 2013).

It can be argued that the higher occupancy rate in the UK and perhaps the underestimation of the internal gains by the Passivhaus standard and calculation in PHPP (Passivhaus planning package) during the summer months, is leading to the increase of the overheating potential for the UK Passivhaus dwellings. Moreover as the climate is changing with warmer summers and more heatwaves expected in the future (Dengel & Swainson, 2012), the potential of overheating during the summer could further be increased for Passivhaus buildings currently being constructed in the UK alongside a higher predicted cooling demand for UK dwellings of around 50 TWh by 2050 and the associated impact (Hopfe & McLeod, 2015).

The issue of overheating in buildings and the need for a strategy to tackle this problem was further recognised in the recent report published during 2014 by the Committee on Climate Change for England, which underlines the importance of providing comfortable and cool environments in the existing and new buildings and calls for incorporation of a standard for overheating. It states the need for "*cost-effective passive cooling measures*" as part of the design to avoid the use of air-conditioning systems in the future as the climate gets warmer (Adaptation Sub-committee, 2014) P.9. Furthermore the changing climate could only be increasing the concern for overheating in buildings as it is expected by 2040 summer temperatures could be the same as the exceptional hot summer of 2003 (Lomas & Porritt, 2017).

One way to combat the potential of overheating in Passivhaus dwellings is to incorporate a purpose designed natural ventilation system as part of the construction. This could possibly increase the ventilation rate and therefore reduce overheating potential, but it must not pose security risks or noise problems compared to more traditional ventilation strategies. Moreover this can further improve the night time ventilation and still provide the opportunity to keep the same Passivhaus ventilation design.

It can be argued that as Passivhaus was originally designed for cold climates and therefore targets the reduction in heating demand, the higher ventilation requirements and overheating during the summer was not necessarily a high priority or in some cases an issue. However as the Passivhaus approach is becoming globally recognised and adopted alongside the changing climate, the importance of addressing summer ventilation can be much higher. Nevertheless incorporating a purpose designed ventilation system during the summer for Passivhaus will not be without its challenges as it can compromise the high airtightness requirements and lead to additional cold bridging for the heating season.

Moreover Passivhaus standard has a high emphasis on air quality and the use of filters as part of the mechanical ventilation with heat recovery (MVHR) which is compromised during the summer time by the use of windows for achieving a higher ventilation rate and therefore cooling. Consequently any proposed natural ventilation system should take this into consideration.

1.2. STATEMENT OF PROBLEM

This thesis sets out to address the concerns for overheating during the summer in Passivhaus dwellings in the UK by investigating the potential of overheating and the possible causes alongside the implications caused by overheating.

Without addressing overheating during the summer the occupant’s health could be at risk as well as a reduction in thermal comfort and occupant satisfaction in Passivhaus buildings. This could consequently reduce the uptake of Passivhaus standard in the UK and reduce the future stock. The reduction of constructing to a very high efficient standard like Passivhaus, which has proven to be an effective option during the winter period, can impact the reduction of CO_2 meanwhile contributing to climate change. Moreover the future changes in the climate could increase the problem of overheating during warmer summers making the current Passivhaus built in the UK to be of much lower efficiency due to their cooling need.

Additional ventilation required during the summer period has been given lower attention in the Passivhaus standard and PHPP calculation, perhaps due to the original nature of the standard aiming to reduce heating load. However natural ventilation can potentially provide the cooling load for the UK climate with a specific strategy and design.

On the other hand, overheating is not limited to Passivhaus buildings and any building can experience overheating in the current climate or in the expected warmer future climate, built either to higher standards or not. The issue of overheating can have a higher impact on elderly and vulnerable people whom are perhaps less inclined to regulate window operation and have higher concerns in respect to security. The expected death from overheating is to rise to 7,000 in 2050 from the current 2,000 people per year in the UK which can only increase the emphasis on this issue (Dengel & Swainson, 2012) (Adaptation Sub-committee, 2014).

1.3. EXPECTED BENEFICIARIES

The potential beneficiaries for this research will be Passivhaus designers and consultants as well as the Passivhaus Institute whom are responsible for further development and updates of the standard. However building owners including individuals, housing associations as well as developers and house builders could also benefit from this research.

Moreover the impact and beneficiaries of this research could be even wider taking thermal comfort and dissatisfaction into consideration in any building with overheating potential. The possibility of incorporation and introduction of a specific natural ventilation system which can overcome security concerns, would potentially have a wide range of beneficiaries not only in the UK but in other climates and countries. Finally, this proposal can potentially benefit other building types such as office buildings which could also be subject to overheating potential.

1.4. AIMS AND OBJECTIVES

The aim of this research is:

> **To investigate the potential and effectiveness of a natural ventilation system providing secured and filtered air during summer for current and future climate in Passivhaus dwellings.**

Research questions:

Why Passivhaus dwellings are subject to overheating during the summer in the UK?

How can natural ventilation be used to eliminate / reduce, overheating potential for UK Passivhaus dwellings?

Can a specific opening area be incorporated to provide a sufficient air change rate for summer to eliminate overheating?

To achieve these aims the following objectives are identified:

I. In depth study of Passivhaus standards and upper comfort temperature limit for summer months as well as different causes of overheating.

II. Detail analysis of data collected from two case study Passivhaus dwellings during the summer, determining the causes contributing to the indoor climate conditions.

III. Thorough examination of proposed natural ventilation systems for the two case study Passivhaus buildings in order to determine an effective strategy for current and future climates using Dynamic and PHPP calculations.

IV. Make recommendations for incorporating suitable natural ventilation strategies to maintain the air quality and reduce the potential for overheating during summer for the benefit of current and future Passivhaus buildings.

1.5. OVERVIEW OF RESEARCH METHODS

Following the in depth literature review into Passivhaus standard and understanding overheating (the possible causes contributing to overheating), a gap in knowledge was identified in respect to overheating in Passivhaus dwellings and the possible rectification. The literature review also covers different strategies and methods of providing natural ventilation and consequently possible cooling as well as understanding climate change and its impact on the overheating problem.

Two case study Passivhaus dwellings were consequently identified for monitoring, one built to Passivhaus and the other refurbished to EnerPhit standard. One building was built using lightweight construction materials and the other benefits from thermal mass, providing good comparison of the two construction types. Extensive monitoring was undertaken during the summer of 2014 providing comparison data for the dynamic thermal model. Other possible contributors to overheating in Passivhaus buildings were also examined by recording the incoming fresh air temperature and surface temperature surrounding the fresh air intake externally.

The dynamic thermal model was used in order to test different natural ventilation options using current and future climate data following validation of the model using the monitored data. The internal heat gains were also recalculated using PHPP8 and used in the dynamic simulation model.

A specific option was proposed following the dynamic simulation and tested in the PHPP model for further validation. The PHPP calculation option was further tested using an additional five Passivhaus buildings. Moreover a thermal bridging calculation was also undertaken in order to ensure the performance of the proposed option during the winter period. Finally all calculations were tested using different future climate scenarios using the dynamic and PHPP model for the two case study buildings.

1.6. INTRODUCTION TO THE CHAPTERS

Following the introduction section, chapter 2 provides a review of the Passivhaus standard and the associated ventilation strategy followed by an investigation into overheating and thermal comfort, focusing on the causes contributing to overheating including climate change. This chapter also includes an overview of natural ventilation including the forces and different strategies as well as an in-depth study of indoor air quality and ventilation rates before concluding with the study of post occupancy evaluation for buildings.

Chapter 3 sets out the methods used for undertaking the research including an introduction to the two case study buildings as well as the explanation of conversion from PHPP7 to PHPP8. The methodology chapter also includes the section for placement of the monitoring equipment as well as the climate data selection. The chapter concludes by exploring the different modelling methods and understanding of thermal imaging and calculation of internal gains during the summer period.

In chapter 4 the monitoring results for the indoor temperatures, relative humidity, indoor CO_2 levels and window operation for different areas of the case study buildings are evaluated as indicated in the methodology section. The ambient temperature using the data obtained from BADC is likewise investigated allowing comparison to the indoor temperatures. This chapter will also compare the monitoring results to the original PHPP model for better understanding of performance gap during the summer period. The impact and importance of climate on overheating is analysed by the use of the PHPP model. This chapter also examines the effect of the material used around the MVHR air intake, lack of insulation on the internal MVHR air ducts and MVHR summer by pass option, on indoor air temperature and overheating. The chapter is concluded by the calculation of the internal heat gain using PHPP8.

Chapter 5 is the dynamic thermal model calculation, starting with the initial model and the comparison of the data to the physical monitoring data leading to the base case model. Furthermore, three proposed options have been tested demonstrating the possibility of reducing and eliminating the overheating potential in the current climate scenario using a natural ventilation system.

In chapter 6, the longevity and the validity of the proposed Option 3 has been examined by testing this option for the future climate scenario of 2050 and 2080 using dynamic thermal simulation. In this chapter, the possibility of eliminating window opening and incorporating Option 3 as the only means of cooling during the summer period has been examined using dynamic modelling alongside PHPP calculation. Lastly, Option 3 has been tested for an additional 5 Passivhaus dwellings using PHPP.

Chapter 7 is the discussion chapter which includes a closer look at PHPP in respect to the climate data and shading as well as the glazing area and the ventilation during the summer. The discussion chapter looks at the monitoring results and the fresh air intake temperature followed by the reappraisal options. Chapter 8 is the conclusion and recommendations followed by recommendations for further research.

CHAPTER 2. LITERATURE REVIEW

2.1. PASSIVHAUS – AN OVERVIEW

Passivhaus (Figure 2-1) is a building defined as:

> *"… a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air".*
>
> (Passive House Institute, n.d.)

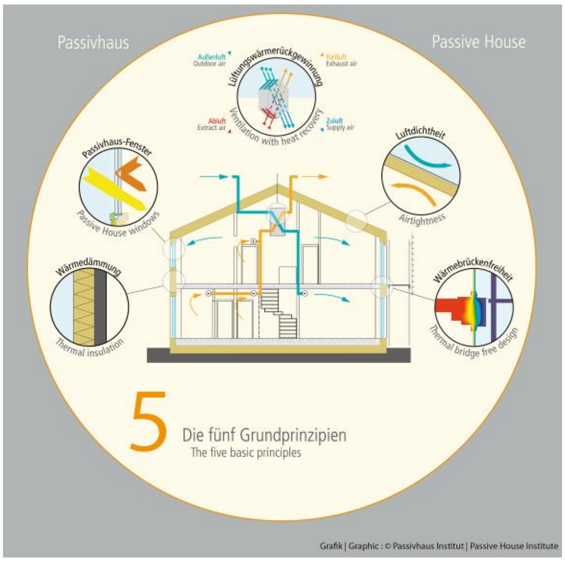


Figure 2-1- The principles for Passivhaus design (source: (Passive House Institute, n.d.)**)**

Passivhaus standard focuses on a specific ventilation requirement and rate in order to achieve thermal comfort and set indoor air quality.

2.1.1. Passivhaus Standard

Over the years Passivhaus standard has been developing from the original criteria that were more specific to central Europe and only targeting annual heating demand (**Q_H**) of ≤ 15kWh/m^2. The airtightness (**n_{50}**) and primary energy demand (**W_p**) requirements were added later on to be, $n_{50} \leq 0.6\ h^{-1}$ at 50 Pascal and $W_p \leq 120$kWh/ (m^2a) (Passive House Institute & RoA Rongen Architects GmbH, 2011).

Annual heating demand for Passivhaus is calculated using equation 2-1 below and figure 2-2 highlight the total heat loss and gains leading to heat demand:

$$\mathbf{Q_H = Q_L - Q_G} \ \text{(losses – gains)}$$

Equation 2-1- Annual heating demand (Passive House Institute, 2007) **P.102**

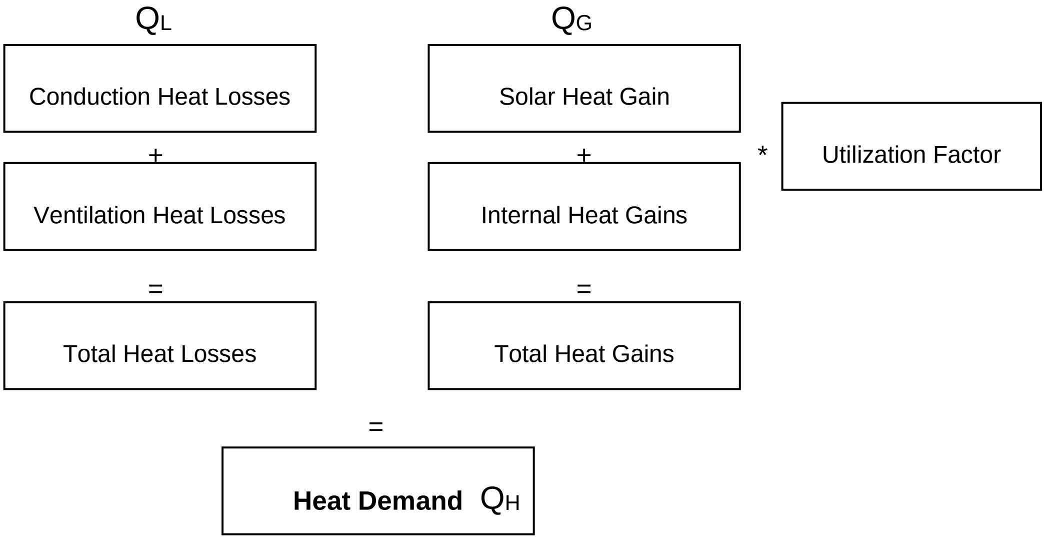


Figure 2-2- Energy balance (source: adapted from Passive House Institute. (Passive House Institute, 2007) **P.93)**

Specific annual heat demand, **q_H**, takes the area (treated floor area) into consideration and it is calculated as:

$$\mathbf{q_H = Q_H / A_{TFA}}$$

Equation 2-2- Specific annual heat demand (Passive House Institute, 2007) **P.102**

If a building meets the heating demand of ≤ 15kWh/m^2, it could fulfil the requirements to be a Passivhaus and this demand, in the central European climate, could be achieved by heating the supply air only. However certification can now be obtained if heating load (**P_H**) is ≤ 10 W/m^2. Moreover following the call for separated cooling demand by Passive-On project and Promotion of European Passive House (PEP) (Passive House Institute & RoA Rongen Architects GmbH, 2011), the requirement for sensible useful cooling demand (**Q_K**), was introduced along with cooling load (**P_K**), of $Q_K \leq 15kWh/m^2$ and $P_K \leq 10\ W/m^2$ highlighting the institute's ongoing improvements and flexibility of the standard.

Meeting the heating and cooling demand for Passivhaus through the supply air, will use the ducting system designed for the ventilation and this can eliminate the need for a secondary system. Furthermore the combination of heating and cooling with ventilation can also make Passivhaus more financially viable (Passive House Institute, n.d.).

The introduction of the primary energy demand limit as part of the Passivhaus requirements, has improved the efficiency of appliances used in Passivhaus, as it not only includes the power usage for heating, cooling, dehumidification and hot water, but it also includes lighting and fixed appliances such as dishwasher and washing machines. The W_p in Passivhaus cannot be counter balanced by onsite energy production from photovoltaic (PV), unlike other standards such as the Code for Sustainable Homes in the UK, and the 120 kWh/ (m^2a) also takes the inefficiency and losses of the power generation from the grid for different energy sources into consideration. In addition there has already been a suggestion for reducing the primary energy demand limit up to half (60kWh/ (m^2a)) by 2050 as the efficiency of the different appliances improves in the future (Passive House Institute, n.d.). This could lead to a reduction of indoor heat gain and potentially lower summer temperatures.

Passivhaus standard addresses all different aspects of energy use and demand through a high level of insulation, an airtight envelope, a thermal bridge free construction and controlled ventilation to provide a minimum 17°C of incoming fresh air when the outside temperature is -10°C (Passive House Institute, 2012). In colder climates this is provided by use of a balanced mechanical ventilation system with heat recovery (MVHR) (Passive House Institute, 2012). For the non-heating season the MVHR is either switched to summer by-pass, as heat exchange is no longer required, or turned off and ventilation relies on occupants opening windows for extra air change and cooling.

Table 2-1 summarises the basic Passivhaus parameters (Passivhaus Institut, 2012):

Table 2-1- Passivhaus parameters

Passivhaus Parameter	**Comment/Explanation**
Fabric U-Value ≤ 0.15 W/m^2K	Minimum for cold climate like the UK
Glass U-Value ≤ 0.8 W/m^2K	Minimum for cold climate like the UK
Window installation U-Value ≤ 0.85 W/m^2K	As built including the window edge Psi-Value
No thermal bridges $\psi < 0.01$ W/(mK)	Good detailing, non-standard needs calculation
Air change rate / person 20-30 m^3h^{-1}	Can differ in different countries
Min air change rate 0.3 h^{-1} related to net volume (TFA X room height (max 2.5))	For hygiene reasons
Occupancy rate 35m^2 / person (min 20 – max 50 m^2 / person)	This can differ in different countries
DHW demand 25L / person @ 60°C with 10°C cold water	
DHW energy demand between 18-35 kWh/(m^2a)	
MVHR efficiency at least 75%	Minimum efficiency, usually higher
Maximum supply air temperature at heating coil to be 52°C	Stops any dust burning in the supply ducts
Temperature difference between inside and surfaces not to exceed 4.2°K	To optimise thermal comfort
Temperature difference between human head and feet to be less than 2°K	To optimise thermal comfort

Passivhaus standard is currently more focused on the building and its energy consumption for heating and cooling (perhaps due to the higher impact) and less on whole building sustainability such as the type of materials used (Passive House Institute & RoA Rongen Architects GmbH, 2011) unlike the UK Code for Sustainable Homes (CSH). CSH was first introduced in December 2006 as a step towards the 2016 zero carbon target with a 1 to 6 rating system. In May 2008 it was made compulsory to assess all the new homes built in England and issue a certificate using the CSH rating. The code included different areas of environmental concerns with energy and CO_2 emissions having the highest available credits of 29 (Gaze et al., 2010).

During 2008 the UK-Green Building Council created a task group to help define the 2016 zero carbon homes and their recommended maximum energy demand was: 39kWh/m^2/year for apartment blocks and mid terrace houses; and 46kWh/m^2/year for semi-detached and end of terrace houses (Zero Carbon Hub, 2009). However the 39 to 46kWh/m^2/year will be even higher in Passivhaus terms as the area calculation method differs and could translate to be around 50kWh/m^2/year which is notably higher than the Passivhaus 15kWh/m^2/year (Cotterell & Dadeby, 2012). The task group also recommended a set of standards for the fabric that can be compared to Passivhaus requirements (Figure 2-3).

	Dwelling type			
	4-storey apt. block	Mid terrace	End terrace / Semi	Detached
Target Fabric Energy Efficiency Standard (kWh/m^2/yr)^f	39	39	46	46
Wall U-value (W/m²K)	0.18	0.18	0.18	0.18
Floor U-value (W/m²K)	0.18	0.18	0.18	0.14
Roof U-value (W/m²K)	0.13	0.13	0.13	0.11
Window U-value (W/m²K)	1.4	1.4	1.4	1.3
Air permeability (m³/m²/hr @ 50Pa)	3	3	3	3
Thermal bridging y-value (W/m²K)	0.05	0.05	0.05	0.04

Figure 2-3- UK 2016 zero carbon building proposed fabric standards (Source:(Zero Carbon Hub, 2009) **P.11)**

It should be said that the mentioned Passivhaus criteria (Table 2-1) has been identified for the central European and the UK climate. For example the window requirements, regardless of the climate, should have a maximum water activity of $a_w \leq 0.80$ (greater value can lead to mould growth) (Passive House Institute & RoA Rongen Architects GmbH, 2011) which can lead to lower U-Value depending on the climate. Water activity is defined as the humidity within the component or the adjacent layer to the component. The surface temperature (f_{Rsi}) is linked to relative indoor air humidity (rH_i) and varies according to the external temperature (Figure 2-4) when complying with the Passivhaus indoor temperature of 20° C.

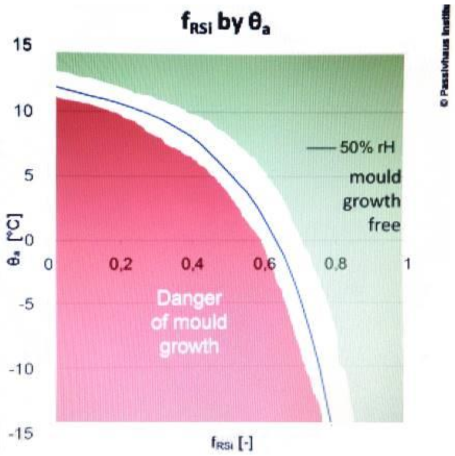


Figure 2-4- Temperature factor in relation to external temperature at 50% rH_i and indoor temperature of 20°C (source: (Passive House Institute & RoA Rongen Architects GmbH, 2011) **P.160)**

Moreover for the building component U-Value, the minimum average surface temperature (Θ_{si}) should differ no more than 4.2K from the average operative room temperature (Θ_{op}) as shown in Equation 3 (Passive House Institute & RoA Rongen Architects GmbH, 2011).

$$\Theta_{si} \geq \Theta_{op} - 4.2\ K$$

Equation 2-3 –Minimum average surface temperature (Passive House Institute & RoA Rongen Architects GmbH, 2011) **P.161**

The 4.2K limit is to achieve comfort and a greater value can lead to discomfort caused by the draught due to cold air falling and can also create radiant heat losses (Passive House Institute & RoA Rongen Architects GmbH, 2011). Therefore the maximum thermal transmittance coefficient can be calculated by using the equation below:

$$U \leq \frac{4.2K}{R_{si}\ m^2K\ /\ W.\ (\Theta_{op}\ K - \Theta_a K)}$$

Equation 2-4- Maximum thermal transmittance coefficient (Passive House Institute & RoA Rongen Architects GmbH, 2011) **P.161**

The energy calculation for Passivhaus is carried out by using Passivhaus Planning Package (PHPP). PHPP is an Excel spreadsheet which has been cross examined using a dynamic modelling simulation software, Dynbil, and data from field study (McLeod et al., 2013). The definition of overheating under PHPP is 10% of the year over 25°C (Cotterell & Dadeby, 2012) as continuous occupation is assumed which is based on the German standard **DIN 1946-2** (McLeod et al., 2013). Currently the weather data used in PHPP for the UK is based on the 22 regions generated by the BRE (Building Research Establishment) using Meteonorm and crosschecked against ASHRAE EPW files, this is much better than the previous version of PHPP which used Manchester as one location for the whole of the UK (McLeod et al., 2012). However the 22 regions still might differ notably from the microclimate for a specific location.

It should be noted that the Passivhaus standards are based on an occupancy rate of 35m^2 / person, which perhaps is not as true for the UK dwellings which generally offer less floor space per person, starting from 25m^2 for a one person dwelling (Adler, 2002). Furthermore new properties in the UK are getting even smaller and are identified to be the smallest within Western Europe (Taylor, 2014) which can therefore have an impact on the internal gains and the ventilation volume.

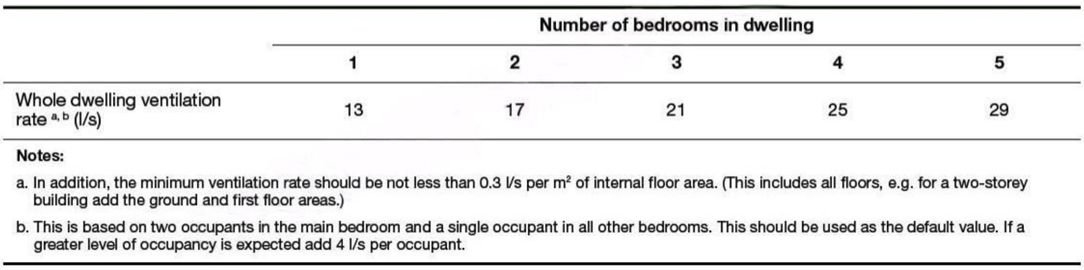
2.1.2. Ventilation in Passivhaus

Passivhaus uses the German standard **DIN 1946-6** for the ventilation requirement and recommends supply air of 20 to 30m^3/h/person for residential buildings and this volume flow rate is distributed to the entire building and not every individual room. Passivhaus also imposes a minimum air change rate of 0.3 which is related to the net volume (**V_v**), calculated by multiplying the room height (maximum 2.5m) by the treated floor area. The 2.5m is not a design limit for the building height, rather the limit for calculating the net volume for the ventilation (Passivhaus Institut, 2012).

The requirements for the extract air are as follows:

- Kitchen 60m^3 /h
- Bathroom 40m^3 /h
- WC / storage 20m^3 /h

Approved Document F - Means of ventilation for England and Wales, requires a different ventilation rate (Figure 2-5) in comparison to the Passivhaus standards as demonstrated below (HM Government, 2010).



	Number of bedrooms in dwelling				
	1	2	3	4	5
Whole dwelling ventilation rate $^{a, b}$ (l/s)	13	17	21	25	29

Notes:

a. In addition, the minimum ventilation rate should be not less than 0.3 l/s per m^2 of internal floor area. (This includes all floors, e.g. for a two-storey building add the ground and first floor areas.)

b. This is based on two occupants in the main bedroom and a single occupant in all other bedrooms. This should be used as the default value. If a greater level of occupancy is expected add 4 l/s per occupant.

Figure 2-5- Whole dwelling ventilation rates (source: (HM Government, 2010) **P.19)**

This difference could influence the ventilation losses, therefore affecting the efficiency of the MVHR unit depending on the occupancy rates and consequently the heating demand for Passivhaus buildings in the UK.

Using MVHR for Passivhaus ventilation, the extract and fresh air supply need to be equal to be able to balance the system and if the requirement for the extract air exceeds the fresh air, then the fresh air will take precedent and the additional extract is met by increasing the extraction for a given period. Moreover the air speed within the room is limited to 0.15m/s and greater than this could cause discomfort. Passivhaus also states that air speed more than 3m/s and 2m/s in the horizontal and vertical ducts respectively, could have noise implications and the air speed for the outlet is limited to 1m/s (Passivhaus Institut, 2012).

Passivhaus follows the European standard **EN 13779** for indoor air quality (IAQ). This is defined in four levels - IDA1 (high quality) to IDA4 (low quality), which suggests a maximum indoor CO_2 level of **1000ppm** (parts per million) compared to a typical outdoor level of **350-450ppm**. The Passivhaus requirement of $30m^3$/h/person is based on IDA2 and the minimum of 0.3ac/h (air change per hour) is also the default option in PHPP. Furthermore the relative humidity level in Passivhaus should be between **35% and 55%** to not only provide a comfortable indoor environment but also eliminate any potential for dampness and mould growth (Cotterell & Dadeby, 2012).

Achieving Passivhaus requirements and obtaining the certification for the UK climate, currently requires the use of a MVHR unit for the ventilation (Passive House Institute, 2012). MVHR works effectively during the winter as it not only provides the required fresh air and extracts the stale air but also pre warms the incoming fresh air by recovering the heat from the exhaust air (Figure 2-6). This will improve the thermal comfort for the occupants and reduce the heating energy demand as the fresh air is pre warmed.

2.1.3. Winter ventilation in Passivhaus

Passivhaus assumes a continuous occupancy throughout the day and a minimum temperature of 20°C during the winter. However the question arises when the building is unoccupied for the majority of the day when occupants are at work and perhaps 20°C is not maintained during this time, how much the MVHR could contribute to the temperature reduction when there are very limited internal gains and no additional heating and perhaps a separated MVHR setting is needed for non-occupied hours with an air change rate of 0.2/h (Crump et al., 2009). Further research could be required for the use of MVHR in winter time and different occupancy patterns but this is not within the scope of this thesis. Moreover, it is possible that a different setting is also needed to be incorporated for different occupancy rates during occupied hours as the rate could change for a short period of time, i.e. a few days, which could lead to under or over ventilating. Perhaps a simple “number of occupants” option on the MVHR control panel could provide the solution.

The ventilation losses from the MVHR is between 2 and 7 kWh/(m²a), compared to an apartment building without MVHR of 20 and 30 kWh/(m²a) (Passive House Institute, n.d.). The efficiency for the MVHR system needs to be a minimum of 75% according to the Passivhaus standard, however much more efficient units are currently available in the market, with up to 90% efficiency. Passivhaus standards also require the maximum electricity used by the MVHR (fan power) to be 0.45Wh/m^3 (of air moved) (Cotterell & Dadeby, 2012).

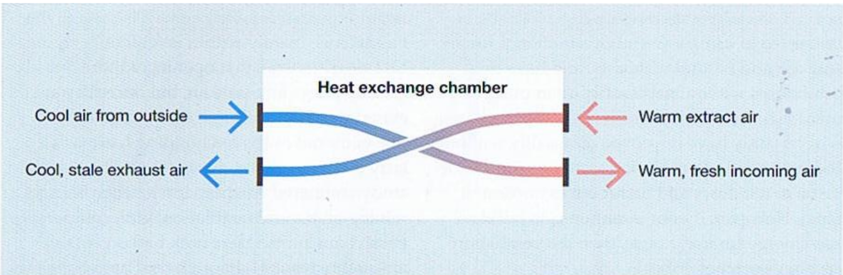


Figure 2-6- MVHR heat recovery chamber (source: (Cotterell & Dadeby, 2012) **P.191)**

MVHR provides the required fresh air to habitable rooms like bedrooms and living rooms and extracts the damp, warm air from wet rooms such as bathrooms and kitchen (centralised system). The corridors are used as transfer zones and no extraction or supply air is provided in this zone (Figure

2-7). Transfer paths are usually created by using the gap under the door or alternatively through the architrave or grills within the door (Figure 2-8).

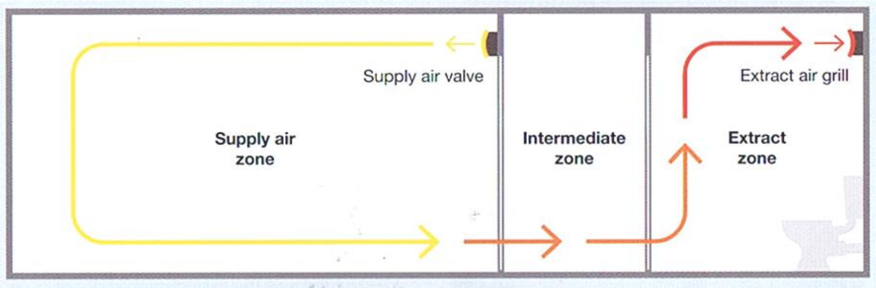


Figure 2-7- Different zones for the centralised MVHR system (source: (Cotterell & Dadeby, 2012) **P.197)**

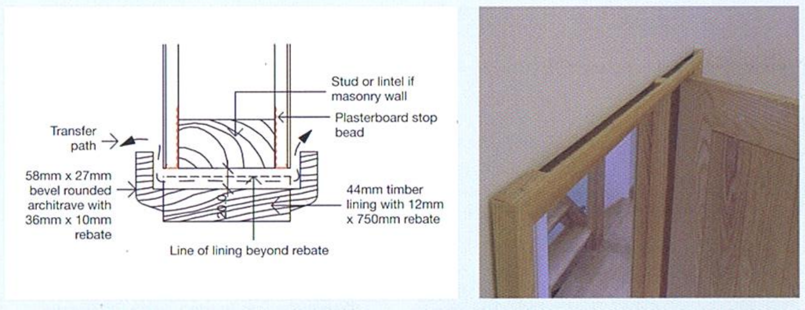


Figure 2-8- 20mm air transfer path as part of architrave (source: (Cotterell & Dadeby, 2012) **P.197)**

2.1.4. Non-winter ventilation in Passivhaus

During the non-heating seasons, the MVHR is either turned off completely or switched to summer by-pass. Throughout this time, MVHR no longer provides heat recovery and therefore is no longer efficient as the building is being mechanically ventilated with the use of electricity leading to higher primary energy demand.

Ventilation is required throughout the year and even more during the summer, not only to provide the minimum amount of clean fresh air for the occupant, but also to reduce the potential for overheating. During the cooling season if MVHR is turned to summer by-bass it will provide the required fresh air of 30m^3 per person per hour (Passive House Institute, 2007) as per Passivhaus standard, but perhaps not the necessary amount required for warmer months to reduce the overheating potential **even in the boost mode** (Richard Partington Architects, 2012). Moreover currently there is no requirement or availability to have **purge mode** for the MVHR unit (Crump et al., 2009). In the summer by-pass mode, MVHR continues extracting the damp, stale air from the wet areas and supplying fresh air to the habitable rooms without the use and therefore the benefit of the heat exchanger.

However there is no requirement for the MVHR to have summer by-pass option under the Passivhaus standard (Passive House Institute, 2007) and as the temperature rises, the MVHR can actually contribute to an increase of indoor temperatures. One option is to turn the MVHR off during the cooling seasons which leaves the question for the ventilation strategy, specially extraction from the wet rooms which is always required as part of the building regulation (HM Government, 2010). Having the MVHR operating during the cooling seasons not only increases the primary energy, but the unit itself could also contribute to the internal heat gain if it is located inside the thermal envelope, even with the unit being highly insulated. This is because although Passivhaus standard has a limit for the electricity used by the MVHR, there is no limit to the heat that is generated by the unit while in operation.

Passivhaus relies on the occupant to open the windows during the summer period for extra ventilation and cooling (Passivhaus Institut, 2012). This might not be as easy or feasible to achieve due to external noise and need for security, especially during the night which can also cause sleep disruption. Opening windows simultaneously while the MVHR is in operation could also affect the ventilation balance and the air movement path; further research could be required in this area as it is not under the scope of this study. Moreover the air quality could be compromised as the incoming fresh air no longer passes through the filter of the MVHR; and although this is the case for most natural ventilation systems, in Passivhaus however, any reduction in air quality could be more pronounced compared with the rest of the year when the MVHR is the only source of ventilation. In other words, maintaining the same air quality throughout the year is essential.

Passivhaus standard requires an F7 (fine-particle) paper (Cotterell & Dadeby, 2012) filter for the incoming fresh air in the MVHR unit and the filter is recommended to be cleaned and changed every six and twelve months respectively, this can vary depending on the manufacturer's recommendations. Moreover a lack of maintenance and dirty filters of the MVHR unit can cause a reduction in the ventilation volume by **15% to 25%** as highlighted in the study carried out in some new energy efficient Dutch houses, using MVHR for ventilation (Crump et al., 2009).

Passivhaus states opening the windows alone twice a day would not provide the required ventilation and to achieve 0.33 ac/h, the occupants would be required to open the windows wide for **5 to 10 minutes** every **three hours** throughout the day, including at night (Passive House Institute, n.d.). Achieving the minimum air change by means of purge ventilation depends on the size of the window and volume of the air; and a study published in the Protocol Volume for the Working Group Number 23 highlighted that windows needed to be opened at least every **6 hours** for an example house (Passive House Institute, n.d.). This recommendation and study focused on the winter period, and for the non-heating season with perhaps more requirement for ventilation and air change, the windows might need to be opened for an even longer period or at more frequent intervals.

Therefore, incorporating a carefully designed natural ventilation system for the summer period could not only provide the required minimum air flow, but also the extra ventilation. This will correspondingly reduce the energy used from the MVHR fan and consequently CO_2 emissions, which will in turn, reduce the primary energy demand for Passivhaus. On the other hand the challenge is not only a natural ventilation system or strategy to provide the ventilation amount but also evenly distribute the air around the building. Moreover a high level of attention to detailing is necessary so as not to compromise the airtightness and cold bridging of Passivhaus alongside the possibility of switching back to MVHR easily during the winter months. In other words, natural ventilation during the summer months is directly linked to the expected Passivhaus requirements for the winter period and most importantly there is inadequate evidence on how to deal with higher summer temperatures and the impact of climate change in a Passivhaus.

2.1.5. Internal gains in Passivhaus

For calculating the effective internal heat gains in residential buildings, PHPP 7 uses a standard value of 2.1W/m^2 and for summer, recently updated, 2.6W/m^2 as a safety measure for summer overheating which is based on the German standard of occupancy density of 35m^2 per person and defined appliance schedule (McLeod et al., 2013). Moreover in PHPP 7 the input from the IHG (internal heat gain) sheet does not feed into the calculation automatically and instead the above value is used (Passive House Institute, 2007). This has been further amended in PHPP 8 allowing the internal heat gain calculation to be carried out and a separate value to be used for the summer period (Passive House Institute, 2013).

In comparison to other standards, Passivhaus calculation for the internal gains of 2.1W/m^2 (from PHPP7 - 2007) is around half the amount. Passivhaus calculation is perhaps more conservative and therefore safer for the winter period and specific heat demand, as some of this free heat gained is counter balanced for unaccounted heat losses due to the evaporation from towels and fresh cold water in the WC cistern. Passivhaus calculation also allows for heat losses from hot water from washing dishes and clothes that is discharged directly to outside without any heat gained (Schnieders, 2009). However the heat gains from hot water storage and distribution are not taken into the consideration in PHPP 7 (Passive House Institute, 2007) which could contribute to higher gains during the summer.

Due to the importance of space heating demand for Passivhaus buildings, the monitoring that was carried out on terraced house settlements in Hannover-Kronsberg or the apartment building in Kassel-Marbachshöh focused on the comparison of the calculated space heating demand and the actual monitored data. The monitoring data confirmed that the 2.1W/m^2 of internal gains is realistic for the winter months (Schnieders, 2009). However what was not necessarily monitored here were the actual internal gains from the appliances etc. to enable comparisons with the PHPP standard calculation.

The internal heat gain of 2.1W/m^2 was based on central Europe and more on Germany, which highlights the importance of this calculation for different locations with different weather data and occupancy. Moreover during the summer period the effect of the heat sinks defined by Passivhaus like water in the WC cistern is also reduced alongside the higher temperature for the incoming cold water which should be taken into consideration especially for warmer climates (Schnieders, 2009).

Other influences on the internal heat gains for different regions, seasons and cultures are listed below (Schnieders, 2009):

- Different amount of time spent indoors
- Seasonal effect on the lighting usage
- Seasonal effect on the cooking pattern
- Cultural effect on the cooking amount

PHPP calculation for the internal heat gain (IHG sheet) if used, accounts for efficient appliances and moderate electricity usage profiles. This in the UK along with perhaps higher occupant density could result in much higher internal heat gains, which has been demonstrated by McLeod et al (2013) calculation for 70m^2 of social housing. The study based on occupancy for three persons, using the CIBSE Guide A for the occupant gains, internal gains were as high as **3.69W/m^2** when the building is fully occupied and **5.05W/m^2** taking the inefficiency of appliances and possibility of higher electricity usage into account (McLeod et al., 2013).

Similarly, the internal gains were identified to be 400W (3.53W/m^2) in the Slovenian Passivhaus built during 2006 which is higher than the suggested value in PHPP and the effective heat capacity measured was 20MJ/K compared to the standard lightweight construction of 24.4MJ/K from PHPP (Mlakar & Štrancar, 2011). Moreover one of the reasons acknowledged for the overheating in the Camden Passive House in London was the monitored internal gains of 3.65W/m^2 despite placing the MVHR outside the thermal envelope, which is again higher than the PHPP 7 standard value (Ridley et al., 2013).

Although the updated PHPP8 addresses some of the issues raised, however using the IHG sheet and calculating the exact appliances and occupancy for every location remains important. Furthermore the effect of climate change could further increase the importance and need for reduction of the internal gains during the summer months (Taylor, 2014).

2.2. OVERHEATING & THERMAL COMFORT

Passivhaus Institute describes the standards in respect of comfort temperatures and the energy required as:

> *"Passive Houses are buildings that need very little energy to achieve a comfortable temperature without the help of either a conventional heating or air conditioning system."*

(Passive House Institute, n.d.)

In specific the standard aims to achieve the comfort temperatures without the use of any air conditioning system.

2.2.1. Thermal comfort

Historically humans have adjusted and used a small amount of energy from local sources to make their environment comfortable alongside the use of natural resources like the sun and wind. However with the development of modern technologies, living comfortably has become more possible in a variety of buildings at the expense of energy (Nicol & Spires, 2013).

The human body regulates its temperature, known as the core body temperature, by releasing heat to keep between 36.1°C and 37.8°C (Dengel & Swainson, 2012) and as warm blooded mammals, keeping the core temperature around 37°C is necessary for keeping the brain and internal organs healthy (Nicol & Spires, 2013). This is controlled by the hypothalamus, part of the human brain, which regulates the temperature balance through careful heat generation and losses, known as thermoregulation. Keeping the core temperature within the required limit is a dynamic process due to changing environment conditions, movement between different spaces or between indoors and outdoors (Nicol & Spires, 2013). Furthermore raising the core temperature above 37.8°C to 38°C or 39°C, can only be temporary to avoid health implications (Dengel & Swainson, 2012).

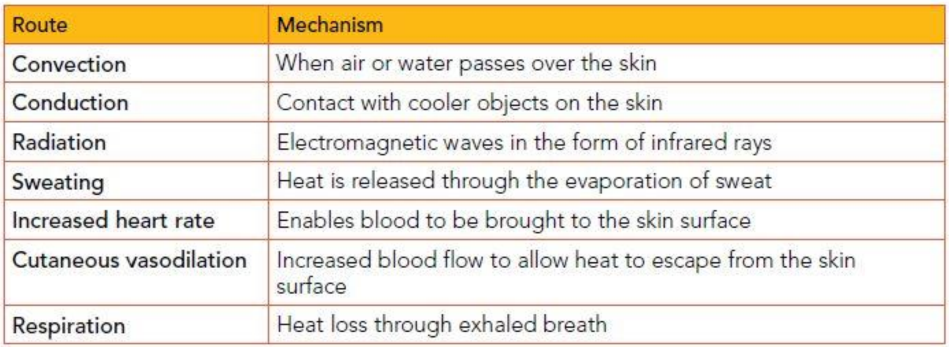
The level of heat production by the human body depends on the activities carried out by a person and most of the energy gained from consumption of food is converted to heat. The human body gains its energy by converting the food into energy through metabolism and the rate of conversion is called the metabolic rate. The regulation of the body temperature, carrying out daily activities and functioning of the human body, uses this energy and also keeps the body core temperature within the limit (Race et al., 2010). For the majority of the time the limit is maintained subconsciously by increasing or decreasing the blood flow or muscle tension and the skin temperature is constantly adjusted in regards to the condition of the body and environment (Nicol & Spires, 2013).

The skin surface of the human body is used for calculating the heat loss and the average area is around 1.7 m^2. This is used when calculating the body's metabolic rate which is expressed in Watts (W) per metre squared of skin surface area (Nicol et al., 2012). Depending on the activity, this can vary broadly for example $40W/m^2$ for a person sleeping (ASHRAE, 2010) or over $400W/m^2$ for a person running (Nicol et al., 2012). The heat is lost to the surrounding air through convection and to different surfaces by radiation. Sweating also helps the body to lose heat through evaporation and a very small amount of heat is lost by means of conduction to surrounding surfaces (Figure 2-9) (Nicol et al., 2012). The simplified equation used for this energy balance is:

$$\mathbf{H = W+S+K+C+R+E+E_{res}+C_{res}}$$

- H: Metabolic production
- W: Work
- S: energy stored in the body (assumed zero over time)
- K, C, R: Heat losses (or gains) (conduction, convection & radiation)
- E: Heat loss by evaporation
- E_{res}, C_{res}: evaporative & convective by respiration

Equation 2-5-Energy balance of the human body (Passive-On, n.d.)



Route	Mechanism
Convection	When air or water passes over the skin
Conduction	Contact with cooler objects on the skin
Radiation	Electromagnetic waves in the form of infrared rays
Sweating	Heat is released through the evaporation of sweat
Increased heart rate	Enables blood to be brought to the skin surface
Cutaneous vasodilation	Increased blood flow to allow heat to escape from the skin surface
Respiration	Heat loss through exhaled breath

Figure 2-9- Different methods of body heat loss (source: (Dengel & Swainson, 2012) **P.10)**

Thermal comfort as defined by ASHRAE is a condition of mind and therefore can differ for individual subjects even if all other conditions remain the same due to physical, physiological and psychological developments (Schnieders, 2009). Generally it is agreed that external conditions such as, air temperature, radiative temperature, air velocity and humidity can influence the thermal comfort (Schnieders, 2009), and the thermal environment can greatly influence the way in which the core body temperature is maintained (Nicol & Spires, 2013). There are three widely recognised international standards for thermal comfort (Nicol et al., 2012) :

- ISO 7730 (2005)
- ASHRAE 55 (2004)
- CEN EN15251 (2007)

The ISO 7730 standard sets the requirement for calculating PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) along with indications for localised effects, whereas the ANSI/ASHRAE standard 55 sets limits for temperature and relative humidity for the majority of the occupants in mechanically serviced buildings. Furthermore from 2004 the adaptive approach has been included in this standard (Nicol & Spires, 2013) and the following formula has been used:

$$\mathbf{T_{comf} = 0.31\ T_{om} + 17.8}$$

- T_{comf}: Thermal comfort
- T_{om}: Monthly mean outdoor temperature (under review to include running mean as well as monthly mean temperatures

Equation 2-6- Comfort equation of naturally conditioned buildings (Nicol et al., 2012) **P.55**

CEN EN15251 is the European standard which encourages energy efficiency without compromising occupant comfort and it is similar to the ANSI/ASHRAE 55 standard in using PMV and regarding the free running buildings it uses the equation below:

$$\mathbf{T_{comf} = 0.33\ T_{rm} + 18.8}$$

- T_{comf}: Thermal comfort
- T_{rm}: exponentially weighted running mean of the daily mean outdoor air temperature as the measure of outdoor temperature

Equation 2-7- Comfort temperature (Nicol et al., 2012) **P.57**

Achieving thermal comfort for around 90 to 95% of occupants in dwellings and offices suggests a set temperature of about 21°C (±1°C) and a range temperature of 18°C to 24°C. During the warmer months an increase of 2K over the 24°C can be tolerated by the adjustment of clothing. Other influences contributing to the comfort are the limit of the surface temperatures to the air temperature of 2-3K and the limit of 2K between the head and foot of the occupant throughout the year. The surface temperature of components should not differ by more than 3-4K and the floor temperature range should be between 19°C to 26°C. Moreover the indoor humidity should be between 40% and 70% alongside an indoor air velocity of less than 0.08m/s. Figures 2-10 and 2-11 are an indication of the percentage of the occupants dissatisfied according to the different room temperatures when the sedentary activity is 1.2 met for summer and winter and the winter and summer clothing are calculated at 1.2 and 0.5 clo respectively. In addition the ASHRAE and ISO 7730 range are also displayed. (Gonzalo & Vallentin, 2014)

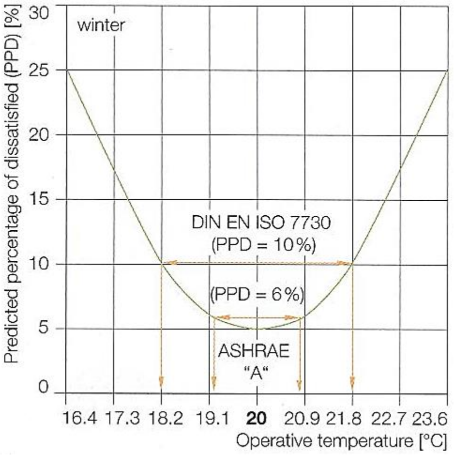
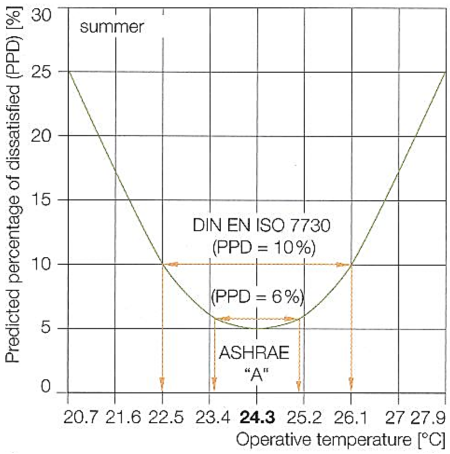


Figure 2-10- PPD in relation to the room temperature during the winter (source: (Gonzalo & Vallentin, 2014) **P.12)**

Figure 2-11- PPD in relation to the room temperature during the summer (source: (Gonzalo & Vallentin, 2014) **P.12)**



Most of the research undertaken with regards to thermal comfort has been in laboratories and controlled environments and this has enabled recording of human response to changes in air temperature, humidity, airspeed, etc. in relation to feeling hot, cold or comfortable (Passive-On, n.d.). Standards from the USA have been used to develop different indexes for thermal comfort like Effective Temperature (ET) and the Standard Effective Temperature (SET). However Fanger's Predicted Mean Vote (PMV) is the index that is used and accepted the most and even sets the basis for EN/ISO7730 standard (Passive-On, n.d.).

The Fanger model is based on data collection from skin temperature and sweat rate measurements for people at a number of different metabolic rates within a climate chamber (Nicol & Spires, 2013). The expansion of Fangers' work by using the ASHRAE (American Society of Heating, Refrigeration, and Air-Conditioning Engineers) scale has led to the creation of PMV tables for a various environmental conditions and clothing with different metabolic rates (Nicol & Spires, 2013). The two different scales that are commonly used for comfort are the ASHRAE scale and the Bedford comfort scale (Schnieders, 2009). The ASHRAE scale, unlike the Bedford comfort scale, does not define a middle comfort level and votes within the three central scales (Table 2-2) are considered as comfortable and votes outside these three central scales are classed as dissatisfied. The discomfort from these scales has been developed into Predicted Percentage Dissatisfied (PPD) (Nicol & Spires, 2013).

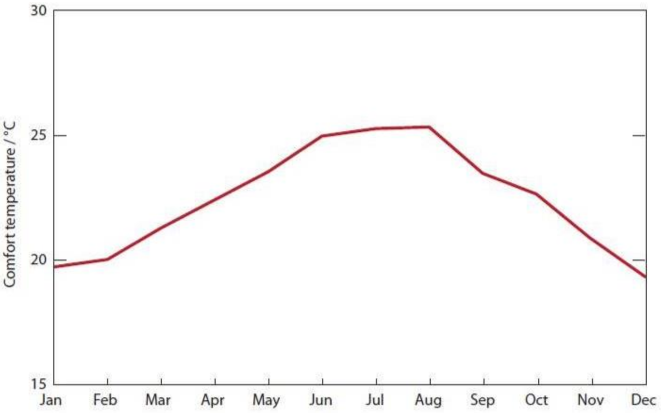
Table 2-2- Numerical equivalents for ASHRAE and Bedford comfort descriptors (source: recreated from (Nicol & Spires, 2013) **P.2)**

ASHRAE comfort scale		Bedford comfort scale	
+3	Hot	7	Much too hot
+2	Warm	6	Too warm
+1	Slightly warm	5	Comfortably warm
0	Neutral	4	Comfortable
–1	Slightly cool	3	Comfortably cool
–2	Cool	2	Too cold
–3	Cold	1	Much too cold

Designing to requirements for PMV and PPD would require an assumption of the occupant’s clothing and certain activities and perhaps impact the designer’s decision in creating a highly serviced building (Nicol & Spires, 2013). However, predicting the end user behaviour and activities would be complicated and difficult. Furthermore the desire for constructing free running buildings with occupants being more in control of their environments would be reduced.

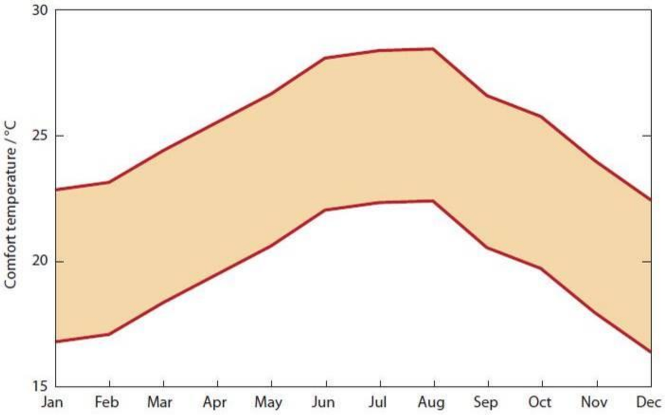
PMV and PPD are studies that were obtained in controlled laboratories and not necessarily taking the effect of the climate or the building into consideration and for free running buildings these studies might not be as accurate when internal temperature could be closely related to the external temperature by opening the windows (Dengel & Swainson, 2012). Therefore as the occupant could adjust and adapt by opening the windows, closing the blinds or changing their clothes, a fixed temperature for thermal comfort could also change in relation with the outdoor average temperature (Race et al., 2010). This has led to the development of adaptive thermal comfort that allows the thermal comfort temperature to be adjusted in line with the average outdoor temperature (Figure 2-12) (Race et al., 2010).

Figure 2-12- Estimated comfort temperature variation for an average person over a year (source: (Race et al., 2010) **P.8)**



However the adaptive thermal comfort could be more complicated when the previous days can influence the comfort temperature of each day and therefore needs to be taken into consideration on a day to day basis. Moreover as achieving thermal comfort for all occupants would be near impossible, instead a band of 80-90% of occupants feeling adequately comfortable is used (Figure 2-13) (Race et al., 2010).

Figure 2-13 – Estimated 80–90% satisfied comfort temperature band variation over a year in existing buildings (source: (Race et al., 2010) **P.9)**



Thermal comfort can be subject to physical and psychological response to the surrounding environment and influenced by social and cultural background, gender, age and behaviour (Passive-On, n.d.). Thermal comfort could be categorised into three broad classifications: Thermal comfort, thermal discomfort and thermal stress. Thermal comfort is when the majority of people are happy with their environments and feel neither too hot nor too cold, however when occupants' satisfaction is reduced with their environment and occupants start feeling either too hot or too cold, it is classed as thermal discomfort. Lastly when buildings are either too hot or too cold to cause potential medical conditions, especially for vulnerable people, then thermal stress has been experienced (Race et al., 2010).

The majority of the studies carried out on thermal comfort have been for offices and not residential buildings (Dengel & Swainson, 2012). The UK residential dwellings are usually free running with no air conditioning and especially important as people spend the night in them.

The combination of the air temperature and mean radiative temperature is defined as operative temperature which has the highest influence on the occupant thermal comfort (Schnieders, 2009). Passivhaus has a very clear and defined temperature limit for the winter period of 20°C and for the summer months the temperature limit is increased to 25°C and even allows for 10% of the time to be over the 25°C. This is based on expected occupant adaptation, but it can be argued that the adaptive level to higher temperature for the occupant of Passivhaus buildings is the range from 20°C to 25°C and it should not be increased further. Moreover for bedrooms, perhaps it should be limited to 24°C as per CIBSE Guide A recommendations for sleeping conditions (Butcher, 2007).

The idea of adaptation through science and literature suggests evidence of human adaptation occurring as early as three days, however the complete development of adaptation can take many years. Some also argue that the speed of adaptation is slower than the speed of climate change (Dengel & Swainson, 2012). The suggested three days for adaptation, could be consequential for vulnerable groups, even if possible at all.

Thermal discomfort during the summer months could be caused from overheating within the building and for vulnerable people such as the elderly, infants and people with medical conditions, overheating could have a higher effect especially when these groups are usually spending the most of their time inside the buildings (Dengel & Swainson, 2012).

2.2.2. Overheating in buildings

Overheating is usually caused by poor design of the building or due to lack of good management or even poor services (Nicol & Spires, 2013). However, overheating could also be caused by designing more airtight buildings with a high level of insulation and a large glazing area (Richard Partington Architects, 2012).

Passivhaus defines the limit for overheating to be 10% of the year above 25°C and the 10% represents temperatures in the range of 25°C-28°C for the occupied hours (100% in Passivhaus). Furthermore if overheating is 20% from PHPP calculation, this equates to temperatures in the range of 25°C-32°C during 20% of the occupied hours and it is recognised by Passivhaus Institute that the accuracy of the calculation below and above the 10% is not very high (Passivhaus Institut, 2012).

Passivhaus Institute recommends the limit of overheating to be around 5% and perhaps even 4% taking climate change into consideration (Passivhaus Institut, 2012). Post occupancy research was carried out by Voss suggesting a 5% limit over 25°C, although this research was undertaken for office buildings but its relevance could be of importance (McLeod et al., 2012). This is also evidenced in the city of Brussels' proposal of passive standard from January 2015 for residential buildings which limits the overheating to below 5% and this is perhaps facilitated by limiting the primary energy to below 45kWh/m^2.yr (Clerfayt, 2014).

Having 10% of the year above 25°C, means that over 36 days of the year a temperature above 25°C is acceptable by Passivhaus standards. Temperatures staying above a certain limit for over a month can cause a serious discomfort for the occupant and perhaps make living in their home almost impossible. Moreover the required 10% is averaged over the **whole year** and for the **whole house** and not necessarily during the summer or in response to outside temperature (Ridley et al., 2013). This could result in overheating in a specific location of the building during the summer which can be overlooked during the design stage by using PHPP.

Currently there is no limit for upper temperature in UK free running residential buildings and following their research, NHBC Foundation suggest an approved national threshold is needed and call for further agreement on whether to base temperature on health or thermal preferences (Dengel & Swainson, 2012). Environmental Design Guide A suggests a limit of **25°C** for living areas and **23°C** for bedrooms and states that temperatures over 24°C in bedrooms can impair sleeping. Environmental Design Guide A also recommends peak daily temperature not exceeding 3K above 25°C and therefore defines the maximum benchmark temperature of 28°C (Butcher, 2007). Furthermore the Guide puts a maximum 1% overheating limit above the 28°C for the occupied hours in residential dwellings and limits this to a maximum of 80 hours. The 80 hours will translate to just over three days if continuous occupancy was assumed.

Moreover the report by the Committee on Climate Change for England published during 2014, also calls for incorporation of a standard for overheating in new buildings to ensure a comfortable environment without the need for air-conditioning and it also states that one in five of the current dwelling stock in England suffer from overheating even in mild summer temperatures (Adaptation Sub-committee, 2014).

Overheating can be a serious problem in buildings particularly affecting the elderly and young. The 2003 heatwave was an illustration of this problem which led to excess deaths especially in Europe (Dengel & Swainson, 2012) and in response to this the first heatwave plan was introduced in England in 2004 which is in place from 1st June to 15th September of every year. Furthermore the heatwave plan is divided into four levels with recommendations of creating cool areas of below 26°C particularly in hospitals and care homes (Public Health England, 2014).

Climate change and increased episodes of heatwaves alongside an aging population and urbanisation can increase the potential of overheating especially in an airtight and highly insulated building which has minimal heat loss. Although more insulation can reduce the heat gain in summer months from outside, it also reduces the loss of heat built up from internal gains and solar radiation. This, along with limited air change, can increase the possibility of overheating.

Overheating in buildings can cause the most discomfort and dissatisfaction for the occupant and high temperature along with lack of fresh air in buildings, is usually at the top of the list of concerns for occupancy satisfaction surveys. (Race et al., 2010). However, having a high temperature in buildings might not only cause discomfort and make the occupant tired or irritable, it can also have a more serious effect for the building users. For instance overheating can cause thermal stress and this level of discomfort can have a higher effect on older or ill occupants and make them experience circulatory, respiratory or other related problems. Moreover in hot periods, people’s productivity and concentration can be effected which can lead to accidents (Race et al., 2010).

Some of the less severe health problems caused by heat are listed below (Dengel & Swainson, 2012) P.11:

- Dehydration
- Prickly heat
- Heat cramps
- Heat oedema (swelling due to build-up of fluid)
- Heat syncope (fainting)
- Heat rash

Dehydration can become a serious problem as the human body continues to lose water and more severe problems caused by heat include mental health issues, heat exhaustion and heat stroke. In a worst case scenario, overheating can cause death as it was estimated by Donaldson during the 30th July to 3rd August 1995 heatwave in England and Wales an increase of 8.9% in mortality (Dengel & Swainson, 2012).

During the summer of 2003, IPCC (Intergovernmental Panel on Climate Change) reported 35,000 excess mortality for the whole of Europe with 15,000 deaths in France during this time as temperatures stayed high for three weeks during the day and night (Dengel & Swainson, 2012). Furthermore the 2014 report by the Committee on Climate Change for England, has highlighted the possibility that half of all summer temperatures will be as high or even higher than the temperature during the summer of 2003, by the 2040s (Adaptation Sub-committee, 2014). Similarly the 2006 heatwave in California caused around 160 deaths mostly older people, and an investigation into the 140 deaths from heat stroke, highlighted that they happened indoors (Crump et al., 2009).

Currently excess deaths from overheating during the summer in the UK are small compared to the winter period with around **2,000** deaths per year during the summer and **25,000** deaths during the winter. However it is known that some of the deaths caused by heat strokes are not recorded due to their similarity to strokes, heart attacks and respiratory illnesses (Dengel & Swainson, 2012). Moreover temperatures above **23°C** during the summer can lead to excess deaths and it was estimated in England during the summer of 2006, an additional 75 deaths occurred per week for every degree rise in temperature (Crump et al., 2009) and it is expected that by the 2050s, deaths caused from overheating to be as high as **7,000** people per year (Adaptation Sub-committee, 2014).

Currently higher building standards such as Passivhaus in the UK, are targeting the winter period. However if through lack of adequate ventilation and poor design, these buildings overheat during the summer months, it can only reduce their benefit and in the future as a hotter climate is expected the number of deaths caused by overheating in buildings could significantly increase.

Everyone exposed to overheating in buildings can suffer from heat related illnesses; however these effects can be higher for older people, children and people with medical conditions. Children not only rely on others with regards to their environment but also their thermoregulation capability is less compared to an adult. Older people due to physical, physiological and social reasons and higher exposure to dehydration and capability of dealing with it can suffer more in overheated buildings. It is also known that the ability to sweat is decreased or even non-existent for those over 75 years of age (Dengel & Swainson, 2012). Furthermore their movement and learning ability might be limited affecting the window operation and overheating mitigation (Lomas & Porritt, 2017). This age category is of importance in the UK specifically, as the elderly population is increasing (Figure 2-14). People who are overweight could also be placed in the vulnerable group since their body will produce more heat in comparison to the average person when carrying out an activity (Dengel & Swainson, 2012).

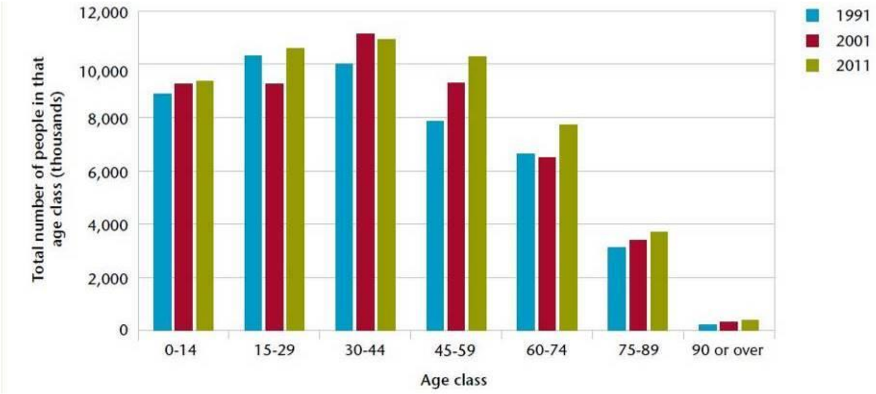


Figure 2-14- UK ageing population (source: (Adaptation Sub-committee, 2014) **P.139)**

HHSRS (Housing Health and Safety Rating System) emphasises on providing dwellings for different people with different lifestyles including elderly and the young and defines the effect of heat on health as:

> *"As temperatures rise, thermal stress increases, initially triggering the body's defence mechanisms such as sweating. High temperatures can increase cardiovascular strain and trauma, and where temperatures exceed* ***25°C****, mortality increases and there is an increase in strokes. Dehydration is a problem primarily for the elderly and the very young."*

(The Office of the Deputy Prime Minister, 2006) P.64

The discomfort experienced by the occupants during the summer might currently be acceptable by some, as higher thermal comfort and less heating requirement is achieved during the winter by designing to Passivhaus standards. However this might not be the same for older people or in the future when higher temperatures are expected. Furthermore this can have a greater impact in terms of energy use and CO_2 emissions if air-conditioning is being deployed.

2.2.3. Causes of overheating

The different factors that can contribute to overheating are outlined below (Dengel & Swainson, 2012) (Richard Partington Architects, 2012):

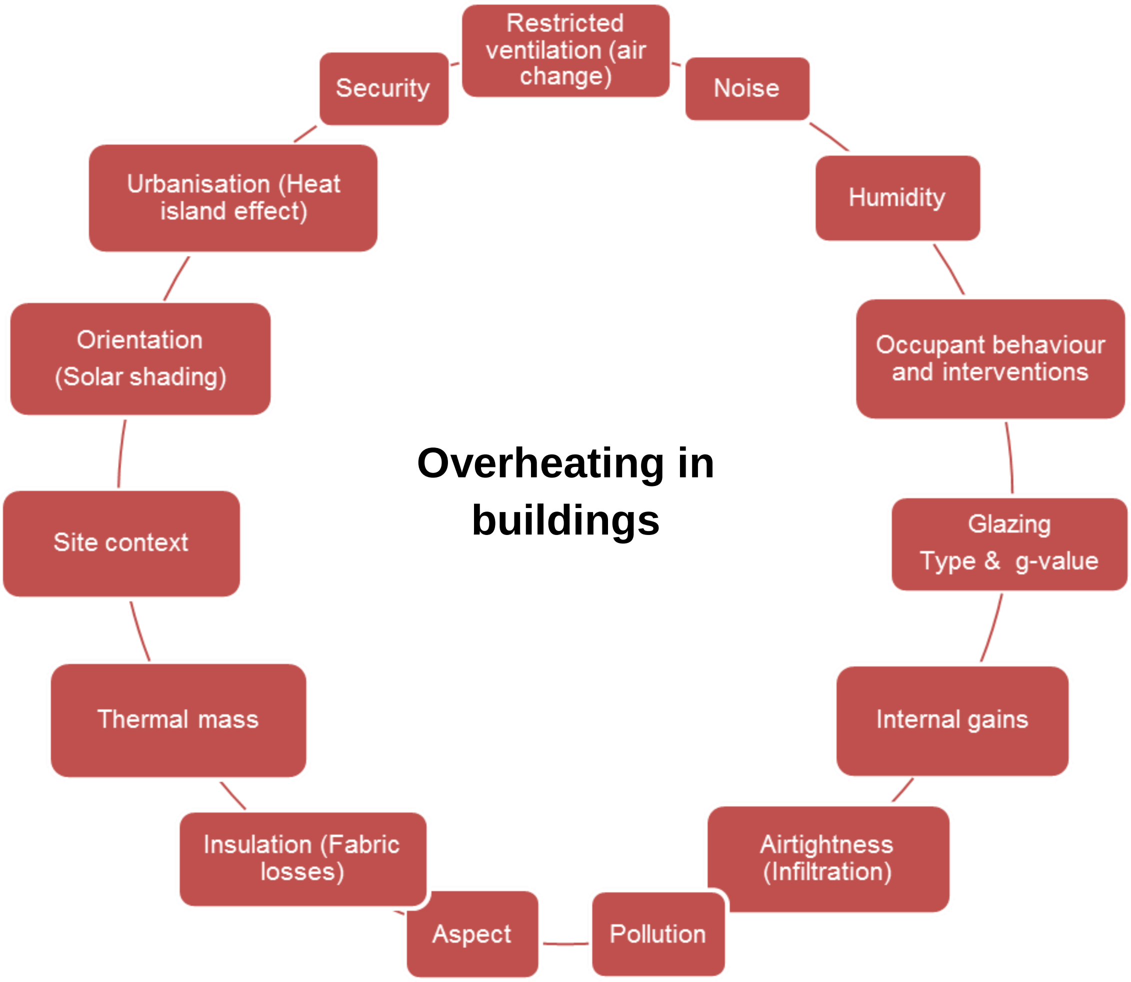


Figure 2-15- Different factors contributing to overheating (source: Author)

The scale and impact of each of these can differ for a given scenario and are perhaps not as easily adjustable or changed due to restriction from planning, orientation or standards. A more in depth analysis for individual or combined factors can be found below:

Glazing, ventilation and airtightness:

A study carried out by NHBC Foundation (Dengel & Swainson, 2012) highlights the potential of increasing overheating in new and refurbished homes due to limited ventilation even more so for smaller properties. NHBC also states that the new buildings constructed to zero carbon standards have overheating problems because of heat gain through uncontrolled glazing and lack of adequate shading in summer along with airtight envelope and no cross ventilation. They also found that in some cases the overheating occurred throughout the whole year and not necessarily only in the summer months.

Traditionally in the UK targeting the colder months has been more important compared to the summer due to cold winters and high energy required to combat the winter discomfort in buildings. The development of a zero carbon building standard and welcoming Passivhaus is perhaps a reflection of this. To achieve the Passivhaus energy limit or even zero carbon standards, the benefit of solar gain is experienced perhaps by a larger glazing area. Using a large glazing area requires an adequate shading system or strategy for the summer months, as excess solar gain during the cooling seasons could contribute to heat built up and consequently overheating in the building.

Passivhaus standards require the use of triple glazing with a minimum g-value of 50% for the UK climate (Cotterell & Dadeby, 2012). The g-value represents the amount of solar heat transferred through the glazing and it is also known as solar heat gain coefficient (SHGC). The minimum 50% is required during the colder seasons to help minimise the heating load and is not necessarily desirable during the summer months. In warmer climates, Passivhaus recognise this and a reduction to 35% in g-value could help in controlling the overheating caused by solar gain (Passive House Institute & RoA Rongen Architects GmbH, 2011). However for the UK climate, during the summer, the solar heat gain should be controlled not by the glazing g-value, but by the use of shading preferably external.

External shading can be a more effective way of controlling the solar heat gain during the warmer months compared to internal blinds as the sun is stopped before entering the building. Fixed shading devices can help further due to their minimum maintenance and robustness. Fixed shading will take the occupant behaviour into consideration and could be more effective in comparison to movable shading devices, especially if the building is unoccupied during the day when the shading is most needed. In the UK the bigger eaves in the roof level and external shading for residential dwelling is not necessarily a tradition, however this perhaps should be considered when designing to the higher building standards and be part of design when obtaining planning consent (Richard Partington Architects, 2012).

Incorporating an openable window in all the habitable rooms is a requirement for Passivhaus in order to provide additional ventilation. However the ventilation rate assumed during the design stage could be reduced dramatically due to concerns regarding noise, security, insects, privacy and restriction due to the way the windows are opened like tilt position (Passivhaus Trust, 2016). The window opening effectiveness can be even more pronounced as Passivhaus walls are thicker due to higher insulation requirement.

Internal gains:

Internal heat gains could play an important role in overheating in buildings especially when designing to Passivhaus standard due to minimum heat escaping from the building. A list of different internal heat gains can be found below:

- Appliances
- Artificial lighting
- Occupants
- Hot water storage
- Hot water distribution pipes
- Fans
- Pumps
- Bathing

As an example if the hot water cylinder is used to store domestic hot water, even with an insulated cylinder still the heat loss could be around **1 to 2 kWh** per day adding to further distribution losses from the boiler and solar hot water system. Appliances and lighting can also contribute to overheating as the majority of the electricity consumed is transformed into heat and as the quantity and appliances are known it is easy to calculate the heat gain. The heat generated from different appliances might be small due to European legislation for more efficiency but it still could be significant and continuous, especially if the appliances are left on standby mode (Dengel & Swainson, 2012).

Thermal mass:

The importance of night time purge ventilation is greater especially if the building benefits from thermal mass. Building materials store heat and emit the heat at a later time, which is known as thermal mass (Richard Partington Architects, 2012). Thermal mass can help to regulate the overheating, if it is combined with a sufficient level of ventilation during the night as the outside temperature drops, otherwise thermal mass can have an opposite effect and contribute to the overheating potential. If the mass does not lose its heat gained during the day by night, it can potentially increase the indoor temperature (McLeod et al., 2013). On the other hand there has been an increasing concern over constructing highly airtight lightweight buildings and the possibility of overheating during the summer and the use of air-conditioning during this time in the UK (Crump et al., 2009).

Currently there is no requirement for minimum or any mass in Passivhaus standard and under the summer sheet in PHPP there are three pre-set options of lightweight (60 Wh/m^{2}K), Mixed (132 Wh/m^{2}K) and Massive (204 Wh/m^{2}K) for the treated floor area to be chosen. Furthermore a different value can be inputted manually if it is known (Passive House Institute, 2007).

Site and humidity:

The site where the building is located can have an impact on the potential of overheating during the summer months. Different factors could restrict the natural ventilation, leading to overheating, for example proximity to airport or railway (noise & air pollution), location of the mechanical services (too close to windows), noisy road, polluting industrial site, odour etc. Moreover having the lower ground floor window too close to the road, parking or pavement could restrict the window operation and therefore limit the ventilation rate (Richard Partington Architects, 2012).

Humidity on the other hand, tends not to have so much effect on the occupant thermal comfort and its importance is related to the temperature. During the warmer months higher relative humidity could reduce the evaporation from the skin by means of sweating and also increase the skin wetness leading to higher discomfort (Schnieders, 2009). Moreover higher humidity levels could affect the building structure and material degradation and also could cause mould growth, bacteria and dust mites to name a few (Figure 2-16) (Cotterell & Dadeby, 2012).

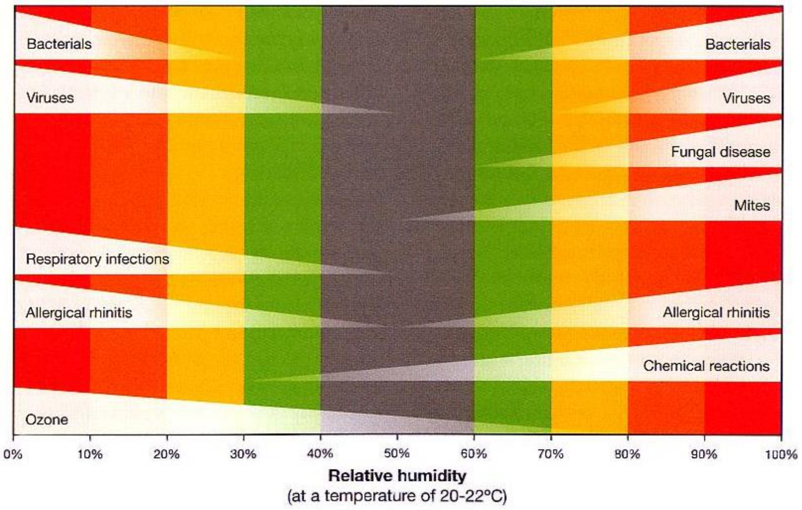


Figure 2-16- Relation between relative humidity and health (source: (Cotterell & Dadeby, 2012) **P.149)**

Noise, pollution and need for security:

Opening the windows might not be an achievable option depending on the occupant behaviour or even their presence, as occupied hours can differ significantly. The time and air change rate that is required to purge the built up heat during the non-occupied period could be considerable. Moreover the frequency of window openings can have a direct effect on overheating percentage occurring in the buildings, and the image below is the demonstration of this in a Passivhaus building (Gonzalo & Vallentin, 2014).

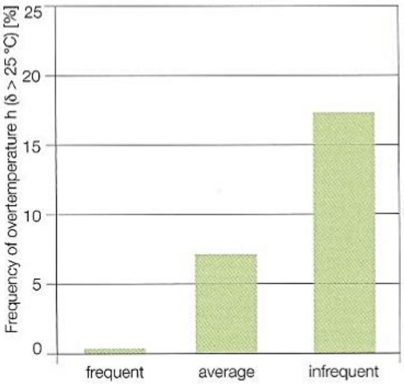
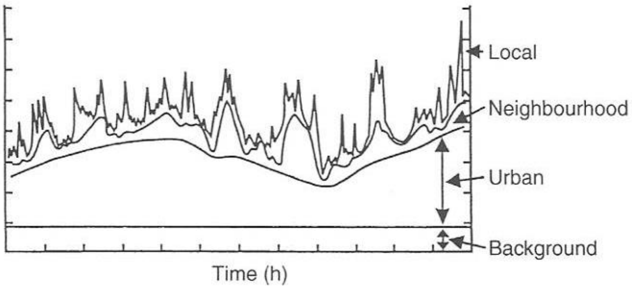


Figure 2-17- relation of the occupant window opening and over hating in a Passivhaus dwelling (source: (Gonzalo & Vallentin, 2014) **P.11)**

Security and safety also reduces the potential of window opening as even in the most secure locations people might not be inclined to leave the windows open during the night (Richard Partington Architects, 2012). On the ground floor, window security restrictors can reduce the ventilation rate to a limited level for purge ventilation and windows with a 50mm opening securely locked in position perhaps will not provide enough ventilation to reduce the potential of overheating (Dengel & Swainson, 2012). On the upper floors also due to safety reasons, window restrictors might be present which can reduce the purge ventilation.

Another potential problem with opening the windows can be the external noise and air pollution. The external noise levels could be possibly more noticeable in Passivhaus when opening the windows as a much quieter internal environment is achieved due to a high level of airtightness and the use of triple glazed windows. This could significantly affect the night time purge ventilation strategy as the occupants' willingness of opening the windows is reduced. Moreover external air pollution, like traffic pollution, can be a factor regarding the reduction in ventilation and it can be categorised in three different sections of: background (5-50Km), neighbourhood (2Km) and local levels. The figure below demonstrates these different levels in combination for a specific location (Awbi, 2003).

Figure 2-18- Different pollution components in relation to time (source: (Awbi, 2003) **P.67)**



Heat Island effect:

Urbanisation and people living in cities has risen by 30% in the past 50 years (Dengel & Swainson, 2012) and the extra heat build-up in cities is known as the urban heat island (UHI) effect (Figure 2-19) which is due to the microclimate within the cities. UHI effect is caused by extra heat build-up in materials used in construction of the buildings and their surroundings, like concrete and brick. This heat further increases the night time temperature which reduces the effectiveness of the night time ventilation strategy (Richard Partington Architects, 2012). UHI effect will not be in the scope of this research.

Figure 2-19- Typical urban heat island profile (source: (Richard Partington Architects, 2012) **P.9)**

Human behaviour:

The limit of overheating and the exact temperature when people feel uncomfortable can vary for different people. Occupants are nevertheless the ultimate importance when designing buildings and they will be the one affected directly by overheating. The occupant behaviour is normally difficult to account for, however their response will be influenced by the mitigation available to them and their understanding of them (Lomas & Porritt, 2017). For buildings without active cooling, natural ventilation will be perhaps the only means of providing cooling and reducing overheating.

The glazing type and airtightness level are part of the Passivhaus standards and cannot be changed to aid the overheating potential during the summer in the UK. Furthermore the shading strategy for the summer period can help to reduce the overheating by controlling the amount of solar heat entering the building. This can be achieved possibly through design and suitable site orientation with the use of relevant shading devices and strategy. However the windows are normally outward opening in the UK which will reduce the possibility of incorporating external shutters (Dengel et al., 2016) and the use of insect mesh.

Insulating the walls and roof to a higher standard for instance can help reducing heat gain from external sources alongside insulating the service pipes etc. (Dengel et al., 2016). However, this is not necessarily possible in the case of Passivhaus buildings as the building benefits from a high level of insulation in the building envelope and the hot water distribution and storage (Passivhaus Institut, 2012).

This research however will concentrate on the reduction of internal gains and providing natural ventilation to aid any potential of overheating. The restriction and limitation of windows being opened during the warmer months, alongside the possible occupant concern over the use of MVHR during the summer (without the benefit of heat exchanger) and even the possibility of MVHR contributing to overheating, will seek a need for a natural ventilation strategy and system.

2.2.4. Overheating in low energy buildings

Overheating can be caused by different reasons in UK dwellings including lack of shading for instance or problem with the heating system (being on during the summer) and lack of maintenance or bad commissioning of the services. However lack of summer ventilation using windows and possibly lower thermal mass can play an even more important role in overheating during the summer period (Gupta & Kapsali, 2016).

Whilst the use of MVHR during the winter could be beneficial as a means of ventilation in central Europe and the UK Passivhaus dwelling, it is not necessarily the most effective during the summer as the rate of ventilation is too low to achieve cooling during this time (Crump et al., 2009). Furthermore the rate of the ventilation could also be reduced subject to maintenance and lack of filter changes. In addition Passivhaus and low energy buildings are subject to higher internal temperature increases even with small fluctuations, due to their minimum heat loss to outside from the fabric, infiltration and exfiltration (Mlakar & Štrancar, 2011).

Research carried out on IAQ and overheating for six social houses in south east UK suggested that the window opening followed the occupant patterns and was not left open at night in the living room, which was perhaps due to security reasons. Moreover a higher ventilation rate was identified to be needed in the bedroom where two adults were sleeping (Gupta & Kapsali, 2016).

The overheating could also be affected due to construction quality and thermal bridging issues (Gupta & Kapsali, 2016). However Passivhaus require a high level of fabric standard which is driven by the surface temperature requirement and thermal comfort. Passivhaus standard also ensures no thermal bridging and the certification procedure and airtightness test enforces the high build quality. Therefore this problem will have a much lower impact in Passivhaus buildings in respect to overheating (Passivhaus Institut, 2012).

On the other hand a high insulation and airtightness level can contribute to overheating if the internal and external heat gains are not removed. Due to better glazing performance, the percentage of glazing is also increased which can increase solar gain and therefore overheating potential (Passivhaus Trust, 2016).

Window opening could help in providing cooling, however the monitoring and survey of 101 homes during August of 2009 in the Greater London area had highlighted the limited use of window when the buildings were overheated above 28°C and 26°C in the living room and bedroom area respectively. More than half of occupants did not open the windows due to security and noise problems and one fifth responded that they would not open any window at night even during the hottest time. However noticeably 75% of people used their shading (curtain/blinds) during the warmer part of the day when only 38% would open most of their windows during the day (Lomas & Porritt, 2017).

Below are some of the examples of overheating in low energy airtight buildings during the summer.

During the summer of 2001 with a peak ambient temperature of 34°C, monitoring carried out for a Passivhaus apartment building in Kassel, recorded around 29°C for the majority of the units with the best case being below 26°C and the indoor temperature passed the 25°C limit for 6% of the year (Schnieders 2009). Likewise the temperature was monitored in terraced houses in Hannover built to Passivhaus standard and for three buildings the indoor temperature during the summer was recorded between 27°C and 29°C. These three buildings were either unoccupied with no night time ventilation, had high electricity usage or were heated during the summer (Schnieders 2009).

The study carried out by BRE on Greenwatt Way development (Chalvey, near Slough, Berkshire), built to code level 6 zero carbon homes, highlighted the problem of overheating during the summer. The 10 dwellings monitored by BRE consisted of flats and houses built with lightweight and heavyweight construction and during the summer of 2011, the worse thing reported by the occupants about the buildings was the overheating. Although besides the use of MVHR, opening windows had also been a means of extra ventilation during this time; still internal temperatures were recorded above 26°C when outside temperatures were barely warm. The complaints about the heat were greater in the lightweight dwelling even though this was perhaps increased by the reduction of occupant willingness to open the windows in these buildings due to their closer proximity to the road and therefore the security implication from it (Dengel & Swainson, 2013). Passivhaus benefits from a higher envelope efficiency and airtightness level in comparison to code level 6 dwellings, increasing the potential of overheating specifically for lightweight construction.

The Slovenian Passivhaus built during 2006 is located in Limbus near Maribor (northern Slovenia), and is a lightweight construction comprising 113m^2 TFA with 260m^3 of internal volume. The average fabric U-Value is around 0.1 W/m^{2}K with window U-Value of 0.8 W/m^{2}K. Southerly oriented windows are shaded by the roof overhang whereas east and west windows benefit from movable occupant controlled venetian blinds during the summer. The importance of excessive night time ventilation and use of shading was identified through monitoring and computer simulation. The lack of use of movable shading for east and west facade was recognised to increase the internal temperature by 15°C which was no longer possible to be reduced by night time ventilation alone (Mlakar & Štrancar, 2011). The occupant's behaviour and concerns can play an important role in respect to overheating, leading to reduction in shading and window operation.

Ravnsborghusene comprises 126 social housing apartments in nine identical 3 to 4 storey high buildings located in Koge, Denmark completed during 2012. The buildings benefit from movable external shading on the East and West windows. A post completion survey was carried out using monitoring data from the BMS (Building Management System) located in the centre of the open kitchen/living room as well as an occupant satisfaction questionnaire with a response rate of 37% which translates to 47 units. The overheating was identified to be more than the 10% over 25°C in more than 60% of the apartments compared to no overheating from the PHPP calculations. Occupants' responses also indicated overheating with 30% reporting discomfort during the summer period (Krintel et al., 2014). The design intent alongside expected additional natural ventilation used for the PHPP calculations, was perhaps the reason for no indication of overheating potential.

The first certified Passivhaus in London is Camden Passive House, which was built using timber frame and consists of two bedrooms with 101m^2 of floor area. The fabric U-Values are between 0.11 W/m^{2}K and 0.067 W/m^{2}K with an air infiltration rate at 50 Pa of 0.44 ac/h. The MVHR unit has been placed outside the thermal envelope in its own insulated structure connected to the dwelling with a manufacturer's claimed efficiency of 92% to achieve 36l/s equivalent to 0.48ac/h. The building is designed to benefit from external movable shading devices with automatic solar control, bearing in mind the high level of overshading due to the building's location. The inward opening tilting windows are designed to encourage summer purge ventilation and night time ventilation with minimum security implications. The owner occupants are a professional couple with neither working from home (Ridley et al., 2013).

The building was constructed during 2010 and has been monitored from July 2011 under the Technology Strategy Board, Building Performance Evaluation Programme. The monitoring data has highlighted that the building not only meets the Passivhaus annual space heating demand of 15kWh/m^2, but also surpasses it by achieving 12.1kWh/m^2 with the annual primary energy demand to be just over the Passivhaus requirement of 120kWh/m^2 and was recorded to be 125kWh/m^2. Summer overheating was identified and for instance the living room exceeded the 25°C limit during the summer by 22.5% of hours. Moreover the summer time averaged ventilation using the windows was **0.14 ac/h** which was identified to be too low and recognised that it needed to be increased to **0.5 ac/h** (Ridley et al., 2013).

However, the occupant survey did not indicate overheating during the summer and the occupants found the building comfortable even with the higher temperatures. It is needed to highlight that one of the occupants had mentioned "*When it gets hot, it gets very hot, but effectively it could be resolved by means of opening windows*" (Ridley et al., 2013) P.77. This tolerance and response to overheating could be put down to owning and building their home to a very high level of efficiency and they would not necessary want to criticise it. Moreover the younger age of the occupants can play a role on their tolerance level.

The recent occupant satisfaction survey carried out using the BUS survey (Building Use Studies) on 21 Passivhaus bungalows, Racecourse estate UK, also highlighted overheating problems in comparison to the BUS 2011 UK housing benchmark. The rate of the ventilation using the MVHR was confirmed to be adequate by site measurement which also confirmed the commissioning of the MVHR to be as per the design requirements. Around 86% of the occupants stated that they usually spend their time at home due to their older age. The survey highlighted dissatisfaction and high temperatures during the summer which was later identified to be perhaps due to lack of window opening especially at night which was put down to security concerns (Siddall et al., 2014).

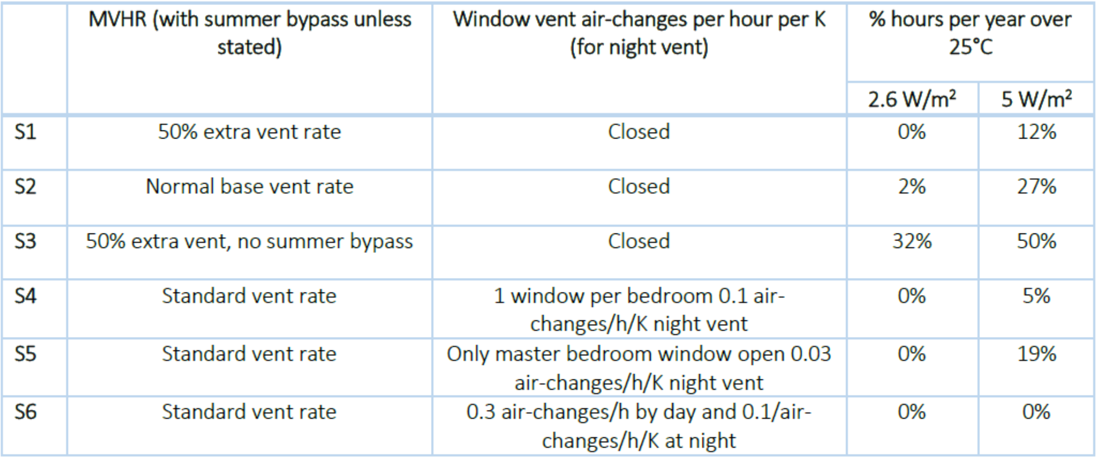
A study on five Passivhaus dwellings and 21 low energy houses in Scotland during 2013 had indicated a high percentage of overheating and up to 49% in the case of one of the Passivhaus buildings when the PHPP calculation had indicated 0.2% of overheating. The overheating was not limited to the summer months and mean temperatures were recorded in excess of 29.5°C and 28.3°C in the bedroom and living room respectively. High temperature recordings in the bedrooms were concerning as the occupant would not be able to release the daytime thermal stress. The occupant questionnaire however highlighted that the occupant would open the windows at night if it was warm except for the ground floor due to security concerns.

Occupant feedback regarding the overheating on the other hand was varied as some with high recorded overheating percentage did not mention overheating whereas others with a lower percentage of overheating in comparison were concerned. It is worth mentioning that all of these buildings are located in a climate which is classed as low risk in respect to overheating potential. Moreover, not one reason was identified to be the main cause of the overheating problem and not even the glazing size as the majority of the monitored spaces did not benefit from a high percentage of glazing area.

All the 26 monitored buildings were built with low thermal mass internally except three, however this was not concluded to be the main problem as one of the properties with high thermal mass also had one of the highest overheating percentages. Cross ventilation was a possibility in the majority of the monitored buildings, however in contrast the majority did not benefit from stack ventilation. Moreover 42% of the buildings did not make use of the possible additional cooling from natural ventilation using windows or trickle vents (Morgan et al., 2017).

Research was also undertaken for a Passivhaus in a rural location (Steel Farm Passivhaus) to examine the relation between overheating and ventilation achieved through different methods taking higher internal gains into consideration. The building area is 150m^2 with a thermal mass of 108 Wh/K per m^2 TFA. The below table demonstrates the different scenarios and the associated overheating percentage (Passivhaus Trust, 2016).

Table 2-3- Overheating risk arising from various design scenarios (Source: (Passivhaus Trust, 2016). Page 13)



	MVHR (with summer bypass unless stated)	Window vent air-changes per hour per K (for night vent)	% hours per year over 25°C	
			2.6 W/m^2	5 W/m^2
S1	50% extra vent rate	Closed	0%	12%
S2	Normal base vent rate	Closed	2%	27%
S3	50% extra vent, no summer bypass	Closed	32%	50%
S4	Standard vent rate	1 window per bedroom 0.1 air-changes/h/K night vent	0%	5%
S5	Standard vent rate	Only master bedroom window open 0.03 air-changes/h/K night vent	0%	19%
S6	Standard vent rate	0.3 air-changes/h by day and 0.1/air-changes/h/K at night	0%	0%

The final option achieving 0.3 air change during the day and 0.1 air change at night, resulted in no overheating even with the higher internal gain option of 5 W/m^2. However this option relies heavily on the occupants' discipline in operating the windows and also benefiting from the building's rural location (Passivhaus Trust, 2016).

The prediction on the effect of climate change in the UK is to expect higher temperatures and more episodes of heatwaves especially for the south east and more urban areas of the UK. Furthermore higher temperatures and higher solar radiation in the future is predicted to make people spend even longer periods inside buildings (Dengel & Swainson, 2012) and can potentially increase the possibility and episodes of overheating in buildings, even more in low energy airtight dwellings.

However other countries across Europe with warmer summer temperatures in comparison to the UK, manage to provide summer comfort within their low energy buildings without the aid of active cooling. This might be due to the design of their buildings and occupant behaviour benefiting from shading and night time ventilation. Furthermore buildings not benefiting from active cooling would have natural ventilation only to provide the required cooling. Perhaps keeping the windows closed during the day when outside is warm and benefiting from night time ventilation, could be a good strategy to ensure comfort within the building (Passivhaus Trust, 2016).

2.2.5. Climate change

Understanding climate and climate change requires first to define weather and its difference in definition with climate. Weather is a description of atmospheric circumstance relative to a specific time and area regarding to different temperature, humidity, wind, pressure, etc. Climate on the other hand is the average and inconsistency of for instance temperature, rain fall and wind in a specific period of time and the World Meteorological Organization has identified this period as 30 years (Intergovernmental Panel on Climate Change, 2013); and climate change is described as:

> *"… a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer."*
>
> (Intergovernmental Panel on Climate Change, 2013) P.126

The World Meteorological Organization along with United Nations Environment Programme during 1988 set up the Intergovernmental Panel on Climate Change (IPCC) to help in understanding climate change, its potential implications and possible adaptation and mitigation options. IPCC has previously published their assessments in different years from 1990 to 2007 and the most recent, with aid of advancement in computing and higher satellite observation capability, during 2013-2014 (Intergovernmental Panel on Climate Change, 2013).

The IPCC working group one report 2013 highlights the reason for climate change due to a small positive imbalance of incoming and outgoing energy from solar radiation. The total solar irradiance (TSI) of around 1361W/m^2 enters the earth's atmosphere in shortwave radiation and half is absorbed by the earth's surface and the other half is either reflected back by different gases etc. (30%) or absorbed by the atmosphere (20%). The outgoing energy in the form of longwave radiation is absorbed by different gases such as CO_2 and water vapour and reemitted in longwave form in all directions. The earth's surface and lower surface of the atmosphere are then heated by the downward radiation generated also known as greenhouse effect. Moreover, human activity is increasing the greenhouse gases and changes in the land usage like deforestation have contributed to further changing the climate (Intergovernmental Panel on Climate Change, 2013).

The recent measurements and ice core records have identified the increase of greenhouse gases such as CO_2 (Figure 2-20) for the past 200 years and for the past 100 years, further observation and use of satellite has confirmed the increase in temperature for land and sea surface (Figure 2-21) (Intergovernmental Panel on Climate Change, 2013).

Figure 2-20 – Atmospheric CO_2 (source: (Intergovernmental Panel on Climate Change, 2013) **P.12)**

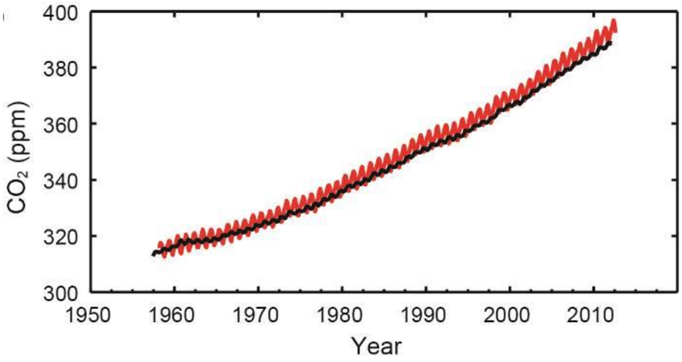
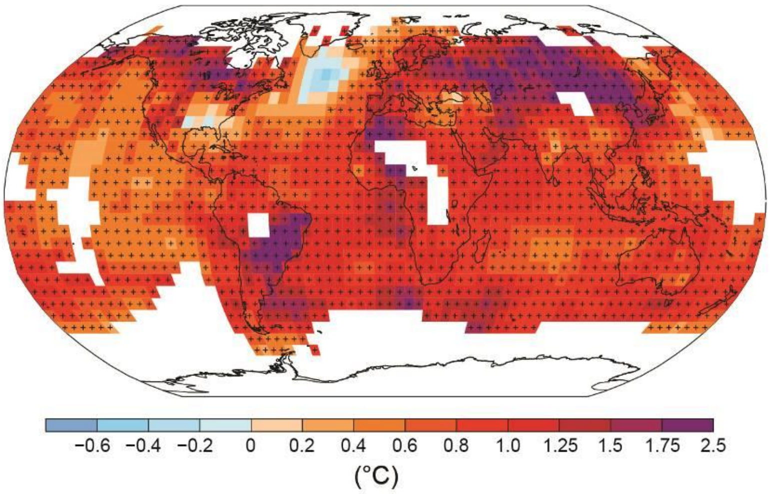


Figure 2-21 – Observed changes in surface temperature 1901-2012 (source: (Intergovernmental Panel on Climate Change, 2013) **P.6)**



The IPCC has published their report and predictions in the following order:

- First Assessment Report 1990 (FAR)
- Second Assessment Report: Climate Change 1995 (SAR)
- Third Assessment Report: Climate Change 2001 (TAR)
- Fourth Assessment Report: Climate Change 2007 (AR4)

Below is the comparison of the observed temperature and CO_2 with the earlier prediction models.

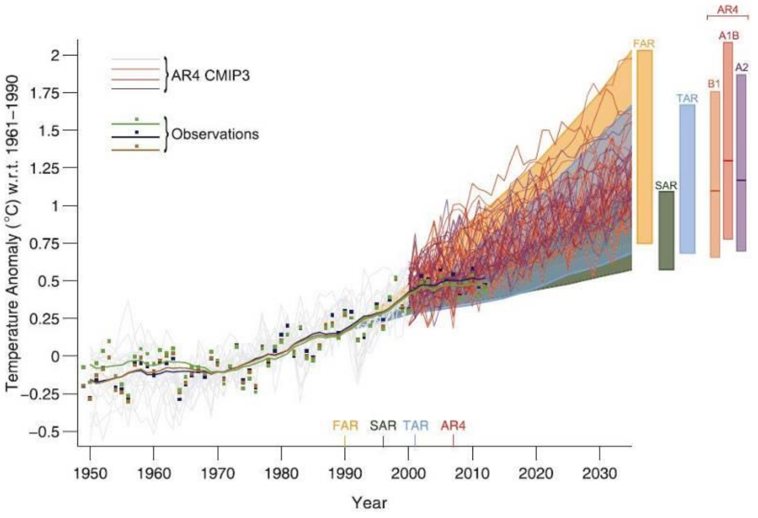


Figure 2-22 - Likely changes in the observed global and annual averaged surface temperature irregularity in relation to 1961–1990 (°C) from 1950 in comparison to the previous IPCC projections. (source: (Intergovernmental Panel on Climate Change, 2013) **P.131)**

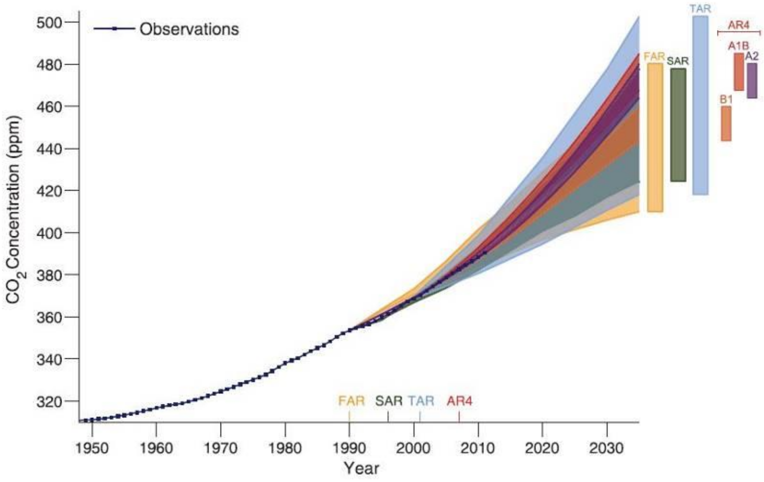


Figure 2-23 - Observed global and annual averaged CO_2 concentrations (ppm) from 1950 in comparison to the previous IPCC projections (source: (Intergovernmental Panel on Climate Change, 2013) **P.132)**

The recent report from IPCC, Fifth Assessment Report (AR5) published in 2013 by working group one (WGI), is using the Model results from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) and also predicts different scenarios (Figure 2-22) using higher resolution modelling and further development in projection of uncertainties leading to more detailed future climate projections (Intergovernmental Panel on Climate Change, 2013).

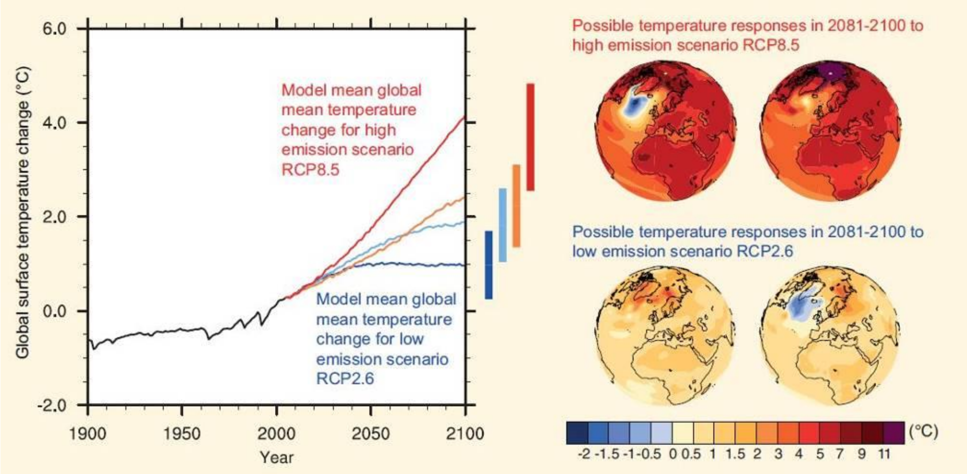


Figure 2-24 - Global mean temperature change averaged throughout all CMIP5 models (comparative to 1986–2005) for the four scenarios from Representative Concentration Pathway (RCP) (source: (Intergovernmental Panel on Climate Change, 2013) **P.1037)**

UK Climate Impacts Programme (UKCIP) first established in 1997, has also published their latest report and data for the UK future climate during 2009 (UK Climate Projections) (UKCP09) following their earlier reports in 1998 and 2002. Their aim has been to assist in decision making and adaptation to climate change which has somewhat already started, in areas like transport, healthcare, water resources and coastal defences (Jenkins et al., 2009).

As the UK climate has been comprehensively monitored since 1772, it has highlighted an increase in temperature for instance for central England around one degree Celsius since the 1970s which has been identified to be due to an increase in greenhouse gases. Furthermore the sea levels around the UK have also been rising by 1mm per year during the 20th century with an even higher rate during the 1990s and 2000s (Jenkins et al., 2009).

UKCP09 uses three different emission scenarios of low, medium and high with three different probabilities on 10%, 50% and 90% with 50% being the '*central estimate*'. UKCP09 presents its probabilistic projections in 25Km resolution over land and with an average for river basins and marine regions for a period of seven overlapping periods of 30 years. Table 2-4 and figure 2-25 & 2-26 are the summary of selected data from UKCP09 using the medium emission scenario (Jenkins et al., 2009):

Table 2-4- UK medium emission scenario with three different probability levels- adapted from (Jenkins et al., 2009) **P.6-7**

Medium emission scenario	10% probability (very likely to be exceeded)	50% probability	90% probability (very likely not to be exceeded)
Changes in summer mean temperatures-south England	2.2°C	4.2°C	6.8°C
Mean daily maximum temperatures-south England	2.2°C	5.4°C	9.5°C
Changes in the warmest day of summer-south England	0.2°C	4.8°C	12.3°C
Precipitation in summer-south England	-65%	-40%	-6%
Summer Relative humidity-south England	-20%	-9%	0%
Summer-mean cloud amount-south England	-33%	-18% Resulting extra 16 W/m^2 shortwave radiation	-2%

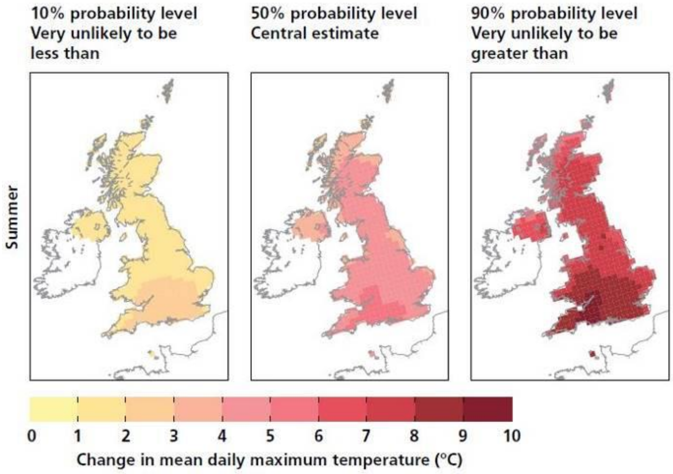


Figure 2-25 – Probabilities of mean daily maximum temperature changes in summer from the medium emissions scenario, by the 2080s (source: (Jenkins et al., 2009) **P.31)**

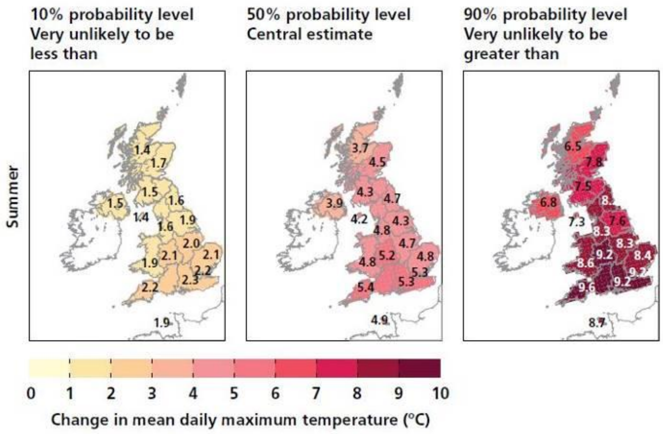
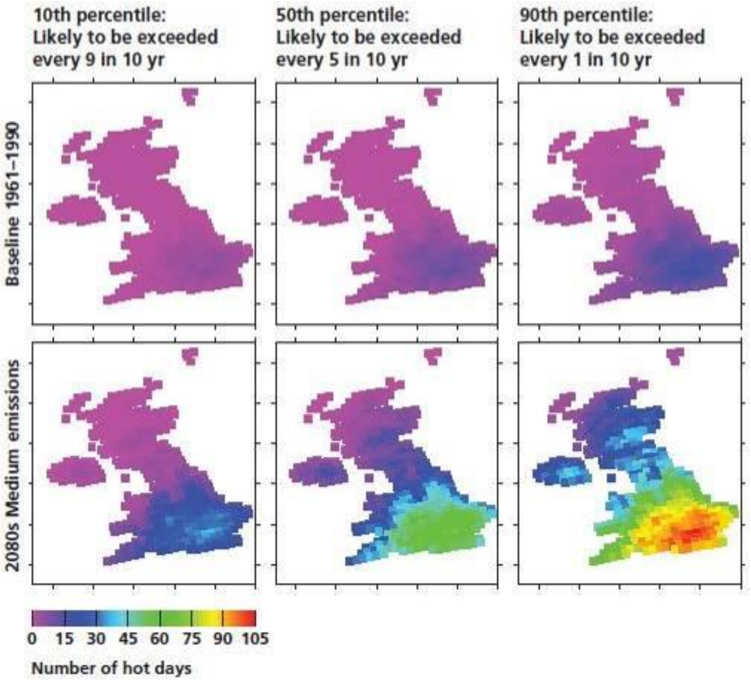


Figure 2-26 – Indication of changes for summer mean daily maximum temperature averaged across different regions (source: (Jenkins et al., 2009) **P.31)**

The 25Km resolution has been divided to administrative regions of Wales, Scotland (three subdivisions), England (nine subdivisions), Isle of Man and Channel Islands. Furthermore uncertainties are also recognised in UKCP09 such as future greenhouse gas emissions caused by human activities, natural climate variability and modelling uncertainties (Jenkins et al., 2009).

Using the weather generator in comparison to the 1961-1990 baselines from the UKCP09, some of the key changes at daily levels are also indicated. The increase in temperature and the number of hot days above 25°C during the summer was noticeable which can be seen from figure 2-27.

Figure 2-27 - Estimated numbers of days a year above 25°C by the Weather Generator, for baseline (1961–1990) and medium emissions (2080s) scenarios (source: (Jenkins et al., 2009) **P.43)**



Moreover the Committee on Climate Change for England’s 2014 report emphasises on the changing climate and rising temperatures and states that the most immediate impact in England will be extreme weather conditions such as heatwaves. It also states the possible higher mortality rate caused by heatwaves as the climate is changing and our population is getting older. The report also highlights the need for adjusting the existing building stock and better design for new buildings and suggests **“*cost-effective passive cooling measures*”** to be used instead of perhaps the use of high CO_2 intensive air-conditioning systems. (Adaptation Sub-committee, 2014) P.9

The changing climate and the predicted higher summer temperatures can only increase the potential of overheating in buildings especially built with higher airtightness and lower heat loss in mind like Passivhaus buildings. The importance of providing specific cooling and consequently reducing the indoor temperature naturally will be higher in the future leading to the possibility of need for refurbishment of buildings that are not currently overheating. Furthermore extreme weather episodes are a possibility for any year and therefore designing buildings to be resilient to these changes and thus have a lower potential of overheating would seem logical (Passivhaus Trust, 2016).

2.3. NATURAL VENTILATION

Natural ventilation is defined as:

> *"Natural ventilation… is the term used to describe the air flow to or from a building through specific openings in the building envelope…"*
>
> (Awbi, 2003) P.304

The specific opening can be designed to maximise the total ventilation rate achieved specially during the summer period.

2.3.1. Driving forces

Today, the most commonly used means of ventilation for dwellings is natural ventilation (Awbi, 2003) where this can be achieved by wind, temperature difference (buoyancy) or both (Figure 2-28). The air flow path within the building achieved due to natural ventilation can vary, however the three most common ways are (Pennycook, 2009):

- Cross ventilation
- Single sided ventilation
- Passive stack ventilation

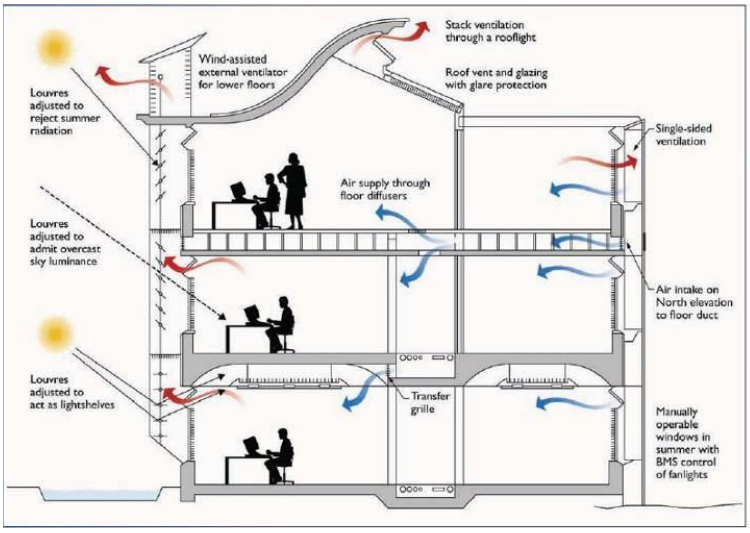


Figure 2-28 – Different natural ventilation strategies (source: (Pennycook, 2009) **P.7)**

Natural ventilation entering the building is directly influenced and affected by the surrounding climate which allows the air to enter the building either by infiltration (through gaps and cracks within the building envelope) or from a purposely provided natural ventilation system (Awbi, 2003). Passivhaus standard requires a very high level of airtightness and therefore the air entering the building from infiltration is potentially very small that can be almost non-existent.

Wind is the most important mechanism for the driving forces of natural ventilation, especially in the hotter climates and it can be defined at global, regional, local and microclimate scale. The daily and seasonal variation occurs at a global scale due to the earth's rotation and orbit around the sun. This is further influenced by the latitude and the spread of land and ocean. The topographical landscape such as mountain and valleys and closeness to the ocean can define the regional scale, which can cover wind around hundreds of kilometres whereas lakes, large rivers, hills and valleys alongside the urban landscape and heat island effect, makes up the influences of the local scale. In a much smaller scale, around a few hundred metres, microclimate scale is affected directly by human activities and urban planning like construction materials, wind breaks and planting hedges etc. (Awbi, 2003).

Understanding wind at the microclimate scale is important when designing naturally ventilated buildings. The direction of the prevailing wind for example can change from day to night, especially in mountain areas and land close to large bodies of water. The soil condition including its colour and capacity to hold water alongside different vegetation can also influence the microclimate. Moreover the local topography and man-made constructions can alter the wind characteristic in the microclimate scale. Urbanisation for instance can reduce the local wind speed by 25%, or cause the wind to increase in speed due to urban canyons (Battle McCarthy Consulting Engineers, 1999).

Designing for natural ventilation using wind can have its challenges as the wind speed can vary according to different heights and obstruction and can consist of turbulence with less predictability. The data used for this is normally the hourly mean wind speed measured at 10m height (Awbi, 2003) and the average wind speed in the UK is 4.5 m/s (Battle McCarthy Consulting Engineers, 1999). The wind can create pressure differences externally and internally and can be influenced by the building shape and the openings within the building. The windward side of the building is under the positive pressure and the leeward side will have a negative pressure (Awbi, 2003).

Temperature difference creates different density of air causing buoyancy which is the force for stack ventilation in buildings. The vertical gradient is created when the openings within the building are in two different heights causing the pressure difference. When stack and wind are used together within a building, the airflow can be determined and if the pressures caused by both forces are both either negative or both positive then the airflow is increased; whereas the airflow can be reduced significantly if the pressures are in the opposite measure to each other (Awbi, 2003). Moreover as the wind speed increases over 2.5 m/s, the wind pressure will exceed the buoyancy effect (Battle McCarthy Consulting Engineers, 1999).

The following factors should be taken into consideration to determine the best natural ventilation strategy (Awbi, 2003) P.324:

- Depth of space with respect to ventilation openings
- Ceiling height
- Exposed thermal mass to the air
- Location of building with respect to environmental pollution sources, such as traffic noise, air pollution, etc.
- Heat gain
- Climate

Introducing openings on two sides of a space will enable cross ventilation which is more effected by the wind than buoyancy (Awbi, 2003). Using cross ventilation can provide a high natural ventilation rate and can help to maximise the benefit of thermal mass during the warmer months by ventilating the building at night (Pennycook, 2009). Positioning the openings on windward and leeward can increase the airflow and be more favourable as the wind pressure will be kept. Moreover deeper plan buildings can be naturally ventilated, from 2.5 times the ceiling height to a maximum of 5 times the ceiling height (Figure 2-29) (Awbi, 2003).

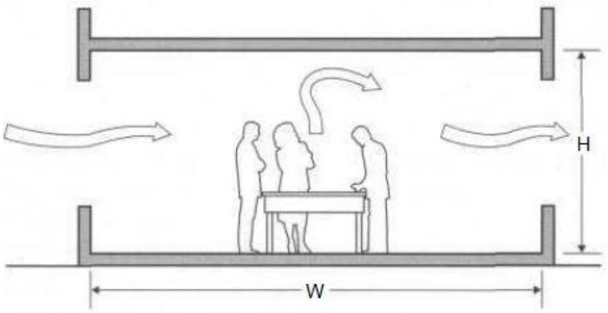


Figure 2-29 – Cross ventilation, W_{max} approx. 5H (source: (Cheshire, 2012) **P.5-10)**

Where cross ventilation is not an option due to restrictions, single sided ventilation can be used to provide the required natural ventilation, which is also the simplest way of providing natural ventilation to a building (Pennycook, 2009). A single opening on one side of a space, allows the air to enter and exit the space by the aid of forces of wind. If more than one opening is introduced at different heights on the same side, the pressure difference from buoyancy can help to increase the ventilation rate. Single sided ventilation is perhaps more suited to moderate climates (Awbi, 2003) and the recommended opening area is around 1/20 of the floor area with maximum floor depth of 2.5 times the floor to ceiling height (Figure 2-30 & 2-31) (Cheshire, 2012).

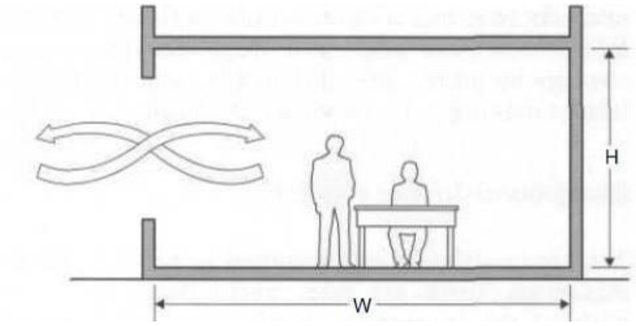


Figure 2-30 – Single-sided ventilation (wind driven) W_{max} approx. 2.5 H (source: (Cheshire, 2012) **P.5-10)**

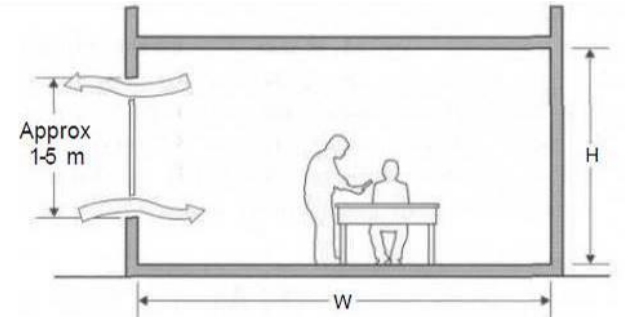


Figure 2-31 – Single-sided ventilation (temperature driven) W_{max} approx. 2.5 H (source: (Cheshire, 2012) **P.5-10)**

Stack ventilation (Figure 2-32) can either be used as the only method of providing natural ventilation or it can be used in conjunction with other strategies to be most effective. Providing a high level opening in the building will allow the hot air that is rising to exit the building and be replaced by cooler air from the openings in the lower part of the building bearing in mind that the outside temperature should be cooler than inside. Stack ventilation could be more effective during the night as the outside temperature falls and the temperature difference between inside and outside is at its highest. When using the stack ventilation shaft, it is important to keep the shaft higher than the building to avoid overheating in the upper floors of the building (Pennycook, 2009).

Incorporating a stack ventilation strategy requires careful design and perhaps use of a wind tunnel or computational fluid dynamic (CFD) modelling. Using CFD analysis will predict the wind effect on the stack ventilation, and allow the designer to minimise the reduction in stack or avoid the reverse in the airflow due to wind forces (Awbi, 2003).

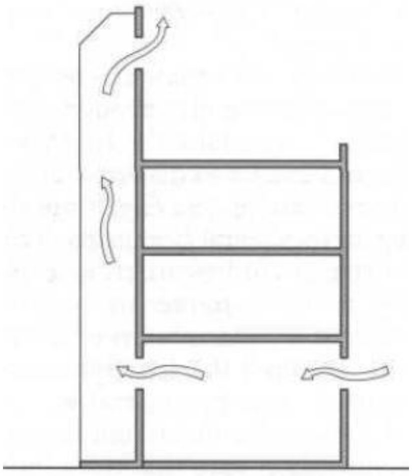


Figure 2-32 – Stack ventilation (source: (Cheshire, 2012) **P.5-10)**

Increasing the ventilation rate and air velocity during the warmer months can help to achieve thermal comfort even if the temperature remains high (Figure 2-33) (Battle McCarthy Consulting Engineers, 1999). However using natural ventilation to aid for cooling can have its limitation as it is perhaps unlikely to be effective when the heat gain is over **40 W/m^2** and therefore the heat gain should be reduced from internal and external sources to a minimum where possible to avoid the need for extra cooling (Pennycook, 2009).

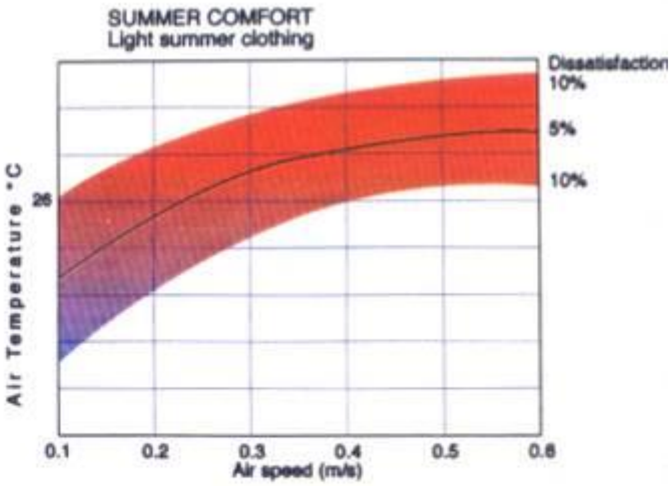


Figure 2-33 – Relation of acceptable temperature and air speed with a limit of 0.8 m/s for comfort (source: (Battle McCarthy Consulting Engineers, 1999) **P.15)**

Key points:

Wind as a means of ventilation can be changeable, unpredictable and have turbulence. It can be effected by obstruction and urbanisation and depends on the height which is usually measured at 10 metres high. On the other hand buoyancy relies on temperature difference and can be used in conjunction with wind for providing a higher ventilation rate.

Single sided ventilation can have limitations and it is better suited for more moderate climates. Cross ventilation is more dependent on wind rather than buoyancy. Stack ventilation allows hot air to exit at a higher level and be replaced by cooler air at a lower level. It can be more effective at night and the shaft should be higher than the building.

Natural ventilation can have limitations and reduces in effectiveness when heat gain is over 40W/m^2.

2.3.2. Available strategies

One of the most basic ways of providing natural ventilation to a building is to use windows. Windows will give the occupant a high level of control and satisfaction in spite of possible localised discomfort and draughts. The use of windows might be restricted due to external noise and pollution; moreover occupant willingness to operate the windows could also be reduced subject to security especially during the night and unoccupied hours. There are many different window designs which affect the way the window is opened (Figure 2-34) and therefore the amount of ventilation provided and protection against the weather (Pennycook, 2009). Passivhaus windows are typically, but not always, inward opening which allows the insulation to cover the frame as much as possible, leading to less heat loss and better Psi-Value for the frame junction (Passivhaus Institut, 2012).

Bottom-hung inward opening fanlight

Air flow	☺ ☺
Ventilation control	☺ ☺ ☺
Weather protection	☺ ☺ ☺
Night ventilation	☺ ☺ ☺ ☺
Relative cost	Medium
BMS controllable	Yes

May obstruct blinds. Good sound control.

Centre pivot

Air flow	☺ ☺ ☺ ☺
Ventilation control	☺ ☺
Weather protection	☺ ☺ ☺
Night ventilation	☺ ☺ ☺
Relative cost	Medium
BMS controllable	Yes

May obstruct blinds preventing adequate glare control for users of computer screens. Can reflect external noise.

Upper fanlight and outward opening casement

Air flow	☺ ☺ ☺
Ventilation control	☺ ☺ ☺ ☺
Weather protection	☺ ☺ ☺ ☺
Night ventilation	☺ ☺ ☺ ☺
Relative cost	High
BMS controllable	Yes

Upper fanlight can be motorised. Good all round performance.

Tilt and turn

Air flow	☺ ☺ ☺
Ventilation control	☺ ☺ ☺
Weather protection	☺ ☺ ☺
Night ventilation	☺ ☺
Relative cost	High
BMS controllable	Yes*

*BMS controllable in one plane only. Complex.

Top-hung outward opening casement

Air flow	☺ ☺ ☺
Ventilation control	☺ ☺
Weather protection	☺ ☺ ☺ ☺
Night ventilation	☺ ☺ ☺
Relative cost	Medium
BMS controllable	Yes

Can reflect noise into room. Secure night vent. May need a governor to restrict opening.

Horizontal sliding sash

Air flow	☺ ☺ ☺ ☺
Ventilation control	☺ ☺
Weather protection	☺ ☺
Night ventilation	☺ ☺
Relative cost	Low
BMS controllable	Yes

No obstruction of internal blinds. Tall openings enable localised stack effect.

Side-hung casement

Air flow	☺ ☺ ☺
Ventilation control	☺ ☺
Weather protection	☺ ☺
Night ventilation	☺
Relative cost	Medium
BMS controllable	Yes

Poor security when open. Rain can enter.

Vertical double sash

Air flow	☺ ☺ ☺ ☺
Ventilation control	☺ ☺ ☺
Weather protection	☺ ☺
Night ventilation	☺ ☺
Relative cost	Low
BMS controllable	Yes

No obstruction of internal blinds. Localised stack effect.

Figure 2-34 – Different window types and openings (source: (Pennycook, 2009) **P.13)**

Providing a bigger window can increase the opening area leading to a higher natural ventilation rate; however this could also cause higher solar gain and glare especially during the summer months (Pennycook, 2009). Moreover the ventilation rate through windows can be affected as the wind direction changes (Battle McCarthy Consulting Engineers, 1999) and window restrictors used for safety and security can significantly reduce the ventilation rate (Dengel & Swainson, 2012). Moreover the rate of the ventilation can be further reduced due to use of curtains or blinds.

The incorporation of trickle vents in windows can provide the required background ventilation during winter time (Pennycook, 2009) if used and understood by the end user as often it is left open or closed depending on the external temperature when the building is handed over. The rate of the ventilation could also be inadequate when using trickle vents as demonstrated in the research, which investigated the suitability of the 2006 Part F, carried out on 22 homes during 2009 with an average airtightness of 6 air change per hour (de Selincourt, 2014). However in the UK the heat loss from trickle vents will be too high to meet the Passivhaus standard, regardless of the possible discomfort from the cold air entering the building (Passivhaus Institut, 2012). Moreover windows can potentially provide single-sided, cross and stack ventilation in a building.

Incorporating side panels into windows (Figure 2-35) will allow the building to benefit from natural ventilation with less security implications and by introducing an insect mesh, especially in rural locations, it will allow for longer operation time and therefore higher natural ventilation rate (Pennycook, 2009). However this system is still limited when taking noise and pollution from outside sources into consideration.

Figure 2-35 – Openable side panel (source: (Pennycook, 2009) **P.17)**

One of the other methods of providing natural ventilation to buildings is to use wind towers (Figure 2-36). Having a vertical shaft above the building, for example, can create negative pressure as the wind passes through and therefore create suction from the building. The wind tower can have a simple structure with a cover over it to stop the rain entering the shaft or can be L shaped (Figure 2-37) for better protection from the rain. An L shaped wind tower will limit the pressure difference as the wind direction changes. Therefore wind towers need to be omnidirectional and face away from the wind to maximise their effectiveness (Battle McCarthy Consulting Engineers, 1999).

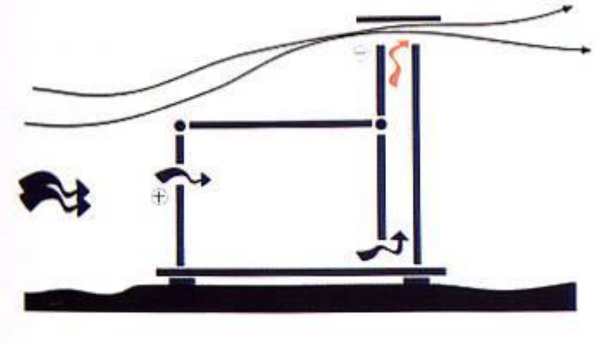


Figure 2-36 – Wind tower design (source: (Battle McCarthy Consulting Engineers, 1999) **P.19)**

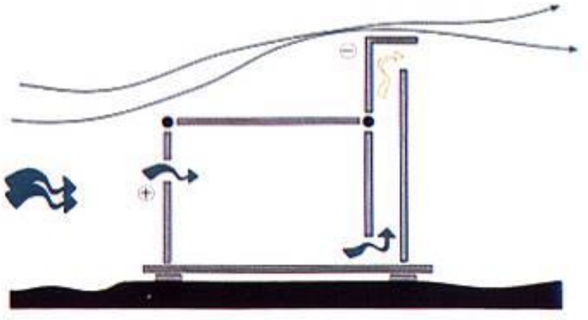
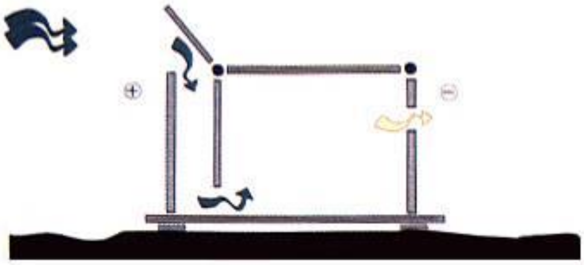


Figure 2-37 – L shaped wind tower design (source: (Battle McCarthy Consulting Engineers, 1999) **P.19)**

Catching the air and directing it into the building can be done by using wind scoops (Figure 2-38). Wind scoops are similar to wind towers, but they are designed to face the wind and therefore to encourage the wind into the building. Like wind towers, the wind scoops need to be omnidirectional which is hard to achieve with a fixed structure (Battle McCarthy Consulting Engineers, 1999).

Figure 2-38 – Wind scoop design (source: (Battle McCarthy Consulting Engineers, 1999) **P.19)**



Using a wind tower in conjunction with a wind scoop (Figure 2-39) allows for higher pressure difference and consequently higher air flow within the building as the intake and extract of air is done at a higher level. This can be done either by having two separated structures or one structure combining the two systems. Having one shaft which is divided into four sections internally will allow the wind to enter the building in any direction through one of the divisions, when the others act as wind towers. This system is known as 'badgir' (windcatcher) (Figure 2-40) which was first used in Iran as a means of providing natural ventilation in a hot arid climate. Using this system, as it is located above the building, will allow for optimisation of building orientation regardless of the prevailing wind direction (Battle McCarthy Consulting Engineers, 1999).

Figure 2-39 – Combination of wind scoop and wind tower (source: (Battle McCarthy Consulting Engineers, 1999) **P.20)**

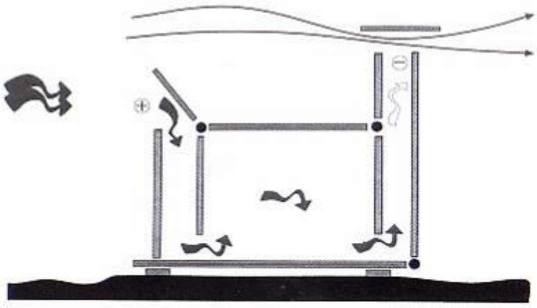
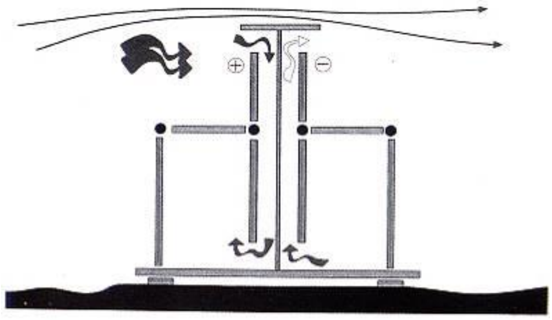


Figure 2-40 – The badgir, combining inlet and outlet (source: (Battle McCarthy Consulting Engineers, 1999) **P.20)**



Windcatchers can perhaps provide a cleaner and higher ventilation rate in comparison to windows, especially in more urban locations as the source of outdoor pollutants like traffic is at the lower height and it reduces as it gets to the roof level (Awbi, 2003). The rate of the ventilation is not affected as the wind direction changes, and they can also allow for deeper plan buildings if centrally located (Battle McCarthy Consulting Engineers, 1999). Furthermore windcatchers (roof mounted) can offer weather protection and the required security, especially for a night time ventilation strategy (Parker & Teekaram, 2005).

Windcatchers can be designed with different shapes in mind; however square and circular forms are the most common (Figure 2-41). Furthermore windcatchers can be made to be static or movable to face the wind as the wind direction changes (Parker & Teekaram, 2005).

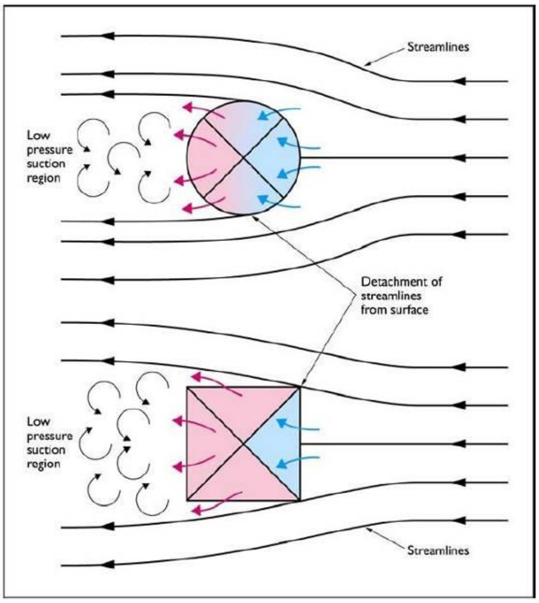


Figure 2-41 – Air flow around different ventilator shapes (source: (Parker & Teekaram, 2005) **P.5)**

The flow of air through windcatchers can vary and be influenced by the wind speed, wind direction and the windcatchers' size. However in low wind speeds the use of stack ventilation can still assist in providing adequate natural ventilation. Below are the results from the wind tunnel test on 0.5m square section fixed windcatchers with 1.5m length (Awbi, 2003).

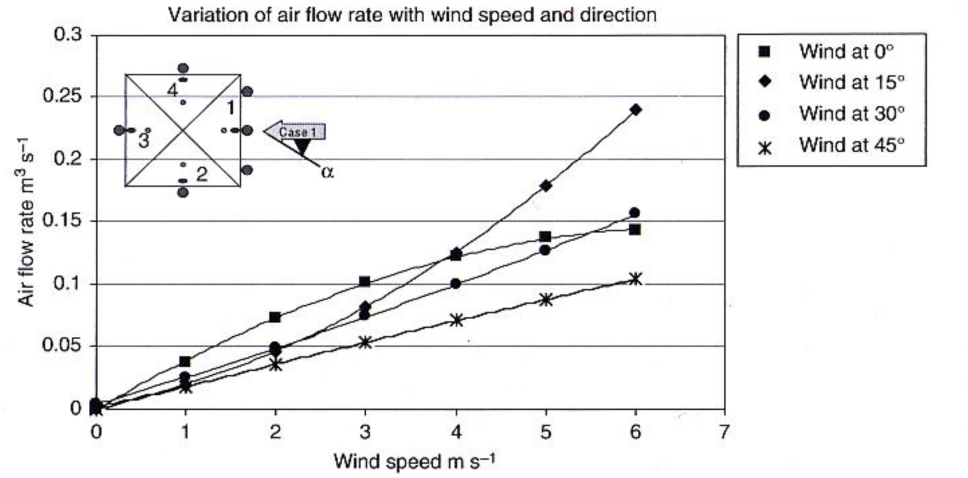


Figure 2-42 – Measurent of air flow for windcatcher of 0.5m square section and 1.5m long (source: (Awbi, 2003) **P.334)**

More modern designs for windcatchers have been used in different building types around the UK with the ability to rotate and face the wind direction for optimum performance. For instance the wind cowl system in ZED factory's approach to natural ventilation (Figure 2.43) provides the required ventilation with even added heat recovery of up to 70% efficiency for the winter period. The system is designed to control the air flow using a bypass valve system in the wind cowl opening and the pressure increase and resistivity in the ducts if the wind speeds are too high (Dunster et al., 2008). To the author's knowledge, windcatchers have yet to be incorporated into Passivhaus design. This could be due to the possibility of cold bridging or implication on the required airtightness levels, however it might also be due to lower acknowledgment of overheating potential in Passivhaus buildings.

Figure 2-43 –Wind cowls at BedZED (source: (Dunster et al., 2008) **P.167)**

A study carried out on a seminar room benefiting from windcatchers in the University of Reading, highlighted that in some parts of the day the ventilation rate was smaller compared to night time ventilation. This was identified to be perhaps due to the higher temperature difference during the night and the local weather conditions (Elmualim & Awbi, 2003). In the case of such conditions when the temperature difference between inside and outside is not high enough and the wind alone is not sufficient to provide the necessary ventilation rate, then the use of solar-induced ventilation could be a viable option. Solar radiation can be employed to heat a specific area of a building to increase the temperature and consequently the stack effect. The three main devices are (Awbi, 2003):

- Trombe wall
- Solar chimney
- Solar roof

All above systems use solar radiation to help increase the air flow either through the use of glass or opaque structure. Trombe wall for instance, uses glass in front of a wall with thermal mass to allow the air within the 50 to 100mm gap to be heated which can be used to help heat the building during the winter. However if the higher opening to the building is replaced with an external opening through the glass during the summer months, trombe wall can help to increase the air flow and cool the building (Figure 2-44) (Awbi, 2003).

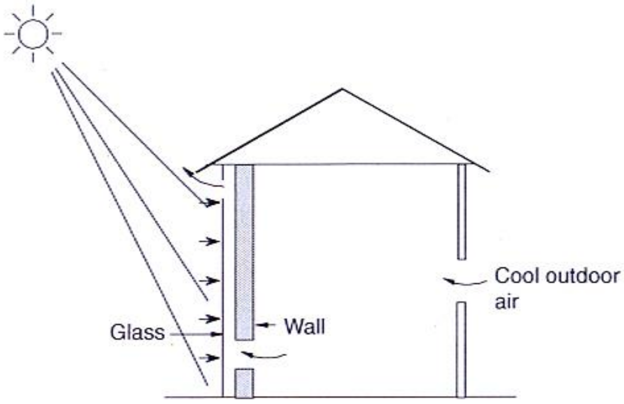


Figure 2-44 – Summer ventilation using trombe wall (source: (Awbi, 2003) **P.336)**

The same principle is applied for solar chimney (Figure 2-45) and solar roof (Figure 2-46) , where the external surface of the ventilation system is heated by the sun and thereby increasing the stack effect through the device (Awbi, 2003). To achieve the best performance, the direction of the sun to the collectors needs to be optimised and in the case of the solar chimney, keeping the height above the building is of importance. Similar to trombe wall, glass can be used to increase the solar gain when designing solar chimney and the use of thermal mass can help to maintain the ventilation rate as the sun radiation is reduced through the day (Pennycook, 2009).

Figure 2-45 – Solar chimney (source: (Awbi, 2003) **P.337)**

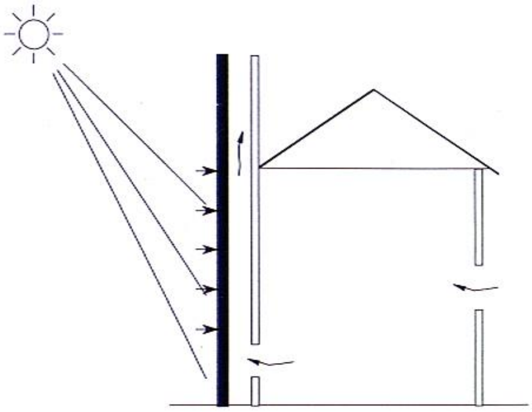
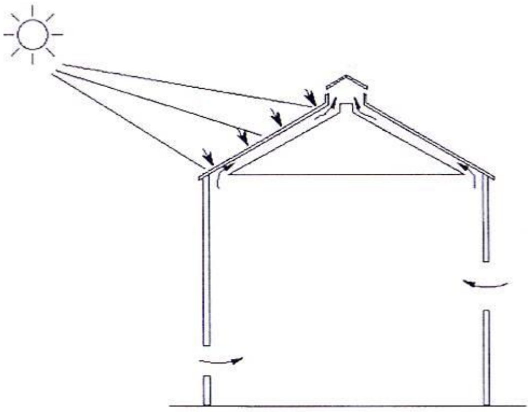


Figure 2-46 – Solar roof ventilator (source: (Awbi, 2003) **P.337)**



Providing cooling for the building could potentially consume a large amount of energy and therefore increase CO_2 emissions (Smith, 2006) and especially as higher temperatures are expected in the future (Parsloe, 2014), the need for a low or non CO_2 emitting cooling strategy and system is at its highest.

Key points:

Windows: high level of control, possible to cause localised discomfort and draughts. Restriction of use may apply due to noise, pollution, security, (especially at night and unoccupied hours). Different designs will offer different weather protection and amount of ventilation. Bigger sizes can increase ventilation but also can increase unwanted solar gain and glare. Window restrictions can reduce ventilation significantly. The ventilation rate can be reduced due to curtain and blind usage.

Side panels for windows improve security and with insect mesh increase operation time especially for rural areas. Limitation to air quality and noise with this system.

Wind towers create suction from the building when located above the building with good security and weather protection. Wind scoops on the other hand will direct the air into the building with a similar design to wind towers.

A combination of wind scoop and wind tower can provide higher air flow as the pressure difference is higher and if designed as one structure it is known as windcatcher. Windcatchers can help in optimising the building orientation regardless of the prevailing wind direction as they are located on the top of the building. The air on the roof level can be cleaner especially in urban locations with less noise implications. They can differ in design and even be movable for optimal performance and added possibility of heat recovery.

Solar radiation can help to increase ventilation and air movement like trombe wall, solar chimney and solar roof. Glass can help to increase the temperature for trombe wall and solar chimney to enhance performance.

2.3.3. Advanced natural ventilation and cooling

The definition of advanced natural ventilation is often used when the building is utilising the benefit of the stack effect as part of the ventilation. Research, although limited, suggests that the use of advanced natural ventilation within buildings can help in providing comfortable buildings throughout the next century for the majority of the locations in the UK (except London) (Lomas, 2007). The following section is not limited to stack effect ventilation.

Traditionally windcatchers not only provided the required ventilation but also the thermal mass of the windcatcher's structure helped to pre-cool the incoming warm air to some extent before entering the building (Soflaee & Shokouhian, 2005). Moreover in some cases the windcatcher was placed away from the building (Figure 2-47) and connection was through underground tunnels which could have helped pre-cool the incoming air. In some cases such as in 'Bam' (a city in Iran), planting was done over the underground tunnel and therefore the moisture from the ground would have helped further to pre-cool the incoming fresh air (Ghobadian, 1999).

Figure 2-47 – Wind scoop placed away from the building (source: (Battle McCarthy Consulting Engineers, 1999) **P.19)**

The ground temperature in the UK below 2m, is fairly constant and stays around 10°C to 14°C which makes it ideal for using ground coupling and can be used with the ventilation during the summer (Figure 2-48) (Smith, 2006). However the system needs to be perfectly airtight and watertight to avoid any contamination such as radon penetrating to the ventilation system and therefore the building. Moreover the possibility of condensation for such a system remains high and consequently the hygiene problems from it, therefore allowance for drainage should be made when using this system. Passivhaus' recommendation is to use double siphon connection to the drainage pipes to minimise any possibility of contamination and back flow (Figure 2-49) with added cost implications, bearing in mind that the siphon could dry out and allow odour to enter the ventilation pipes (Passivhaus Institut, 2012). Moreover the effectiveness of the system can be reduced as the ground surrounding the ventilation ducts starts to heat up and therefore a periodical operation would be beneficial for a more effective cooling effect (Parsloe, 2014).

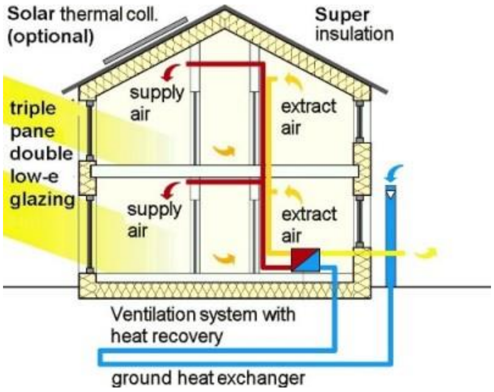


Figure 2-48 – Ground heat exchanger in Passivhaus (source: (Passive House Institute, n.d.)**)**

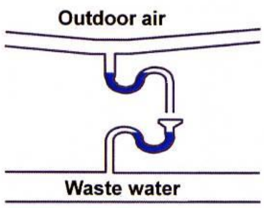


Figure 2-49 – Double siphon system (source: (Passivhaus Institut, 2012)**)**

An alternative to the air subsoil heat exchanger system is to use subsoil brine heat exchanger (Figure 2-50), which is similar in concept with less hygiene implications. The system uses brine to exchange heat with underground pipes laid either around or directly under the building. In comparison to the air subsoil heat exchanger, the subsoil brine system is less efficient as it uses additional electrical pumps (Passivhaus Institut, 2012).

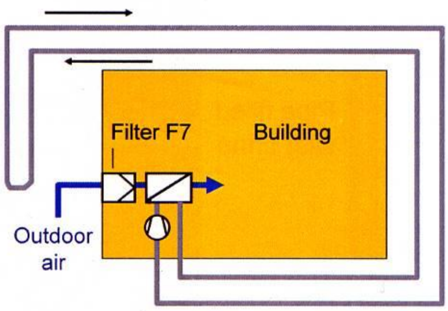


Figure 2-50 – Brine/air heat exchanger benefitting from condensate drain and circulation pump (source: : (Passivhaus Institut, 2012)**)**

Water and humidification has also been used in some traditional Iranian architecture in the hot and dry climate. The use of fountains for instance to humidify the incoming fresh air and ultimately providing cooling for the occupant (Schnieders, 2009) or passing the air from windcatchers over water to not only humidify the air but also reduce any dust from it. Passive downdraught evaporative cooling (PDEC) uses the same principle in more modern applications (Schnieders, 2009). As the name suggests, PDEC uses no mechanical system to drive the air and it relies on buoyancy or wind driven natural ventilation. PDEC uses the evaporation of water within the ventilation and therefore the cooling effect from it. However the system might not be completely passive as electricity can be used to pump the water and needless to say the water usage. PEDC has been more implemented in non-residential buildings rather than residential application; however recently there has been research carried out to incorporate the system into residential buildings by the University of Nottingham (Ford et al., 2012).

A prototype dwelling was designed and built by Nottingham University students in response to the 2010 Solar Decathlon Europe event in Madrid (Figure 2-51), using PEDC as a cooling strategy instead of the air-conditioning approach. The system uses nozzle technology to spray water into the ventilation air from the roof and in doing so the system uses around 40 litres of water with 3.5kWh of electricity for a typical 5 hours in operation per day (Ford et al., 2012).

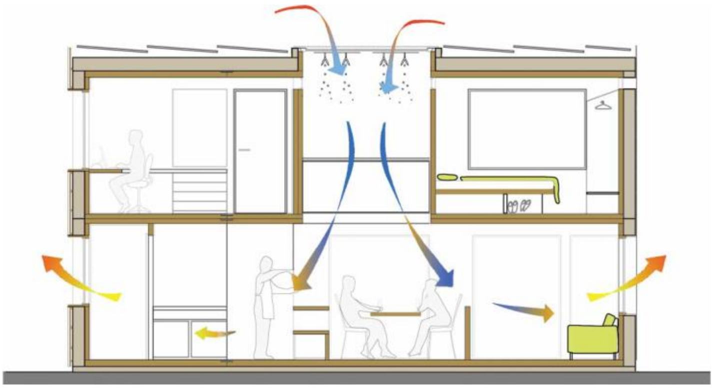


Figure 2-51 - Section indicating the daytime air flow path during the summer (source: (Ford et al., 2012) **P. 293)**

Using PEDC in a climate like Madrid with a typical relative humidity of below 30% could be very effective in achieving the required cooling and comfort during this time (Ford et al., 2012). However this system might not be as effective in the UK climate with a typical relative humidity of around 70% or above, during the summer.

Using thermal mass could help in reducing and regulating temperature during the summer months especially if it is used in combination with a night time ventilation strategy (McLeod et al., 2013). Another strategy for reducing internal temperature which works in a similar manner to thermal mass is the use of phase change material (PCM). Using PCM in conjunction with the ventilation system could help in reducing the internal air temperature. A system developed by D. Etheridge and D. Race, uses PCM in the ceiling and during the day air is passed over the PCM with assistance of a fan to help reduce the temperature as the PCM changes from solid to liquid and in doing so the latent heat helps to cool the air (Figure 2-52). During the night the PCM is cooled by outside air as the fan is reversed and external vents are being opened to outside (Figure 2-53) (Smith, 2006).

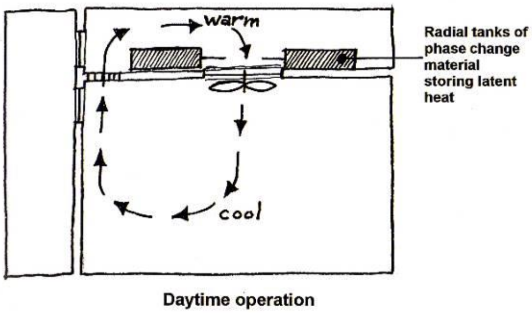


Figure 2-52 – PCM daytime operation (source: (Smith, 2006) **P.35)**

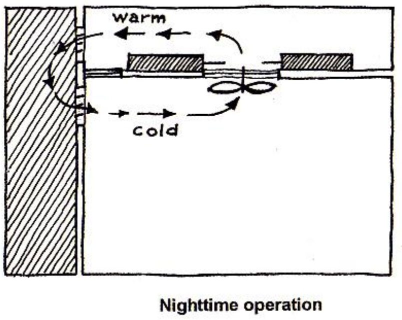
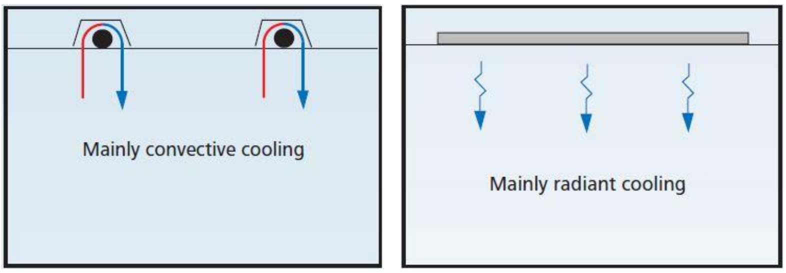


Figure 2-53 – PCM night time operation (source: (Smith, 2006) **P.36)**

An alternative system to PCM is to use the hollow slabs, as part of the building structure, and by passing the air through the concrete slabs, the benefit of the concrete's thermal mass can be utilised and help to pre-cool the incoming fresh air. The slabs are cooled by night time ventilation method and can be as effective as achieving up to 50W/m^2 of cooling (Parsloe, 2014). Water can also be used in relatively high temperatures of 15 to 16°C in chilled beams and chilled ceiling systems (Figure 2-54). Both systems similarly help to cool the inside temperature either by convection or by radiant cooling effect (Parsloe, 2014). Chilled beams and ceilings have been used in buildings for many years however primarily in more commercial applications such as offices (CBCA, 2012).

Figure 2-54 – Chilled beams and chilled ceiling (source: (Parsloe, 2014) **P.20)**



Providing fresh cool air and therefore a cooler indoor environment during the summer months could also be influenced greatly by the microclimate surrounding the ventilation intake. Currently there are **no requirements** for the location of the fresh air intake in regards to temperature (Dengel & Swainson, 2012) and during the summer, if the external surface surrounding the fresh air intake benefits from thermal mass, it could contribute to overheating potential. This could especially affect the night time cooling as during the night the area around the fresh air intake will be warmer and consequently warmer incoming air. This is of a particular importance as the night time ventilation strategy coupled with sufficient extent of internal thermal mass can reduce heat gain by around 20 to 30W/m^2 and consequently reducing the day time peak temperature by 2 to 3°C. Night time cooling can be most effective when the outside temperature falls below 20°C during the night (Smith, 2006) and this could be very effective in the UK as the night time external temperature always falls below the day time comfort temperature (Parsloe, 2014).

Furthermore, currently there is no requirement for a minimum distance between the intake and outlet for the MVHR as part of the Passivhaus standard (Passivhaus Institut, 2012), therefore the location of fresh air intake in relation to the sun's orientation, immediate adjacent material and proximity to exhaust air outlet could play an important part in overall overheating potential for Passivhaus residential buildings. This was also identified to be one of the causes of overheating for new flats which have been built after 2000 as the intake and extract were positioned too close together on the south wall (Taylor, 2014). Moreover positioning the exhaust air and fresh air intake too close on the same facade increases the potential of cross-contamination and short circuiting which in effect can reduce the indoor air quality (Awbi, 2003).

Providing adequate ventilation should help to maintain the indoor air temperature alongside achieving a good level of IAQ and maintaining acceptable relative humidity for the occupants.

Key points:

Thermal mass and the use of ground can help in reducing the incoming fresh air temperature from windcatchers. UK ground temperature below 2m is ideal for cooling as it is consistent and around 10°C to 14°C. However the use of ground coupling is subject to contamination and needs to be airtight and watertight. Providing drainage is recommended with the use of double siphon connection with inspection chamber which is subject to drying out. If the local ground temperature increases due to the system use the effectiveness will reduce and periodical operation is recommended. The use of subsoil brine heat exchanger can improve hygiene problems in comparison with added additional electrical pump.

Water and humidification can help in the cooling effect like PDEC. PDEC uses buoyancy or wind with evaporation of water for cooling effect. The system is not completely passive due to pumping the water and also the implication of water usage. Water and humidification is better suited in a drier climate.

Thermal mass and PCM can also aid in cooling especially if used in conjunction with night ventilation. Chilled beams and ceilings work in a similar concept which are usually used in more commercial applications.

Night time ventilation can help in reducing heat gain by 20 to 30W/m^2 leading to lowering the day time peak temperature of 2 to 3°C when used in conjunction with thermal mass. Night time cooling is more effective when the ambient temperature is below 20°C which is all the time in the UK.

The positioning and location of the fresh air intake and extract and their proximity to each other can compromise the cooling effect leading to cross contamination and possible overheating.

2.3.4. Indoor air quality and ventilation rates

Indoor air quality (IAQ) plays an important role in achieving thermal comfort for the building occupants (Clancy, 2011) and as a typical person in countries like the USA and the UK, spends around 90% of the day indoors, the effect of IAQ can be even greater on the occupant health and wellbeing (Cotterell & Dadeby, 2012). Moreover the importance of IAQ has been further emphasised since one of the main tools for the reduction in energy demand in buildings, is achieving a higher building airtightness, and therefore this can potentially lead to lower IAQ and a lack of fresh air (Dengel & Swainson, 2013). A good level of IAQ can be defined as: *"… air with no known contaminants at harmful concentrations*." (Clancy, 2011) P.2

There are limited publications regarding the IAQ in highly insulated and airtight buildings in the UK to highlight the possible effect of poor IAQ on the health and wellbeing of occupants. Although there are difficulties in directly connecting poor IAQ and health in some cases, there is still evidence of health implications from irritation due to unwanted odour to cancer (Crump et al., 2009).

Some of the more common pollutants in the building that can reduce the IAQ are listed below (Clancy, 2011):

- Gaseous pollutants
- Volatile Organic Compounds (VOC)
- Odours
- Particulates

From the different gaseous pollutants in the building, carbon dioxide (CO_2) perhaps has highest proportion in comparison and can be harmful in high concentrations, causing drowsiness and even unconsciousness at very high levels (Clancy, 2011). CO_2 levels are also used as an indicator for IAQ in Passivhaus, and is set to be between 400-600ppm with a maximum indoor

CO_2 level of 1000ppm which is also the recommendation from ASHRAE and the US Occupational Safety and Health Administration (OSHA) (Cotterell & Dadeby, 2012).

For the past 160 years the recommended rate of ventilation in the USA has changed from 2.51 l/person to 15 l/person and down to 2 l/person which can perhaps be put down to the technology development, energy cost, changes of our building design and lifestyle. The graph below is the demonstration of these changes (Awbi, 2003).

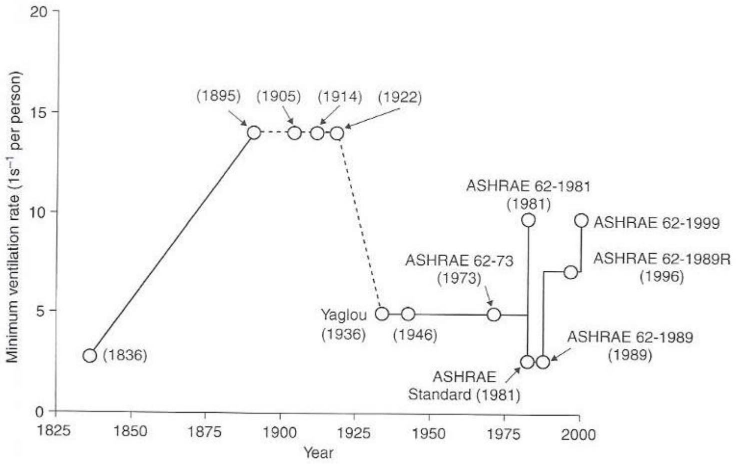
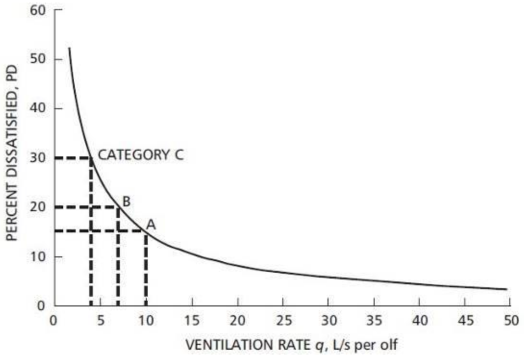


Figure 2-55- Minimum ventilation rate fluctuations in in the USA (source: (Awbi, 2003) **P.69)**

The indoor CO_2 levels can be increased by the occupants themselves and the use of appliances. The level of the CO_2 concentration can also be an indication of the ventilation rate. For example 800 to 1000 ppm for an occupant in a sedentary position can represent 10 l/s per person (Clancy, 2011). In addition, the calculation for the Passivhaus ventilation rate, to achieve 400-600 ppm, is $30m^3$ /hr per person (Cotterell & Dadeby, 2012). (10 l/s per person = $36m^3$ /hr per person)

Furthermore Fanger's unit of olf was created based on an occupant experiencing thermal comfort in a seated position to be able to quantify odour and therefore '*decipol is one olf ventilated at the rate of 10 l/s of unpolluted air'* (Clancy, 2011). Below is the Fanger's diagram for the relationship between ventilation rate per olf (units: l/s per olf) and PPD (Clancy, 2011).

Figure 2-56- Relation of PPD and ventilation rate per standard person (source: (Clancy, 2011) **P 7)**



Some of the other gaseous pollutants are (Clancy, 2011) P.5:

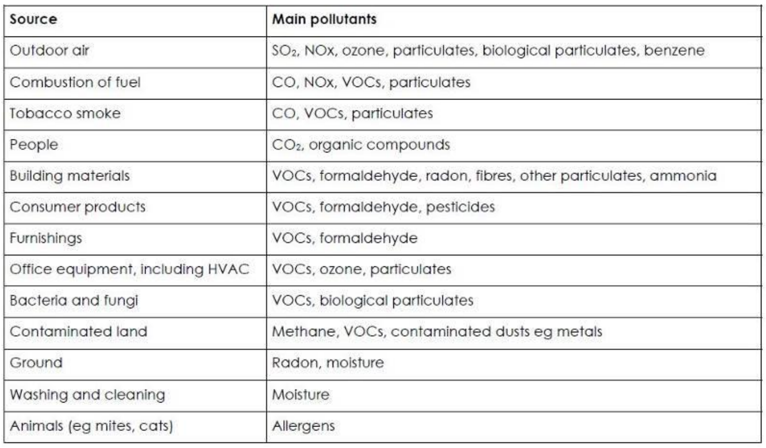
- Carbon monoxide (CO)
- Nitrogen oxide (NO)
- Nitrogen dioxide (NO_2)
- Sulphur dioxide
- Ozone (O_3)
- Radon (location dependent)

Carbon monoxide on the other hand can be highly toxic especially in more airtight buildings and because of this the requirement to use a carbon monoxide alarm has now been included in part L of the approved document for England and Wales. Lack of oxygen or faulty equipment during combustion, can be the cause of CO. Another source for CO can be from outside especially from vehicles in operation (Clancy, 2011).

High temperature incineration can be the cause for NO and NO_2 generation, whereas sulphur dioxide is produced from burning fuel containing sulphur dioxide like fuel oil. Ozone can be formed from the action of sunlight on nitrous oxides with a relatively sharp odour while radon is more naturally released into the atmosphere from igneous rocks like granite (Clancy, 2011).

Volatile Organic Compounds (VOC) can be from the use of paint, glue and laminates holding benzene as solvent. VOC contain benzene, formaldehyde and trichloroethylene and can have a strong odour. Moreover odour could be also caused from cooking, drainage and WC, different materials, furnishers and from human sweat (Clancy, 2011).

Particulates can vary in size from 0.1 to 10,000 µm and could be due to combustion, generated by occupants, different fabrics, aerosol spray, dust-mites/insects and moulds. Health problems like lung irritation, bronchial asthma and allergic rhinitis could be caused by biogenic or biological particulates like fungi, moulds, mites, bacteria, viruses and pollen (Clancy, 2011). Below figure is the summary for different air pollutants and their main sources (Crump et al., 2009):



Source	Main pollutants
Outdoor air	SO_2, NOx, ozone, particulates, biological particulates, benzene
Combustion of fuel	CO, NOx, VOCs, particulates
Tobacco smoke	CO, VOCs, particulates
People	CO_2, organic compounds
Building materials	VOCs, formaldehyde, radon, fibres, other particulates, ammonia
Consumer products	VOCs, formaldehyde, pesticides
Furnishings	VOCs, formaldehyde
Office equipment, including HVAC	VOCs, ozone, particulates
Bacteria and fungi	VOCs, biological particulates
Contaminated land	Methane, VOCs, contaminated dusts eg metals
Ground	Radon, moisture
Washing and cleaning	Moisture
Animals (eg mites, cats)	Allergens

Figure 2-57- Indoor air pollutants (source: (Crump et al., 2009) **P.7)**

The European Commission Scientific Committee on Health and Environmental Risks has highlighted that air pollutants are higher indoors compared to outdoors and can contain around 900 chemicals, particles and biological materials that can be a risk to the occupant health. Some of the health effects that can be caused by poor IAQ are highlighted below (Crump et al., 2009) P.9-10:

- Allergic and asthma symptoms
- Lung cancer
- Chronic obstructive pulmonary disease (COPD)
- Airborne respiratory infections
- Cardiovascular disease (CVD)
- Odour and irritation (sick building syndrome symptoms)

Asthma is one of the worrying problems and is growing with the UK and US having the highest number of people suffering from it (Cotterell & Dadeby, 2012). Asthma is also on the rise throughout Europe with 3 to 8% of adults suffering from asthma and even higher in the younger population. The high relative humidity causing dampness and mould growth can contribute to increase in respiratory and asthma problems by around 30% to 50% as highlighted in the study carried out by Fisk in 2007 (Crump et al., 2009).

Lung cancer has the highest rate of death in comparison to other forms of cancer in the EU countries at around 20% with the majority related to smoking which is now banned in public buildings in the UK. However the problem of poor IAQ caused by smoking still remains in the residential buildings with 0.5% and 4.6% of lung cancer, in males and females respectively caused by ETS (environmental tobacco smoke) in the EU countries. Moreover around 9% of lung cancer is caused by exposure to radon with 2000 deaths from it in the UK every year. (Crump et al., 2009).

Poor IAQ not only can have a negative effect on the occupant health but also could have an economical effect for example from sick building syndrome and consequential absences in the office buildings. The US Environmental Protection Agency (EPA) estimated during 2001 alone, around $150 to $200 billion could be the cost of avoidance for poor IAQ (Crump et al., 2009). Moreover the reaction to improve IAQ is also affected by lack of occupant detection of low IAQ, i.e. high CO_2 and RH levels, and people usually increase the ventilation when feeling too warm (de Selincourt, 2014) which is often too late and the indoor temperature already is too high.

By increasing the ventilation rate, the IAQ can perhaps be improved, leading to higher thermal comfort. However the increased indoor air speed could cause occupant dissatisfaction and thermal discomfort (Clancy, 2011) and the reduction of indoor pollution and acoustic implications needs to be prioritised which would be more important prior to increasing the ventilation rate (British Standard Institute, 1999). Passivhaus standard therefore, requires a maximum indoor air speed of 0.15m/s to ensure higher occupant thermal satisfaction with limiting the sound travel from mechanical ventilation systems (Cotterell & Dadeby, 2012).

The use of MVHR has been positive in some cases and has proven to be improving the IAQ; however this has not been the case for all the buildings and even been less effective due to occupant usage and behaviour. The lack of maintenance and regular cleaning of the ducts inlet and outlet is perhaps the most important cause for this beside the occupant behaviour and in some cases lack of use of the system. Moreover the summer usage of mechanical ventilation has been a concern for the building occupants leading to lack of usage during this time; and to improve the IAQ, following a research on new homes in the Netherlands, cleaning the filters every two weeks and basic natural ventilation during the summer was recommended (Crump et al., 2009).

Indoor Air quality in Passivhaus dwelling is usually classed as good with especially lower CO_2 levels (Cotterell & Dadeby, 2012). However lower relative humidity during the winter has been an issue in some cases and the use of humidity recovery has been recommended in certain locations (Passive House Institute & RoA Rongen Architects GmbH, 2011). Moreover the level of CO was reported to be very high in one of the four dwellings, using a gas cooker rather than electrical, in the study carried by Balvers et al during 2008 in the Netherlands, which could be due to use of recirculation of air in the cooker hood as part of Passivhaus standard (Crump et al., 2009).

One of the best ways to determine the IAQ and thermal comfort of the building occupants is to monitor the CO_2 level and carrying out an occupant questionnaire, leading to a full Post Occupancy Evaluation.

2.4. POST OCCUPANCY EVALUATION

The term Post Occupancy Evaluation study (POE) was perhaps first used in the USA during the 70's to examine building performance from the occupant perspective. POE allows not only answering the question whether the building is performing as it was intended in the design stage, but also to explore and examine the actual building performance which gives the opportunity for future improvements and knowledge transfer (Leaman, 2004). In the UK during the 1960's the Royal Institute of British Architects (RIBA) brought in stage M–feedback, allowing the architect to gather information on their completed buildings which was later withdrawn during the 70's despite its success (Bordass & Leaman, 2005). Some of the other terms used in the industry are, post project review or customer satisfaction survey (Jaunzens et al., 2003).

Carrying out a POE study requires a decision on the most suitable technique for the given project to allow for the efficiency and speed of data gathering, obtaining reliable and sufficient information (not too much) and limiting the disruption to the occupants and building owners. The possibility of choosing a less appropriate method from the vast range of techniques for a given project could be high which can lead to loss of time and obtaining insufficient data (Leaman, 2004). Over the last twenty years several different methods of POE have been developed to help in improving the building performance and occupant health, comfort and ultimately satisfaction (Nicol & Roaf, 2005).

PROBE (Post-occupancy Review Of Buildings and their Engineering) studies have owed their success in employing the following three robust and practical methods (Leaman, 2004):

- The Energy Assessment and Reporting Methodology (EARM)
- Building Use Studies (BUS)
- An air pressure test to CIBSE TM$_{23}$ requirements

EARM allows examining supply and demand energy performance of the building and by comparison to the benchmark gives the understanding of how the building is performing. It also highlights the areas of where the building is performing well and perhaps not so well. Whereas BUS occupant satisfaction questionnaire, examines the occupant thermal comfort, productivity, indoor air quality and health (Leaman, 2004) to name a few on a scale of 1-7. The Bus method has been used since 1990's not only for PROBE projects but also on Carbon Trust's Low Carbon Accelerator, Low Carbon Building Programme and also on the Technology Strategy Board's Building Performance Evaluation programme (Arup, 2014).

Carrying out a POE study can have its difficulties, as it can highlight some problems with the building leading to reduction of value from the client's point of view and the responsibility and therefore associated effect on personal indemnity insurance from the design team's point of view. Moreover it will be an extra cost added to the project when the project could have been finished. The POE can be undertaken by the client, representative of the project team or an independent person depending on the cost, level of detail, equipment requirements and the skill for interpretation of the results (Jaunzens et al., 2003). Below is a table highlighting different POE techniques which is designed more for office buildings; however it can be adjusted to specific projects.

Method	Benefits	Cost or resource requirements	Notes	Suitability for this research
Questionnaires	- Allows to collect detailed qualitative data from occupants - Permits benchmarking - The problem can be geographically identified - Allows a wide based opinion - Can easily be re-produced in a precise way to ascertain trends or answer to any remedial works	- Involves skilled design to guarantee questions are clear, unbiased and diagnostic - Needs time to complete - Needs time to chase replies - Needs resources to analyse replies, might require, graphical presentation	- Identify the need for either standard or tailored questionnaire - Make sure simplicity of the questionnaire, 20–30 minutes maximum time to complete - Determination of acceptable degree of statistical rigour is needed - Make sure occupants are clear about the actions required in response to the questionnaire results - Electronic questionnaires are also available	- It can be suitable, however due to nature and scale (two residential buildings only) other methods like interviews could prove better. - It can be obtained by email if chosen.
Focus groups	- Management time is kept to a minimum in arranging the focus group schedule - Requires less staff (might need more time) - Particular problems could be discussed in detail	- Needs expertise to enable a fair discussion - Small group of people can provide variable degree of qualitative data - Staff opinions could influence the result	- 6–8 people is the recommended size for focus group - Maximum one hour of time - Selection process could be beneficial - Responses might be effected and bias by voluntary attendance and	- Not suitable for this research

	- Should be flexible to allow exploration of different areas	- Anonymity is lost	selected attendance requires time management	
Interviews	- A range of issues can be discussed - Time restriction might apply	- Allows for detailed qualitative data however in certain areas - Anonymity is lost - Responses might be bias - End user might not be represented	- Careful selection is needed to ensure balanced perspective	- Could be suitable and should be considered
Physical monitoring	- Objective quantitative data can be obtained - The problem can be geographically identified - Problem can be identified in respect to time	- Measurement and result interpretation needs expert knowledge - May require specific equipment or outside consultants - Equipment may need to be left on site for a long time	- For comparison reasons an acceptable environment might need to be selected - A clear monitoring strategy is required - BMS data could be used subject to its accuracy - Energy can also be included with monitoring to determine efficiency	- Suitable and will be used
Observations	- Requires less people - End user input and time is not needed - Quantitative data can be obtained - Can be unbiased and can highlight issues that were not included previously	- Comparison might be difficult subject to methodology	- Detail study can be carried out in a specific area or time	- Could be suitable and should be considered
Study of records	- After data collection, it requires less people	- Specialist knowledge is required for the interpretation of the results - Further sub-metering may be needed	- Vast expert knowledge is available - Project team can help client in regards to record keeping	- Could have been useful, but not available

Table 2-5- POE Techniques table, adapted from (Jaunzens et al., 2003) **P.8**

Carrying out a POE survey will allow for evaluating the performance of the building, and the occupant of the building will provide the measurements and therefore the questions should be designed in this respect, i.e. *‘how often is the building hot in summer?’.* Whereas Field studies of thermal comfort (FSTC) are designed to examine the responses to the building and questions the occupant’s feelings at a given time, i.e. *‘I feel hot now’* (Nicol & Roaf, 2005) P.339. For purposes of this research the POE methods will be used to evaluate and compare the building performance against the design intent.

CHAPTER 3. RESEARCH METHODOLOGY

3.1. OVERVIEW OF METHODS

Selecting a suitable method is driven by the aim of the research and therefore, quantitative and qualitative methods were considered. The quantitative method is normally used to examine pre-determined theories and provide generalised data and results answering the research question that emphases on 'what'. On the other hand, the qualitative approach sets to provide more in depth study by illumination and better understanding of a complex issue answering a question of 'why' and 'how' (Marshall, 1996).

This research sets to answer the questions; Why Passivhaus dwellings are subject to overheating during the summer in the UK? ; how can natural ventilation be used to eliminate / reduce, overheating potential for UK Passivhaus dwellings? ; and, can a specific opening area be incorporated to provide a sufficient air change rate for summer to eliminate overheating?

Therefore due to the nature of the research and limitations of obtaining larger data collection (access to buildings / number of buildings), the qualitative approach was selected allowing a more in depth analysis and examination. Consequently a case study approach was chosen as part of the qualitative method. Case studies will allow for a more detailed study i.e. monitoring the building for the entire summer rather than monitoring larger samples for a week during the summer period. The findings of the typical case study can subsequently be applied to larger samples in general.

Selecting the sample and the sample size should be representative of the study. Different methods can be used to select the samples like, random, probability, incidental or quota samples. Random methods of selecting the samples is normally considered a good method as it provides the best approach to generalise the data. However for this research this was not possible as the access to buildings for monitoring purposes was limited and therefore judgment sampling also known as purposeful sampling method under the qualitative study was used (Marshall, 1996).

Passivhaus institute has data for 86 certified buildings on their website which 73 of them are residential buildings (Passivhaus Institut, 2017). From the 73 dwellings there are 32 built with lightweight construction using timber and the rest benefit from higher thermal mass. The majority of the 73 buildings are new build (detached) Passivhaus dwellings with 8 being refurbishment to EnerPHit criteria. Although this data does not cover all certified buildings in the UK, however this is the only data accessible from the Passivhaus institute.

Two detached Passivhaus dwellings were selected one new build (lightweight) and the other retrofit (thermally massive) for monitoring and examination using the judgment sampling method, providing a representative sample of certified Passivhaus dwellings in the UK with the limitation of securing access to more certified dwellings.

Physical monitoring; using data loggers obtained for monitoring temperature, RH, indoor CO_2 levels, incoming supply fresh air temperature (MVHR) and window operation for the two case study buildings. The monitoring results were used to determine whether Passivhaus dwellings are subject to overheating and allowing further investigation into causes contributing to this.

Furthermore the uncertainty and variability of data input in dynamic thermal modelling can affect the overheating prediction significantly especially in respect to natural ventilation and window opening for example (Lomas & Porritt, 2017). Therefore physical monitoring of the case study buildings was used to reduce the prediction for the data input for the dynamic thermal modelling and increase the validity of the model.

Thermal imaging camera; was used for examining the micro climate surrounding the MVHR fresh air intake in addition to monitoring the fresh air temperature at the room outlet, allowing examination of the effect of the location and material used adjacent to the fresh air intake on the incoming fresh air temperature during the warmest part of the summer.

Dynamic thermal modelling; was used to determine the suitability and effectiveness of the proposed natural ventilation system in order to reduce or eliminate possible overheating in Passivhaus dwellings using current and future climate data. Future climate data was used to test the resilience of the proposed system during the warmer future summer months.

Passivhaus Planning Package (8) (PHPP 8); was used to calculate the internal heat gains during the summer from the actual appliances schedule and examine the effect of lack of summer by pass on possible overheating.

Psi-Value calculations; were carried out in order to ensure that the proposed natural ventilation system would not increase heat loss and therefore increase the heating load during the winter period.

Examination of wider context; finally, the proposed system was incorporated into the PHPP calculation and an additional five Passivhaus dwellings were examined using PHPP calculations increasing the sample size in theoretical method.

All construction data, PHPP calculations, drawings, specifications, client information and access permission were courtesy of Eco Design Consultants (author’s previous employer). Figure 3-1 is the research design diagram highlighting the steps and the process, starting with literature review (highlighted in blue).

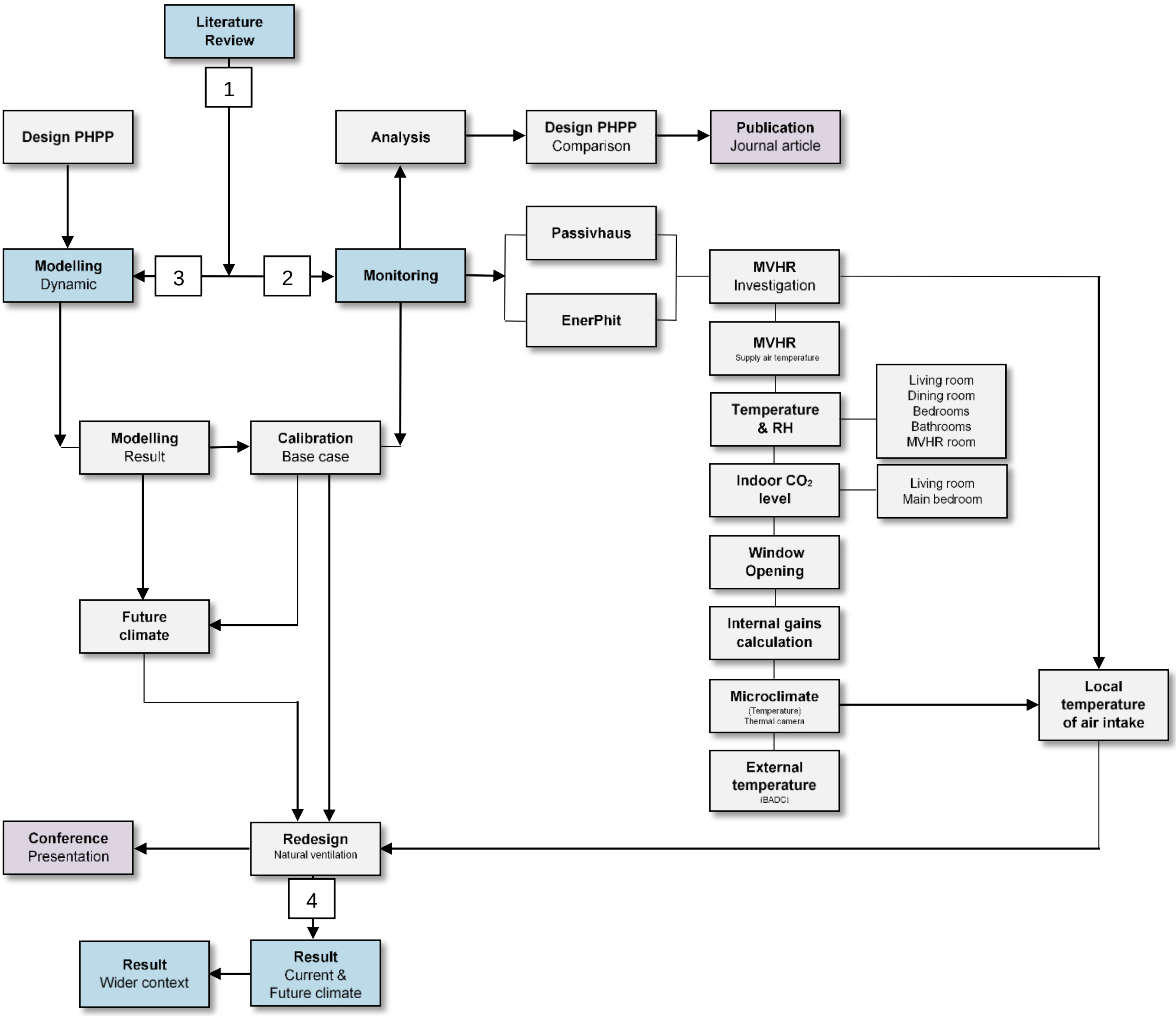


Figure 3-1- Research design diagram

3.2. INTRODUCTION TO THE CASE STUDY BUILDINGS

The two selected buildings were chosen to give a range of different construction methods in terms of lightweight versus heavyweight, also new build and refurbishment. Both buildings were actual projects undertaken by the office where the author was employed prior to undertaking this research. Below is the description of the two buildings alongside the data extracted from PHPP calculations.

3.2.1. Building One – Passivhaus

The first case study building ‘Passivhaus’ is a new build dwelling over three storeys which was constructed during 2011 using a lightweight timber material. Building One has been tested to have one of the highest levels of airtightness in the UK of 0.07 air change rate at 50 Pascal pressure. Moreover the building had used PHPP7 during the design stage and certification. Below is a summary of information and external and internal images of the building.

- 5 bedrooms
- TFA: 182.1m^2
- Internal heat gains: 2.1W/m^2
- Ventilation volume (V_v): 455m^3
- Climate area (PHPP): Thames Valley

Figure 3-2- View of the front (source: author)

Figure 3-3- View of the rear (source: author)

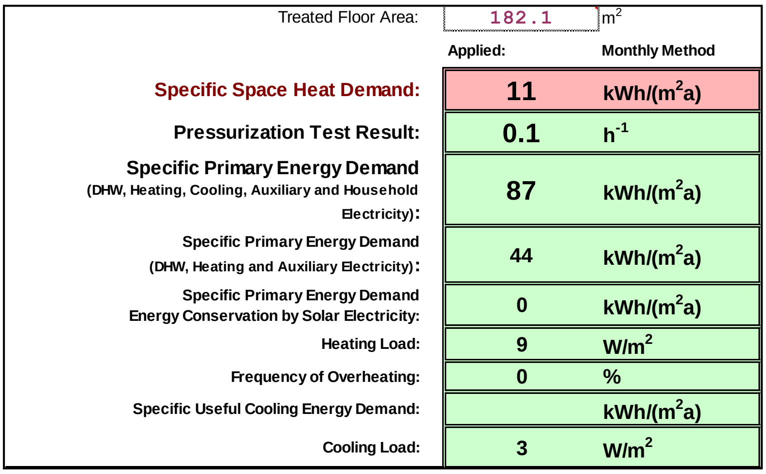
Figure 3-4- View of the kitchen (source: author)

Figure 3-5- View of the living room (source: author)

Figure 3-6- View of the dining room (source: author)

Figure 3-3 shows the building in its rural location with minimal overshadowing on the large glazing area to the south. The kitchen is open plan to the dining room and located in the north side of the building with small glazing area (Figure 3-4). The living and dining room are located in the south side of the building with a large glazing area and internal and external blinds (Figures 3-5 and 3-6). Figures 3-5 and 3-6 also highlight the two large fans used by the occupants.

Below is the extract from the verification sheet highlighting the low heating load as well as the airtightness level.



Treated Floor Area:	182.1	m^2
	Applied:	Monthly Method
Specific Space Heat Demand:	**11**	**kWh/(m^2a)**
Pressurization Test Result:	**0.1**	**h^{-1}**
Specific Primary Energy Demand **(DHW, Heating, Cooling, Auxiliary and Household Electricity):**	**87**	**kWh/(m^2a)**
Specific Primary Energy Demand **(DHW, Heating and Auxiliary Electricity):**	**44**	**kWh/(m^2a)**
Specific Primary Energy Demand **Energy Conservation by Solar Electricity:**	**0**	**kWh/(m^2a)**
Heating Load:	**9**	**W/m^2**
Frequency of Overheating:	**0**	**%**
Specific Useful Cooling Energy Demand:		**kWh/(m^2a)**
Cooling Load:	**3**	**W/m^2**

Figure 3-7- Extraction from the verification sheet (source: PHPP7 - Eco Design Consultants)

The climate data used in the PHPP calculation is Thames Valley area (number 2) as indicated in the map below and figure 3-9 demonstrates the solar radiation and the ambient temperature extracted from the PHPP.

Figure 3-8- Map indicating the different climate areas used in PHPP for the UK (source:(BRE Group, 2011)**)**

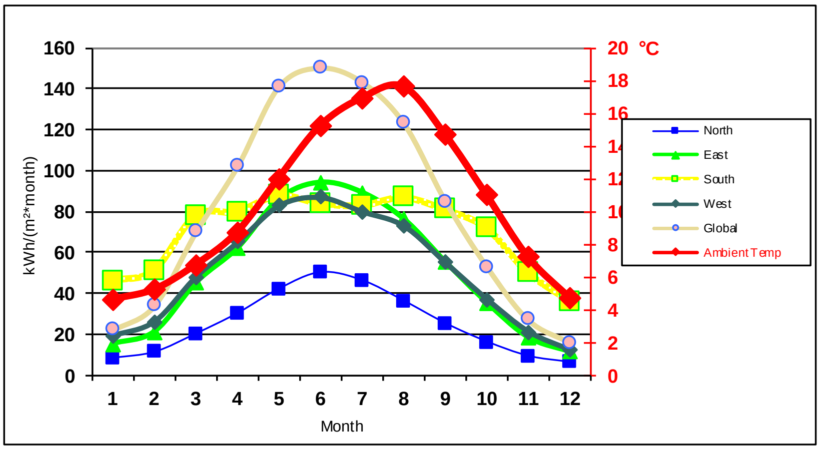
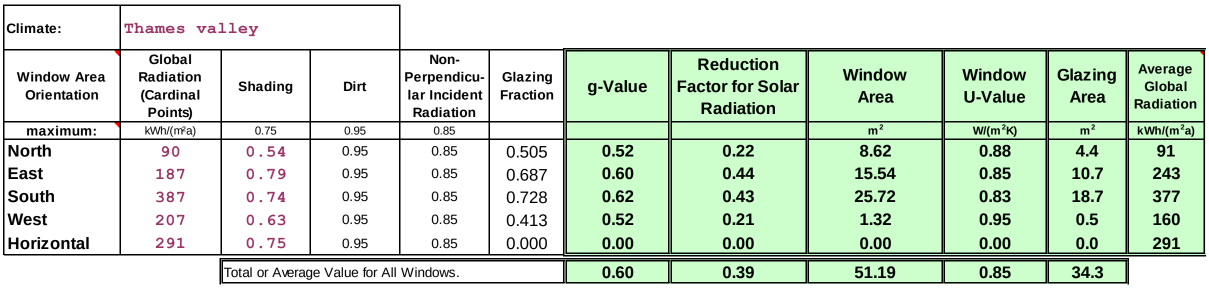


Figure 3-9- Solar radiation & ambient temperature - Thames Valley area (source: PHPP7 - Eco Design Consultants)

The building's components average U-Values are as listed below:

- Exterior wall 0.082 W/(m^{2}K)
- Roof 0.113 W/(m^{2}K)
- Floor 0.120 W/(m^{2}K)
- North windows 0.876 W/(m^{2}K)
- East windows 0.850 W/(m^{2}K)
- South windows 0.834 W/(m^{2}K)
- West windows 0.950 W/(m^{2}K)

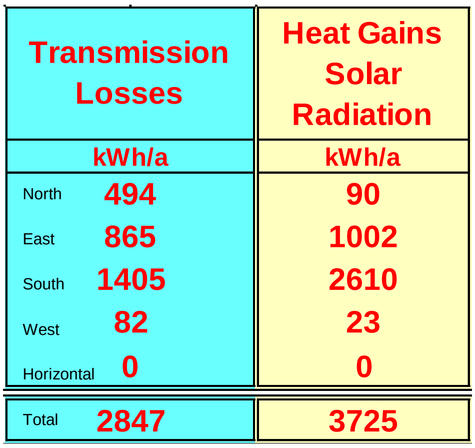
Window information summary indicating the g-Value and U-Value for different façades of the building alongside the average global radiation used by PHPP7 from the climate file can be seen in the table below. The average g-value is 0.6 and the average U-Value is 0.85W/m^{2}K, within the Passivhaus requirements for the UK climate.



Climate:	Thames valley										
Window Area Orientation	Global Radiation (Cardinal Points)	Shading	Dirt	Non-Perpendicular Incident Radiation	Glazing Fraction	g-Value	Reduction Factor for Solar Radiation	Window Area	Window U-Value	Glazing Area	Average Global Radiation
maximum:	kWh/(m²a)	0.75	0.95	0.85				m²	W/(m²K)	m²	kWh/(m²a)
North	90	0.54	0.95	0.85	0.505	0.52	0.22	8.62	0.88	4.4	91
East	187	0.79	0.95	0.85	0.687	0.60	0.44	15.54	0.85	10.7	243
South	387	0.74	0.95	0.85	0.728	0.62	0.43	25.72	0.83	18.7	377
West	207	0.63	0.95	0.85	0.413	0.52	0.21	1.32	0.95	0.5	160
Horizontal	291	0.75	0.95	0.85	0.000	0.00	0.00	0.00	0.00	0.0	291
		Total or Average Value for All Windows.				0.60	0.39	51.19	0.85	34.3	

Figure 3-10- Window information summary (source: PHPP7 - Eco Design Consultants)

Furthermore the window and glazing area used in different orientations can be seen in the above table and the image below is the indication of the total gains and losses through windows for the heating season in different orientations and total in kWh/a.



	Transmission Losses	Heat Gains Solar Radiation
	kWh/a	kWh/a
North	494	90
East	865	1002
South	1405	2610
West	82	23
Horizontal	0	0
Total	2847	3725

Figure 3-11- Total gains and losses during winter from windows in relation to the orientation in kWh/a (source: PHPP7 - Eco Design Consultants)

The building is privately rented by a family of three (two adults and one child) which is a lower occupancy rate comparing to PHPP of five persons and certainly much lower than the average in the UK for a five bedroom house. However the standard occupancy (from PHPP) was used during the design and final Passivhaus certification as required by PHPP standard.

The building has been constructed using a lightweight construction material and therefore the value used representing this in PHPP (specific capacity) was 60Wh/K per m^2 TFA. The walls are constructed using timber and insulated using Warmcell insulation whereas the floor benefits from Supertherm expanded polystyrene insulation boards under the concrete floor slab which also is the only thermal mass used in the building. However by using timber boards as the floor finish on the ground floor, the benefit from the floor's thermal mass has been restricted. The roof is also timber with mineral wool insulation and the windows are Optiwin triple glazed.

Below are typical details indicating the wall and floor build up.

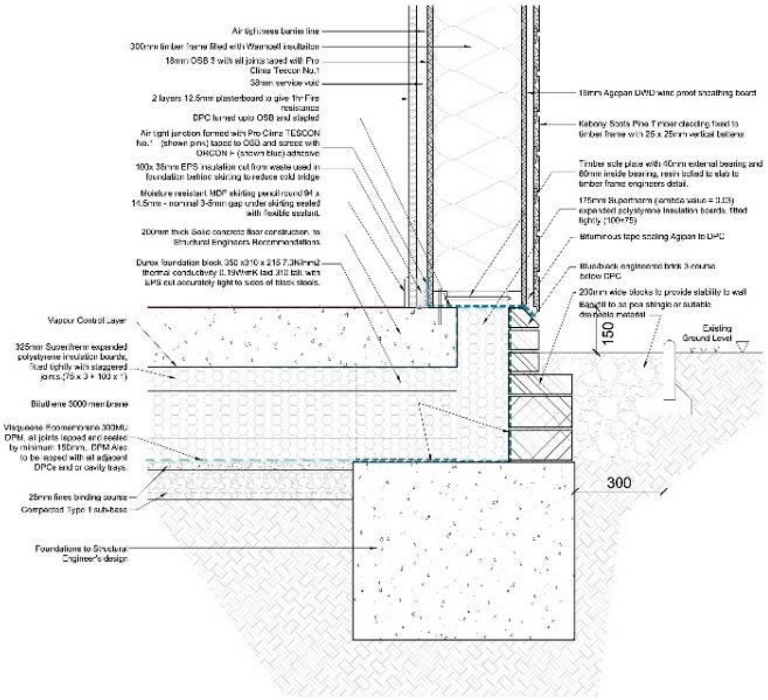


Figure 3-12- Section detail showing the floor build up and junction to the wall (source: Eco Design Consultants)

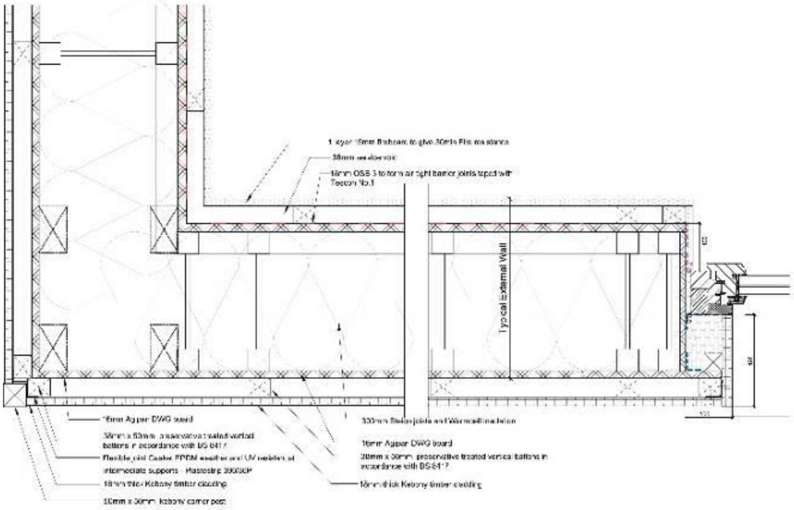


Figure 3-13- Plan detail showing the wall build up (source: Eco Design Consultants)

3.2.2. Building Two – EnerPhit

The case study Building Two 'EnerPhit' is a refurbishment and extension to an existing two storey heavy mass building completed during 2012 using a lightweight timber material for the second floor extension. The airtightness is within the Passivhaus requirement for refurbishment buildings of 1 air change rate at 50 Pascal pressure. Moreover similarly to Building One, PHPP7 was used for the design and certification. Below is a summary of information and external and internal images of the building.

- 5 bedrooms
- TFA: 173.2m^2
- Internal heat gains: 2.1W/m^2
- Ventilation volume (V_v): 433m^3
- Climate area (PHPP): Midlands

Figure 3-14- View of the front (source: author)

Figure 3-15- View of the rear (source: author)

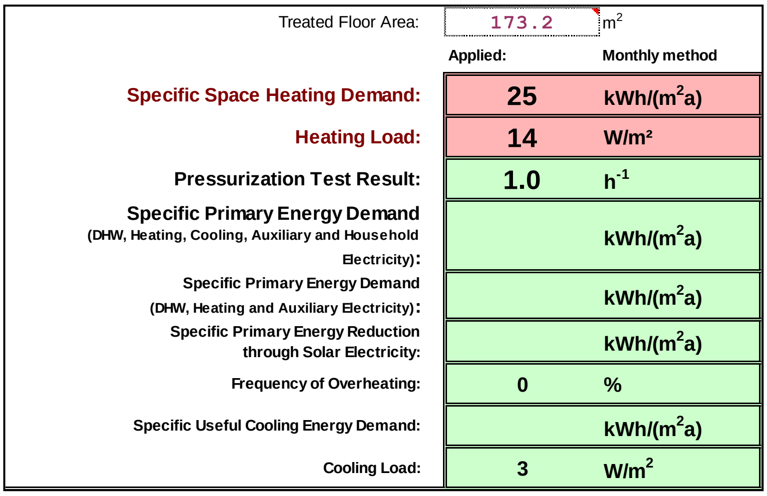

Figure 3-16- View of the kitchen (source: author)


Figure 3-17- View of the dining room (source: author)


Figure 3-18- View of the living room (source: author)

Figures 3-14 and 3-15 show the building in its context and the proximity of the neighbouring buildings highlighting the limited overshadowing. The kitchen is open plan to the dining room with no windows whereas the dining room benefits from a large glazing area (Figures 3-16 and 3-17). The living room which is separate and accessed from a corridor also benefits from a large glazing area (Figure 3-18).

Below is the extract from the verification sheet highlighting the heating load as well as the airtightness level meeting the EnerPhit standard.



Treated Floor Area:	173.2	m^2
	Applied:	Monthly method
Specific Space Heating Demand:	**25**	**$kWh/(m^2a)$**
Heating Load:	**14**	**W/m²**
Pressurization Test Result:	**1.0**	**h^{-1}**
Specific Primary Energy Demand **(DHW, Heating, Cooling, Auxiliary and Household Electricity):**		**$kWh/(m^2a)$**
Specific Primary Energy Demand **(DHW, Heating and Auxiliary Electricity):**		**$kWh/(m^2a)$**
Specific Primary Energy Reduction through Solar Electricity:		**$kWh/(m^2a)$**
Frequency of Overheating:	**0**	**%**
Specific Useful Cooling Energy Demand:		**$kWh/(m^2a)$**
Cooling Load:	**3**	**W/m^2**

Figure 3-19- Extraction from the verification sheet (source: PHPP7 - Eco Design Consultants)

The climate data used in the PHPP calculation for building two is Midlands area (number 7) as indicated in the map below and figure 3-21 demonstrates the solar radiation & ambient temperature extracted from the PHPP.

Figure 3-20- Map indicating the different climate areas used in PHPP for the UK (source: (BRE Group, 2011)**)**

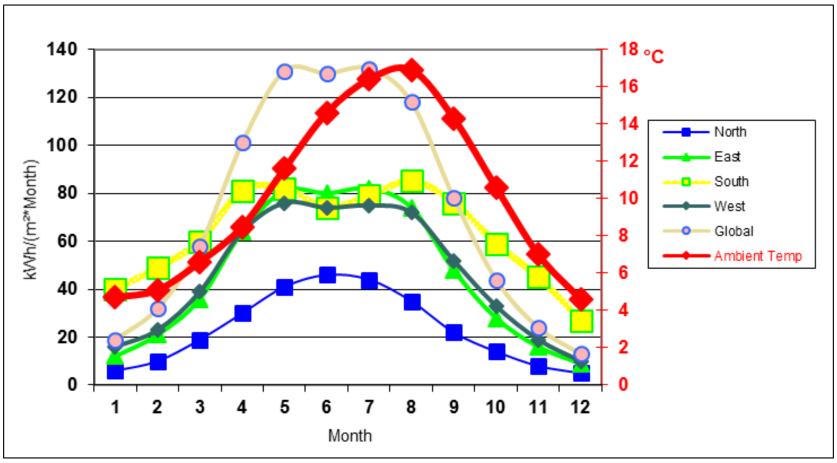
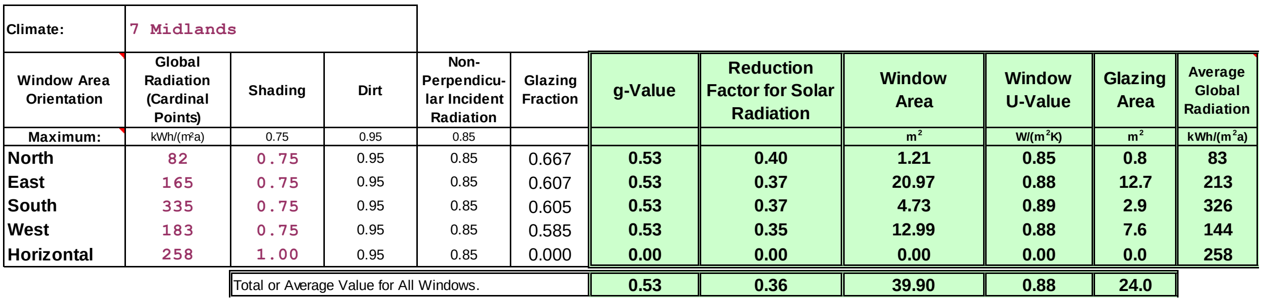


Figure 3-21- Solar radiation & ambient temperature - Midlands area from (source: PHPP7 - Eco Design Consultants)

The building's components average U-Values are as listed below:

- Exterior wall 0.098 W/(m^{2}K)
- Roof 0.100 W/(m^{2}K)
- Floor 0.139 W/(m^{2}K)
- North windows 0.850 W/(m^{2}K)
- East windows 0.878 W/(m^{2}K)
- South windows 0.890 W/(m^{2}K)
- West windows 0.878 W/(m^{2}K)

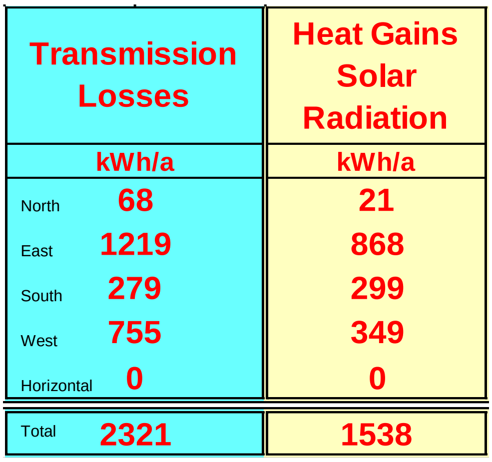
Window information summary indicating the g-Value and U-Value for different façades of the building alongside the average global radiation used by PHPP7 from the climate file for the heating season can be seen from Figures 3-22 and 3-23. The average g-Value is 0.53 (lower than Building One) and the average U-Value is 0.88W/m^{2}K (higher than Building One).



Climate:	7 Midlands										
Window Area Orientation	Global Radiation (Cardinal Points)	Shading	Dirt	Non-Perpendicular Incident Radiation	Glazing Fraction	g-Value	Reduction Factor for Solar Radiation	Window Area	Window U-Value	Glazing Area	Average Global Radiation
Maximum:	kWh/(m²a)	0.75	0.95	0.85				m²	W/(m²K)	m²	kWh/(m²a)
North	82	0.75	0.95	0.85	0.667	0.53	0.40	1.21	0.85	0.8	83
East	165	0.75	0.95	0.85	0.607	0.53	0.37	20.97	0.88	12.7	213
South	335	0.75	0.95	0.85	0.605	0.53	0.37	4.73	0.89	2.9	326
West	183	0.75	0.95	0.85	0.585	0.53	0.35	12.99	0.88	7.6	144
Horizontal	258	1.00	0.95	0.85	0.000	0.00	0.00	0.00	0.00	0.0	258
		Total or Average Value for All Windows.				0.53	0.36	39.90	0.88	24.0	

Figure 3-22- Windows information summary (source: PHPP7 - Eco Design Consultants)

Figure 3-23- Total gains and losses during winter from windows in relation to the orientation in kWh/a (source: PHPP7-Eco Design Consultants)



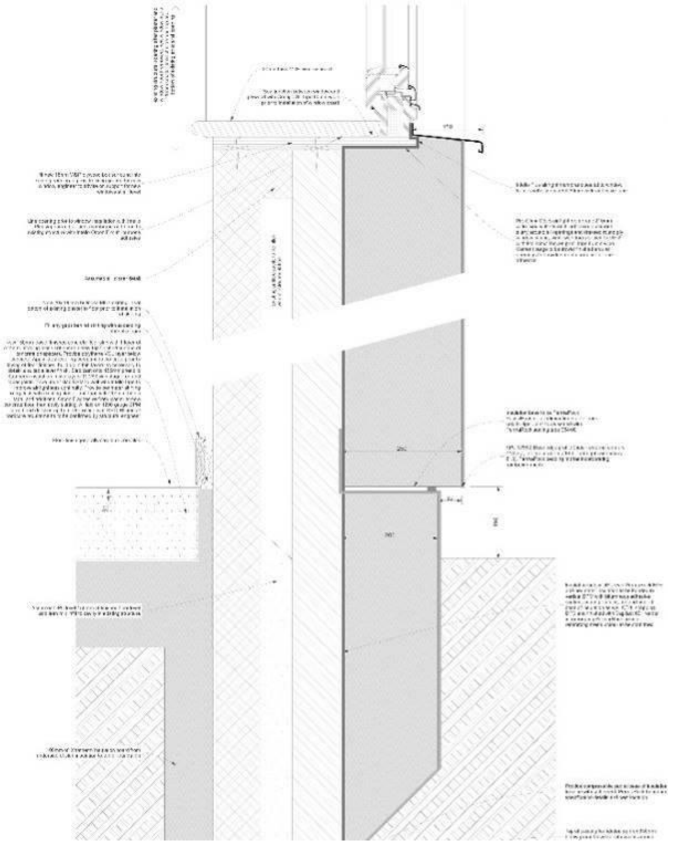
	Transmission Losses	Heat Gains Solar Radiation
	kWh/a	kWh/a
North	68	21
East	1219	868
South	279	299
West	755	349
Horizontal	0	0
Total	2321	1538

The building is owner occupied by a family of four (two adults and two children) at the time of monitoring. The occupancy rate is close to the standard used in the PHPP calculation of 5 persons which is lower than the UK average for a 5 bedroom house.

The building had been originally constructed using a more heavyweight construction material and by adding the insulation externally, the thermal mass has not been reduced. However the first floor extension has been constructed from a lightweight material and therefore the value used representing this in PHPP (specific capacity) was 132Wh/K per m^2 TFA. The existing cavity walls have been fully filled and insulated further externally and finished with render. The new first floor wall is timber with insulation between and over with render as the facing material. To achieve the required U-Value, the floor was excavated and insulation was placed below the concrete slab to obtain the thermal mass. The roof is I beam with mineral wool insulation and the windows are Eco Passive triple glazed.

Below are typical details indicating the wall and floor build up.

Figure 3-24- Section detail showing the floor and existing insulated wall build up (source: Eco Design Consultants)



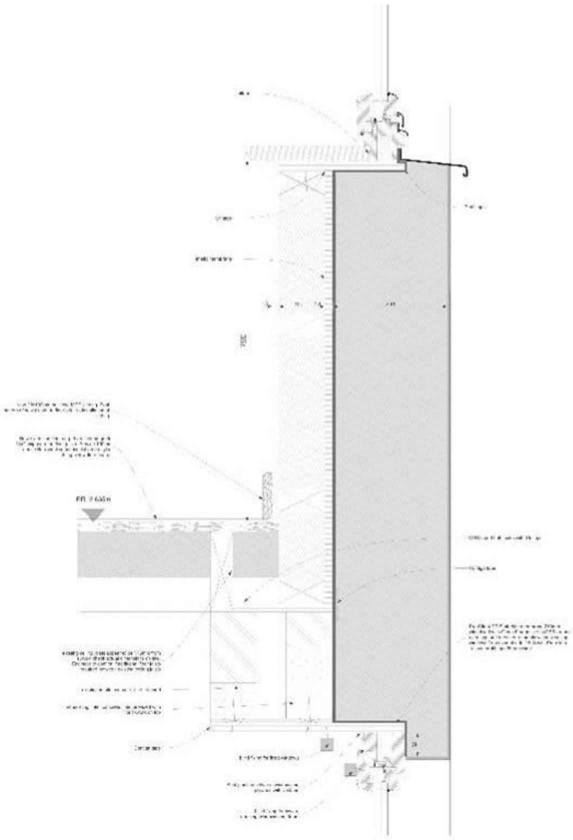


Figure 3-25- Section detail showing the new first floor wall (source: Eco Design Consultants)

3.3. PHPP CALCULATION

PHPP is an Excel spreadsheet using static methods of calculation which has been cross examined using Dynbil (dynamic modelling simulation software), and data from field study (McLeod et al., 2013). PHPP was first published in 1998 and works in conjunction with a comprehensive manual (Lewis, 2014).

The Excel spreadsheet has been divided into several different sheets allowing input for different sections accordingly. PHPP has a high accuracy track record of energy balance as far as +/- 0.5kWh/m^{2}a (Lewis, 2014) which will be around 3.3%. The accuracy is also driven by the incorporation of tolerances and correction factors like daily weather and to some degree, human behaviour (Passivhaus Trust, 2016). However the performance gap during the summer period and the overheating might not be as favourable (Lomas & Porritt, 2017).

PHPP uses monthly climate data and it is based on a single zone calculation. Therefore different temperatures in a specific location might be overlooked as it will be averaged for the entire building. The summer ventilation and internal gain calculation relies on the designer input and therefore experience, which can have a high impact on the overheating calculation and percentage (Passivhaus Trust, 2016).

PHPP calculation is not only used for design purposes, but also is a requirement for obtaining Passivhaus certification and the final calculation has to be submitted to the certified body alongside other documents such as drawings, Psi-Value calculation (where applicable), airtightness test, etc. (Passive House Institute, n.d.)

The input into PHPP can be divided into three sections of Heating, Cooling and Primary energy. Additional Psi-Value calculations may be required and can be obtained by using a separate software and the information added to

PHPP. The image below is a demonstration of the data input requirements and the linkage between the different sheets.

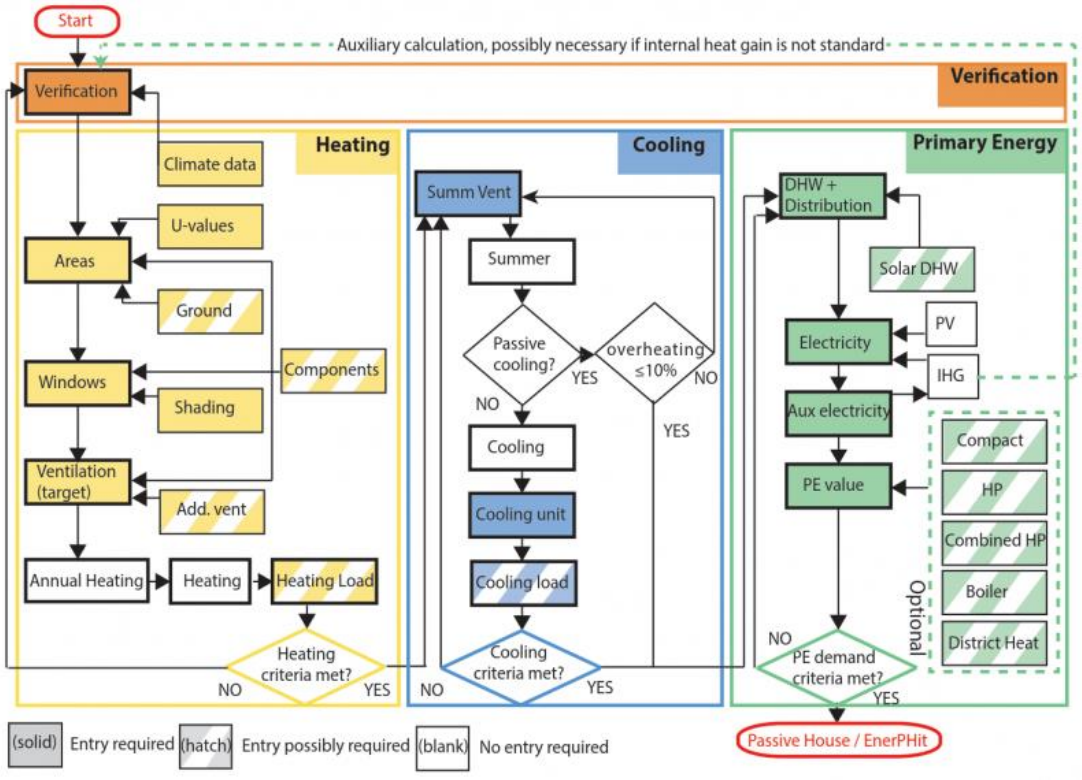


Figure 3-26- Flow chart demonstrating the data input requirements and linkage between the sheets (Source: (Lewis, 2014) p.60).

The input for heating demand can be broken down, however there is no specific order and the information can be entered as it becomes available. The image below is the demonstration of the recommended data input order.

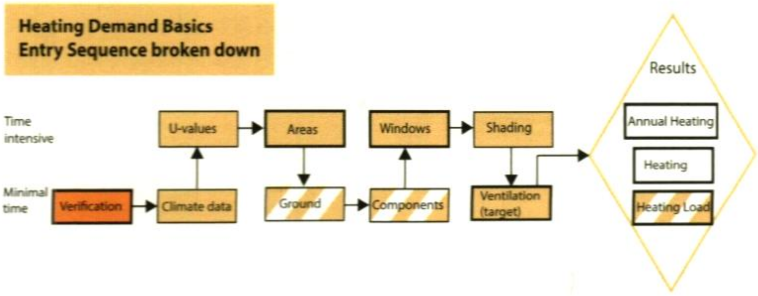


Figure 3-27- Heating demand information input for PHPP (Source: (Lewis, 2014) p.63)

The heating demand is calculated as the difference of the total losses and gains taking the utilisation factor into consideration. Utilisation factor is used as a standard value based on the international standard of ISO 13790, when the heat from irradiation and internal gains is not available evenly. This correction is automatically taken into consideration by PHPP which was originally derived from a comprehensive dynamic simulation calculation.

The formula used in PHPP for calculating heating demand is:

Specific Heat Demand = Transmission + Ventilation - η * (Solar + IHG)

$$Q_H = Q_T + Q_V - \eta^*(Q_S + Q_I)$$

utilisation factor

Equation 3-1- PHPP heating demand calculation (Source: (Passivhaus Institut, 2012) **)**

And the gains and losses are calculated using the formulas below:

Area of thermal envelope * U-value * Temperature-correction factor * Heating degree hours

$$Q_T = A * U * f_t * G_t$$

Air volume * Effective air change * Heat cap. air * Heating degree hours

$$Q_V = V_v * n_v * c_p\rho * G_t$$

reduction factor * g-value * window area *global irradiation

$$Q_S = r * g * A_w * G$$

Length heating period * spec. Internal Heat Gains * Treated Floor Area

$$Q_I = t_{Heat} * q_i * A_{TFA}$$

Equation 3-2- PHPP heat gains and losses calculation (Source: (Passivhaus Institut, 2012) **)**

It should be noted that the area calculations for PHPP are carried out using external dimensions which is different from the UK standard which uses internal dimensions. Moreover the internal gains calculation uses a specific value of 2.1 W/m^2 eliminating over compensation.

The cooling and the primary energy can also be broken down and the below images are the demonstration of the data input and linking between the sheets.

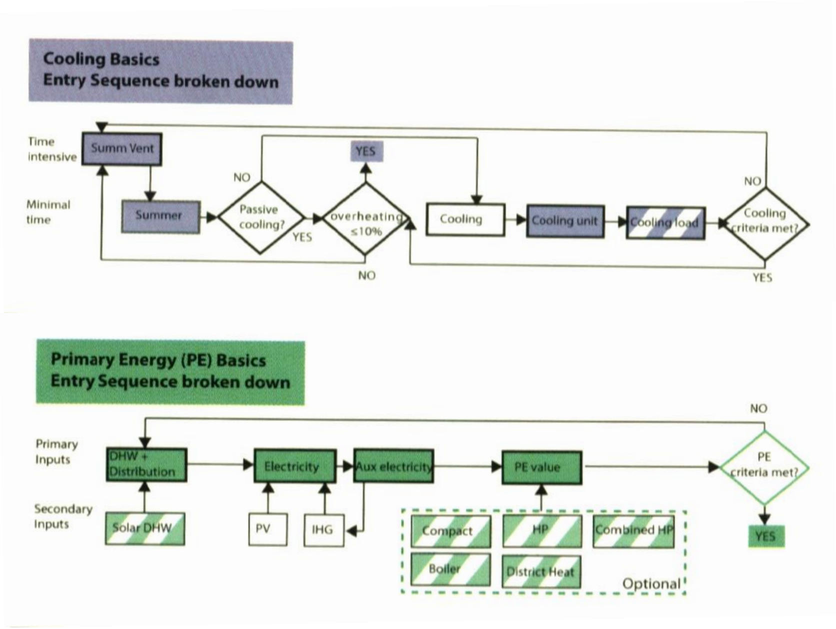


Figure 3-28- Cooling demand and primary energy information input for PHPP (Source: (Lewis, 2014) **p. 140 & 160)**

The cooling load calculation is similar to the heating and is the result of an energy balance of solar and the internal gains, conduction and ventilation losses or gains for a design day. The cooling capacity is calculated on a daily average assuming the fabric (mass) of the building can take the fluctuation into account during the day. PHPP also calculates the daily temperature fluctuation due to solar gain and recommends this not to be over 3 K as the cooling load might not be sufficient for a design day (Passive House Institute, 2007).

Moreover the primary energy demand calculation is required as part of the standard and it is the onsite energy used taking the inefficiencies of the production and delivery of the energy to the building. This is usually classed as unregulated emissions in the UK building regulations and not taken into consideration. The primary energy demand is the total energy required for heating, domestic hot water, auxiliary and household electricity in relation to treated floor area and needs to be below 120kWh/(m^2a) (Lewis, 2014).

The data from the PHPP calculation (certification / PHPP7) for the two case study buildings was used in creating the dynamic thermal model as well as the comparison to the monitored data. Recalculation was undertaken using the newer version of PHPP (PHPP8) which allows for a separated internal heat gain calculation during the summer period. The impact of the location and therefore the climate data was tested using PHPP alongside the MVHR summer by pass option in order to investigate the different causes contributing to overheating.

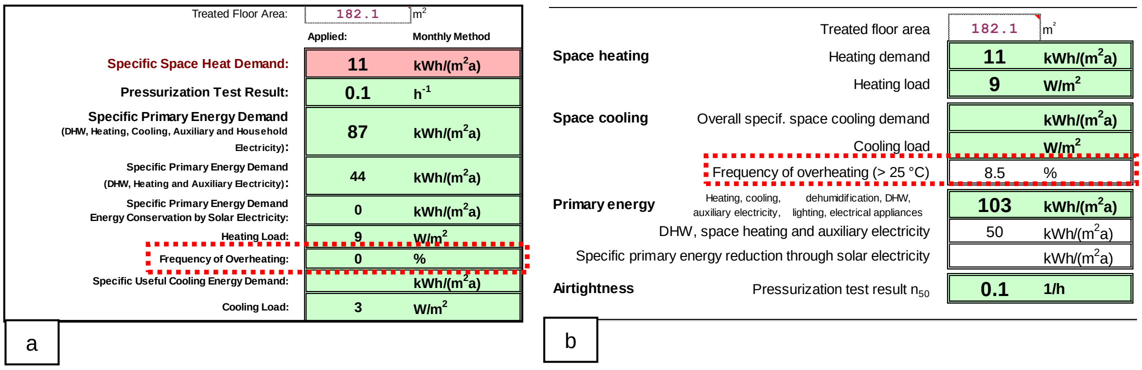
Finally, the proposed natural ventilation option was tested in PHPP for the two case study buildings using the current and future weather data as well as on an additional five Passivhaus dwellings.

3.3.1. Conversion from PHPP 7 to PHPP 8

During the design stage for both buildings and also for the certification purposes, PHPP7 was used as the latest version of the program at the time. Since then, Passivhaus institute has released PHPP8 with further improvements especially for additional internal gains and therefore higher accuracy for calculating the potential of overheating during the summer period. Some of the other changes in PHPP8 include: input for building component orientation and therefore, the effect of the solar gain on the different opaque surfaces with different material and colour properties; different options for summer bypass; cooling and a dehumidification option.

Using PHPP7, neither of the two buildings had shown any percentage of overheating during the summer period and the decision was made to carry out the calculation in PHPP8 to examine the effect of higher internal gains and therefore higher overheating potential. Recalculation was carried out with the same climate data previously used for both buildings and for Building One there was no change in the heating requirement. However in the case of Building Two the specific space heat demand was reduced from 25kWh/(m^2a) to 20kWh/(m^2a) which is thought to be due to a slight difference in the solar radiation from the climate data which is part of the PHPP. The higher available solar radiation has consequently led to higher solar gain through the windows in the building during the heating season which was increased by 185kWh/a from 1538kWh/a to 1723 kWh/a, and therefore less requirement for heating.

Below are direct comparisons between PHPP7 and PHPP8 verification sheets for both buildings which also indicate the higher potential for overheating during the cooling season.



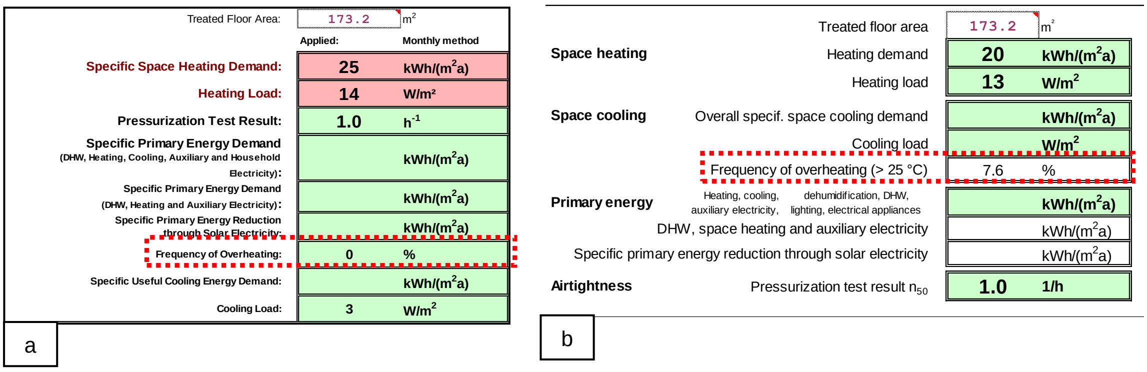
Treated Floor Area:	182.1	m²
	Applied:	Monthly Method
Specific Space Heat Demand:	11	kWh/(m²a)
Pressurization Test Result:	0.1	h⁻¹
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	87	kWh/(m²a)
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	44	kWh/(m²a)
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	0	kWh/(m²a)
Heating Load:	9	W/m²
Frequency of Overheating:	0	%
Specific Useful Cooling Energy Demand:		kWh/(m²a)
Cooling Load:	3	W/m²

a

	Treated floor area	182.1	m²
Space heating	Heating demand	11	kWh/(m²a)
	Heating load	9	W/m²
Space cooling	Overall specif. space cooling demand		kWh/(m²a)
	Cooling load		W/m²
	Frequency of overheating (> 25 °C)	8.5	%
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances	103	kWh/(m²a)
	DHW, space heating and auxiliary electricity	50	kWh/(m²a)
	Specific primary energy reduction through solar electricity		kWh/(m²a)
Airtightness	Pressurization test result n_{50}	0.1	1/h

b

Figure 3-29- Extract from PHPP verification sheet showing: (a) the original PHPP7 and (b) the recalculation from PHPP8 for Building One (source: Eco Design Consultants & Author)



Treated Floor Area:	173.2	m²
	Applied:	Monthly method
Specific Space Heating Demand:	25	kWh/(m²a)
Heating Load:	14	W/m²
Pressurization Test Result:	1.0	h⁻¹
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):		kWh/(m²a)
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):		kWh/(m²a)
Specific Primary Energy Reduction through Solar Electricity:		kWh/(m²a)
Frequency of Overheating:	0	%
Specific Useful Cooling Energy Demand:		kWh/(m²a)
Cooling Load:	3	W/m²

a

	Treated floor area	173.2	m²
Space heating	Heating demand	20	kWh/(m²a)
	Heating load	13	W/m²
Space cooling	Overall specif. space cooling demand		kWh/(m²a)
	Cooling load		W/m²
	Frequency of overheating (> 25 °C)	7.6	%
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances		kWh/(m²a)
	DHW, space heating and auxiliary electricity		kWh/(m²a)
	Specific primary energy reduction through solar electricity		kWh/(m²a)
Airtightness	Pressurization test result n_{50}	1.0	1/h

b

Figure 3-30- Extract from PHPP verification sheet showing: (a) the original PHPP7 and (b) the recalculation from PHPP8 for Building Two (source: Eco Design Consultants & Author)

Moreover, PHPP8 provides additional information regarding the time that the internal temperature exceeds the 25°C limit in comparison to the external temperature alongside additional ventilation requirements and the cooling demand for the different months of the year. Below is this information extracted from PHPP8 for Building One and Two respectively.

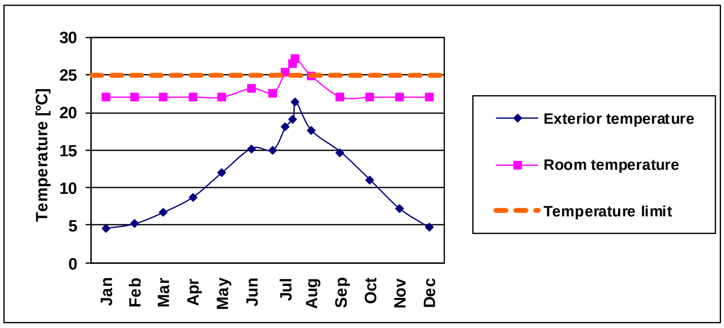


Figure 3-31- The external temperature and the indoor temperature, highlighting the times that the indoor temperature exceeds the 25°C limit for Building One - monthly (source: PHPP8)

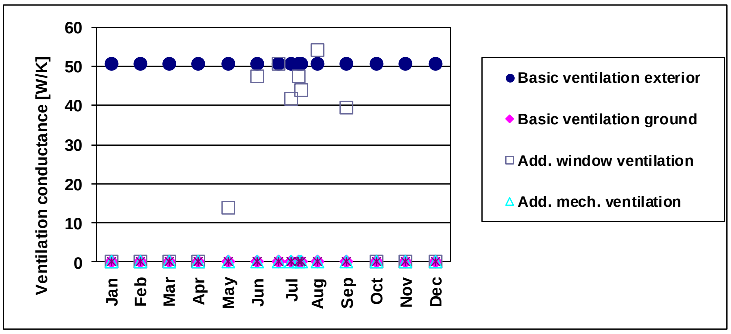


Figure 3-32- The different ventilation recommendations from PHPP8 for Building One (source: PHPP8)

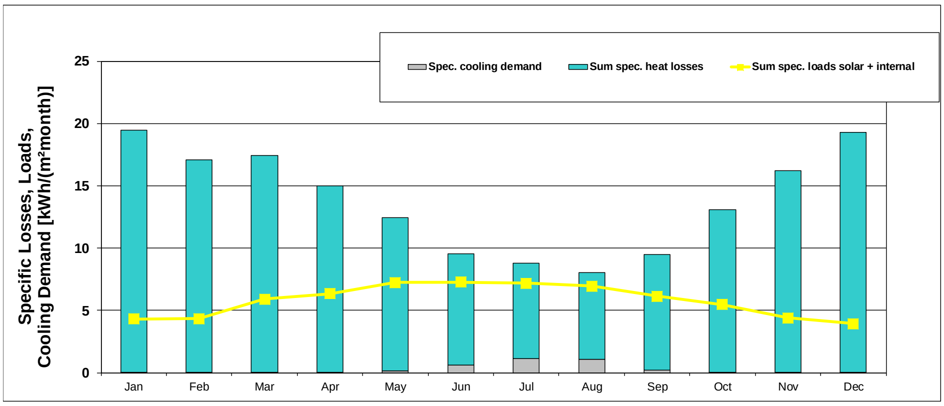


Figure 3-33- The months with cooling demand in grey - Building One (source: PHPP8)

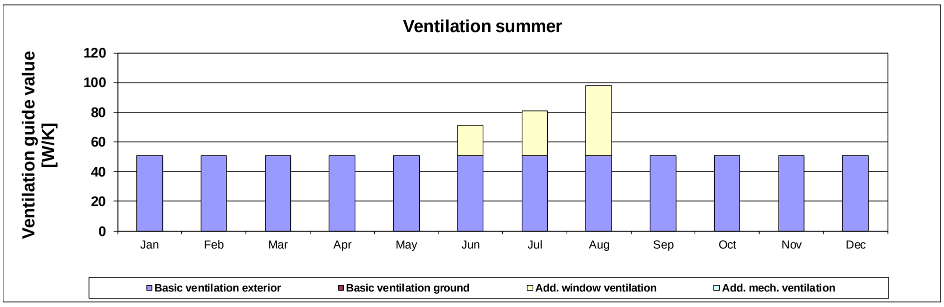


Figure 3-34- Additional ventilation requirements during the months of June, July and August – Building One (source: PHPP8)

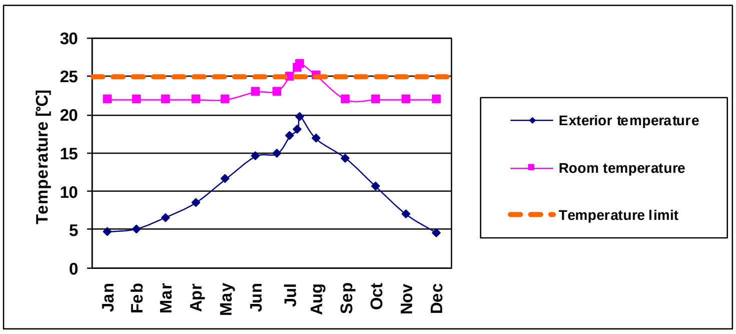


Figure 3-35- External temperature and the indoor temperature, highlighting the times that the indoor temperature exceeds the 25°C limit for Building Two – monthly (source: PHPP8)

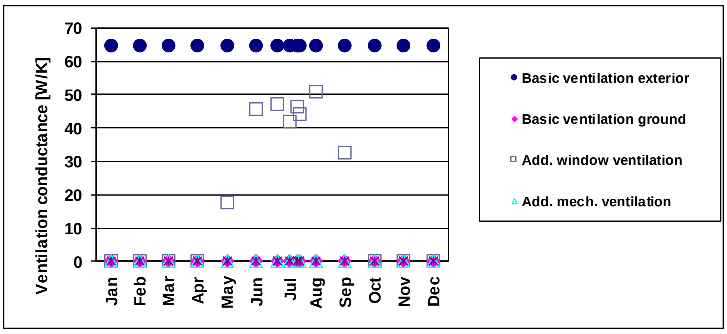


Figure 3-36- Different ventilation recommendations from PHPP8 for Building Two (source: PHPP8)

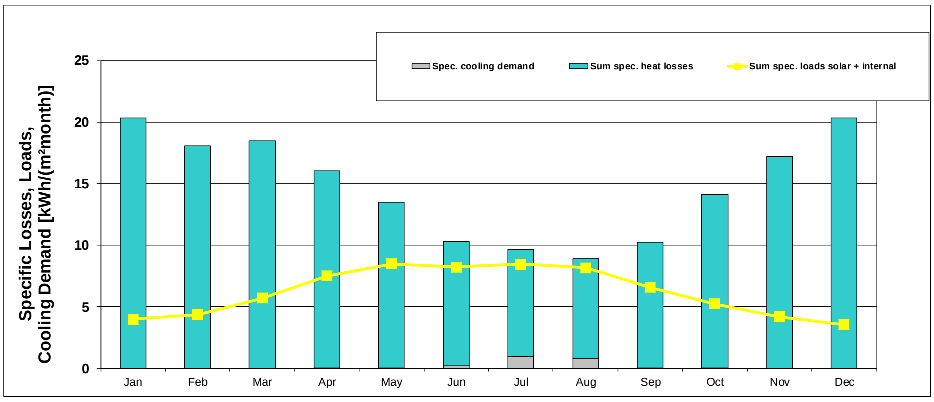


Figure 3-37- Months with cooling demand in grey - Building Two (source: PHPP8)

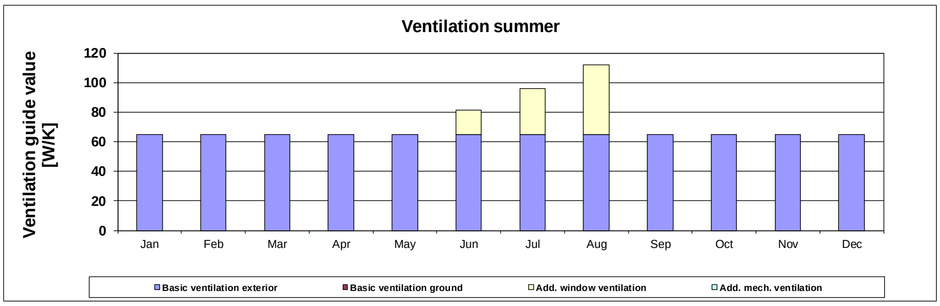


Figure 3-38- Additional ventilation requirements during the months of June, July and August – Building Two (source: PHPP8)

In summary, the recalculation carried out using PHPP8 has indicated higher internal gains and therefore a higher potential of overheating during the summer period for both buildings and consequently higher ventilation requirements or cooling.

3.4. PLACEMENT OF THE MONITORING EQUIPMENT

Monitoring has been carried out during the summer of 2014 to record the internal temperatures and relative humidity, CO_2 levels (key areas) and air temperature from the MVHR supply outlet (key areas). Furthermore window state loggers were used to determine the frequency and duration of windows being opened.

The data loggers used were HOBO U10 and U12, monitoring temperatures and RH every 15 minutes, I-Buttons were placed inside the MVHR outlet set to record hourly, Telaire 7001 CO_2 sensors in conjunction with HOBO U12 were used to monitor the indoor CO_2 and the ambient hourly temperatures were obtained from the British Atmospheric data centre (BADC) for the two locations during 2014.

Data loggers were used to monitor the performance of the two case study buildings to be able to compare the results with PHPP calculation used during the design and certification stage, and also aid in creating the Base Case dynamic model. The internal temperatures have been monitored in the majority of the internal spaces for both buildings with some exceptions due to the limitation of the equipment availability. The locations, therefore, are chosen to reflect a good representation of the buildings' performance and the spaces that are used and occupied in line with ASHRAE standard 55 (2004) where it states that the monitoring equipment needs to be placed in the occupied spaces and locations where people are expected to spend their time in (Jakob et al., 2004). Therefore the corridors and storage rooms were not monitored. However the location of the MVHR was monitored to record the temperature surrounding the MVHR even though MVHR locations were either in the storage room or in the loft space (part of the thermal envelope) used as storage.

Data loggers were used to monitor the temperature and relative humidity of all main spaces i.e. living room, dining room, bedrooms, bathrooms etc. to be able to not only assess the building performance but also allow for analysing the internal environment conditions and occupants' thermal comfort. All data loggers were placed away from direct sunlight and within the expected occupied location as it is known and following consultation with the occupant and not in the centre of the room which would have been recommended if the end user location was not known (Jakob et al., 2004) The loggers were placed around 800mm to 1000mm in height from the ground within the ASHRAE standard 55 requirement of 0.6 to 1.1m for operative temperature for seated and standing occupants respectively (Jakob et al., 2004). However there were some exceptions due to location restrictions (i.e. kitchen), to monitor the true representation on the internal conditions even though in Passivhaus the temperature unification is more apparent and also a requirement. Moreover where possible door frames were used to reduce any possible damage caused by the sticky Velcro used in securing the loggers in place.

The monitoring equipment was first placed in both buildings around 15th April 2014 and due to access restrictions, a decision was made to download the recorded data after five to six months running the risk of data loss due to possible problems with the equipment. The months prior to and after the summer months, were chosen to be included not only due to the access arrangements, but also allowing the examination of a wider range of data. Moreover intervals for recording was set to be every 15 minutes.

The internal CO_2 was monitored in the two main habitable spaces (living room and main bedroom) of both buildings to assess the effectiveness of the ventilation and air change. Monitoring the internal CO_2 for more locations in the building could have proven beneficial, however due to limitation of the number of equipment available, the decision was made to limit this to the two locations for each building.

Smaller data loggers were placed in the fresh air inlet of the MVHR to monitor the temperature of the incoming fresh air in the living room and the main bedroom with a smaller monitoring capacity focusing on the summer months with a delayed start. Moreover occupants were consulted to identify nine windows in each building, which would be used the most, for monitoring. Therefore state loggers with window sensors were placed by the windows to record the intervals and duration of the windows being opened. This can be used in conjunction with the internal temperature and the internal CO_2 levels to further understand the occupant behaviour and effectiveness of the ventilation achieved through the windows. The majority of the windows are tilt and turn in both buildings and the limitation of the sensors used for the windows is that the sensors would not be able to differentiate how the windows are opened i.e. tilted or turned or whether windows are fully or partially opened. Nevertheless the sensors would still give an indication that the windows were opened or closed, as well as duration and time that the windows were operated.

The internal and external blinds could have also been monitored to aid this research, however due to the limitation of the equipment required the data from the PHPP and construction was used alongside additional amendments implemented by the occupants after building completion. The list and associated location of all the equipment used for the building monitoring and their specifications can be found in Appendix B.

3.4.1. Building One – Passivhaus

The drawings and images show the location of the equipment used for monitoring.

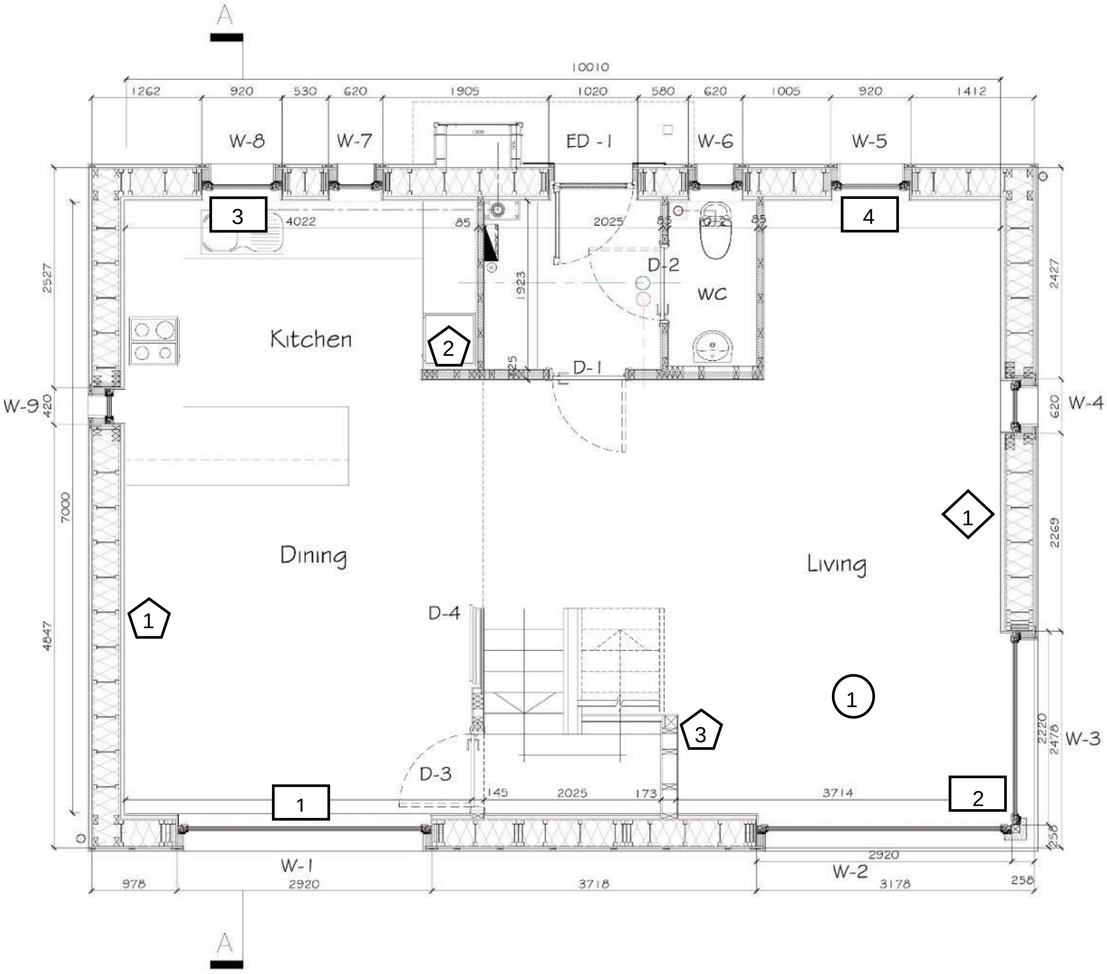
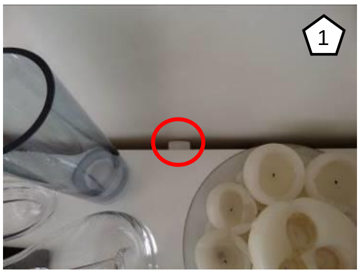


Figure 3-39- Ground floor plan (source: Eco Design consultants)



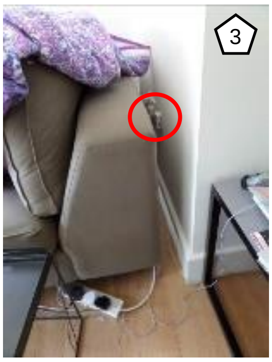


Figure 3-40- Temperature & RH data logger - From left to right located behind the shelving units in the dining room, on the top of the cabinets in the kitchen, on the side of the sofa in the living room (source: author)

Figure 3-41- Temperature data logger located in the fresh air outlet in the living room (source: author)

Figure 3-42- CO_2 logger located on the shelf in the living room (source: author)

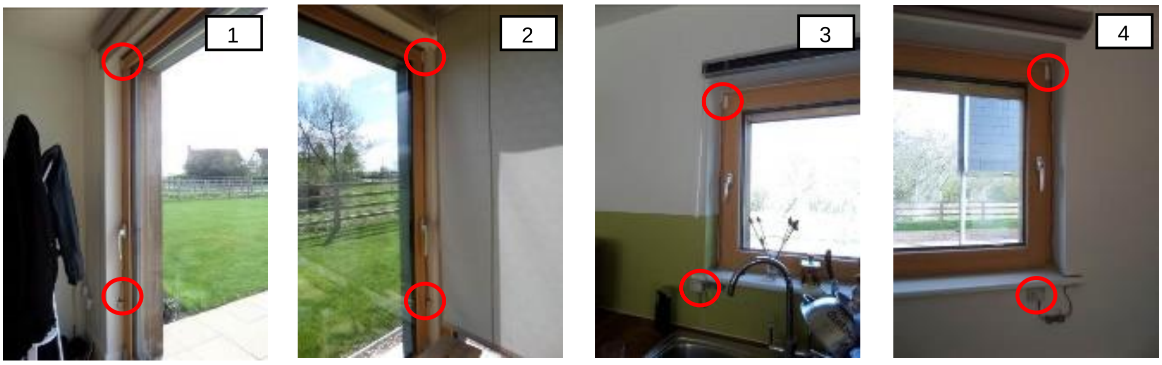


Figure 3-43- State logger & window sensor - From left to right located on the tilt & slide window in the dining room, living room, kitchen and study area (source: author)

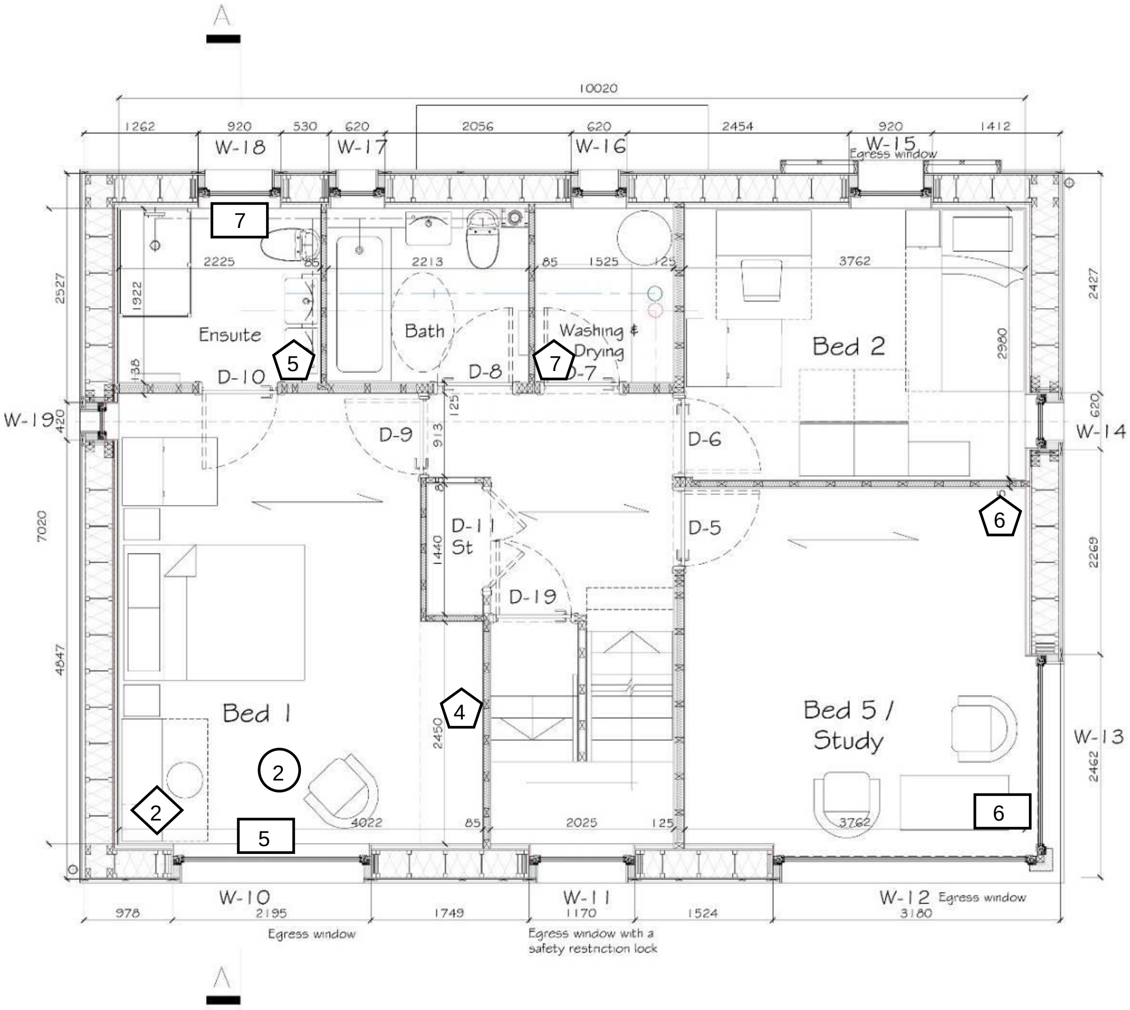


Figure 3-44- First floor plan (source: Eco Design consultants)

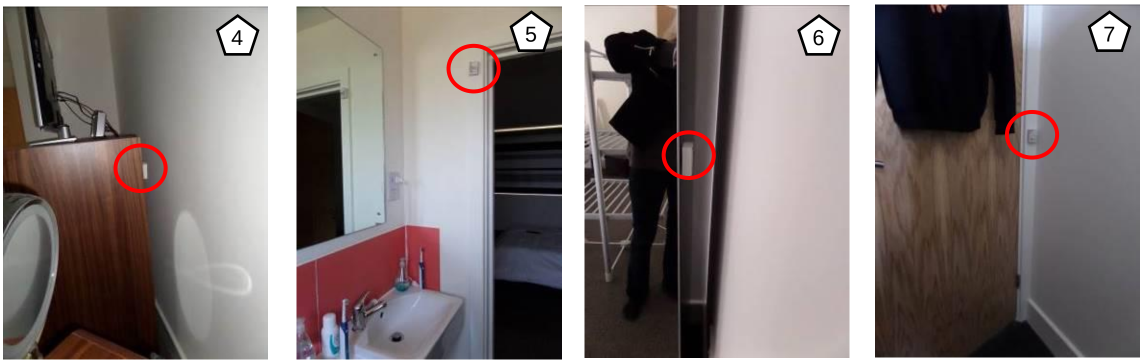


Figure 3-45- Temperature & RH data logger – From left to right - located behind the shaving units in the main bedroom, on the door frame higher than the 1m in the master bathroom, behind the cupboard in bedroom 5 and on the door frame in the drying room where the hot water cylinder is placed (source: author)

Figure 3-46- CO_2 logger located on the shelf in the main bedroom (source: author)

Figure 3-47- Temperature data logger located in the fresh air outlet in the main bedroom (source: author)

Figure 3-48- State logger & window sensor - From left to right - located on the tilt & turn window in the main bedroom, bedroom and master bathroom (source: author)

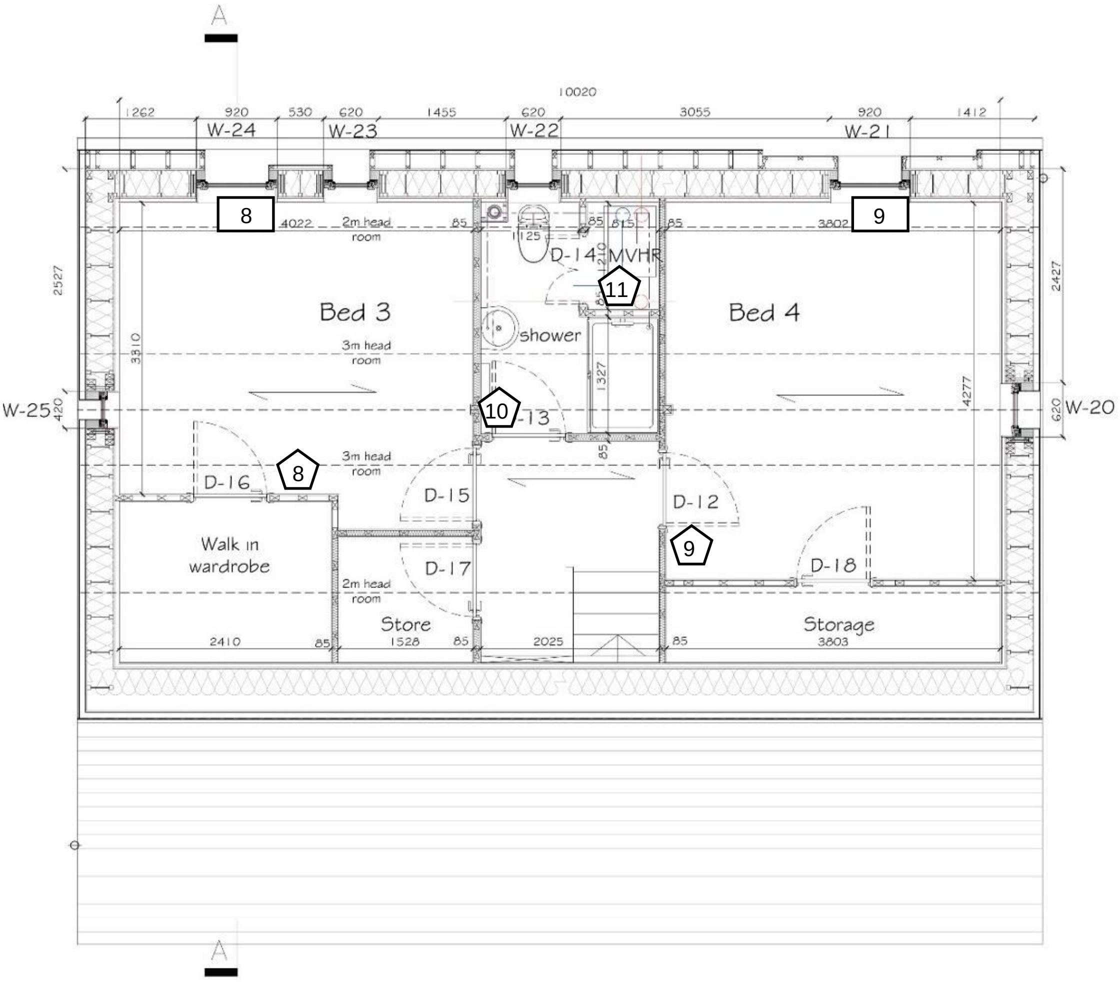


Figure 3-49- Second floor plan (source: Eco Design consultants)

Figure 3-50- Temperature & RH data logger – From left to right - located on the door frame in bedroom 3 and bedroom 4 (source: author)

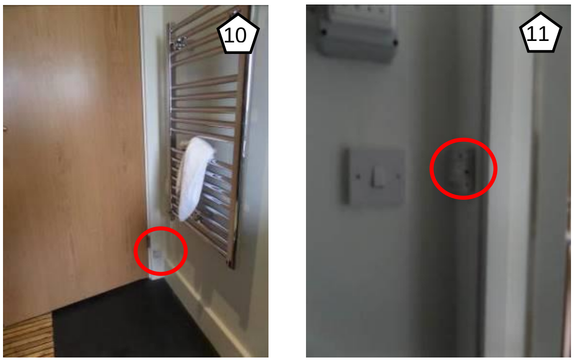


Figure 3-51- Temperature & RH data logger - From left to right - located on the door frame below the 1m height in the second floor shower room and the storage room housing the MVHR unit (source: author)

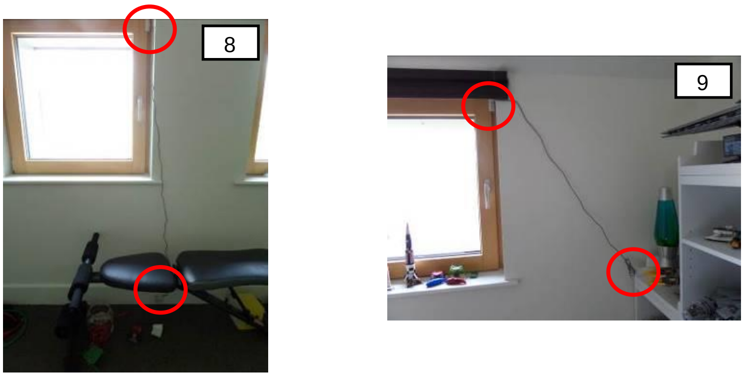


Figure 3-52- State logger & window sensor – From left to right - located on the tilt & turn window in bedroom 3 and bedroom 4 (source: author)

3.4.2. Building Two – EnerPhit

The drawings and images below show the location of the equipment used for monitoring.

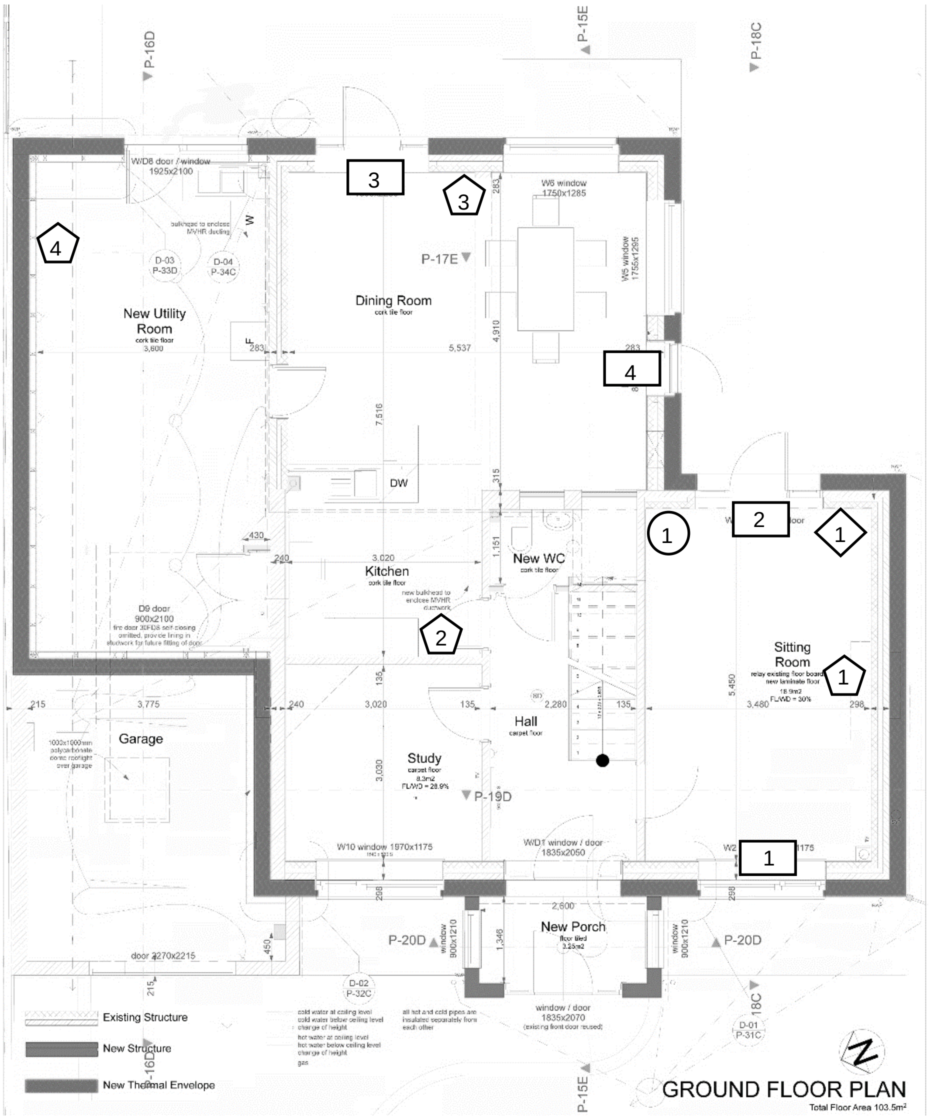


Figure 3-53- Ground floor plan (source: Eco Design consultants)

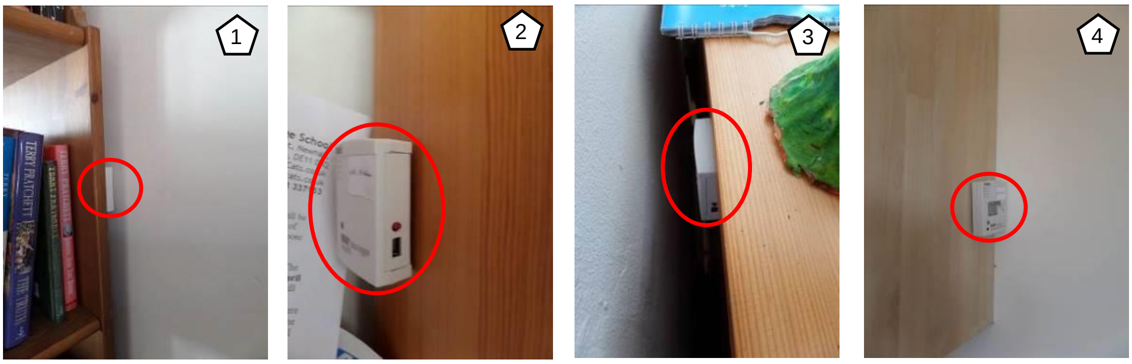


Figure 3-54- Temperature & RH data logger - From left to right - located on the side of the bookshelf in living room, on the side of the cabinet in kitchen, behind a storage unit in dining room and on the side of the cabinet in utility room (source: author)

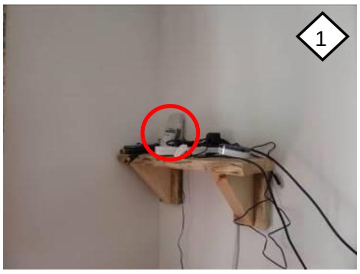


Figure 3-55- CO_2 logger located on the shelf in the living room (source: author)

Figure 3-56- Temperature data logger located in the fresh air outlet in the living room (source: author)

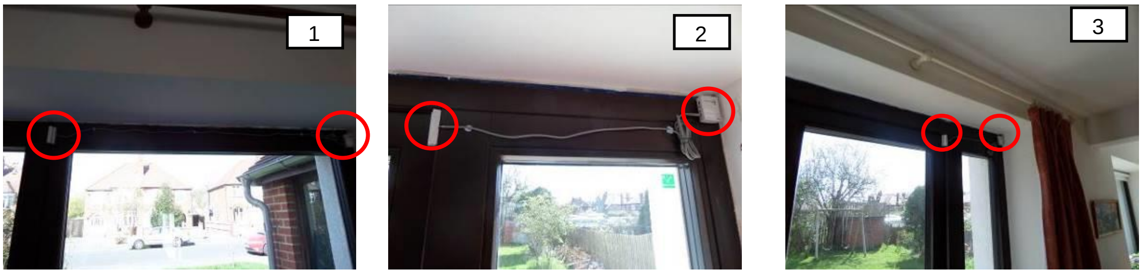


Figure 3-57- State logger & window sensor – From left to right - located on the tilt & turn window in living room, patio door in living room and patio door in dining room (source: author)

Figure 3-58- State logger & window sensor located on the door in dining room (source: author)

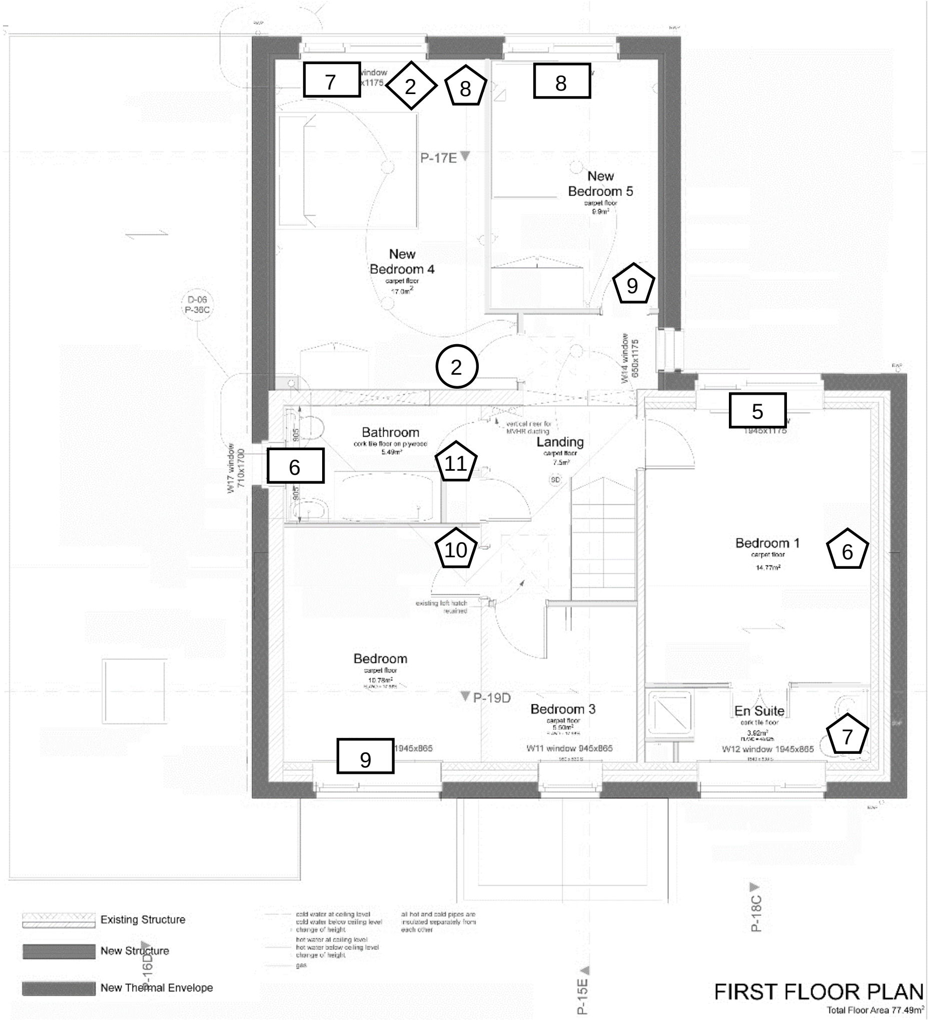


Figure 3-59- First floor plan (source: Eco Design consultants)

Figure 3-60- Temperature & RH data logger _ From left to right - located on the side of storage unit in master bedroom, on the mirror in master bathroom, on the side of the storage unit in bedroom 4 (used as the main bedroom) – Also CO2 logger located on the storage unit (source: author)

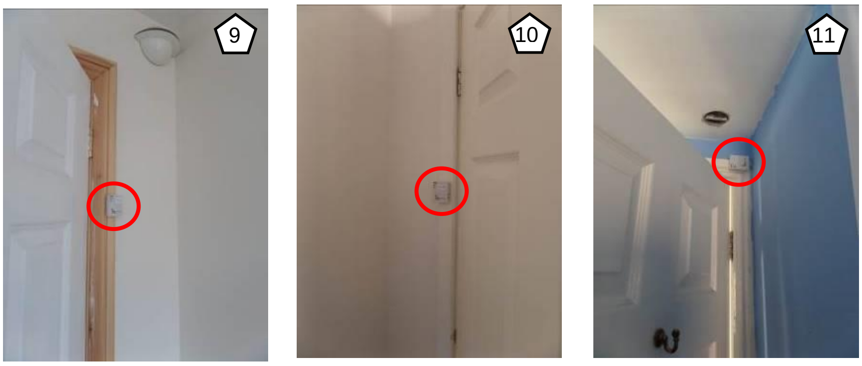


Figure 3-61- Temperature & RH data logger –From left to right - located and on the door frame in bathroom 5, on the door frame in bathroom 2 and on the door frame higher than the 1m height in bathroom (source: author)

Figure 3-62- Temperature data logger located in fresh air outlet- bedroom 4 (source: author)

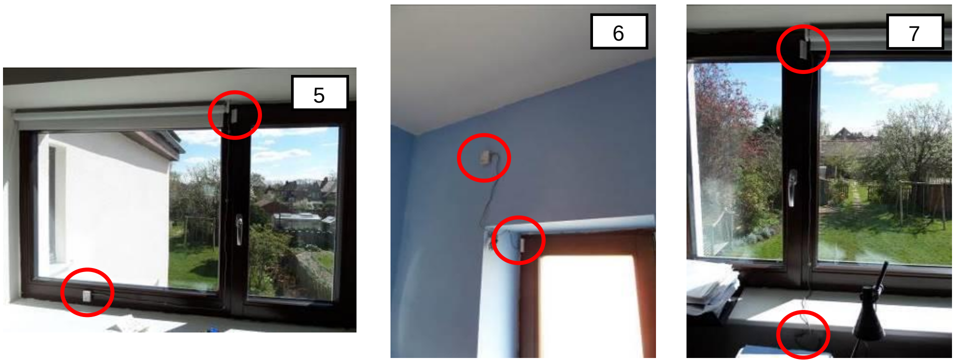


Figure 3-63- State logger & window sensor – From left to right- located on the tilt & turn window in master bedroom, bathroom and bedroom 4 (used as the main bedroom) (source: author)

Figure 3-64- State logger & window sensor located on the tilt & turn window in bedroom 5 and bedroom 2 (source: author)

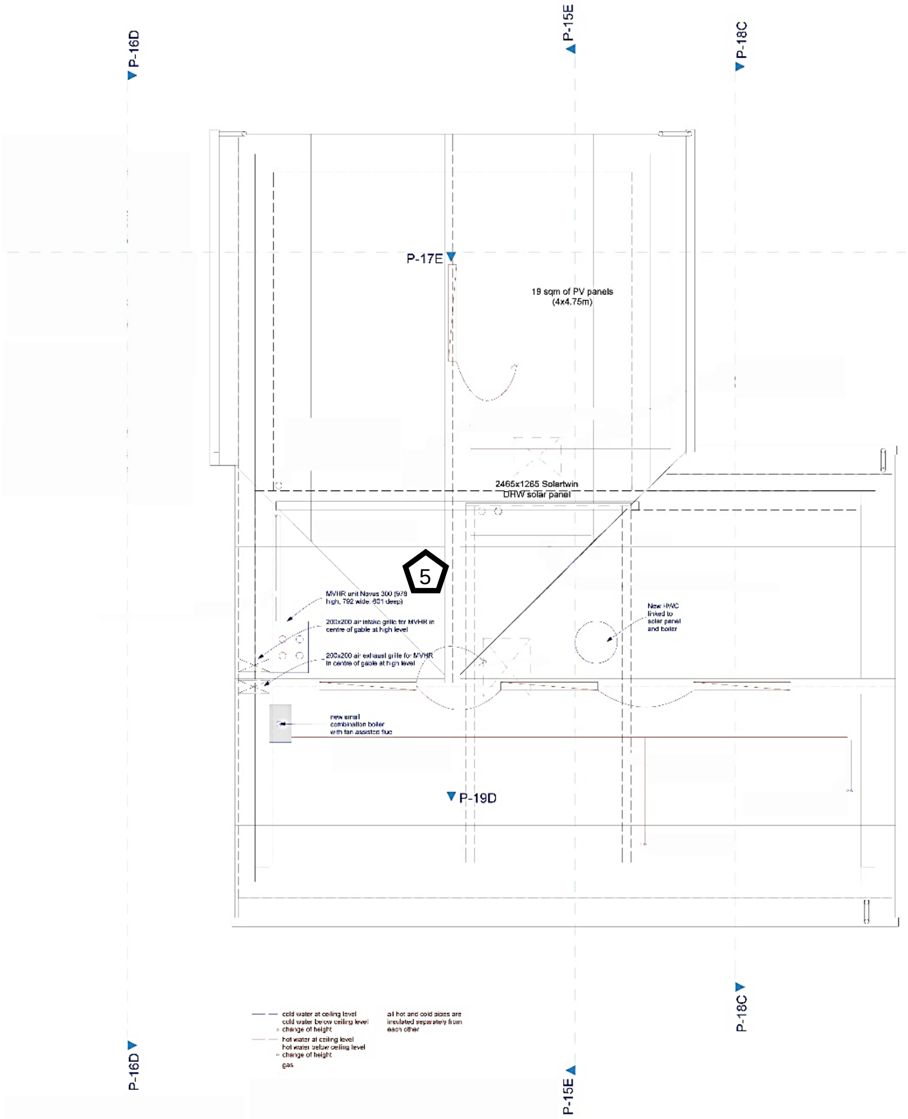


Figure 3-65- Attic floor plan (source: Eco Design consultants)

Figure 3-66- Temperature & RH data logger located in the door attic space housing the MVHR unit (part of the thermal envelope) (source: author)

3.5. DYNAMIC THERMAL MODELLING

3.5.1. Overview

Dynamic simulation models (DSMs) imitate the heat transfer from a building dynamically using the external and internal conditions for a specific time scale (i.e. hourly) (Jankovic, 2012). The air is assumed to be fairly mixed and using the mean radiant temperature at the centre of the room, the operative temperature is simulated (Nicol & Spires, 2013). There are several dynamic thermal modelling programs available with close similarity such as IES (Integrated Environmental Solutions Virtual Environment), TRNSYS (A TRaNsient System Simulation program), TAS Building Designer and DesignBuilder (using EnergyPlus calculation) allowing higher accuracy and output detail in comparison to a simpler steady state software like PHPP.

For dynamic modelling simulation, EnergyPlus calculation engine within the DesignBuilder program has been used. EnergyPlus was initially developed in the USA based on BLAST and DOE-2 around 1970s to 1980s. It benefits from a highly inclusive list of heat transfer and HVAC systems alongside materials. The weather data format used in EnergyPlus (EPW) is one of the main formats used by the industry. However the program is more simulation based and lacks the graphic user interface (Jankovic, 2012). Therefore third party software packages like DesignBuilder can be used in order to create the graphical input of a building.

DesignBuilder can either be used for SBEM (Simplified Building Energy Model) calculations to generate an Energy Performance Certificate or Building Regulation Compliance Report, or for a full dynamic simulation which uses the EnergyPlus engine. The version used for this research is, DesignBuilder v3.4 which uses version v8.1 EnergyPlus for its calculation. The program benefits from an easy to use interface and drawing capability. Some of the features are listed below (DesignBuilder Software Ltd, 2010):

- OpenGL geometric modeller allows building models to be assembled by positioning ‘blocks’ in 3-D space. Blocks can be cut and stretched allowing just about any geometry to be modelled.
- Easy to use CFD function integrated with the simulation model and optionally using EnergyPlus outputs to define CFD boundary conditions.
- Natural ventilation can be modelled with the option for ventilation openings to be based on a ventilation set point temperature. Option for Mixed mode operation in ‘change-over’ with HVAC.
- Shading by louvres, overhangs and sidefins as well as internal and mid pane blinds.
- ASHRAE worldwide design weather data and locations (4429 data sets) are included with the software and more than 2100 EnergyPlus hourly weather files are automatically downloaded as required.

DesignBuilder also allows for wall thickness to be drawn to the exact specification as reality and therefore permits a direct comparison to information used in PHPP in regards to window location within the wall thickness and the associated reduction in solar gain. Moreover the simple and easy drawing function from DesignBuilder allowed for modelling complex and difficult geometries.

Dynamic thermal modelling allows for simulating and calculating the indoor temperatures, allowing direct comparison to monitoring data and overall summer overheating percentage from PHPP. On the other hand CFD (Computational Fluid Dynamics) software, would allow for detailed air movement prediction within the building and programs like Phoenics or Ansys can be used for CFD calculations (CHAM Limited, 2015) (ANSYS Inc., 2016). As dynamic thermal modelling can provide the required analysis for the research objectives, decision was made not to use CFD also influenced by the author’s experience in this area.

3.5.2. Creating the dynamic thermal models

The initial dynamic thermal models were created using the data from the PHPP calculations from the certification alongside construction drawings and specification for both buildings. The plans were imported into DesignBuilder to be used as the base and elevations and sections were used as reference to create the overall geometry. The opaque elements were created in DesignBuilder by inputting the data from the PHPP arriving at the same U-Value. The windows were made by using the simple method of creating windows, inputting the U-Value and g-Value and constructing the frame matching the PHPP data. Moreover the calculated Psi-Values from PHPP were also entered for the individual areas. The table below summarises the information inputted into DesignBuilder and for more detail of the construction build-up refer to Appendix E.

Table 3-1 – Construction value used for dynamic thermal models

	Building One	Building Two
TFA	182.1m^2	173.2m^2
Exterior wall U-Value	0.082 W/(m^{2}K)	0.098 W/(m^{2}K)
Roof U-Value	0.113 W/(m^{2}K)	0.100 W/(m^{2}K)
Floor U-Value	0.120 W/(m^{2}K)	0.139 W/(m^{2}K)
Glass U-Value	0.7 W/(m^{2}K)	0.55 W/(m^{2}K)
Glass g-Value	0.52	0.53
Frame U-Value	0.913 W/(m^{2}K)	0.913 W/(m^{2}K)
Psi-Value Wall – ground floor	0.00 W/mK	0.15 W/mK
Psi- Value window head	0.00 W/mK	0.04 W/mK
Psi- Value window cill	0.001 W/mK	0.02 W/mK
Psi- Value window cill	0.001 W/mK	0.02 W/mK

The airtightness of the buildings was set to the Passivhaus air change per hour calculation method in DesignBuilder matching the test data for each building being 0.07 and 0.1 ac/h respectively. In regards to ventilation, MVHR was used reflecting the same efficiency used in PHPP of 81.3% and 91.2% for Building One and Two. Additional summer ventilation was set to ‘scheduled’ achieving the data used in the PHPP of 0.22 ac/h through windows during the summer nights. The occupancy rate and number was set to Passivhaus standard of 100% and 5 persons for both buildings. Moreover 2.1 W/m^2 of internal heat gain was used for the entire year as per the PHPP7 calculation. The shading was created externally using the data from the PHPP shading sheet alongside any trees and buildings in the surrounding area achieving on average around 40% and 50% of solar gain reduction for Building One and Two. The windows were positioned in accordance to the data used in PHPP and the reveal depth was 290mm and 100mm for Building One and Two respectively.

Furthermore the information obtained from the monitoring was used to create the base case model (see below); and the windcatcher as well as the low level opening was modelled to test the natural ventilation. The windcatcher was created based on the Monodraught Classic Square design 125 (900mm by 900mm on plan and 1.5m in height) (see section 5.5.1) using GRP achieving a U-Value of 3.94W/m^{2}K. Louvres were placed externally (600mm long by 850mm wide) and scheduled to be open all the time as per the actual product and additional louvres were placed internally at the ceiling level (similar to Monodraught grilles) and scheduled to be open during the summer period.

The low level opening was created within the walls as an opening with louvres operating during the summer period only. The louvres were placed to create 60% reduction in opening representing the proposed filters and resistance due to the design (see section 5.5.3).

3.5.3. Comparison to monitoring data

The dynamic thermal model was used for testing the proposed natural ventilation system which could have used the data and design of a typical Passivhaus dwelling in the UK. However, the case study buildings (used for monitoring purposes) which were selected using judgment sampling method were used instead, which can provide a representative sample of typical Passivhaus dwellings in the UK.

The aim of the dynamic thermal model has not been to create a realistic scenario using the two case study buildings. Therefore the data from the monitoring has been compared to the dynamic thermal model highlighting the possible reason for overheating in Passivhaus buildings allowing for a better base case model. Consequently the occupancy rate and number was kept to the Passivhaus standard and only the data, which is not reflecting the actual building during the design stage, has been changed. Moreover the climate data has been kept to the data used in PHPP calculation as it will be the data used by Passivhaus designers also influenced by the limitation of obtaining the actual solar radiation for the two locations.

The gap between the monitoring and modelling was noticeable during the summer only and in order to reduce this gap the following steps were taken:

- Internal heat gain during the summer was recalculated using PHPP8 and the actual appliances schedule (obtained from the finished buildings). The recalculated internal heat gain was used to replace the initial 2.1 W/m^2 during the summer.
- The additional natural ventilation using the windows (schedule) was changed to the ‘calculated’ option in DesignBuilder and data from the window monitoring was inputted to the individual windows reflecting the actual usage. The duration and percentage of window opening was created using the tilt window opening and the angle, as well as a higher percentage of openings for patio doors, reflecting the actual operation.
- The shading was updated using the data from the finished buildings and further amendments implemented by the occupant were taken into consideration.

The missing data from non-monitored windows and windows with data loss, was estimated based on the other monitored windows and information obtained from occupants. For more detail and information refer to section 4.2.2.

3.6. WEATHER DATA

3.6.1. Current weather data:

Passivhaus Planning Package (PHPP) uses regional weather data for the UK divided into 22 areas as indicated from the image below. The weather data for each area has been generated by the BRE using the Meteonorm weather generation program.

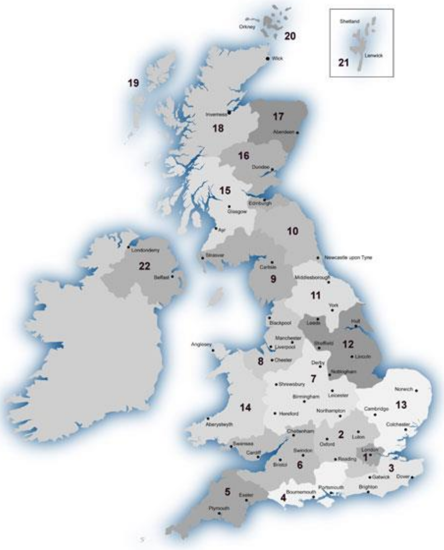
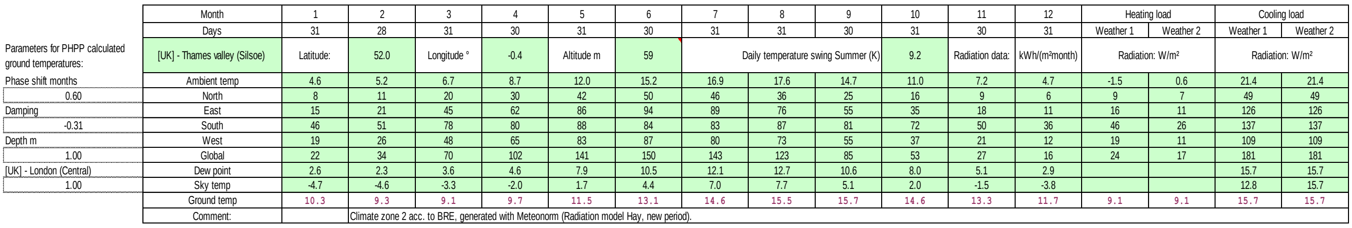


Figure 3-67 – Image map indicating the different climate areas used in PHPP for the UK (source:(BRE Group, 2011)**)**

Meteonorm allows the user to export different weather data for almost any location in the world by accessing 8325 weather stations and five geostationary satellites capable of covering the globe. The weather data can be exported in various formats including Excel (csv) which was used in PHPP or EnergyPlus (epw) for dynamic simulation analysis. When exporting the data to be used in dynamic simulation, the program allows the user to export directly into the required format i.e. EnergyPlus format which is the format used in DesignBuilder (Meteonorm, n.d.).

Although PHPP7 was used for the two reference buildings during the design stage as well as for certification purposes, recalculation was done using the newest version of PHPP available at the time (PHPP8) which had improved internal gain calculations and therefore more accurate overheating estimation during the summer.

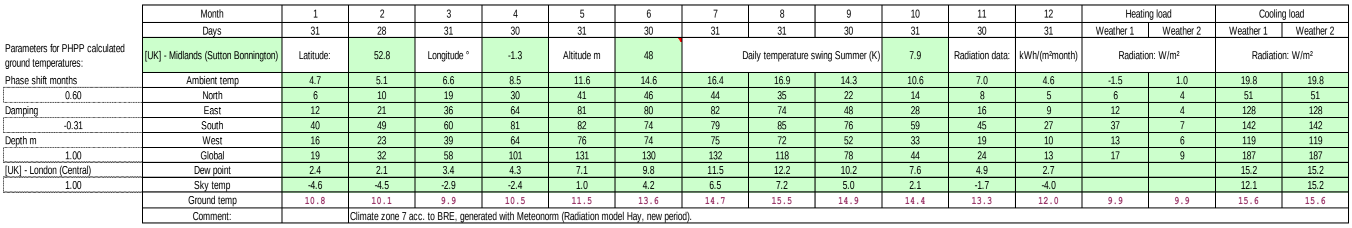
The weather data used for PHPP8, same as the previous version, uses the data generated by the BRE from Meteonorm. The weather data used for Building One (Passivhaus) as indicated previously, is the Thames Valley region (area 2) (Figure 3-67). The weather data for area 2 has been generated from the Silsoe weather station and below is the extract from PHPP8 indicating the weather data which is almost identical to the data used in PHPP7.



	Month	1	2	3	4	5	6	7	8	9	10	11	12	Heating load		Cooling load	
	Days	31	28	31	30	31	30	31	31	30	31	30	31	Weather 1	Weather 2	Weather 1	Weather 2
Parameters for PHPP calculated ground temperatures:	[UK] - Thames valley (Silsoe)	Latitude:	52.0	Longitude °	-0.4	Altitude m	59	Daily temperature swing Summer (K)			9.2	Radiation data:	kWh/(m^2month)	Radiation: W/m^2		Radiation: W/m^2	
Phase shift months	Ambient temp	4.6	5.2	6.7	8.7	12.0	15.2	16.9	17.6	14.7	11.0	7.2	4.7	-1.5	0.6	21.4	21.4
0.60	North	8	11	20	30	42	50	46	36	25	16	9	6	9	7	49	49
Damping	East	15	21	45	62	86	94	89	76	55	35	18	11	16	11	126	126
-0.31	South	46	51	78	80	88	84	83	87	81	72	50	36	46	26	137	137
Depth m	West	19	26	48	65	83	87	80	73	55	37	21	12	19	11	109	109
1.00	Global	22	34	70	102	141	150	143	123	85	53	27	16	24	17	181	181
[UK] - London (Central)	Dew point	2.6	2.3	3.6	4.6	7.9	10.5	12.1	12.7	10.6	8.0	5.1	2.9			15.7	15.7
1.00	Sky temp	-4.7	-4.6	-3.3	-2.0	1.7	4.4	7.0	7.7	5.1	2.0	-1.5	-3.8			12.8	15.7
	Ground temp	10.3	9.3	9.1	9.7	11.5	13.1	14.6	15.5	15.7	14.6	13.3	11.7	9.1	9.1	15.7	15.7
	Comment:		Climate zone 2 acc. to BRE, generated with Meteonorm (Radiation model Hay, new period).														

Figure 3-68- Weather data used in PHPP8 for Building One

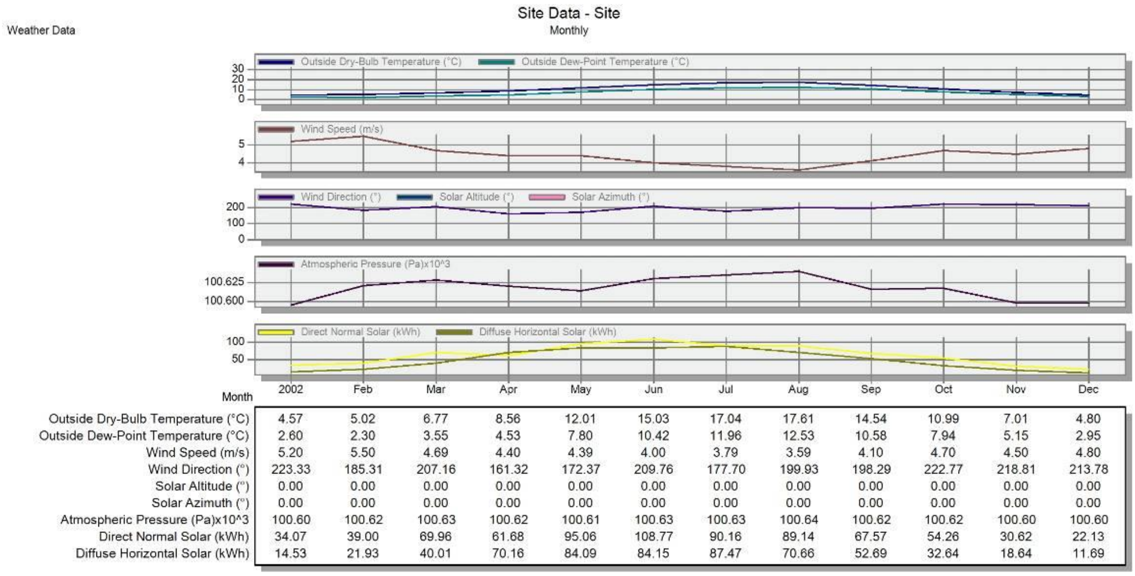
For Building Two (EnerPhit), area 7 (Figure 3-67) has been used which uses the weather data generated from the Sutton Bonnington station. Below is the extract from PHPP8 indicating the weather data which also is almost identical to PHPP7 with a slightly higher solar radiation on the different surfaces.



	Month	1	2	3	4	5	6	7	8	9	10	11	12	Heating load		Cooling load	
	Days	31	28	31	30	31	30	31	31	30	31	30	31	Weather 1	Weather 2	Weather 1	Weather 2
Parameters for PHPP calculated ground temperatures:	[UK] - Midlands (Sutton Bonnington)	Latitude:	52.8	Longitude °	-1.3	Altitude m	48	Daily temperature swing Summer (K)			7.9	Radiation data:	kWh/(m^2month)	Radiation: W/m^2		Radiation: W/m^2	
Phase shift months	Ambient temp	4.7	5.1	6.6	8.5	11.6	14.6	16.4	16.9	14.3	10.6	7.0	4.6	-1.5	1.0	19.8	19.8
0.60	North	6	10	19	30	41	46	44	35	22	14	8	5	6	4	51	51
Damping	East	12	21	36	64	81	80	82	74	48	28	16	9	12	4	128	128
-0.31	South	40	49	60	81	82	74	79	85	76	59	45	27	37	7	142	142
Depth m	West	16	23	39	64	76	74	75	72	52	33	19	10	13	6	119	119
1.00	Global	19	32	58	101	131	130	132	118	78	44	24	13	17	9	187	187
[UK] - London (Central)	Dew point	2.4	2.1	3.4	4.3	7.1	9.8	11.5	12.2	10.2	7.6	4.9	2.7			15.2	15.2
1.00	Sky temp	-4.6	-4.5	-2.9	-2.4	1.0	4.2	6.5	7.2	5.0	2.1	-1.7	-4.0			12.1	15.2
	Ground temp	10.8	10.1	9.9	10.5	11.5	13.6	14.7	15.5	14.9	14.4	13.3	12.0	9.9	9.9	15.6	15.6
	Comment:		Climate zone 7 acc. to BRE, generated with Meteonorm (Radiation model Hay, new period).														

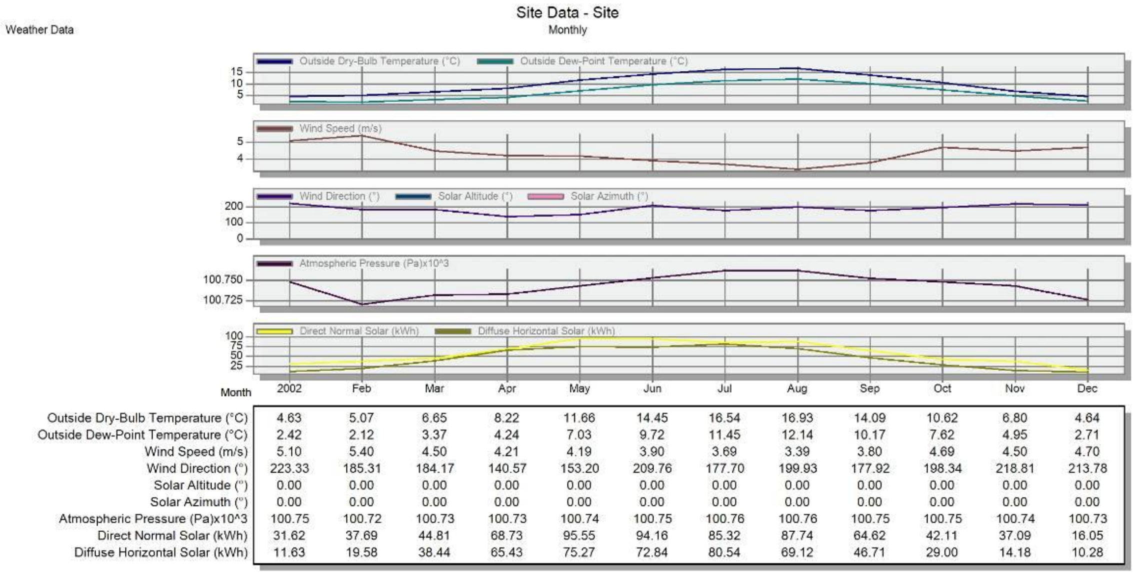
Figure 3-69- Weather data used in PHPP8 for Building Two

In order to ensure the use of the same weather data for carrying out the dynamic thermal modelling calculation, Meteonorm was used to regenerate the weather data for the two stations (Silsoe & Sutton Bonnington) and exported in the EnergyPlus format to be used in DesignBuilder for the first model. This would allow direct comparison between PHPP calculation values and the dynamic model calculations. Moreover DesignBuilder uses hourly weather data to carry out the dynamic calculations, whereas PHPP uses a monthly method. Nevertheless below is the extract of the weather data for the two buildings using the monthly values for comparison purposes from DesignBuilder.



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outside Dry-Bulb Temperature (°C)	4.57	5.02	6.77	8.56	12.01	15.03	17.04	17.61	14.54	10.99	7.01	4.80
Outside Dew-Point Temperature (°C)	2.60	2.30	3.55	4.53	7.80	10.42	11.96	12.53	10.58	7.94	5.15	2.95
Wind Speed (m/s)	5.20	5.50	4.69	4.40	4.39	4.00	3.79	3.59	4.10	4.70	4.50	4.80
Wind Direction (°)	223.33	185.31	207.16	161.32	172.37	209.76	177.70	199.93	198.29	222.77	218.81	213.78
Solar Altitude (°)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar Azimuth (°)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric Pressure (Pa)x10^3	100.60	100.62	100.63	100.62	100.61	100.63	100.63	100.64	100.62	100.62	100.60	100.60
Direct Normal Solar (kWh)	34.07	39.00	69.96	61.68	95.06	108.77	90.16	89.14	67.57	54.26	30.62	22.13
Diffuse Horizontal Solar (kWh)	14.53	21.93	40.01	70.16	84.09	84.15	87.47	70.66	52.69	32.64	18.64	11.69

Figure 3-70- Monthly weather data extracted from DesignBuilder for Building One



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outside Dry-Bulb Temperature (°C)	4.63	5.07	6.65	8.22	11.66	14.45	16.54	16.93	14.09	10.62	6.80	4.64
Outside Dew-Point Temperature (°C)	2.42	2.12	3.37	4.24	7.03	9.72	11.45	12.14	10.17	7.62	4.95	2.71
Wind Speed (m/s)	5.10	5.40	4.50	4.21	4.19	3.90	3.69	3.39	3.80	4.69	4.50	4.70
Wind Direction (°)	223.33	185.31	184.17	140.57	153.20	209.76	177.70	199.93	177.92	198.34	218.81	213.78
Solar Altitude (°)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar Azimuth (°)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Atmospheric Pressure (Pa)x10^3	100.75	100.72	100.73	100.73	100.74	100.75	100.76	100.76	100.75	100.75	100.74	100.73
Direct Normal Solar (kWh)	31.62	37.69	44.81	68.73	95.55	94.16	85.32	87.74	64.62	42.11	37.09	16.05
Diffuse Horizontal Solar (kWh)	11.63	19.58	38.44	65.43	75.27	72.84	80.54	69.12	46.71	29.00	14.18	10.28

Figure 3-71- Monthly weather data extracted from DesignBuilder for Building Two

The weather data comparison from PHPP and DesignBuilder as expected are almost the same with small (decimal point) differences in some months for instance when comparing the monthly average temperature. The tables below are the direct comparison for monthly average temperatures from PHPP and DesignBuilder for the two locations.

Table 3-2- Monthly average temperature comparing PHPP values to DesignBuilder in °C for Silsoe (Building One)

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PHPP	4.6	5.2	6.7	8.7	12.0	15.2	16.9	17.6	14.7	11.0	7.2	4.7
DesignBuilder	4.57	5.02	6.77	8.56	12.01	15.03	17.04	17.61	14.54	10.99	7.01	4.80

Table 3-3- Monthly average temperature comparing PHPP values to DesignBuilder in °C for Sutton Bonnington (Building Two)

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PHPP	4.7	5.1	6.6	8.5	11.6	14.6	16.4	16.9	14.3	10.6	7.0	4.6
DesignBuilder	4.63	5.07	6.65	8.22	11.66	14.45	16.54	16.93	14.09	10.62	6.8	4.64

It is important to highlight that the two locations used from Meteonorm in PHPP (Silsoe & Sutton Bonnington) were very close to the actual locations of the two buildings which makes the weather data reliable for these sites. However if the buildings were located further away from the stations, as PHPP uses large regional weather data, the accuracy of the data would have been reduced.

The Meteonorm weather data used is for the recent period from 1991 till 2010 which is averaged out to create a representative data (Meteonorm, n.d.). In order to obtain the actual data for the duration of the monitoring period and make comparison to data used from Meteonorm, two locations near the sites were identified from the British Atmospheric Data Centre (BADC). The nearest location to building one is Woburn (station ID 458) which is very close to Silsoe and the closest station to building two currently recording is the same station used in PHPP, Sutton Bonnington (station ID 554).

Below is the average monthly weather data for a period of one year from October 2013 to the end of September 2014 in comparison to the previous monthly temperatures used in PHPP and DesignBuilder for building one.

Table 3-4- Monthly average temperature comparing PHPP values and DesignBuilder to the data for one year of 2013-2014 from BADC in °C for Silsoe (Building One) & Woburn (station ID 458)

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PHPP	4.6	5.2	6.7	8.7	12.0	15.2	16.9	17.6	14.7	11.0	7.2	4.7
DesignBuilder	4.57	5.02	6.77	8.56	12.01	15.03	17.04	17.61	14.54	10.99	7.01	4.80
BADC	5.88	6.37	7.49	9.99	12.08	15.20	18.21	15.48	14.90	12.46	6.37	6.54

The monthly average temperatures from BADC for 2013-14, which was the period used for the monitoring of the building, is highly comparable to the data used in PHPP and DesignBuilder, especially for the five months of May to the end of September when the monitoring had taken place. The three months of May, June and September are almost identical leaving July slightly warmer and August slightly cooler.

The table below demonstrates the monthly average temperature recorded from BADC for building two during October 2013 until the end of September 2014 in relation to data from PHPP and DesignBuilder.

Table 3-5- Monthly average temperature comparing PHPP values and DesignBuilder to the data for one year of 2013-2014 from BADC in °C Sutton Bonnington (Building Two) (station ID 554)

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PHPP	4.7	5.1	6.6	8.5	11.6	14.6	16.4	16.9	14.3	10.6	7.0	4.6
DesignBuilder	4.63	5.07	6.65	8.22	11.66	14.45	16.54	16.93	14.09	10.62	6.8	4.64
BADC	5.78	6.42	7.5	10.1	12.35	15.31	17.93	15.23	14.77	12.5	6.50	6.66

For the five months of May till the end of September, the monthly temperature from BADC was recorded to be close to the data from PHPP and DesignBuilder with the exception of July and August. July was recorded to be warmer while August was cooler.

The above tables are a demonstration of the close relation between the data from Meteonorm and the actual data obtained from BADC. Furthermore the solar radiation from BADC is not available for the two sites or any close station during 2014 to allow comparison or generation of weather data to be used for the dynamic modelling. The research aim is to provide a possible natural ventilation system which can be used during the design stage and applied to other buildings and occupants and therefore the decision was made to use the climate data from Meteonorm.

3.6.2. Future weather data:

The climate data used in PHPP has been obtained from the Meteonorm program as previously stated. Since PHPP is the tool used by Passivhaus designers and consultants to achieve Passivhaus standard (and importantly the requirements for the summer overheating), therefore, the future climate data from the Meteonorm could be used for designing for future climate.

Meteonorm uses the average of the 18 future climate models from the IPCC report 2007 to create three future climate data scenarios of B1 (low), A1B (mid) and A2 (high) for different periods until 2100 (Meteonorm, n.d.).

Currently there is no requirement for carrying out any future climate design as part of the Building Regulations or Passivhaus standard and no particular future scenario is recommended; or any specific ways to reduce the number of possible scenarios for the design purposes. However, the scenarios can be narrowed down depending on the risk for the buildings and the client (Hacker et al., 2009). Perhaps some of the amendments and adaptations for buildings could take effect in different stages in the future (i.e. 2020, 2050 and 2080) to reduce the impact and optimise the effectiveness of the recommendation specifically for existing buildings (Gething & Puckett, 2013).

In order to narrow down the future climate scenarios and timescale for this research, the age of the buildings has been taken into account and as they probably would still be around beyond 2050, the timescale of 2050 has therefore been chosen. Moreover the different scenarios for 2050 can be reduced to one by the use of ‘pattern scaling factor’ and by using the high scenario in 2050, it would not only cover all the projections up to itself but also cover the low and medium low of 2080 (UKCP02) as can be seen from the Figure 3-72.

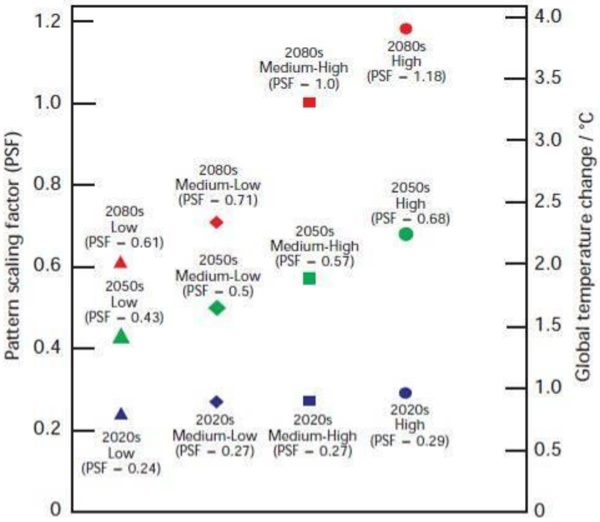


Figure 3-72- Pattern scaling factor for different scenarios from UKCP02 (Source: (Hacker et al., 2009) **P15)**

Moreover the high scenario of 2080 was also taken into consideration to examine the worse scenario of climate change and its impact on the reference buildings to evaluate the feasibility of the proposed natural ventilation strategies.

Below is the extract from Meteonorm future climate data for the two locations with respect to the proposed year and scenario, in comparison to the current data.

Table 3-6- Monthly average temperature comparing future data to the initial data in °C -Silsoe (Building One)

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PHPP	4.6	5.2	6.7	8.7	12.0	15.2	16.9	17.6	14.7	11.0	7.2	4.7
DesignBuilder	4.57	5.02	6.77	8.56	12.01	15.03	17.04	17.61	14.54	10.99	7.01	4.80
BADC	5.88	6.37	7.49	9.99	12.08	15.20	18.21	15.48	14.90	12.46	6.37	6.54
Future data 2050 – A2	5.81	5.73	7.23	9.24	12.46	15.22	17.53	17.74	15.75	12.78	8.58	7.04
Future data 2080 – A2	6.71	6.20	8.17	10.07	13.42	16.29	18.83	19.19	16.92	13.79	9.53	7.90

Table 3-7- Monthly average temperature comparing future data to the initial data in °C - Sutton Bonnington (Building Two)

Months	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
PHPP	4.7	5.1	6.6	8.5	11.6	14.6	16.4	16.9	14.3	10.6	7.0	4.6
DesignBuilder	4.63	5.07	6.65	8.22	11.66	14.45	16.54	16.93	14.09	10.62	6.8	4.64
BADC	5.78	6.42	7.5	10.1	12.35	15.31	17.93	15.23	14.77	12.5	6.50	6.66
Future data 2050 – A2	5.07	5.18	7.19	9.52	12.67	15.45	17.55	17.89	15.50	12.37	8.16	6.46
Future data 2080 – A2	5.86	5.60	8.13	10.34	13.63	16.51	18.84	19.35	16.68	13.39	9.11	7.32

As expected the future temperatures are warmer than the current data, however the average temperatures for July from BADC was recorded to be even warmer during 2014 than the data for 2050 (A2) for both locations.

3.7. THERMAL IMAGING

Thermal imaging cameras were first sold and used commercially during 1965 to inspect high voltage power lines and more recently the building industry has been benefiting from the valuable data and information that can be captured by thermal imaging cameras. The camera creates the image by converting the captured intensity of radiation in the infrared part of the electromagnetic spectrum (FLIR, 2014).

In cold climates thermal imaging cameras can help to detect heat loss during the winter and consequently energy loss from buildings, for instance by detecting missing insulation. However in warmer climates, thermal imaging cameras are used during the summer months to check the insulation for keeping the cool air inside the building (FLIR, 2014).

A thermal imaging camera was used during the summer to capture the surface temperature surrounding the fresh air intake of the MVHR during the hottest time of the day and repeat this several times throughout the day until night time to examine the effect of material used adjacent to the fresh air intake and its thermal mass. This was done on a non-rainy and still day as the water and wind on the surface can influence the temperature and the reading from the camera. Moreover the emissivity of the material was used to optimise the result.

3.8. INTERNAL GAIN & OVERHEATING CALCULATIONS

3.8.1. Internal gain

Carrying out the literature review had highlighted the importance of the internal gains during the summer and the possible contribution to overheating associated with it. PHPP7 takes a conservative approach and uses a standard value of 2.1 W/m^2 for the internal heat gain calculation for the entire year. Furthermore the higher density in the UK alongside extra heat gains from the domestic hot water storage and distribution, a smaller heat sink during the summer as well as the heat gain associated from the use of the MVHR during the cooling season, emphasises the importance of carrying out calculations for the internal heat gains on the two case study buildings.

The two case study buildings had used PHPP7 during the design stage and the certification, using the standard value of 2.1 W/m^2, therefore it was necessary to carry out a more representative internal heat gain calculation. One method considered was to calculate the use of all the appliances and lighting by means of electricity usage and frequency of use similar to the process used for Camden Passivhaus. This method would require monitoring electricity used for every appliance in the building to be able to calculate the associated heat generated divided to the treated floor area. Although this approach would have provided a fair representation of the internal gains for the summer, it would have been limited to the current occupant behaviour and lifestyle.

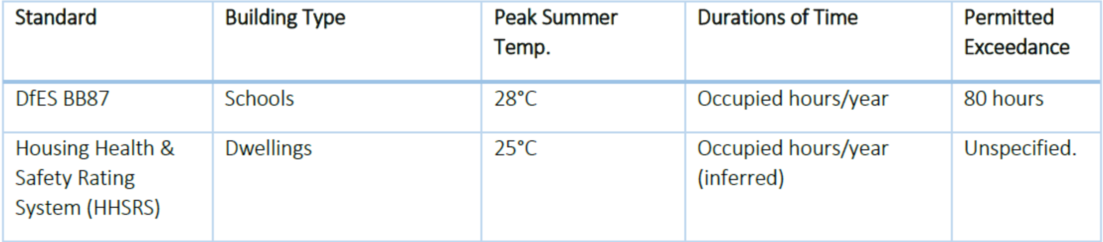
Passivhaus institute have since released their latest version of PHPP (PHPP8) which recognised the concern for the higher internal heat gains during the summer and therefore the associated overheating risk caused from it. The PHPP8 has been amended to differentiate the internal heat gains during the winter and the summer, therefore the standard value of 2.1 W/m^2 is increased during the cooling season from the internal heat gain (IHG) sheet taking the extra heat gain from the domestic hot water storage and distribution as well as the gains from the MVHR system, if it is placed inside the thermal envelope, into consideration (Passive House Institute, 2013).

Therefore a decision was made to use PHPP8 to carry out the internal heat gain calculation for the two case study buildings during the summer time which also reflects a more realistic appliance schedule for the completed two buildings. The results were comparable to the examples from the literature review section on the internal gains which gave confidence in using the value for further analysis.

3.8.2. Overheating calculation & Effective window opening

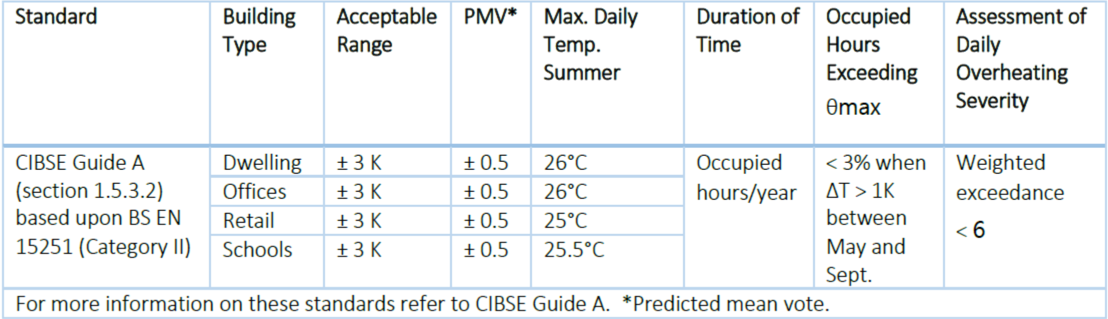
Although there is currently no specific standard and limit for overheating or set temperature in the UK, however there are several different guidance and standards worldwide and within the UK for dwellings and non-domestic buildings (Passivhaus Trust, 2016). The tables below are some of the standards for the UK.

Table 3-8- DfES and HHSRS overheating standards (Passivhaus Trust, 2016) Page 4



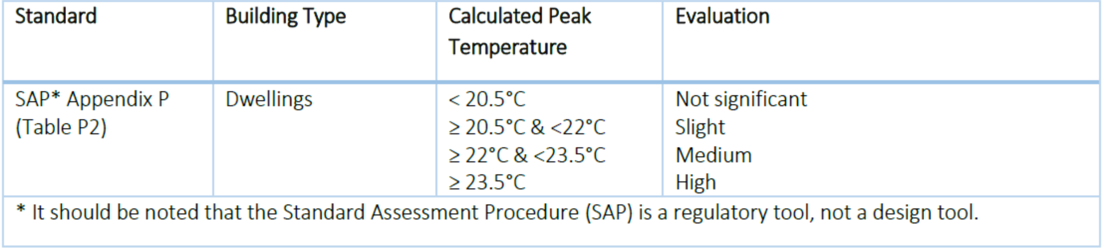
Standard	Building Type	Peak Summer Temp.	Durations of Time	Permitted Exceedance
DfES BB87	Schools	28°C	Occupied hours/year	80 hours
Housing Health & Safety Rating System (HHSRS)	Dwellings	25°C	Occupied hours/year (inferred)	Unspecified.

Table 3-9- CIBSE overheating standards (Passivhaus Trust, 2016) Page 4



Standard	Building Type	Acceptable Range	PMV*	Max. Daily Temp. Summer	Duration of Time	Occupied Hours Exceeding θmax	Assessment of Daily Overheating Severity
CIBSE Guide A (section 1.5.3.2) based upon BS EN 15251 (Category II)	Dwelling	± 3 K	± 0.5	26°C	Occupied hours/year	< 3% when ΔT > 1K between May and Sept.	Weighted exceedance < 6
	Offices	± 3 K	± 0.5	26°C			
	Retail	± 3 K	± 0.5	25°C			
	Schools	± 3 K	± 0.5	25.5°C			
For more information on these standards refer to CIBSE Guide A. *Predicted mean vote.							

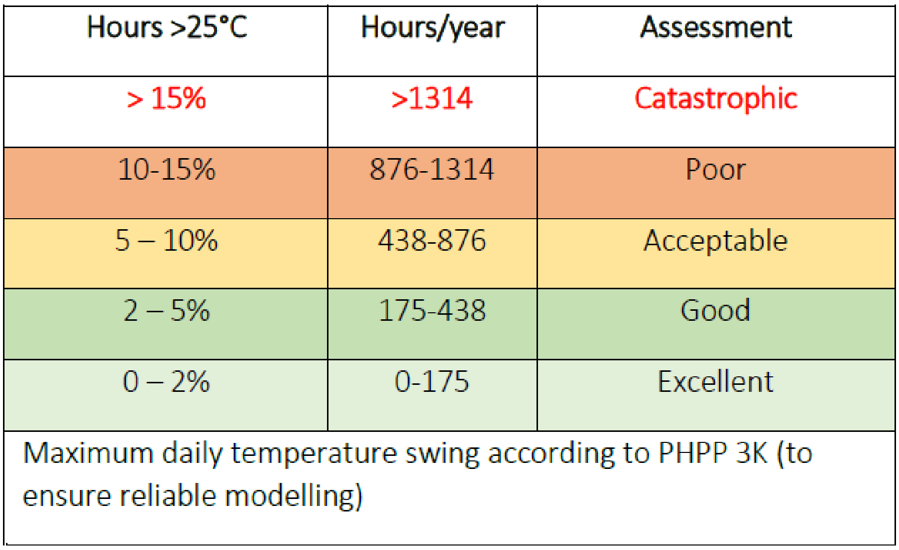
Table 3-10- SAP overheating standards (Passivhaus Trust, 2016) Page 4



Standard	Building Type	Calculated Peak Temperature	Evaluation
SAP* Appendix P (Table P2)	Dwellings	< 20.5°C ≥ 20.5°C & <22°C ≥ 22°C & <23.5°C ≥ 23.5°C	Not significant Slight Medium High

* It should be noted that the Standard Assessment Procedure (SAP) is a regulatory tool, not a design tool.

However Passivhaus require a specific method and limit for their standard which is also used for certification purposes using the PHPP calculation tool. The limit is set to 25°C and with 10% allowance to be over the 25°C for the total hours of the year (10% overheating over 25°C will be 876 hours a year) (Passivhaus Trust, 2016). Furthermore taking the changing climate into consideration, the good practice limit has been suggested to be 5% and perhaps during the design stage this aim should be towards 0% over the 25°C limit (Morgan et al., 2017). The image below is the scale recommended by the standard for the Passivhaus designers.



Hours >25°C	Hours/year	Assessment
> 15%	>1314	Catastrophic
10-15%	876-1314	Poor
5 – 10%	438-876	Acceptable
2 – 5%	175-438	Good
0 – 2%	0-175	Excellent

Maximum daily temperature swing according to PHPP 3K (to ensure reliable modelling)

Figure 3-73- Summer comfort scale for Passivhaus buildings (source: (Passivhaus Trust, 2016) P.5)

Passivhaus has a very specific and defined overheating criteria and limit which is for the total hours of the year rather than the occupied hours (Passivhaus Trust, 2016). Furthermore the 25°C temperature is a recognised threshold for health identified in the UK government's Housing Health and Safety Rating System. Perhaps the use of TM52 (CIBSE) standard (using adaptive comfort) is currently limited as it is more focused on non-domestic buildings (Morgan et al., 2017) and there are limitations in its usage, specifically for bedroom and sleeping conditions (Lomas & Porritt, 2017).

Therefore the Passivhaus overheating calculation method has been used for this research which also is the requirement for the Passivhaus certification. The overheating percentage was calculated using the hourly data and the percentage of hours over the 25°C was calculated for the whole year. Therefore the data is presented using percentage for the individual spaces and the average for the entire building as per Passivhaus requirement.

The effective window opening:

The effective window opening was calculated using the tilt window option as it was used the most by the occupiers of the two buildings. The total area of every openable window was measured using the CAD drawings. The windows are 85mm inward opening and therefore a triangle was drawn to measure the effective operable area of the window using tilt (see image). The total was the sum of the two triangles (either side) plus the area of the rectangle above which is the 85mm times the window length.

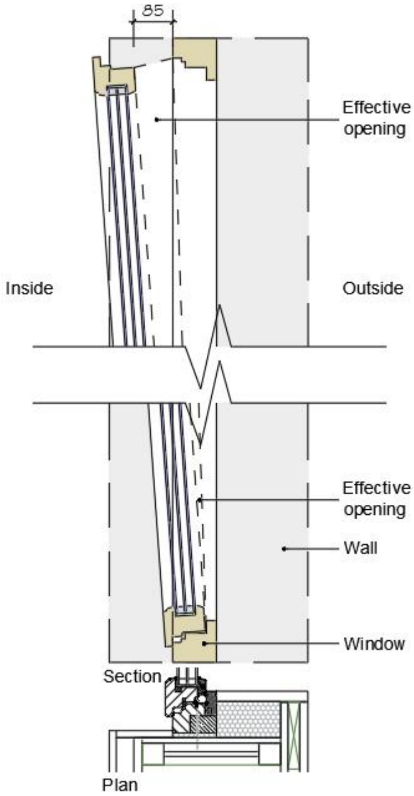


Figure 3-74 – Effective openable window area calculation using tilt option

3.9. PSI-VALUE CALCULATION

Thermal bridging can happen at any junction or building elements when more than one element or material is used. Thermal bridging can result in additional heat loss and contribute to lower surface temperature causing discomfort, condensation and consequently mould growth. Thermal bridging can be divided into two categories: repeating, which is calculated as part of the U-Value, and non-repeating, which needs additional calculation. The non-repeating thermal bridging can be at one point or linear. The linear thermal bridging is called Psi and is the total heat loss through a specific detail or junction. Passivhaus classes any Psi-Value below 0.01W/(mK) as thermal bridge free and not required to be part of the calculation (Lewis, 2014).

The Psi-Value can be calculated using the formula below:

$$\Psi * L = L2D - U * A$$

Where L2D is the total heat loss from a junction
U is the U-value
A is the area
Ψ is the thermal bridging
L is the length

Equation 3-3 – Psi value equation

The additional heat loss at different junctions due to thermal bridging can be higher in buildings with advanced fabric efficiency. Furthermore there has been development for simple calculation techniques, however almost all non-repeating thermal bridging would require calculation of heat flow either in two or three dimensions (Ward & Sanders, 2007).

There are a several different programmes available for carrying out thermal bridging calculation such as Passitherm, PSI Therm and Therm allowing for 2D and 3D Psi-Value calculations.

Therm is a heat transfer program developed at Lawrence Berkeley National Laboratory which is available free to use (Berkeley Lab, 2015). Therm is one of the main tools used for undertaking Psi-Value calculations in the UK offering simplicity and yet accurate results.

Thermal bridging calculation therefore was undertaken in order to ensure the proposed natural ventilation system would not have a negative impact on the winter performance of the building. The CAD drawings were used as the underlay in Therm and heat flow calculation was carried out using the standard boundary condition of 0°C and 20°C externally and internally. Additional required material was created in Therm by inputting the thermal conductivity of each material and the surface resistance values were designated using the standard values from the table below.

Table 3-11- Standard values for surface resistance (Source: (Passive House Institute, 2007) **P.55)**

Direction of Heat Flow			
	Upward	Horizontal	Downward
R_{si} [m^2K/W] Thermal Resistance of the Interior Surface	0.10	0.13	0.17
R_{se} [m^2K/W] Thermal Resistance of the Exterior Surface	0.04		
R_{se} [m^2K/W] Thermal Resistance of the Below Ground Exterior Surface	0		

The wall was created in Therm for 1m in length allowing for the U-Value calculation. The proposed low level vent was modelled separately and then combined with the wall in a third model. Similarly, the roof and the windcatcher were drawn as separate models as well as the combination of the two. Finally, the report from Therm was exported to Excel for each element and the combination model to calculate the Psi-Value for the windcatcher and the low level vent.

CHAPTER 4. CASE STUDY BUILDINGS

4.1. INTRODUCTION

In this chapter the monitoring results for the indoor temperatures, relative humidity, indoor CO_2 levels and window operation for different areas of the case study buildings are evaluated as indicated in the methodology section (Section 3.3.1). The ambient temperature using the data obtained from BADC is likewise investigated allowing comparison to the indoor temperatures. This chapter will also compare the monitoring results to the original PHPP model for better understanding of performance gap during the summer period. The impact and importance of climate on overheating is analysed by the use of the PHPP model. This chapter also examines the effect of the material used around the MVHR air intake, lack of insulation on the internal MVHR air ducts and MVHR summer by pass option, on indoor air temperature and overheating. The chapter is concluded by the calculation of the internal heat gain using PHPP8.

4.2. PHYSICAL MONITORING DATA AND RESULTS

4.2.1. Ambient Temperature

The ambient temperatures from the monitoring period have been examined due to the direct relation and influence on the indoor temperatures for the two locations. The external temperatures have been below 25°C for the majority of the time except some days in July when the temperature peaked at 29.5°C and 28.9°C for the two locations respectively. The night time temperatures have generally been cool reaching as low as 6°C even during the warmest part of the year. The graphs for the hourly temperature data for can be found in Appendix C and D.

The monthly mean temperature has also been examined alongside the maximum and minimum temperature from May to September. The monthly mean temperature was calculated to be between 12°C and 12.3°C in May to 18.2°C and 17.9°C in July for Building One and Two (Figure 4-1 & 4-2).

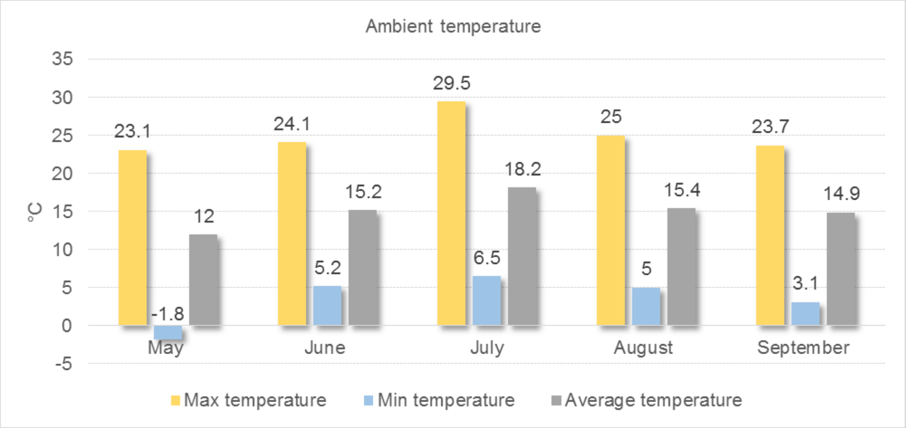


Figure 4-1- Max, Min and Mean monthly ambient temperature – Building One

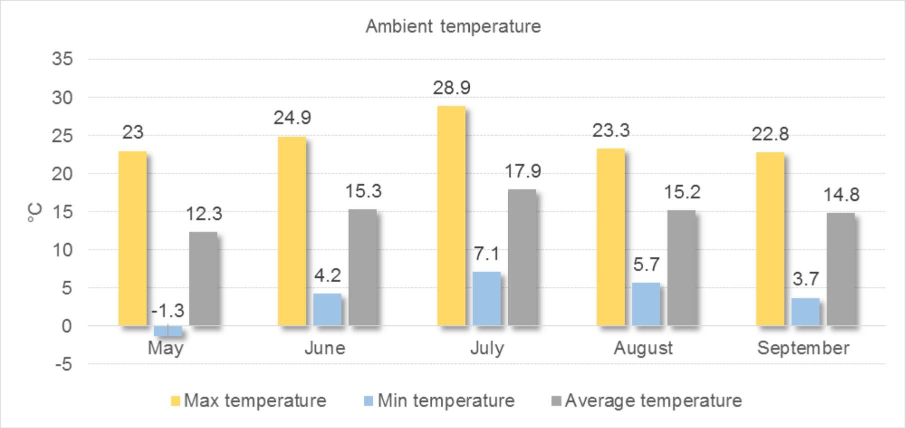


Figure 4-2 - Min and Mean monthly ambient temperature – Building Two

4.2.2. Monitoring Results

Temperature, relative humidity (RH), indoor CO_2 levels and window operations were measured in different spaces as identified in the methodology section for the two case study buildings and the following is the results and analysis for the three months of the summer of 2014. The data for May and September can be found in Appendix C and D. The aim has been to investigate the two buildings' performance, in order to increase the confidence in the dynamic thermal model.

The indoor temperature and RH have been examined in respect to the ambient temperature and window opening for June, July and August. It should be noted that an accuracy margin of +/- 0.4°C should be taken into consideration for HOBO data loggers.

1 Dining room (Building One)

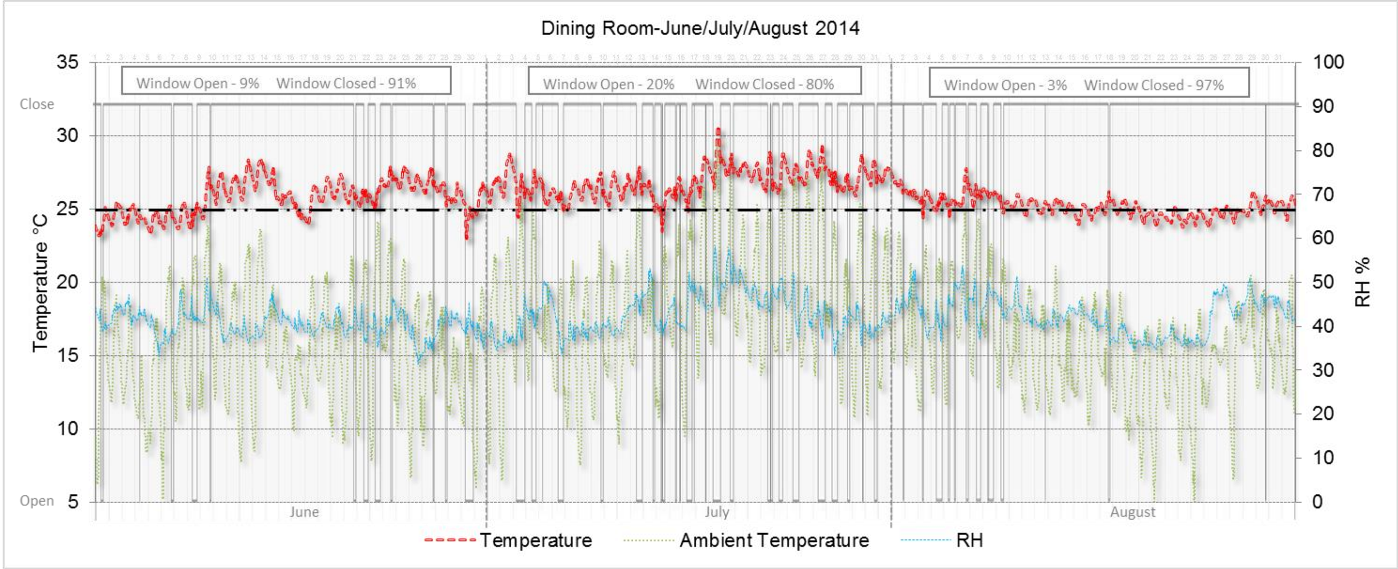


Figure 4-3 – Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

3 Dining room (Building Two) (D7)

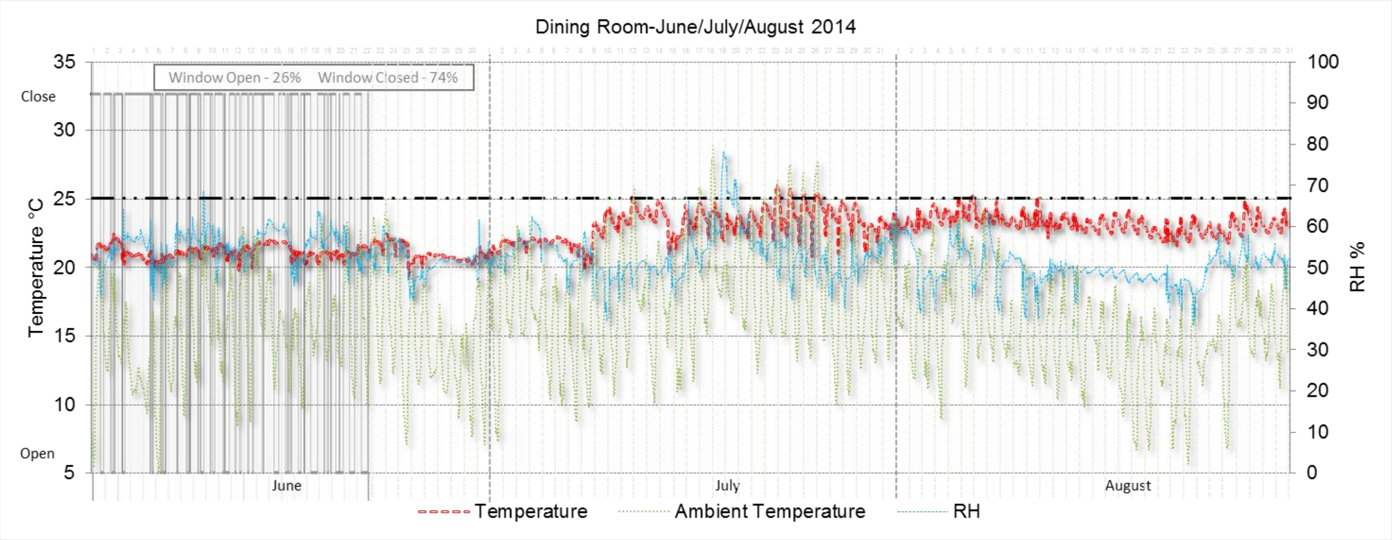


Figure 4-4- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

Building One is under occupied (3 people) and the mechanical ventilation (MVHR) is designed and commissioned for a higher occupancy rate (5 people) effecting the internal RH. The windows can be opened on tilt and turn or tilt and slide system, however the windows are mainly opened on tilt by the occupant. The tilt is 85mm inwards reducing the airflow and associated cooling.

During the monitoring period the RH in the dining room was recorded generally to be between 30% & 60% which although falls within the Passivhaus standard, it is arguably on the lower side especially during the cooler months. The ambient temperature during May and September never passed 25°C, however the dining room, despite the higher mechanical ventilation rate, was experiencing high temperatures during this period and was recorded to be over 25°C for 20.87% and 61.97% respectively suggesting ineffective ventilation and therefore cooling. During these months the natural ventilation through window operation was limited to 2% and 4%, contributing to higher temperatures and there was no window operation when the room had reached 27°C i.e. in the afternoon of the 17th May (between 3pm and 4pm) and 19th May (between 2:30pm and 5pm).

The dining room benefits from a large floor to ceiling window (just over 6m^2) facing towards the South, encouraging solar gain during the winter period. The window benefits from internal and external blinds (manually operated) which are used by the occupant, more due to privacy reasons rather than reduction of solar gain. Moreover the lower occupancy rate and therefore lower internal heat gain should contribute to lower temperatures in this building. However the dining room was overheated for 71.24% during June, when the window was opened for 9% of the time. The temperature passed 28°C during the 12th (2:30pm till 7pm) and 13th (12pm till 9pm) when the ambient temperature was between 21°C and 23°C, indicating lower effectiveness of the natural ventilation rate and associated cooling.

The percentage of window opening during July was higher at 20% when the internal temperatures were recorded to be over the 25°C limit for the majority of the time (97.92%) and passed 30°C. Moreover the indoor temperature was over 30°C between 3:30pm and 7:30pm on the 18th when the outside temperature was between 29.5°C and 26°C. The window was left open during the whole day on the 18th from 7:40am until 9:46pm which highlighted that the occupants opened the window regardless of the outside temperature and closed the window during the cooler period at night.

During August the window was opened for a total of only 7% when the space was overheated for 60% of the time. The temperature was over 27°C between 2:45pm and 7:30pm on the 6th August when the ambient temperature was recorded between 16°C and 18.5°C during the same hours. The window was opened from 5:38pm until 9:05pm which did not help to reduce the temperature.

Overall the number of recordings of overheating in the dining room during the 5 months of monitoring, was 9160 which would translate to just over 62% of the time. This would equate to over 95 days that the space was recorded to be higher than the required limit. Assuming that the dining room would not be overheated during the rest of the year, the overheating percentage for the entire year can be calculated at just over 26%.

On the other hand, Building Two's dining room experienced a lower overall temperature and the RH was generally between 40% and 70% during the monitoring period. The building occupation (4 people) is closer to the designed and the commissioned MVHR rate of 5 people, contributing to higher RH. Furthermore the windows in this building are similar to Building One in operation with an inwards tilt of 85mm, however the ground floor benefits from glazed patio doors which open fully rather than tilt. Consequently there was no overheating during May and September experienced 0.1% of overheating.

D7 is the main patio door and window from the dining room that gives access to the garden and it is used the most by the occupants to go the garden. During May the door was operated several times, however it was left open for 9% of the time. The patio door continued to be used frequently during June which consequently led to the logger running out of space on the 22nd of June. During June till the 22nd, the door was opened for 26% of the time and there was no overheating in this month. However during July the space was overheated 4.13% and somewhat (0.71%) during August despite the possible frequent use of the door.

The overall number of times that the temperatures were recorded to be above the 25°C limit was 147 which would translate to be 1.53 days. The percentage of overheating for the five months of monitoring was 1% which would be 0.41% of the year if there were no further recordings above the 25°C limit.

The dining room in Building One overheated much more when the same room in Building Two experienced much lower indoor temperatures during the summer months. The RH was in a similar range and perhaps on the lower side during the cooler period. The window operation was perhaps more in

Building Two and achieving a better rate of ventilation due to opening the patio door fully in comparison to the tilt opening in Building One.

2 Kitchen (Building One)

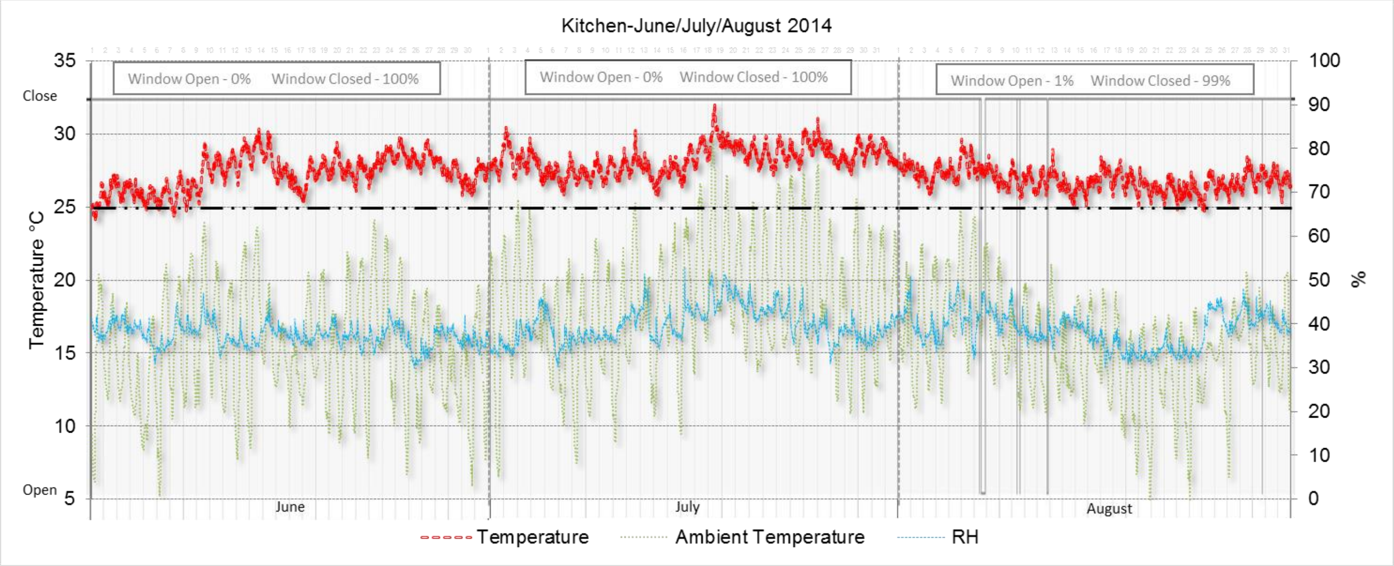


Figure 4-5- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

2 Kitchen (Building Two) (D4)

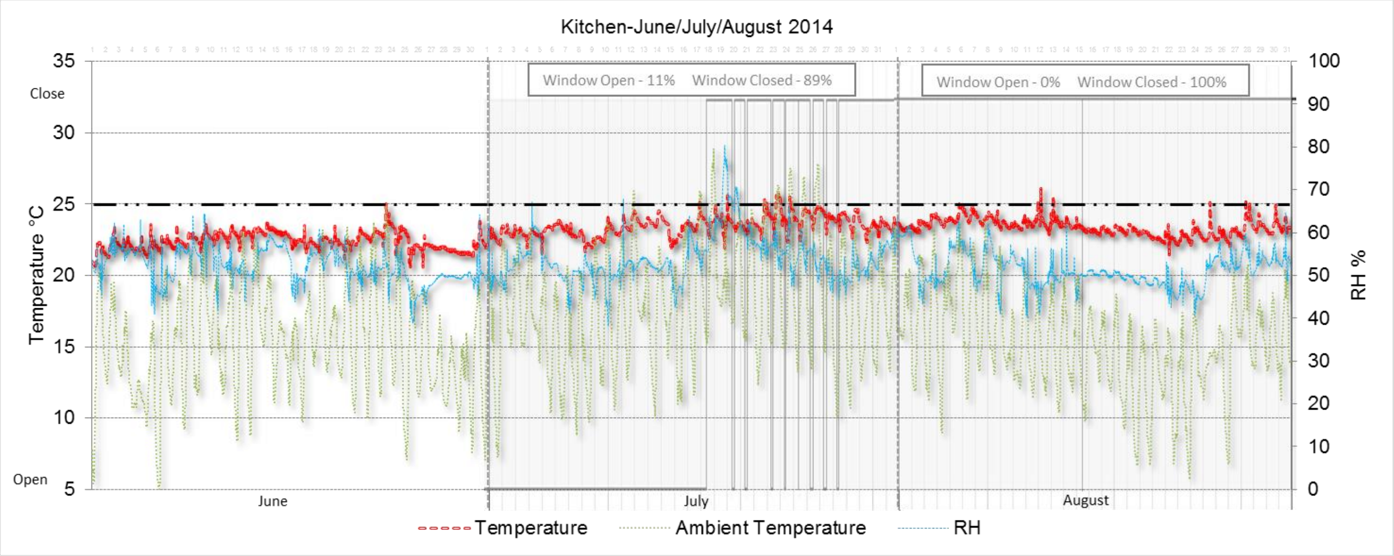


Figure 4-6- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

The lower RH was similar in the kitchen of Building One and was recorded to be between high 20s and 50% during the five months of monitoring period with lower percentage during the cooler months despite the nature of the usage of the space. The kitchen is relatively large in size and is open plan to the rest of the ground floor with smaller windows to the North and West. The floor area of the kitchen and the dining room is 28m^2 and the glazing area is 27% of the combined floor area. The total effective window opening is 0.5m^2 (tilt) which is 1.78% of the floor area. The internal and external gain contributed to over 66% of overheating during May with limited window operation. The highest temperature in the kitchen during May was recorded on the 19th (11:45am till 3:00pm) and reached over 29°C when the window was not opened for the whole day. The ambient temperature during the 19th was at a maximum of 23°C at 12 noon, indicating lower willingness of window opening and cooling by the occupant. Cross ventilation would have been encouraged if the window was opened more often increasing the rate of ventilation through the window usage.

The lack of window opening during June (none) contributed to higher percentage of overheating of 97.43% in the kitchen. The indoor temperature passed 29°C many times during this month and even went above 30°C between 8:00pm till 9:00pm on the 13th and 3:00pm till 4:00pm on the 14th. The ambient temperature was recorded to be 18.7°C and 19°C respectively which would have helped reducing the indoor temperatures if the occupant had chosen to open the window during this time.

The occupant continued to not open the window during July and August which led to overheating of 100% and 99.5% respectively. The highest temperatures in July were recorded on the 18th between 3:00pm and 8:15pm and went over 31°C when the outside temperature was between 29.5°C and 21.9°C. The kitchen was once again overheated during September for 99.76% of the time when the window was not opened at all during this month. The maximum ambient temperature reached 23.6°C during September which could have been beneficial in reducing the indoor temperature if the window was operated during this month. Moreover this window would have helped the cross ventilation from the dining room as also the window is a north facing window.

During the five months of monitoring, the kitchen was recorded to be over the 25°C limit 13588 times which would be 92.52% of the time. The 13588 would be equivalent to over 141 days of overheating during the five months. If the space was not overheated during the rest of the year, the percentage of overheating would be 38.77%.

Fluctuation in RH was more noticeable in Building Two’s kitchen perhaps due to the deep plan of the layout, lack of direct window to the space and the associated activity; and it was generally between 40% or just above 70% with some exceptions during July when it passed 80%. The closer occupancy level to the design of the MVHR ventilation rate keeps the RH at a higher percentage, especially during the winter in comparison to Building One.

The kitchen is open plan to the dining area with an additional sitting space similar to Building One benefiting from south facing windows. The window area is 28% of the floor area which is similar to Building one at 27%, however the space temperature recording indicated very low overheating percentage during June, July, August and September at 0.03%, 1.85%, 0.44% and 0.10%.

The kitchen in this building does not benefit from an immediate window, however the patio door in the dining room and the glazed side door (D4) also part of the dining room (sitting space) could help in providing additional ventilation for the kitchen. D4 is used occasionally according to the occupant and the recordings were interrupted from 24th of May until 17th of July and therefore have not been taken into account. During May till the 24th the door was operated for 6% of the time and the data was lost for June as the sensor was reading the door to be open for the entire month which therefore has been disregarded. The recordings resumed on the 17th of July and indicated 11% operation during this period. During August and September the door was not opened for almost the entire time.

The total number of times that the kitchen was recorded to be over the Passivhaus limit during the five months of monitoring was 72, which would be 0.49% of the time. The 0.49% would be just under one day if it was continuous (0.75 days). Assuming no further overheating would occur, the total amount of time that the space would be overheated for the whole year is 0.2%.

Comparing the two buildings' kitchen monitored data, it shows much lower indoor temperatures in Building Two with more effective overall additional natural ventilation through the use of windows and patio doors.

3 Living Room

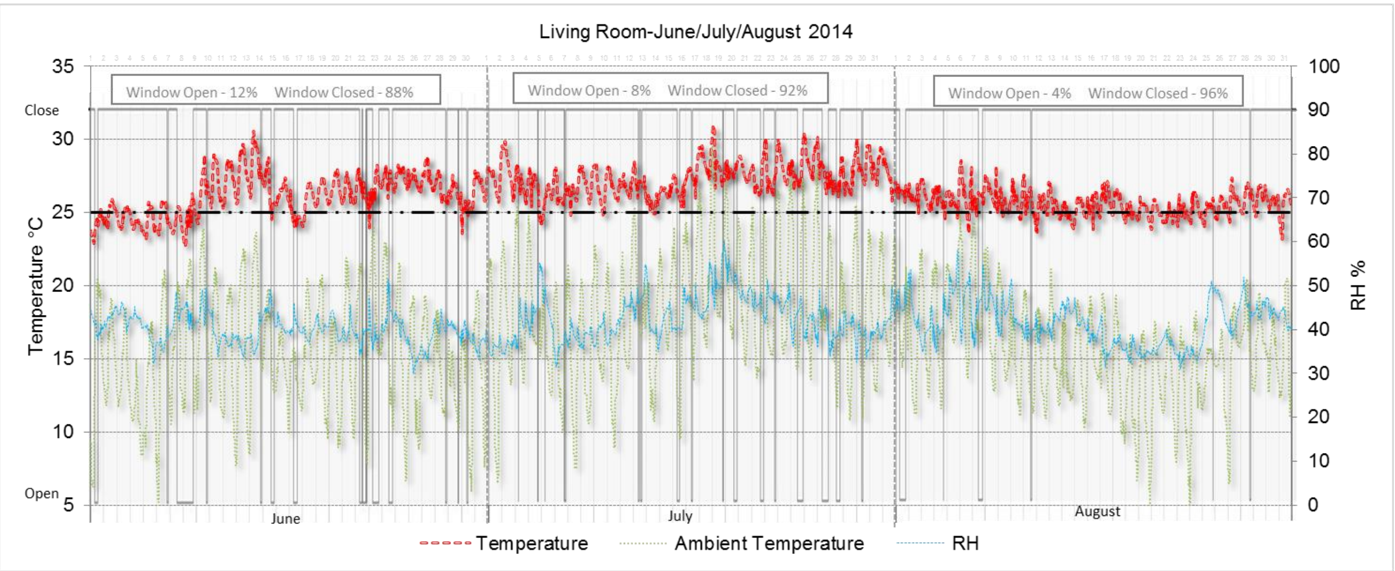


Figure 4-7- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

1 Sitting room

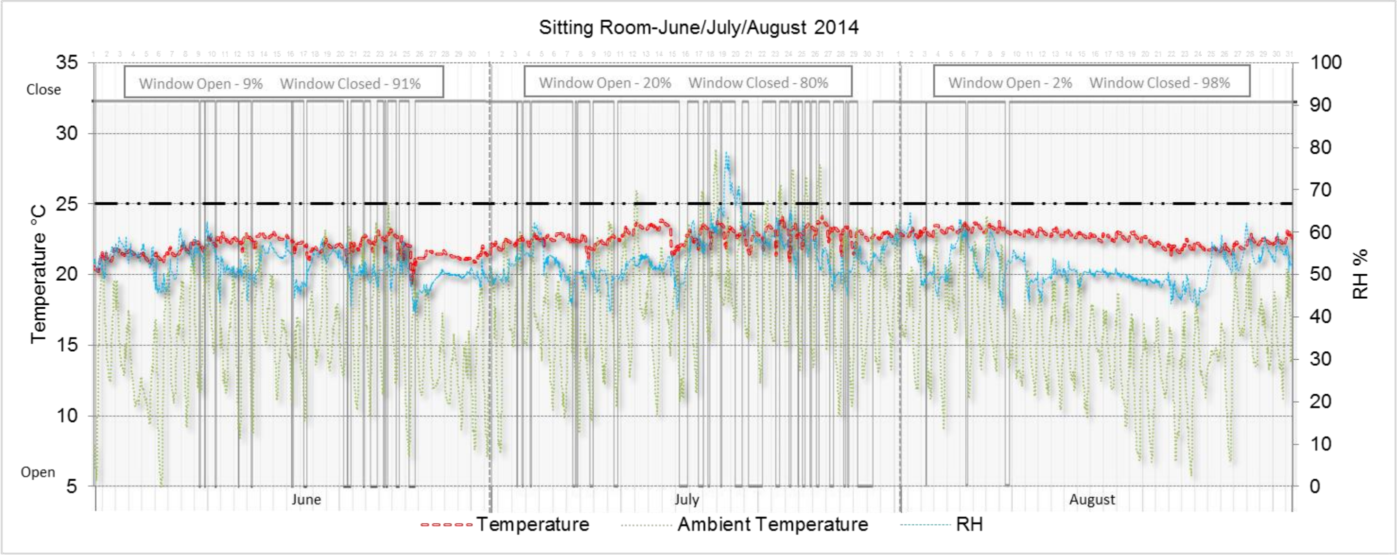


Figure 4-8- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

1 Living room

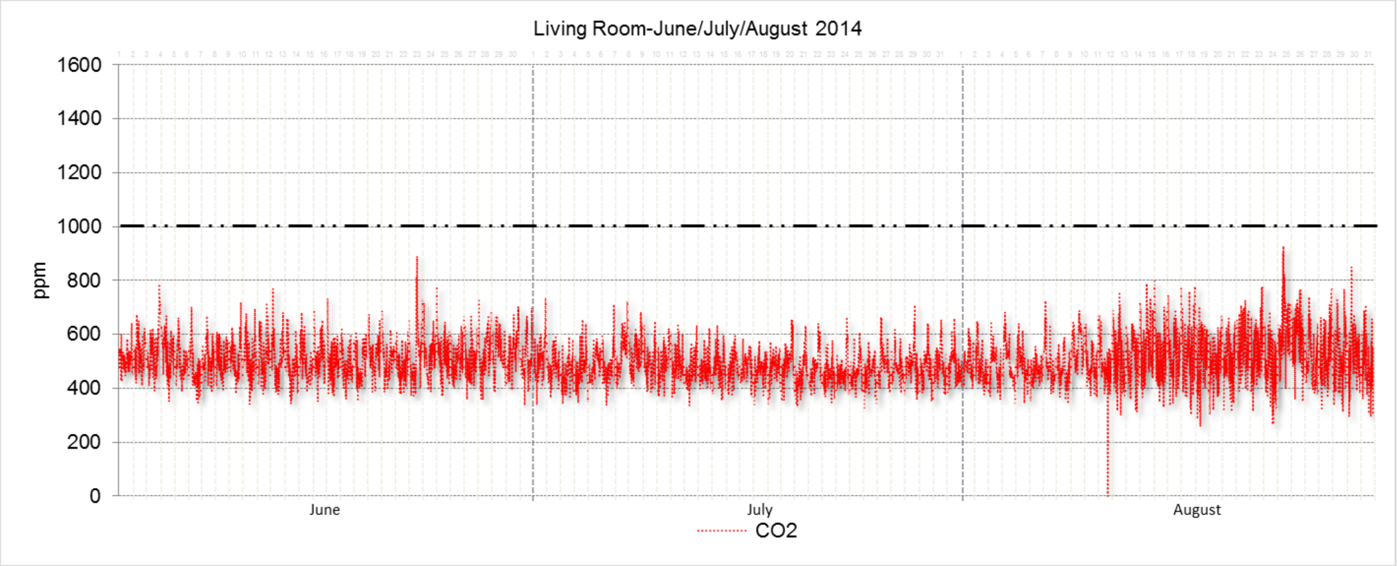


Figure 4-9- Measured indoor CO_2 level (Building One)

1 Sitting room

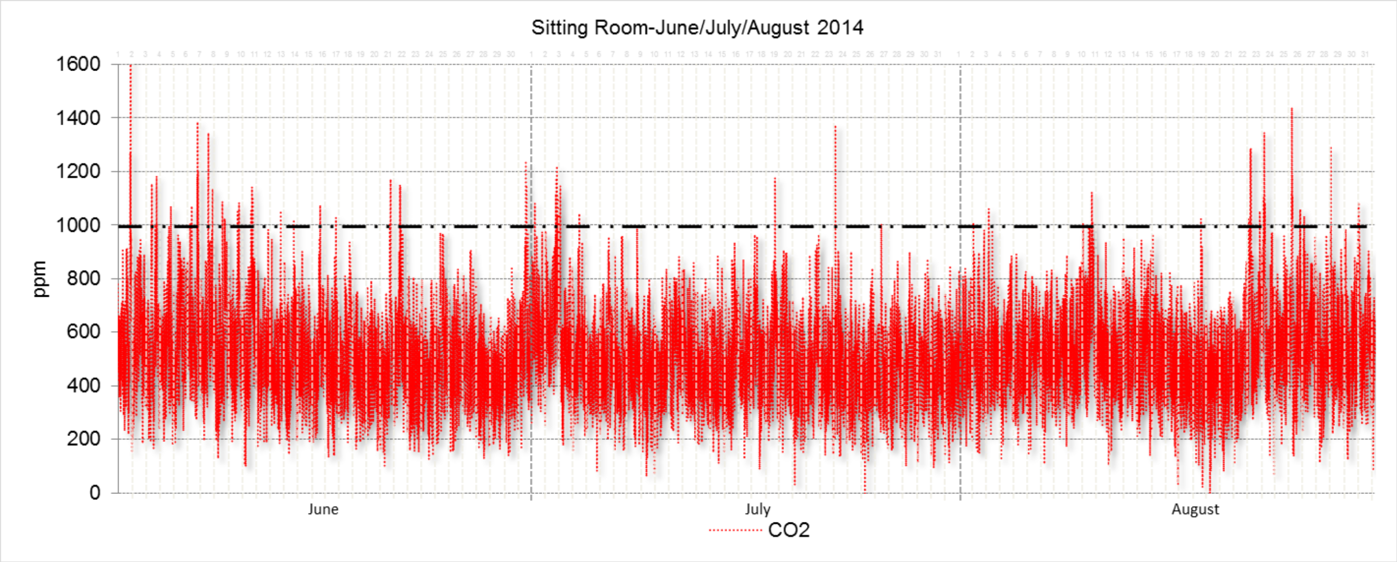


Figure 4-10- Measured indoor CO_2 level (Building Two)

The higher ventilation rate achieved through the use of MVHR in the colder months continued to influence the lower RH in the living room (Building One) which was recorded to be between 30% and 60% during the monitoring period.

The living room benefits from an even larger window to the South and South East with internal and external blinds (14m^2 – 58.8% of the total floor area including the office space). Despite the use of the blinds the external gains alongside internal gain contributed to high level of overheating in this space which was not discharged through the use of natural ventilation. The window (window 2) (from 15th till the end of May) was opened 11% of the time when the room was overheated for 32.13% during May. The indoor temperature passed 27°C for almost the whole day during the 16th, 19th and 20th when the window was opened for 2 hours, 3.5 hours and 1 minute respectively. The outdoor temperature reached a maximum of 21°C on the 16th, 23°C on the 19th and 18.8°C on the 20th. During June the window was left open for 12% of the month when the room was overheated for 76.76% of the time. The temperature was above 30°C in the living room from 10am till 12:30pm on the

13th and was overheated for the whole day. The window was opened from 1pm till 6:45pm and the ambient temperature reached a maximum of 23.6°C on this day.

The space was overheated for almost the whole time during July by 98.45% when the window was opened for only 8% of the time. The indoor temperature was above 30°C from 2:30pm until 7:00pm during the 18th and 25th when the window was opened from 7:00pm till 8:27pm on the 18th and not opened at all during the 25th. The ambient temperature during the time that the window was open was between 26.1°C and 21°C. The overheating during August was recorded for 77.61% of the month when the window was only opened for 4% of the time. The warmest indoor temperature during this month was recorded on the 6th from 2:30pm till 6:00pm which was over 28°C. During this time the window was not opened and in fact the window was not opened for the entire day on the 6th. The ambient temperature was between 25°C and 23°C and never passed 25°C for the whole day.

Living room temperatures were yet again high during September and the percentage over the 25°C was 72.70% when similar to last month the window was opened for 4% of the time. The indoor temperature was at its highest during the afternoon of the 9th from 1:00pm till 5pm and was over 28°C. The window was opened from 4:49pm till 7:42pm on this day and the outdoor temperature reached a maximum of 21°C at 2:00pm. There was a problem with the sensor from the 20th which has not been taken into account for the percentage calculation. The space was overheating irrelevant to outdoor temperature or the percentage that the window was opened, indicating that the heat built up within the space caused by perhaps limited solar gain or the internal gain was not escaping the space.

Overall during the five months of monitoring, the living room temperature was recorded to be above the limit for 71.47% of the time. The number of the recordings over 25°C was 10497 which would be just over 109 days. Taking account of no overheating for the rest of the year, the space has been over

25°C for 29.95% of the whole year which is much higher than the 10% limit set by Passivhaus standard.

The occupant operated the windows regardless of the ambient or internal temperature and limited effort was made to maximise the natural ventilation rate by benefiting from cross ventilation. Window 5 is located in the far end of the living room which is used as a home office. The use of this window would encourage the cross ventilation in the living room and would have benefit from cooler air from the north side of the building. This window was operated more often (18%) compared to Window 2 which was 11% during May. During June, the window was opened 20% of the time when the living room temperatures were over the limit for 76.76% and Window 2 was opened for 12% of the time during this month and the indoor temperature reached over 30°C. For instance during the 13th when indoor temperatures were recorded above 30°C, Window 2 was opened from 1pm till 6:45pm and Window 5 was opened from 11:40am till 10:00pm. The ambient temperature was recorded at a highest of 23.6°C which highlights the lower impact of opening the windows in reducing the temperature for this space.

The living room was overheated for 98.45% of the time during July and Window 5 was opened much more often during this month at 33%. However Window 2 was opened for 8% of the time only which reduced the opportunity for cross ventilation. The indoor temperature exceeded 30°C during the 18th when the ambient temperature was a maximum of 26.1°C at the time. This also suggests less effective air flow through the windows when they are opened. The total effective window opening is 0.67m^2 for the living room and the office space which is 2.8% of the total area. Window 5 was once again opened more often compared to Window 2 at 29% and 4% respectively. Overheating was 77.61% of the time during the month of August. The highest indoor temperature in the living room was recorded over 28°C on the 6th when the ambient temperature was never over 25°C. The living room temperatures were similarly high during September and the space was overheated for 72.70% of the time. Window 5 was opened for 16% and Window 2, similarly to the previous month, was opened 4% of the time. In general the windows were opened less often during this month compared to August, but yet again the overheating was very similar in percentage.

The total ventilation rate achieved through the use of windows and the MVHR was perhaps adequate to the number of the people. Overall the CO_2 levels were always below 1000ppm in the living room with a few exceptions during the five months of monitoring. The average of times that the limits where exceeded during the five months in the living room was 0.46%. The total number of incidents recorded above the limit was 68 times which would translate to 0.7 days. The built up heat therefore needs higher and more effective ventilation strategy to ensure lower indoor temperatures.

The more sufficient MVHR rate to the actual occupation rate resulted in better RH during the cooler months in the sitting room of Building Two which was between 40% and 60% overall with some exceptions. Window 2 is located in the front of the property and is one of two windows monitored in the sitting room. During May the window was opened for only one percent of the month. The room was not overheated during this time and therefore perhaps the higher ventilation was not necessary. However the CO_2 levels during May were over the limit for 5.14% of the time, making the rate of air change achieved by the use of the MVHR slightly too low. As the outdoor temperatures were increased during June, the percentage of the window opening and its frequency were also increased (9%) keeping the room below the 25°C limit and decreased the CO_2 levels to 1.53% during this period. During July the window was opened for 20% of the month and consequently there was no overheating in the space, whilst the CO_2 levels were recorded to be over the limit for only 0.54% of the time.

The indoor temperatures never exceeded the Passivhaus limit during August and the percentage of the window being opened was reduced to 2% during this period. The CO_2 levels on the other hand were increased to 1.18% during this time as lower ventilation was achieved by opening the window. During September the window was not opened for the entire month and the CO_2

levels were slightly increased to 1.53% with no overheating in the sitting room during this time.

W-D3 is the patio door on the opposite side of the sitting room making the possibility of cross ventilation if used at the same time as W2. However the data was lost from this window as the sensors were too far apart after adjustment by the occupant. In the interview with the occupant, they stated that the operation of this window would have been very small. The sitting room was not overheated during the five months of monitoring and therefore it can be assumed that it would not be over the limit for the entire year.

The Building One living room was overheated at a much higher percentage in comparison to Building Two possibly due to higher glazing area of 58.8% of the floor area to 32% in Building Two. The natural ventilation rate was also a contributor as the total effective openable area on tilt was 0.67m^2 in comparison to 1.8m^2 of the combined patio door opening (fully) and W2 on tilt in Building Two.

4 Master bedroom (bedroom 1)

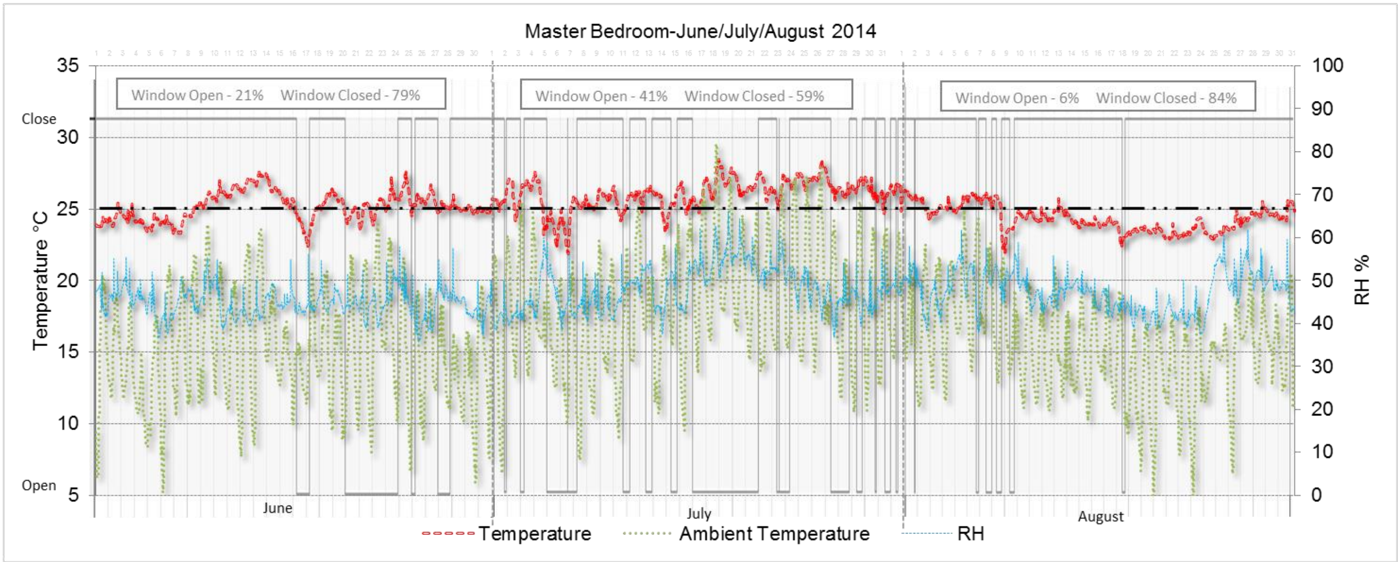


Figure 4-11- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

8 Bedroom 4 (Main bedroom)

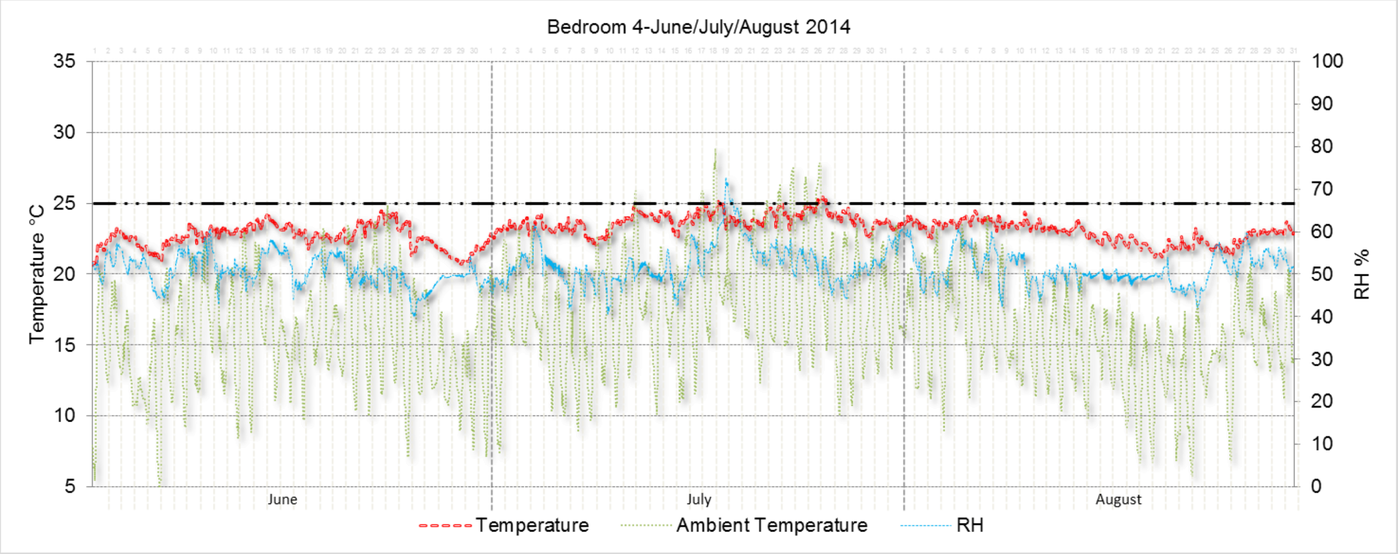


Figure 4-12- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

2 Master Bedroom

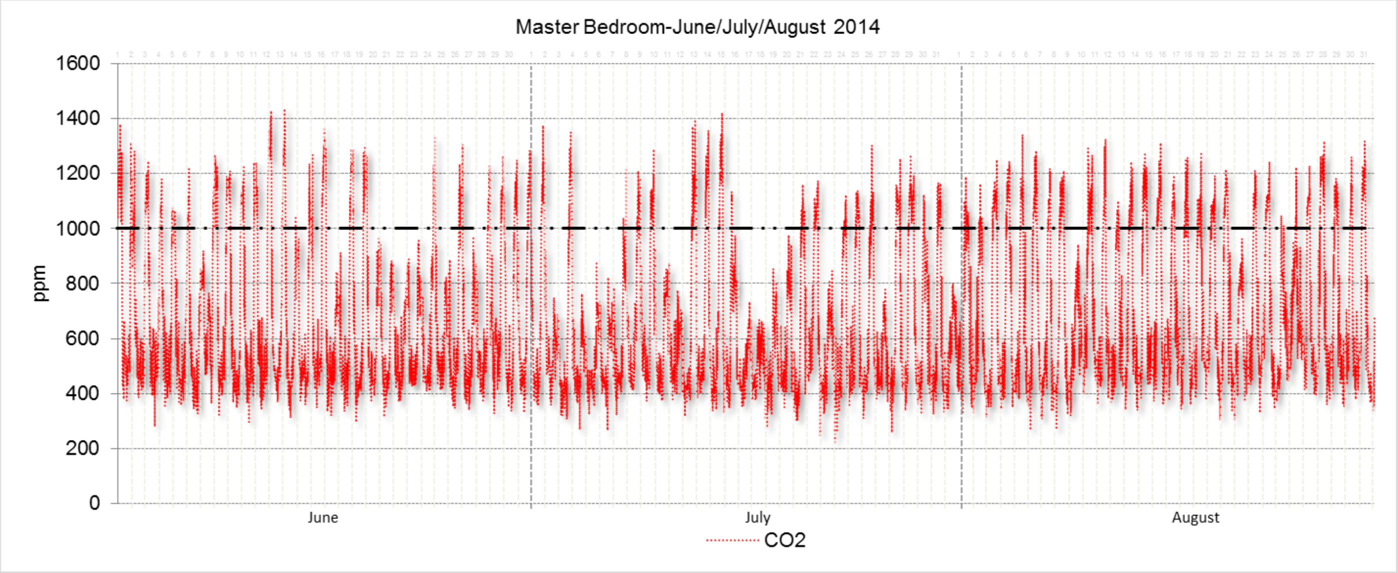


Figure 4-13- Measured indoor CO_2 level (Building One)

2 Main bedroom (bedroom 4)

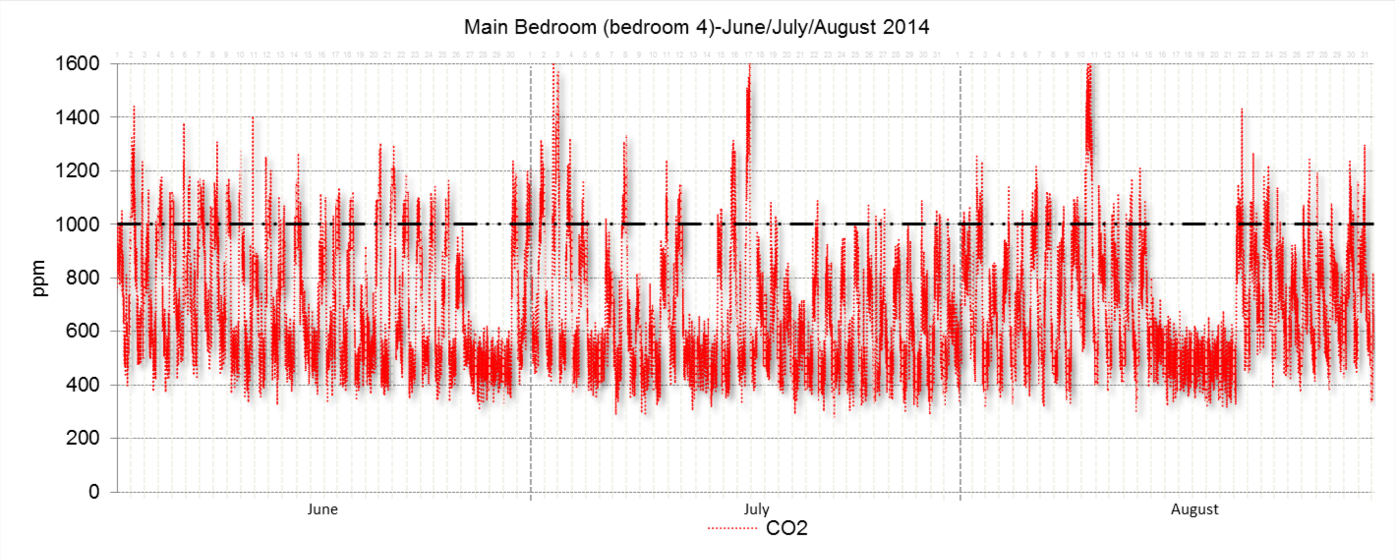


Figure 4-14- Measured indoor CO$_2$ level (Building Two)

Lower RH was experienced in the first floor in the master bedroom (Building One), similarly to the ground floor spaces, and was between 30% and 65% with lower percentage during the cooler months. The effectiveness of natural ventilation was noticed in this space as overheating occurred even during May (15.97% of the time) and the temperature reached a maximum of 26°C when the window was opened for 15% during this month. The percentage of glazing is lower at 20% of the floor area and despite the first floor location, the window was not left open during the night to benefit from the cooler temperature at night for the whole month of May. The master bedroom was more often over the 25°C limit during June at 56.69%. The window was opened for 21% of the time and left open even during the night. The temperature was recorded over 27°C for a few times during the month of June on the 12th, 13th, 14th and the 24th. The window was not opened from the 12th till 14th at all and was opened for almost the whole day and night on the 24th. The ambient temperature for all the dates never went over 22.6°C at its highest.

One of the highest temperatures in the bedroom was recorded in July with the highest percentage of overheating at 85.61%. At the same time the window was opened more often and was left open for 41% of the month. The room temperature passed 28°C for the majority of the day of the 18th and 26th when the window was left open for the whole day on the 18th and was closed all day on the 26th. The highest ambient temperature recorded was 29.5°C and 27.2°C for the 18th and 24th respectively.

The overheating was less during August in the bedroom at 25.95% of the month and the window was left open for much less of the time at 6%. The indoor temperature stayed more or less between 23°C and mid 26°C. However the ambient temperature was also cooler during this month with the maximum temperature of 25°C. The ambient temperatures were even lower during September with the highest temperature of 23.6°C. However the indoor overheating was increased to 41.47% which could only be caused by the lack of window opening recorded at 1%. The window was open for 3.5 hours on the afternoon of the 3rd and just over an hour during the afternoon of the 22nd.

The master bedroom was overheated for over 45% of the time during the monitoring period making the number of incidents recorded to be 6620. The 6620 would translate to be just short of 69 days. Assuming no further overheating for the rest of the year, the master bedroom would be overheated for 18.89% of the time which is less compared to the spaces on the ground floor but still almost double the allowed 10% limit.

The master bedroom's CO_2 levels were increased past the 1000ppm limit generally during the night when the occupants were sleeping highlighting that the ventilation rate for the bedroom is not adequate during this time. The total recordings over the limit during this time was 2530 which can translate to just over 26 days and 18.94% of the time. From May to September the percentage over the required level was calculated to be; 22.03%, 16.29%, 13.35%, 21.51% and 22.75%. The CO_2 level reached as high as 1920ppm during May when the windows were not opened frequently (15%), however it was generally below 1400ppm during the other months. It is needed to be mentioned that the CO_2 monitoring equipment was disrupted in the first half of May (due to occupants disconnecting the power by mistake) and therefore was not included in the calculation.

Window 16 is located in Bedroom 4 (Building Two) which is used as the main bedroom and the recordings from this window seemed to be compromised during the five months of recordings as it either was left open for the entire month or for very long time during each month. The bedroom was overheated during July and the CO_2 levels were recorded to be above the limit for every month during the monitoring period meaning that either the window was not operated often or the effectiveness of the window opening was limited. The effective window opening on tilt is $0.13m^2$ and 0.76% of the floor area when the window is 13% of the floor area. The graphs for each month (Appendix D) indicate the problem with the recordings which therefore have not been taken into account.

The satisfactory level of RH specifically during the cooler months was once again an indication of the adequate ventilation rate achieved by the use of the MVHR in this building which was generally between 40% and 60%. The area of window is around 13% of the floor area which is lower than Building One at 20%. However the overheating percentage was much lower in this space and was none during May and June. There was an increase in the temperature levels with 2.59% of overheating during the month of July. The temperatures were above 23°C for most of August, however there was no recording above 25°C and similarly no overheating in September.

During the five months of monitoring, the number of recordings over 25°C were 77 times which translates to 0.52% and 0.8 days of overheating. Assuming no further overheating during the rest of the year, the total overheating percentage would be 0.21%.

The CO_2 levels were monitored in this space to examine the effectiveness of the air change achieved by the use of the MVHR and window openings. The lower effectiveness of the ventilation rate was noticed by the increase of the

CO2 levels especially during the night. The percentage of the times that the CO2 levels were recorded to be over the 1000ppm level during May to September was calculated to be 22.92%, 14.31%, 8.13%, 8.84% and 16.22%. The peak in CO2 measurements was highest during July and reached 1600ppm whereas the overall CO2 levels were improved.

Bedroom 4 CO2 levels were over the 1000ppm limit for 14.07% of the time on average during the five months of monitoring and the number of recordings was 2066. The 2066 times would translate to just over 21 days that the bedroom CO2 levels were over the limit. The increase was generally during the night and the highest percentage was during the cooler months when the windows were probably opened the least, highlighting the inadequate rate of ventilation achieved during this time by the use of the MVHR.

5 Master Bathroom

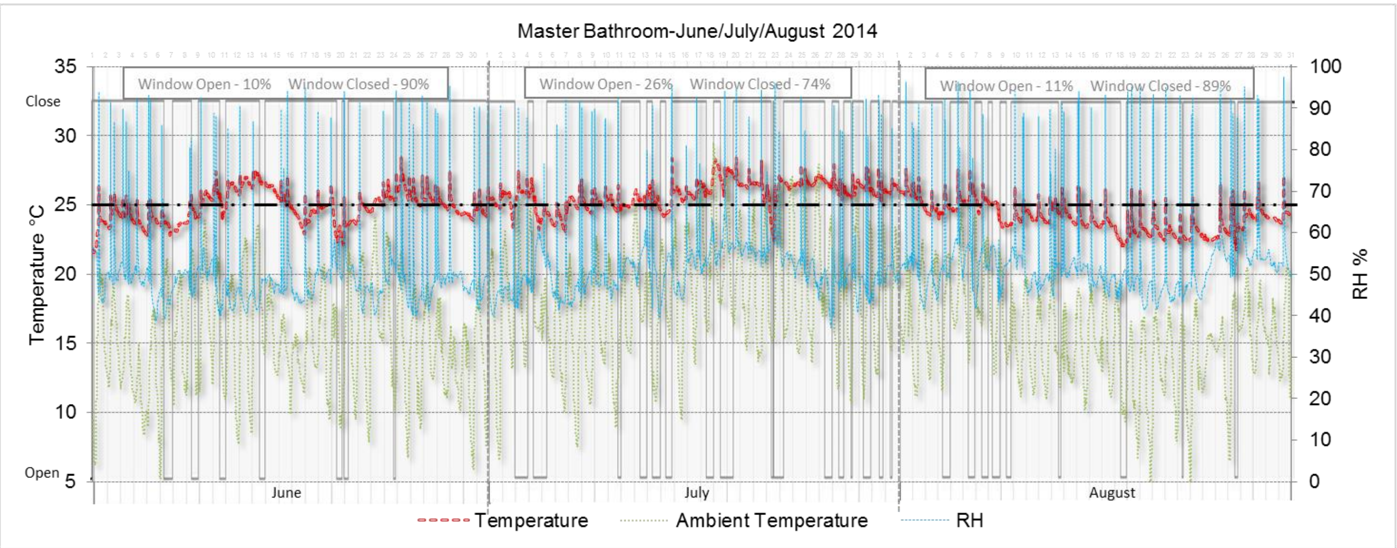


Figure 4-15- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

7 Master En-suite

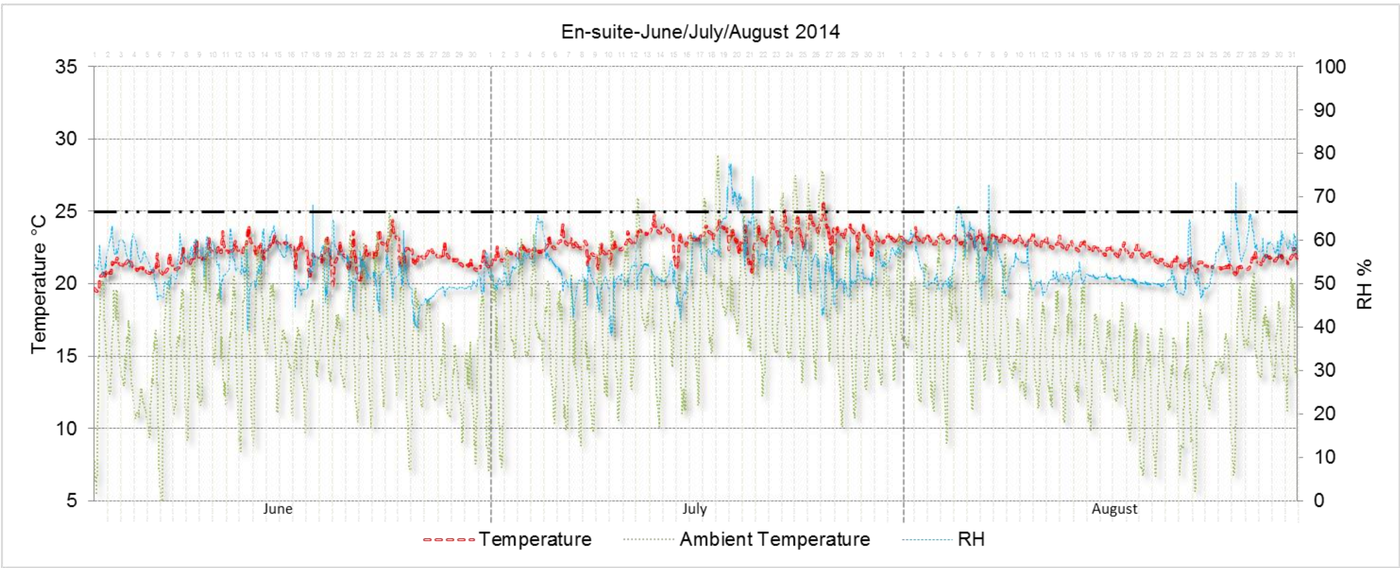


Figure 4-16- Measured indoor temperature and RH, comparison to ambient temperature (Building Two)

The master bathroom (Building One) is located on the north side of the building with no further glazing in any other direction (21% glazing to floor area). The RH was recorded to be high during some parts of the day as expected, reaching 95% during the monitored period which is perhaps higher than intended with the continuous use of the MVHR.

Overheating was recorded in this space despite the room's orientation and smaller window to floor ratio perhaps due to the build-up of heat in other rooms as well as lower effectiveness of the ventilation through the window and the use of the MVHR. Furthermore the benefit of cross ventilation was also limited through the bedroom window. During May the master bathroom was overheated for 6.15% of the month with the window being opened for 26% during this time. The RH was also recorded over 95% for instance on the 15th during the early morning which was perhaps when the occupants were using the shower, but the window was not opened that day. During the month of June, the overheating was increased to 43.17% of the time and in contrast the window was opened for 10% of the time only. There was an increase in temperature and RH during the time that the occupants used the space, however the window was not opened during or just after these periods.

The bathroom was further overheated up to 76.64% of the time during July when the window was opened for 26% during this period. The temperature was recorded over 28°C during the afternoon of the 18th when the space was not necessarily used for taking shower. During this time the window was not opened and the ambient temperature was 29.5°C at its highest. The overheating was less during August and was recorded for 20.61% of the time when the window was opened for 11% during this month. Similarly there was an increase in the RH and temperature during the time of bathing when the window was kept closed during and just after use.

The overheating percentage was reduced during September as the ambient temperature also dropped and the overheating was recorded at 16.19%. The window was opened for 12% of the time during this month similar to August. There were increases in RH and temperature during the time that the space was used and the window was not necessarily opened during these periods.

Despite the north facing location and the smaller glazing area of the master bathroom, the overheating was 32.58% during the five months of monitoring. The space was recorded to be above 25°C for 4785 times which would be just under 50 days. For the whole year, if no further overheating was recorded, the space would be over the Passivhaus limit for 13.65% of the time.

The master bedroom in Building Two, is not used as the main bedroom and therefore the En-suite is also not used frequently. The lack of regular usage of the space alongside the room orientation (North West), should contribute to less fluctuations in temperature and RH. The RH was generally between 40% and 65% during the monitoring period with a couple of incidents going above and reaching 80% which can be assumed was during the time that the space was used.

There was no episode of overheating during May and June in the En-suite. However there was a slight increase in the temperatures and there was even 0.54% of overheating during July. During August, there was no overheating and the temperatures in September were also never above the Passivhaus limit. The overall overheating was 0.11% of the time during the monitoring period with 16 recordings over the 25°C limit. The 16 incidents would translate to 0.16 days and the percentage of the overheating would be 0.045% for the whole year taking no further overheating recordings into consideration.

6 Bedroom 5

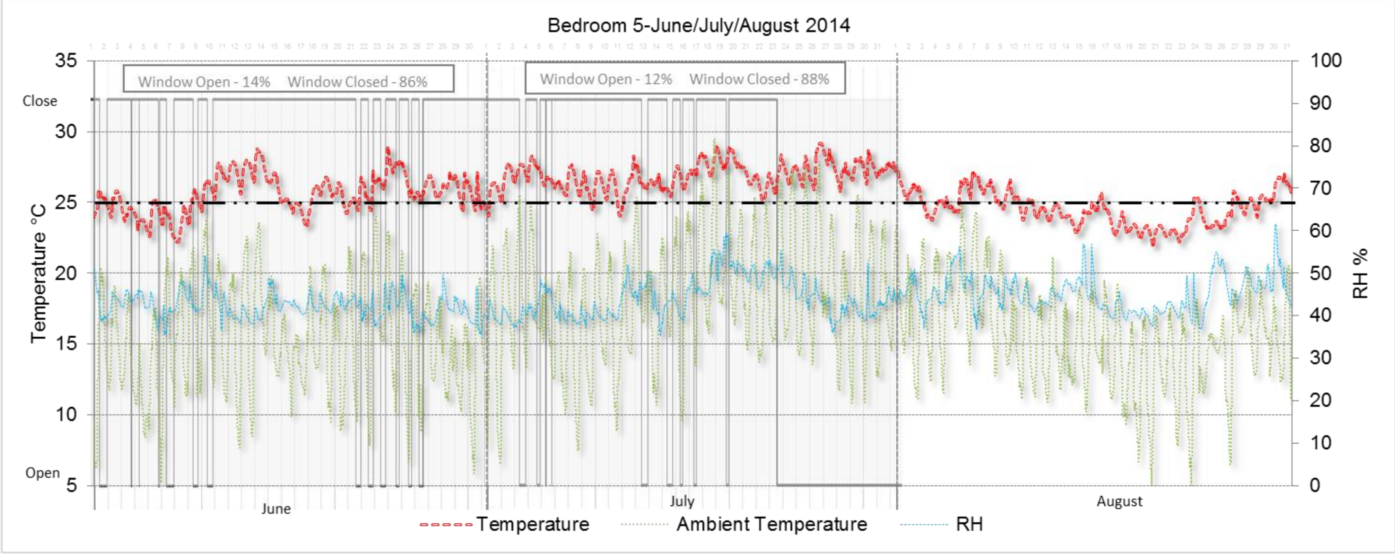


Figure 4-17- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

9 Bedroom 5

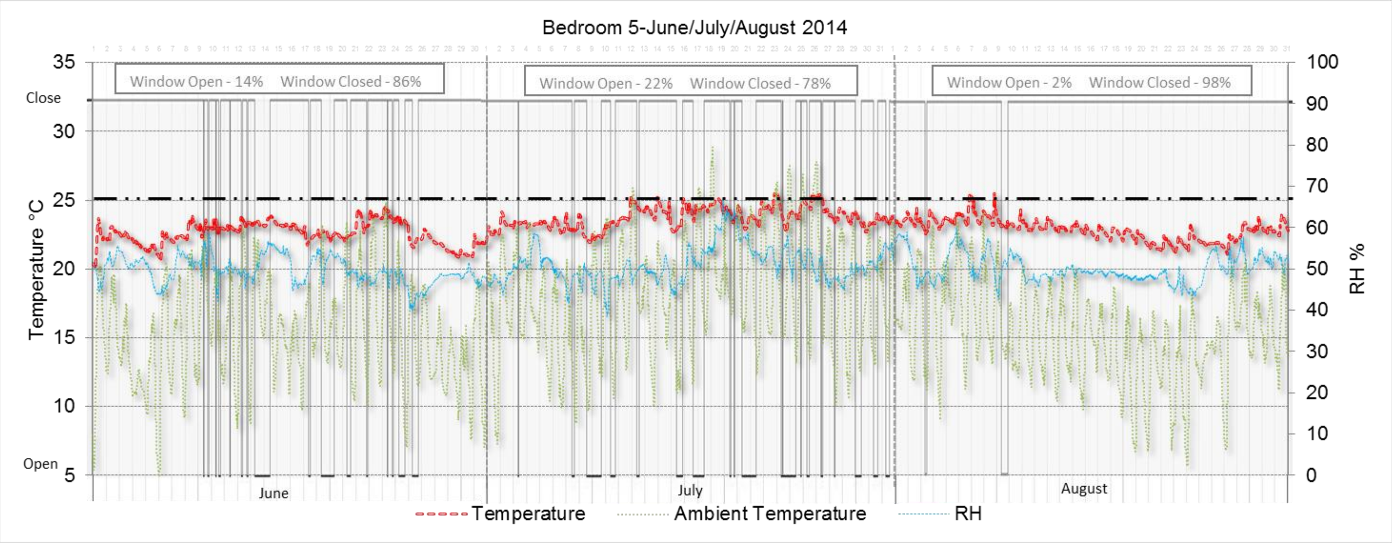


Figure 4-18- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

The very large south facing glazing percentage to floor area of 82% influenced the highest overheating percentage in the bedrooms, in bedroom 5 of Building One. The effective window opening is also limited to $0.2m^2$ which is 1.35% of the floor area when the window is opened on tilt, making the natural ventilation and cooling limited.

This bedroom is used the least and sometimes is used for drying clothes by the occupants which did not help to increase the RH and was recorded between 30% and 65% during the monitoring period. The overheating was 54.03% of the time during the month of May with the window being open for 6% of the time only. The indoor temperature was recorded as high as 26.65°C during the 13th in the afternoon when the ambient temperature was 14.7°C at its highest. During June bedroom 5 was overheated for an even higher percentage of the time at 68.08% and the window was also opened for longer at 14%. The indoor temperatures passed 28°C for the whole of the day on the 13th and for the majority of the day on the 23rd. The window was not opened on the 13th and it was opened for 5.5 hours on the 23rd when the temperatures outside were recorded to be around 23°C at highest.

The bedroom was overheated for the majority of the month during July and the window was opened for 12% of the time. However the sensor had problems from the 22nd of the month and did not record for the rest of the monitoring period which therefore has not been taken into account. The indoor temperatures passed 28°C for several days during this month and passed 29°C for the whole afternoon on the 26th. The bedroom was overheated for 38.49% of the time during August and 38.24% during September.

Bedroom 5 was overheated during the five months of monitoring for 7936 recordings which would be around 82.6 days and 54.03% of the time. Moreover, expecting no further overheating the space would be over the limit for 22.64% of the year.

Window 15 is the operable window in Bedroom 5 of Building Two, which is used as a child's bedroom. The overall operation of the window during May was 26%, however at the beginning of the month the window was left open for a long time continuously suggesting a problem with the position of the sensor. Although the temperatures reached over 24°C during May, there was no overheating in this month. On the night of the 17th the temperature exceeded 24°C when the window was closed and the outside temperature was around 12°C. The window was opened for 14% of the time during the month of June and there was no overheating recorded during this time. The only night that the window was left open was during the night of the 13th when the outside temperature was recorded to be 15°C at its lowest and the indoor temperature was over 23°C for the entire night.

During July the bedroom was overheated for 6.55% of the time when the window was opened for 22% of the month. The window was opened for a very small amount of the time during August and it was calculated to be around 2% during this month. The bedroom was still overheated during this month, however for 0.94% of the time as the outdoor temperature was cooler during this period. Between the 8th and 9th the temperature was recorded above the 25°C limit when the outside temperature was 22.1°C at its highest which could be due to thermal mass of the building and affected by the previous day when the ambient temperature was 24.1°C.

The window was not opened for the whole month during September even though the bedroom was overheated for 0.17% of the time. This is the only month that the window was not opened in this room during the monitoring period and there was some overheating despite the cooler external temperatures highlighting the need for higher air change and ventilation.

The RH was recorded to be between 40% and 65% in Bedroom 5 during May to September. Bedroom 5 was overheated for 1.55% of the time during the five months of monitoring which could be 0.65% of the year. The overall number of recordings over the 25°C limit was 228 which would be around 2.3 days in total.

7 Drying room

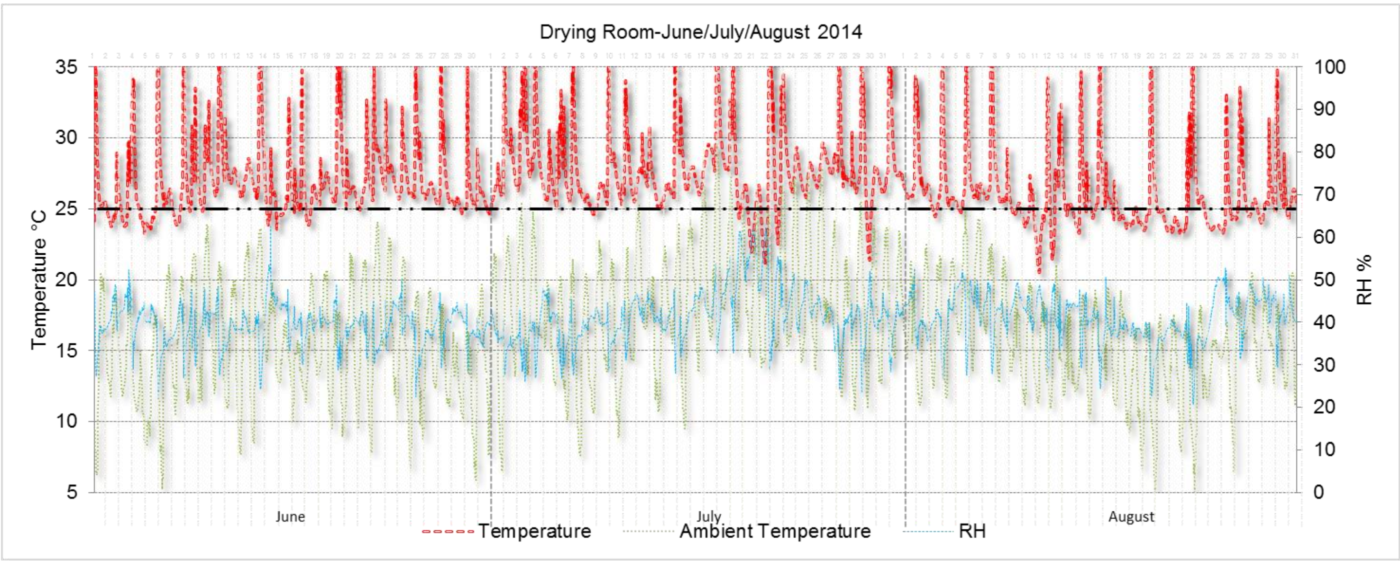


Figure 4-19- Measured indoor temperature and RH, comparison to ambient temperature (Building One)

4 Utility room

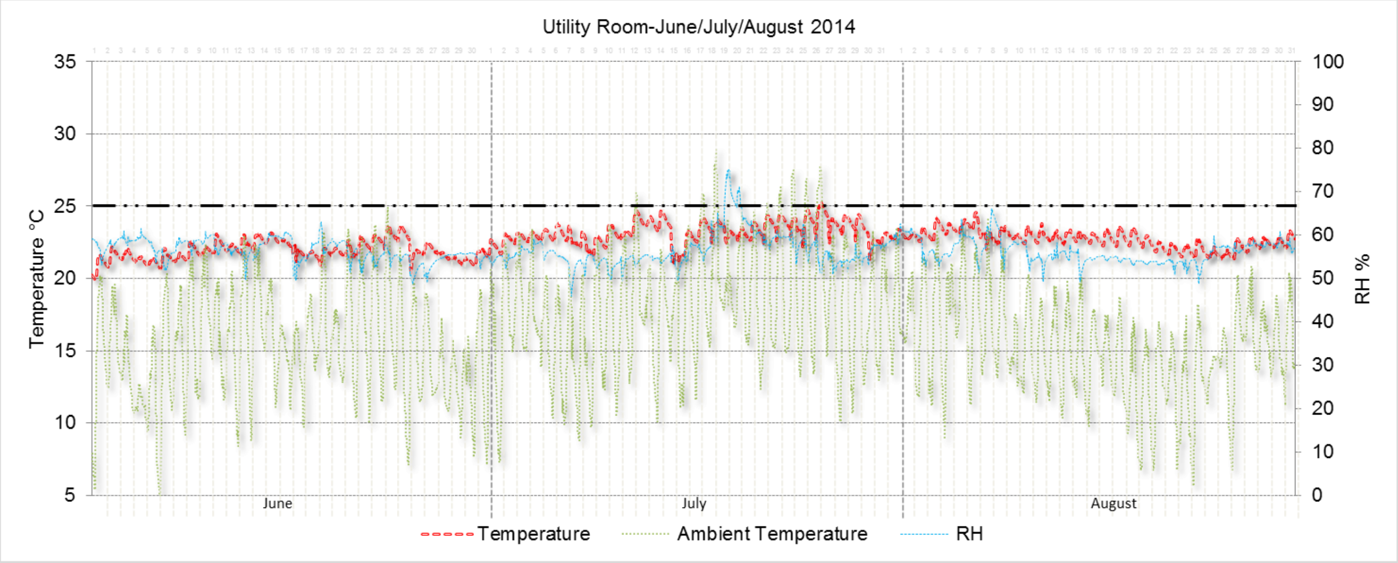


Figure 4-20- Measured indoor temperature and RH, comparison to ambient temperature (Building Two)

The heat released from the hot water storage tank which is located in the drying room (first floor – Building One) contributed to high temperature recordings despite the north facing location of the room. The RH was lower in this space and was recorded between 20% and 60%. The temperature saw very large fluctuations during May, from just under 22°C to 42°C. The 42°C was recorded in the afternoon of the 6th at 2:45pm and overall the space was overheated for 45.75% of the month. This increases the importance of taking the extra heat gain from the hot water storage into consideration during the summer months.

Similarly to the previous month the temperature fluctuated during June and stayed above the limit for 82.84%. The wide range of temperatures continued during July also and the space was over the 25°C for 91.13% of the time and August was no different regarding the temperature range with slightly less overheating percentage at 60.64%. Despite the lower ambient temperature, there was almost no change in the internal temperature measurement during September and the space was overheated by 59.64% of the month.

Overall the drying room was measured to be over the 25°C limit for 67.94% of the five months and the incidents recorded above the limit were 9978 times. This would mean that the space was overheated for 103.9 days of the five months. Assuming no further overheating, the percentage over 25°C for the whole year would be 28.47%.

On the other hand, the utility room is located behind the garage on the ground floor in Building Two and benefits from a large floor area and small glazing ratio (10% window to floor area). The RH was slightly higher compared to other areas on the ground floor, affected by the clothes drying etc., but still at an acceptable level of 50% to 70%.

There was no overheating during May and June in this space. However during July there was some overheating in the room and the percentage of the overheating was calculated at 0.97% of the month. There was an increase in the indoor temperature during the early part of August, but it never exceeded the limit and therefore there was no overheating in this month. There were no significant changes in the temperatures during September and subsequently no overheating.

The total number of times that the temperature was recorded over the limit during the five months of monitoring was 29 which would be 0.20%. The 29 times also would translate to be 0.3 days during this period. The percentage of overheating for the whole year would also be 0.08% if no more incidences of overheating were recorded during the year.

8 Bedroom 3

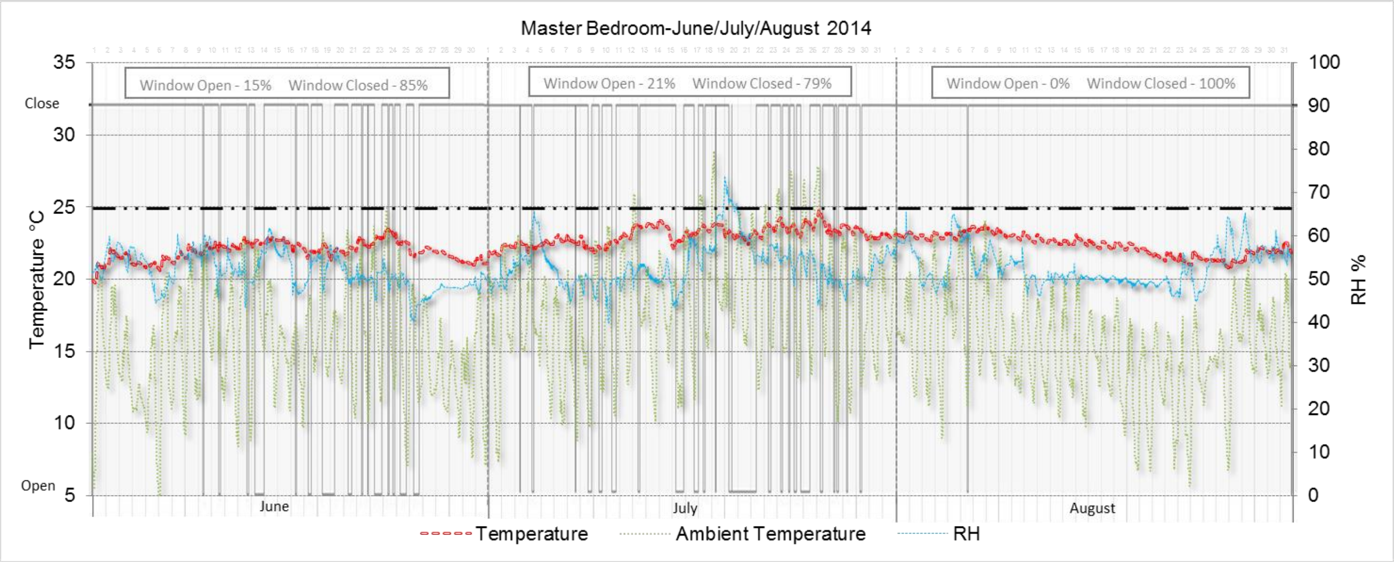


Figure 4-21- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

6 Bedroom 1 (master bedroom)

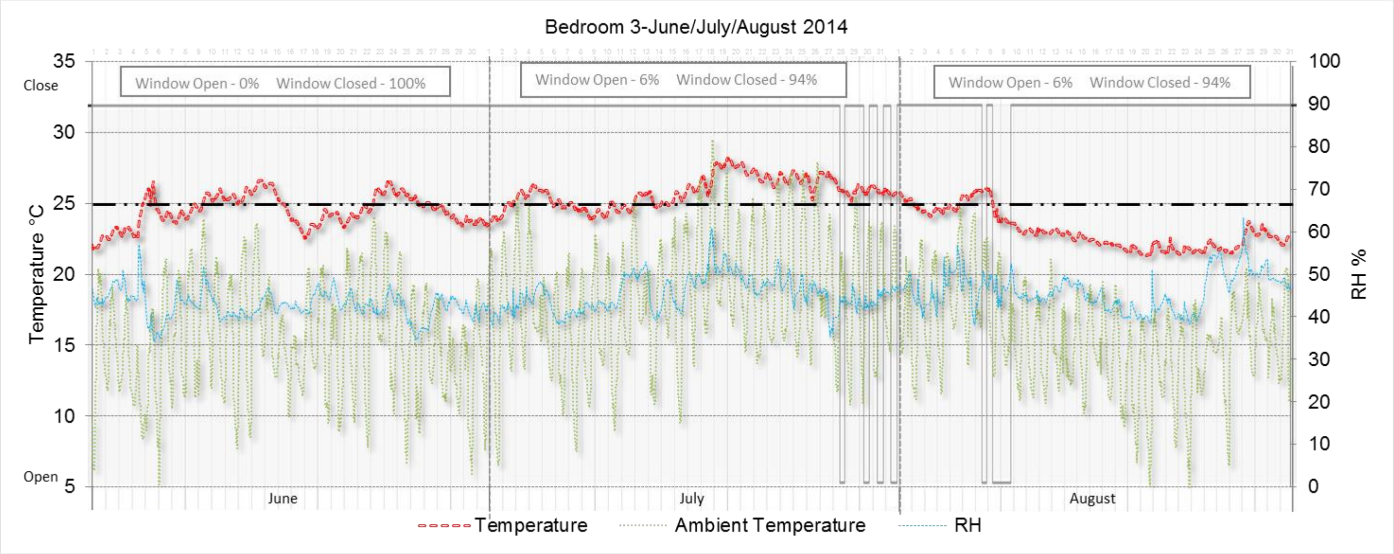


Figure 4-22- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

The lack of use of Bedroom 3 (Building One) which is located in the second floor contributed to the lower RH which was recorded to be between 30% and 55% during the monitoring period. This space does not benefit from any glazing to the south, however the space was overheated for 7% of the month during May and the window was not opened at all during this time. Opening the window in bedroom 3 could have encouraged the stack effect and perhaps reduce the temperature in the lower spaces of the building. The overheating was increased during June and reached 35.57% of the time when once again the window in this room was not opened for the whole month. During July the percentage of overheating reached as high as 71.87% of the time and the window was opened a few times towards the end of the month for a total of 6%.

The window was left open for almost the whole day during the 27th, 29th, 30th and 31st however, this did not help to reduce the temperature in the other spaces of the house. The benefit of stack effect and possible increase of ventilation and therefore cooling was not maximised by the occupants and for example the living room was over the limit during all these days as the window was not open in the living room during this time when the ambient temperature was never over 25.5°C. The bedroom was overheated less during August and it was recorded to be 14.76% of the time. The window was opened for the same amount of the time as the previous month and it was 6%. The window was opened for the whole day on the 7th and for 24 hours from the morning of the 8th till the following morning. During both days, the indoor temperatures were above the 25°C limit when the ambient temperatures were recorded at 24.3°C at the highest. There was no overheating recorded during September in bedroom 3 and also the window was not opened for the entire month.

Bedroom 3 was over the limit for 25.94% of the five months and for a total of just below 40 days meaning 3810 recordings over 25°C. Assuming no further overheating incidents occurred, the space would be overheated for 10.87% of the year.

Drying clothes in Bedroom 1 (Building Two) had contributed to some increase in RH during June reaching as high as 70%, however the recording was generally between 40% and 60% during the monitoring period. The bedroom is not used as per the design intent (master bedroom) and it was rather unoccupied during the monitoring period.

During May, there was no overheating recorded in this space and the window operation was very limited at 1%. During June the window was opened for 15% of the time even though there was nobody staying in this bedroom meaning that the occupants were putting effort to make sure the extra ventilation is achieved in this room as the outdoor temperatures rose. There was no overheating during this period.

Similarly to the previous months there was no overheating in this bedroom during the month of July. The temperature was recorded very close to 25°C however it never passed the limit and the window was opened almost every day during this period. The total percentage of window opening was calculated to be around 21%. During August as the outdoor temperatures decreased, the window was opened only once for a very small period of the time almost being 0% during this month. Moreover the bedroom was not experiencing any high temperatures over the 25°C limit during August. The temperatures in Bedroom 1, similarly to the previous months, were never over the limit and the window was also not opened for the entire month of September.

9 Bedroom 4

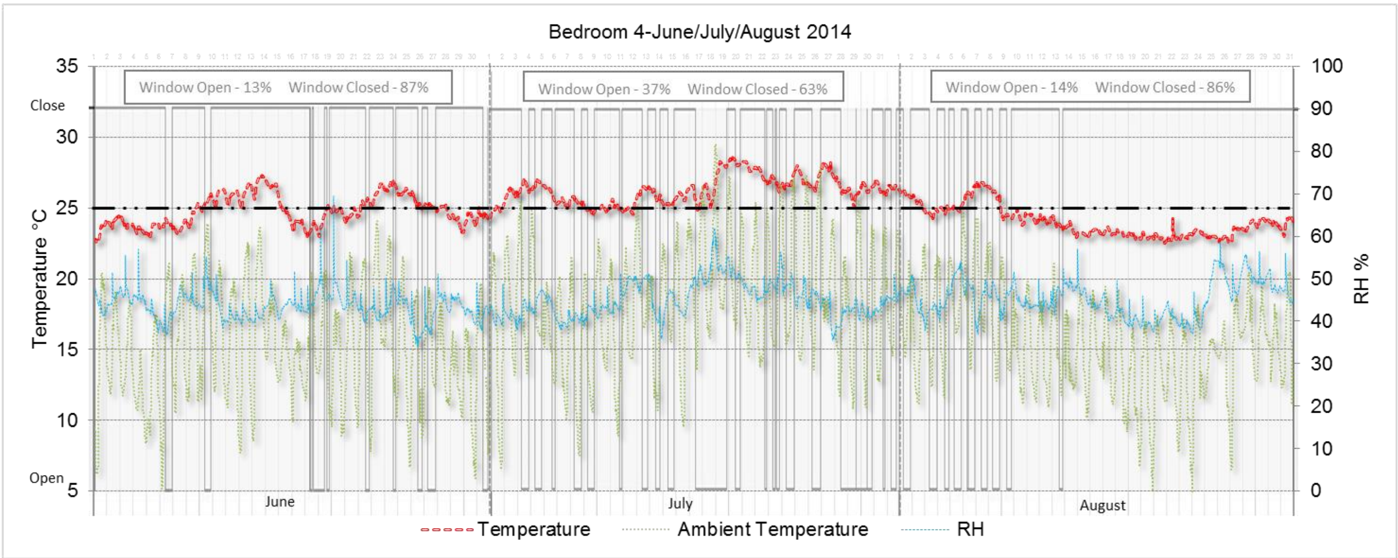


Figure 4-23- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building One)

9 Bedroom 2

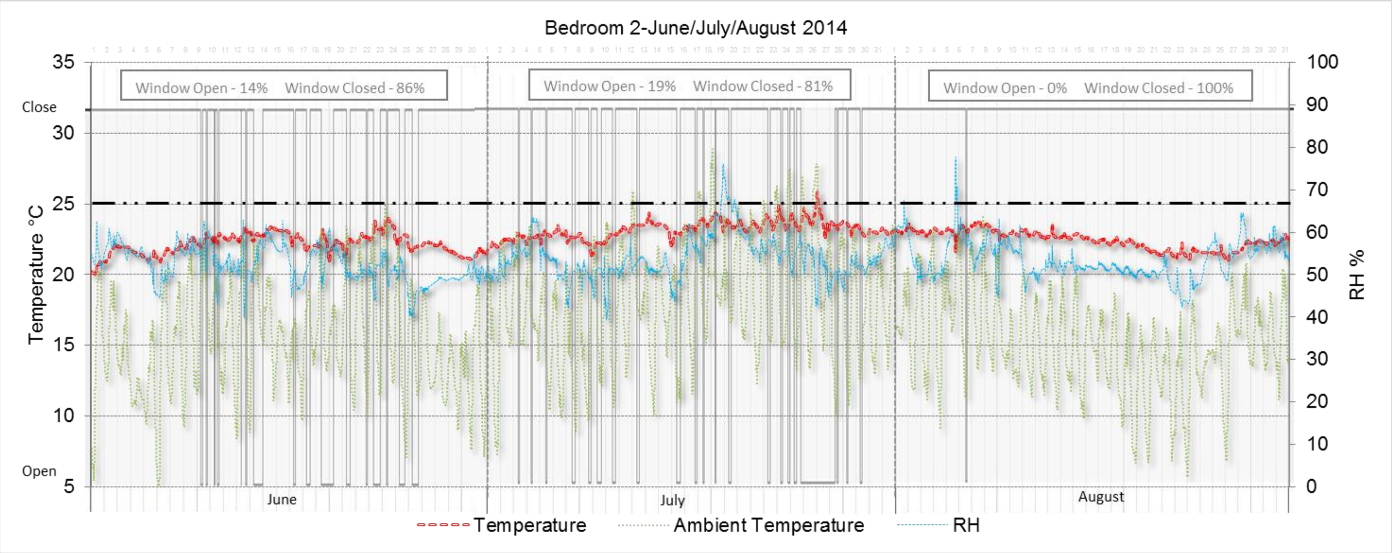


Figure 4-24- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

The lower RH during the colder period was once again evidenced in Bedroom 4 of Building One and was recorded to be between 30% and 60%. The bedroom is located on the second floor with no south facing windows and is used as the child’s bedroom. Overheating was recorded despite the lack of south facing windows and low window to floor ratio of 11%. During the month of May the space was overheated for 12% and the window was opened for 17% of the time. The window was left open for a whole 24 hours on the 25th and 26th when the ambient temperature was at 16.9°C at its highest. The overheating percentage was increased to 42.93% of the time during June whereas the window operation was actually reduced and it was recorded at 13% of the month. For example the indoor temperatures reached above 27°C on the 13th and never went below 26.48°C even during the night. The ambient temperature was between 8.5°C and 23.6°C during this time and the window was not operated at all to benefit from extra ventilation and cooling effect.

Overheating in the bedroom was the highest during July at 87.97% of the time and the window was also opened the most at 37% of the month. The indoor temperatures were recorded over 28°C for almost three days continuously on the 19th till 21st and the window was opened for the majority of the day during the 19th and for just over 5 hours on the afternoon of the 21st. The window was not opened during the night and the ambient temperatures were a maximum of 26.8°C, 24.6°C and 25.4°C respectively. During August the space was overheated for 20% of the month and the window was opened for 14% during this period, however the window was not opened from the 13th onwards. The bedroom was overheated for much less during September and it was over the limit for 1.42% of the time. The window was also opened for 3% only during this month.

During the five months of monitoring the space was overheated for 33.03% of the time. The incidents recorded over 25°C were 4851 which would translate to 50.53 days. Moreover assuming no overheating for the rest of the year, the space would be overheated for 13.84%.

Window 18 is located in Bedroom 2 which is situated at the front of the property of Building Two looking towards the road. During the month of May there was no overheating recorded in this space and also the window was operated for 2% of the time during this month. The window was opened more often during June and it was calculated to be 14% of the month. Similarly to the previous month, there was no overheating during June in Bedroom 2 with temperatures staying below 24°C for the entire month.

The temperature rise during July had an impact on the internal temperatures and despite the window being opened for 19% of the time during this month, the bedroom was overheated for 0.5% during this period. There was no overheating recorded during August in Bedroom 2 as the external temperature dropped and also the window was not opened for almost the entire month. Similar to August, the internal temperatures in Bedroom 2 stayed below the 25°C limit in September and the window also was not opened at all during this period.

10 Second floor shower

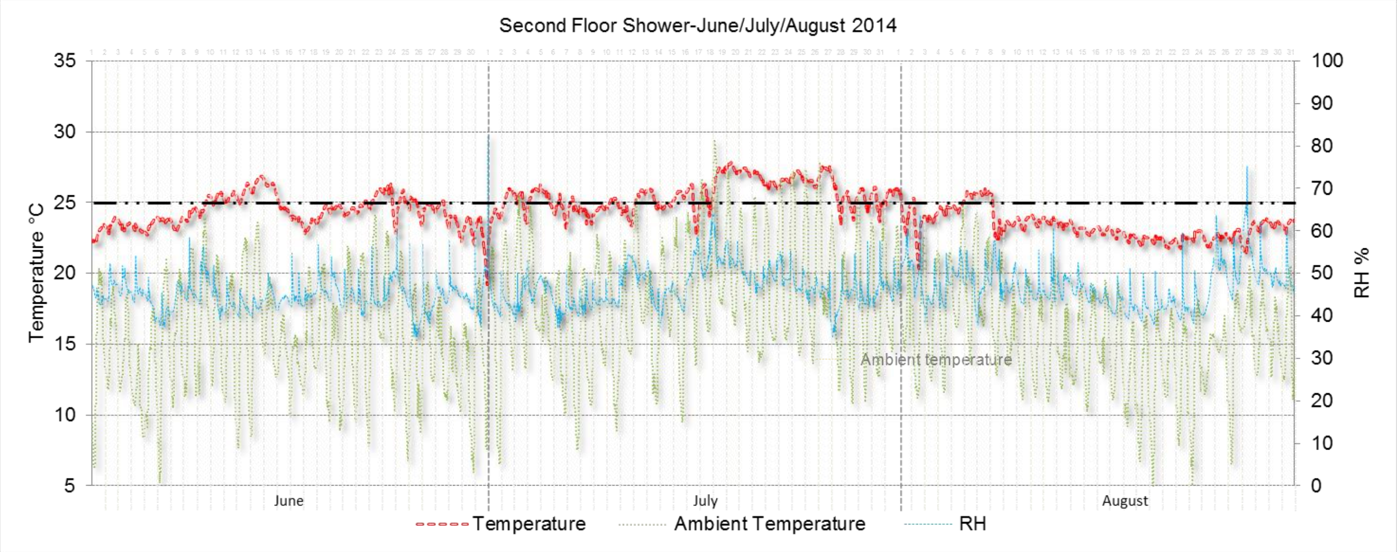


Figure 4-25- Measured indoor temperature and RH, comparison to ambient temperature (Building One)

11 Bathroom

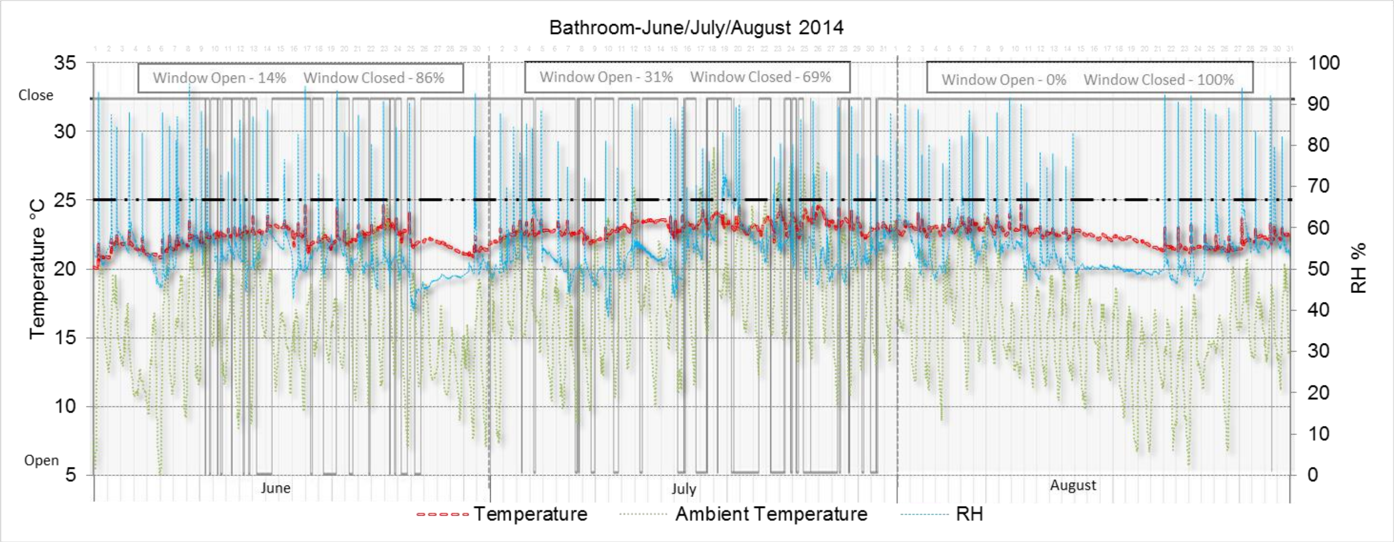


Figure 4-26- Measured indoor temperature, RH, window operation, comparison to ambient temperature (Building Two)

The nature of the use of the second floor shower (Building One) contributed to a high RH recording of 80%, however the RH was in general on the lower side and was between 30% and 60%. The less frequent use of this room alongside a small north facing window should have reduced or eliminated any overheating in this space. However the temperature was above the limit for 5.71% during May but also was recorded as low as 17°C during the afternoon of the 26th. During June the temperature was over the 25°C for 29.5% of the time and the temperature passed just over 27°C and stayed over the limit for 63.87% of the month during July. During August the temperature passed the 25°C for 11.23% of the time whereas September saw no overheating.

Overall the space was overheated for 22.15% of the time during the five months of monitoring. The number of recordings over 25°C was 3253, meaning 33.88 days over the limit. The total overheating percentage for the whole year would be 9.28% if no further overheating would occur.

The main bathroom is located to the side of Building Two with a small northeast window. The space which is used the most by the family, did not necessarily overheat during the five months of monitoring however the RH was recorded to be over 90% during the time of use. During May the window was not opened regularly and it was calculated to be for 1% of the month only. The MVHR boost option was also either not used or if used did not help to reduce the RH during the time of use. During June the window was operated more regularly and in total for 14% of the time. However the window was either not opened during or just after the use of the bathroom, to aid in the reduction of high RH or if it was opened the RH was not reduced immediately. For instance on the 13th the window was opened from 6:45am for the whole day and RH was recorded to be 86.72% at the time of use and took around half an hour to come down to 52%.

During July the RH was similarly recorded to be over 90% at the time that the room was probably used and the window was opened for longer during this period at around 31% of the time. The higher percentage of window opening did not help in regulating the RH during this month and there were peaks in the RH recordings. There was no overheating in the bathroom during August, however the RH was similar to the previous month and reached over 90% during the use of the bathroom. The window on the other hand was not opened at all during this month which can highlight the low effectiveness of the air change achieved by the MVHR. During September the recordings for RH continued to highlight peaks reaching over 90% when similarly to August the window was not opened for the entire month.

From May till the end of September, there was no overheating in the bathroom and it can only be assumed that there won't be any overheating for the whole year.

11 MVHR Room

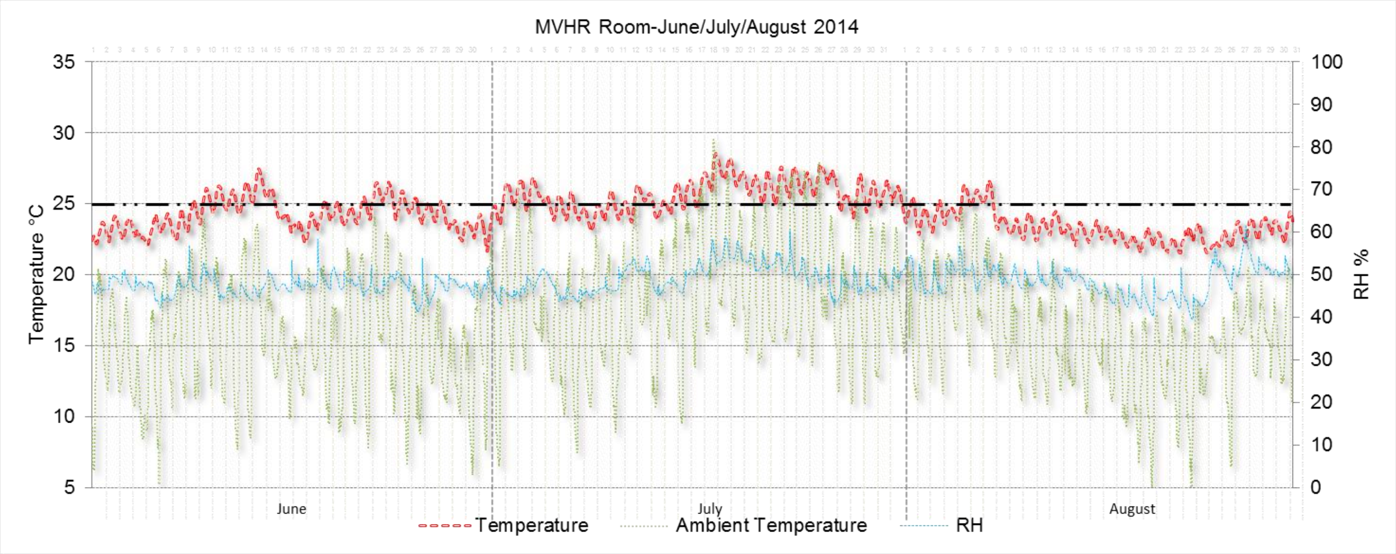


Figure 4-27- Measured indoor temperature and RH, comparison to ambient temperature (Building One)

5 Loft (MVHR housing)

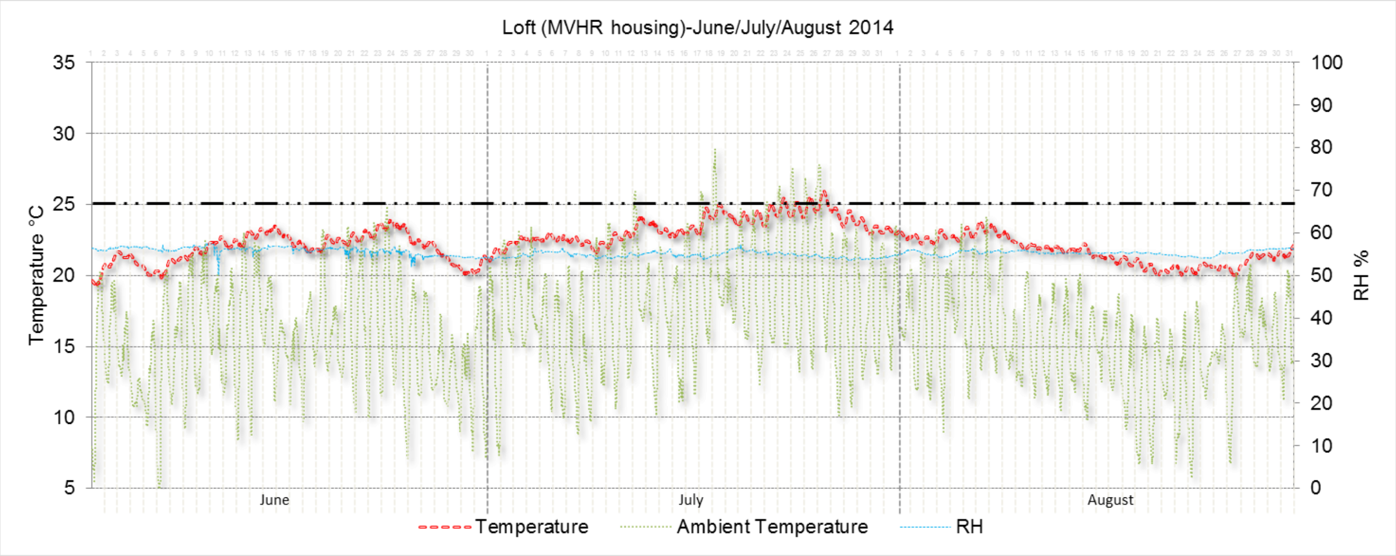


Figure 4-28- Measured indoor temperature and RH, comparison to ambient temperature (Building Two)

The MVHR is located in the cupboard with no glazing and accessed from the shower room in the second floor of Building One. To examine the impact of the heat gained from MVHR the temperature and RH were recorded in this space and during the monitoring period, impact of the shower usage did not affect the RH and the RH was generally between 30% and 60%.

The only source of heat gain in this space is the MVHR and over the five months the space was overheated for 23.25% indicating the importance of taking the additional heat gain into consideration during the summer period.

The temperature was over the 25°C limit for 7.56% of the time during May whereas the temperature exceeded 27°C during June and stayed over the limit for 26.1% of the time. During July the temperature was over the limit for 67.6% of the time and reached a maximum of just over 28°C. The temperature was lower in August and stayed above 25°C for 11.73% of the month and there was still evidence of overheating in the MVHR room during September even though there was no overheating in the shower room. The percentage of the time over the limit was 2.7%. The number of times recorded over 25°C was 3414 which would be 35.5 days. The percentage of overheating for the whole year would be 9.74% assuming no further overheating incidences.

The MVHR unit in Building Two is housed in the loft which is part of the thermal envelope, meaning that the insulation is at the roof level and not in the ceiling of the first floor. The aim of monitoring this space was to examine the impact of the heat generated from the MVHR unit. However the loft where the MVHR is located is a very large space and not part of the habitable rooms, making the impact and heat generated by the MVHR very difficult to quantify.

Nevertheless, the opportunity was taken to examine the impact of the room temperature on the delivered air temperature into habitable spaces i.e. living room, when the MVHR ducts are not insulated in the loft, as part of the Passivhaus standard. During May, the temperature of the loft was never above the Passivhaus limit and the RH was fairly constant around 55%.

The RH was similar to May during the months of June to September and stayed around 55%. There were some increases in the temperature during June, however it never went above the 25°C limit. There were further increases in the temperature during July and it even overheated for 5.68% of the time. The temperatures stayed below the 25°C limit for the month of August and September temperatures were very similar to August with no overheating in the loft.

The loft with no internal gains except for the MVHR unit and no glazing, was still overheated for 1.15% of the time during the five months of monitoring. The total number of recordings over the limit was 169 which would be just over 1.7 days. If no further overheating was assumed, the total overheating percentage for the whole year would be 0.48%.

The table below demonstrates the average overheating for each floor and then the overall building during the five months and the whole year taking no further possible overheating into account for the rest of the year for Building One.

Table 4-1- Average overheating percentage per floor & whole building for the 5 months and one year

Floors	Spaces	May to September overheating %	Total year overheating %	Average overheating -May to September per floor	Average overheating total year per floor	Average overheating - May to September - whole building	Average overheating - total year whole building
GF	Dining room	62%	26%				
GF	Kitchen	92.52%	38.77%				
GF	Living room	71.47%	29.95%				
GF				**75.33%**	**31.57%**		
FF	Main Bedroom	45%	18.89%`				
FF	Master En-suite	32.58%	13.65%				
FF	Bedroom 5	54.03%	22.64%				
FF	Drying room	67.94%	28.47%				
FF				**49.88%**	**20.91%**		
SF	Bedroom 3	25.94%	10.87%				
SF	Bedroom 4	33.03%	13.84%				
SF	SF Shower	22.15%	9.28%				
SF	MVHR Room	23.25%	9.74%				
SF				**26.09%**	**10.93%**		
Whole building						**50.43%**	**21.13%**

As it can be seen from the above table the building was overheated by **50.43%** during the five months of monitoring and a total of **21.13%** for the whole year. One important observation is the reduction of overheating in higher floors. The ground floor was the warmest and the second floor the coolest meaning that the heat does not rise in Passivhaus which could be down to the high level of airtightness reducing the stack effect. This fact highlights the importance and benefit of increasing stack effect in Passivhaus buildings during the warmer months of the year. Another important point to make is that the percentage of overheating differed for each space, however when averaging the building this can be underestimated which is the case when using PHPP.

Nevertheless the building was overheated for an average of **21.13%** of the year. However the percentages for the total building is only taking the spaces monitored and the rest of the building is not taken into consideration which could reduce the overall average of overheating. The RH was relatively low which highlights the higher ventilation achieved by the MVHR especially during the colder months as the building is under occupied and the MVHR is configured to supply air based on the building area and not necessarily the number of occupants.

The table below demonstrates the average overheating for each floor and the overall building during the monitoring period and the whole year assuming no further possible overheating incidents for the rest of the year for Building Two.

Table 4-2- Average overheating percentage per floor & whole building for the 5 months and one year

Floors	Spaces	5 Months	Total year	Average 5 month each floor	Average year each floor	Average 5 months whole building	Average year whole building
GF	Siting room	0%	0%				
GF	Kitchen	0.49%	0.2%				
GF	Dining room	1%	0.41%				
GF	Utility	0.2%	0.08%`				
GF				**0.42%**	**0.17%**		
FF	Bedroom 1	0%	0%				
FF	Master En-suite	0.11%	0.045%				
FF	Bedroom4	0.52%	0.21%				
FF	Bedroom 5	1.55%	0.65%				
FF	Bedroom 2	0.10%	0.042%				
FF	Bathroom	0%	0%				
FF				**0.38%**	**0.15%**		
Loft	MVHR Room	1.15%	0.48%	**1.15%**	**0.48%**		
Whole building						**0.65%**	**0.26%**

The average percentage of overheating for the five months of monitoring was 0.65% and 0.26% for the whole year as it can be seen from the above table. Similarly to Building One, the overheating was reduced from the ground floor to the first floor meaning that the heat did not necessarily rise which could be due to the very airtight envelope of Passivhaus which limits the stack effect in the building. The loft which is similar in floor area in comparison to the other floors, with no glazing, was overheated the most on average. There was no direct connection from the first floor to the loft except for a sealed and airtight loft hatch. This highlights the importance of insulating the MVHR ducting unit especially during the warmer part of the year and the associated heat gains from the space.

The building was overheated for 0.26% of the year only which was much less than Building One. Moreover Building Two is located further north with a cooler climate in comparison, with more thermal mass and less glazing area which would have helped in regulating and reducing any overheating potential. The occupants for this building, are much more aware and engaging with the operation of the building and they installed new internal blackout blinds for this summer as there had been more overheating incidents during the previous year.

In general the windows in Building One were either not open at the time that it was needed or in some cases they were not opened at all. During the time that the windows were opened and kept open for a long time, the effectiveness of higher ventilation and therefore consequent cooling was not apparent. This can only be down to lack of air change achieved by opening the windows and also perhaps the occupant only opened the window by tilting rather than fully opening the windows due to security concerns. The windows were also opened on the warmest time of the day which possibly would have been better to be kept closed. The internal and external blinds were also drawn throughout the day and night which would have reduced the airflow achieved through the windows. Furthermore, in general the windows were not left open during the night especially the windows on the ground floor (not even on tilt) due to security and noise reasons. When the occupants were asked whether they would leave the windows open when not at home, the answer was *‘never’*.

The table below indicates the percentage of the window openings during June, July and August with the average of the three months and the building in total.

Table 4-3- Indicating the percentage of window openings between June and August and the average per floor and building total

Floors	Window	June	July	August	Average three month	Average Floor	Average whole building
GF	1- W1 - Dining room	9%	20%	7%	12%		
GF	2- W2 - Living room	12%	8%	4%	8%		
GF	3- W8 - Kitchen	0%	0%	1%	0.3%		
GF	4- W5 - Living room / office	20%	33%	29%	27.3%		
GF						**11.9%**	
FF	5-W10 - Main bedroom	21%	41%	6%	22.6%		
FF	6- W12 - Bedroom 5	14%	12%	-----	13%		
FF	7- W18 - Master En-suite	10%	26%	11%	15.6%		
FF						**17.06%**	
SF	8- W24 - Bedroom 3	0%	6%	6%	4%		
SF	9- W21 - Bedroom 4	13%	37%	14%	21.3%		
SF						**12.65%**	
Whole building							**13.87%**

On average the windows were open for 13.87% during the three summer months and the percentage of window openings were similar on different floors with the first floor having the highest percentage at 17.06% (Table 4-2).

Moreover the percentages of overheating for all the monitored rooms were examined in relation to the window opening, average of RH and indoor CO_2 levels over the 1000ppm level (living room and master bedroom) for the three summer months. In general the RH average was low in all the rooms during the three months and was around 40% making the building slightly dry. The windows were not operated when they were needed and during the time that the windows were open the natural ventilation achieved was low leading to overheating in all the rooms.

On the other hand, the occupants of Building Two have adopted a strict regime in operating windows according to internal and external temperature and as at least one of the occupants spends the majority of the time at home, this has been made possible. Moreover the use of blinds are also part of the regime as there had been higher overheating percentage in the previous summer as noted by the occupant.

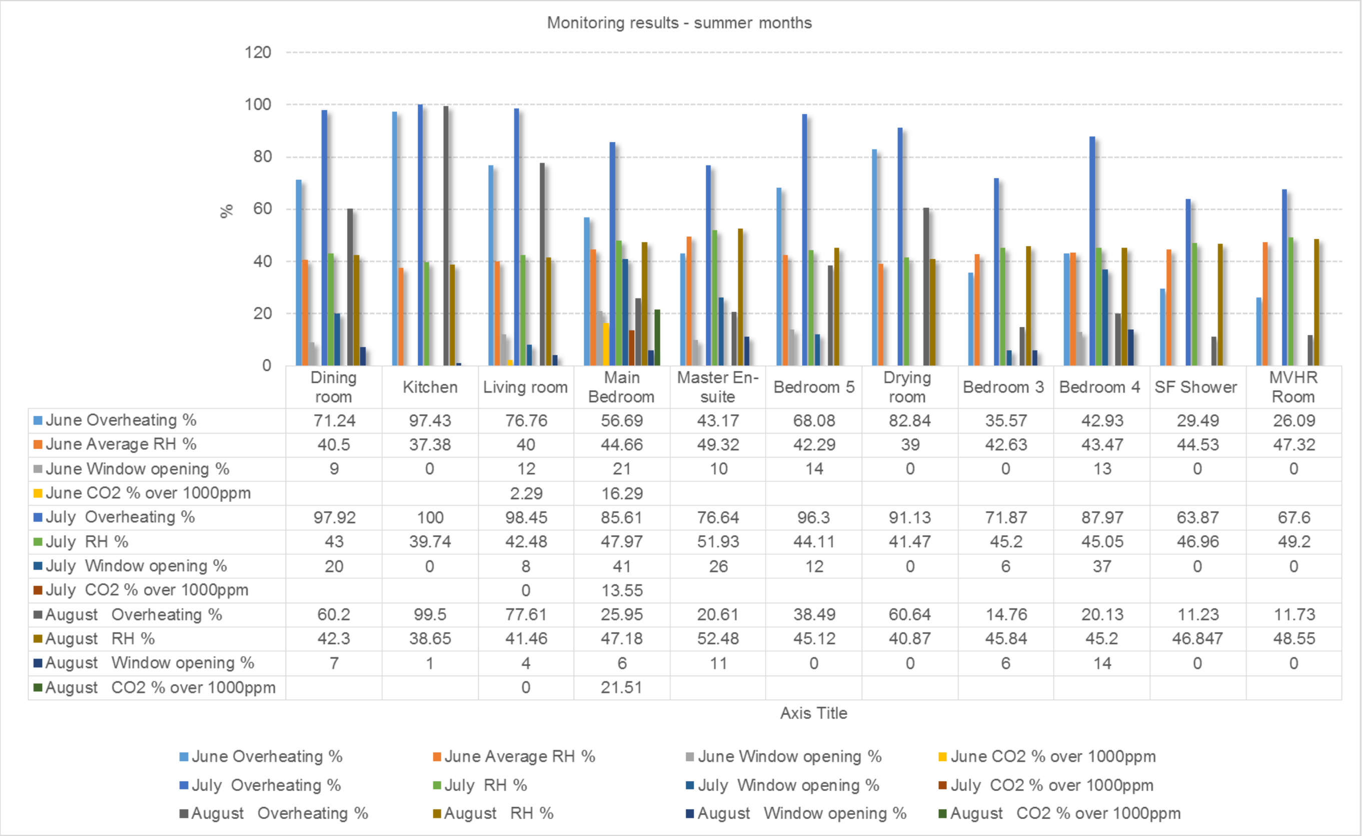
The table below indicates the percentage of the window openings during June, July and August with the average of the three months and the building in total.

Table 4-4- The percentage of window openings during June to August and the average per floor and building total

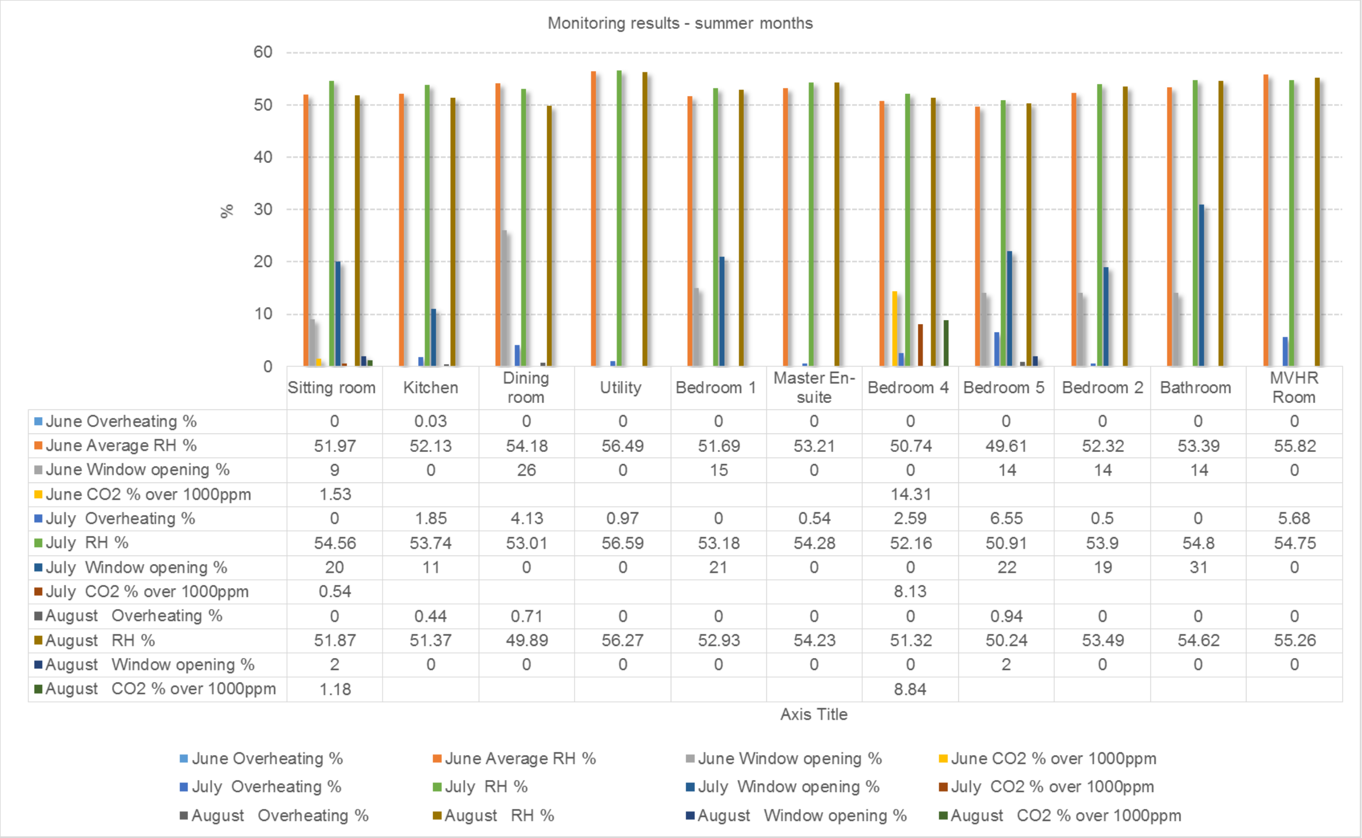
Floors	Window	June	July	August	Average three month	Average Floor	Average whole building
GF	1- W2 – Sitting room	9%	20%	2%	10.3%		
GF	2- W-D3 – Sitting room	-----	-----	-----	-----		
GF	3- D7 – Dining room	26%	-----	-----	26%		
GF	4- D4 – Dining room	-----	11%	0%	5.5%		
GF						**13.9%**	
FF	5-W13 Bedroom 1	15%	21%	0%	12%		
FF	6- W17 - Bathroom	14%	31%	0%	15%		
FF	7- W16 – Bedroom 4	-----	-----	-----	-----		
FF	8- W15 - Bedroom 5	14%	22%	2%	12.6%		
FF	9- W18 - Bedroom 2	14%	19%	0%	11%		
FF						**12.65%**	
Whole building							**13.27%**

On average the windows in Building Two were open for 13.27% during the three summer months which is very similar to Building One and the percentage of window openings were close on both floors with the ground floor having the highest percentage at 13.9%.

Moreover the percentages of overheating for all the monitored rooms were examined in relation to the window opening, average of RH and indoor CO_2 levels above the 1000ppm level (living room and main bedroom) for the three summer months. In general the RH average was better in this building in comparison to Building One at over 50%. The windows were opened a similar percentage to Building One, however this resulted in more effective ventilation and cooling effect with a significantly lower overheating percentage. The inward opening tilt system influences the total opening area of the window and therefore the possible natural ventilation rate and the associated possible cooling. The windows are open for only 85mm inwards with thick walls reducing the flow of the air. However Building Two benefited from glazed patio doors which were operated on the turn system increasing the openable area significantly and therefore the ventilation rate.



	Dining room	Kitchen	Living room	Main Bedroom	Master En-suite	Bedroom 5	Drying room	Bedroom 3	Bedroom 4	SF Shower	MVHR Room
June Overheating %	71.24	97.43	76.76	56.69	43.17	68.08	82.84	35.57	42.93	29.49	26.09
June Average RH %	40.5	37.38	40	44.66	49.32	42.29	39	42.63	43.47	44.53	47.32
June Window opening %	9	0	12	21	10	14	0	0	13	0	0
June CO2 % over 1000ppm			2.29	16.29							
July Overheating %	97.92	100	98.45	85.61	76.64	96.3	91.13	71.87	87.97	63.87	67.6
July RH %	43	39.74	42.48	47.97	51.93	44.11	41.47	45.2	45.05	46.96	49.2
July Window opening %	20	0	8	41	26	12	0	6	37	0	0
July CO2 % over 1000ppm			0	13.55							
August Overheating %	60.2	99.5	77.61	25.95	20.61	38.49	60.64	14.76	20.13	11.23	11.73
August RH %	42.3	38.65	41.46	47.18	52.48	45.12	40.87	45.84	45.2	46.847	48.55
August Window opening %	7	1	4	6	11	0	0	6	14	0	0
August CO2 % over 1000ppm			0	21.51							



	Sitting room	Kitchen	Dining room	Utility	Bedroom 1	Master En-suite	Bedroom 4	Bedroom 5	Bedroom 2	Bathroom	MVHR Room
June Overheating %	0	0.03	0	0	0	0	0	0	0	0	0
June Average RH %	51.97	52.13	54.18	56.49	51.69	53.21	50.74	49.61	52.32	53.39	55.82
June Window opening %	9	0	26	0	15	0	0	14	14	14	0
June CO2 % over 1000ppm	1.53						14.31				
July Overheating %	0	1.85	4.13	0.97	0	0.54	2.59	6.55	0.5	0	5.68
July RH %	54.56	53.74	53.01	56.59	53.18	54.28	52.16	50.91	53.9	54.8	54.75
July Window opening %	20	11	0	0	21	0	0	22	19	31	0
July CO2 % over 1000ppm	0.54						8.13				
August Overheating %	0	0.44	0.71	0	0	0	0	0.94	0	0	0
August RH %	51.87	51.37	49.89	56.27	52.93	54.23	51.32	50.24	53.49	54.62	55.26
August Window opening %	2	0	0	0	0	0	0	2	0	0	0
August CO2 % over 1000ppm	1.18						8.84				

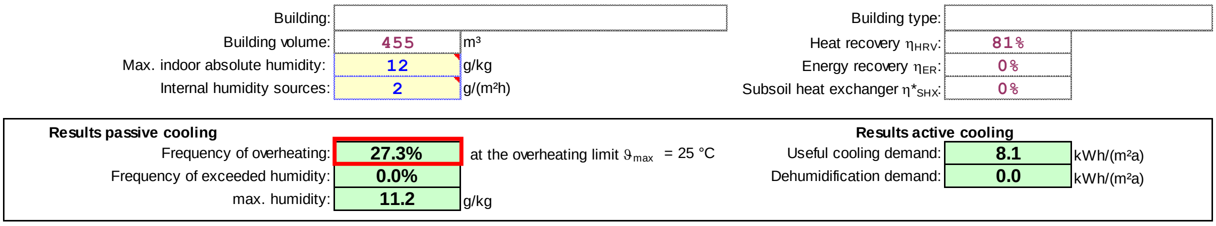
Figure 4-29- Monitoring result summary for Building One and Two – three summer months

4.2.3. Comparison of monitored data to PHPP calculations

PHPP8 results had indicated 8.5% of overheating during the summer for Building One with 0.22 air change per hour at night. To achieve the 0.22 of air change, four windows were specified to be opened on the ground floor for 10% of the night (on tilt) and eight windows on the first and second floor for 50% of the night similarly tilted. Effort was made to ensure shading patterns during the summer for this building’s model was representative of the actual building as the client keeps the shading closed due to privacy reasons.

Monitoring the building had indicated 21.13% of overheating for the whole of the year assuming the building was not overheated during the rest of the year. Considering that not every space was monitored in the building like the cupboards, corridors, etc. the percentage could be less weighted against the total floor area as per Passivhaus standard. Nevertheless the overheating percentage from the actual monitoring was much higher than the results from the recalculation done using PHPP8 and considerably more from the original calculation using PHPP7.

The results from window monitoring had indicated very limited or no night ventilation and the majority of windows were operated during the day time only. Eliminating the night ventilation from the PHPP8 calculation will increase the frequency of the overheating to 27.3% as it can be seen from the figure below.



Building:
Building volume: 455 m³
Max. indoor absolute humidity: 12 g/kg
Internal humidity sources: 2 g/(m²h)

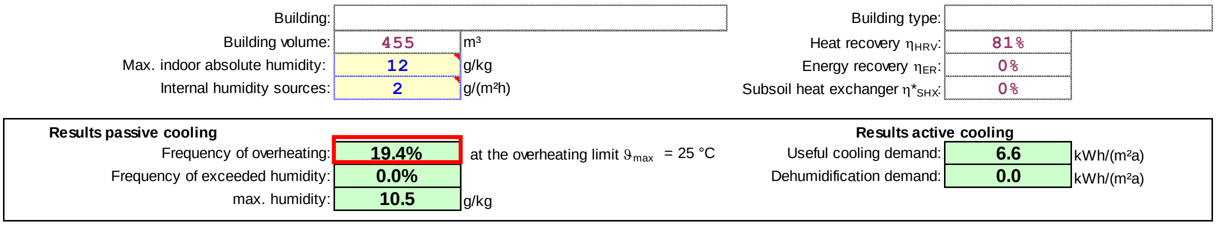
Building type:
Heat recovery η_{HRV}: 81%
Energy recovery η_{ER}: 0%
Subsoil heat exchanger η^*_{SHX}: 0%

Results passive cooling
Frequency of overheating: 27.3% at the overheating limit ϑ_{max} = 25 °C
Frequency of exceeded humidity: 0.0%
max. humidity: 11.2 g/kg

Results active cooling
Useful cooling demand: 8.1 kWh/(m²a)
Dehumidification demand: 0.0 kWh/(m²a)

Figure 4-30- Image indicating the frequency of the overheating using no additional ventilation

Moreover, introducing additional ventilation using the windows during the day will help to reduce the overheating percentage to 0.6% and at 2.5 ac/h the overheating would stay at 0.6%. However at 3.6 ac/h the overheating increases to 0.7%, (Table 4-5) indicating the importance of night time cooling. The 0.15 air change per hour will reduce the overheating to 19.4% (Figure 4-31) closer to the monitoring results (with a possible +/- 3.33% of PHPP accuracy - 18.76% to 20%).



Building:
Building volume: 455 m³
Max. indoor absolute humidity: 12 g/kg
Internal humidity sources: 2 g/(m²h)

Building type:
Heat recovery η_{HRV}: 81%
Energy recovery η_{ER}: 0%
Subsoil heat exchanger η^*_{SHX}: 0%

Results passive cooling
Frequency of overheating: **19.4%** at the overheating limit ϑ_{max} = 25 °C
Frequency of exceeded humidity: **0.0%**
max. humidity: **10.5** g/kg

Results active cooling
Useful cooling demand: **6.6** kWh/(m²a)
Dehumidification demand: **0.0** kWh/(m²a)

Figure 4-31- Image indicating the frequency of the overheating using windows during day for additional ventilation

Table 4-5 – Daytime ventilation and overheating

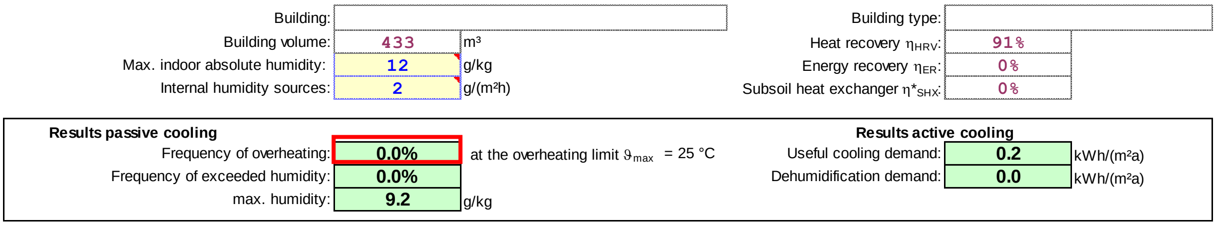
Additional Daytime Ventilation Rate using windows	0	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	2.5
Overheating percentage	27.3%	22.0%	19.4%	17.1%	15%	13.1%	11.3%	9.9%	8.8%	7.8%	0.6%

The recalculation with no night time ventilation and with 0.15 air change per hour additional ventilation achieved during the day has made the frequency of the overheating comparable to the actual monitoring results. This highlights the importance in specifying night time ventilation in PHPP which might not be achieved especially at 50% of the time during the night in addition to the limited day time ventilation achieved by using the windows.

Recalculation carried out using PHPP8 for Building Two had indicated 7.6% of overheating during the summer. Similarly to Building One, night time ventilation was used at 0.22 air change per hour. The additional calculation using PHPP7 had not indicated any overheating and therefore no summer shading was entered into PHPP or specified for the building. However currently the occupants are using blackout internal blinds following some overheating during the previous summer in 2013.

Monitoring the temperature had indicated 0.26% of overheating for the entire year assuming no further incidents of overheating were recorded for the whole building. The 0.26% does not take the corridors, cupboards, etc. into consideration as they were not monitored and perhaps this would further reduce the percentage of overheating. Moreover similarly to Building One, window monitoring indicated very little or no window operation during the night and the majority of the window opening was during the day.

The calculation from PHPP8 indicates a much higher percentage of overheating in comparison to the actual monitoring results. Therefore taking the additional shading used by the occupants into consideration alongside no night time ventilation and limited day time natural ventilation, recalculation was carried out using PHPP8 as can be seen below.



Building:
Building volume: 433 m³
Max. indoor absolute humidity: 12 g/kg
Internal humidity sources: 2 g/(m²h)

Building type:
Heat recovery η_{HRV}: 91%
Energy recovery η_{ER}: 0%
Subsoil heat exchanger η^*_{SHX}: 0%

Results passive cooling
Frequency of overheating: **0.0%** at the overheating limit ϑ_{max} = 25 °C
Frequency of exceeded humidity: **0.0%**
max. humidity: **9.2** g/kg

Results active cooling
Useful cooling demand: **0.2** kWh/(m²a)
Dehumidification demand: **0.0** kWh/(m²a)

Figure 4-32- Overheating percentage using windows during for additional day time ventilation and the actual shading used in the building

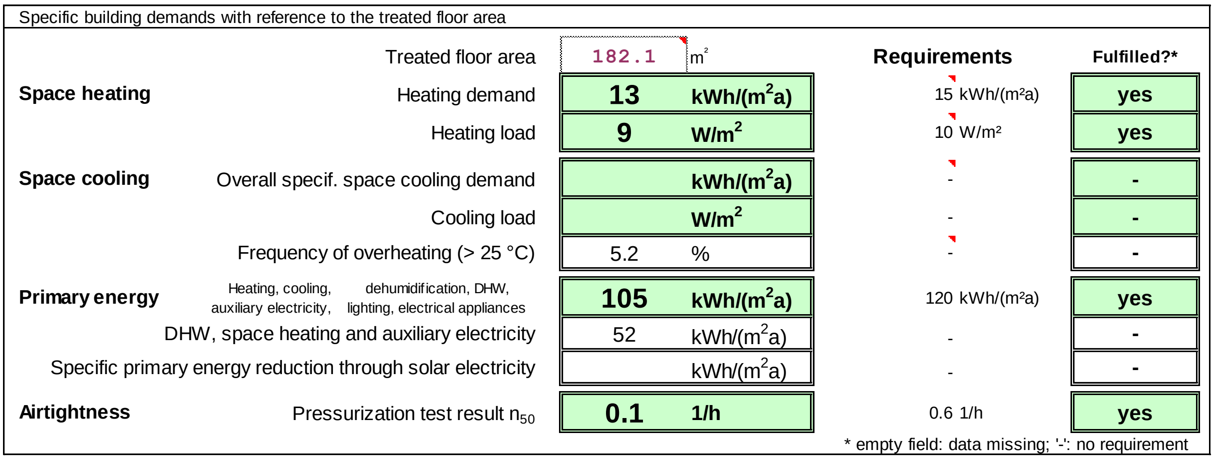
Additional summer shading was entered as 60% reduction and day time natural ventilation of 0.15 air change per hour. The frequency of the overheating has been therefore reduced to 0% which is comparable to the actual monitoring results.

Once again the importance of inputting the correct and representative data into PHPP has been highlighted especially the limitation for night time ventilation using the windows.

4.2.4. Location-based PHPP investigation

Building One benefits from lightweight construction and 34.29m^2 of glazing area which 18.73m^2 of it is south facing as mentioned in the building's introduction section (Section 3.2.1). The recalculation using PHPP8 had highlighted 8.5% of overheating during the summer with 'Thames Valley' used for its climate data.

Investigation was carried out to examine the effect of relocating the building to the location of Building Two with respect to the overheating percentage, keeping all the rest of the inputs the same. Below are the results using 'Midlands' as the climate which is used for Building Two.



Specific building demands with reference to the treated floor area

	Treated floor area	182.1	m^2	**Requirements**	**Fulfilled?***
Space heating	Heating demand	**13**	**$kWh/(m^2a)$**	15 $kWh/(m^2a)$	**yes**
	Heating load	**9**	**W/m^2**	10 W/m^2	**yes**
Space cooling	Overall specif. space cooling demand		**$kWh/(m^2a)$**	-	**-**
	Cooling load		**W/m^2**	-	**-**
	Frequency of overheating (> 25 °C)	5.2	%	-	**-**
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances	**105**	**$kWh/(m^2a)$**	120 $kWh/(m^2a)$	**yes**
	DHW, space heating and auxiliary electricity	52	$kWh/(m^2a)$	-	**-**
	Specific primary energy reduction through solar electricity		$kWh/(m^2a)$	-	**-**
Airtightness	Pressurization test result n_{50}	**0.1**	**1/h**	0.6 1/h	**yes**

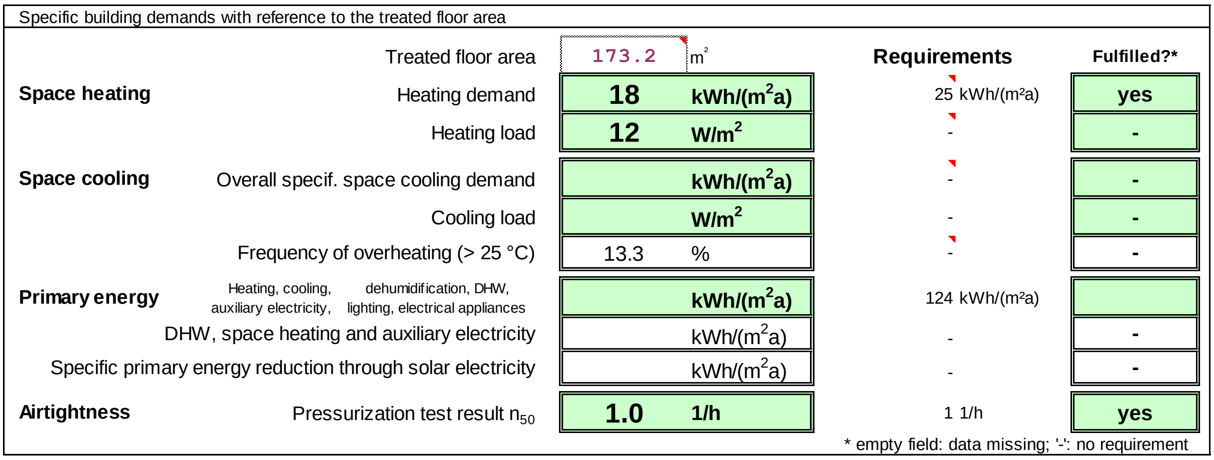
* empty field: data missing; '-': no requirement

Figure 4-33- Extraction from the verification sheet using Building Two's weather data

The heating demand was increased from 11kWh/(m^{2}a) to 13 kWh/(m^{2}a) and the heating load was not changed and stayed at 9W/m^2. More importantly the overheating percentage was reduced from 8.5% to 5.2% if the building was constructed in the location of Building Two. The building would have still been certified as Passivhaus as the heating demand and the heating load are under the required limit, however the cooler climate would have reduced the overheating by around 3.3% which is a relatively noticeable amount.

Building Two uses heavyweight construction with less glazing area in comparison to Building One. The glazing area is 23.91m^2 with only 2.86m^2 of south glazing which is over 10m^2 and 15m^2 less respectively compared to Building One. Using PHPP8, the overheating percentage was calculated as 7.6% during the summer with ‘Midlands’ as its climate data.

Investigation was carried out to examine the effect of relocating the building to the location of Building One in respect to the overheating percentage keeping all the rest of the data the same. Below are the results using ‘Thames Valley’ as the climate which is used for Building One.



Specific building demands with reference to the treated floor area

				Requirements	Fulfilled?*
	Treated floor area	173.2	m^2		
Space heating	Heating demand	**18**	**kWh/(m^{2}a)**	25 kWh/(m²a)	**yes**
	Heating load	**12**	**W/m^2**	-	**-**
Space cooling	Overall specif. space cooling demand		**kWh/(m^{2}a)**	-	**-**
	Cooling load		**W/m^2**	-	**-**
	Frequency of overheating (> 25 °C)	13.3	%	-	**-**
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances		**kWh/(m^{2}a)**	124 kWh/(m²a)	
	DHW, space heating and auxiliary electricity		kWh/(m^{2}a)	-	**-**
	Specific primary energy reduction through solar electricity		kWh/(m^{2}a)	-	**-**
Airtightness	Pressurization test result n_{50}	**1.0**	**1/h**	1 1/h	**yes**

* empty field: data missing; '-': no requirement

Figure 4-34- Extraction from the verification sheet using Building One’s weather data

The heating demand was reduced from 20kWh/(m^{2}a) to 18kWh/(m^{2}a) with a small reduction in heating load from 13W/m^2 to 12W/m^2. Moreover the overheating percentage was increased from 7.6% to almost double at 13.3%. The building would have met the EnerPhit requirement for the heating demand, however the overheating would have passed the 10% limit if the building was constructed in the location of Building One.

4.3. INVESTIGATION INTO MVHR USAGE DURING SUMMER

Using the MVHR during the summer as part of the ventilation strategy in Passivhaus is required as there will be a need for the extraction from the wet rooms and kitchen even if the windows are kept open in other parts of the building at all times. As highlighted in the literature review and now recognised in PHPP8, there will be an extra heat gain associated from the use of MVHR during the summer time which is calculated under the internal heat gain section. The literature review had also indicated the possibility of low ventilation rate achieved by using the MVHR during the summer alongside a question regarding the summer bypass option which is not a requirement of the Passivhaus standard. Moreover the fixed occupancy rate of 35m^2 per person can not only have an impact on the internal heat gains specifically for smaller dwellings during the summer (Grant & Clarke, n.d.), but also it can have implications for the ventilation requirements especially during a short period of change in occupation rate which can lead to over or under ventilating.

4.3.1. Summer bypass option

Building One Passivhaus uses ‘Zehnder-Comfoair 550’ for the mechanical ventilation with heat recovery (Figure 4-35) with effective heat recovery efficiency calculated from the PHPP at 81.3%. The certified efficiency for ‘Comfoair 550’ is 84% with an electrical efficiency of 0.31Wh/m^3 and the unit range is 110-308m^3/h. The unit and its control are located inside the thermal envelope in the cupboard located on the second floor, accessed from the bathroom.

Figure 4-35- MVHR unit located in the cupboard (image on the left) and the control also located in the cupboard (image on the right) (source: author)

The figures below indicate the layout and location of the MVHR and its ducting for the different floors.

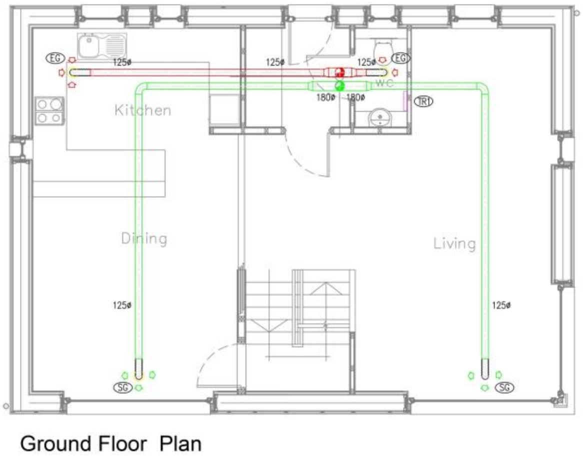


Figure 4-36- GF plan indicating the MVHR ducting layout – green is the supply air and red is the extract air (source: Eco Design consultants)

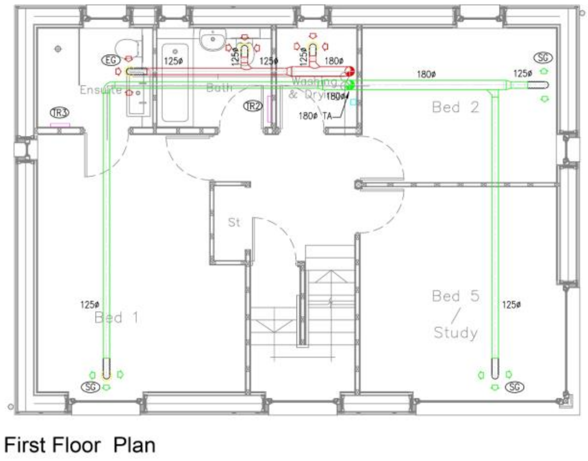


Figure 4-37- FF plan indicating the MVHR ducting layout – green is the supply air and red is the extract air (source: Eco Design consultants)

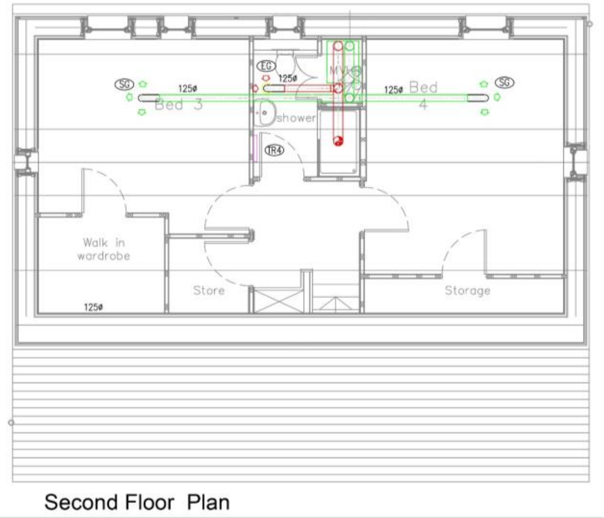


Figure 4-38- SF plan indicating the MVHR ducting layout and the location of the MVHR unit – green is the supply air and red is the extract air – MVHR is located in a separated cupboard in the second floor bathroom (source: Eco Design consultants)

The supply fresh air is through the Northeast wall at a high level and the extract exhaust air through the roof above (Figure 4-39). Moreover the unit benefits from summer bypass option which is automatically activated by pre-setting the required comfort temperature. The summer bypass is activated when the comfort temperature is passed and if the outdoor temperature is not too high to allow the indoor temperature to stay as close as possible to the pre-set comfort temperature. The comfort temperature has been set to 21°C as recommended by the manufacturer.

Figure 4-39- Rear elevation (northeast) indicating the location of the extract through the roof and the fresh air through the wall (highlighted in red) (source: author)

The building had used PHPP7 during the design stage and the certification and since then PHPP7 has been updated by Passivhaus institute to PHPP8. The new PHPP summer ventilation sheet, has been restructured considerably with four new options regarding the summer bypass mode. The four options are (Passive House Institute, 2013):

- None (Always bypass or pure supply air ventilation unit)
- Automatic bypass, controlled by temperature difference
- Automatic bypass, controlled by enthalpy difference
- Always (no bypass)

The initial calculation using PHPP7 had indicated no potential overheating when the MVHR is used throughout the year with summer bypass option and night time ventilation achieving an additional 0.22 air change /h by operating the window during the night. However carrying out the calculation using PHPP8 with higher internal heat gains indicates 8.5% frequency of overheating. The same rate of ventilation has been entered for the night time ventilation with summer bypass option controlled by the temperature.

Moreover it should be noted that the new PHPP recognises the difficulty or even impossibility of night time ventilation due to security, noise, weather conditions and insurance purposes (Passive House Institute, 2013).

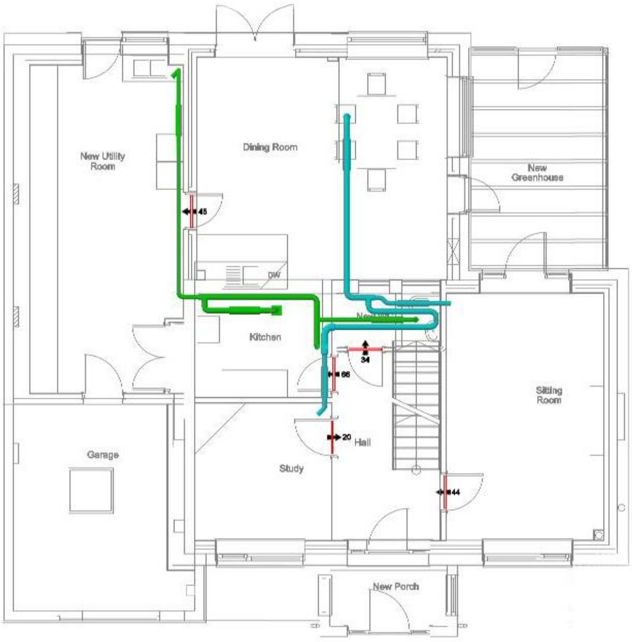
Recalculation was carried out to see the effect of the summer bypass option keeping all the other data the same. Selecting the ‘no bypass option’ for the summer period (always) will increase the frequency of the overheating from 8.5% to 17.1% which is no longer acceptable under the Passivhaus standard of 10% for overheating.

Building Two (EnerPhit) has been designed using a ‘PAUL novus 300’ MVHR unit with effective heat recovery efficiency calculated from the PHPP of 91.2%. The certified efficiency for ‘PAUL novus 300’ is 93% with electrical efficiency of 0.24Wh/m^3 and the unit range is 121-231 m^3/h (Figure 4-40)

Figure 4-40- MVHR unit located in the loft (part of the thermal envelope) (image on the left) - MVHR control located in the second floor landing (image on the right) (source: author)

The following figures indicate the layout and location of the MVHR and its ducting for the different floors.

Figure 4-41- Ground floor plan indicating the MVHR ducting layout – blue is the supply air and green is the extract air (source: Eco Design Consultants)



Ground Floor

Figure 4-42- First floor plan indicating the MVHR ducting layout – blue is the supply air and green is the extract air (source: Eco Design Consultants)

First Floor

The MVHR unit is located in the attic space which is part of the thermal envelope and the supply air and extract are located in the northeast wall close together with the extract being located below the supply air which can increase the possibility of short-circuiting as it can be seen from the figures below. Moreover the unit benefits from automatic summer bypass option set at 23°C.

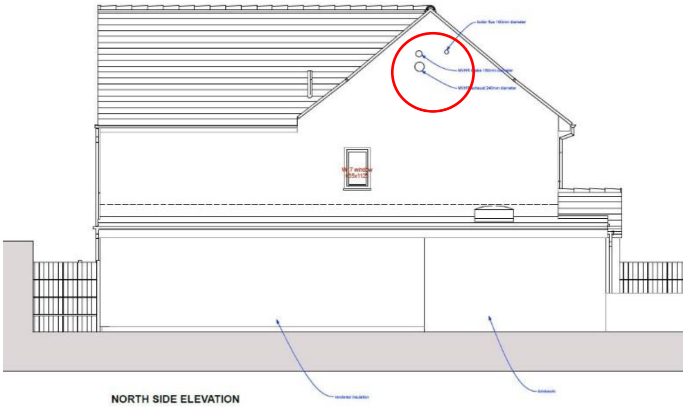


Figure 4-43- Northeast elevation drawing indicating the supply and extract air location through the wall also location of the boiler flue on the right (source: Eco Design Consultants)

Figure 4-44- View of the building showing the as built location of supply and extract air as well as the boiler flue (source: author)

The extraction for the boiler has also been located close to the supply air (right hand side) which can increase the possibility of contamination and reduction of the indoor air quality. Moreover recalculation was also carried out for this building using PHPP8 which indicated 7.6% overheating problem compared to the previous calculation with much less internal heat gain and 0% overheating potential. Both calculations benefit from night time cooling from manual window opening with 0.22 air change /h.

Summer bypass option controlled by the temperature was used to calculate the summer ventilation leading to 7.6% of overheating. Carrying out the calculation by selecting ‘no bypass option’ for the summer period (‘always’) will increase the frequency of the overheating from 7.6% to 19.8%.

4.3.2. Air duct insulation and temperature

The temperature of the incoming fresh air could be increased internally as there are no requirements under the Passivhaus standard for insulating the MVHR ducts inside the thermal envelope after the MVHR unit with no post heater. Although this might be beneficial during the winter time, the lack of insulation might be a further contributor to the summer overheating as the internal temperature rise can increase the incoming fresh air temperature depending on the location and length of the supply fresh air ducts. In order to examine this, temperature loggers where placed in the supply air outlet of the living room and the master bedroom to monitor the relation of the internal temperature and the incoming fresh air temperature. It should be noted that an accuracy margin of +/- 0.5°C should be taken into consideration.

The figures below indicate the supply air temperature in relation to ambient and indoor temperature for June, July and up to the 13th August in the master bedroom and the living room.

Master Bedroom:

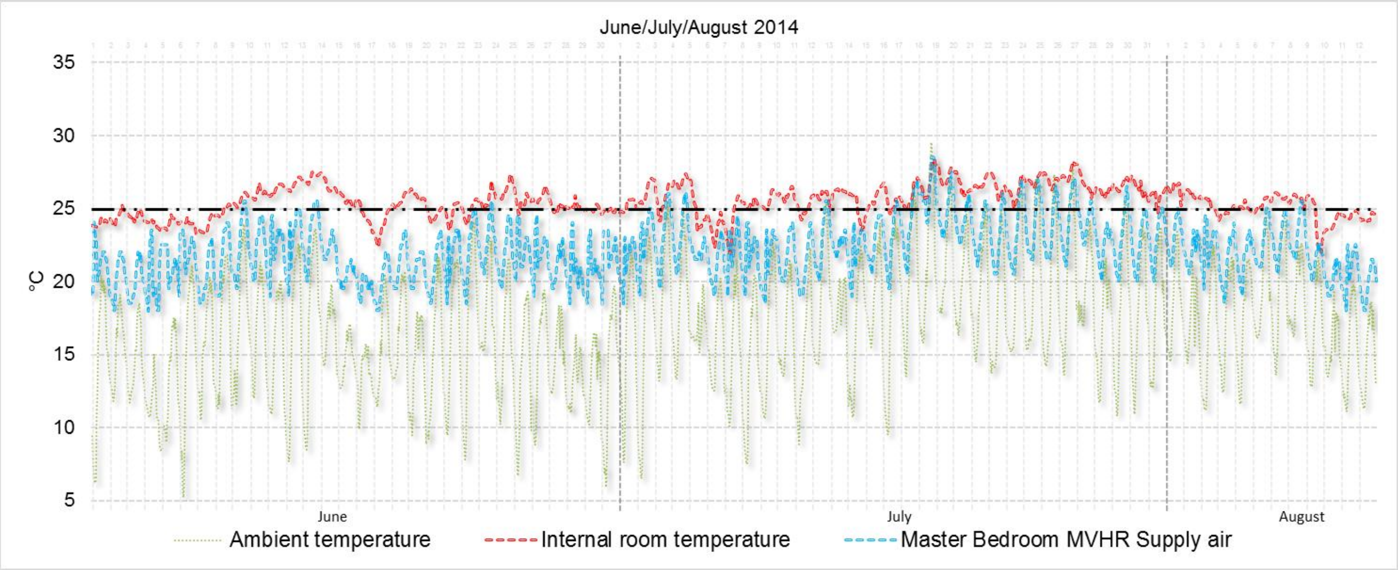


Figure 4-45- Hourly supply air temperature in relation to ambient and the internal temperature – Master Bedroom – Building One

Living room:

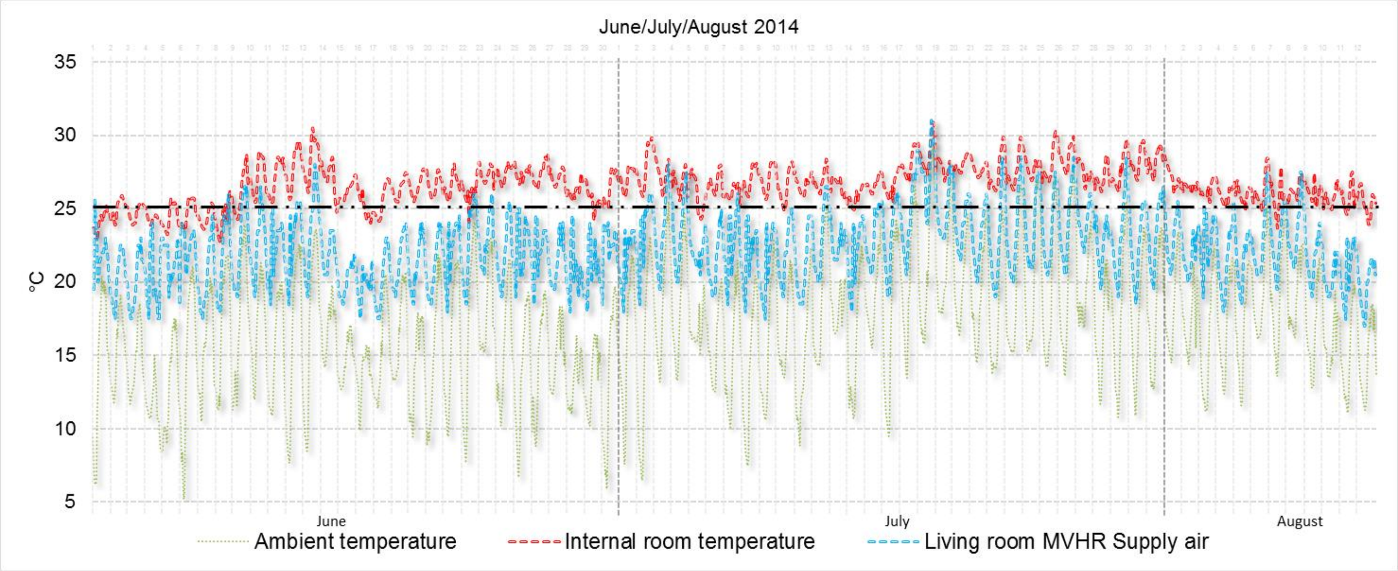


Figure 4-46- Hourly supply air temperature in relation to ambient and the internal temperature – Living Room - Building One

As it can be seen from the above graphs, almost all the time the incoming fresh air from the MVHR has been higher than the ambient temperature for both locations despite the summer bypass option being activated. The higher incoming fresh air temperature has perhaps been influenced by the lack of insulation around the duct and in some cases the higher microclimate surrounding the intake externally (refer to section 4.3.1)

Moreover the summer bypass option is deactivated below 21°C as can be seen from above and the incoming fresh air temperature therefore has been kept as close to 20°C as possible regardless of higher internal temperatures and perhaps the need for cooling. This option should be possible to turn off especially if the night time cooling is part of the ventilation strategy and used to reduce the internal thermal mass temperature.

Further investigation is also required to examine the incoming fresh air temperature as it is entering the MVHR and just after the unit, as well as the entry point to the room to distinguish the level of increase in temperature at different stages, which due to limitations has not been part of this research.

Similarly to Building One, the possible effect of temperature rise on the incoming fresh air and the influence of the internal temperature on this was examined by placing temperature loggers in the MVHR fresh air outlet to the main bedroom and the sitting room. Although the MVHR unit for this building is located inside the thermal envelope (like Building One), it is actually located in the loft which is not necessarily used regularly and only as a storage space. Therefore no glazing and no additional internal gains are present in this space and the majority of the MVHR ducts are located in this relatively large space. Moreover the lack of solar gain and internal gains has led to less temperature fluctuations and even lower temperatures in the loft (refer to section 5.1.1).

The figures below indicate the supply air temperature in relation to ambient and indoor temperature for June, July and up to 13th August in the main bedroom and the sitting room.

Main Bedroom:

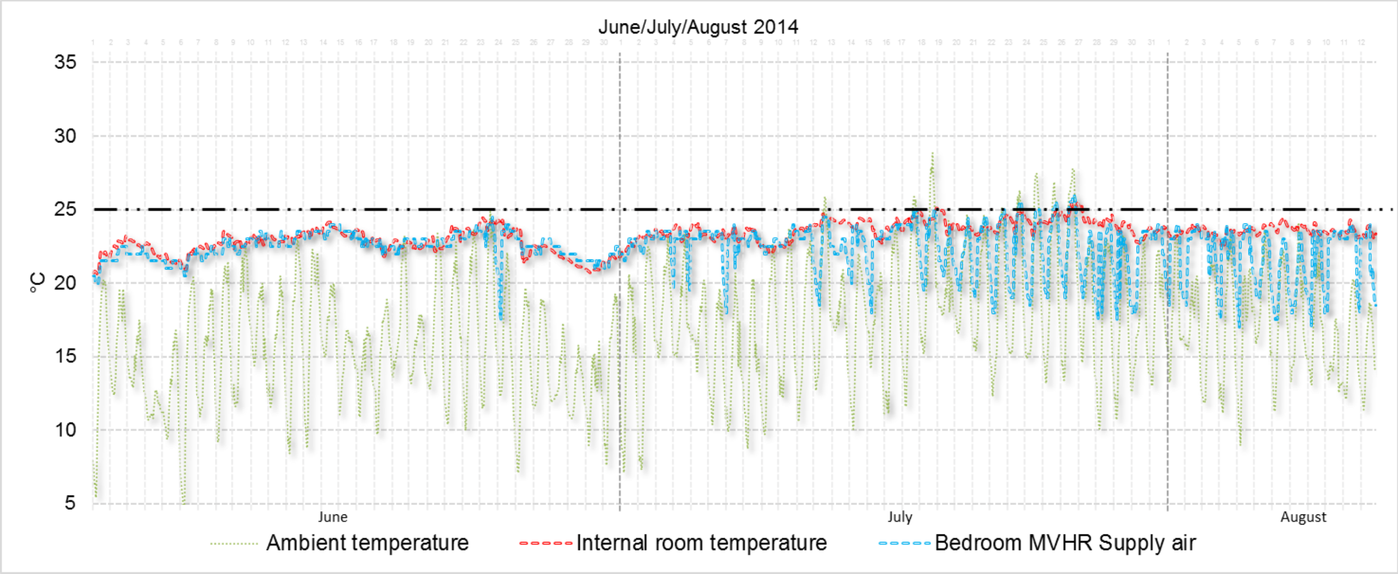


Figure 4-47- Hourly supply air temperature in relation to ambient and the internal temperature – Building Two

As it can be seen from the above and below graphs, during the majority of the time the incoming fresh air from the MVHR has been higher than the ambient temperature for both rooms like the Building One, however the temperatures are within the summer bypass setting of 23°C. The lack of insulation around the incoming fresh air ducts has perhaps less effect for this building as the loft space (where the majority of ducts are run) is cooler and generally around 23°C - 24°C. The effect of the microclimate surrounding the intake externally is examined in section 4.3.1.

Moreover the summer bypass option is deactivated below 23°C as can be seen from above and the incoming fresh air temperature therefore has been kept as close to 20°C as possible regardless of internal temperatures and possible desire for cooling. This option should be possible to turn off especially if the night time cooling is part of the ventilation strategy and used to reduce the internal thermal mass temperature especially as the window operation is almost non-existent during the night (refer to section 5.1.3).

Further investigation however is required to examine the incoming fresh air temperature at the point of entry into the MVHR and just after the unit as well as the entry point to the room to distinguish the level of increase in temperature at different stages which has not been part of this research. The graphs below are the relation of the incoming fresh air temperature compared to the ambient and room temperature for the sitting room.

Sitting room:

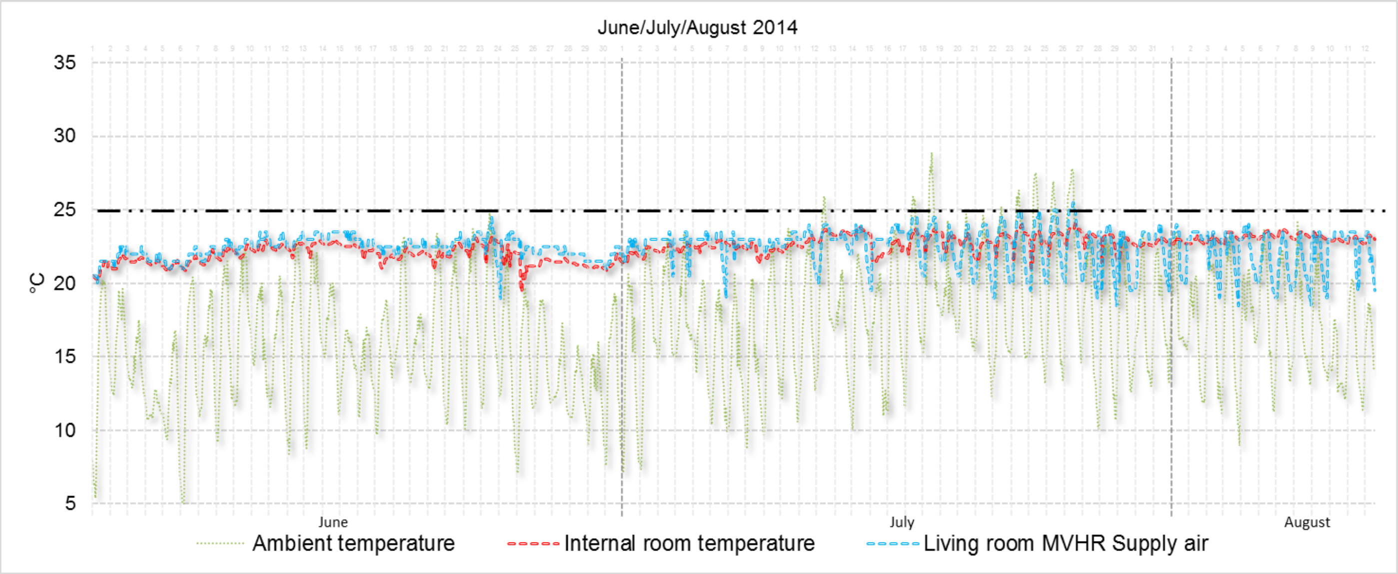


Figure 4-48- Hourly supply air temperature in relation to ambient and the internal temperature – Building Two

4.4. FRESH AIR INTAKE AND LOCALISED MICROCLIMATE

In order to control and reduce the potential of overheating in buildings especially in very airtight buildings like Passivhaus, it is important to provide an adequate rate of ventilation especially during the cooling season. Passivhaus ventilation in the UK climate requires the use of MVHR and the two case study buildings chosen, continue using MVHR during the summer period with the benefit of summer bypass option and this has provided the opportunity to examine the microclimate surrounding the fresh air intake of the MVHR. The property of the surface material used adjacent to the fresh air intake and its colour as well as the location and proximity to the exhaust air can play an important role in providing cool fresh air into the building.

Passivhaus institute has also acknowledged the importance of the properties and type of material used in the façade, the solar absorbency associated with the orientation and the material absorbency. This has led to the incorporation of a dedicated section in the area sheet in PHPP8 for orientation of walls, exterior absorptivity and emissivity, also a reduction factor associated with the shading which can have an important impact in the warmer climate. Although this is not necessarily directly linked to the temperature of the incoming fresh air, nevertheless the importance of the material type and its absorbency has now been included in the PHPP8. (Passive House Institute, 2013)

As the Passivhaus requirements and the Building Regulations do not currently make any reference to the location of the fresh air intake (section 3.3.3), in this section the following will be examined:

- Material properties immediate to the fresh air intake (Thermal mass of the material)
- Material colour (absorption)
- Location of the intake (in relation to the sun & height)
- Positioning of the intake (in regards to exhaust air)
- Night time ventilation (in regards to temperature)

For this experiment a thermal imaging camera was used for capturing the surface temperature of the material used close to the fresh air intake. The measurement was repeated every hour throughout the day, from 9:00am until 10:00p.m on 16th July 2014 when the temperature stayed fairly warm and mostly sunny.

4.4.1. Material thermal mass and temperature

The fresh air intake for building one (Passivhaus) has been located on the northeast wall (20° to east from the north) with the exhaust outlet being located on the roof and therefore above the fresh air intake (Figure 4-53). The distance between the intake and extract is fairly close approximately 600mm away from each other. However positioning the extract above the intake has reduced the possibility of cross contamination and short circuiting especially during the winter period, because the exhaust air will always be warmer than the ambient air temperature and therefore rise away from the intake. Moreover by locating the extract on the roof rather than the wall, it has increased the benefit of the higher wind speed and lack of obstruction and ensures the possibility of the short circuiting has been kept to a minimum.

Figure 4-49- Northeast façade indicating the position of the MVHR extract and intake, extract is located on the roof and the intake on the wall below the extract.

The northeast wall has been constructed using a lightweight structure, achieving a U-Value of 0.137 W/m^{2}K. The 300mm timber frame structure has been filled with Warmcell insulation and the 18mm OSB board provides the airtight layer internally with a 38mm service gap and 2 layers of 12.5mm plasterboard. Externally surrounding the MVHR fresh air intake, the wall has been finished using dark grey fibre cement tiles over battens and counter battens.

The surface temperature of the dark grey fibre cement tiles adjacent to the MVHR fresh air intake were measured using a thermal imaging camera throughout the day to examine the effect of the material's thermal mass. Figure 4-54 demonstrates the surface temperature of the material in relation to the external temperature during the 16th July for every hour from 9:00am until 10:00pm.

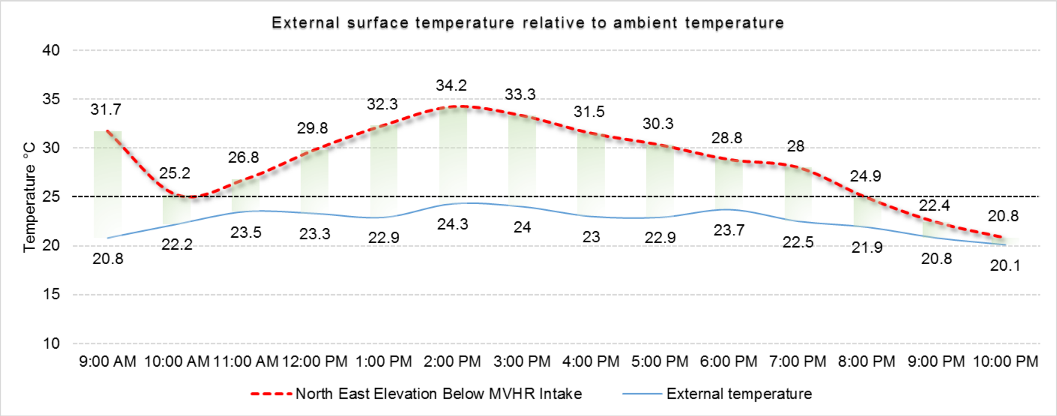
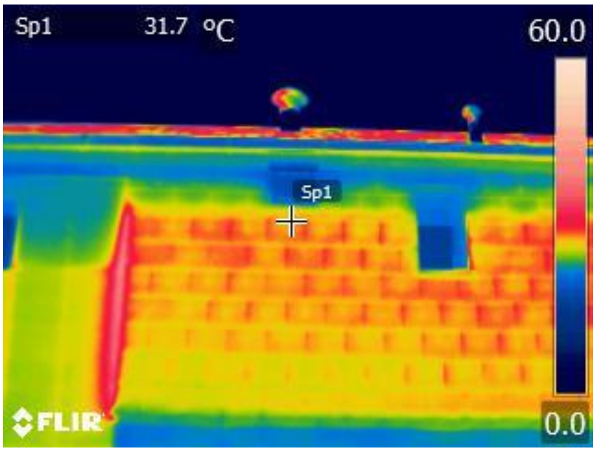


Figure 4-50- Relation between the surface temperature surrounding the MVHR fresh air intake and the ambient temperature. (Sunset at 9:14pm.)

As the MVHR intake is located on the northeast façade, during the early time of the day the microclimate surrounding the fresh air intake is influenced by the direct solar gain even though the ambient temperature is not necessarily too high. This is also effected by the material's dark colour which helps to absorb the heat from the sun and therefore reaching above 31°C at 9:00am (Figure 4-55). However by 10:00am the sun moves around and the area is no longer under the direct solar gain which helps the temperature of the tiles to fall to around 25°C. This temperature drop is also helped by the limited thermal mass of the material due to the thickness of the tiles and the lightweight construction.

Figure 4-51- Surface temperature of 31.7°C measured at 9:00am (MVHR fresh air intake – Northeast elevation)



The surface temperature of the fibre cement tiles reaches around 34°C (Figure 4-56) during the day as the ambient temperature rises, however the 34°C is much less compared to the 52°C of the southeast façade under the direct sunlight (Figure 4-57) which highlights the importance of the location of the fresh air intake regarding the orientation and possible shading.

Figure 4-52- Surface temperature reaching 34.2°C measured at 2:00pm (MVHR fresh air intake – Northeast elevation)

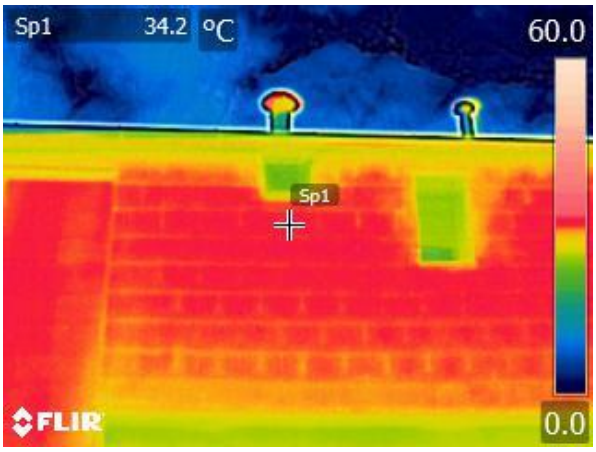
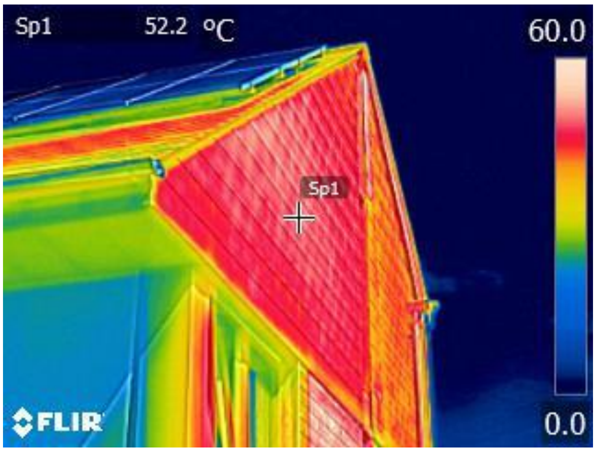
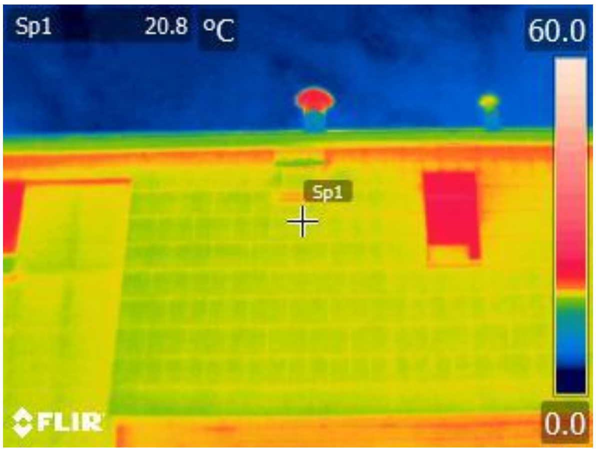


Figure 4-53- Surface temperature reaching 52.2°C measured at 11:00am (Southeast elevation)



As the ambient temperature falls back to around 20°C at 10:00pm, the surface temperature of the fibre cement tiles also falls to just above the ambient temperature at 20.8°C (Figure 4-58). This temperature drop should help the night time ventilation and ensure that the temperature of the incoming fresh air is not unnecessarily too high and importantly above the thermal comfort for night time cooling.

Figure 4-54- Surface temperature reaching 20.8°C measured at 10:00pm (MVHR fresh air intake – Northeast elevation)



Subsequently the temperature of the grass on the ground below the MVHR fresh air intake (grass in front of the entrance door) was measured at 3:00pm and 10:00pm to investigate the softer surface and use of vegetation in relation to temperature. The temperature of the grass was recorded at just over 23°C (Figure 4-59) when the tiles of the wall were above 33°C at 3:00pm and during the night (10:00pm), the grass temperature fell to 19.6°C (Figure 4-60) which was much closer to the ambient temperature.

Figure 4-55- Grass temperature of 23.4°C on the ground measured at 3:00pm

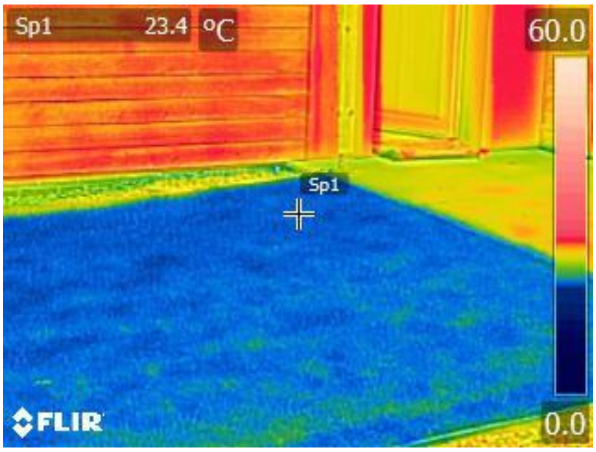
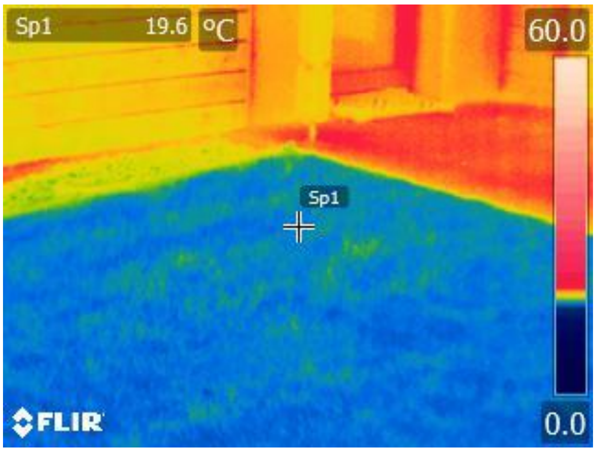


Figure 4-56- Grass temperature of 19.6°C on the ground measured at 10:00pm



Similarly to Building One (Section 4.3), the surface temperature of the material surrounding the fresh air intake was examined by using a thermal imaging camera on the 17th July 2014 from 9:00am until 10:00pm to study the following:

- Material properties immediate to the fresh air intake (Thermal mass of the material)
- Material colour (absorption)
- Location of the intake (in relation to the sun & height)
- Positioning of the intake (in regards to exhaust air)
- Night time ventilation (in regards to temperature)

The MVHR fresh air intake for Building Two (EnerPhit) has also been located in the northeast wall (20° to east from the north) which makes the two buildings highly comparable for this examination. However the extract air for this building has been located on the same wall and not above the fresh air intake and rather below it with approximately 800mm distance in between. This arrangement and positioning of the intake and extract could increase the possibility of cross contamination and short circuiting between the extract and intake air. Short circuiting could be especially increased during the winter period as the extract air will almost always be warmer than the ambient air and therefore rise towards the fresh air intake (Figure 5-61).

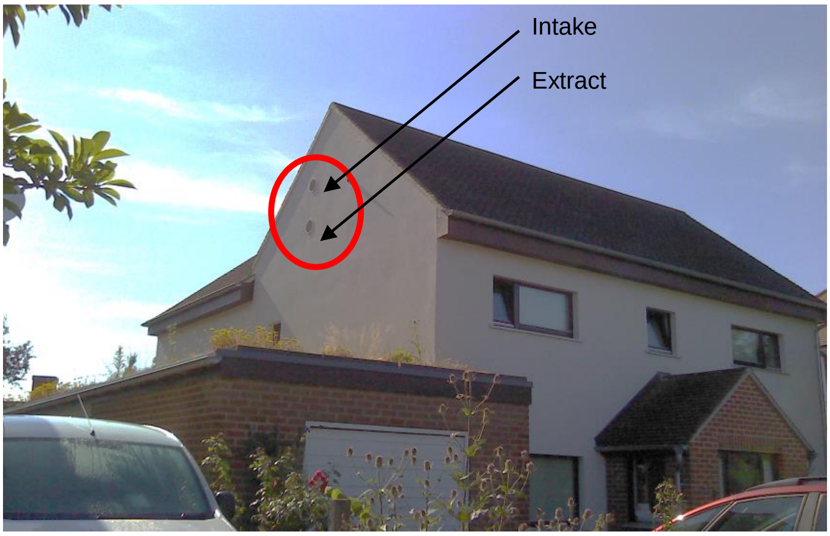


Figure 4-57- Northeast façade indicating the position of the MVHR extract and intake, extract is located below the intake on the wall.

The external wall surrounding the MVHR fresh air intake benefits from thermal mass internally but not necessarily externally. The existing fully filled cavity wall has been plastered internally to provide the finish and the airtightness layer and the external brick leaf has been covered using 250mm Neopor insulation with 10mm light colour render achieving a U-Value of 0.098 W/m^{2}K.

The surface temperature of render was measured from 9:00am till 10:00pm hourly to be able to examine the thermal mass and absorbency of the material using a thermal imaging camera. The figure below demonstrates the surface temperature of the material in relation to the external temperature.

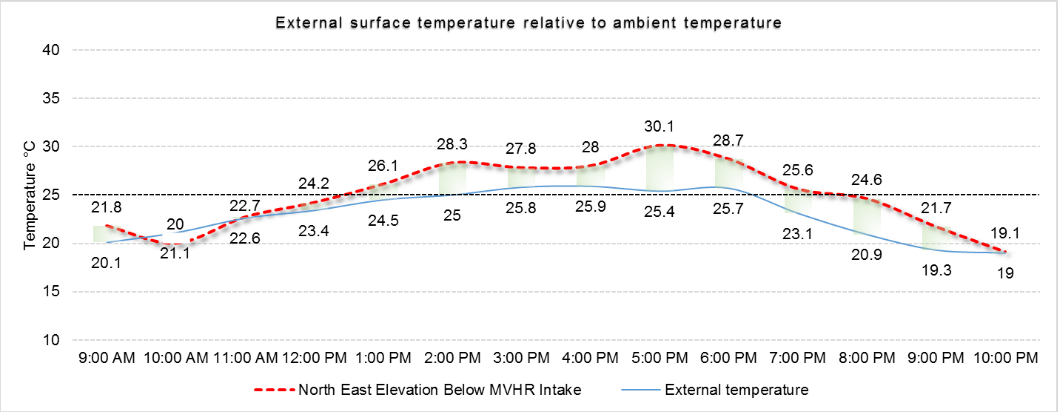


Figure 4-58- Relation between the surface temperature surrounding the MVHR fresh air intake and the ambient temperature. (Sunset at 9:21pm.)

The orientation of the MVHR fresh air intake in relation to the sun allows the direct solar gain to heat up the surface during the early part of the day and as it can be seen from the graph above at 9:00am the surface temperature of the render reaches almost 22°C when the outside temperature is 20°C. However as the sun moves around and the area is no longer under the direct solar gain the surface temperature of the render falls to around 20°C. This temperature drop is perhaps also achieved due to the limited amount of thermal mass of the 10mm render and its light colour leading to lower absorbency (Figure 4-63).

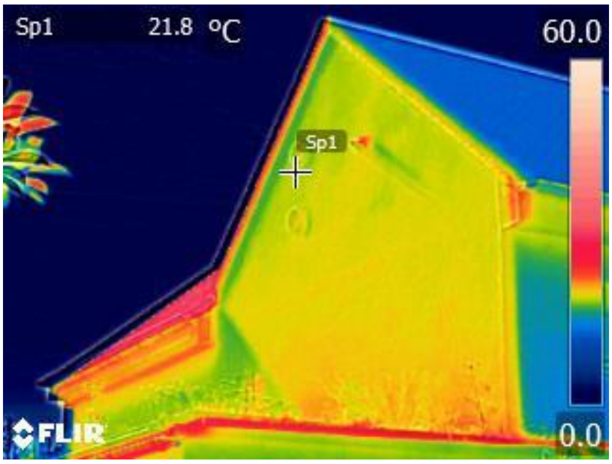


Figure 4-59- Surface temperature of 21.8°C measured at 9:00am (MVHR fresh air intake – Northeast elevation)

The surface temperature of the render surrounding the MVHR fresh air intake reaches just over 30°C when the ambient temperature is over 25°C at 5:00pm (Figure 4-64). However this is much lower compared to the 43°C of the front elevation (southwest) measured at the same hour under the direct solar gain (Figure 4-65). At 10:00pm the surface temperature of the render falls to 19.1°C when the outside temperature is 19°C. This could be down to the material colour and its low thermal mass, however this could have also been influenced by the green roof over the garage below the MVHR intake which could help to reduce the surrounding temperature as it can be seen from Figure 4-64.

Figure 4-60- Surface temperature reaching 30.1°C measured at 5:00pm (MVHR fresh air intake – Northeast elevation)

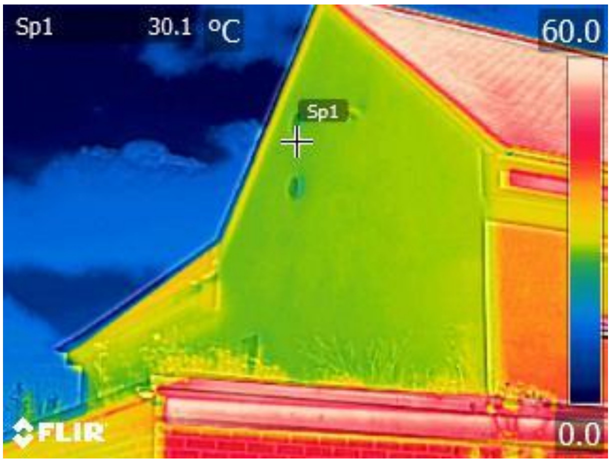
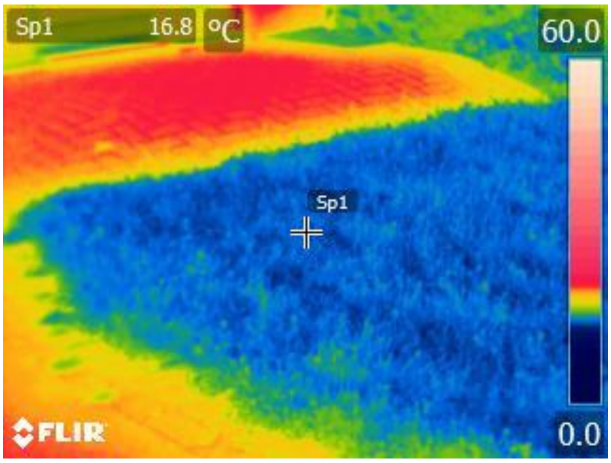


Figure 4-61- Surface temperature reaching 43.0°C measured at 5:00pm (Southwest elevation)

Subsequently the surface temperature of the grass in front of the building was also examined at 9:00pm which was measured as 16.8°C (Figure 4-66) when the surface temperature surrounding the MVHR fresh air intake was recorded to be 21.7°C and the front elevation was recorded to be 23.3°C.

Figure 4-62- Grass temperature of 16.8°C on the ground measured at 9:00pm



4.4.2. Incoming fresh air temperature

The temperature of the MVHR supply air was measured at the outlet located in the living room and the master bedroom to further examine the impact of the material used surrounding the MVHR supply air externally. Data loggers were placed in the outlet at the point that the air would enter the room to measure the temperature every hour throughout the day. The MVHR unit benefits from an automatic summer bypass option set at 21°C which ensures that the incoming air is not preheated as the internal temperature increases. The automatic summer bypass is set to be deactivated when the external temperature is too high and allows the internal temperature to reduce the incoming fresh air temperature if it is cooler than the outside air. Therefore the incoming fresh air temperature should stay close to the ambient temperature and above 20°C as the heat exchanger would also automatically be reactivated below this level.

The automatic summer bypass would work when the internal temperature exceeds the set point, however it would not allow the MVHR to be used for night time cooling during the summer as the heat exchanger is reactivated when the internal temperature falls below 21°C in order to keep the temperature as close as possible to 20°C. Nevertheless the incoming fresh air temperature should not exceed the ambient temperature.

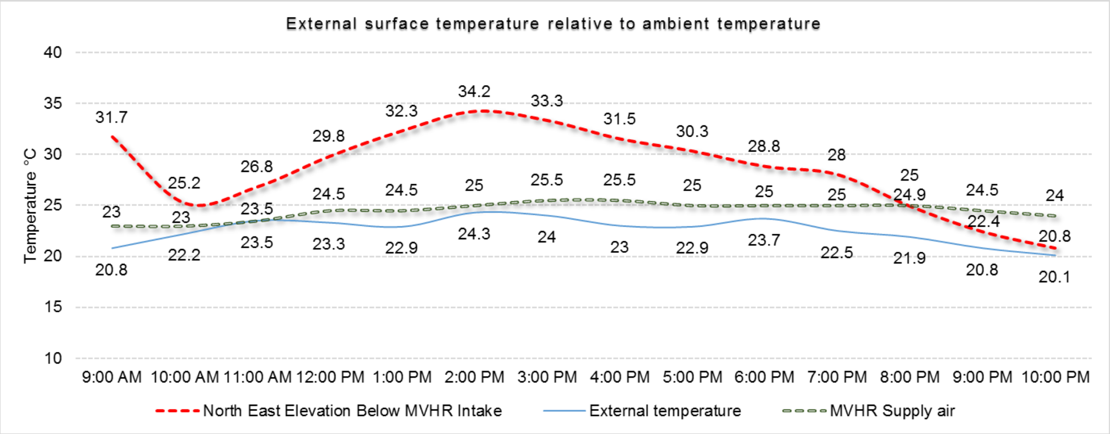


Figure 4-63- The temperature at the outlet of the MVHR supply air located in the master bedroom in relation to ambient and the external surface temperature

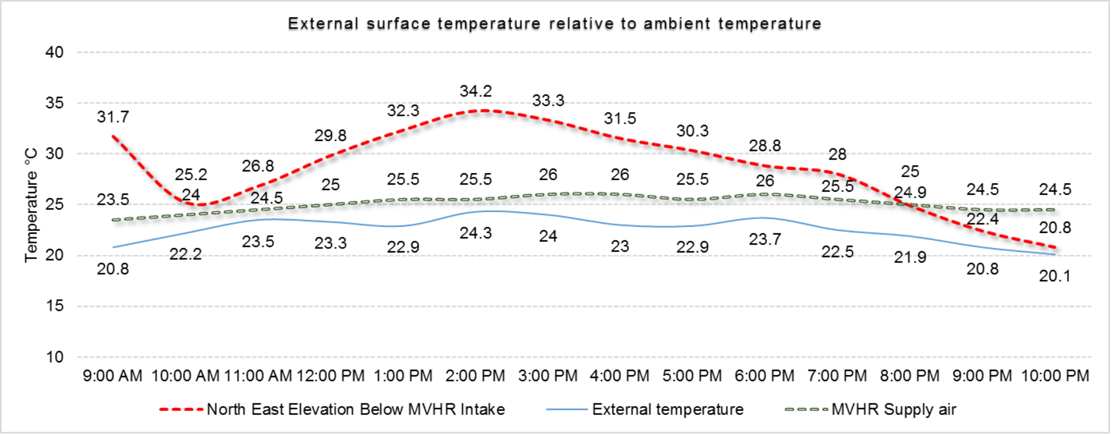


Figure 4-64- The temperature at the outlet of the MVHR supply air located in the living room in relation to ambient and the external surface temperature

The above figures show the temperature measurements for the MVHR supply air for the master bedroom and the living room respectively, during the 16th of July 2014 in relation to the ambient temperature and the surface temperature surrounding the MVHR supply air.

During the early part of the morning (9:00am) the incoming fresh air temperature is possibly influenced by the temperature surrounding the MVHR fresh air intake and is increased by 2.2°C and 2.7°C for the two locations (living room & master bedroom) compared to the ambient air temperature. Moreover for the rest of the day, the incoming temperature was always above the ambient temperature for both locations and even after 8:00pm as the external surface temperature falls, the incoming air was still higher than the ambient temperature. This could be due to the lack of insulation surrounding the MVHR duct and the internal room temperature (refer to section 4.2.2).

The temperature of the MVHR supply air was also measured for Building Two at the outlet located in the sitting room and the main bedroom. This was to investigate the influence of the MVHR location and the use of the material surrounding the air intake. Small data loggers were located inside the fresh air outlet (similar to Building One) and set to measure the temperature of the incoming fresh air hourly. The MVHR summer by pass for this building is also automatic and it is set at a higher temperature of 23°C compared to 21°C in Building One.

The figures below show the temperature measurements for the MVHR supply air to the main bedroom (bedroom 4) and the sitting room respectively, on the 17th July 2014 in relation to the ambient temperature and the surface temperature of the material surrounding the MVHR supply air intake.

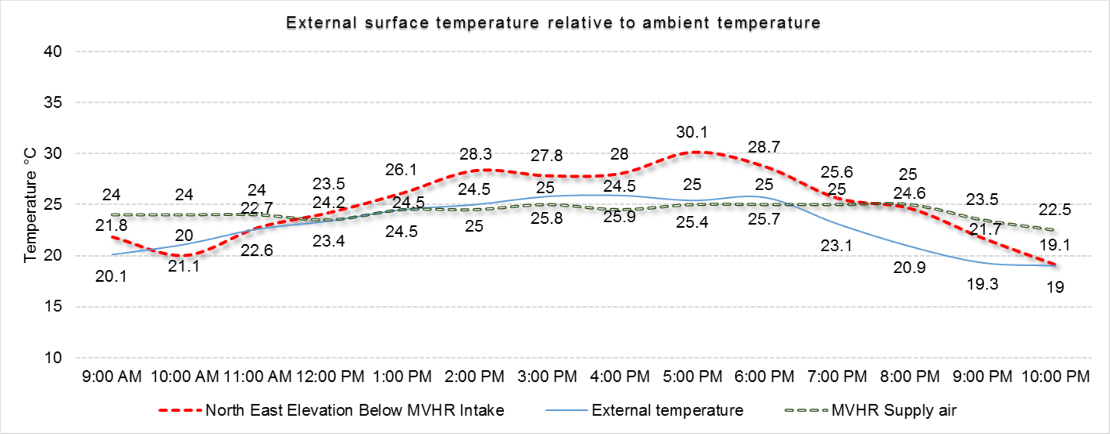


Figure 4-65- Temperature at the outlet of the MVHR supply air located in the main bedroom in relation to ambient and the external surface temperature

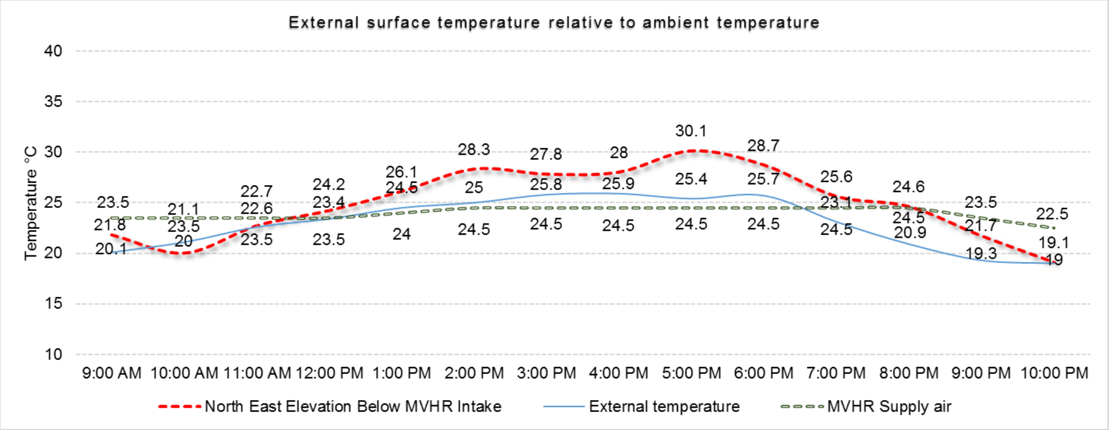


Figure 4-66- Temperature at the outlet of the MVHR supply air located in the sitting room in relation to ambient and the external surface temperature

The summer bypass for the MVHR as previously mentioned, has been set to 23°C which means that until the internal temperature passes 23°C the summer bypass will not be activated. As can be seen from the above graphs, the incoming fresh air temperature is generally close to ambient temperature and in some cases even just below. However during the early part of the morning and the night, the incoming fresh air temperature goes above the ambient temperature which is possibly due to the summer bypass temperature set at 23°C.

The influence of the temperature surrounding the MVHR intake seems to be less for this building as the temperature is generally lower compared to Building One, however the lack of insulation for the ducts after the MVHR unit can have an impact on the incoming fresh air temperature (refer to section 5.2.2). Moreover the MVHR unit is located in the loft which is part of the thermal envelope with no glazing and during the day the temperature in the loft stays around 22°C to 23°C. This possibly helps in regulating the temperature during the warmer part of the day when ambient temperature is at its highest. Nevertheless the MVHR supply air intake has been located in the north east façade with a light colour and low thermal mass material surrounding the intake which is ideal for the summer ventilation.

However further investigation is required and examination of the air temperature at the point of the entry into the MVHR unit, just after the MVHR heat exchanger as well as the outlet, which has not been possible in this research, to study the exact temperature increase and percentage in different parts of the system.

4.5. INTERNAL HEAT GAIN CALCULATION RESULT

The Passivhaus case study building, using PHPP7 calculation, with aid of night time cooling by opening the windows, had no overheating potential with a cooling load of 3 W/m^2. However this was not the same when using the PHPP8 with higher internal heat gains during the summer and the overheating percentage was increased to **8.5%** using the same ventilation strategy. The hot water storage and distribution alone contributed to an extra 238 W of heat gain which translates to a total of **3.65 W/m^2** of internal heat gain compared to the previous standard value of 2.1 W/m^2.

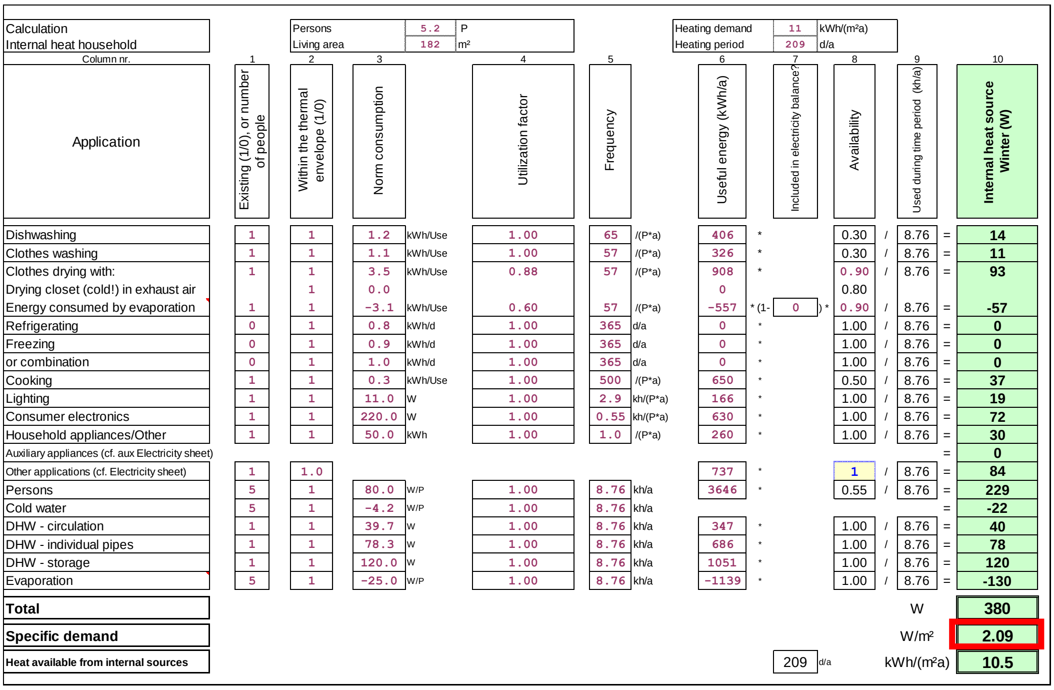
The standard occupancy from the PHPP was used for this calculation at 5 persons, which for a five bedroom house with just over 182m^2 of TFA seems on the conservative side. However the actual occupancy is 3 persons with two adults and one child. Furthermore, PHPP takes the cold water heat sink per person of -4.2 W into account which is therefore calculated to be -22 W in total.

A further calculation was carried out to reflect the actual occupancy rate of 3 persons which as expected reduced the internal heat gain from 3.65 W/m^2 during the summer to 2.78 W/m^2 and consequently reduced the overheating percentage from 8.5% to 5.6%. Figure 4-71 is the extract from PHPP8 for the internal gain calculation using the actual occupancy for the winter and summer period.

Utilisation pattern:	Dwelling	2.10	W/m²
Type of values used:	Standard	2.78	W/m² in summer

Figure 4-67- Winter and summer internal heat gains calculation

The internal heat gain for the winter was calculated to be within the suggested standard value of 2.1 W/m^2 when using the standard occupancy from PHPP. Figure 4-72 shows the internal heat gain calculation from PHPP8 using the standard occupancy for the winter period. Further background calculation plus the gains from the hot water distribution and storage will add up to be the internal heat gain for the summer period.



Calculation
Internal heat household

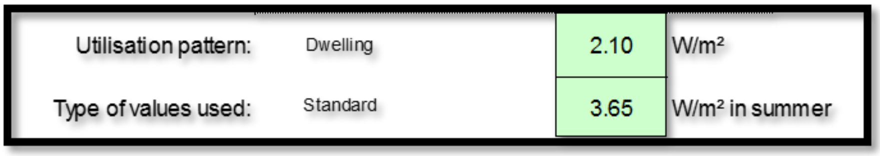
Persons 5.2 P
Living area 182 m²

Heating demand 11 kWh/(m²a)
Heating period 209 d/a

Column nr.	1	2	3		4	5		6		7		8		9		10
Application	Existing (1/0), or number of people	Within the thermal envelope (1/0)	Norm consumption		Utilization factor	Frequency		Useful energy (kWh/a)		Included in electricity balance?		Availability		Used during time period (kh/a)		**Internal heat source Winter (W)**
Dishwashing	1	1	1.2	kWh/Use	1.00	65	/(P*a)	406	*			0.30	/	8.76	=	**14**
Clothes washing	1	1	1.1	kWh/Use	1.00	57	/(P*a)	326	*			0.30	/	8.76	=	**11**
Clothes drying with:	1	1	3.5	kWh/Use	0.88	57	/(P*a)	908	*			0.90	/	8.76	=	**93**
Drying closet (cold!) in exhaust air		1	0.0					0				0.80				
Energy consumed by evaporation	1	1	-3.1	kWh/Use	0.60	57	/(P*a)	-557	* (1-	0	) *	0.90	/	8.76	=	**-57**
Refrigerating	0	1	0.8	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	**0**
Freezing	0	1	0.9	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	**0**
or combination	0	1	1.0	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	**0**
Cooking	1	1	0.3	kWh/Use	1.00	500	/(P*a)	650	*			0.50	/	8.76	=	**37**
Lighting	1	1	11.0	W	1.00	2.9	kh/(P*a)	166	*			1.00	/	8.76	=	**19**
Consumer electronics	1	1	220.0	W	1.00	0.55	kh/(P*a)	630	*			1.00	/	8.76	=	**72**
Household appliances/Other	1	1	50.0	kWh	1.00	1.0	/(P*a)	260	*			1.00	/	8.76	=	**30**
Auxiliary appliances (cf. aux Electricity sheet)															=	**0**
Other applications (cf. Electricity sheet)	1	1.0						737	*			1	/	8.76	=	**84**
Persons	5	1	80.0	W/P	1.00	8.76	kh/a	3646	*			0.55	/	8.76	=	**229**
Cold water	5	1	-4.2	W/P	1.00	8.76	kh/a								=	**-22**
DHW - circulation	1	1	39.7	W	1.00	8.76	kh/a	347	*			1.00	/	8.76	=	**40**
DHW - individual pipes	1	1	78.3	W	1.00	8.76	kh/a	686	*			1.00	/	8.76	=	**78**
DHW - storage	1	1	120.0	W	1.00	8.76	kh/a	1051	*			1.00	/	8.76	=	**120**
Evaporation	5	1	-25.0	W/P	1.00	8.76	kh/a	-1139	*			1.00	/	8.76	=	**-130**
Total														W		**380**
Specific demand														W/m²		**2.09**
Heat available from internal sources										209	d/a			kWh/(m²a)		**10.5**

Figure 4-68- Winter internal heat gains calculation from PHPP8 – calculated winter internal heat gain is 2.09W/m2

The figure below is the extract from the PHPP8 internal heat gain calculation sheet indicating the two different values for the winter (standard value) and the summer when using the standard occupancy rate of 5 (calculated value).



Utilisation pattern:	Dwelling	2.10	W/m²
Type of values used:	Standard	3.65	W/m² in summer

Figure 4-69- Winter and summer internal heat gains calculation

The calculation from PHPP7 for Building Two (like Building One), had not indicated any overheating problem when windows are used for night time cooling with the same 3W/m^2 cooling load. However the overheating potential was increased to **7.6%** when using PHPP8 and keeping the same approach for the ventilation strategy. The hot water storage and distribution has contributed to a total of 211W and the internal heat gain for summer is calculated to be **3.50W/m^2** making it noticeably higher than the standard value of 2.1W/m^2.

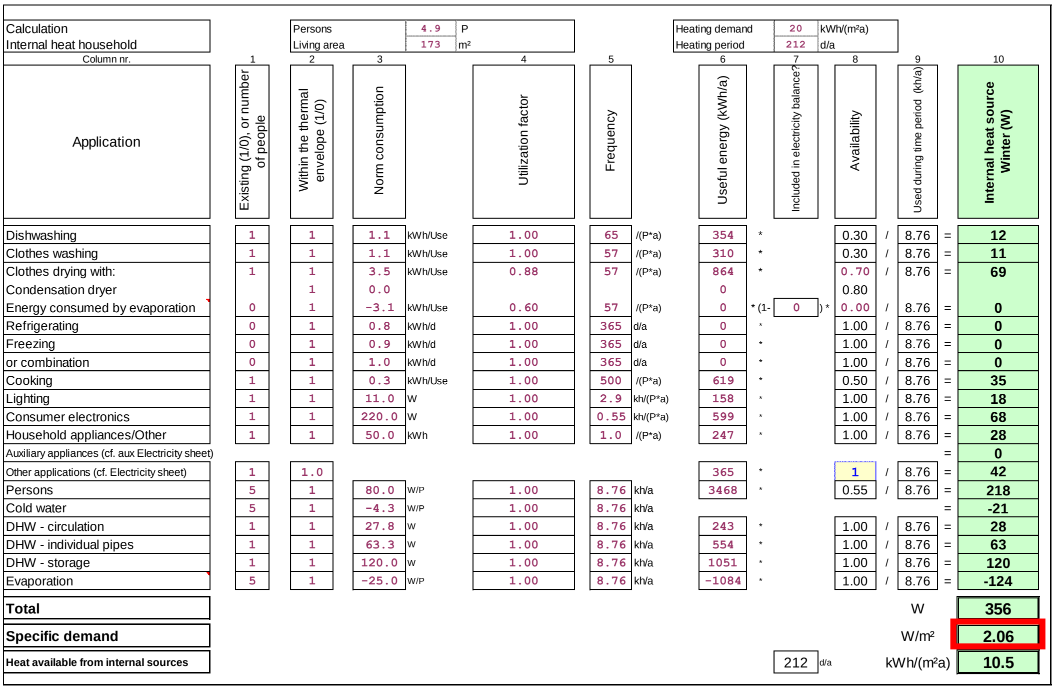
The standard occupancy rate from PHPP for this building is 5 persons which was used for this calculation. The 5 persons for the building with TFA of just over 173m^2 is perhaps on the lower side. The actual occupancy rate for the building is 2 adults and 2 children. Moreover the cold water heat sink is calculated to be -21W with further evaporation losses of -124W.

Further examination was undertaken to take account of the actual occupancy rate for the building of 4 persons at the time of monitoring and consequently the internal heat gains were reduced to 3.08W/m^2 and subsequently a reduction to the frequency of overheating to 6.4%. The figure below (Figure 4-74) is the extract from PHPP8 indicating the heat gain for winter and summer for the 4 person occupancy.

Utilisation pattern:	Dwelling	2.10	W/m^2
Type of values used:	Standard	3.08	W/m^2 in summer

Figure 4-70- Winter and summer internal heat gains calculation

The winter internal heat gain was calculated to be 2.06 W/m^2 for the standard occupancy which is within the standard value from PHPP. The figure below shows the internal heat gain calculation from PHPP8 for the winter period. Further background calculations including heat gain from MVHR usage plus the gains from the hot water distribution and storage will add up to the internal heat gain for the summer period.



Calculation
Internal heat household

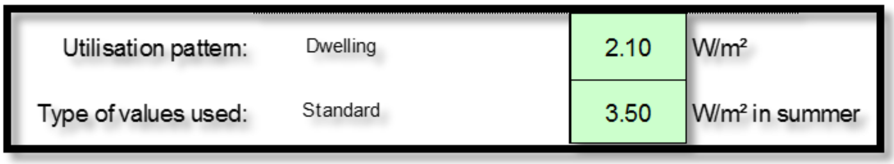
Persons 4.9 P
Living area 173 m²

Heating demand 20 kWh/(m²a)
Heating period 212 d/a

Column nr.	1	2	3		4	5		6		7		8		9		10
Application	Existing (1/0), or number of people	Within the thermal envelope (1/0)	Norm consumption		Utilization factor	Frequency		Useful energy (kWh/a)		Included in electricity balance?		Availability		Used during time period (kh/a)		Internal heat source Winter (W)
Dishwashing	1	1	1.1	kWh/Use	1.00	65	/(P*a)	354	*			0.30	/	8.76	=	12
Clothes washing	1	1	1.1	kWh/Use	1.00	57	/(P*a)	310	*			0.30	/	8.76	=	11
Clothes drying with:	1	1	3.5	kWh/Use	0.88	57	/(P*a)	864	*			0.70	/	8.76	=	69
Condensation dryer		1	0.0					0				0.80				
Energy consumed by evaporation	0	1	-3.1	kWh/Use	0.60	57	/(P*a)	0	* (1-	0	) *	0.00	/	8.76	=	0
Refrigerating	0	1	0.8	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
Freezing	0	1	0.9	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
or combination	0	1	1.0	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
Cooking	1	1	0.3	kWh/Use	1.00	500	/(P*a)	619	*			0.50	/	8.76	=	35
Lighting	1	1	11.0	W	1.00	2.9	kh/(P*a)	158	*			1.00	/	8.76	=	18
Consumer electronics	1	1	220.0	W	1.00	0.55	kh/(P*a)	599	*			1.00	/	8.76	=	68
Household appliances/Other	1	1	50.0	kWh	1.00	1.0	/(P*a)	247	*			1.00	/	8.76	=	28
Auxiliary appliances (cf. aux Electricity sheet)															=	0
Other applications (cf. Electricity sheet)	1	1.0						365	*			1	/	8.76	=	42
Persons	5	1	80.0	W/P	1.00	8.76	kh/a	3468	*			0.55	/	8.76	=	218
Cold water	5	1	-4.3	W/P	1.00	8.76	kh/a								=	-21
DHW - circulation	1	1	27.8	W	1.00	8.76	kh/a	243	*			1.00	/	8.76	=	28
DHW - individual pipes	1	1	63.3	W	1.00	8.76	kh/a	554	*			1.00	/	8.76	=	63
DHW - storage	1	1	120.0	W	1.00	8.76	kh/a	1051	*			1.00	/	8.76	=	120
Evaporation	5	1	-25.0	W/P	1.00	8.76	kh/a	-1084	*			1.00	/	8.76	=	-124
Total														W		**356**
Specific demand														W/m²		**2.06**
Heat available from internal sources										212	d/a			kWh/(m²a)		**10.5**

Figure 4-71- Winter internal heat gains calculation from PHPP8 - calculated winter internal heat gain is 2.06W/m^2

The figure below is the extract from the PHPP8 internal heat gain calculation sheet indicating the two different values for the winter (standard value) and the summer (calculated value) using the standard occupancy.



Utilisation pattern:	Dwelling	2.10	W/m²
Type of values used:	Standard	3.50	W/m² in summer

Figure 4-72- Winter and summer internal heat gains calculation

CHAPTER 5. DYNAMIC THERMAL MODEL

5.1. INTRODUCTION

Chapter 5 is the dynamic thermal model calculation, starting with the initial model and the comparison of the data to the physical monitoring data leading to the base case model. Furthermore, three proposed options have been tested demonstrating the possibility of reducing and eliminating the overheating potential in the current climate scenario using a natural ventilation system.

5.2. INITIAL MODEL

The initial dynamic thermal model for Building One was created using all the data from PHPP used during the design and the certification stage reflecting the as built information. Consequently all the opaque U-Values were created to the exact construction specification in DesignBuilder and for the glazing, the simple method was used to input the exact U-Value and g-Value for the glass and creating the frame using the information from PHPP. Mechanical ventilation with heat recovery was used as per the information obtained from PHPP with the same ventilation rate of 0.22 ac/h through windows during the summer nights. The infiltration was set to 0.07 ac/h (the value used in PHPP) which was obtained from the airtightness test after the building's completion. Moreover a set value of 2.1 W/m^2 was used for the internal gains as per the PHPP7 standard value for the whole year.

Heating was set to be 20°C as per Passivhaus standard with cooling set at 25°C throughout the year with 100% occupancy rate to allow the direct comparison of the heating and cooling load to PHPP. The values from the PHPP shading sheet were used to recreate the same shading for winter and summer alongside the building form, trees and window reveals (refer to methodology section for more detail). Below is the extract from DesignBuilder showing the visual image of the building (Figure 5-1).

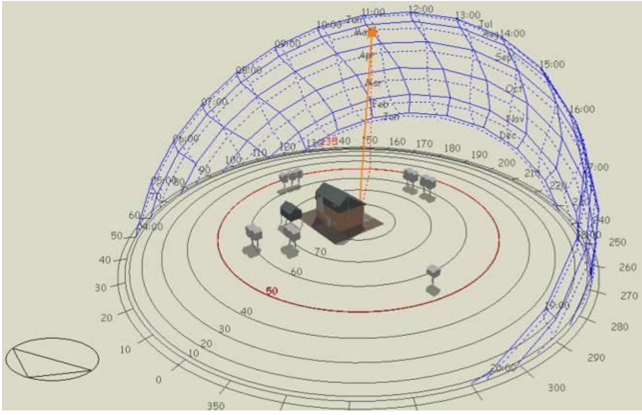
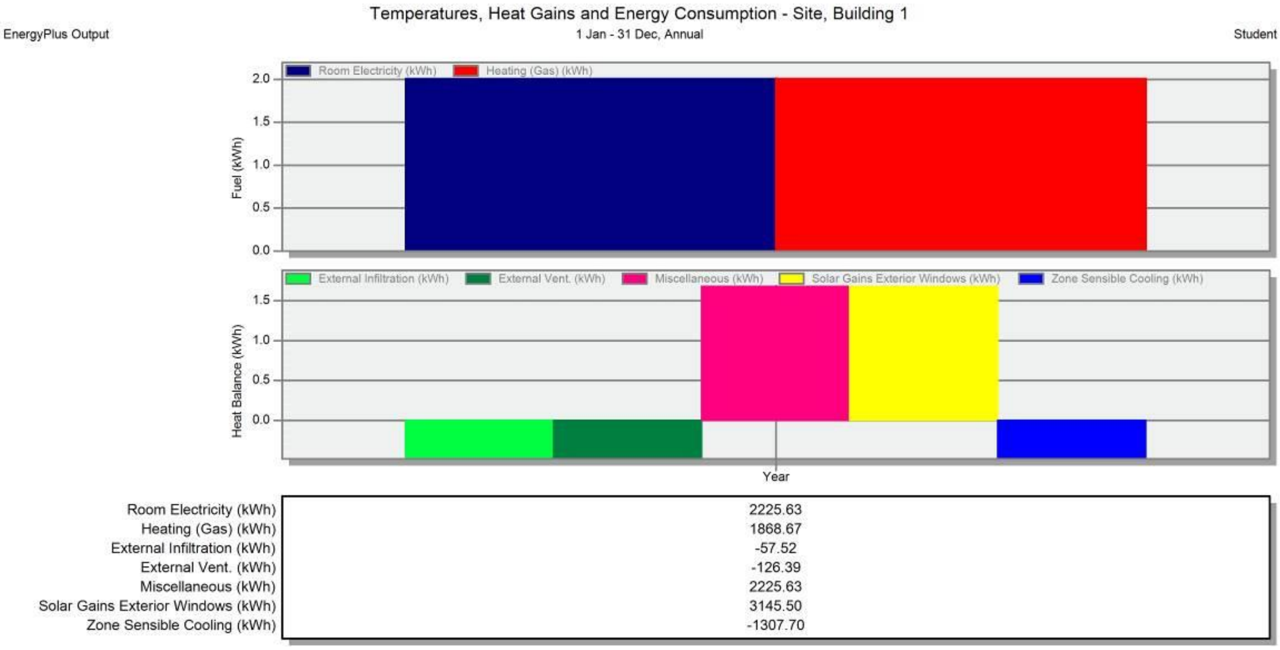


Figure 5-1- Visual image of the building from DesignBuilder

In order to make comparison between the data from the dynamic thermal model and data obtained from PHPP, the annual method was used alongside hourly temperature data to examine the frequency of the temperature surpassing the 25°C limit. The image below is the information for the annual load from DesignBuilder (Figure 5-2).



Room Electricity (kWh)	2225.63
Heating (Gas) (kWh)	1868.67
External Infiltration (kWh)	-57.52
External Vent. (kWh)	-126.39
Miscellaneous (kWh)	2225.63
Solar Gains Exterior Windows (kWh)	3145.50
Zone Sensible Cooling (kWh)	-1307.70

Figure 5-2- The annual heating and cooling load for the building from DesignBuilder

The calculation from PHPP uses the annual heating load per m^2 and therefore the total heating load from the dynamic model of 1868.67 kWh needs to be divided by the treated floor area from PHPP of 182.1m^2 which would be 10.26 kWh/m^2 per year. The specific heat demand from PHPP7 and the recalculation using PHPP8 was 11 kWh/m^2 per year indicating a very small difference between the two models. This supports the accuracy of the PHPP calculation for the heating demand. However this was not necessarily the case when comparing the data for cooling and the temperature during the summer.

The calculation from PHPP7 had no overheating with 3W/m^2 of cooling load which was not provided for the building and PHPP8 had indicated 8.5% frequency of the temperature being above the 25°C limit. Moreover using PHPP8 to provide cooling would require a specific cooling load of 3 kWh/m^2 per year with no further overheating potential.

On the contrary, the calculation from the dynamic model had indicated a total cooling load of 1307.70 kWh per annum which would translate to 7.18 kWh/m^2 per annum. PHPP7 showed no indication of overheating and the PHPP8 cooling load was 3 kWh/m^2 as mentioned above which, compared to the dynamic model, was less than half the value.

Hourly temperature data was used to examine the frequency of the overheating from the DesignBuilder model and the figure below (Figure 5-3) is the average annual temperature data for the entire building in comparison to the external temperature.

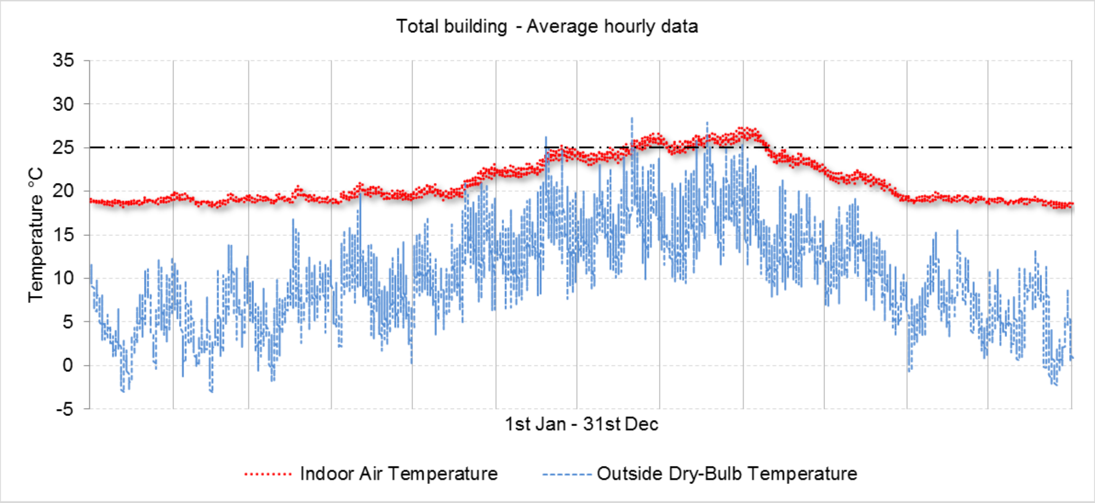


Figure 5-3- The average hourly temperature for the building from DesignBuilder

The above hourly data had indicated 12.09% of overheating above the 25°C limit compared to no overheating from PHPP7 and 8.5% of overheating from PHPP8. Table 5-1 indicates the direct comparison between the dynamic thermal model and the calculation from PHPP8 in regards to heating demand, overheating percentage and cooling load.

Table 5-1- The difference between dynamic model and PHPP8 calculations

Model type	**Specific heat demand**	**Overheating percentage**	**Cooling Load**
PHPP8	11 kWh/(m^2a)	8.5%	3 kWh/(m^2a)
Dynamic	10.26 kWh/(m^2a)	12.09%	7.18 kWh/(m^2a)

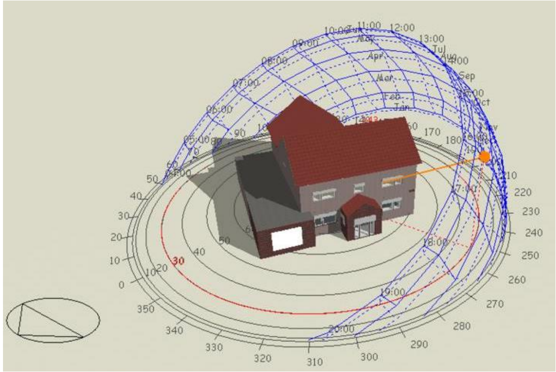
The above calculations indicate the lower accuracy in the PHPP calculation for the summer period especially for PHPP7 which was used in designing and certifying the building. The overheating percentage was higher from the dynamic model and the cooling load was noticeably higher than the value from PHPP8. This underlines the additional work required in PHPP regarding the warmer period of the year. Nevertheless the dynamic model is comparable to PHPP and it has underlined the potential of overheating for the building.

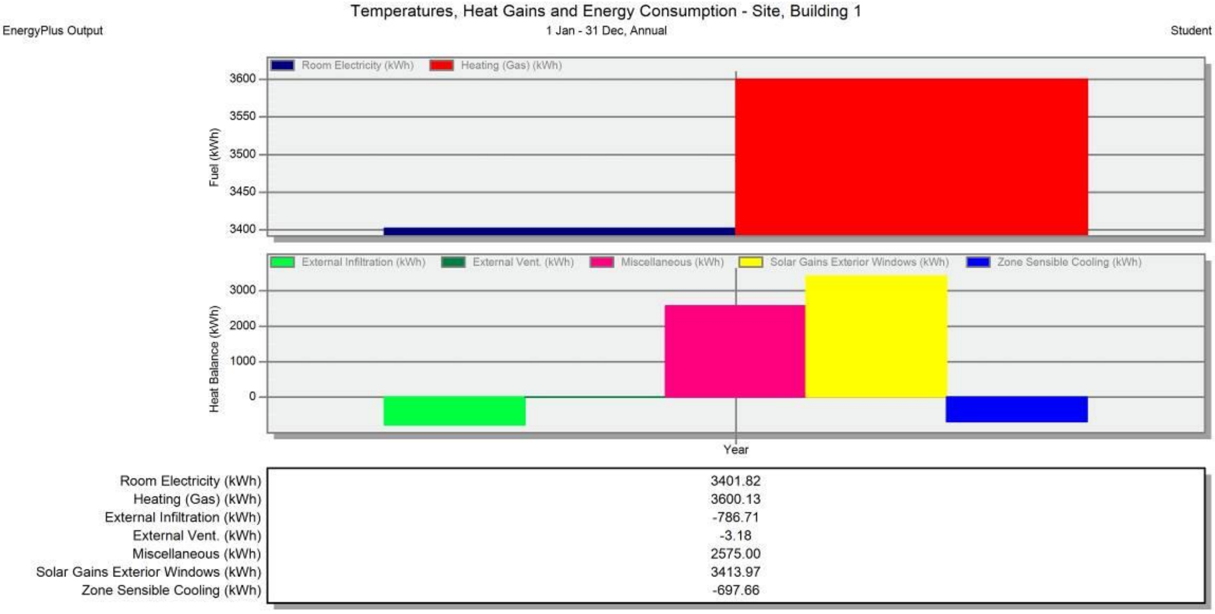
Similar to Building One, the data from the PHPP calculation was used to create the initial dynamic thermal model for Building Two. Material specification was used to build all the opaque components reflecting the same U-Values used in PHPP. Similarly the window frame was created by using simple glazing input of the g-value and the U-Value. For the ventilation, mechanical ventilation with heat recovery was used to reflect the same performance as per data used in PHPP. Additional natural ventilation through window use was inputted for the summer period of 0.22ac/h alongside an exact infiltration value of 1ac/h for the building airtightness. Moreover the standard value was used for the internal gains set as 2.1W/m^2.

The heating and cooling temperature was set to 20°C and 25°C respectively to reflect the Passivhaus standard with a 100% occupancy rate. It is important to highlight that if no value was entered for the shading in PHPP, the shading sheet will automatically take 25% reduction for every window of the building and would not require any further data input. The original PHPP calculation for this building had used this option and also no additional shading in the summer was specified. This was perhaps due to no potential of overheating from PHPP7 which was used for this building during the design and certification stage. Therefore when creating the dynamic model, specific external shading was drawn to 25% of the glazing area of every window to reflect the PHPP calculation.

For comparison purposes between the dynamic thermal model and calculations carried out using PHPP, the annual method was used alongside hourly temperature data to examine the frequency of the temperature exceeding the 25°C limit (refer to methodology section for more detail). Figures 5-4 and 5-5 are visual images of the building as well as the information for the annual load from DesignBuilder.

Figure 5-4- Visual image of the building from DesignBuilder





Room Electricity (kWh)	3401.82
Heating (Gas) (kWh)	3600.13
External Infiltration (kWh)	-786.71
External Vent. (kWh)	-3.18
Miscellaneous (kWh)	2575.00
Solar Gains Exterior Windows (kWh)	3413.97
Zone Sensible Cooling (kWh)	-697.66

Figure 5-5- The annual heating and cooling load for the building from DesignBuilder

The total heating load for this building was calculated to be 3600.13kWh and the TFA of the building from PHPP is 173.2m^2 making the heating load calculated for every square metre to be 20.78kWh/m^2 per year. The specific heat demand from PHPP7 was calculated to be 25kWh/m^{2}a which is higher than the value from the dynamic model. However the specific heat demand from recalculation using PHPP8, was 20kWh/m^2 which uses the updated weather data that was also used in the dynamic model (refer to methodology section on the weather data (3.6)). Nevertheless once again the PHPP calculation for the heating proved to be reliable but not necessarily for the cooling and the frequency of the overheating.

Similar to Building One, PHPP7 had not indicated any overheating potential and therefore any load for the specific cooling demand, with 3W/m^2 of cooling load. However PHPP8 calculation had highlighted 7.6% of overheating which is expected as there is no shading specified during the summer in the shading sheet as per PHPP7. Calculation was carried out for the cooling demand using PHPP8 and the value was, 2kWh/m^{2}a which would lead to no more overheating potential.

The calculation from the dynamic model for the cooling demand was 697.66kWh per year which translates to 4.02kWh/m^{2}a, this value is comparable to PHPP. However the frequency of the overheating on the hourly basis was around half compared to PHPP8 at 4.46% and higher than PHPP7. Figure 5-6 below is the average annual temperature data for the entire building in comparison to the external temperature.

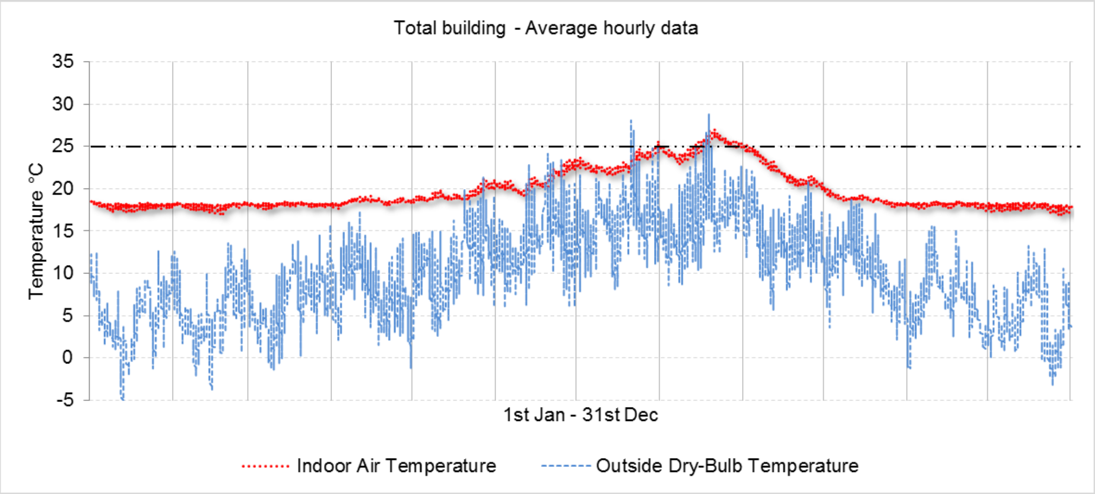


Figure 5-6- Average hourly temperature for the building from DesignBuilder

Table 5-2 indicates the direct comparison between the dynamic thermal model and the calculation from PHPP8 in regards to heating demand, overheating percentage and cooling load.

Table 5-2- Difference between dynamic and PHPP8 calculations

Model type	Specific heat demand	Overheating percentage	Cooling Load
PHPP8	20 kWh/(m^{2}a)	7.6%	2 kWh/(m^{2}a)
Dynamic	20.78 kWh/(m^{2}a)	4.46%	4.02 kWh/(m^{2}a)

The above calculations indicate the heating demand from the two models are almost identical, however the overheating percentage from PHPP8 was higher in comparison but had a lower cooling load. This could highlight a lower confidence in PHPP regarding the cooling load and consideration of thermal mass which could explain the higher overheating percentage and lower cooling load. Nevertheless the dynamic model is comparable to PHPP8 and also indicates a potential for overheating.

5.3. COMPARISON TO THE PHYSICAL MONITORING DATA

Comparison between the monitored data and the dynamic thermal model was made in order to examine the possible difference from model to the measured building temperature. The overall overheating from the monitoring of the building was calculated to be 21.13% of the time during the summer which is higher in comparison to the dynamic thermal model at 12.09%. The 21.13% as previously mentioned, could be slightly less taking the larger floor area into the calculation as some areas were not monitored like corridors or storage cupboards.

Nevertheless, all the data used in creating the initial thermal model, was to the information from the PHPP calculation which is highly comparable to what was actually built. The nature of Passivhaus design and quality control during the construction phase reduces the possible area of difference. Even the shading is very close to the actual usage of the building and therefore the occupant pattern and operation of the building like window openings and perhaps higher internal gains could be the major plausible reason for a higher percentage of overheating from the monitoring results. Figures 5-7 & 5-8 are direct monthly comparisons of internal temperatures in different rooms between the monitoring data and the initial thermal model results to establish the difference.

Living room:

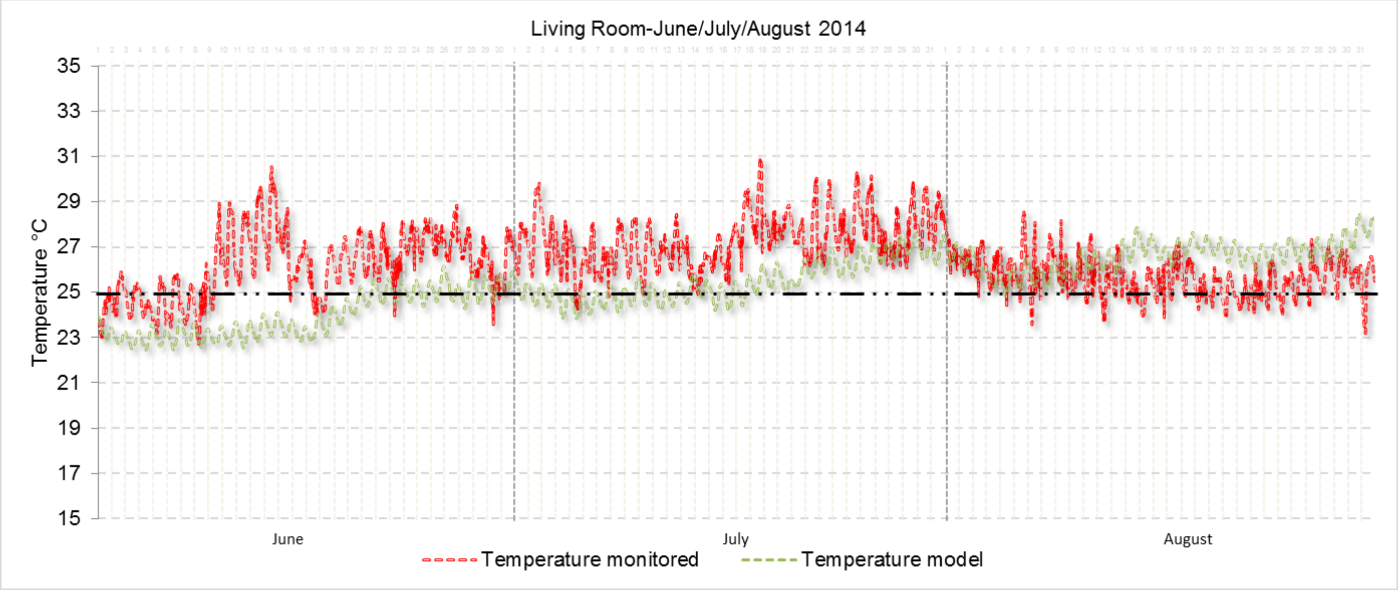


Figure 5-7- The difference in internal temperature between monitored and initial model – Living room –

Master bedroom:

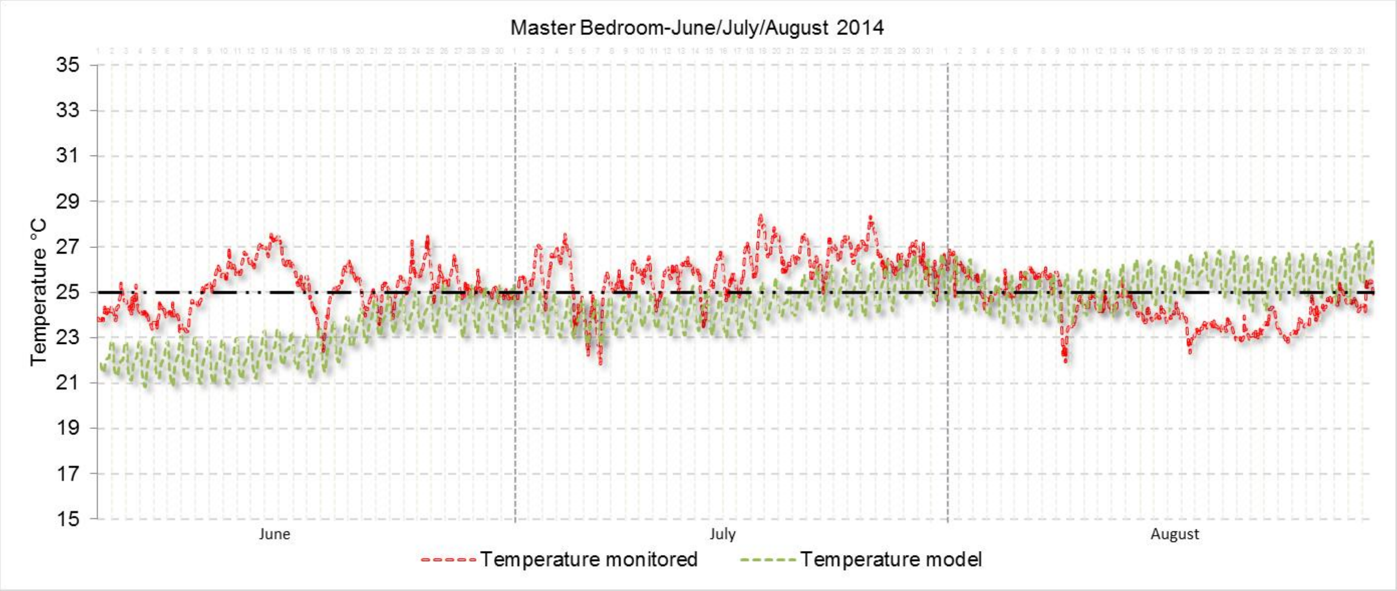


Figure 5-8- The difference in internal temperature between monitored and initial model – Master bedroom

The closer examination of the hourly temperature data, highlights the higher temperatures in the living room and the master bedroom leading to higher overheating percentage over the 25°C limit. However this is not the case during the August period especially towards the latter part of the month which is perhaps due to the difference in the ambient temperature data between the monitored and data used for the dynamic thermal model.

Similar comparison was made for Building Two to examine the difference between the monitored data and the data from the dynamic thermal model. The overheating for the whole year calculated from the initial model was 4.46% which is higher than the 0.26% from the monitored data. The 0.26% could be even less when taking the higher floor area from non-monitored spaces like corridors and storage cupboards into consideration.

The shading data used in PHPP7 (which was used for the dynamic model) was not necessarily reflecting the actual shading used in the building which would influence the higher solar radiation and therefore overheating potential. The adjustment in the shading in the dynamic model alongside the occupant behaviour in operating the windows etc. and the higher internal gains could aid in amending the model.

Figures 5-9 & 5-10 are some direct monthly comparisons of internal temperatures in different rooms between the monitoring data and the initial thermal model results to establish the difference between the data.

Sitting Room:

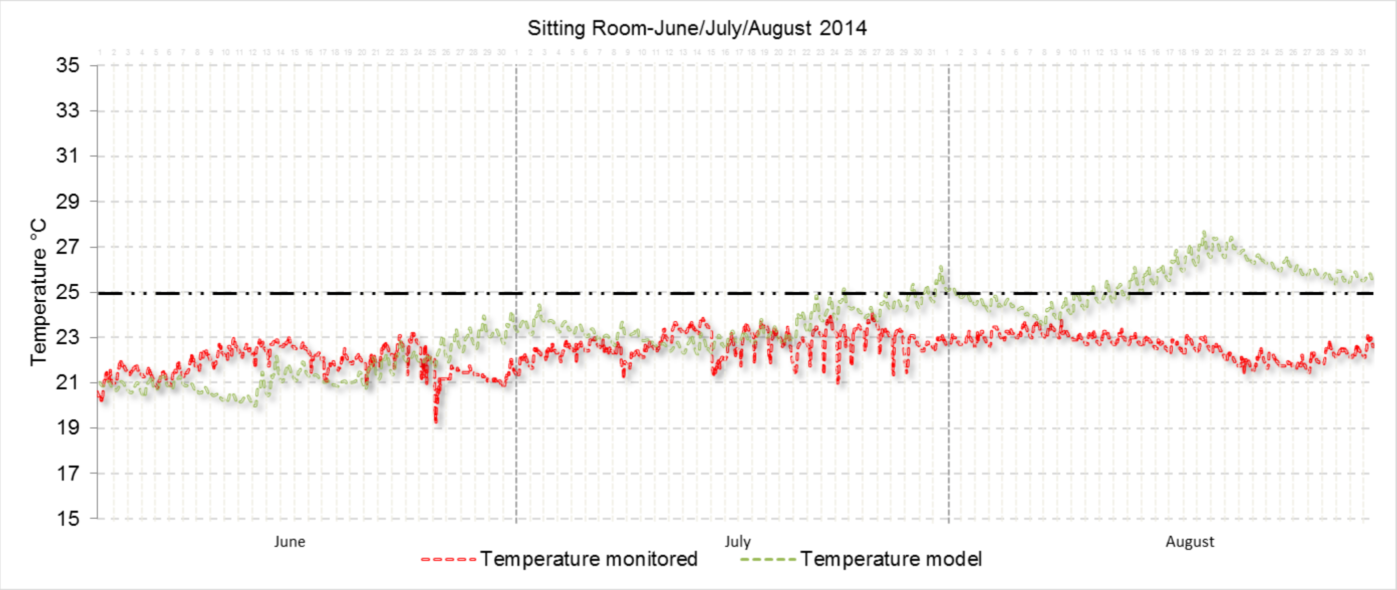


Figure 5-9- Difference in internal temperature between monitored and initial model – Sitting room

Main bedroom (bedroom 4):

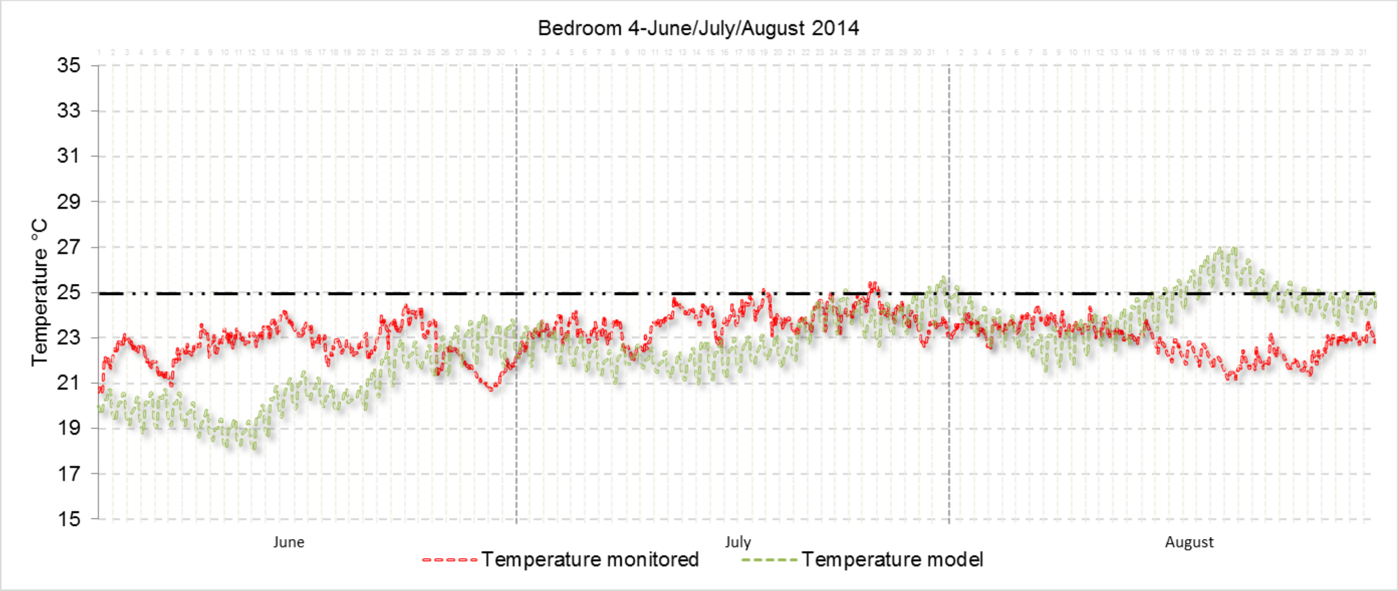


Figure 5-10- Difference in internal temperature between monitored and initial model – Bedroom 4 – June 2014

The difference between the monitored data and the dynamic thermal model appears to be less for Building Two and even during a small part of June, the dynamic thermal temperature is higher for both the sitting room and main bedroom. A similar difference also is apparent during the latter part of August and even temperatures were above the 25°C limit, which again was put to difference in the ambient temperature data used.

5.4. BASE CASE MODEL

The aim is to create a base case model that reflects the actual building and associated performance gap and overheating percentage. However the intention was to create a strategy that can be used during the design stage and be applicable for different buildings. Therefore the climate data used is not the exact data from BADC for the summer 2014 for the two sites and rather the data used by PHPP, also influenced by the lack of availability of the solar information for the two sites.

Furthermore the internal heat gain is higher than the data used initially using PHPP7 for Building One and therefore the internal gains were changed from the standard 2.1W/m^2 to the calculated 3.65W/m^2. The ventilation using the windows during the summer was also changed from scheduled to calculated natural ventilation (in DesignBuilder). The data obtained from monitoring the window operation was used to create different schedules for the individual windows during the three months of summer. Individual schedules were created for every window representing the actual operation in percentage. The windows were open in tilt and the percentage of the opening was inputted from the monitored data reflecting the actual time that the windows were opened as best as possible for every window.

Finally, the shading during the summer was slightly amended to reflect the actual shading used in the building. The overall overheating of the building was increased to be 19.55% which is much closer to the monitored data of 21.13%. The occupant pattern and density was kept to the data that will be used in PHPP as the standard requirement.

Table 5-3 & 5-4 are the comparison between the modelled and measured data for the maximum daily temperature and minimum daily temperatures averaged over the month and their average in the living room and the master bedroom respectively.

Table 5-3- Difference in the measured and model data for the three months of summer

	Measured Mean monthly Max	Model Mean monthly Max	Difference °C	Measured Mean monthly Min	Model Mean monthly Min	Difference °C	Measured Average	Model Average	Difference °C
June	27.47	26.51	**1.03**	24.76	24.87	**-0.11**	26.12	25.69	**0.43**
July	28.71	28.30	**0.41**	25.96	26.62	**-0.66**	27.34	27.46	**-0.12**
August	26.82	28.03	**-1.21**	24.45	26.18	**-1.73**	25.64	27.10	**-1.46**

Table 5-4- Difference in the measured and model data for the three months of summer

	Measured Mean monthly Max	Model Mean monthly Max	Difference °C	Measured Mean monthly Min	Model Mean monthly Min	Difference °C	Measured Average	Model Average	Difference °C
June	25.88	24.43	**1.45**	24.52	22.49	**2.03**	25.20	23.46	**1.74**
July	26.97	26.39	**0.58**	25.08	24.50	**0.58**	26.02	25.44	**0.58**
August	24.89	27.25	**-2.36**	23.79	25.36	**-1.57**	24.34	26.30	**-1.96**

The direct comparison of the two values from the above table, highlights the closeness of the model to the measured data with a slight difference during August. Therefore the model with amended internal heat gain, window operation and 19.55% of overheating percentage was used as the base case for this research.

Similar to Building One, the model for Building Two was adjusted to reflect the calculated internal gains which were 3.50W/m^2 and also the ventilation was changed from scheduled to calculated natural ventilation using the windows. The information obtained from the monitored data regarding the window opening pattern and duration was implemented into the model as best as possible to reflect the actual window operation in the building.

Finally, the shading was amended to represent a closer relation to the actual shading used by the occupant and for instance taking the internal shading installed by the client last year into consideration. The overall overheating of the building was calculated to be 1.79% which is much closer to the monitored data of 0.26%.

Table 5-5 & 5-6 are the comparison between the two measurements for the maximum daily temperature and minimum daily temperatures averaged over the month and their average for the sitting room and the main bedroom respectively.

Table 5-5- The difference in the measured and model data for the three months of summer

	Measured Mean monthly Max	Model Mean monthly Max	Difference °C	Measured Mean monthly Min	Model Mean monthly Min	Difference °C	Measured Average	Model Average	Difference °C
June	22.32	22.19	**0.13**	21.34	21.08	**0.26**	21.83	21.64	**0.19**
July	23.29	23.82	**-0.53**	22.00	22.00	**0**	22.65	22.91	**-0.26**
August	22.98	24.64	**-1.66**	22.36	22.78	**-0.47**	22.67	23.71	**-1.04**

Table 5-6- The difference in the measured and model data for the three months of summer

	Measured Mean monthly Max	Model Mean monthly Max	Difference °C	Measured Mean monthly Min	Model Mean monthly Min	Difference °C	Measured Average	Model Average	Difference °C
June	23.01	21.82	**1.19**	22.14	20.35	**1.79**	22.62	21.08	**1.54**
July	24.27	23.85	**0.42**	23.22	22.40	**0.82**	23.75	23.12	**0.63**
August	23.27	25.07	**-1.8**	22.49	23.64	**-1.15**	22.85	24.35	**-1.5**

The examination of the above two tables, highlights the closeness between the model and the monitored data over the three months of summer and the overall overheating percentage is also closer. Therefore the model with amended internal heat gain, window operation and 1.79% of overheating percentage was used as the base case for this research.

5.5. PROPOSAL

One of the most effective methods of preventing buildings from overheating is to provide shading and therefore reduce external gain (Dengel et al., 2016). However both case study buildings already benefited from a shading system which were used by the occupant in line with the provision during the design stage. Moreover, providing a ventilation system passively which avoids additional energy use and therefore CO_2 emissions is important. It is also vital to consider the noise implications however due to passive ventilation (Dengel et al., 2016) and possible reduction in IAQ.

Any system needs to consider the occupant’s behaviour and therefore effective usage of the system which might be reduced due to lack of use (Dengel et al., 2016). Overheating can easily be put down to occupant behaviour, however the question needs to be what is reasonable to ask from the occupant which is directly linked to the building design (Passivhaus Trust, 2016). Furthermore the ventilation rate needs to be increased to around 1 to 1.5 ac/h during the summer which is not perhaps possible by the use of the MVHR system and purge ventilation should be at least 4 ac/h (Dengel et al., 2016).

In order to reduce the overheating percentage during the summer months for Building One, three different options were proposed to increase the natural ventilation and consequently aim to reduce the overheating. The options are proposed following the literature review (sections 2.3.1, 2.3.2 and 2.3.3) which highlights the implications of noise, security, weather (rain & solar), insects and air quality associated with the use of different available systems and strategies. Moreover as Building Two did not experience a high percentage of overheating as indicated previously by the monitoring data and dynamic thermal model, the concentration will be on Building One only.

5.5.1. Option 1

Option one is to use the existing MVHR ducts already designed for the mechanical ventilation and connect them to a windcatcher during the summer period and turn the MVHR off during this time. The windcatcher is to be connected to the ducts at the point that the MVHR is connected giving the option to switch to natural ventilation during the summer. The aim is to increase ventilation and also save the energy that would have been used by the MVHR during this time. The windcatcher would be providing fresh air as well as extract the same way that the MVHR would have by connecting the extract duct and fresh duct separately to the windcatcher.

The base case model was used in order to examine the effectiveness of this option. The model was drawn with the MVHR ducts placed in the exact location as per the completed building. In order to make the MVHR ducts within the ceiling of each floor, the floor thickness was created as an individual zone and the ducts were drawn as partitions using the same material as per the actual ducts. Figure 5-11 is extracts from the dynamic model indicating the duct locations per floor.

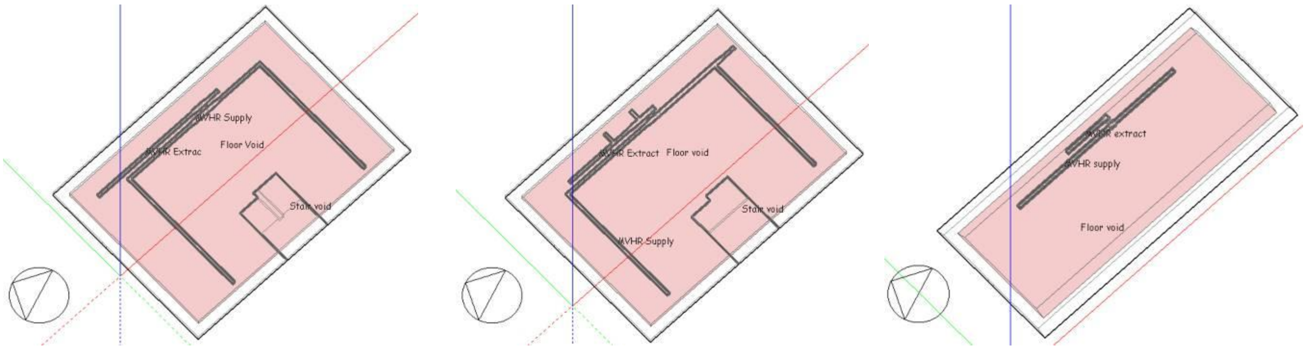
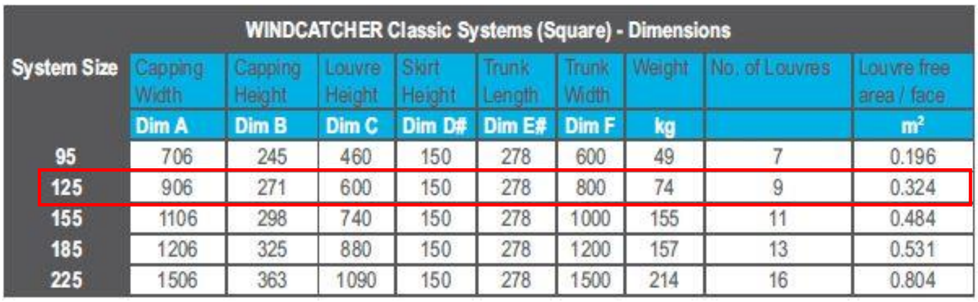


Figure 5-11- MVHR ducts drawing from the dynamic model – Ground, first and second floor from left to right

The windcatcher was drawn based on the Monodraught Classic Square design 125 used to provide natural ventilation to buildings. The image and data for the classic square design can be seen in Figure 5-12- & 5-13.

Figure 5-12- Monodraught windcatcher classic square (source: (Monodraught, 2015)**)**



WINDCATCHER Classic Systems (Square) - Dimensions

System Size	Capping Width	Capping Height	Louvre Height	Skirt Height	Trunk Length	Trunk Width	Weight	No. of Louvres	Louvre free area / face
	Dim A	Dim B	Dim C	Dim D#	Dim E#	Dim F	kg		m^2
95	706	245	460	150	278	600	49	7	0.196
125	906	271	600	150	278	800	74	9	0.324
155	1106	298	740	150	278	1000	155	11	0.484
185	1206	325	880	150	278	1200	157	13	0.531
225	1506	363	1090	150	278	1500	214	16	0.804

Figure 5-13- Monodraught windcatcher classic square data (source: (Monodraught, 2015)**)**

Figure 5-14 is the extract from the dynamic model indicating the windcatcher location on the roof of Building One.

Figure 5-14- Extract from the dynamic model indicating the windcatcher drawing

The windcatcher was located on the roof above the storage cupboard housing the MVHR unit and connected to the MVHR supply and extract ducts bypassing the MVHR. Consequently the windcatcher is located to the north side of the building benefiting from less direct solar gains and cooler surrounding material temperature. The windcatcher was divided evenly into two sections internally, with one for the supply and the other for the extract.

The louvres were located at the exact location as per the Monodraught Classic Square design externally and scheduled to be open all the time as per the actual product. Moreover additional louvres were placed internally at the ceiling level similar to Monodraught grilles and scheduled to be open during the summer period throughout the day and night.

The MVHR was switched off during the summer allowing the windcatcher to use the ducts for providing and extracting fresh air. However controlling the supply and extract is not easily achieved with this type of windcatcher design. As the windcatcher is static and would not rotate as the wind changes direction, therefore the extract and supply could be reversed due to wind direction. This would not be desirable when the extract from the kitchen and toilets would be restricted. Moreover the incoming fresh air is not filtered in this design, which might not be as bad, as the incoming fresh air is from the roof level and perhaps has less pollution.

Nevertheless the incorporation of the windcatcher using the MVHR ducting led to a reduction in the overheating percentage from 19.55% to 12.08%. Below is the building average hourly data using the windcatcher (Figure 5-15).

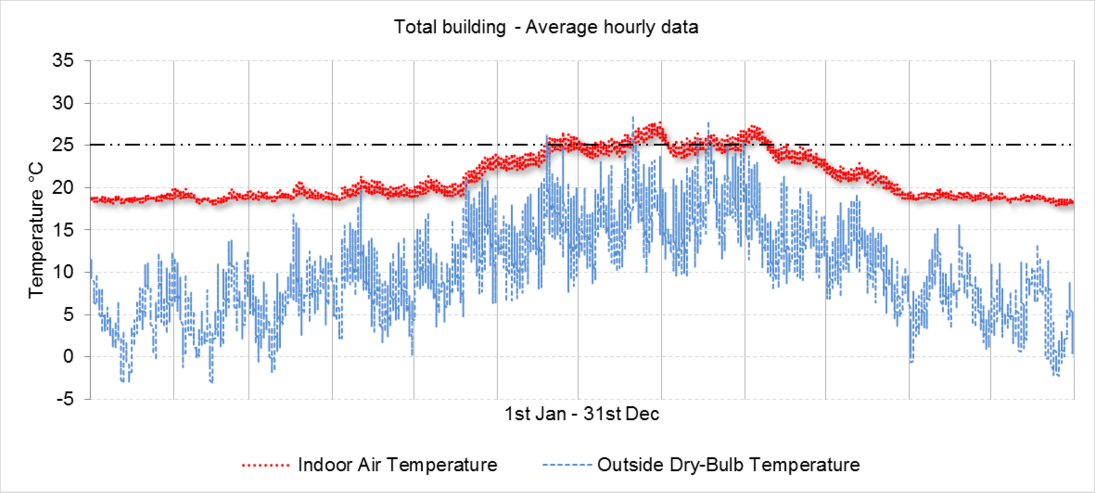


Figure 5-15- Building average hourly data indicating the overheating percentage of 12.08%.

The Monodraught Classic Square design allows occupants to control the volume of the fresh air by adjusting the internal ceiling grille and provides natural ventilation throughout the day and night securely with much less noise implication in comparison to opening windows. Although this option has increased the natural ventilation and consequently reduced the overheating percentage in the building, however it has not completely eliminated the overheating problem.

5.5.2. Option 2

The same windcatcher design was used for this option except that the windcatcher is now located over the staircase to benefit from the stack effect through the stair well. Consequently the windcatcher is located on the south side of the roof receiving not only more direct solar gain but also a higher surface temperature of local material surrounding it. The windcatcher was drawn and divided into four sections as per the Monodraught classic square design. The images below are extractions from the dynamic model indicating the location and the drawing for the windcatcher.

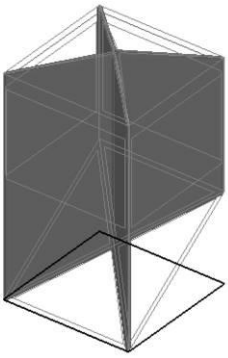


Figure 5-16- Windcatcher drawing for option 2

Figure 5-17- Extract from the dynamic model indicating the windcatcher location

Similar to option one, the external vents were scheduled to be open all the time with the internal vents to be open during the summer periods only. The percentage of overheating was reduced from the original 19.55% to 14.08%, which is around 2% more overheating than option one. This was put to the possible higher solar gain due to the location of the windcatcher and higher local temperature surrounding the windcatcher. Below is the building average hourly data for option 2 (Figure 5-18).

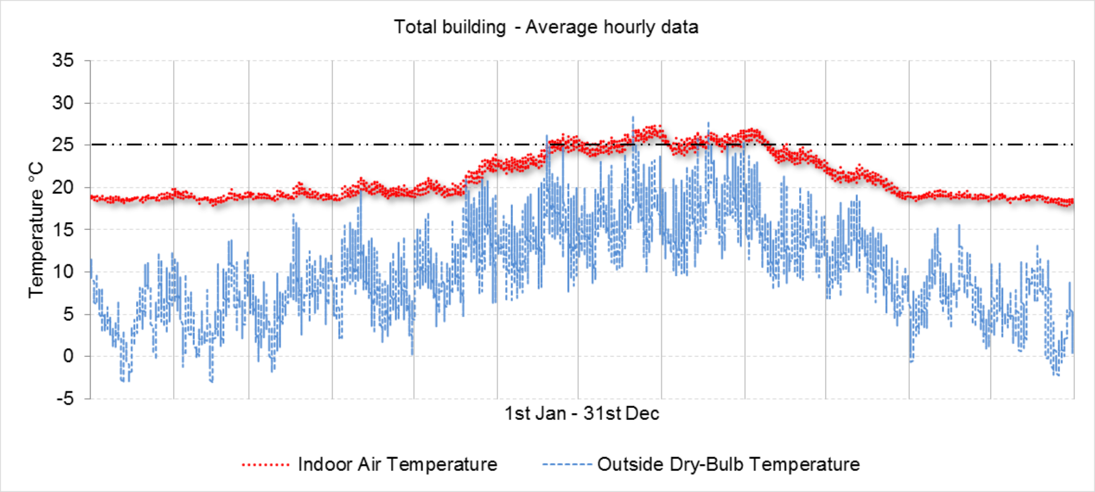


Figure 5-18- Building average hourly data indicating the overheating percentage of 14.08%

As mentioned above the overheating percentage for option 2 is more than the first option even though the volume of the ventilation was expected to be more due to the benefit of the stack effect and elimination of the resistance in the ducting system. Further investigation was carried out in order to establish whether the south location and higher temperature of the material surrounding the windcatcher has contributed to the higher overheating percentage.

Initially the windcatcher was kept with the same design and all the vents were removed except on the north side (Figure 5-19) to examine the effect of the higher solar gain on the windcatcher. As can be seen from Figure 5-20, the percentage of the overheating was reduced from 14.08% to 13.14%. However this option could have also increased the stack effect as the prevailing wind is from the southwest direction.

Figure 5-19- Extract from the dynamic model indicating the windcatcher vent located on north side only

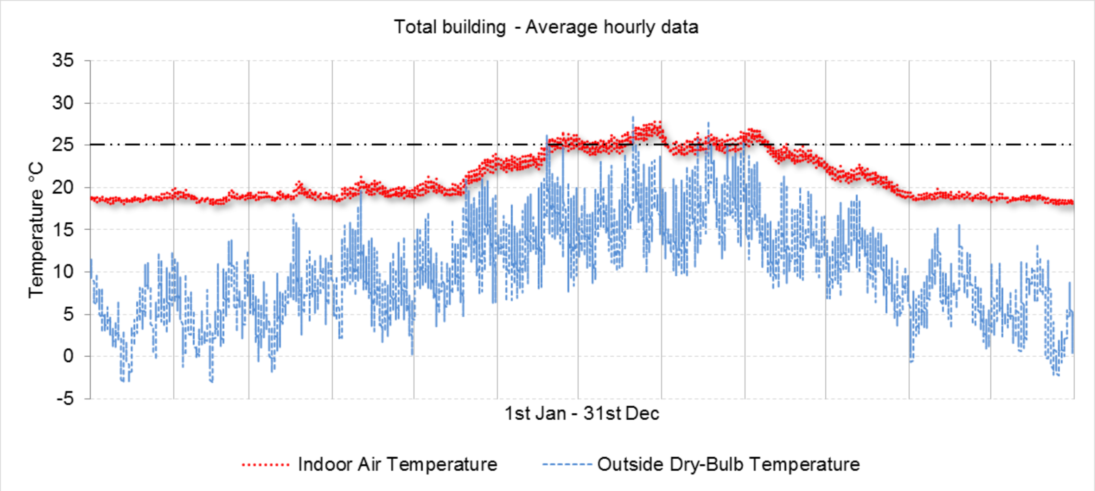


Figure 5-20- Building average hourly data indicating the overheating percentage of 13.14%

Furthermore the design of the windcatcher was adjusted to have north facing vents only in order to further increase the stack effect and consequently increase the overall ventilation achieved through the windcatcher. The new design reduced the overheating to 12.58% compared to the previous 13.14%. Figures 5-21 and 5-22 are the extract from the dynamic model highlighting the amendment to the windcatcher design as well as the average hourly temperature indicating the further reduction in overheating percentage.

Figure 5-21- Extract from the dynamic model indicating the windcatcher amended design

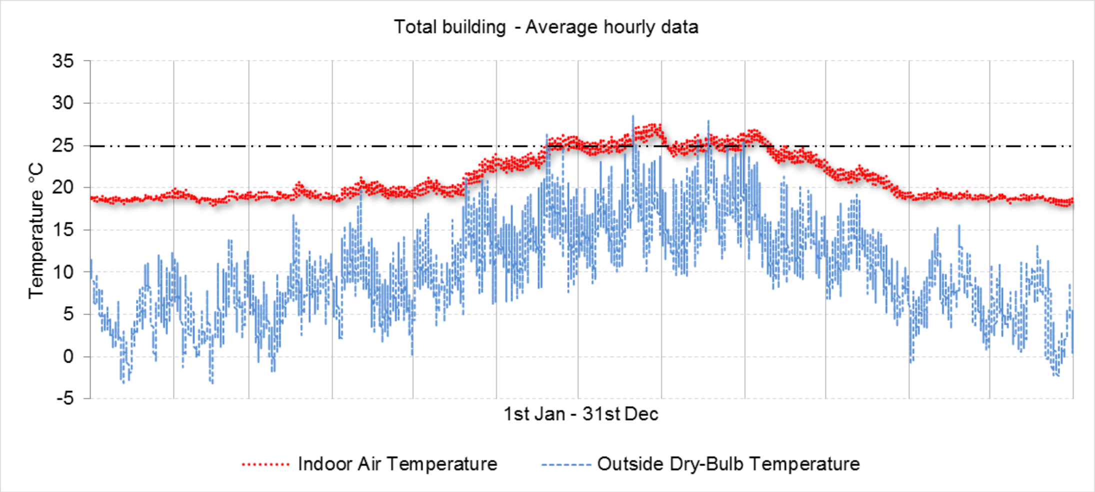


Figure 5-22- Building average hourly data indicating the overheating percentage of 12.58%

In order to ensure the solar radiation is kept outside and is not affecting the overall heat gain and overheating, the windcatcher build-up U-Value was improved in line with the rest of the building. The recalculation indicated a further reduction to the overall overheating for a small percentage of 0.08%. This was only a small improvement and therefore the roof material surrounding the windcatcher was amended to have a green roof. The images below (Figures 5-23 and 5-24) highlight the area covered by the green roof as well as the further improvement to the overall overheating percentage which was reduced to 12%. In all these simulations the MVHR was kept operational and turning it off contributed to an assumed reduction in the total ventilation rates and therefore a reduction to the improvement of the overheating percentage.

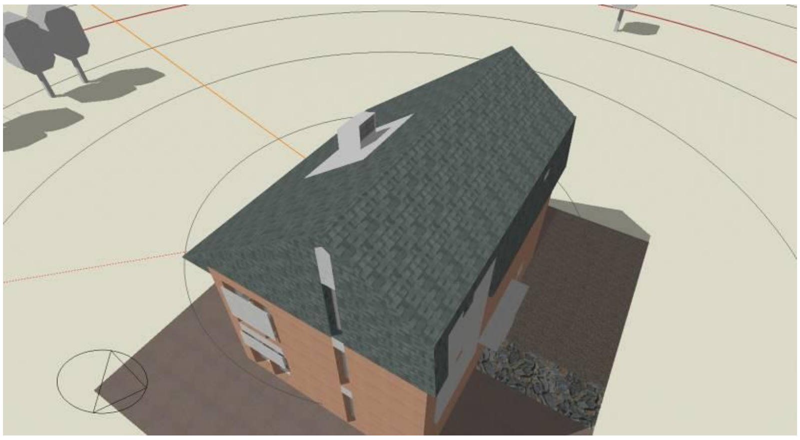


Figure 5-23- Extract from the dynamic model indicating the green roof surrounding the windcatcher

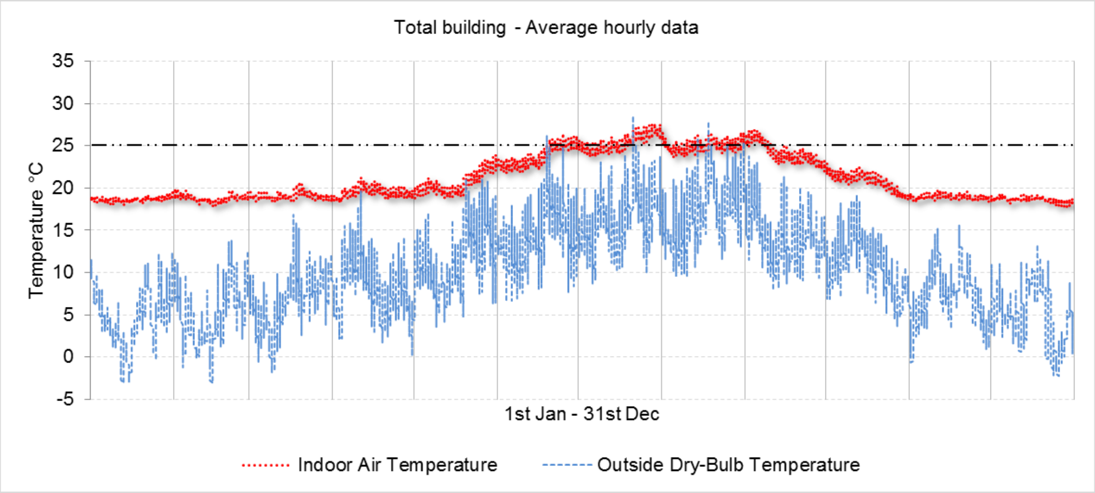


Figure 5-24- Building average hourly data indicating the overheating percentage of 12 %

Table 5-7 is a summary of all the different iterations as part of this option and the associated overheating percentage.

Table 5-7- Percentage of overheating for different scenarios for option 2

Base case model	Monodraught classic square design	Monodraught north vent only	Windcatcher new design	Windcatcher new design improved U-Value	Windcatcher new design improved U-Value – green roof
19.55%	14.08%	13.14%.	12.58%	12.5%	12%

Option two with improvements and amendments to the windcatcher design and introduction of a green roof around the windcatcher only improved the overall overheating percentage by 0.08% compared to the first option. Option two is using more of the stack effect and therefore air extraction rather than purposely introducing fresh air into the building ideally at a low level opening to increase the ventilation effectiveness of the building.

5.5.3. Option 3

Option 3 uses the last iteration from option 2 which included the windcatcher over the staircase with amended design and improved U-Value as well as a green roof around the windcatcher as the base. However for this option new low level openings were introduced to increase the overall effectiveness of the ventilation rate. The new low level opening is designed to ensure the security concerns by the occupants have been addressed by keeping the opening around 200mm above the ground and the clear opening is limited to 100mm in width. Moreover in order to keep the air quality the same as per the MVHR, filters are incorporated as part of the design with the possibility to be changed and cleaned. The new opening design also takes the solar gain into consideration by eliminating any solar gain reaching the inside of the building. Figures 5-25 to 5-28 are illustrations of the proposed new low level opening.

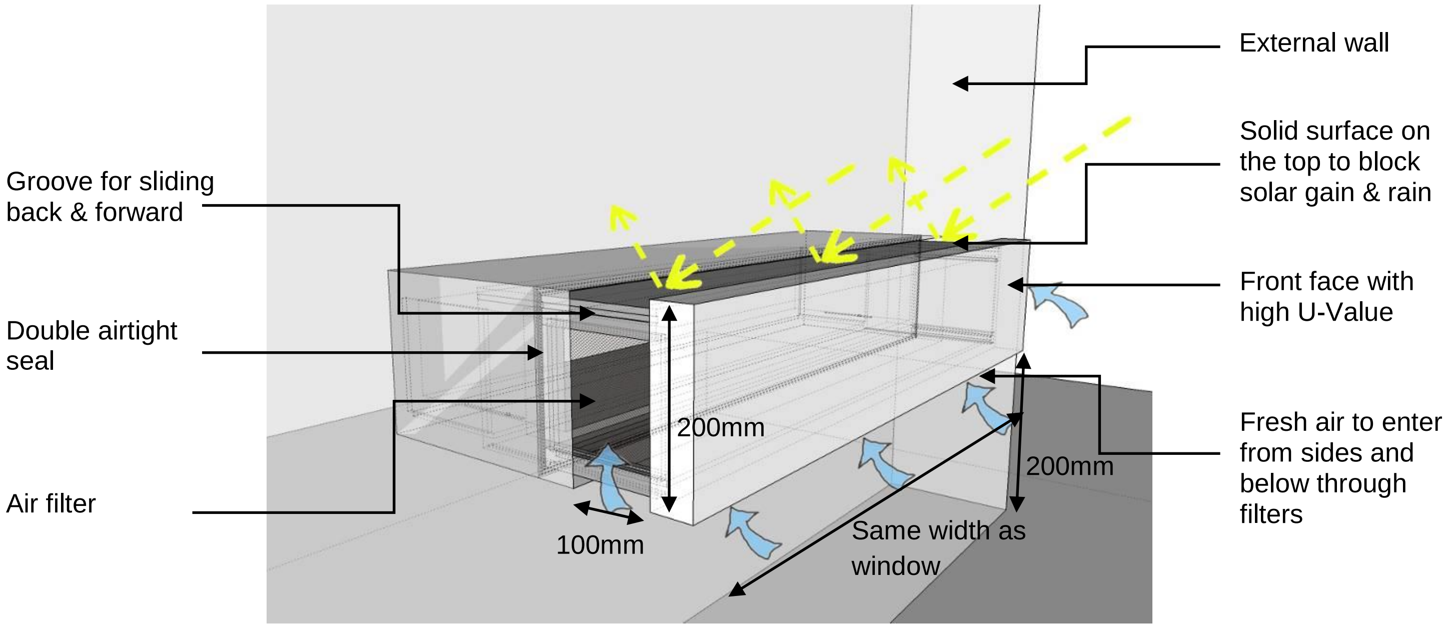


Figure 5-25- External view of the low level opening

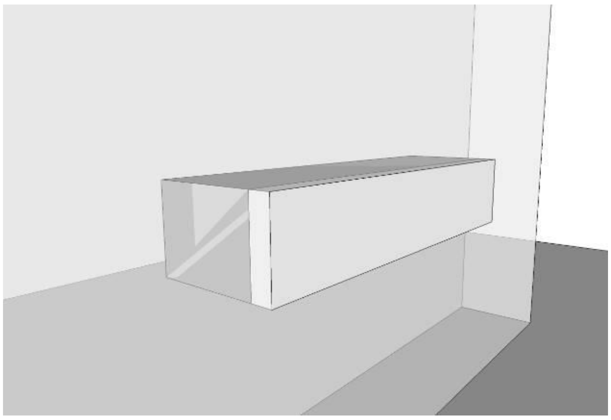


Figure 5-26- External view – when the opening is closed it will be part of the wall and achieve almost the same U-Value

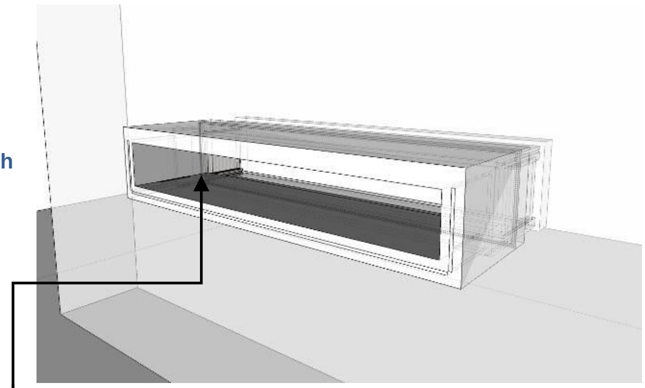


Figure 5-27- Internal view – part of the wall with possibility to slide the filters out for cleaning and changing

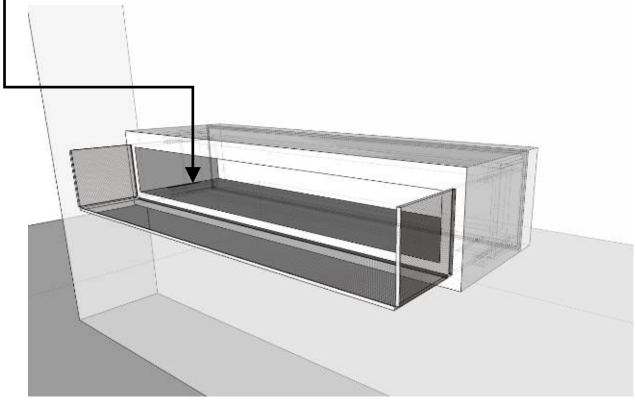


Figure 5-28- Filters slide open with lever handle which also allows the opening to be pushed out

The introduction of the secure low level opening allows fresh air to enter the building and the windcatcher over the staircase uses the stack effect and encourages a higher flow of fresh air (Low level opening distance to windcatcher: GF 8.5m, FF 5.5m & SF 3m). The new low level opening has been introduced in every room with windows and located below the window (200mm above floor level), with the opening being 1/50th of the floor area (each room) (total opening, just under 1/50th of the TFA). This will allow the occupants to leave it open even during the unoccupied hours with the possibility of local adjustment and control.

The new opening has been designed to slide outwards with grooves using a lever handle system. The lever handle also works to allow the filters to be pulled out from inside for cleaning and changing. Externally the finish can potentially match any finish as per the building for low impact or aluminium for creating a contrast. The build-up of the external face uses high performance insulation material (Spacetherm) to achieve a U-Value which is very close to the Passivhaus standard. This option can ensure that the overall building performance during the winter period would not be compromised. Moreover, double airtight seals have been incorporated as part of the design to ensure the required airtightness set by Passivhaus standard.

The proposed height from the floor is to be around 200mm to encourage the cool air entering the building at lower level and consequently with the combination of windcatcher design, a higher air change is achieved. The 200mm height from the floor also increases the security alongside the maximum 100mm clear opening. Moreover the 100mm clear opening would meet the Building Regulations regarding the safety for children.

The introduction of the air filters would not only help to ensure the high quality of fresh air during the summer but also make sure that no insects would enter the building alongside some protection from the external noise. Moreover the design of the system protects the building from rain and allows for longer operation during the summer period.

The new low level opening was drawn in the dynamic thermal model as an opening operated during the summer only and in order to create the effect of the filter and the consequent resistance to the air flow, louvres were placed in the opening. The new design was tested as Option 3 to examine the effect of the possible higher ventilation achieved by the introduction of the new low level opening.

The overall overheating percentage was reduced to 0% as can be seen from Figure 5-29.

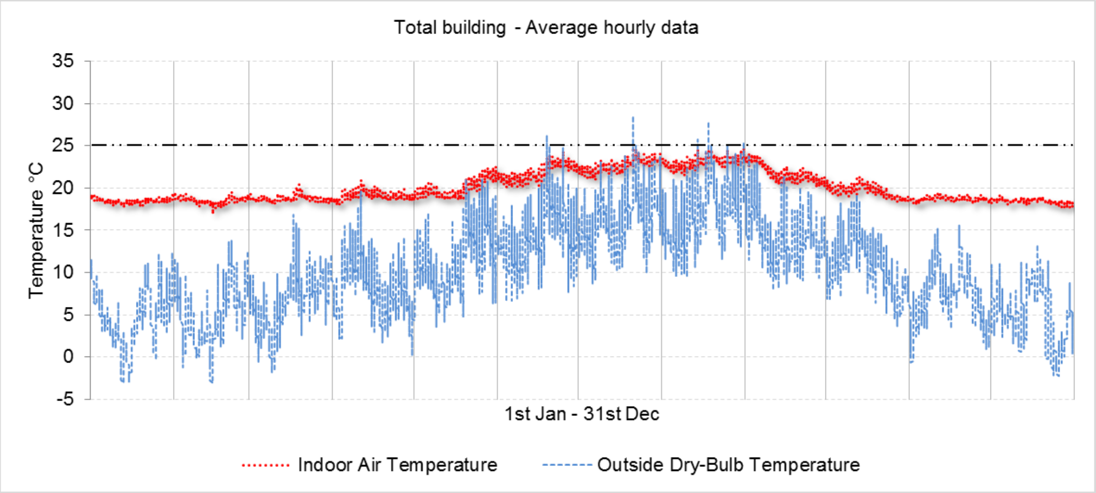


Figure 5-29- Building average hourly data indicating the overheating percentage of 0%

The combination of the new low level design and windcatcher over the staircase has resulted in no overheating for this building. However the above graph is the average for the entire building and therefore the individual spaces were examined in order to test the overheating for each space. Figures 5-30 to 5-35 are hourly temperatures during the summer for the living room and the master bedroom in comparison to the monitored data and base case model.

Living room

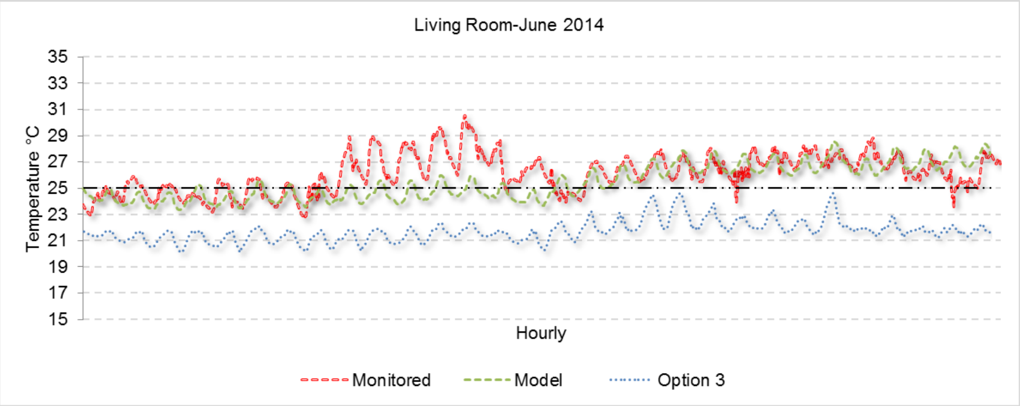


Figure 5-30- Hourly data for option 3 in comparison to base case model and monitored temperatures

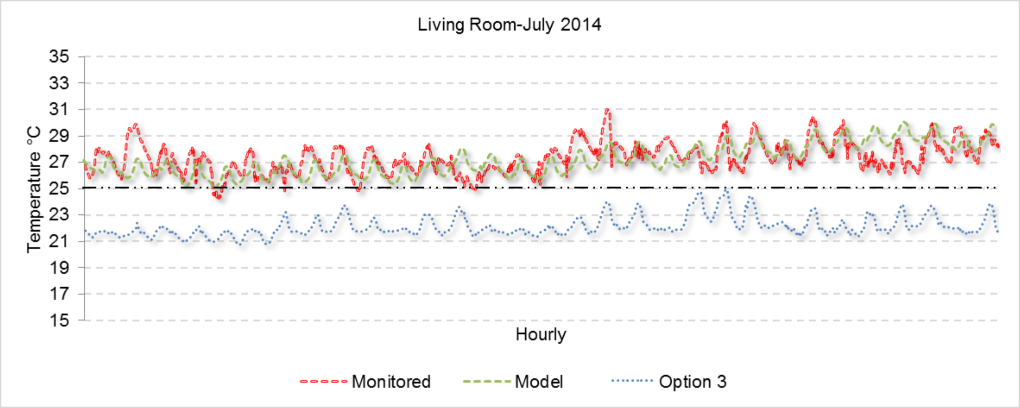


Figure 5-31- Hourly data for option 3 in comparison to base case model and monitored temperatures

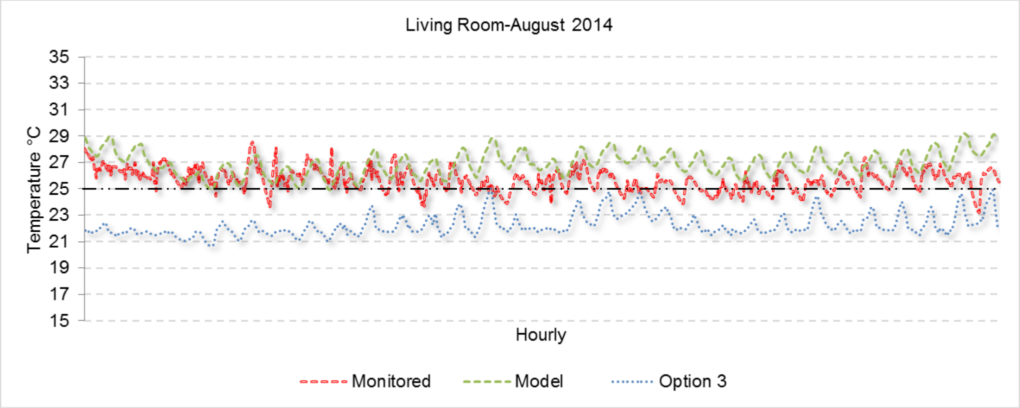


Figure 5-32- Hourly data for option 3 in comparison to base case model and monitored temperatures

Master bedroom:

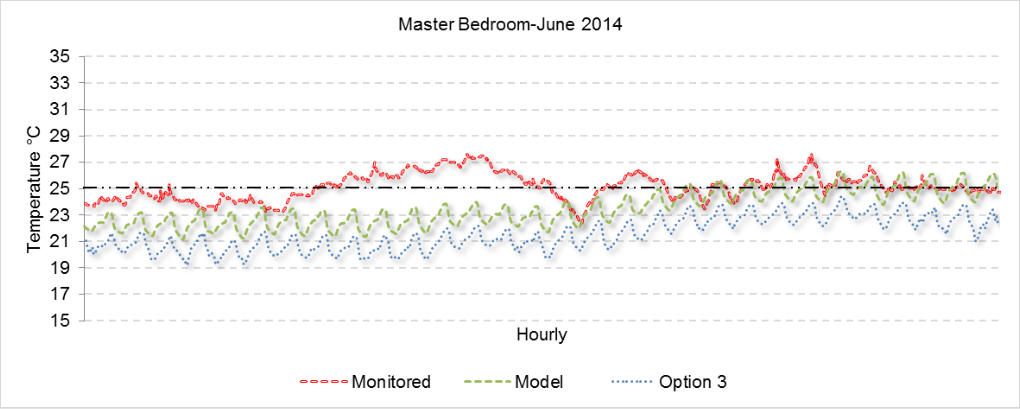


Figure 5-33- Hourly data for option 3 in comparison to base case model and monitored temperatures

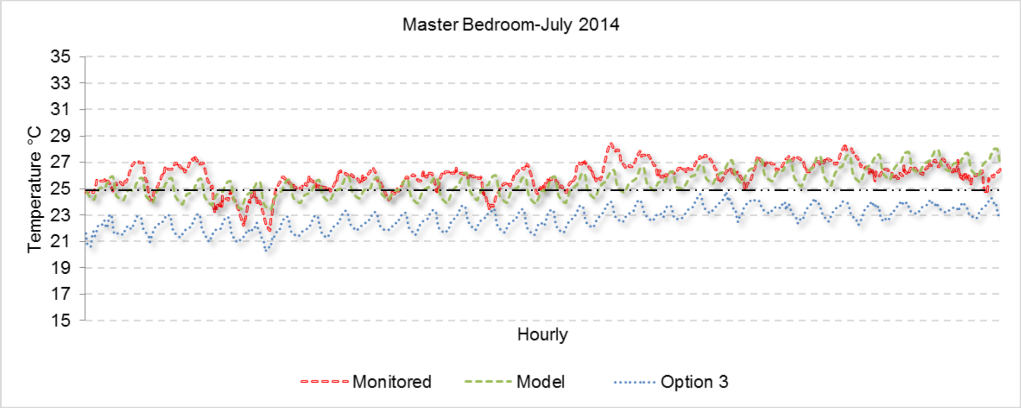


Figure 5-34- Hourly data for option 3 in comparison to base case model and monitored temperatures

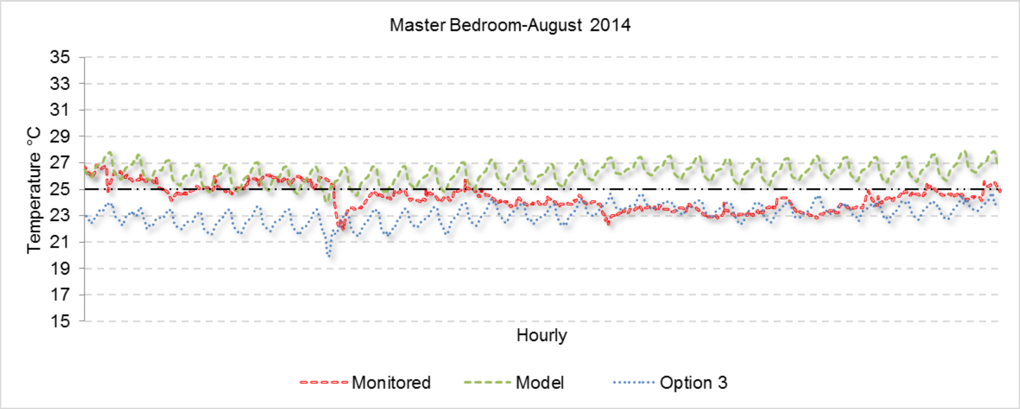


Figure 5-35- Hourly data for option 3 in comparison to base case model and monitored temperatures

The examination of the above graphs highlights that the indoor temperatures for the master bedroom as well as the living room never passed the 25°C limit during the three months of summer. The highest temperature was recorded to be high 24°C in the living room for a small period of the time and temperatures were generally between 20°C and 24°C.

Option 3 has prevented any overheating potential and ensured that the temperatures are kept within Passivhaus limit during the warmer part of the year. However this proposal should not compromise the overall performance of the building and therefore increase the heating load during the winter time. Any additional cold bridging and reduction in airtightness can make the building to no longer meet the Passivhaus limit for heating. Therefore the detailing for both low level opening as well as the windcatcher was carried out alongside Psi-Value calculations to ensure that the proposed system is in line with the Passivhaus requirements.

The actual wall detail for this building was used to incorporate the proposed low level opening structure with the same finish as per the building. The image below is the drawing for the opening within the wall.

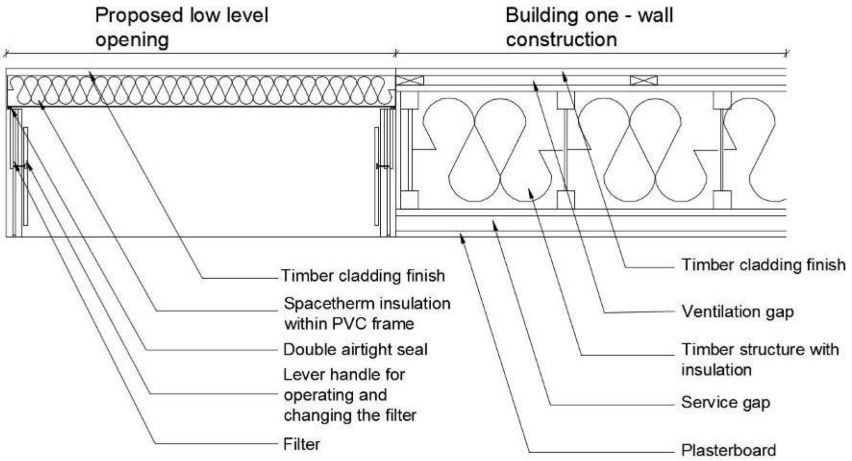


Figure 5-36- Low level opening within wall construction

Moreover this detail was examined for cold bridging by using the Therm programme to calculate the Psi-Value of the junction between the wall and the new opening. Figures 5-37 to 5-39 are extractions from the program indicating the isobars as well as heat flux for the junction.

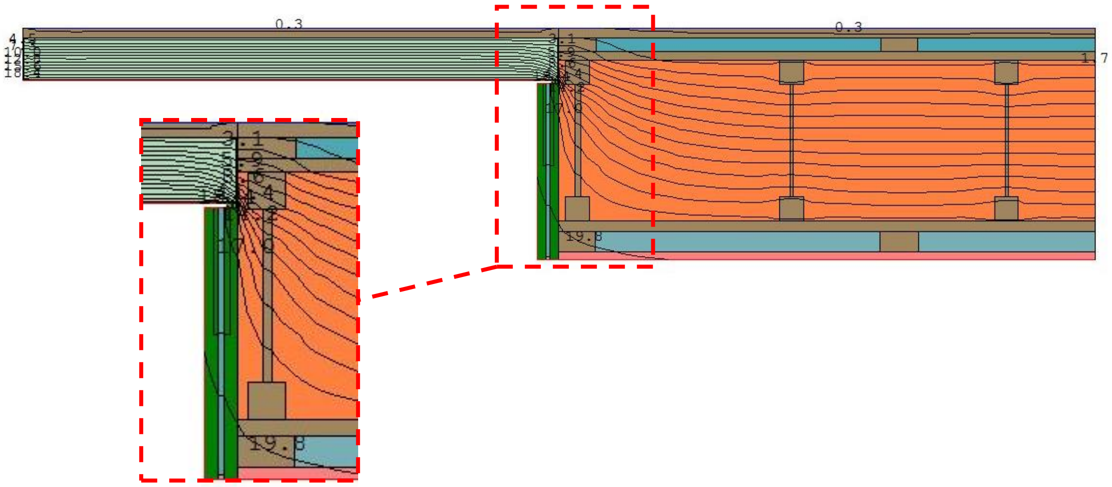


Figure 5-37- Image from Therm model indicating the isobars

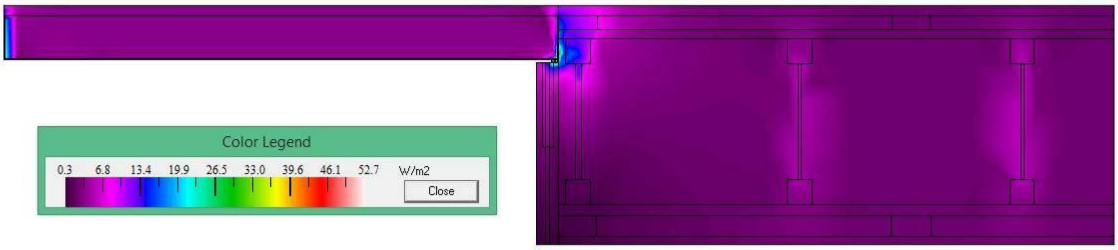


Figure 5-38- Image from Therm model using infrared and temperature scale

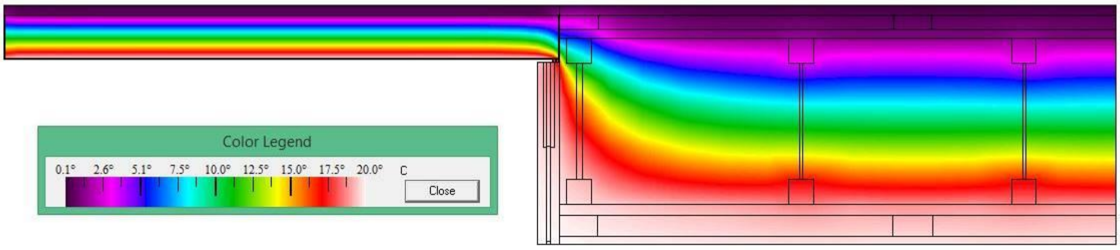
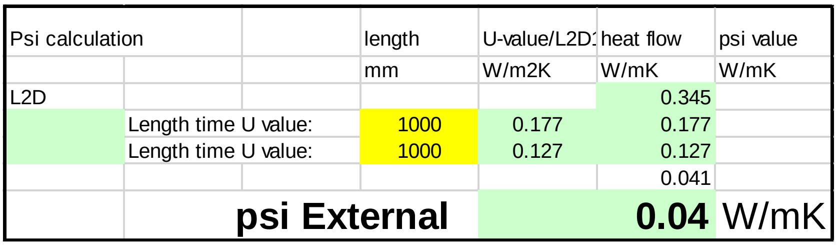


Figure 5-39- Image from Therm model using flux magnitude and temperature scale

The Psi-Value calculation was 0.04 W/mK which is the same value as the standard window junction in Passivhaus when using PHPP. The detail similar to the window junction could be further improved by amending the insulating thickness or position in relation to the wall insulation to result in a lower value. Moreover the U-Value of the proposed opening is much better in comparison to the U-Value for the windows. Below is the calculation for the Psi-Value for the junction.



Psi calculation			length	U-value/L2D:	heat flow	psi value
			mm	W/m2K	W/mK	W/mK
L2D					0.345	
	Length time U value:		1000	0.177	0.177	
	Length time U value:		1000	0.127	0.127	
					0.041	
		psi External			0.04	W/mK

Figure 5-40- Psi-Value calculation for the junction

A similar exercise was carried out for the windcatcher design to examine the possible effect of the cold bridging caused by the introduction of the windcatcher as part of Passivhaus design. The image below is the drawing for the windcatcher within the actual roof construction.

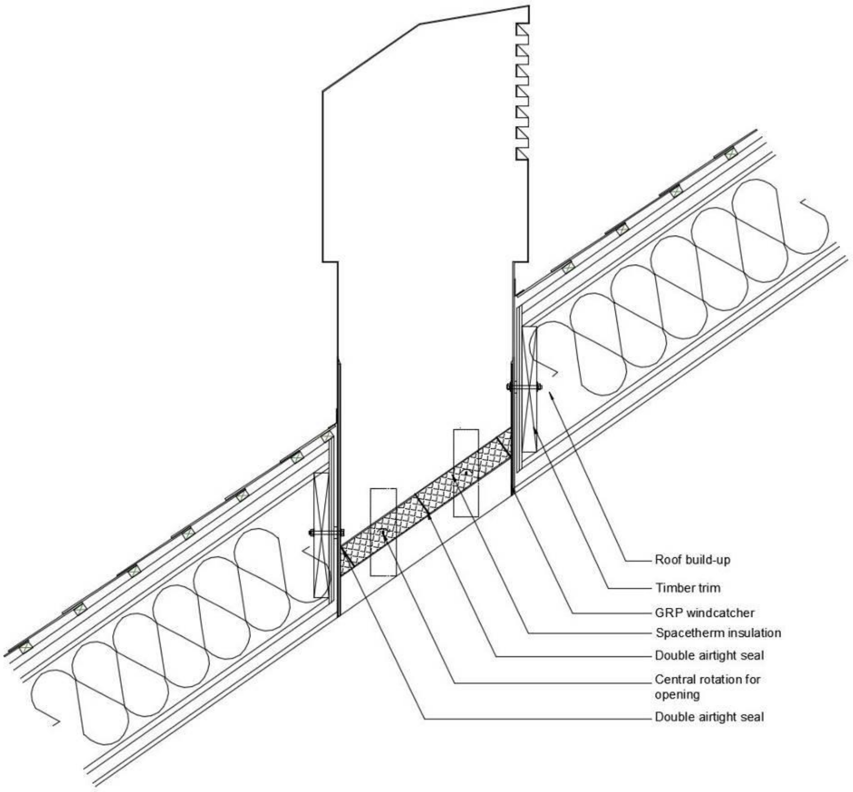


Figure 5-41- Windcatcher within roof construction

Spacetherm insulation was used to close the windcatcher at the bottom in line with the roof insulation using a double seal airtight detail to ensure the thermal and airtightness requirements during the colder months of the year. The insulated detail can be operated by rotation during the summer to allow the warmer air to escape the building. The junction for the windcatcher and the roof was also examined for cold bridging by using the Therm software. Figures 5-42 to 5-44 are extractions from the program indicating the isobars as well as heat flux for the junction.

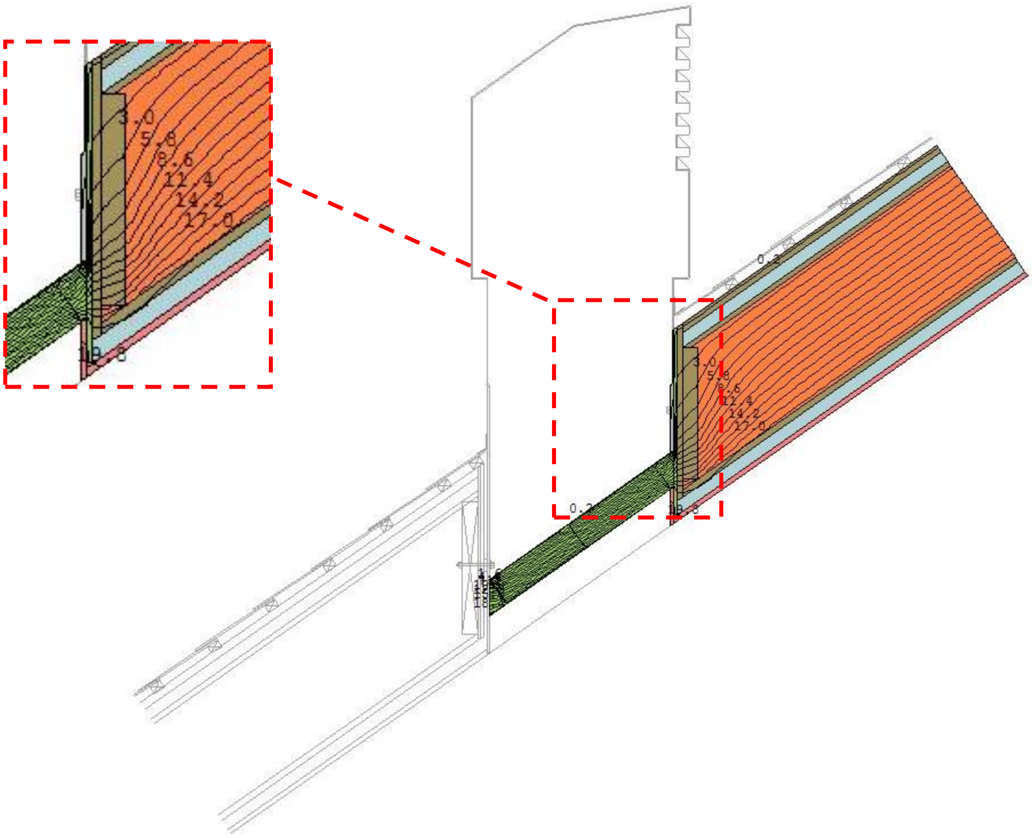


Figure 5-42- Image from Therm model indicating the isobars

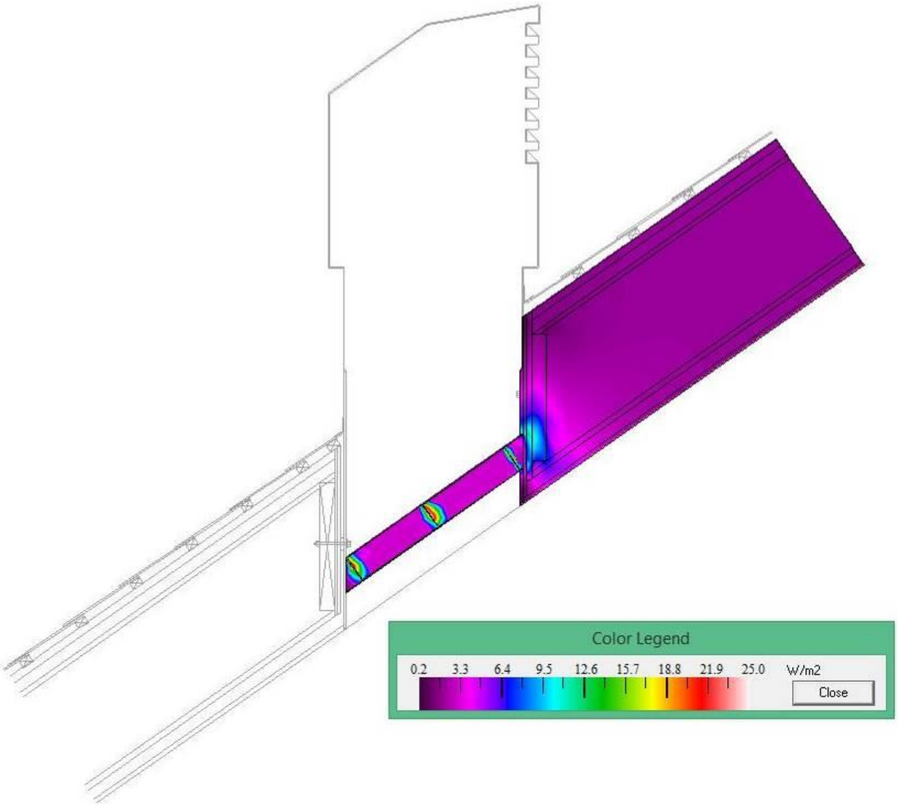


Figure 5-43- Image from Therm model using infrared and temperature scale

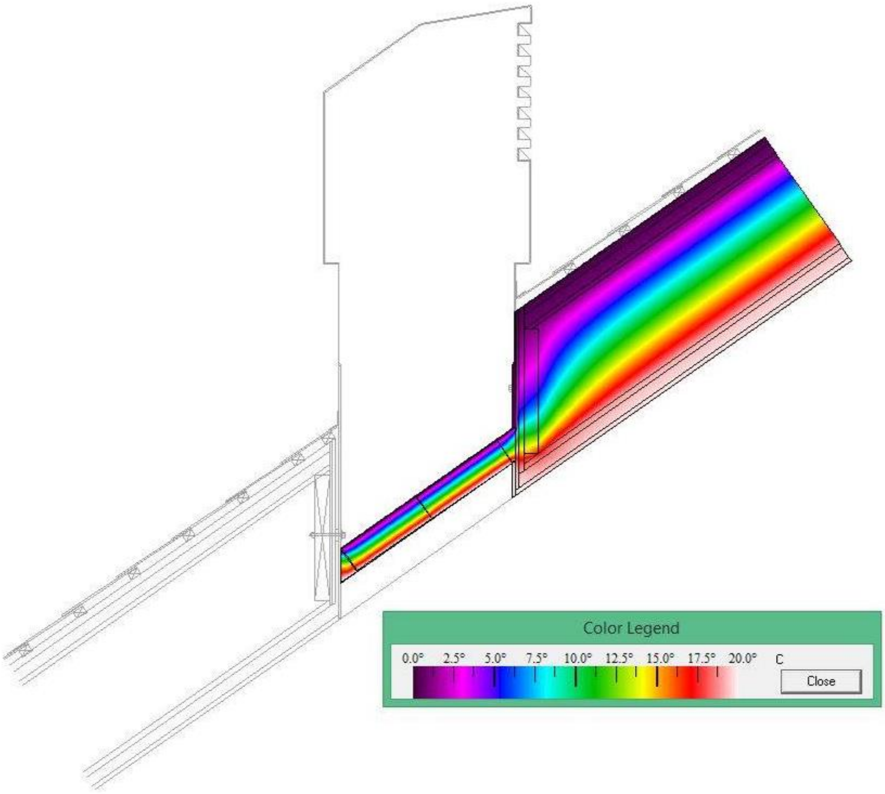
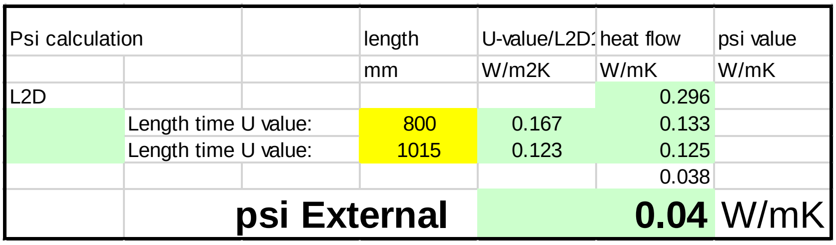


Figure 5-44- Image from Therm model using flux magnitude and temperature scale

The Psi-Value for this junction was also calculated to be 0.4 W/mK similar to the standard window junction in PHPP. The opening however is smaller in comparison to a window and therefore the linear thermal bridging would be very small. Below is the calculation for the junction between the windcatcher and the roof.



Psi calculation			length	U-value/L2D	heat flow	psi value
			mm	W/m2K	W/mK	W/mK
L2D					0.296	
	Length time U value:		800	0.167	0.133	
	Length time U value:		1015	0.123	0.125	
					0.038	
			psi External		**0.04**	W/mK

Figure 5-45- Psi-Value calculation for the junction

The combination of the low level opening as well as the windcatcher used to extract the hot air above the staircase would not only eliminate the overheating percentage by possibly increasing the ventilation rate, but also ensure the winter performance of the building has not been compromised. Moreover if the low level opening was used instead of opening windows and windows were only used to provide views and harvest the solar gain during the winter, the window frame thickness could be reduced in size and therefore more solar gain would be entering the building during the winter and consequently have a lower heating requirement.

CHAPTER 6. LONGEVITY AND VALIDITY

6.1. INTRODUCTION

In chapter 6, the longevity and the validity of the proposed Option 3 has been examined by testing this option for the future climate scenario of 2050 and 2080 using dynamic thermal simulation. In this chapter, the possibility of eliminating window opening and incorporating Option 3 as the only means of cooling during the summer period has been examined using dynamic modelling alongside PHPP calculation. Lastly, Option 3 has been tested for an additional 5 Passivhaus dwellings using PHPP.

6.2. BASE CASE AND THE FUTURE CLIMATE

The base model (Building One) was re-examined using the future climate data (refer to section 3.6.2) to evaluate the impact of climate change. The two future climate data scenarios used were 2050 A2 and 2080 A2 and consequently the overheating for the building was increased from the calculated 19.55% to 24.32% and 30.53% respectively.

The overheating percentage could be increased around 5% during 2050 and over 10% in 2080 climate scenarios during the summer period as indicated in figures 6-1 and 6-2 which are the average hourly temperatures for the whole building during the two periods respectively. The average hourly temperature during 2080 could be over the 25°C for the whole of the summer period reaching 30°C, which could make the building almost unbearable during the summer months (Figure 6-2)

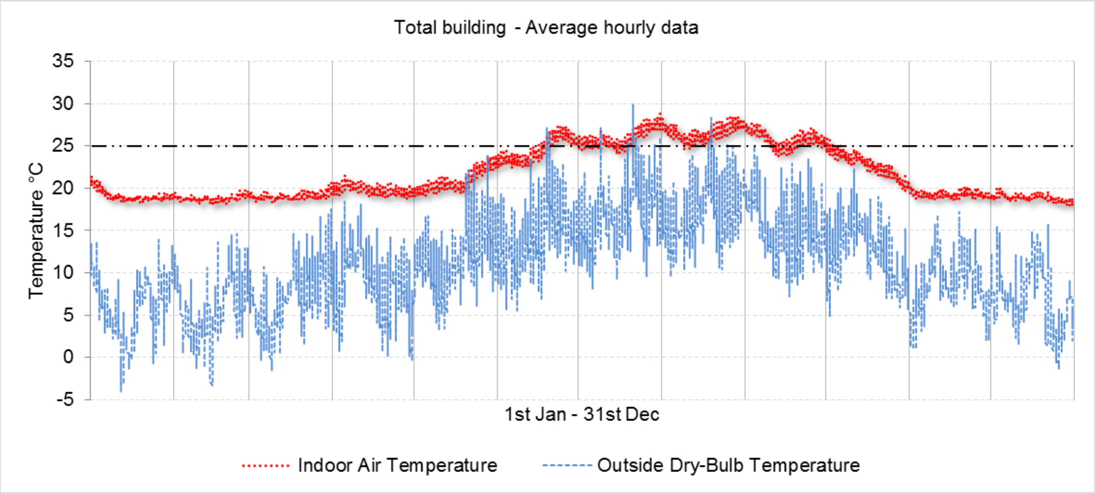


Figure 6-1- Average hourly temperatures of the whole building using 2050 A2 climate data

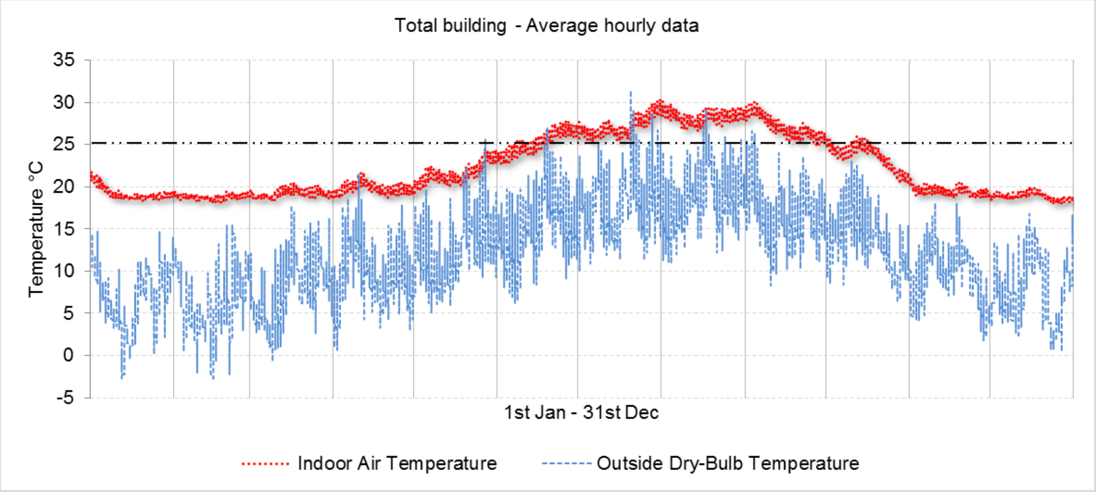


Figure 6-2- Average hourly temperatures of the whole building using 2080 A2 climate data

Comparison was made between the modelled and monitored data in regards to the frequency of the temperature above the 25°C limit including the future scenarios allowing better understanding of the possible increase in the overheating percentage due to changing climate. Figure 6-3 is the summary of the comparison.

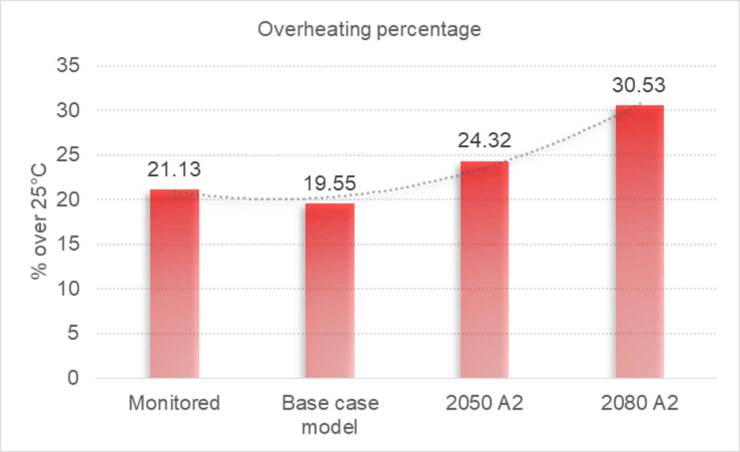


Figure 6-3- Percentage of overheating for different scenarios in comparison to the base case model and monitored data (Building One)

Similar to Building One, the future climates for 2050 A2 and 2080 A2 (refer to section 3.6.2) were used for Building Two to examine the impact of the climate change on the building and to study frequency and the possible increased percentage of overheating. The overheating percentage for this building was also increased and the increase was from the calculated 1.79% to 7.43% and 15.66% using the 2050 and 2080 data respectively. Figures 6-4 and 6-5 are indications of the average hourly temperatures for the whole building for 2050 and 2080.

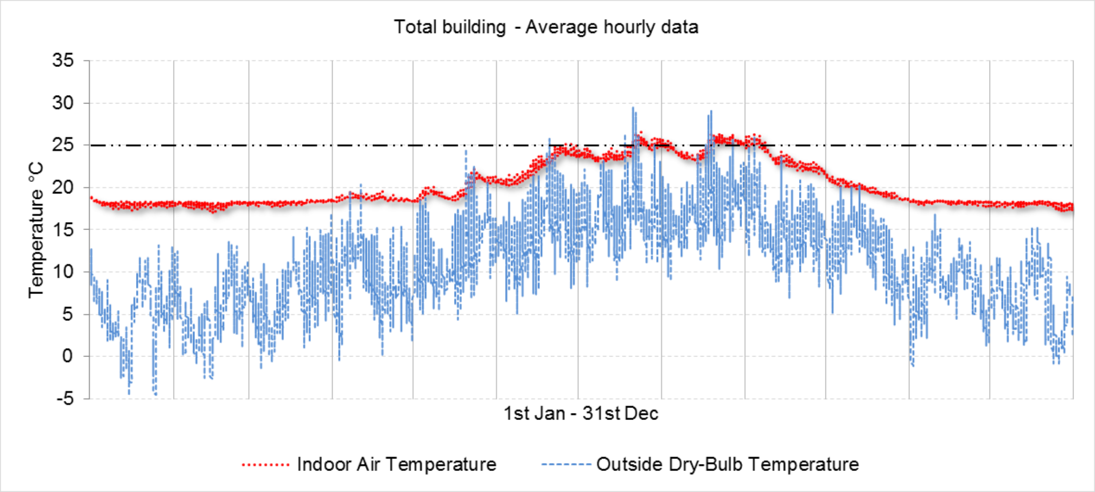


Figure 6-4- Average hourly temperatures for the whole building using 2050 A2 climate data

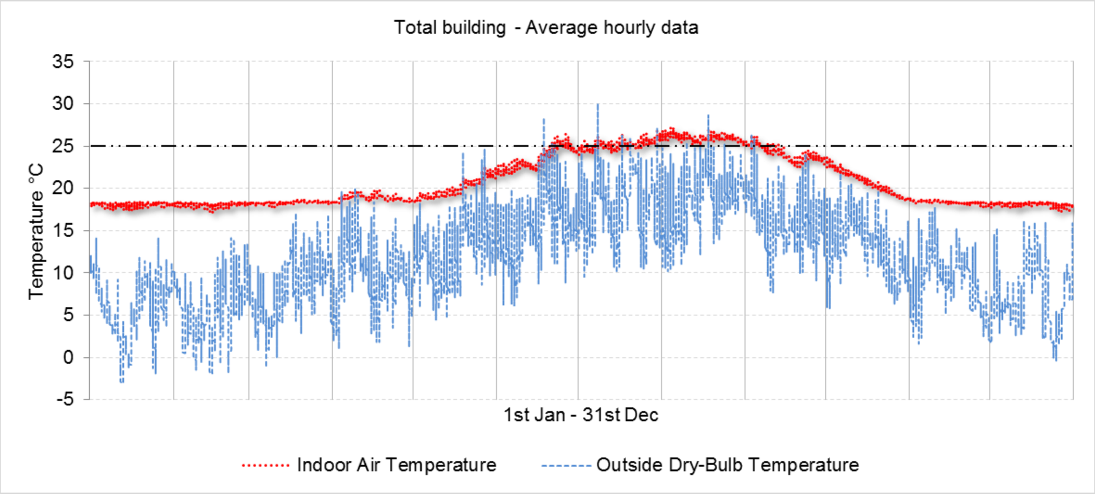


Figure 6-5- Average hourly temperatures for the whole building using 2080 A2 climate data

Although the overall overheating percentage is lower for this building and was calculated to be 15.66% at the worst, however the increase in overheating percentage was noticed to be higher (around 7%) during 2050 and around a further 8% for 2080 in comparison to Building One.

The image below highlights the comparison between the modelled and monitored data in regards to the frequency of the temperature above the 25°C limit including the future scenarios.

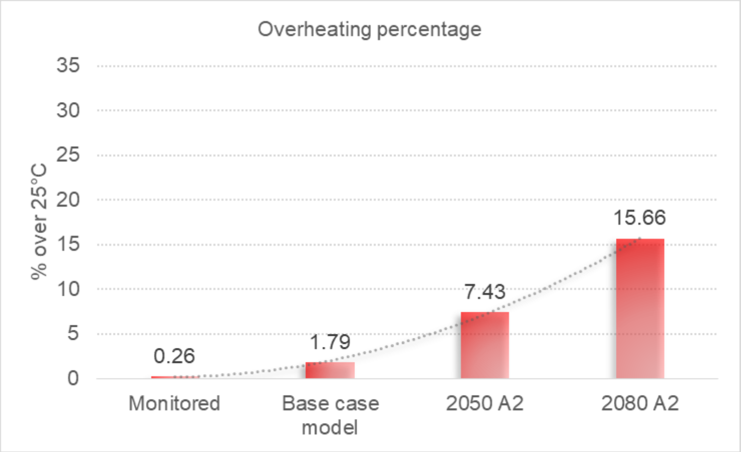


Figure 6-6- Percentage of overheating for different scenarios in comparison to the base case model and monitored data (Building Two)

6.3. PROPOSAL: FUTURE CLIMATE

Future climate data was used as per the earlier discussion in the weather data section (3.6) using 2050 and 2080 climate data. Consequently all three options were tested to examine the impact of the warmer future climate and therefore the suitability of the different options.

6.3.1. Option 1

Carrying out the calculation for Option 1 (see section 5.5.1), had resulted in a reduction of overheating from 19.55% (base case) to 12.08% using the current climate data. Furthermore when using the 2050 climate data the overheating percentage was increased to 15.08% as perhaps expected. The graph below (Figure 6-7) is the hourly data for the building in relation to the ambient temperature indicating the overheating percentage.

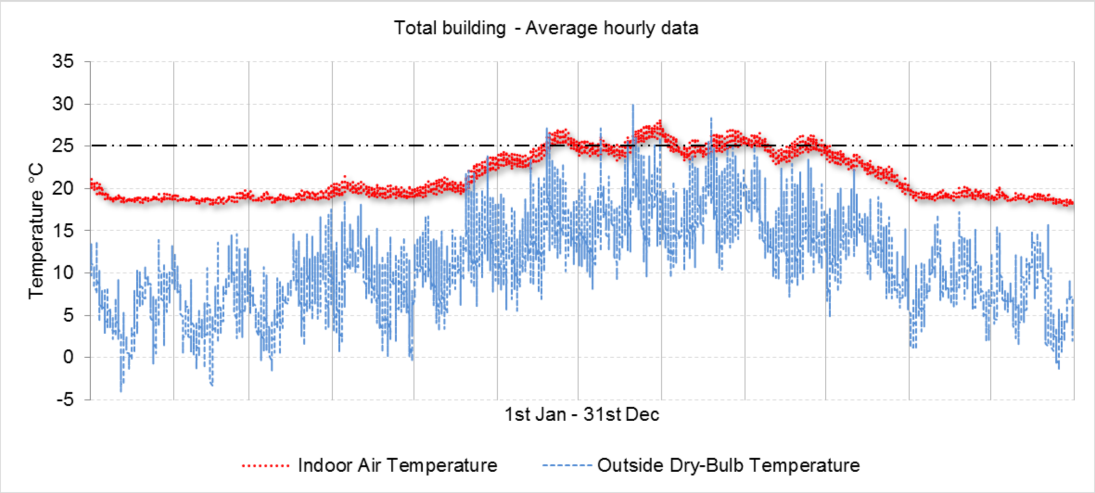


Figure 6-7- Building average hourly data indicating the overheating percentage of 15.08%.

Although the overheating is around 15%, however it is lower than the initial 24.32% without the windcatcher option. The system is still effective to some extent and contributes to a reduction of overheating percentage by about 9%.

Similarly the 2080 climate data was used to further examine the even higher temperatures during the summer. Figure 6-8 is the hourly data for the building in relation to the ambient temperature indicating the overheating percentage.

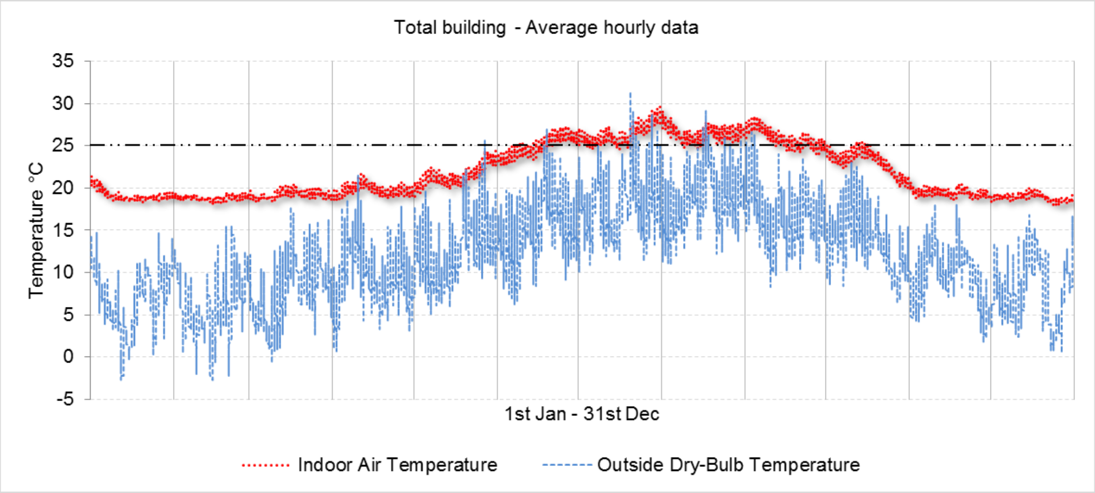


Figure 6-8- Building average hourly data indicating the overheating percentage of 25.93%.

The overheating percentage was increased as expected from 12.08% to 25.93% when using the 2080 data. However again the overheating percentage is around 5% better with the incorporation of the windcatcher in comparison to the previous 30.53% of overheating. Noticeably the improvement percentage has been reduced during 2080 when comparing to 2050. The smaller improvement in overheating percentage for 2080 could have been the influence of the greater need for increase in ventilation rate and therefore the possible associated cooling. Below is the summary for the different climate data and the overheating percentage for option 1.

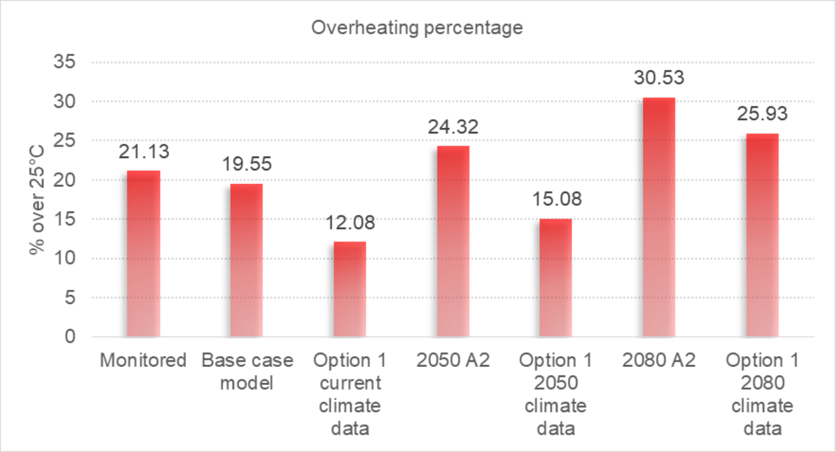


Figure 6-9- Overheating percentage in relation to climate data – Option 1, Building One

Similar to Building One, MVHR ducts were used for Building Two, to be connected to a windcatcher at the point where the MVHR is located (loft space) giving the option to switch between the MVHR and windcatcher during the winter and summer period. The windcatcher was connected to the extract and intake ducts separately as per Building One with the limitation of wind direction changes and therefore possibility of changes in extract and supply. Moreover the same technique was used in drawing the MVHR ducts as part of the floor void using the actual material properties for the ducts as per Building One. Figure 6-10 is an extract from the dynamic model indicating the duct locations per floor.

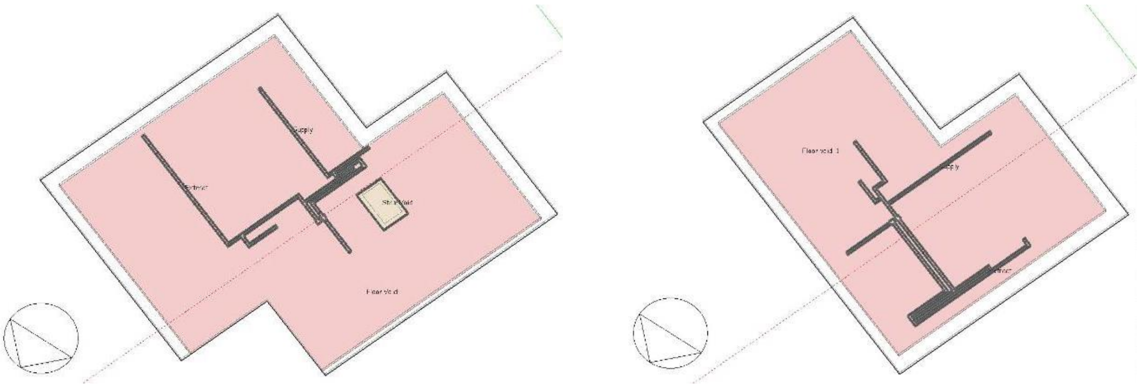


Figure 6-10- MVHR ducts drawing from the dynamic model – Ground and first floor from left to right

The same Monodraught Classic Square design 125 was used for this building in order to provide natural ventilation, located on the Northeast side of the roof. The image below (Figure 6-11) is the extract from the dynamic model indicating the location for the windcatcher on the roof of Building Two.

Figure 6-11- Extract from the dynamic model indicating the windcatcher drawing

The external louvres were scheduled to be open throughout with internal louvres being open during the summer only replicating the actual design for this type of product. The MVHR unit also was switched off during the summer as previously mentioned allowing the ducts to be used by the windcatcher with some energy savings and consequently reduction in CO_2 emissions associated with it.

The base case model using the 2050 climate data had resulted in 7.43% of overheating which was reduced to 4.63% by the introduction of option 1. Below is the building average hourly data using the windcatcher (Figure 6-12).

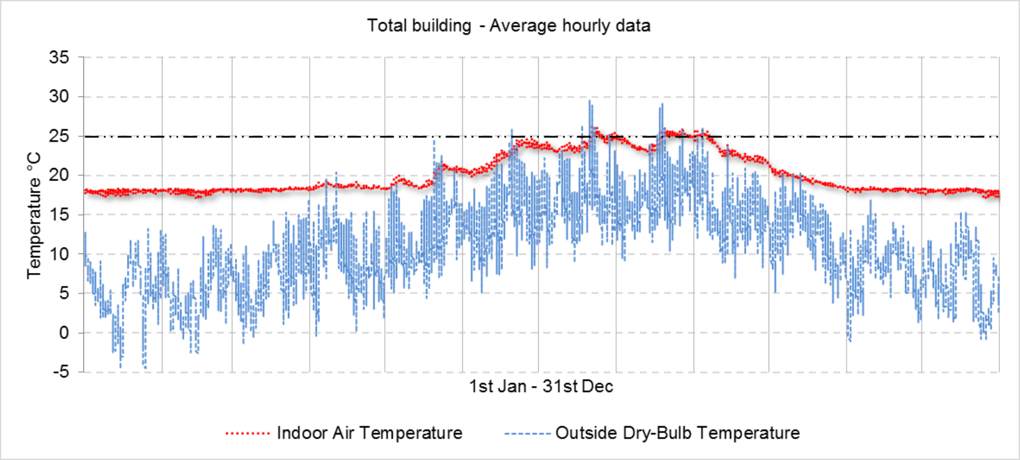


Figure 6-12- Average hourly temperatures for the whole building using 2050 A2 climate data

When using the 2080 climate data the overall overheating was initially calculated to be 15.66%. Furthermore the introduction of option 1 has helped in the reduction of overheating to 11.83% as can be seen from the building's average hourly data using the windcatcher below (Figure 6-13).

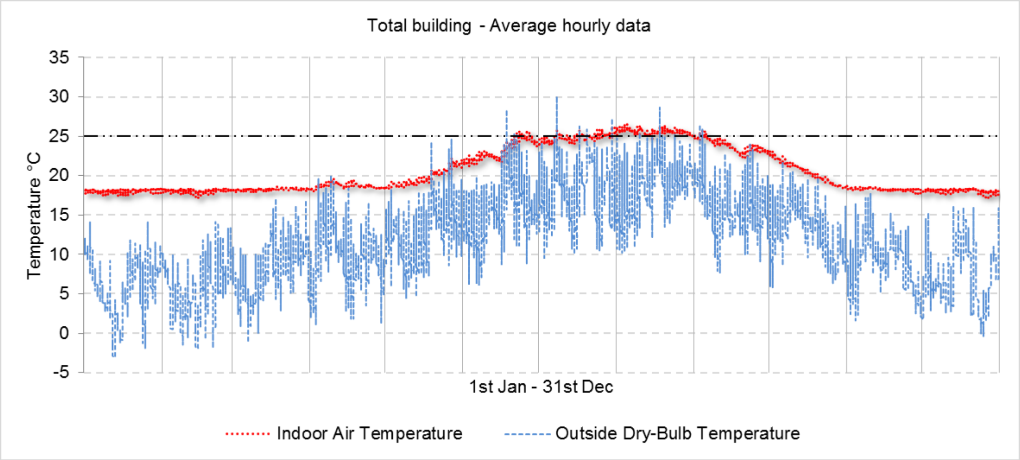


Figure 6-13- Average hourly temperatures for the whole building using 2080 A2 climate data

The introduction of the windcatcher could help to increase the natural ventilation and consequently reduce the overheating percentage securely with lower pollution or noise implication in comparison to window usage. However similarly to Building One, although higher natural ventilation has helped in the reduction of overheating, but this option did not completely eliminate the overheating percentage.

Below is the summary of the calculation for the overheating percentage in relation to the climate and the introduction of option 1.

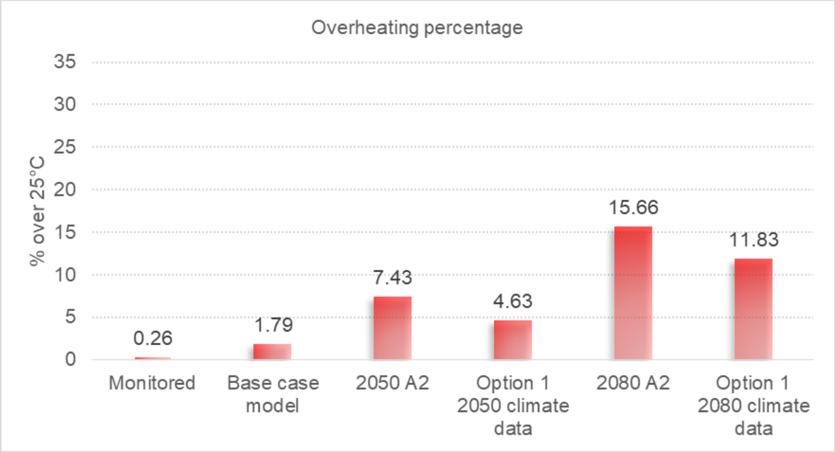


Figure 6-14- Overheating percentage in relation to climate data – Option 1, Building Two

6.3.2. Option 2

Option two was undertaken using different amendments in order to optimise the effectiveness of the use of the windcatcher over the staircase located towards the south side of the building. The overall overheating was reduced to 12% in comparison to 19.55% from the base case model. To examine the effect of higher temperature in the future, the 2050 climate data was used and the overheating percentage was increased to 14.16%. The graph below (Figure 6-15) is the hourly data for the building in relation to the ambient temperature indicating the overheating percentage.

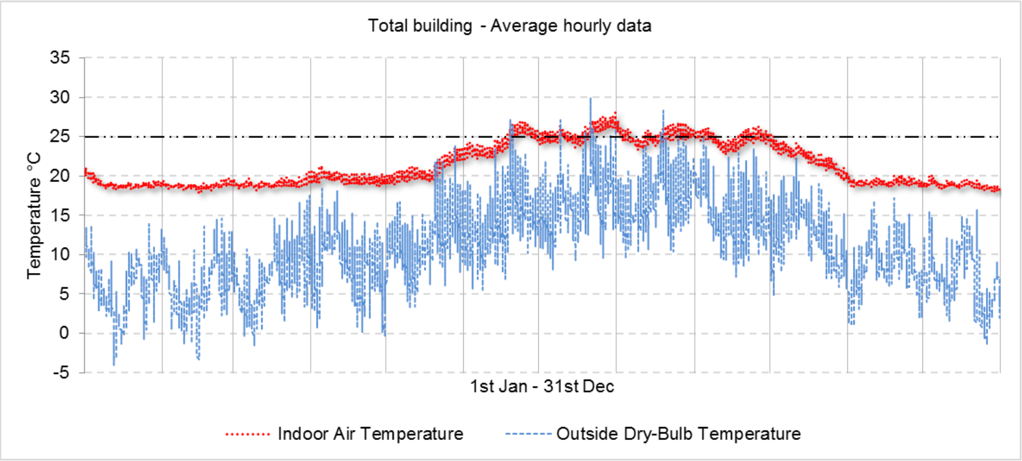


Figure 6-15- Building average hourly data indicating the overheating percentage of 14.16%.

The 14.16% is higher than the required limit of 10%, however it is much lower than the initial 24.32% overheating percentage without the use of the windcatcher.

Furthermore the higher future climate data for 2080 was also examined and Figure 6-16 is the hourly data for the building in relation to the ambient temperature indicating the overheating percentage.

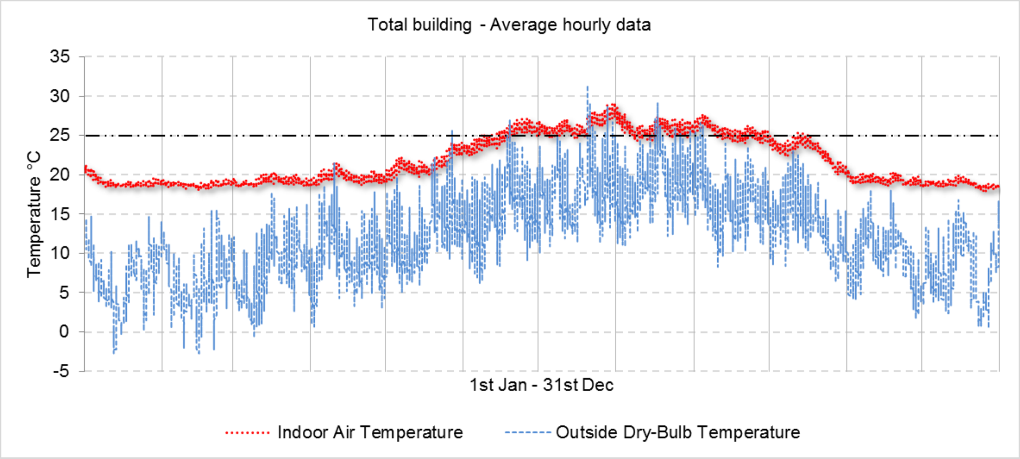


Figure 6-16- Building average hourly data indicating the overheating percentage of 24.12%.

Overheating was increased to 24.12% when using the climate data for 2080 which is once again lower than the initial model overheating percentage of 30.53%. Below is the summary for the different climate data and the overheating percentage for option 2.

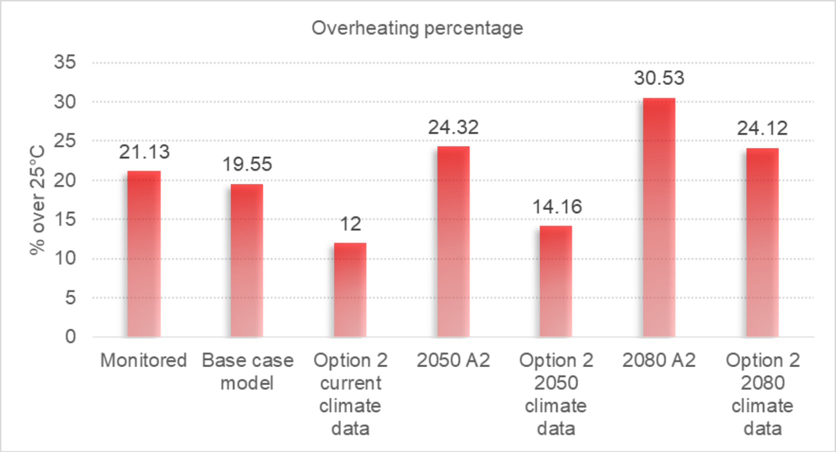


Figure 6-17- Overheating percentage in relation to climate data – Building One, Option 2

Option two has been proven to be more effective when using the future climate data in comparison to option one even though the percentage of overheating was very similar at around 12% when using the current climate data. The overheating was lower by about 1% during 2050 and over 1.5%

during 2080 indicating the possible higher effectiveness of lower localised temperature by the use of a green roof.

The same steps were also taken for Building Two as per Building One by locating the windcatcher over the staircase followed by further amendments. The location over the staircase should help in increasing the stack effect leading to a higher ventilation rate and therefore a reduction in the overall overheating percentage. The image below (Figure 6-18) is an extraction from the dynamic model indicating the location of the windcatcher.

Figure 6-18- Extract from the dynamic model indicating the windcatcher location

The design and opening schedule was kept exactly as per option 1, however the overheating was reduced from the original 7.43% using the 2050 climate data to 2.87% in comparison to the first option of 4.63% indicating the higher effectiveness of the stack effect over the staircase. Moreover further amendments were undertaken in several steps as per Building One to examine the possible improvements to the overall overheating percentage.

Therefore the new improved design with louvres facing the North direction only was tested and the overheating was further reduced to 2.49%. The introduction of a green roof surrounding the windcatcher further helped in reducing the overheating percentage to 2.32%. Moreover the introduction of a higher U-Value material for the windcatcher in combination with the previous improvements resulted in the best reduction of overheating to 2.09% in total. Table 6-5 is the summary of all the different iterations as part of this option and the associated overheating percentage.

Table 6-1- Percentage of overheating for different scenarios for option 2

Base case-2050	Monodraught classic square design	Windcatcher new design north direction only	Windcatcher new design green roof	Windcatcher new design-green roof-improved U-Value –
7.43%	2.87%	2.49%	2.32%	2.09%

Figure 6-19 is the building average hourly data for option 2 with all the improvements using the 2050 climate data.

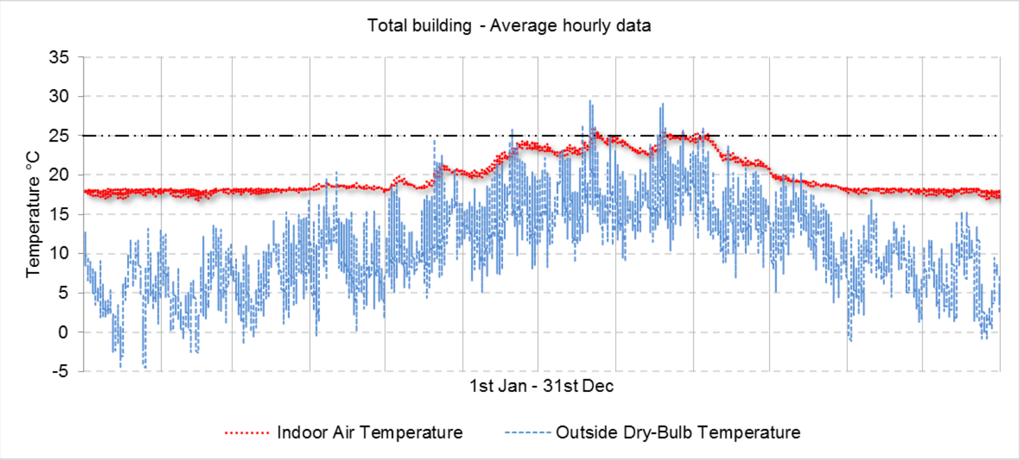


Figure 6-19- Average hourly temperatures for the whole building using 2050 A2 climate data

The latest model was used to examine the predicted higher temperatures during 2080 which resulted in an improvement of overheating percentage from the original 15.66% to 7.04% which is almost a 5% reduction from option 1 at

11.83%. Below is the building average hourly data for option 2 with all the improvements using the 2080 climate data (Figure 6-20).

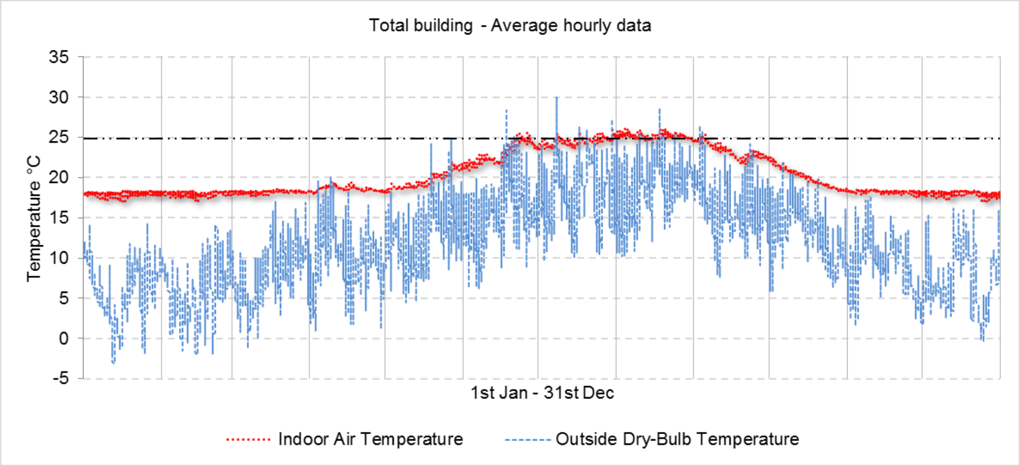


Figure 6-20- Average hourly temperatures for the whole building using 2080 A2 climate data

Option 2, using the benefit of higher stack effect from the staircase has led to more reduction in overheating percentage, however as experienced in Building One the introduction of a specific low level opening can perhaps improve the overall ventilation rate and therefore help in reducing the overheating percentage.

Below is the summary of the calculation for the overheating percentage in relation to the climate and the introduction of option 2.

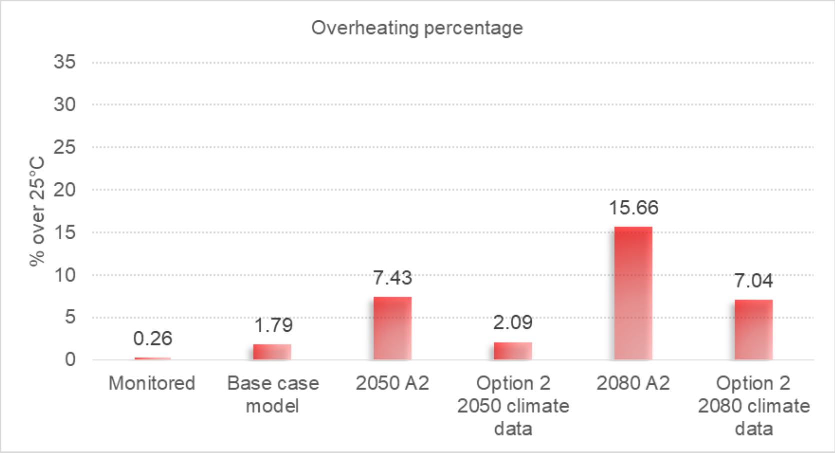


Figure 6-21- Overheating percentage in relation to climate data – Building Two, Option 2

6.3.3. Option 3

The combination of the new low level opening design and the use of the windcatcher in option 3 resulted in no overheating percentage when using the current climate data. However the higher temperature during the summer in the future could increase the possibility of overheating and therefore climate data for 2050 and 2080 was used to examine the possible impact and increase on the overheating percentage for option three. The graph below is the hourly data for the building in relation to the ambient temperature indicating the overheating percentage using 2050 data (Figure 6-22).

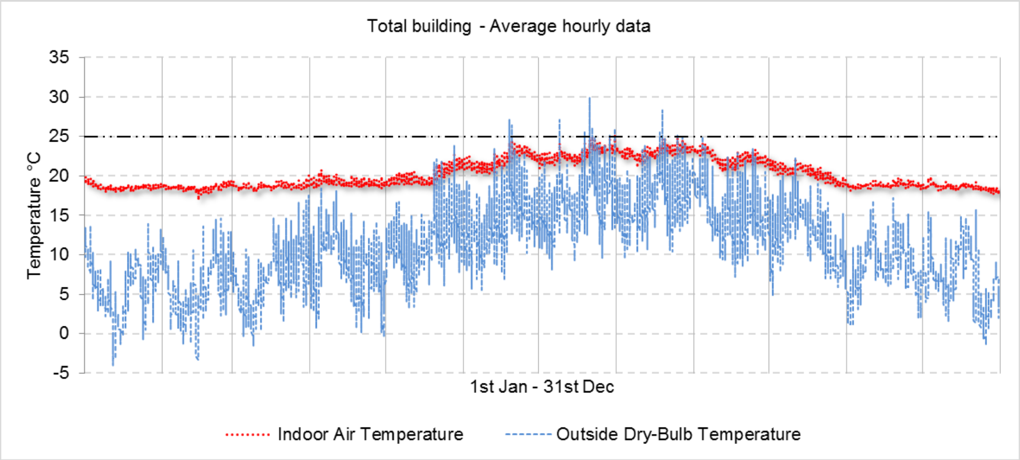


Figure 6-22- Building average hourly data indicating the overheating percentage of 0.01%.

The graph above indicates that the overheating percentage was increased from zero to 0.01% during 2050 which is almost zero, highlighting the effectiveness of the proposed strategy and design even during the projected warmer period in 2050.

Figure 6-23 is the hourly data for the building in relation to the ambient temperature indicating the overheating percentage using 2080 data.

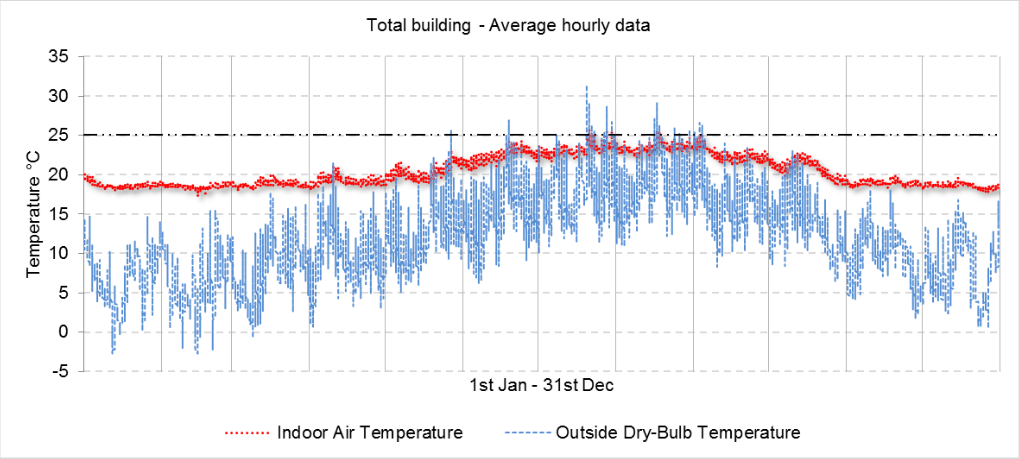


Figure 6-23- Building average hourly data indicating the overheating percentage of 0.51%

Option 3 has proven once again to be a robust system even during 2080 as the overheating was contained to 0.51%. This option can indicate the potential of natural ventilation for cooling even as far as 2080 in the UK climate with expected warmer summer temperatures and allow the indoor temperatures to be kept below the 25°C limit. However the master bedroom temperatures were simulated to be over 24°C, which is although within the Passivhaus requirement but over the suggested CIBSE's 24°C limit for sleeping. Nevertheless this option could help to eliminate the use of any cooling or air conditioning for many years to come, reducing the usage of high energy intensive air conditioning and associated CO_2 emissions contributing to change in the climate.

Similar to Building One the last iteration of option 2 was used in conjunction with the introduction of a specific low level ventilation design to encourage a higher rate of ventilation for Building Two.

The graphs below (Figures 6-24 and 6-25) demonstrate the building average hourly data for this option in reference to the overheating percentage using the future climate data during 2050 and 2080 respectively. The overheating was calculated to be 0.05% during 2050 and 0% during 2080.

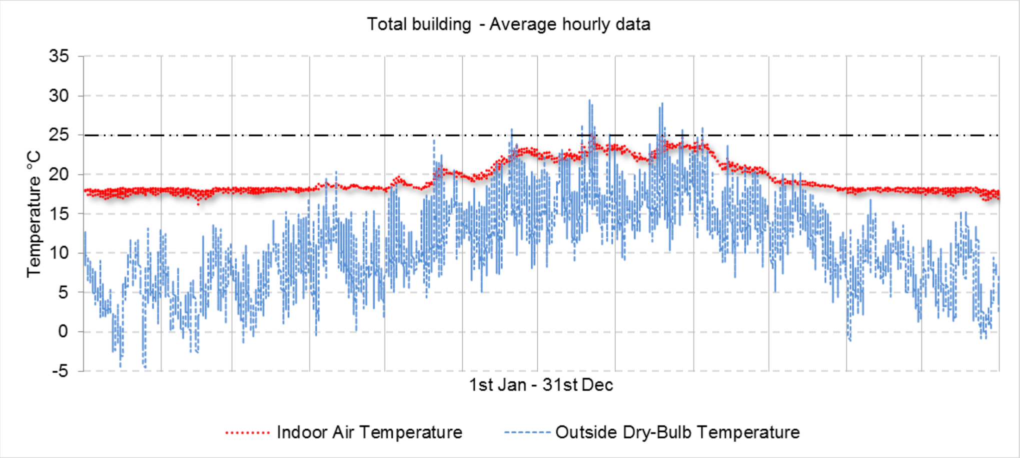


Figure 6-24- Average hourly temperatures for the whole building using 2050 A2 climate data

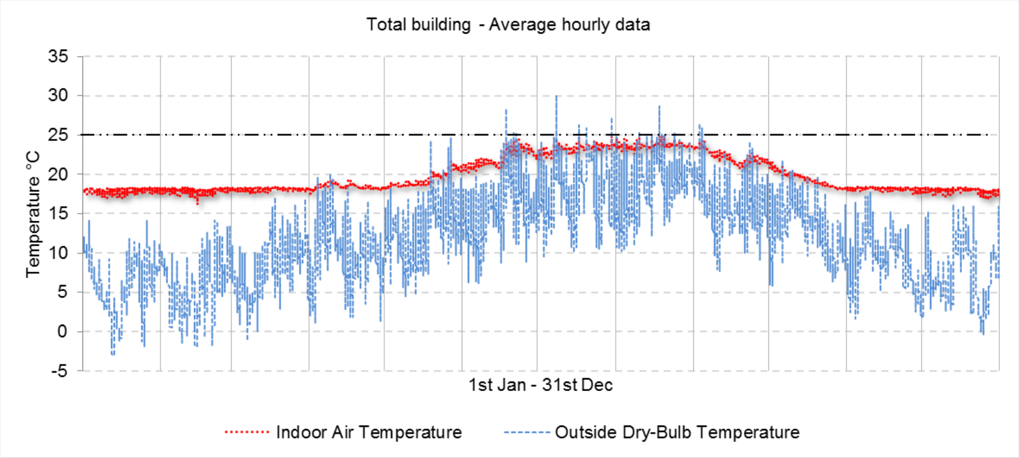


Figure 6-25- Average hourly temperatures for the whole building using 2080 A2 climate data

This option once again has proven to be a robust and effective proposal in the reduction of overheating potential during the possible warmer future climate. Noticeably the building may experience some slight overheating during 2050 when it would not be the case during 2080. However a closer examination into the overall summer temperatures highlights the higher average temperatures during 2080 as perhaps expected.

Moreover the higher thermal mass of Building Two appears to be more effective during 2080 in comparison to Building One and the overheating was 0% for this building in comparison to 0.51% for Building One. Below is the summary of all the calculations for the overheating percentage in relation to the climate and the introduction of different options for the two buildings.

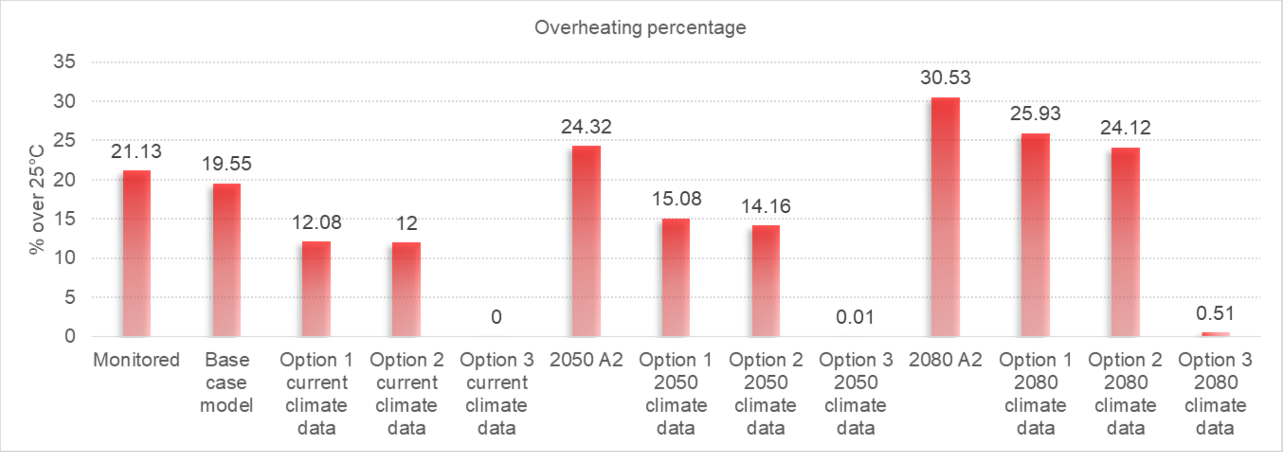


Figure 6-26- Overheating percentage in relation to climate data – Building One

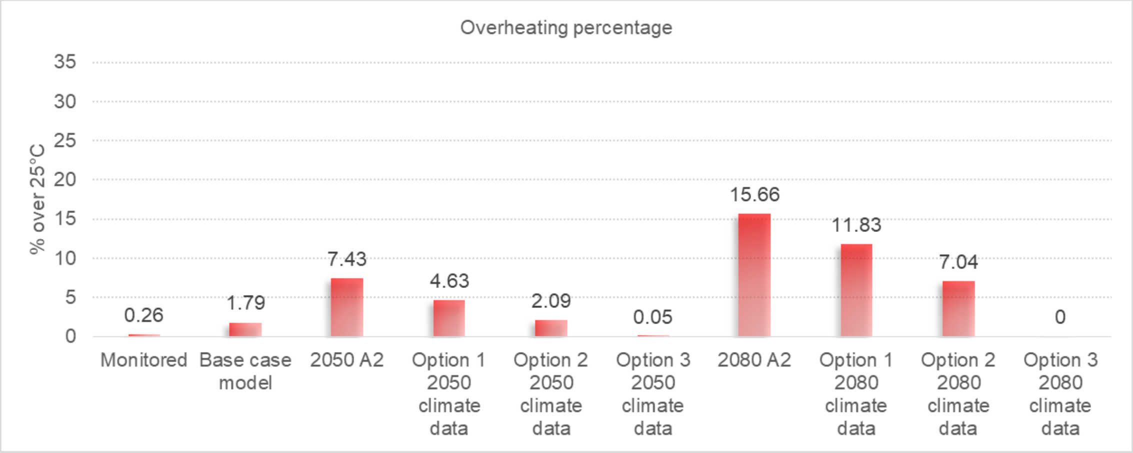


Figure 6-27- Overheating percentage in relation to climate data – Building Two

6.4. ELIMINATING WINDOW USAGE

The proposed system (Option 3) offers the occupant the opportunity to not only increase the natural ventilation and therefore reduce the overheating potential. It also offers the same filtered air as per the MVHR, naturally and addresses the security, insect problem and noise implication by some extent with no additional solar gains. However the study was undertaken by keeping the current window opening patterns and therefore the possibility of eliminating eliminate window opening was further investigated.

6.4.1. Option 3 without opening of windows (Building One)

The dynamic model was used to test whether it was possible to eliminate window opening altogether and only use Option 3. Therefore all the windows were set to be closed and the natural ventilation was achieved by the use of Option 3 only. The graph below (Figure 6-28) is the average hourly temperature data for the entire house.

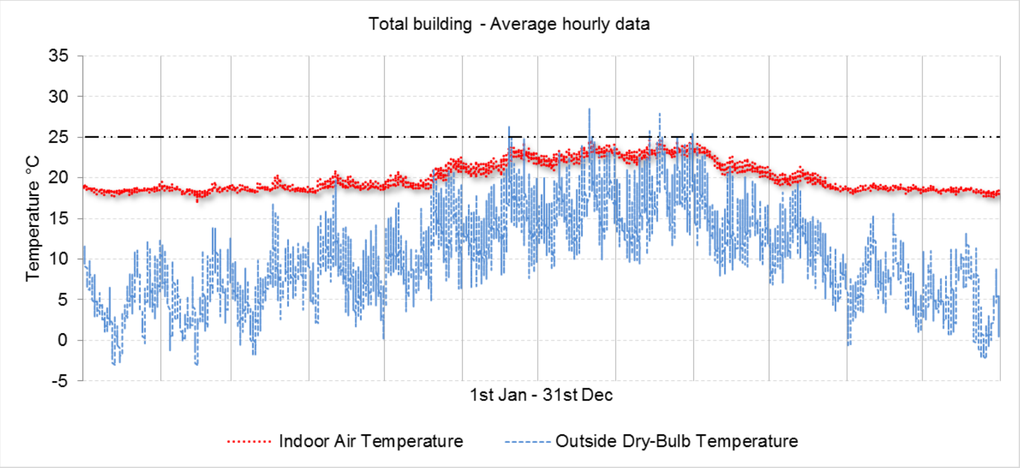


Figure 6-28- Building average hourly data indicating the overheating percentage of 0%.

As indicated from the above graph, there was no overheating and Option 3 has proven to be an adequate option for replacing the window opening and providing the required ventilation securely and filtered. This could allow for reduction in the window frame which will consequently increase the solar gain especially during the winter or perhaps a reduction of window area achieving the same solar gains which in either case can not only improve the overall winter performance but also offer some reduction and savings in the cost of the windows. These benefits have not been investigated further as it would not be possible in the scope of this research.

The total building daily average ventilation was increased to an average of 0.72 for the three months of summer and was between 0.25 to a maximum of 1.85 ac/h (comparing to the initial 0.22 ac/h at night from PHPP). Moreover, the MVHR was kept in operation providing the minimum fresh air and the required extraction from the wet rooms. Figure 6-29 is the daily average ac/h for the three months of the summer.

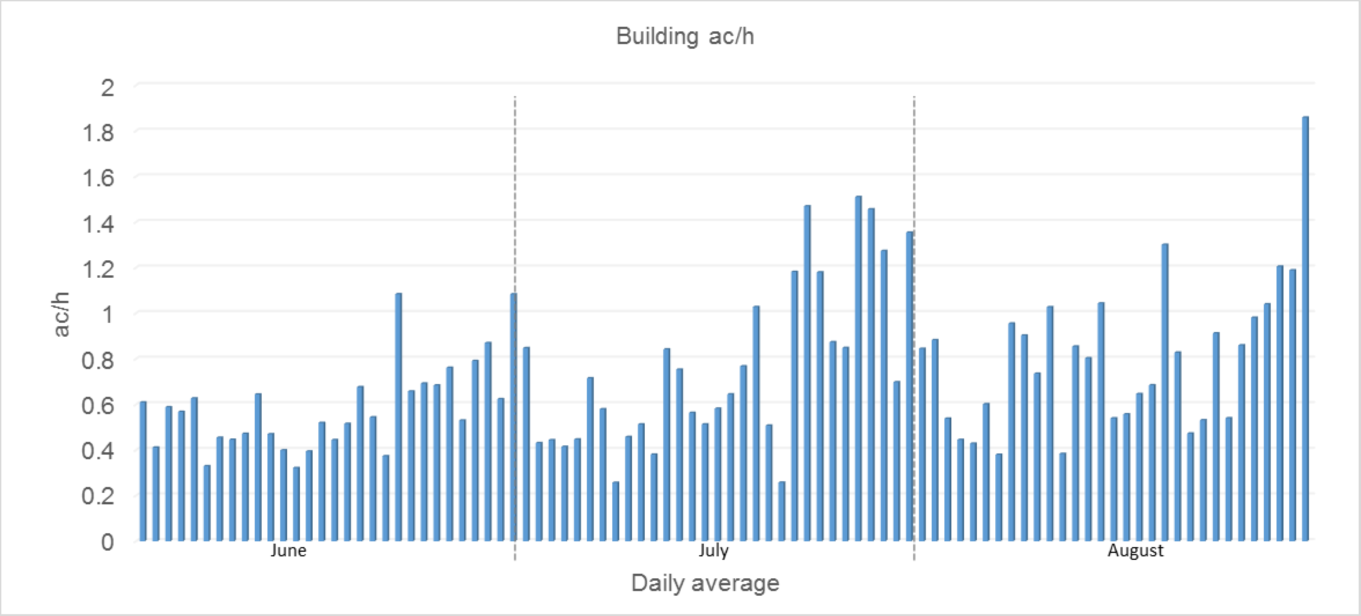


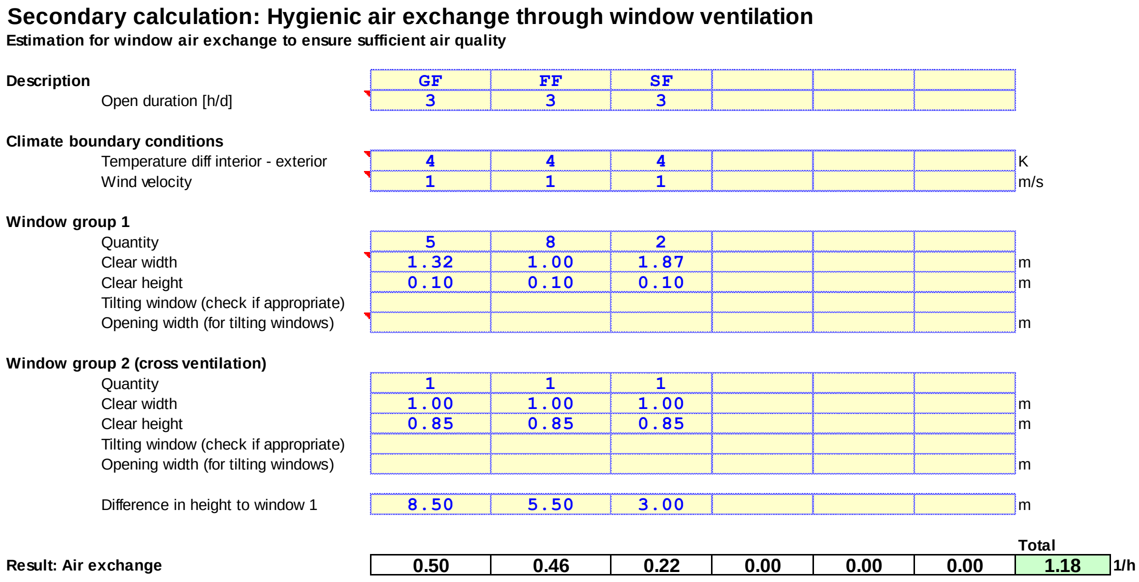
Figure 6-29- Daily average ac/h for the entire building.

6.4.2. Option 3 and PHPP (Building One)

The possibility of eliminating the window opening was further tested in PHPP by incorporating Option 3 into the PHPP calculation using the summer vent sheet. Initially the PHPP8 model was used and the specified night time ventilation at 0.22 air change per hour was removed and no day time natural ventilation was allowed for, this resulted in 27.3% of overheating.

The summer vent sheet was used to test Option 3 by calculating the daytime and night time ventilation from the secondary calculation section. All the new openings for each floor were entered separately and the stack effect using the windcatcher was introduced by the use of group two option and entering the height difference from the low level openings on each floor (Figures 6-30 & 6-31). In order to simulate the reduction factor from the filters for the low level opening and louvres in the windcatcher, a 60% reduction was assumed based on insect screen reduction percentage of 50% (Brumbaugh, 2004) and 10% more was for allowing the resistance due to layout and internal doors. The reduction factor was entered by reducing the daytime ventilation from 12 hours to 3 hours and during the night time the option of reduction factor provided in PHPP was used and 40% was entered (60% reduction).

Below are calculations from the PHPP SummVent sheet for daytime and night time natural ventilation using Option 3 respectively for Building One.

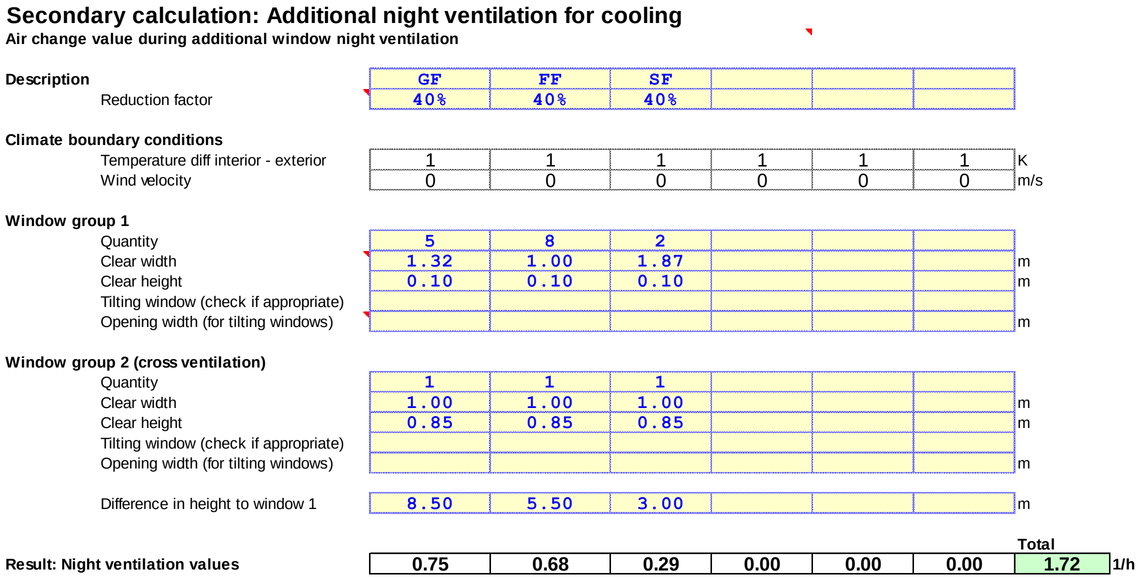


Secondary calculation: Hygienic air exchange through window ventilation

Estimation for window air exchange to ensure sufficient air quality

Description	GF	FF	SF					
Open duration [h/d]	3	3	3					
Climate boundary conditions								
Temperature diff interior - exterior	4	4	4					K
Wind velocity	1	1	1					m/s
Window group 1								
Quantity	5	8	2					
Clear width	1.32	1.00	1.87					m
Clear height	0.10	0.10	0.10					m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Window group 2 (cross ventilation)								
Quantity	1	1	1					
Clear width	1.00	1.00	1.00					m
Clear height	0.85	0.85	0.85					m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Difference in height to window 1	8.50	5.50	3.00					m
							Total	
Result: Air exchange	**0.50**	**0.46**	**0.22**	**0.00**	**0.00**	**0.00**	**1.18**	**1/h**

Figure 6-30- PHPP daytime summer ventilation using Option 3 – Building One



Secondary calculation: Additional night ventilation for cooling

Air change value during additional window night ventilation

Description	GF	FF	SF					
Reduction factor	40%	40%	40%					
Climate boundary conditions								
Temperature diff interior - exterior	1	1	1	1	1	1		K
Wind velocity	0	0	0	0	0	0		m/s
Window group 1								
Quantity	5	8	2					
Clear width	1.32	1.00	1.87					m
Clear height	0.10	0.10	0.10					m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Window group 2 (cross ventilation)								
Quantity	1	1	1					
Clear width	1.00	1.00	1.00					m
Clear height	0.85	0.85	0.85					m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Difference in height to window 1	8.50	5.50	3.00					m
							Total	
Result: Night ventilation values	**0.75**	**0.68**	**0.29**	**0.00**	**0.00**	**0.00**	**1.72**	**1/h**

Figure 6-31- PHPP night time summer ventilation using Option 3 – Building One

The temperature difference and wind velocity for day and night was kept to the PHPP recommendation and standard (Day 4K & 1m/s) (Night 1K & 0m/s) as indicated from the above images and the air change per hour was calculated to be **1.18** and **1.72** for day and night time ventilation using Option 3 with reduction factor. The reduction factor was used in order to account for any resistance to air flow due to the filters and louvre usage and any obstruction internally. The higher natural ventilation resulted in almost no overheating using PHPP from the previous 27.3% to 0.1% which is similar to the dynamic thermal model calculation.

The possibility of incorporating this option as part of the Passivhaus design has been therefore explored and this can be tested by using PHPP during the design stage to ensure the benefit of the proposed system for the individual building as it has been crossed examined using the dynamic simulation model. This option also could help to reduce the performance gap caused by different occupant behaviour during the summer period especially for the night time cooling. However the strategy needs further studies to validate it through physical prototyping and experiments.

In order to test this option in PHPP for the future climate similar to the dynamic model, future climate data was created using Meteonorm for 2050 and 2080 (A2) and imported into PHPP. Consequently Option 3 was tested using 2050 and 2080 climate data allowing the design to be tested in PHPP for the future.

The overheating percentage during 2050 is staying at 0.1% and during 2080 it was increased to 0.5% which is well within the requirements and desired level. More importantly the overheating percentage is very similar to the dynamic thermal model calculation of 0.1% for 2050 and 0.51% for 2080 increasing the confidence in the proposed option and its incorporation within PHPP calculation.

Summary:

The monitoring results had indicated over 50% of overheating for the whole building during the five months of monitoring period and much higher percentage for the individual rooms per month. For instance the kitchen was overheated for almost 100% of the time during the three summer months despite being located in the north side of the building and benefiting from an open plan layout. The RH was generally lower than the desired level and averaged around 40% during the three summer months. The indoor CO_2 levels on the other hand where recorded to be within the Passivhaus required level in the living room and generally passed the limit in the bedroom only during the night. The windows were opened on average for 13.87% during the summer and were limited to day time and therefore reducing the benefit of cooler night temperatures.

The monitoring results were compared to the original PHPP calculation allowing adjustment to the PHPP model using the window operation during the summer. The importance of the location and climate was examined by changing the location of the building which resulted in reduction of overheating of 3.3%. The influence of the lack of summer bypass, location and material properties used around the MVHR fresh air intake and the lack of insulation around the internal MVHR ducts were examined on the overall overheating potential. It was concluded that careful consideration is needed in order to reduce any further contribution from the mentioned areas on the overheating percentage. Furthermore the internal heat gain was recalculated using PHPP8 which was increased to $3.65W/m^2$ increasing the overheating percentage.

The initial thermal dynamic model was drawn using the data from the original PHPP model and was further amended using the monitoring data, internal heat calculation and actual shading pattern used by the occupant (base case). The base case model was tested using future data (2050 & 2080) which led to an increase in overheating percentage of 24.32% and 30.53% respectively compared to the base case model of 19.55%.

Three different options were tested in order to increase the overall natural ventilation and consequently reduce the overheating percentage. The options are prerequisite to one another leading to option 3 resulting in no overheating. The options were further examined using future climate data and although the higher temperature in 2080 resulted in an increase in the total overheating, however it was limited to 0.51% when using Option 3.

Finally Option 3 was tested in order to replace any window opening using the dynamic thermal model and PHPP calculation, allowing for reduction in window frames and providing secure and filtered air without any further increase in solar gain. This option was proved to be effective in reducing the overheating percentage and suggestion was made in implementing the option in the PHPP calculation.

The possibility of the elimination of window operations was exercised for Building Two similarly to Building One and as the original building was not used due to limited overheating percentage for the reappraisal options the model using the 2050 climate data was used.

6.4.3. Option 3 without opening of windows (Building Two)

Option 3 using the 2050 climate data was remodelled with no window being opened to ensure the effectiveness of the proposed system for Building Two allowing the fresh air being filtered keeping the air quality the same as per the MVHR during the winter. The graph below (Figure 6-36) is the average hourly temperature data for the entire house.

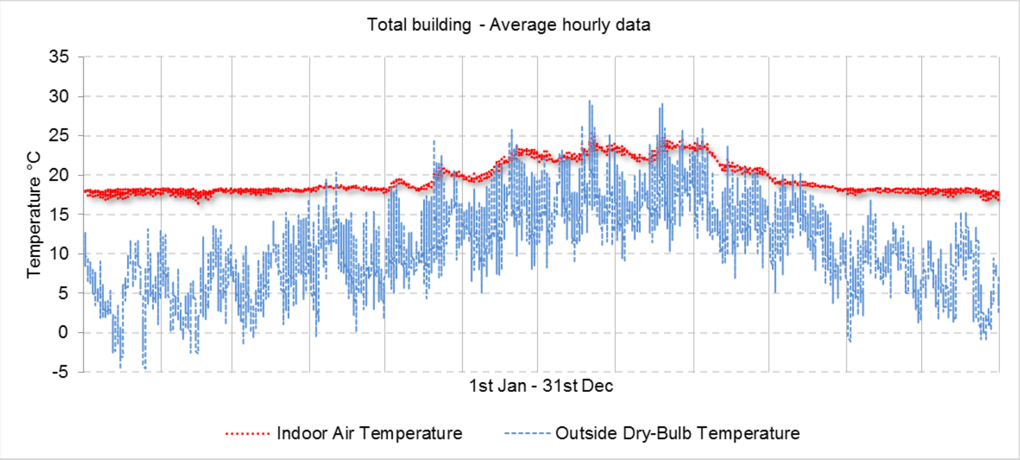


Figure 6-32- Building average hourly data indicating the overheating percentage of 0.05%.

The overheating percentage as can be seen from the graph above, remained the same at 0.05% ensuring that the proposed option can provide an adequate ventilation rate with no requirements for window opening similar to Building One. The idea of separating the ventilation from windows and using windows for view to outside, light and solar gain can offer a reduction in cost and possibility of increasing the solar gain benefiting the winter performance of the building.

The opening was calculated to be 1/50th of the floor area (each room) (total opening, just over 1/50th of the TFA). The total building daily average ventilation was increased to an average of 0.42 ac/h for the three months of summer and was between 0.10 ac/h to a maximum of 1.26 ac/h (comparing to the initial 0.22 ac/h from PHPP). Figure 6-37 is the daily average ac/h for the three months of the summer.

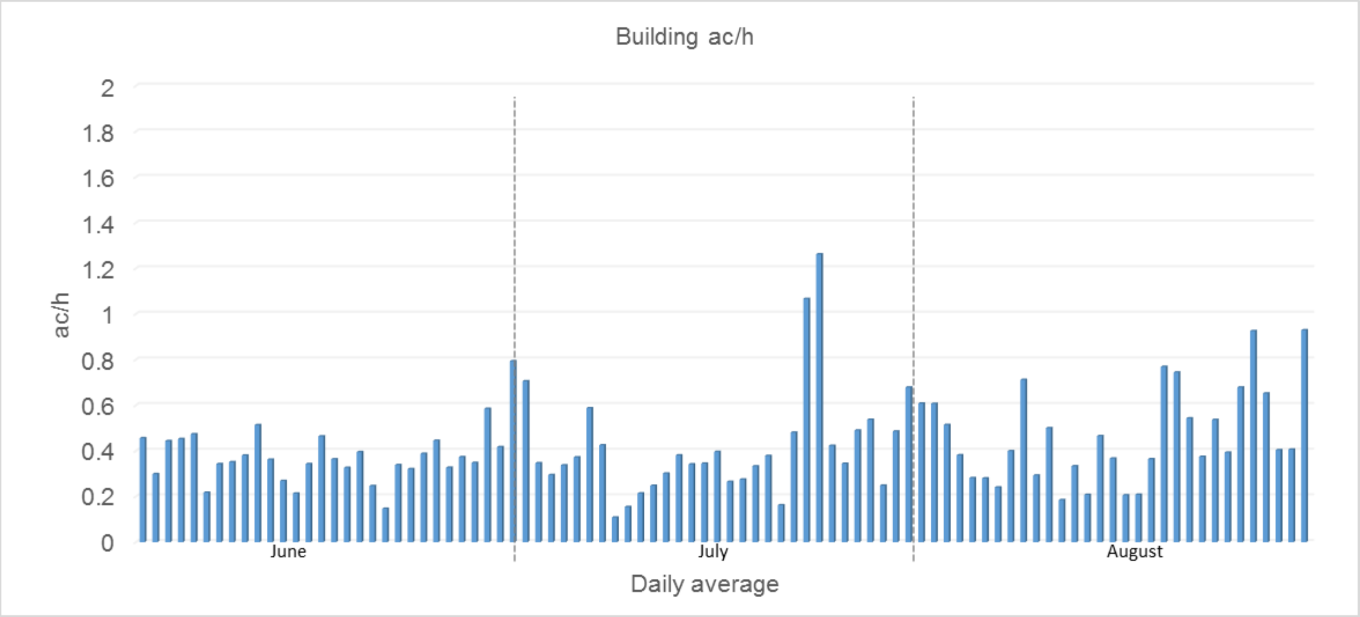
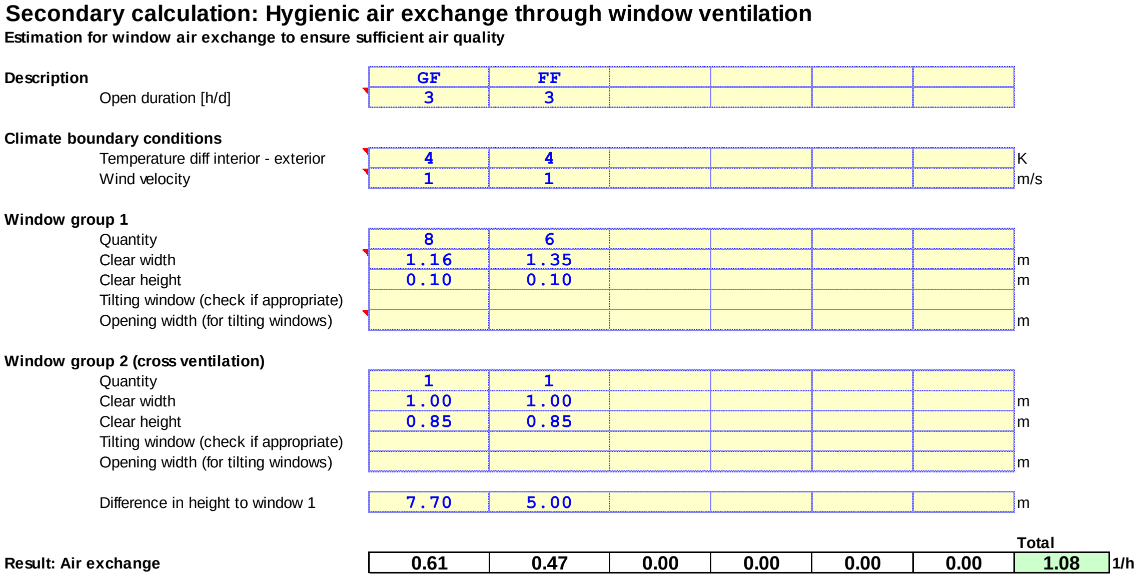


Figure 6-33- Daily average ac/h for the entire building.

6.4.4. Option 3 and PHPP (Building Two)

Similar to Building One, PHPP was used to examine the possibility of the elimination of window openings and the incorporation of Option 3 as part of the ventilation strategy for the summer. Therefore the PHPP8 calculation was used and any extra ventilation due to the use of windows during the day and night was deleted. This resulted in 9.5% of overheating if no windows were opened.

The SummVent sheet was used to calculate the possible higher ventilation rate achieved by the use of option 3. The same method as per Building One was used with 60% reduction factor for day and night time ventilation. The graphs below (Figures 6-34 and 6-35) are calculations from the PHPP SummVent sheet for daytime and night time natural ventilation using Option 3 respectively.

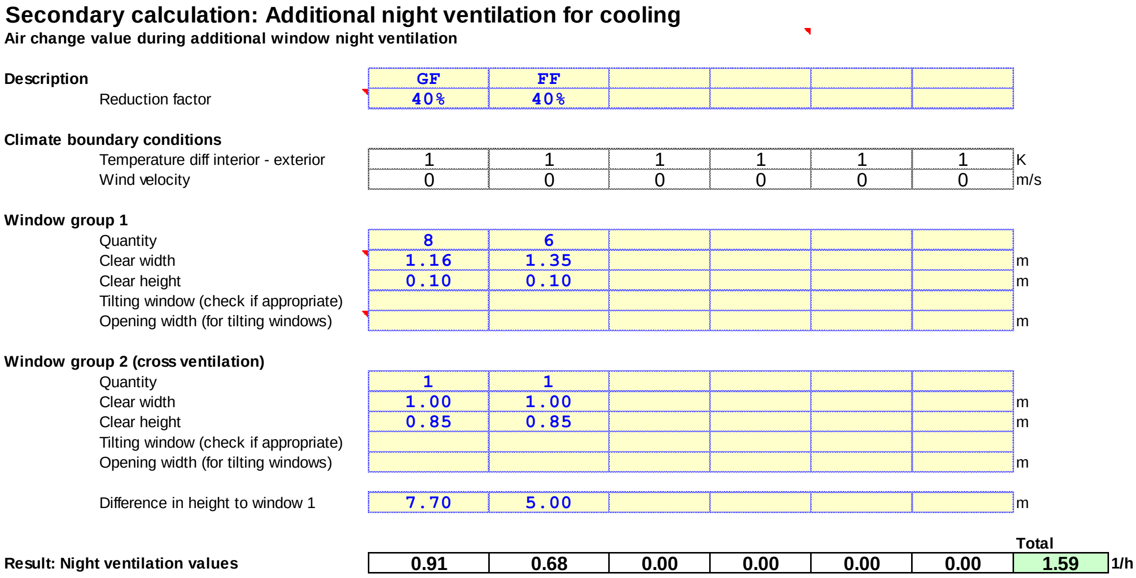


Secondary calculation: Hygienic air exchange through window ventilation

Estimation for window air exchange to ensure sufficient air quality

Description	GF	FF						
Open duration [h/d]	3	3						
Climate boundary conditions								
Temperature diff interior - exterior	4	4						K
Wind velocity	1	1						m/s
Window group 1								
Quantity	8	6						
Clear width	1.16	1.35						m
Clear height	0.10	0.10						m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Window group 2 (cross ventilation)								
Quantity	1	1						
Clear width	1.00	1.00						m
Clear height	0.85	0.85						m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Difference in height to window 1	7.70	5.00						m
							Total	
Result: Air exchange	0.61	0.47	0.00	0.00	0.00	0.00	1.08	1/h

Figure 6-34- PHPP daytime summer ventilation using Option 3 – Building Two



Secondary calculation: Additional night ventilation for cooling

Air change value during additional window night ventilation

Description	GF	FF						
Reduction factor	40%	40%						
Climate boundary conditions								
Temperature diff interior - exterior	1	1	1	1	1	1		K
Wind velocity	0	0	0	0	0	0		m/s
Window group 1								
Quantity	8	6						
Clear width	1.16	1.35						m
Clear height	0.10	0.10						m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Window group 2 (cross ventilation)								
Quantity	1	1						
Clear width	1.00	1.00						m
Clear height	0.85	0.85						m
Tilting window (check if appropriate)								
Opening width (for tilting windows)								m
Difference in height to window 1	7.70	5.00						m
							Total	
Result: Night ventilation values	0.91	0.68	0.00	0.00	0.00	0.00	1.59	1/h

Figure 6-35- PHPP night-time summer ventilation using Option 3 – Building Two

The air change per hour was calculated to be **1.08** for the day time and **1.59** during the night time which resulted to a reduction of overheating percentage to 0% similar to the dynamic thermal model calculation at 0.05%.

The same exercise was repeated using the climate data for 2050 and 2080 generated from Meteonorm and imported into PHPP ensuring future performance of the proposed system. The overheating percentage stayed at 0% for the both climate scenario, indicating the effectiveness of the system and importantly it was the same as per the dynamic thermal model increasing the confidence in the proposed option.

Summary:

The monitoring results for Building Two had indicated a lower overheating percentage of 0.65% for the whole building during the five months of monitoring period. The highest overheating percentage was recorded during July in bedroom 5 at 6.55%. The RH was generally higher in comparison to Building One and averaged around 50% during the three summer months. The indoor CO_2 levels were recorded generally to be within the Passivhaus required level in the sitting room and passed the limit in the main bedroom mainly during the night. The windows were opened on average for 13.27% during the summer and were mostly operated during the day and not at night-time or unoccupied hours.

The monitoring results were compared to the original PHPP calculation allowing adjustment to the PHPP model using the window operation during the summer. The examination of location and climate led to an increase in overheating percentage of 5.7% using the PHPP model. The influence of the lack of summer bypass, location and material properties used around the MVHR fresh air intake and the lack of insulation around the internal MVHR ducts on overheating potential were also examined for this building, highlighting the potential of contribution to overheating percentage. Furthermore the internal heat gain was recalculated using PHPP8 which was increased to 3.50W/m^2 increasing the overheating percentage.

The initial thermal dynamic model was drawn using the data from the original PHPP model and was further amended using the monitoring data, internal heat calculation and actual shading pattern used by the occupant (base case). The base case model was tested using future data (2050 & 2080) which led to an overheating percentage of 7.43% and 15.66% respectively compared to the base case model of 1.79% using current climate data.

Three different options were tested in order to increase the overall natural ventilation and consequently reduce the overheating percentage concentrating on the future scenarios. The options are prerequisite to one another leading to option 3 resulting in no overheating. Finally option 3 was tested in order to replace any window opening using the dynamic thermal model and PHPP calculation, allowing for reduction in window frames and providing secure and filtered air without any further increase in solar gain. This option was proved to be effective in reducing any overheating potential and suggestion was made in implementing this option in the PHPP calculation.

6.5. EXAMINATION OF OPTION 3 IN A WIDER CONTEXT

Option 3 was tested using a dynamic thermal model for the two case study buildings as well as being incorporated into the PHPP calculation with the replacement of window openings. The elimination of window opening and replacing it with Option 3 was proven to be viable and addressing areas of concern such as security and air quality. However a wider context would be required to not only ensure the effectiveness of the system but also explore any limitations, if it was to be incorporated as an option for providing natural ventilation for Passivhaus dwellings during the summer period. Therefore PHPP data for an additional 5 residential Passivhaus buildings was obtained which some are at the design stage and some have just been completed to Passivhaus or EnerPhit standard.

Marsh Flatts Farm:

- TFA: 315.18m^2
- Internal heat gains: 2.1W/m^2 (winter) - 4W/m^2 (summer)
- Ventilation volume (Vv): 788m3
- Climate area (PHPP): Midlands-Sutton Bonnington

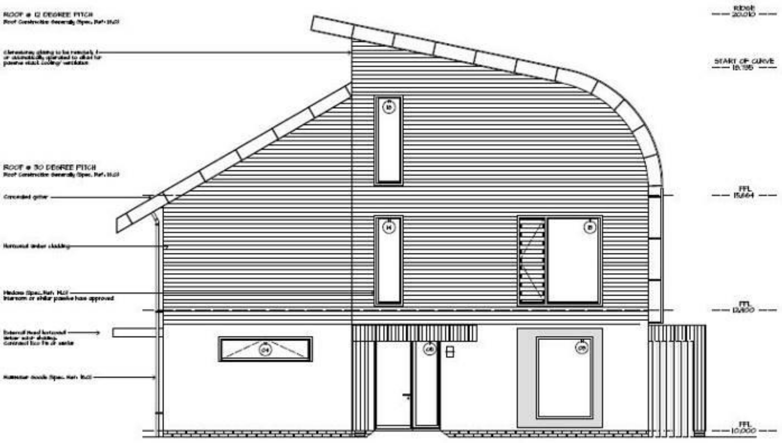
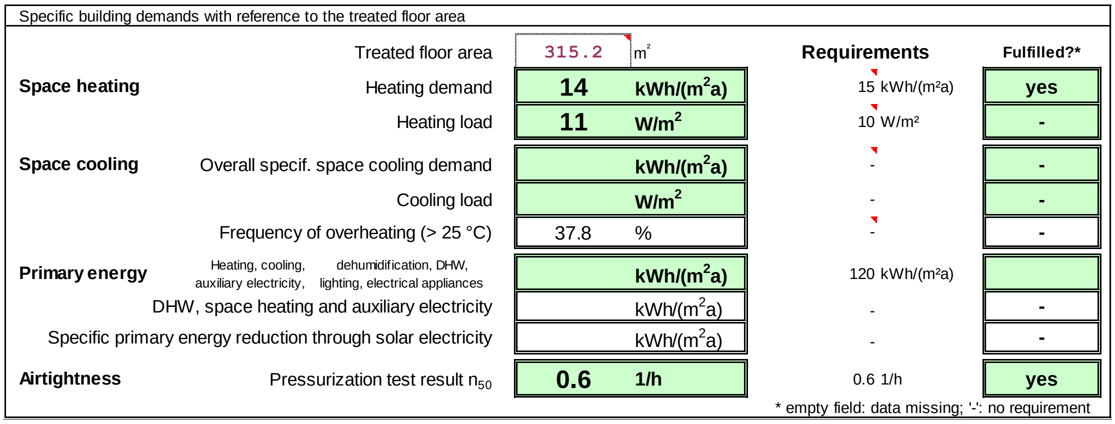


Figure 6-36- Marsh Flatts Farm, East elevation (source: Eco Design Consultants)

The building is at the design stage and will be built to Passivhaus standard. Below is the extract from the verification sheet (PHPP calculation) with all windows being closed indicating the possible overheating percentage.



Specific building demands with reference to the treated floor area

	Treated floor area	315.2	m^2	**Requirements**	**Fulfilled?***
Space heating	Heating demand	**14**	**kWh/(m^{2}a)**	15 kWh/(m^{2}a)	**yes**
	Heating load	**11**	**W/m^2**	10 W/m^2	**-**
Space cooling	Overall specif. space cooling demand		**kWh/(m^{2}a)**	-	**-**
	Cooling load		**W/m^2**	-	**-**
	Frequency of overheating (> 25 °C)	37.8	%	-	**-**
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances		**kWh/(m^{2}a)**	120 kWh/(m^{2}a)	
	DHW, space heating and auxiliary electricity		kWh/(m^{2}a)	-	**-**
	Specific primary energy reduction through solar electricity		kWh/(m^{2}a)	-	**-**
Airtightness	Pressurization test result n_{50}	**0.6**	**1/h**	0.6 1/h	**yes**

* empty field: data missing; '-': no requirement

Figure 6-37- PHPP verification sheet – indicating the possible overheating percentage

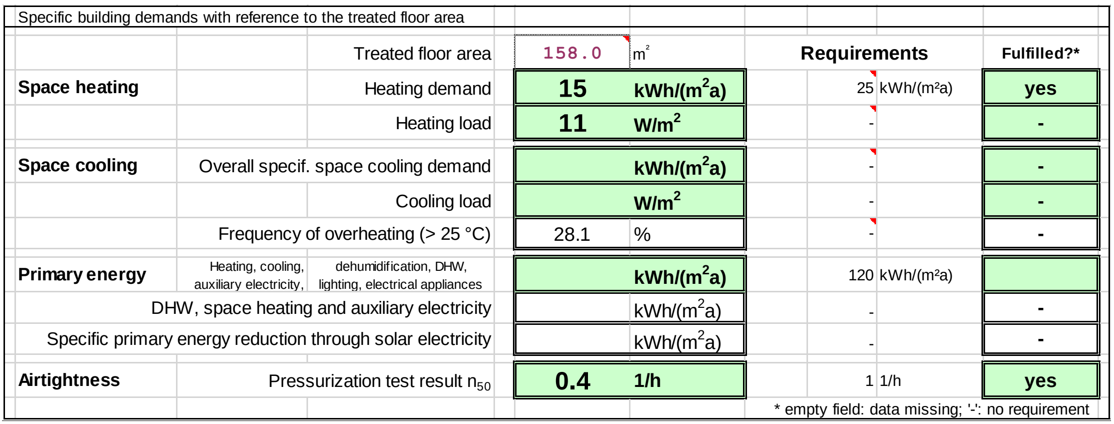
As can be seen from above, the overheating percentage can be as high as 37.8% if no windows were opened during the warmer part of the year. Therefore option three was tested to replace any need for window openings and the use of Option 3 allowed for 0.97 air change per hour during the daytime and 1.42 air change per hour during the night time leading to no overheating potential using 1/50th of the TFA for the low level openings.

Ashby de la Zouch:

- TFA: 158m^2
- Internal heat gains: 2.1W/m^2 (winter) – 4.2W/m^2 (summer)
- Ventilation volume (V_v): 395m^3
- Climate area (PHPP): Midlands-Sutton Bonnington

Figure 6-38- Ashby de la Zouch front elevation (source: Eco Design Consultants)

The building will be new build to Passivhaus standard and is currently at the design stage. Below is the extract from the verification sheet (PHPP calculation) with all windows being closed indicating the possible overheating percentage.



Specific building demands with reference to the treated floor area

	Treated floor area	158.0	m^2	**Requirements**		**Fulfilled?***
Space heating	Heating demand	**15**	**kWh/(m^{2}a)**	25	kWh/(m²a)	**yes**
	Heating load	**11**	**W/m^2**	-		**-**
Space cooling	Overall specif. space cooling demand		**kWh/(m^{2}a)**	-		**-**
	Cooling load		**W/m^2**	-		**-**
	Frequency of overheating (> 25 °C)	28.1	%	-		**-**
Primary energy	Heating, cooling, auxiliary electricity, dehumidification, DHW, lighting, electrical appliances		**kWh/(m^{2}a)**	120	kWh/(m²a)	
	DHW, space heating and auxiliary electricity		kWh/(m^{2}a)	-		**-**
	Specific primary energy reduction through solar electricity		kWh/(m^{2}a)	-		**-**
Airtightness	Pressurization test result n_{50}	**0.4**	**1/h**	1	1/h	**yes**

* empty field: data missing; '-': no requirement

Figure 6-39- PHPP verification sheet – indicating the possible overheating percentage

The overheating percentage was calculated to be just over 28% if windows were not to be opened during the summer. Option 3 was incorporated as part of the PHPP calculation replacing any need for window opening. The use of Option 3 can eliminate any potential of overheating and can provide 1.29 air change per hour during the day and 1.89 air change per hour during the night.

Hiley Road:

- TFA: 111.4m^2
- Internal heat gains: 2.1W/m^2 (winter) – 4.2W/m^2 (summer)
- Ventilation volume (V$_v$): 278m^3
- Climate area (PHPP): Thames Valley-Silsoe

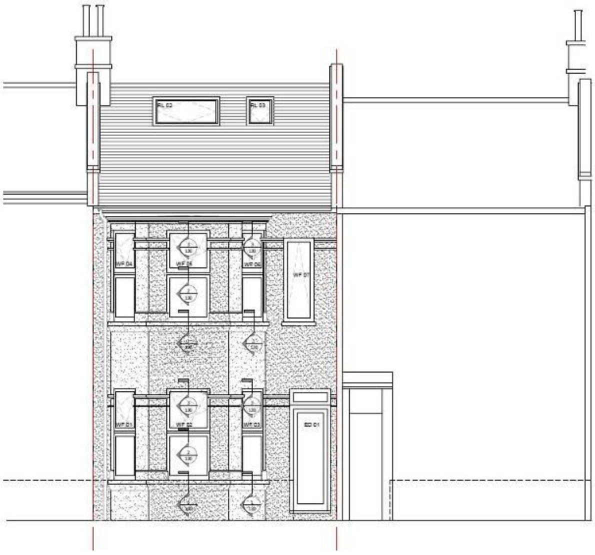
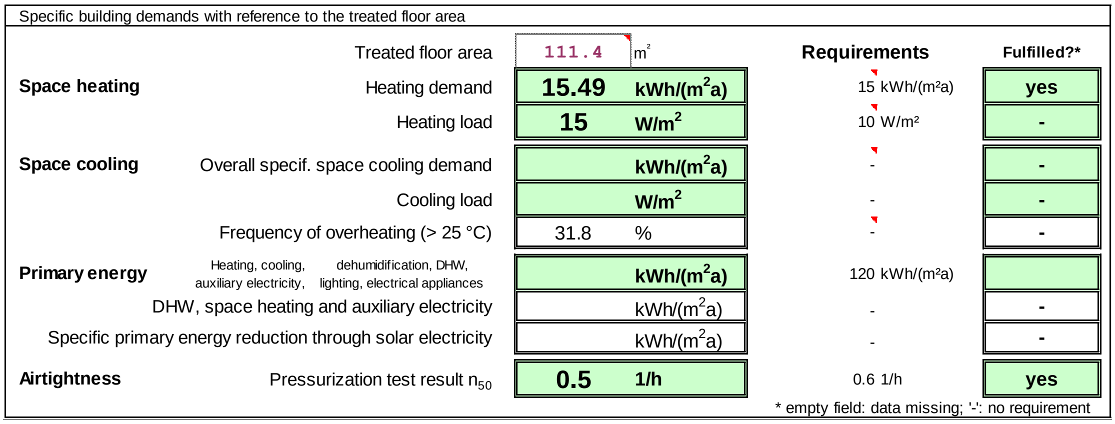


Figure 6-40- Hiley Road front elevation (source: Eco Design Consultants)

This project is a refurbishment however to full Passivhaus standard rather than the EnerPhit standard and was completed in late 2015. Below is the extract from the Verification Sheet (PHPP calculation) with all windows being closed indicating the possible overheating percentage.



Specific building demands with reference to the treated floor area

	Treated floor area	111.4	m^2	**Requirements**	**Fulfilled?***
Space heating	Heating demand	**15.49**	**$kWh/(m^2a)$**	15 kWh/(m²a)	**yes**
	Heating load	**15**	**W/m^2**	10 W/m²	**-**
Space cooling	Overall specif. space cooling demand		**$kWh/(m^2a)$**	-	**-**
	Cooling load		**W/m^2**	-	**-**
	Frequency of overheating (> 25 °C)	31.8	%	-	**-**
Primary energy	Heating, cooling, auxiliary electricity, dehumidification, DHW, lighting, electrical appliances		**$kWh/(m^2a)$**	120 kWh/(m²a)	
	DHW, space heating and auxiliary electricity		$kWh/(m^2a)$	-	**-**
	Specific primary energy reduction through solar electricity		$kWh/(m^2a)$	-	**-**
Airtightness	Pressurization test result n_{50}	**0.5**	**1/h**	0.6 1/h	**yes**

* empty field: data missing; '-': no requirement

Figure 6-41- PHPP verification sheet – indicating the possible overheating percentage

The calculation using PHPP with no window operation has indicated 31.8% of potential overheating as can be seen from above. The incorporation of Option 3 can potentially replace the need for any window openings and can provide 1.32 air change per hour during the day and 1.96 air change per hour during the night eliminating any overheating potential.

Carstone:

- TFA: 213.9m^2
- Internal heat gains: 2.1W/m^2 (winter) – 3.4W/m^2 (summer)
- Ventilation volume (V_V): 535m^3
- Climate area (PHPP): Thames Valley-Silsoe

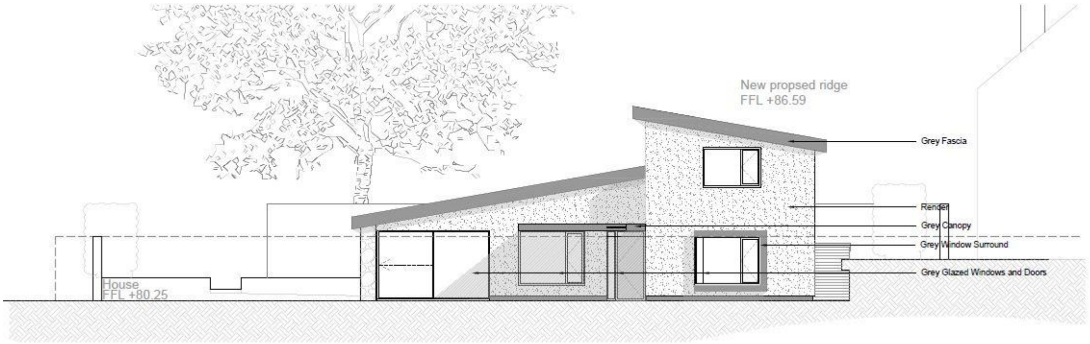
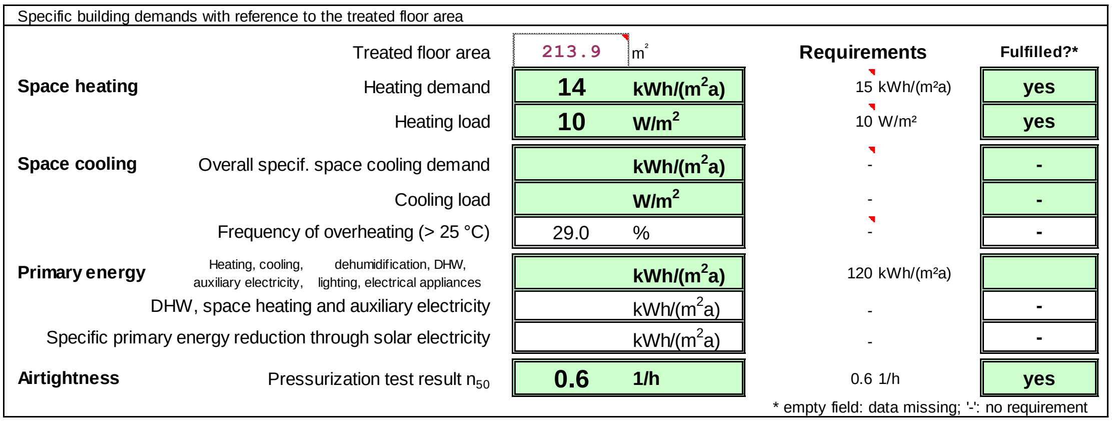


Figure 6-42- Carstone south elevation (source: Eco Design Consultants)

Carstone is a new build to Passivhaus standard at the rear of an existing large site and is currently at the tender stage (late 2015). Below is the extract from the verification sheet (PHPP calculation) with all windows being closed indicating the possible overheating percentage.



Specific building demands with reference to the treated floor area

				Requirements	Fulfilled?*
	Treated floor area	213.9	m^2		
Space heating	Heating demand	**14**	**kWh/(m^{2}a)**	15 kWh/(m^{2}a)	**yes**
	Heating load	**10**	**W/m^2**	10 W/m^2	**yes**
Space cooling	Overall specif. space cooling demand		**kWh/(m^{2}a)**	-	**-**
	Cooling load		**W/m^2**	-	**-**
	Frequency of overheating (> 25 °C)	29.0	%	-	**-**
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances		**kWh/(m^{2}a)**	120 kWh/(m^{2}a)	
	DHW, space heating and auxiliary electricity		kWh/(m^{2}a)	-	**-**
	Specific primary energy reduction through solar electricity		kWh/(m^{2}a)	-	**-**
Airtightness	Pressurization test result n_{50}	**0.6**	**1/h**	0.6 1/h	**yes**

* empty field: data missing; '-': no requirement

Figure 6-43- PHPP verification sheet – indicating the possible overheating percentage

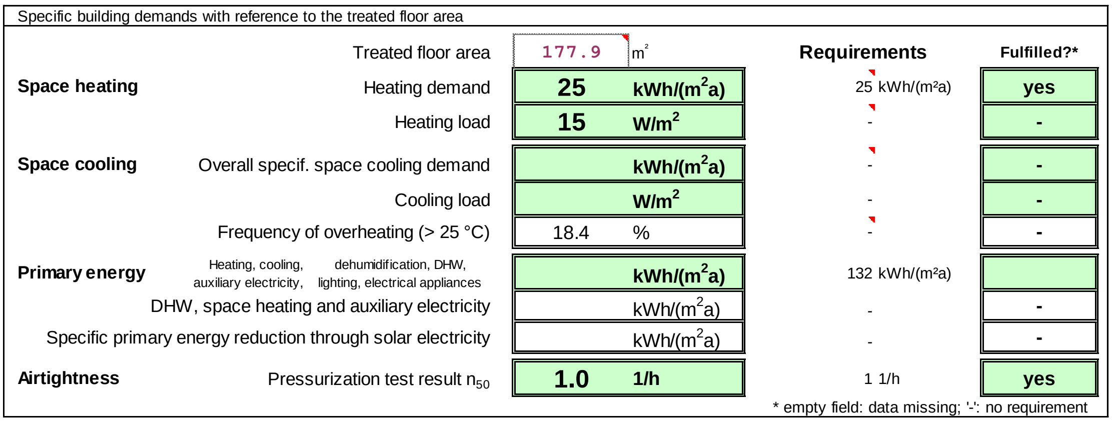
The overheating percentage from the PHPP calculation was at 29% for this building if no windows were opened for extra ventilation and cooling. The overheating percentage for this building was reduced to 0.1% with the incorporation of Option 3 and not zero like the other earlier buildings with 0.89 and 1.24 air change per hour during the day and night respectively. The lower air change and therefore lower cooling effect is due to a restriction in placing the low level openings caused by the design of the building leading to limited available external walls.

Lee Cross:

- TFA: 177.9m^2
- Internal heat gains: 2.1W/m^2 (winter) – 5.7W/m^2 (summer)
- Ventilation volume (V_v): 445m^3
- Climate area (PHPP): Thames Valley-Silsoe

Figure 6-44- Lee Cross south elevation (source: Eco Design Consultants)

Lee Cross is a refurbishment of a 1970’s building to EnerPhit standard which was completed during 2015. Below is the extract from the verification sheet (PHPP calculation) with all windows being closed indicating the possible overheating percentage.



Specific building demands with reference to the treated floor area

	Treated floor area	177.9	m^2	**Requirements**	**Fulfilled?***
Space heating	Heating demand	**25**	**kWh/(m^{2}a)**	25 kWh/(m²a)	**yes**
	Heating load	**15**	**W/m^2**	-	**-**
Space cooling	Overall specif. space cooling demand		**kWh/(m^{2}a)**	-	**-**
	Cooling load		**W/m^2**	-	**-**
	Frequency of overheating (> 25 °C)	18.4	%	-	**-**
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances		**kWh/(m^{2}a)**	132 kWh/(m²a)	
	DHW, space heating and auxiliary electricity		kWh/(m^{2}a)	-	**-**
	Specific primary energy reduction through solar electricity		kWh/(m^{2}a)	-	**-**
Airtightness	Pressurization test result n_{50}	**1.0**	**1/h**	1 1/h	**yes**

* empty field: data missing; '-': no requirement

Figure 6-45- PHPP verification sheet – indicating the possible overheating percentage

This building would also be subject to a high overheating percentage of 18.4% if no windows were operated. However this is not as high as the previous buildings which is perhaps due to the lower airtightness and heating demand set for EnerPhit standard.

Although the overheating percentage was reduced to 0.1% only, but it was not eliminated completely which was put down to a restriction in incorporating the low level openings due to floor to ceiling windows. The ventilation was calculated to be 0.92 air change per hour during the day and 1.31 air change per hour during the night time.

A closer examination of these examples highlights the higher internal gains during the summer period which can contribute to the overheating percentage for all the buildings. The use of option three can provide the required natural ventilation and therefore cooling effect cleanly and securely for all the buildings highlighting the effectiveness of the system. However restrictions might apply due to lack of available external wall for instance to incorporate the low level opening due to the internal layout and floor to ceiling glazing height. The main findings of the analysis can lead to conclusion that the proposed option three can not only be used in the new design but also in the refurbishment and even future refurbishment of the existing buildings currently built to Passivhaus standards. However care needs to be taken to maximize the low level openings for the best results which can be restricted due to the design of the building.

CHAPTER 7. DISCUSSION OF FINDINGS

7.1. FORWARD

The aim of this research has been to investigate and propose a natural ventilation system that can provide the required ventilation for summer (reducing the overheating potential) without compromising the security, air quality and causing additional heat loss in winter for UK Passivhaus dwellings. Furthermore the proposed system was to be tested using the future climate data alongside the current, ensuring the durability and longevity of the proposed system.

Before drawing conclusions in the final chapter, the implications of the research in relation to the wider context and the existing body of research will be discussed in this chapter.

7.2. DESIGNING PASSIVHAUS DWELLINGS IN THE UK

Passivhaus standard is based on achieving thermal comfort with a low level of energy demand for heating and cooling. Passivhaus requires a well-defined minimum temperature of 20°C for the winter periods, whereas the maximum summer temperature is increased to 25°C with an additional 10% allowance over this limit (Passive House Institute, 2012). The standard is more focused towards the cooler periods of the year, perhaps due to the climate of its origin country (Germany). The concerns regarding the possible summer overheating in the UK have been increased in recent years with limited available research and monitoring data due to more recent uptake of the standard in the UK (McLeod et al., 2013).

Passivhaus is also known to have a lower performance gap and calculation using PHPP benefits from high accuracy (Lewis, 2014). Although this was true for the two reference buildings in comparison to the dynamic model for the heating load, however the performance gap was noticeably higher for the summer overheating.

There are different factors contributing to overheating in buildings in general like the construction quality and thermal bridging (Gupta & Kapsali, 2016), which are not necessarily the problem in Passivhaus buildings as they require a much higher standard of build and quality control with no thermal bridging (Passivhaus Institut, 2012). On the other hand, the build-up of heat from internal and external sources are much more difficult to be discharged due to minimum heat loss through fabric and high level of airtightness in Passivhaus buildings (Mlakar & Štrancar, 2011).

The monitoring of the two reference Passivhaus buildings have indicated some of these concerns alongside highlighting different temperatures and overheating percentage in different areas of the buildings. This has been more pronounced in the case of Building One which can be easily overlooked during the design stage using PHPP. The PHPP calculation averages the overheating for the entire building and for the whole year (Passive House Institute, 2013). The table below is a summary for the two case study buildings in regards to the overheating percentage for the individual areas during the five months of the monitoring period as well as the entire year. The right hand columns are the average calculation per floor and for the whole building if no further overheating incidents were recorded.

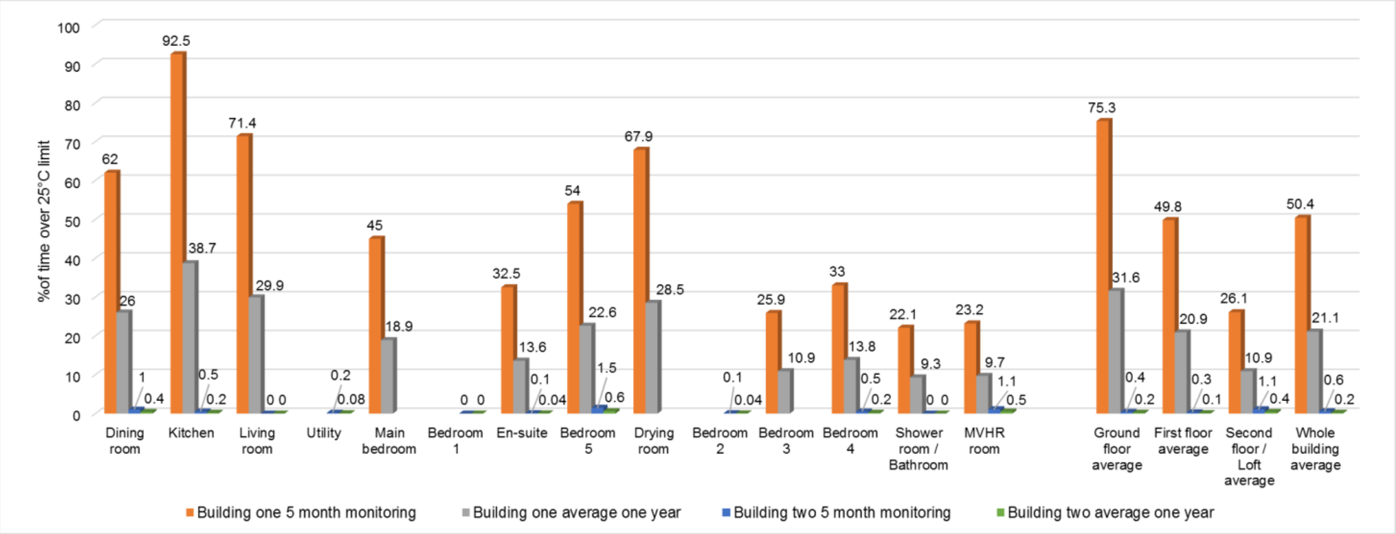


Figure 7-1- Overheating percentage for different rooms and period

The overheating in the kitchen of Building One was over 92% during the monitoring period despite the open layout and north side location. The living room and the dining room also experienced a high percentage of overheating reaching as high as 71% much above the design limit. The temperatures in the bedrooms were also recorded to be over the required limit for a high proportion of the time making sleeping perhaps less comfortable for the occupants. However Passivhaus calculations average the overheating for the whole house and the entire year which is not necessarily during the summer period or in response to outside temperature (Ridley et al., 2013). This therefore reduced the overheating percentage to just over 21% when averaged for the whole house during the entire year in Building One. On the other hand Building Two constructed to EnerPhit standards experienced much lower temperatures and overheating percentage. Higher summer ventilation and benefit of thermal mass can contribute to lower temperatures during the warmer part of the year (Gupta & Kapsali, 2016). The occupant awareness and behaviour alongside the method of window opening (turn) as well as higher thermal mass, in conjunction with a lower airtightness level, lower ambient temperatures and lower glazing area in Building Two led to a lower percentage of overheating.

The increased glazing area which can benefit solar gain during the heating seasons can contribute to overheating in Passivhaus dwellings (Richard Partington Architects, 2012). For instance the glazing ratio to floor area in the living room (Building One) was around 59% and the glazing in bedroom 5 was 82%, and despite the usage of blinds (internally and externally) these areas were recorded to have a high percentage of overheating. The different room temperatures should be incorporated as part of the PHPP calculation and perhaps work with the glazing area in relation to floor area.

Moreover examining the average overheating percentage for each floor, highlights the cooler temperatures in the higher floors for both buildings meaning the hot air was not rising as perhaps expected. This temperature difference could be influenced by the glazing area and their locations in each floor, however the lack of heat rising from the lower floors to the upper floors could be down to the very high airtightness level required by Passivhaus standard. This highlights the opportunity of increasing the summer ventilation rate by benefiting from stack effect.

Passivhaus require a specific indoor CO_2 level of 400-600ppm with upper limit of 1000ppm which is used as the indicator to IAQ (Cotterell & Dadeby, 2012). The CO_2 monitoring highlighted adequate indoor CO_2 levels in the living rooms for both buildings but not necessarily in the main bedrooms specifically during the night as the occupants were sleeping. The level of ventilation achieved in the main bedroom with two people sleeping could benefit from an increase as part of the Passivhaus standard. The graph below demonstrates the percentage of the time that the CO_2 levels passed the required level of 1000ppm in both buildings' monitored areas.

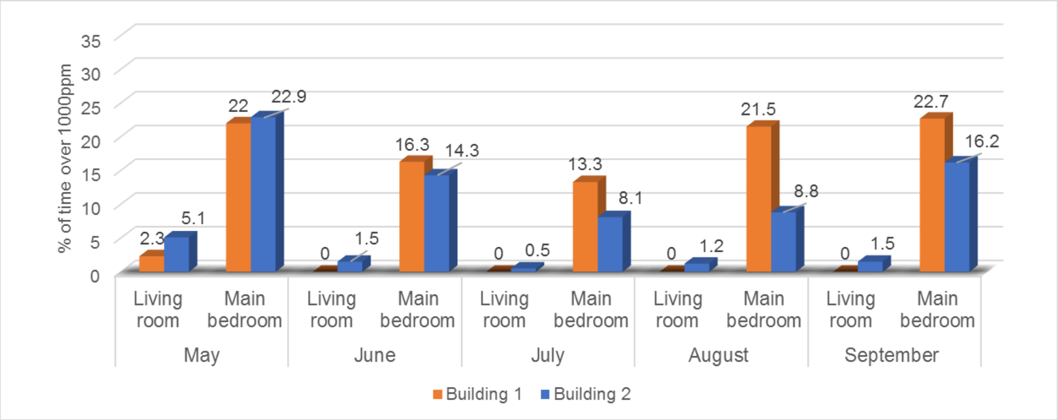
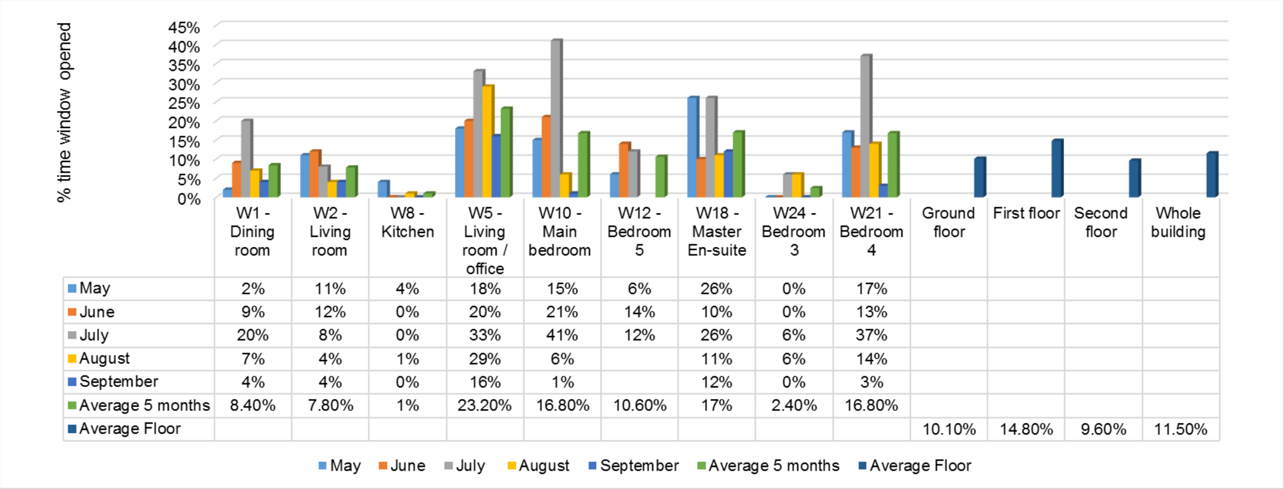


Figure 7-2- Percentage of indoor CO_2 levels over the 1000ppm standard

Monitoring the windows for both properties highlighted almost no night time operation and therefore cooling during the night. However the effectiveness of the ventilation and therefore cooling achieved through the very similar percentage of window operation (in both buildings), were not the same as the percentage of overheating which was higher in Building One. This was concluded to be due to the way that the windows were operated and the restriction of air flow from the heavy usage of internal and external blinds in Building One. The windows usage pattern during the summer and possible negative impact of lower thermal mass was felt to be influencing the overheating percentage especially in the case of Building One similar to the research carried out by Gupta and Kapsali during 2016 (Gupta & Kapsali, 2016). The tables below are the monthly average for window operation for the two case study buildings alongside the average for different floors and the entire building.

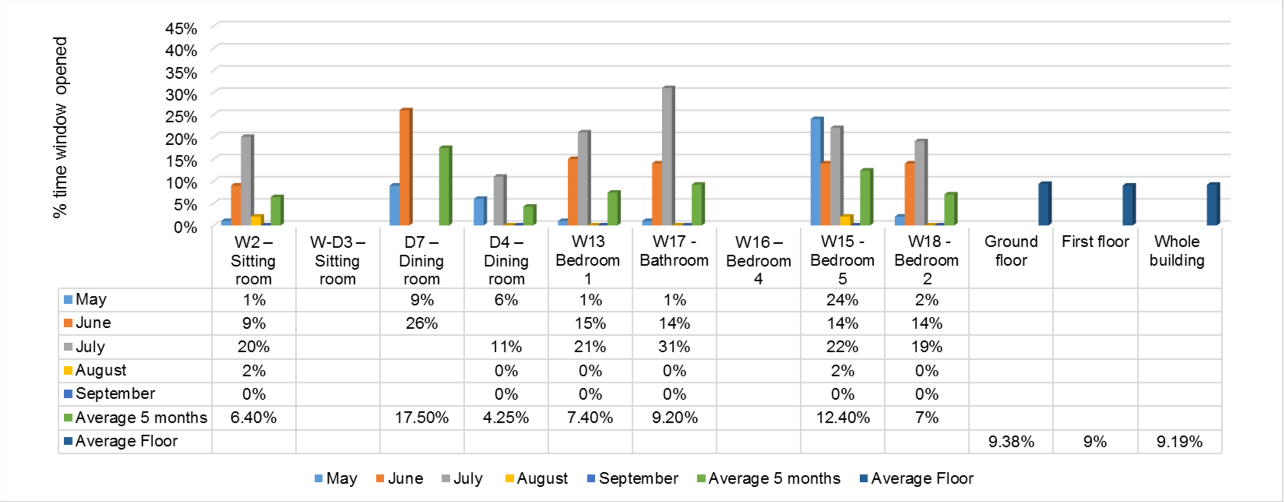
Building One:



	W1 - Dining room	W2 - Living room	W8 - Kitchen	W5 - Living room / office	W10 - Main bedroom	W12 - Bedroom 5	W18 - Master En-suite	W24 - Bedroom 3	W21 - Bedroom 4	Ground floor	First floor	Second floor	Whole building
■ May	2%	11%	4%	18%	15%	6%	26%	0%	17%				
■ June	9%	12%	0%	20%	21%	14%	10%	0%	13%				
■ July	20%	8%	0%	33%	41%	12%	26%	6%	37%				
■ August	7%	4%	1%	29%	6%		11%	6%	14%				
■ September	4%	4%	0%	16%	1%		12%	0%	3%				
■ Average 5 months	8.40%	7.80%	1%	23.20%	16.80%	10.60%	17%	2.40%	16.80%				
■ Average Floor										10.10%	14.80%	9.60%	11.50%

Figure 7-3- The percentage of window operations- Building One

Building Two:



	W2 – Sitting room	W-D3 – Sitting room	D7 – Dining room	D4 – Dining room	W13 Bedroom 1	W17 - Bathroom	W16 – Bedroom 4	W15 - Bedroom 5	W18 - Bedroom 2	Ground floor	First floor	Whole building
■ May	1%		9%	6%	1%	1%		24%	2%			
■ June	9%		26%		15%	14%		14%	14%			
■ July	20%			11%	21%	31%		22%	19%			
■ August	2%			0%	0%	0%		2%	0%			
■ September	0%			0%	0%	0%		0%	0%			
■ Average 5 months	6.40%		17.50%	4.25%	7.40%	9.20%		12.40%	7%			
■ Average Floor										9.38%	9%	9.19%

Figure 7-4- The percentage of window operations- Building Two

The occupant behaviour is one of the most difficult aspects to account for during the design stage leading to a higher performance gap. The introduction of percentage of window and shading operation in PHPP can reduce the possible performance gap during the summer. Introduction of different percentages of shading operation and the associated possible overheating percentage for instance, could increase the designer's understanding of the possible overheating percentage and also it can be used as the operational manual passed to the client and occupier. The table below shows the suggested options that can be added to the summer shading section as part of PHPP. A very similar option could be incorporated for the window operation during the day and night time.

Table 7-1- Suggested shading percentage table for PHPP

Shading percentage	Overheating percentage
0% summer movable shading	% of overheating
10% summer movable shading	% of overheating
30% summer movable shading	% of overheating
50% summer movable shading	% of overheating
70% summer movable shading	% of overheating
90% summer movable shading	% of overheating

The shading option used in PHPP is perhaps limited due to the steady state and nature of the Excel spreadsheet. The shading sheet for instance allows the user to only input the specific object in front of the glazing (Passive House Institute, 2007) and would not take into account the movement of the sun throughout the day. This limitation would be even higher for the glazing located on the East and West facade as the angle of the sun is not direct even at midday. Factoring in a safety percentage for the above recommended table can further improve the summer shading sheet in PHPP.

On the other hand, climate data used in PHPP has been improved since the original release to 22 regional subsections for the UK (McLeod et al., 2012), however smaller areas could help for a higher resolution in climate data and more effective representation of microclimate surrounding the individual buildings. This was examined using the two reference buildings by switching the buildings’ location and investigating the possible increase in overheating percentage. The overheating percentage was effected by 3% to 6% highlighting the importance of different climate data. Moreover an option for future climate scenarios could also be added in order to allow individual buildings to be tested for the possible higher expected temperatures in the future.

The glazing area can also play an important part in the overall overheating percentage and the associated solar gain into the building. The glazing area in the UK is perhaps maximised to ensure lower heating demand during the winter period, increasing the overheating potential during summer. The two case study buildings' TFA are very close however Building One benefited from over 10m^2 higher glazing area in comparison to Building Two. The solar gain information in the window sheet from PHPP only concentrates on the heating and not the total solar gain or the summer period (Passive House Institute, 2007). This can be easily mistaken during the design stage and perhaps additional information for the summer and total solar gains should be added in PHPP.

The internal heat gain calculation has been further improved in PHPP8 in response to possible higher internal gains during the summer and possibility of their contribution to summer overheating. However both case study buildings had used the earlier PHPP which uses a set value of 2.1W/m^2 as internal gain during winter and summer. Recalculation for internal gains using the as built equipment schedule resulted in an increase of internal gain to 3.65W/m^2 and 3.50W/m^2 for Building One and Building Two respectively.

The higher calculated internal gains contributed to higher summer temperatures and overheating percentage which was further used in the modelling phase allowing a better model. The standard internal heat gain of 2.1W/m^2 used during the winter is perhaps on the conservative side to allow for any uncalculated heat sinks during this period. There is currently no higher limit of internal gain during the summer and it could be beneficial to allow for a standard internal heat gain (i.e. **5W/m^2**) during the summer to ensure lower possibilities of overheating.

Similar to movable shading devices, the natural ventilation through the windows is subject to assumption during the design stage and affected by several different factors. The possible reduction of air flow by the use of internal and external blinds is very difficult to account for alongside the unpredicted occupant patterns and behaviour. The blind operation could also be influenced by the internal lighting level.

The monitoring results indicated almost no night time ventilation for both of the buildings whereas 0.22 air change per hour was assumed in the original PHPP calculations. The 0.22 air change per hour was calculated using the summer ventilation sheet in PHPP, assuming window opening during the night. Perhaps the designer should either not take night time cooling into account or calculate the consequences of lack of night time ventilation and provide it as part of the building manual to the occupants.

Furthermore removing the night time ventilation and reducing the additional natural ventilation (day time) through window usage to 0.15 air change per hour during the summer resulted in a much closer PHPP calculation in comparison to the monitored data. However the natural ventilation achieved by the use of windows would not be filtered and would not address the occupant concerns in regards to security and noise implications.

7.3. FACTORS CONTRIBUTING TO POSSIBLE OVERHEATING

Passivhaus dwellings can be subject to higher internal temperature increases even with small fluctuations, due to their minimum heat loss to outside from the fabric, infiltration and exfiltration (Mlakar & Štrancar, 2011). Therefore in conjunction with the use of shading during the summer and consequently reduction of additional heat gain, attention should be made to other possible factors increasing the internal heat gains.

The MVHR design could have an implication in regards to the overall ventilation and summer overheating and the rate of ventilation from the MVHR alone will not be adequate for providing cooling during the summer period (Crump et al., 2009). The location of the unit and the associated heat gain from the continuous use of the unit should be taken into account during the design stage (Passive House Institute, 2013) alongside the location of intake and extract. The proximity of the fresh air intake to the extract can result in short circuiting and possible contamination which was highlighted in the case of Building Two. The extract was located below the intake on the wall in close proximity to each other and the boiler flue was also located near the intake and extract.

The summer bypass option should also be a requirement as part of Passivhaus design which is currently not mandatory (Passive House Institute, 2013). It was indicated that the lack of summer bypass can contribute to higher summer temperatures using PHPP8 recalculations for the two buildings. Passivhaus institute’s recent research also claims the possibility of around 5Kwh/m^{2}a of cooling due to the use of summer by pass option (Passivhaus Institut, 2016). The efficiency of the MVHR in Building Two is around 10% better than Building One which perhaps can have an effect on the efficiency of the summer bypass option. Air Flow Solutions for instance claim that their new MVHR system offers summer bypass option as standard with 100% efficiency for the summer bypass option (Airflow Developments Limited, 2015).

The MVHR summer bypass option for Building One and Building Two is activated at 21°C and 23°C respectively (comfort temperature). Therefore if the indoor temperature exceeds this limit (and the ambient temperature is lower than the indoor temperature), the MVHR bypasses the heat exchanger allowing cooler outdoor air to enter the building directly. However the heat exchanger would be reactivated at night if the indoor temperature falls below the ‘comfort temperature’, without consideration for possible night time cooling as might be desirable in the summer. This is crucial especially if night time ventilation was factored into the design for cooling the internal thermal mass of the building. Perhaps a summer option in addition to summer bypass option could be incorporated as part of the MVHR control allowing the occupant to benefit from summer night time cooling.

The MVHR control could also benefit from an option allowing the occupant to adjust the ventilation rate according to the level of occupation or indoor CO_2 levels. This option can increase the occupant control and ensure the best ventilation rate which can reduce energy use as well as better humidity control as the rate of occupation changes. Furthermore an automatic unoccupied option can help to further reduce energy use as well as excessive heat loss during the winter period as the internal gains are reduced and the need for extra ventilation does not exist.

Moreover the material properties and the effect of thermal mass surrounding the MVHR intake was examined in section 4.3 and 5.3 for Building One and Two by the aid of a thermal imaging camera on the 16th and 17th July 2014. However both buildings’ MVHR intake has been located away from the South direction with very low thermal mass. The maximum surface temperature recorded surrounding the MVHR for Building One was 34.2°C when the southeast wall reached 52.2°C. Similarly for Building Two the highest temperature was just over 30°C when the Southwest wall was as high as 43°C. Due to lack of thermal mass from the material surrounding the MVHR intake for both buildings, the surface temperature of the material dropped to almost the ambient temperature of around 19°C to 20°C as the ambient temperature was reduced during the night.

The surface temperatures were compared with an additional building using cavity wall with 100mm brick finish externally monitored during the 18th July 2014 from 1:00pm till 10:00pm. The graph below is the surface temperature of the brick in relation to the ambient temperature measurements.

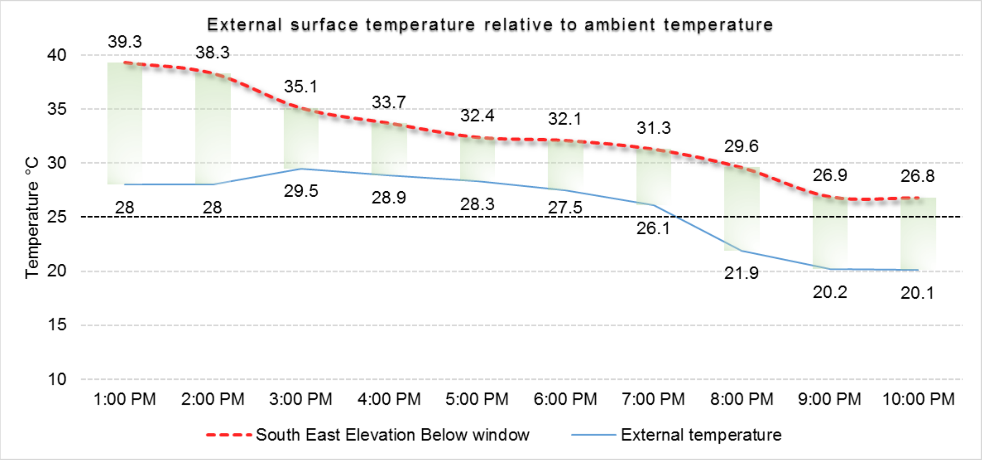


Figure 7-5- Surface temperature in respect to ambient temperature

The cavity wall monitored received direct solar gain till 2:30pm when the drop in temperature is apparent. The ambient temperature was higher in comparison to the 16th and 17th however, the surface temperature of the brick was not significantly higher than the other buildings when it was not under the direct solar gain. The higher thermal mass of the brick kept the temperature high during the night when the ambient temperature dropped and stayed just below 27°C when the ambient temperature was around 20°C. The figure below demonstrates the relation between the three buildings in regards to their maximum and minimum surface temperatures of the wall monitored when not in direct solar gain.

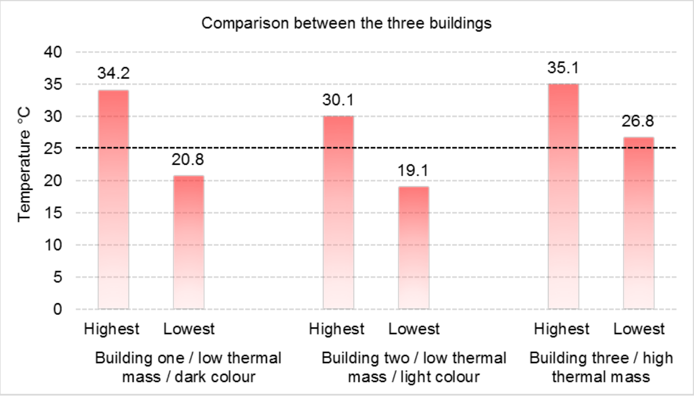


Figure 7-6- Comparison of the three measured buildings max & min surface temperature

The higher thermal mass of the material keeps the surface temperature high and requires a longer period to lose its temperature. Especially during the night time, the incoming fresh air could be effected by the thermal mass and higher temperatures contributing to higher potential of overheating. This exercise has highlighted the importance of type and colour of the material used close to the fresh air intake and the effect of the material's thermal mass in relation to the temperature especially retaining its temperature as the ambient temperature falls during the night.

The two reference buildings benefit from a low thermal mass material surrounding the MVHR fresh air intake and also the intake has been located as close to the north orientation as possible. The orientation and positioning of the fresh air intake in relation to the sun and exhaust air extract can also not only influence the fresh air temperature but it can reduce the quality of the air due to short circuiting between the fresh and exhaust air. Therefore when designing a specific natural ventilation system, care is needed for positioning the fresh air intake and the type of material used to ensure the temperature of the fresh air is not effected and increased unnecessarily by the choice of the surrounding material, orientation and lack of shading during the cooling season.

Moreover during the winter it might be desirable to orientate the MVHR fresh air intake towards the south (northern hemisphere) to benefit from the direct solar gain and even use a more thermally massive material surrounding the intake to increase the local temperature and therefore improve the efficiency of the MVHR. Providing a separate natural ventilation system during the summer period could allow for this as the MVHR is no longer required and used during this time.

In addition, the lack of insulation for the internal MVHR ducts can lead to temperature increase of the incoming fresh air. This is not required as part of Passivhaus standard (Passivhaus Institut, 2012) and therefore as the internal temperature rises during the summer, the incoming fresh air temperature can be affected similar to the MVHR heat exchanger. The examination of the incoming fresh air temperatures in the main bedroom and the living room for the two buildings in comparison to the room temperatures, highlighted the possible influence.

7.4. REAPPRAISAL

Three options were tested of which the first and second are prerequisites to the last option indicating the path taken in proposing option 3. The initial option was to introduce a windcatcher as part of Passivhaus design based on the Monodraught classic square design using the existing MVHR ducting system which led to a reduction in overheating as summarised in the table below.

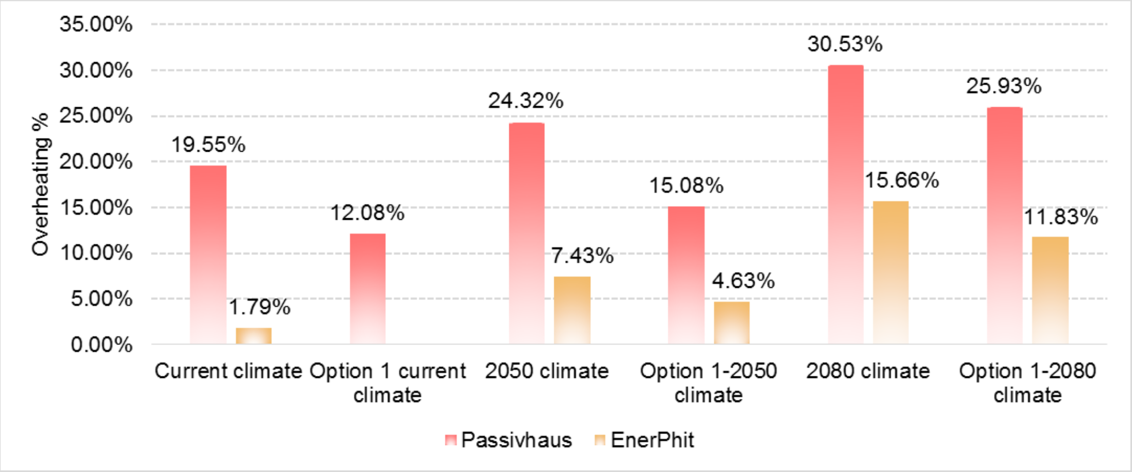


Figure 7-7- Overheating percentages for option 1 for different climate data

The reduction in overheating was noticeable, however not necessarily resolving the issue completely alongside the possibility of change in intake and extract due to wind direction. Therefore a second option was tested to locate the windcatcher over the staircase to benefit from higher stack effect achieved from the stairwell. The second option was in stages and the last iteration benefited from the improvement in the windcatcher's U-Value, change in the windcatcher design for higher stack effect and the introduction of a green roof surrounding the windcatcher locally. The graph below summarises the reduction of overheating percentage for both buildings using the last iteration for option two.

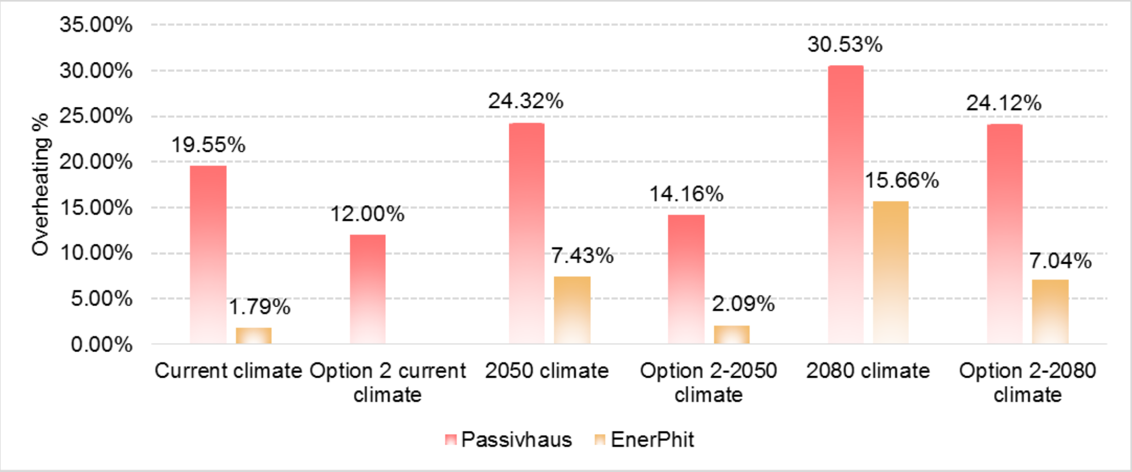


Figure 7-8- Overheating percentages for option 2 for different climate data

Option two offered a better reduction in overall overheating percentage especially in the case of Building Two, however it also highlighted the importance of increasing the fresh air intake from a low level as it was benefiting from the windcatcher for extract only. Consequently Option 3 was tested by the introduction of a new low level opening design in conjunction with the windcatcher, which also addresses the security and noise concerns by some extent alongside filtering the incoming fresh air to ensure the air quality has been maintained as per the winter ventilation using the MVHR. The new design also ensures no additional solar gains or rain entering the building and care has also been taken in detailing both the windcatcher and new low level opening in terms of cold bridging and possible additional heat loss during the winter.

The introduction of a low level opening and benefit from the stack effect from the windcatcher resulted in almost no overheating for both buildings for not only the current climate but also the future climates. This option also offers the possibility of introducing cooling for the low level opening in warmer climates by perhaps humidification or dehumidification (depending on climate) of the incoming fresh air or the incorporation of a thermal mass material in the opening and possibly cold water circulation which has not been part and scope of this research.

The graph below summarises the reduction of overheating percentage for both buildings using Option 3.

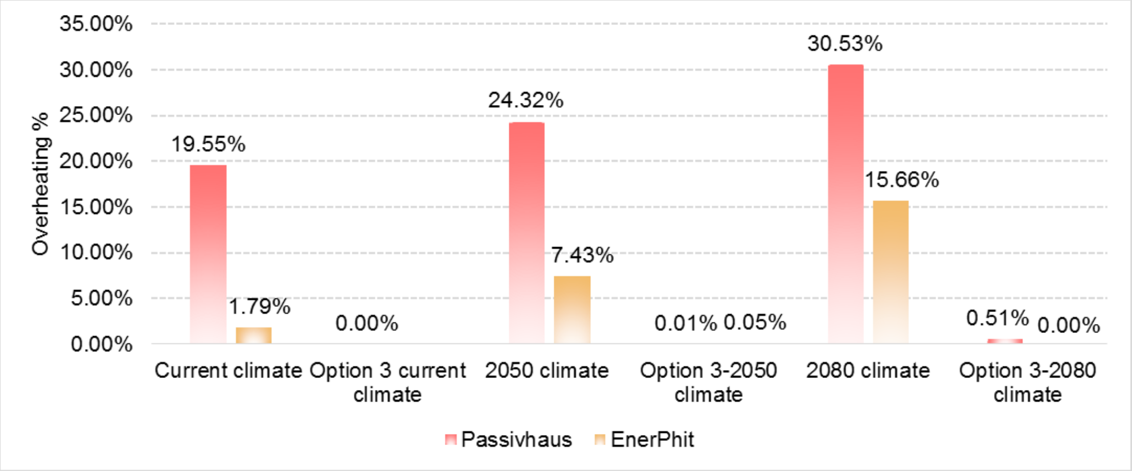


Figure 7-9- Overheating percentages for option 2 for different climate data

Noticeably using Option 3, Building One with a lower thermal mass offers a small fraction of improvement in overheating percentage during the 2050 climate and Building Two with higher thermal mass performs better during the 2080 climate highlighting the possible benefit of higher thermal mass during the warmer periods.

Option 3 was tested using PHPP calculation and suggestion was made in order to incorporate this as part of the summer ventilation option. The PHPP calculation was proven to be in line with the dynamic simulation for the two case study buildings. However incorporation of the system in PHPP needs further investigation in a wider context. Therefore a further five additional dwellings in the UK were tested using Option 3 as part of their ventilation with no additional natural ventilation through window openings. The analysis of all calculations increases the confidence in the proposed system and the possibility of the incorporation of Option 3 as part of possible natural ventilation in the UK Passivhaus dwellings. Furthermore more data could become available as the uptake of Passivhaus increases in the UK and Option 3 could also be used for other building types not constructed to Passivhaus standard.

CHAPTER 8. CONCLUSION AND FURTHER WORK

8.1 SUMMARY OF WORK UNDERTAKEN

This section provides a summary of the work undertaken and below are some of the key points and findings from the literature review, monitoring and modelling categorised reflecting the research objectives:

Summary drawn for Objective I:

"In depth study of Passivhaus standards and upper comfort temperature limit for summer months as well as different causes of overheating."

This objective was met by an extensive literature review and increased knowledge in Passivhaus design.

- The most common causes of overheating in UK domestic buildings are a high level of insulation, airtightness and large glazing area.
- Passivhaus overheating limit is 10% of the year over 25°C and it is averaged for the entire building.
- Passivhaus generally benefits from the use of MVHR and specific winter indoor temperature, however it uses a higher temperature limit during the summer.
- Overheating can be a serious problem in buildings particularly affecting the elderly and young increasing the importance of designing for the summer in the UK.
- Climate change and increased episodes of heatwaves alongside urbanisation can increase the potential of overheating.

- It is expected that by the 2050s deaths caused from overheating may be as high as 7,000 people per year in the UK.

- Different factors that can contribute to overheating are outlined below:

  Restricted ventilation, Noise, Humidity, Occupant behaviour, Glazing, Internal gains, Airtightness, Pollution, Aspect, Insulation, Thermal mass, Site context, Orientation (shading), Urbanisation (heat island effect) and Security.

- Internal heat gain during the summer can be much higher than the original assumption in Passivhaus Planning Package (version 7) of 2.1 W/m^2. In this study internal heat gains were calculated to be 3.65 W/m^2 and 3.5 W/m^2 for the two case study buildings.

- Window opening can be limited due to local discomfort and weather implications (i.e. letting rain into the building).

- Ventilation at the roof level can have less noise implications and especially in urban locations be cleaner.

- Cooling cannot be achieved during the summer by using MVHR alone, not even with boost mode and there is no purge option for MVHR.

- There are examples of overheating in Passivhaus dwellings as they are subject to higher internal temperature increases even with small fluctuations due to their minimum heat loss to outside from the fabric, infiltration and exfiltration.

Summary drawn for Objective II:

“Detail analysis of data collected from two case study Passivhaus dwellings during the summer, determining the causes contributing to the indoor climate conditions.”

This objective was met by detailed monitoring of two case study Passivhaus dwellings and in depth analysis of the monitored data.

- Occupants operate windows regardless of outside temperature and usually after the indoor temperature is already over the thermal comfort level. For instance the window in Building One (dining room – W1) was opened on July 18th when outside temperature was just below 30°C, increasing the indoor temperature from around 26°C to 30°C. Moreover the window in the living room (W2) was opened on June 13th when the inside temperature was just over 29°C and the outside was 21°C.

- Natural ventilation during the night is very limited or non-existent in the buildings studied which could be due to noise and security concerns. The living room window for example in Building One was not opened during the night throughout June, July and August.

- Natural ventilation through windows can be limited due to the way windows open or reduced significantly due to window safety restrictions. For instance bottom hung inwards opening windows provide limited effective air flow due to thickness and the position of the wall. Internal and external blinds can also reduce air flow considerably. The internal and external blinds on the ground floor of Building One were closed for the majority of the time.

- The positioning and location of the fresh air intake and extract and their proximity to each other in the case study buildings compromised the cooling effect leading to cross contamination and overheating. Temperature increase was recorded surrounding the fresh air intake and the close proximity of the intake and extract was noted especially in the case of Building Two.

- The higher internal gains in UK Passivhaus dwellings (higher density and lower appliance efficiency) can contribute to a higher potential of overheating.

- The Passivhaus indoor air quality (air pollutants and air borne contaminants) is reduced during the summer as the air is not filtered through the use of windows like the MVHR in winter.

- Monitoring results highlighted a high level of overheating especially for the individual areas in the case of Building One. This is not indicated when using PHPP as the overheating is averaged over the year and for the whole building rather than individual rooms. The monitoring of kitchen and living room (Building One) indicated overheating of 77% to 100% in July and August compared to the average of 21.13% for the entire year.

- Cooler temperatures on the higher floors for both buildings were recorded leading to a lower overheating percentage. In particular, overheating was up to 49% less in the second floor compared to the ground floor (Building One) during the monitored period. This indicated that hot air was not rising due to the high level of airtightness of these buildings.

- There was a lower ventilation rate in the bedrooms especially during the night as the high indoor CO_2 levels indicated for both buildings. Therefore the required $30m^3/h/person$ was not achieved in the main bedrooms where two adults slept.

Summary drawn for Objective III:

“Thorough examination of proposed natural ventilation systems for the two case study Passivhaus buildings in order to determine an effective strategy for current and future climates using Dynamic and PHPP calculations.”

This objective was met by detailed investigation and simulation using dynamic thermal modelling.

- Three different options were tested, all based on incorporating a windcatcher as part of the ventilation system leading to Option 3. The windcatcher would allow an increase to the stack effect in Passivhaus which was noticed to be limited from the temperature analysis of monitoring data. Option 3 provided a possible natural ventilation strategy to be proposed eliminating the summer overheating potential.

- The combination of the windcatcher used for extract only and the new low level opening (Option 3) resulted in possible higher natural ventilation and consequently cooling for both buildings. The overheating percentage therefore was eliminated (both buildings) and temperatures were below 25°C during the summer months.
- The low level opening was 200mm from the ground and 200mm in height with 100mm clear opening. The width was calculated to achieve 1/50th of the room area and around 1/50th of the TFA in total.
- Option 3 was also effective in eliminating possible overheating, using the future climate data (for both buildings) and even removed the need for windows to be opened.
- The elimination of any window operation was tested in PHPP and the method of incorporating Option 3 in PHPP was tested leading to comparison and validation of the data from the dynamic thermal model.
- The ventilation rate was increased from the assumed night time ventilation of 0.22 ac/h from the PHPP calculation to an average of 1.45 ac/h and 1.33 ac/h for Building One and Two.
- The daily average ventilation rate using the dynamic thermal model was calculated to be maximum 1.85 ac/h - 1.26 ac/h and minimum 0.25 ac/h - 0.10 ac/h during the summer period for Building One and Two. The Building Two calculation was carried out using 2050 climate data (as the building was not overheating under the current climate), which perhaps influences the ac/h.
- The design and the detailing for the windcatcher and low level opening was tested for the possible extra heat loss during the winter allowing the same Psi-Value used by the window in PHPP to be achieved.

- Option 3 offers natural ventilation using filters, addressing: security, weather (rain & solar gain) and possible noise reduction (due to the filter usage / low level), increasing air movement leading to cooler indoor temperatures.

Summary drawn for Objective IV:

“Make recommendations for incorporating suitable natural ventilation strategies to maintain the air quality and reduce the potential for overheating during summer for the benefit of current and future Passivhaus buildings.”

This objective was met by the use of dynamic thermal models alongside input using PHPP software.

- Evidence suggests that Option 3 would be effective in a wider context as it was tested on a further five Passivhaus buildings using the PHPP calculation with no window openings and the results indicated no overheating potential.
- It was recommended that Option 3 be incorporated as part of PHPP calculation allowing the Passivhaus designers and consultants to propose Option 3 as a natural ventilation strategy.

8.2 CONCLUSION

Overheating can be a problem in residential buildings in the UK affected by lower fabric performance and internal gains (Gupta & Gregg, 2013) (Mavrogianni et al., 2012), however this is different for buildings constructed to a higher efficiency standard such as Passivhaus benefiting from a high level of fabric performance and airtightness level. The overheating caused in high efficient buildings like Passivhaus cannot necessarily be addressed by fabric improvement as the fabric is already designed to a high standard.

On the other hand high efficient buildings can be overheated due to their high level of insulation and airtightness (Richard Partington Architects, 2012) meaning it is more difficult to disperse built up heat whether from internal or external sources. The monitoring results in this research highlighted the potential of overheating in a Passivhaus dwelling in the UK constructed using a lightweight construction technique. The importance of construction material and the building design in respect to glazing size and shading was noted. However, more importantly, occupant behaviour can play a significant role on overheating (Gupta & Gregg, 2013) increasing the importance of natural ventilation in such buildings (Vardoulakis et al., 2015), which was also highlighted in the two monitored buildings.

Moreover, indoor summer temperatures can be directly related to the occupant activity such as window operation and control of indoor heat gain. The window operation is probably more related to building user’s habit and preferences rather than fabric performance (Gupta & Kapsali, 2016). Nevertheless what is expected and is reasonable to ask from the occupants needs to be taken into consideration when designing to Passivhaus standard (Passivhaus Trust, 2016).

Moreover the building regulations state the required background ventilation and the purge ventilation is needed to extract indoor pollutants. However there is no referral to overheating control or mitigation (Lomas & Porritt, 2017) or required higher ventilation rate during the summer period. The monitoring of the two case study buildings for this research had highlighted very limited or no window operation during the night, similar to research carried out by Mavrogiannia et al. (2017) for 101 dwellings in London where 70% of occupants were reluctant to open windows (Mavrogianni et al., 2017) . The initial PHPP calculation (during the design stage) had incorporated night-time cooling of 0.22 ac/h as part of the ventilation strategy. This research suggested that the ventilation rate needs to be increased to around 1 to 1.5 ac/h during the summer period, reducing the overheating potential, which is not perhaps possible by the use of the MVHR system alone (Dengel et al., 2016).

Overheating can occur due to factors other than the external and internal heat gains as the monitoring results indicated. The ventilation achieved through the use of MVHR in Passivhaus dwellings for instance, can have an impact on overheating. The material properties used around the MVHR intake alongside the location of the fresh air intake (in respect to shading and height from the ground) can effect indoor temperatures. Moreover the lack of insulation surrounding the MVHR ducts internally can also potentially increase the incoming fresh air temperatures contributing to overheating during the summer.

On the other hand, natural ventilation through the use of windows can have implications such as security and noise causing a reduction in operation and duration, this can contribute to a difference between design intent and actual operation leading to a reduction in the ventilation rate and cause overheating (Baborska-narożny et al., 2017). For example the windows were opened in tilt mode for the majority of the time (both buildings) restricting the airflow resulting in reduction in possible cooling. Security and noise were also contributors in the reduction of window operation and lack of window opening especially during the night and unoccupied periods as indicated by the monitoring and occupant consultation. Moreover, the indoor air quality in Passivhaus buildings can be compromised by the use of the windows as the incoming fresh air is no longer filtered as in the winter period when using MVHR.

Passivhaus buildings are known for their high indoor air quality due to the use of MVHR and the benefits of filters within the system. However, the ventilation achieved through the use of MVHR in the warmer part of the year is not sufficient for cooling not even in the boost mode (Mcgill et al., 2017) (Richard Partington Architects, 2012). This was also apparent from the monitoring results as there had been overheating in the cooler months when the window operation was minimum and MVHR was the main means of ventilation.

During the summer period window opening is encouraged to achieve a higher ventilation rate without the benefit of any filtration effecting the indoor air quality. This needs to be identified and addressed by an alternative natural ventilation strategy and design ensuring the same IAQ during the summer.

Continuous natural ventilation is needed to eliminate overheating (Lee & Steemers, 2017) and also the natural ventilation rate can be reduced significantly due to concerns regarding noise, security, insects, privacy and restriction due to the way the windows are opened like tilt position (Passivhaus Trust, 2016). The proposed option using a low level opening for introducing cool air through filters into the building and the extract using the windcatcher at roof level, can overcome many of the concerns such as security, poor IAQ, rain infiltration and solar gain. This option was proven to be very effective in providing the required cooling effect and eliminating any overheating potential. Further detailing and Psi-Value calculations were undertaken ensuring building high performance is not compromised during the winter period by the incorporation of this system.

Moreover, the changes in our climate can also be a further contributor to overheating in buildings and the adaptation to change in our climate is needed and should be part of the UK carbon reduction retrofitting strategy (Mavrogianni et al., 2012) (Liu & Coley, 2015).The buildings with low or no overheating potential, can also experience overheating as in the case of Building Two, when future weather data is taken into consideration. Therefore the strategy and design of current buildings needs to take future climate into account, reducing the risk of overheating in the future.

The use of a dynamic thermal model led to the proposal of Option 3, taking into consideration the challenges associated with validation of a dynamic model derived from assumptions made when creating the model (Symonds et al., 2017). Nevertheless Option 3 was tested for Building One which was experiencing high levels of overheating, using current and future climate data as well as Building Two which would potentially experience overheating in the future if no action was taken. This option was effective for all scenarios tested, even allowing for no window opening (during summer) ensuring the high IAQ is achieved throughout the year by incorporating filters as part of the system. Furthermore the potential of no window opening would allow for the reduction of window frames contributing to higher solar gain during the winter period and lower thermal bridging between the glass and the window frame. This can effectively improve not only the summer performance of the building, but also reduce the heating load during the winter period.

The proposed option can potentially increase the natural ventilation rate during the summer to an average of around 1 ac/h which is possible due to the increase in stack effect. The use of stack effect can be very important as it was identified to be one of the problems from monitoring results of 26 buildings built to Passivhaus / high efficiency in Scotland (Morgan et al., 2017). Furthermore the monitoring results from the two case study buildings also suggested that the heat did not rise as the overheating was more in the lower floors.

The low level opening is designed to achieve around 1/50th of the TFA. The increased rate was calculated to be maximum 1.85 ac/h - 1.26 ac/h and minimum 0.25 ac/h - 0.10 ac/h for Building One and Two, using dynamic modelling. The PHPP calculation achieved an average of 1.45 ac/h and 1.33 ac/h for Building One and Two in line with the recommended summer ventilation rate (Dengel et al., 2016).

Adaptation of existing buildings is required taking climate change into consideration especially in suburban areas (Williams et al., 2013) The proposed option can not only be incorporated as part of new Passivhaus but also EnerPhit design or refurbishment of the current Passivhaus stock experiencing overheating now or in a few years when warmer summers are predicted. Option 3 can be tested using PHPP calculations allowing the designers to be more confident with their design for not only the current climate but also for the future climate by using the future climate data as part of their calculations. This option not only benefits Passivhaus designers and consultants, but also increases confidence for homeowners interested in the

Passivhaus standard. Moreover the proposed option can be adopted by Passivhaus Institute and be incorporated as part of the PHPP calculation as an option for providing summer ventilation.

Finally, the overheating problem is not necessarily limited to Passivhaus buildings and can affect any dwelling type in the UK especially when climate change is taken into consideration. Overheating will have a higher impact on the elderly and young whom are perhaps less inclined to open windows for additional ventilation (Dengel & Swainson, 2012) and consequently lower indoor air quality (Vellei et al., 2017). Recognition of this problem is currently limited in comparison to issues associated with the winter period and there is also limited planning for the prevention in the future (Gupta et al., 2017). Therefore a system like Option 3 can potentially be incorporated into any design or building standard and future refurbishment of the current building stock providing natural ventilation and cooling. Moreover as the system is more secure and weather proof than the use of windows, it can be in operation for longer (even during unoccupied periods) providing a high level of IAQ throughout the warmer months of the year. Moreover, the proposed option can be potentially adopted for different climates with a potential benefit of humidification and dehumidification as part of the design for additional cooling.

8.3 CONTRIBUTION TO KNOWLEDGE AND RECOMMENDATIONS

This research was set to investigate the possible overheating potential during the summer period in the UK Passivhaus dwellings. The research highlighted this potential in the case study Passivhaus dwelling constructed using low thermal mass and high airtightness level. The overheating percentage was however much lower in the case of the second building constructed to EnerPhit standards with higher thermal mass and lower airtightness level. The possible causes contributing to summer overheating beside solar gain was investigated and tested using monitoring, PHPP and dynamic thermal calculation. Recommendation therefore was suggested in order to reduce heat gain and consequently lowering the indoor temperature.

The monitoring results also highlighted the problem of high overheating percentage in individual rooms which is not taken into consideration when using PHPP. The calculation from PHPP averages the overheating for the whole building irrespective of orientation or glazing ratio to the floor area. This can be an important issue as some rooms might be overheated for a long time such as the kitchen or the living room of Building One.

The importance of the material used and the micro climate surrounding the fresh air intake was also identified as well as the need for insulation for the MVHR ducts, contributing to higher incoming fresh air temperature and therefore increase in indoor temperatures.

The aim of the research was also to investigate the possibility of providing natural ventilation securely without increasing solar gain and reducing the air quality. Several different options were tested following an extensive literature review and ‘Option 3’ was proposed. Option 3 incorporates the use of windcatchers as part of Passivhaus design, which has not been done previously and introduces a low level ventilation design with filters to provide the required natural ventilation. This option provided the possibility of eliminating any overheating potential not only for the current climate but also using the projected future climate data. This is achieved by increasing the stack effect in Passivhaus buildings with a high level of airtightness which was identified to be an issue from the monitoring results as the heat did not rise to the upper floors.

The proposed option increases the stack ventilation and achieves around 1 ac/h using the low level opening and windcatcher. The low level opening is designed to be 1/50th of the floor area with a reduction factor of 60% due to the design and the proposed filters. The use of filters ensures the same IAQ achieved during the winter which otherwise is lost by the use of windows. The windcatcher was created based on Monodraught Classic Square design 125 which is 900mm by 900mm on plan.

Proposal was made in order to incorporate Option 3 in PHPP calculation for Passivhaus consultants and designers. Furthermore this proposal was cross examined using an additional five Passivhaus dwellings in the UK which was proven to be effective and highlighted any possible limitation with the proposed option.

Recommendations:

- The MVHR intake and extract location should be part of Passivhaus standard providing guidance for orientation, shading, material used surrounding the fresh air intake and proximity between inlet and outlet in respect to the climate.
- MVHR ducts should be insulated internally in order to reduce any possible additional temperature increase on the incoming fresh air.
- Designers should contemplate the possibility of overheating not only for the current climate but also use future climate data when designing Passivhaus buildings.
- The future climate data should be included in the PHPP climate sheet by Passivhaus Institute.

- Designers should not rely on night time ventilation solely as a method of providing cooling during the summer.
- Designers should allow for different scenarios for shading operation and additional ventilation through window opening, taking occupant behaviour into account.
- Designers should be aware of the reduction on IAQ achieved due to window opening during the summer in comparison to winter through MVHR's filter.
- Overheating percentage for individual spaces to be incorporated as part of PHPP as well as the entire building's average.
- The internal gain calculation has been added to the PHPP, however a maximum level (i.e. $5W/m^2$) should be recommended as well as a minimum (i.e. $3.5W/m^2$) as standard, similar to the winter period of $2.1W/m^2$.
- MVHR to have summer bypass as standard and be part of the Passivhaus requirement.
- MVHR control to have unoccupied period and number of occupants input as standard as well as an automatic indoor CO_2 level control
- Option 3 could be incorporated as part of the PHPP calculation for the summer ventilation strategy by Passivhaus Institute.

8.4 LIMITATION OF THE RESEARCH:

Some of the limitations of this research have been listed below:

- Monitoring the blinds (internal and external) in order to examine the frequency of use and effectiveness of solar gain reduction through blind usage and reduction of air flow - The blinds were not monitored due to financial limitations and availability of monitoring equipment for this purpose and therefore the input into the dynamic thermal model was from the PHPP calculation rather than monitored data. This limited the available monitored data to be used for simulation and design data was used increasing the gap between the reality and the simulation.
- Wider range of case study buildings (monitored) with different design and locations - Monitoring and modelling a higher number of buildings would have increased the quantity of primary data, increasing confidence in the validation of the proposed option. This could not be done due to the availability of the buildings which could be monitored and accessed.
- The MVHR incoming fresh air was monitored at the point where it enters the room, however the temperature was not measured just before entering the MVHR and just after the unit to examine the level of change in temperature at different stages. This was not done due to financial constraints and increased disruption for the occupants - This could have allowed for a better analysis and examination of the impact for the suggested improvements.
- Some of the window sensors did not stay in place which led to data losses – This was due to the way the equipment was secured in order to reduce any possible damage. In specific, up to the 15th of May data was lost for all windows in Building One which was not therefore taken into account as it was outside of the summer period and one window

had partial data loss during the summer. In Building Two, the data was lost for the entire summer for two windows, one window experienced partial data loss and one patio door exceeded the logger data capacity. Therefore some assumptions had to be made when inputting data into the dynamic thermal model by comparison to other available data and occupant input.

- Lack of monitoring the indoor CO_2 levels in all the habitable rooms – CO_2 levels were monitored only for two rooms (living and main bedroom) in the two case study buildings due to financial constraints. The higher possible data would have increased cross examination of the ventilation achieved through window opening in relation to indoor CO_2 levels and also provide more data for creating and closing the gap between the dynamic thermal model and the monitored data.
- Although the majority of the windows were monitored in consultation with the occupants however monitoring all the operable windows in the buildings was not achieved – This was influenced by the available number of loggers and consequently the data input for the unmonitored windows in the dynamic thermal model was estimated using other available data and input from the occupant. This would have allowed for a more accurate data input for all windows in the dynamic model and possibly reduce the gap further between the dynamic model and the monitored data.
- Window monitoring did not include the angle of the windows being opened - Windows were monitored for opening and closing duration and operation time in respect to time of the day, however the sensors used were not able to record how wide the windows were opened. This would have given better input data for the dynamic modelling which was estimated by observation and the angle of the window tilt limit.

- The use of actual climate data during the monitored period for creation of the base case dynamic model. This was not available due to limitation of obtaining the solar radiation information.
- Lack of laboratory testing of the proposed system to calculate the exact air flow – This would increase the confidence in the proposed system by cross examination of the data and allow for further validation of the proposed option. This was not possible to undertake in the time and scope of this research and will be part of future research.

8.5 FURTHER RESEARCH

I. MVHR controls need closer investigation especially during the unoccupied periods during the heating seasons as the internal gains can be very limited and the use of MVHR could increase the heat loss. Moreover occupant patterns are very unpredictable and can affect the ventilation rate considerably which could be incorporated as part of the MVHR control.

II. Opening windows simultaneously while the MVHR is in operation could affect the ventilation balance and the air movement path; further research would be required in this area examining the affect.

III. Further investigation would be also required to examine the air temperature at the point of entering the MVHR, immediately after exiting the unit as well as the entry point into the room to establish the level of increase in the temperature at the different stages during the cooling season.

IV. Manufacturing the low level opening at one to one scale and lab test to examine the air flow rate for different conditions etc. as well as a costing exercise comparing to cost saving from windows.

V. Further investigation into the incorporation of low impact cooling like humidification and dehumidification as part of the Option 3 design could increase the benefit of the system especially for warmer climates with more cooling requirements.

VI. The proposed system needs to be examined in different climate conditions (temperature and humidity) in order to test the limit of the system in achieving cooling.

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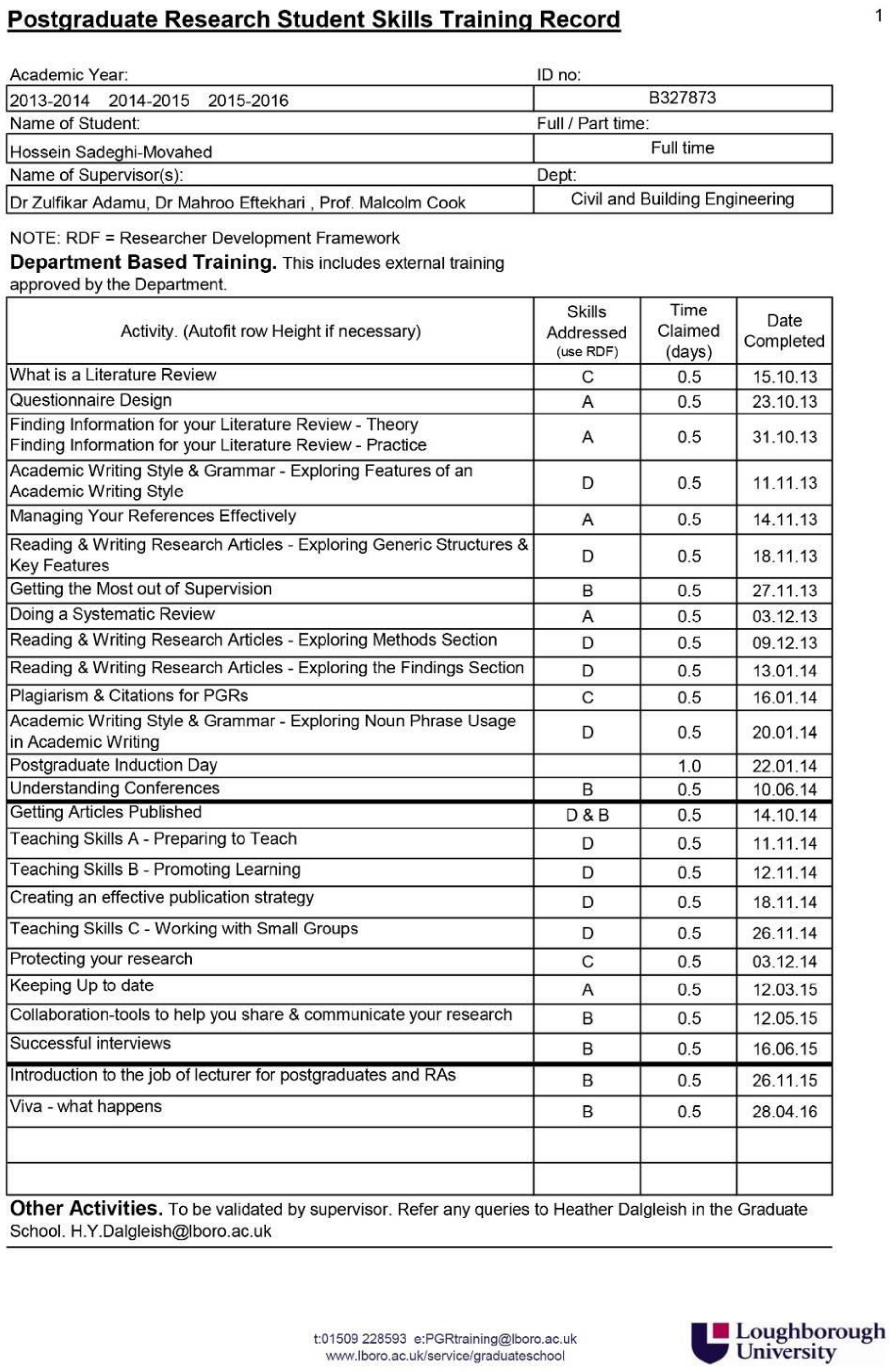
APPENDIX A



Postgraduate Research Student Skills Training Record

1

Academic Year:	ID no:
2013-2014 2014-2015 2015-2016	B327873
Name of Student:	Full / Part time:
Hossein Sadeghi-Movahed	Full time
Name of Supervisor(s):	Dept:
Dr Zulfikar Adamu, Dr Mahroo Eftekhari , Prof. Malcolm Cook	Civil and Building Engineering

NOTE: RDF = Researcher Development Framework

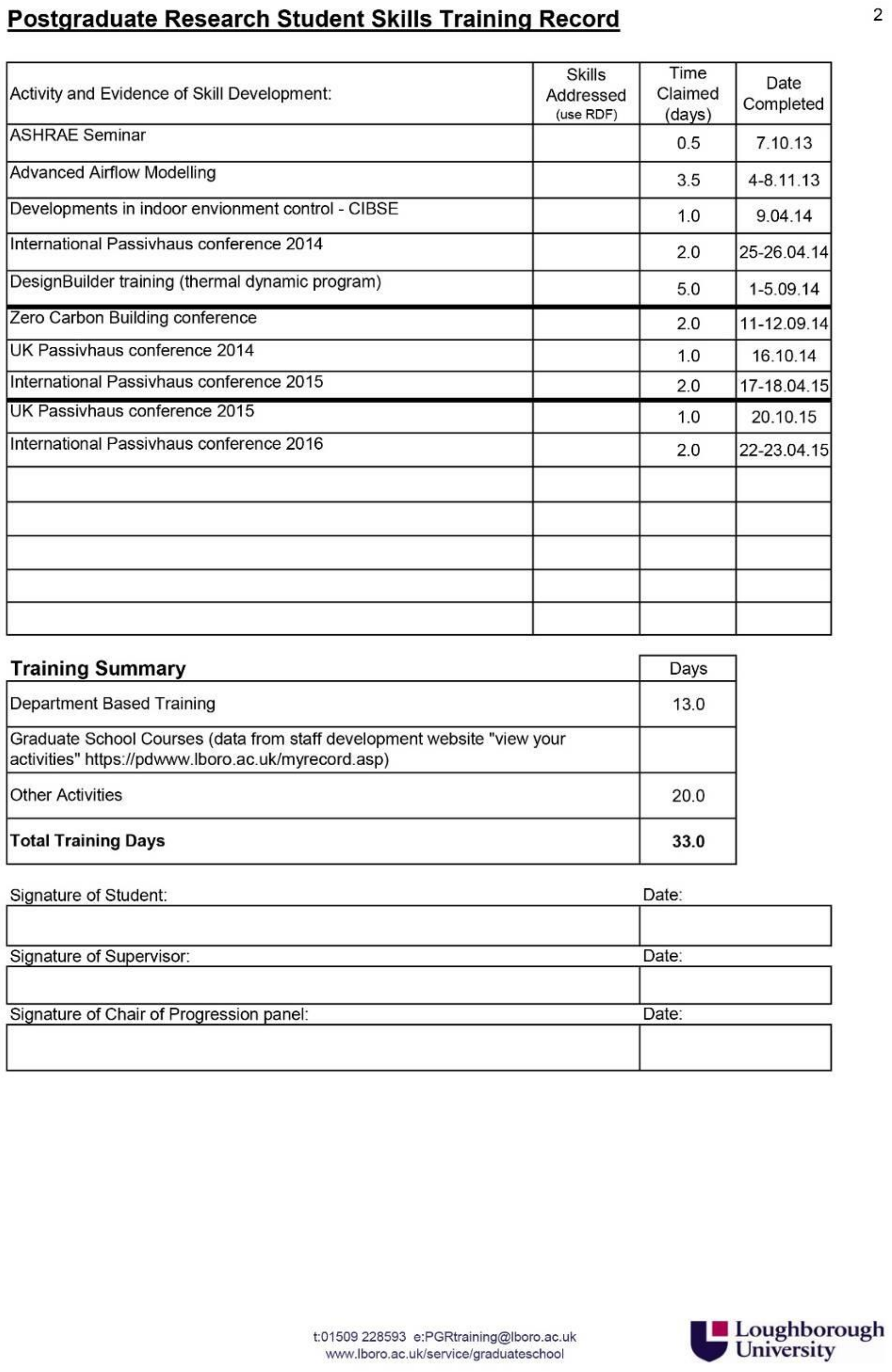
Department Based Training. This includes external training approved by the Department.

Activity. (Autofit row Height if necessary)	Skills Addressed (use RDF)	Time Claimed (days)	Date Completed
What is a Literature Review	C	0.5	15.10.13
Questionnaire Design	A	0.5	23.10.13
Finding Information for your Literature Review - Theory Finding Information for your Literature Review - Practice	A	0.5	31.10.13
Academic Writing Style & Grammar - Exploring Features of an Academic Writing Style	D	0.5	11.11.13
Managing Your References Effectively	A	0.5	14.11.13
Reading & Writing Research Articles - Exploring Generic Structures & Key Features	D	0.5	18.11.13
Getting the Most out of Supervision	B	0.5	27.11.13
Doing a Systematic Review	A	0.5	03.12.13
Reading & Writing Research Articles - Exploring Methods Section	D	0.5	09.12.13
Reading & Writing Research Articles - Exploring the Findings Section	D	0.5	13.01.14
Plagiarism & Citations for PGRs	C	0.5	16.01.14
Academic Writing Style & Grammar - Exploring Noun Phrase Usage in Academic Writing	D	0.5	20.01.14
Postgraduate Induction Day		1.0	22.01.14
Understanding Conferences	B	0.5	10.06.14
Getting Articles Published	D & B	0.5	14.10.14
Teaching Skills A - Preparing to Teach	D	0.5	11.11.14
Teaching Skills B - Promoting Learning	D	0.5	12.11.14
Creating an effective publication strategy	D	0.5	18.11.14
Teaching Skills C - Working with Small Groups	D	0.5	26.11.14
Protecting your research	C	0.5	03.12.14
Keeping Up to date	A	0.5	12.03.15
Collaboration-tools to help you share & communicate your research	B	0.5	12.05.15
Successful interviews	B	0.5	16.06.15
Introduction to the job of lecturer for postgraduates and RAs	B	0.5	26.11.15
Viva - what happens	B	0.5	28.04.16

Other Activities. To be validated by supervisor. Refer any queries to Heather Dalgleish in the Graduate School. H.Y.Dalgleish@lboro.ac.uk

t:01509 228593 e:PGRtraining@lboro.ac.uk
www.lboro.ac.uk/service/graduateschool

Loughborough University



Postgraduate Research Student Skills Training Record

Activity and Evidence of Skill Development:	Skills Addressed (use RDF)	Time Claimed (days)	Date Completed
ASHRAE Seminar		0.5	7.10.13
Advanced Airflow Modelling		3.5	4-8.11.13
Developments in indoor envionment control - CIBSE		1.0	9.04.14
International Passivhaus conference 2014		2.0	25-26.04.14
DesignBuilder training (thermal dynamic program)		5.0	1-5.09.14
Zero Carbon Building conference		2.0	11-12.09.14
UK Passivhaus conference 2014		1.0	16.10.14
International Passivhaus conference 2015		2.0	17-18.04.15
UK Passivhaus conference 2015		1.0	20.10.15
International Passivhaus conference 2016		2.0	22-23.04.15

Training Summary	Days
Department Based Training	13.0
Graduate School Courses (data from staff development website "view your activities" https://pdwww.lboro.ac.uk/myrecord.asp)	
Other Activities	20.0
Total Training Days	**33.0**

Signature of Student:	Date:
Signature of Supervisor:	**Date:**
Signature of Chair of Progression panel:	**Date:**

APPENDIX B

List of the monitoring equipment and locations:

Building one – Passivhaus

Temperature / RH

Location	Equipment
1-Ph-Dining Room	U10
2-Ph-Kitchen	U10
3-Ph-Living Room	U10
4-Ph-Master Bedroom	U10
5-Ph-Master Bathroom	U10
6-Ph- Bedroom 5	U10
7-Ph-Drying Room	U10
8-Ph-Bedroom 3	U10
9-Ph-Bedroom 4	U10
10-Ph-Second floor Shower	U10
11-Ph-MVHR Room	U12

MVHR supply air temperature

Location	Equipment
1-Ph-Living Room	I-Button
2-Ph-Master Bedroom	I-Button

CO_2 / Lux

Location	Equipment
1-Ph-Living Room	U12 + CO_2
2-Ph-Master Bedroom	U12 + CO_2

Outdoor temperature

Location	Equipment
Below external staircase X3	Pendant

Window openings

Location	Equipment
1-Ph-W-1	U9
2-Ph-W-2	U9
3-Ph-W-8	U9
4-Ph-W-5	U9
5-Ph-W-10	U9
6-Ph-W-12	U9
7-Ph-W-18	U9
8-Ph-W-24	U9
9-Ph-W-21	U9

Building two – EnerPhit

Temperature / RH

Location	**Equipment**
1-EP-Siting Room	U10
2-EP-Kitchen	U10
3-EP-Dining Room	U10
4-EP-Utility	U12
5-EP-Loft (MVHR Room)	U10
6-EP- Master Bedroom	U10
7-EP- Master Bathroom	U10
8-EP-Bedroom 4	U10
9-EP-Bedroom 5	U10
10-EP- Bedroom 2	U10
11-EP-Bathroom	U10

MVHR supply air temperature

Location	**Equipment**
1-EP-Siting Room	I-Button
2-EP-Bedroom 4	I-Button

CO_2 / Lux

Location	**Equipment**
1-EP-Siting Room	U12 + CO_2
2-EP-Bedroom 4	U12 + CO_2

Outdoor temperature

Location	**Equipment**
Below external shed roof X3	Pendant

Window openings

Location	**Equipment**
1-EP-W-2	U9
2-EP-W-D3	U9
3-EP-D-7	U9
4-EP-D-4	U9
5-EP-W-13	U9
6-EP-W-17	U9
7-EP-W-16	U9
8-EP-W-15	U9
9-EP-W-18	U9

The equipment specifications:

http://www.onsetcomp.com/

HOBO U10

Temperature Measurement Range: -20ºC to +70ºC

Accuracy: ± 0.4ºC at 25ºC

RH Range: 25% to 95% RH (5ºC to 55ºC)

Memory Capacity: 52K 10-bit measurements

Operating Range: -20ºC to +70ºC, 0% to 95% RH non-condensing

HOBO U12

Temperature Range: -20ºC to +70ºC

Relative Humidity Range: 5% to 95% RH

Light Level Range: 1 to 3000 lumens/ft²

64K memory (43,000 12-bit measurements)

Operating Range: -20ºC to +70ºC, 5% to 95% RH non-condensing, non-fogging

External input for use in indoor environments

HOBO U9

Operating Range: -20º to +70ºC (0 to 95%RH)

Memory: 26K to 43K time-stamped state changes

Telaire 7001 CO2 Sensor - TEL-7001

0 to 2500 ppm when using the CABLE-CO2 and a U12 or ZW

32°F to 122°F (0°C to 50°C), 0 to 95% RH, non-condensing

Accuracy: ±50 ppm or 5% of reading, whichever is greater

I-Button

http://www.measurementsystems.co.uk/

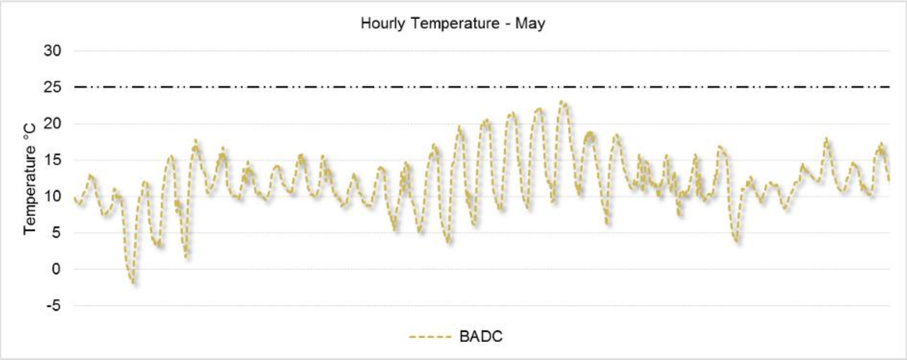
Memory Size: 512 bytes

Measurement Range: -40 to +85°C

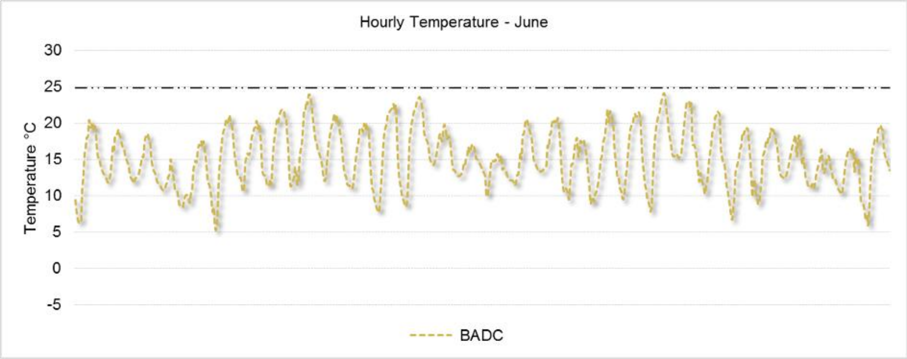
Data Logger Accuracy: correctible to +/- 0.5°C

APPENDIX C

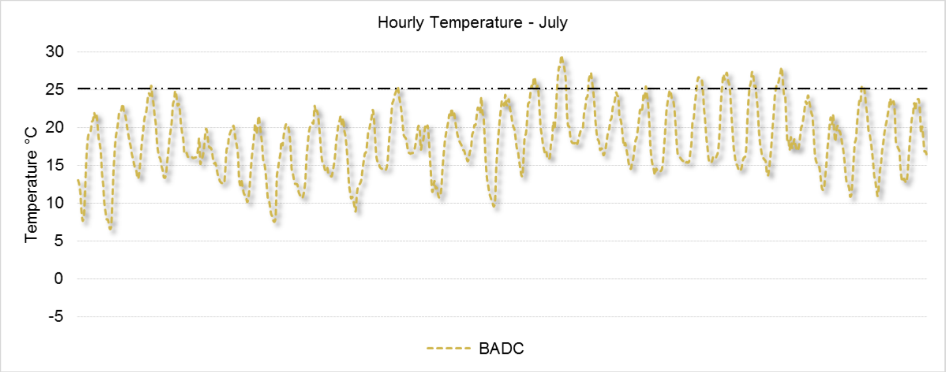
Ambient temperatures for May and September – Building One:



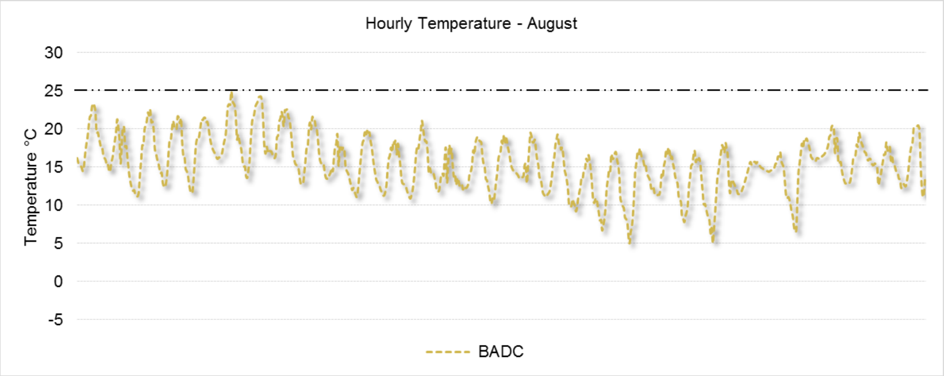
Ambient temperature May 2014 (BADC)



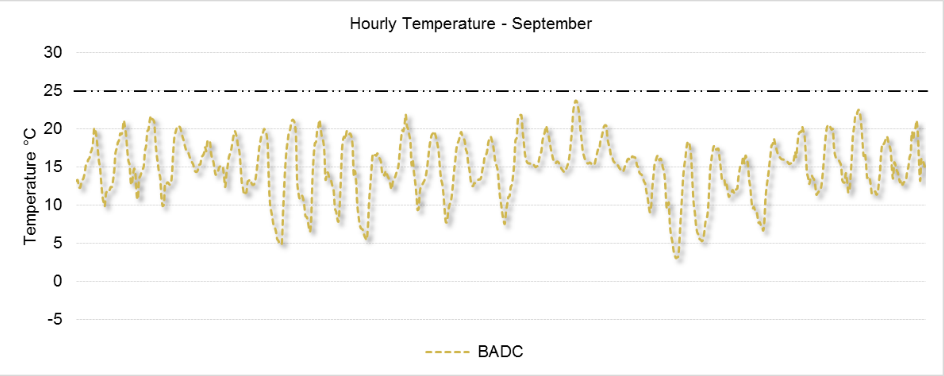
Ambient temperature June 2014 (BADC)



Ambient temperature July 2014 (BADC)

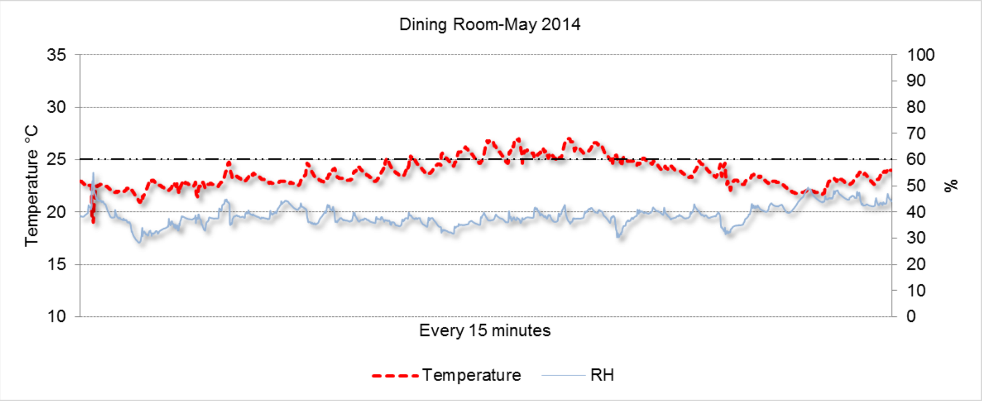


Ambient temperature Aguste 2014 (BADC)

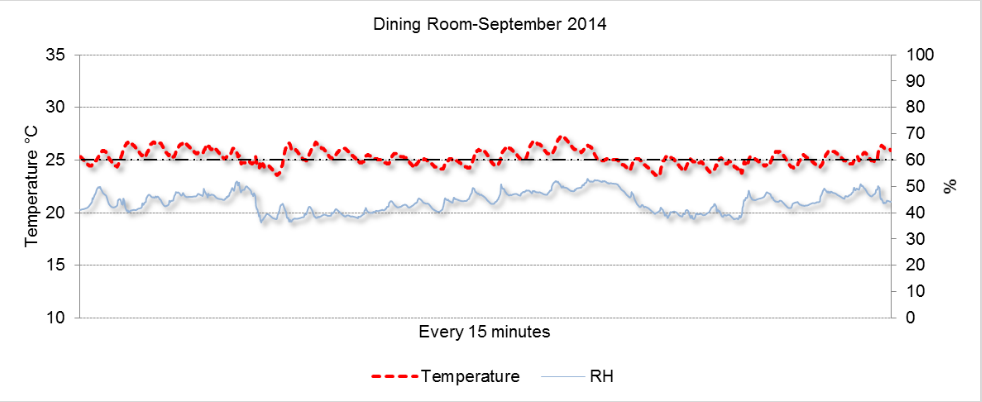


Ambient temperature September 2014 (BADC)

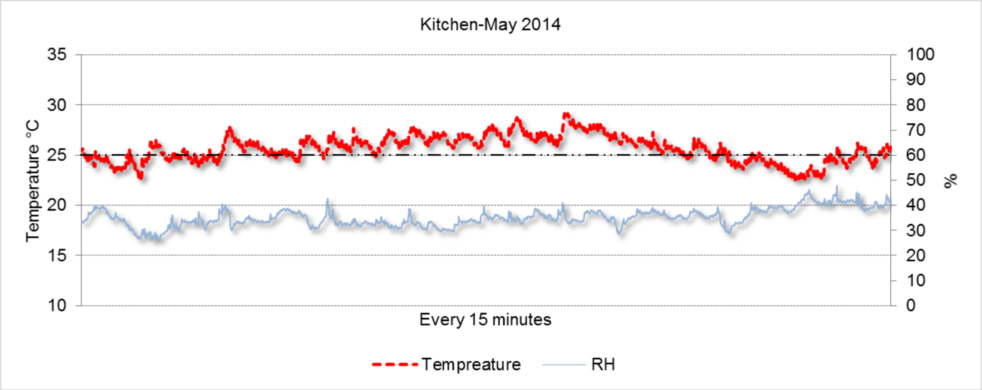
Indoor temperatures for May and September – Building One:



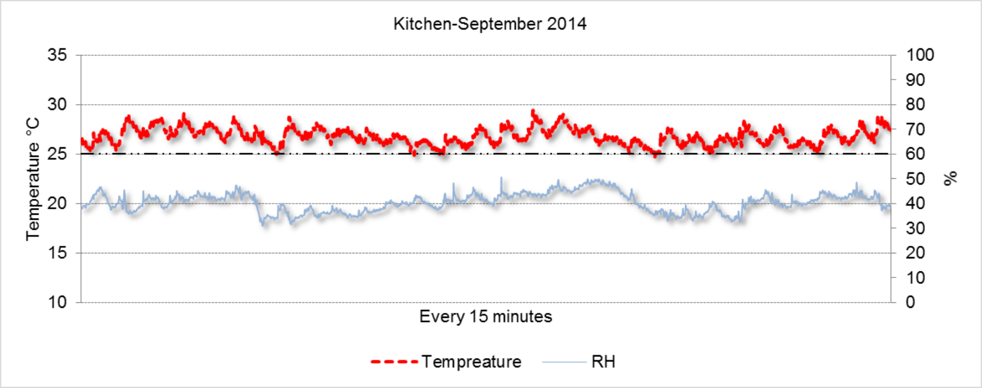
Measured temperature & RH (Dining room - May 2014)



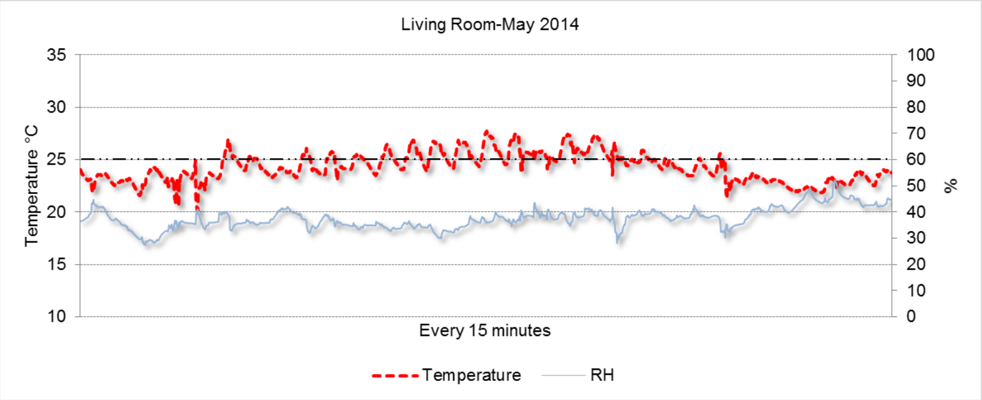
Measured temperature & RH (Dining room - September 2014)



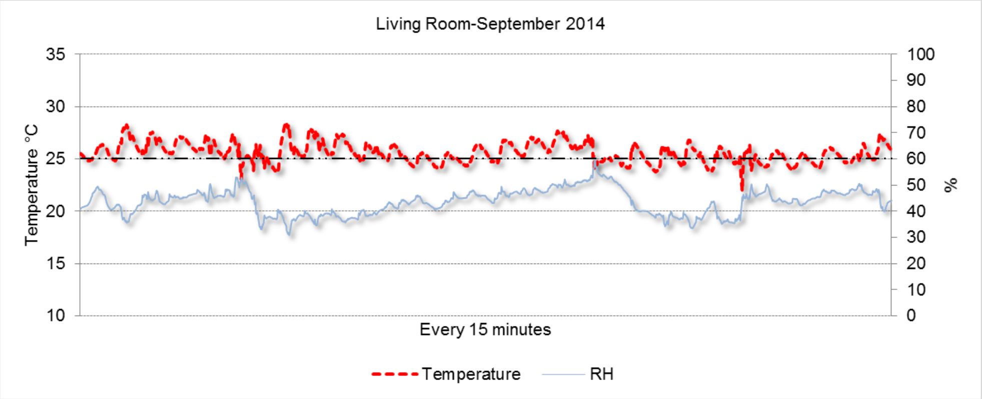
Measured temperature & RH (Kitchen - May 2014)



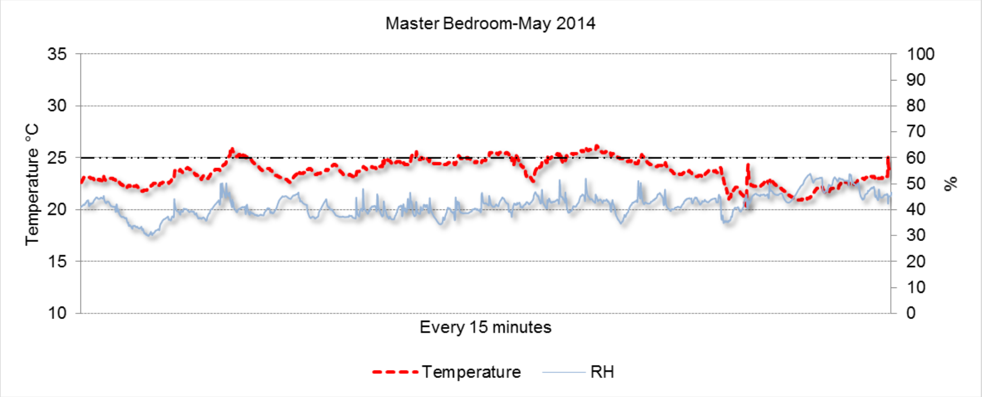
Measured temperature & RH (Kitchen - September 2014)



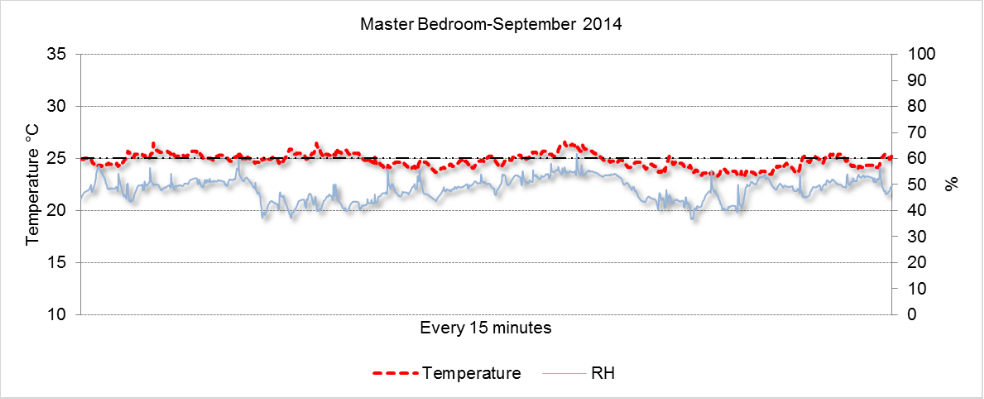
Measured temperature & RH (Living room - May 2014)



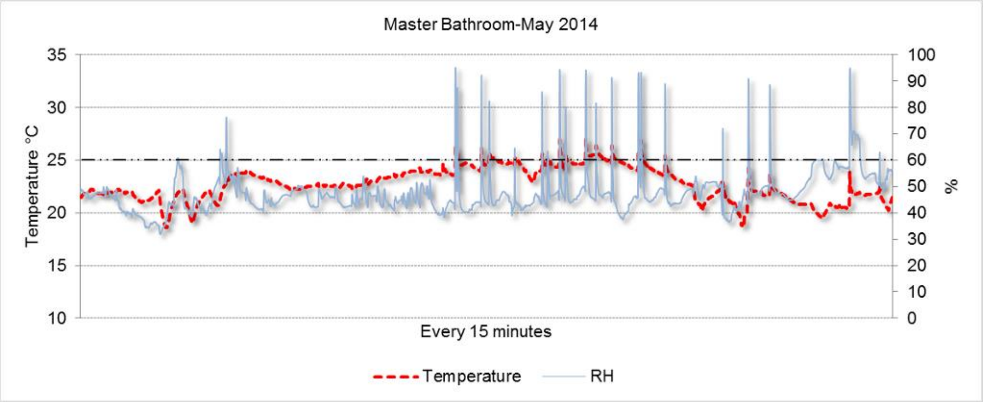
Measured temperature & RH (Living room - September 2014)



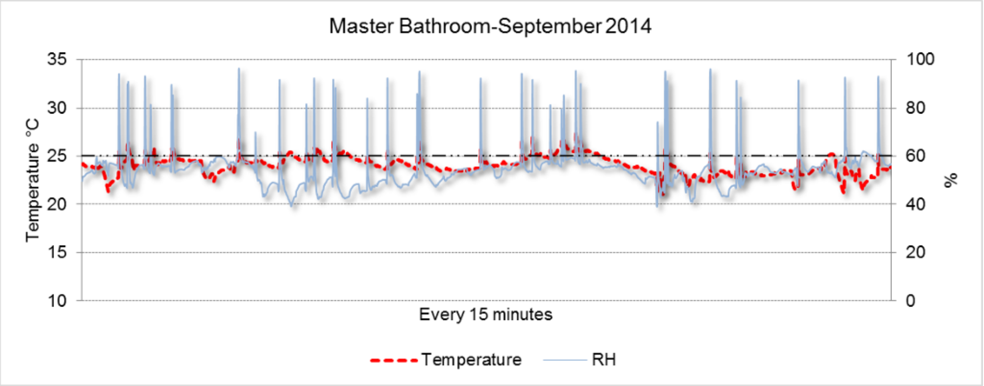
Measured temperature & RH (Master bedroom - May 2014)



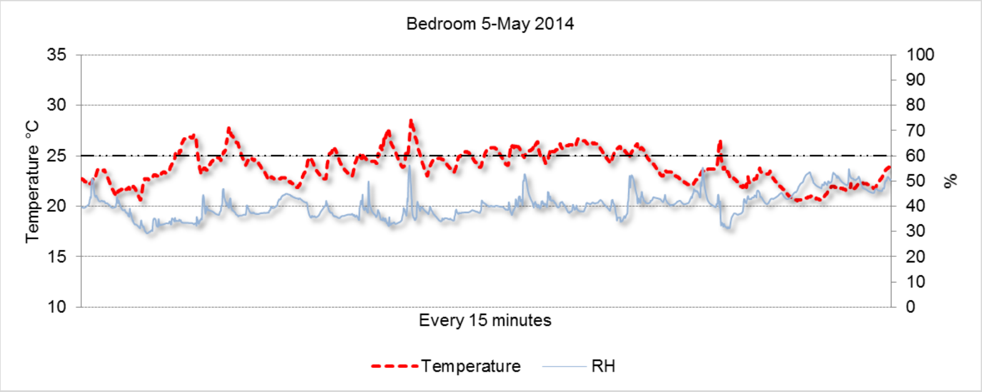
Measured temperature & RH (Master bedroom - September 2014)



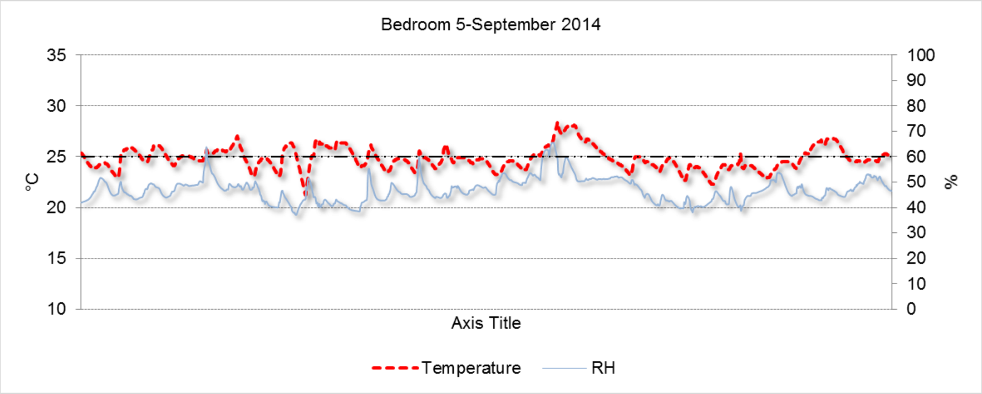
Measured temperature & RH (Master Bathroom - May 2014)



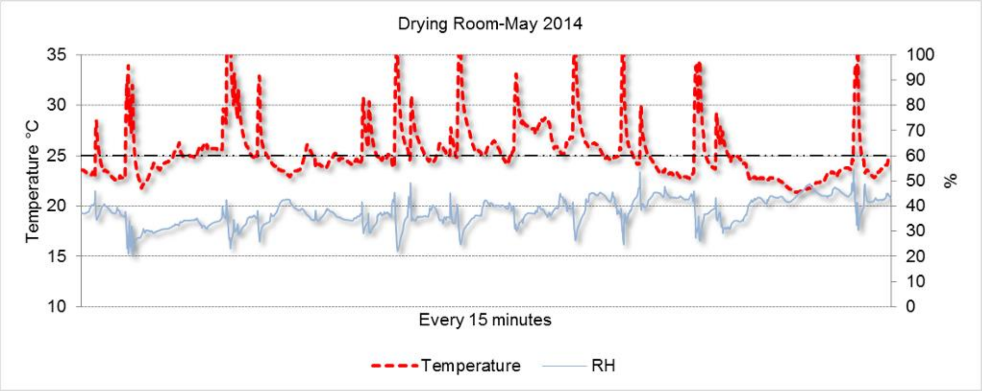
Measured temperature & RH (Master Bathroom - September 2014)



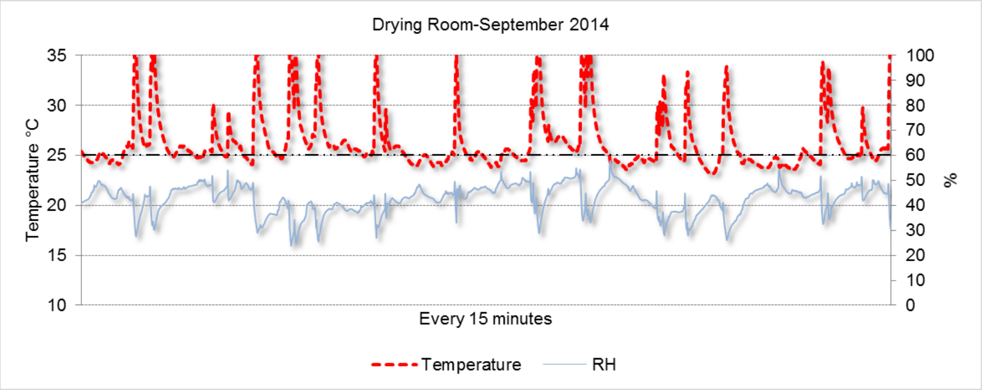
Measured temperature & RH (Bedroom 5 - May 2014)



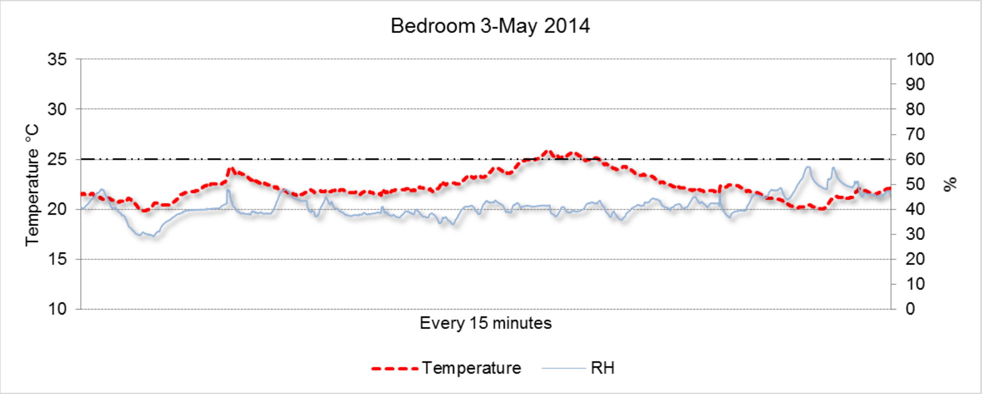
Measured temperature & RH (Bedroom 5 - September 2014)



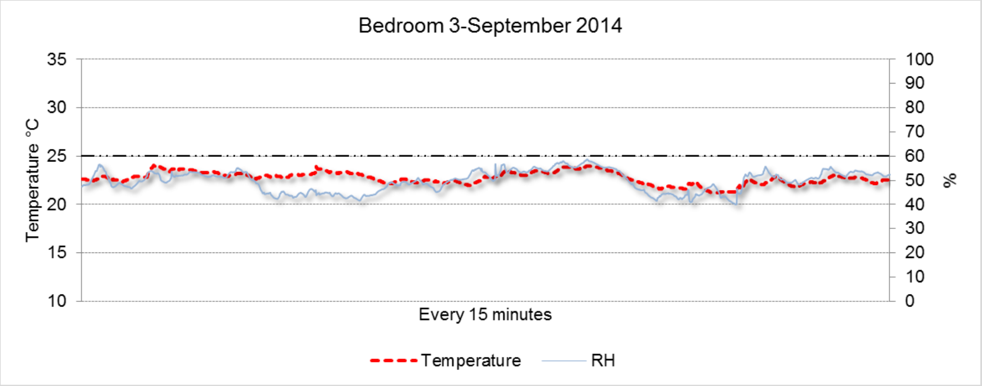
Measured temperature & RH (Drying room - May 2014)



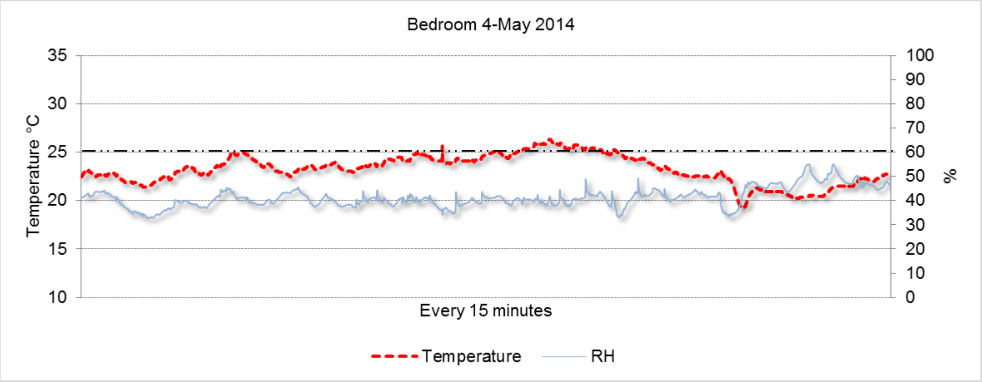
Measured temperature & RH (Drying room - September 2014)



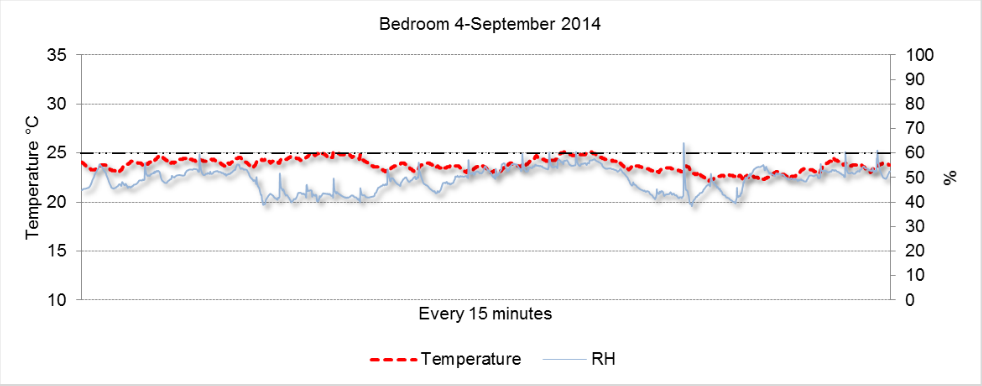
Measured temperature & RH (Bedroom 3 - May 2014)



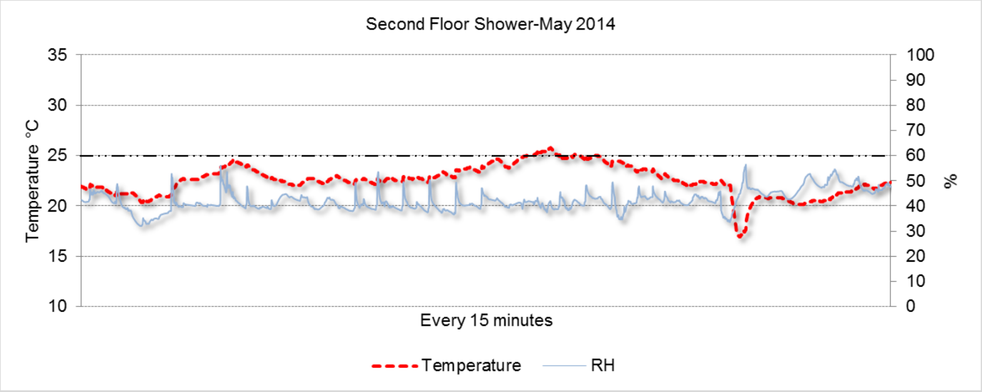
Measured temperature & RH (Bedroom 3 - September 2014)



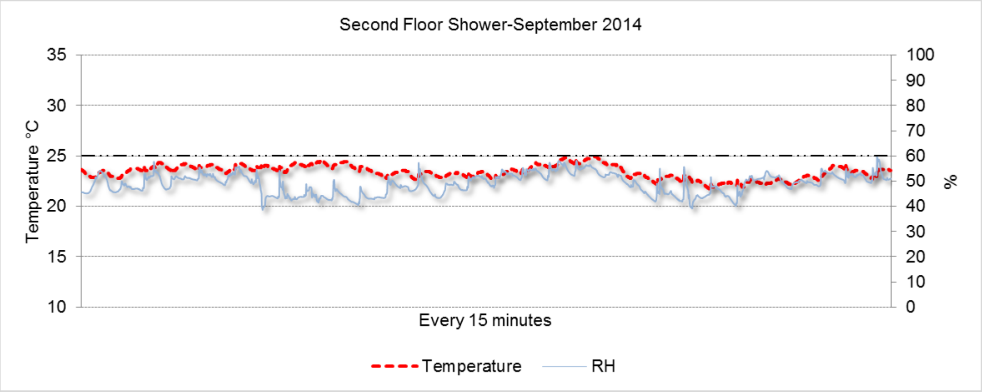
Measured temperature & RH (Bedroom 4 - May 2014)



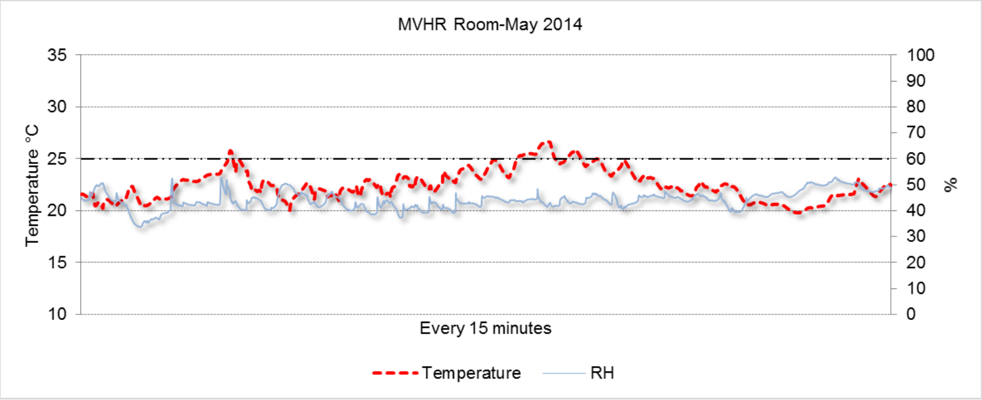
Measured temperature & RH (Bedroom 4 - September 2014)



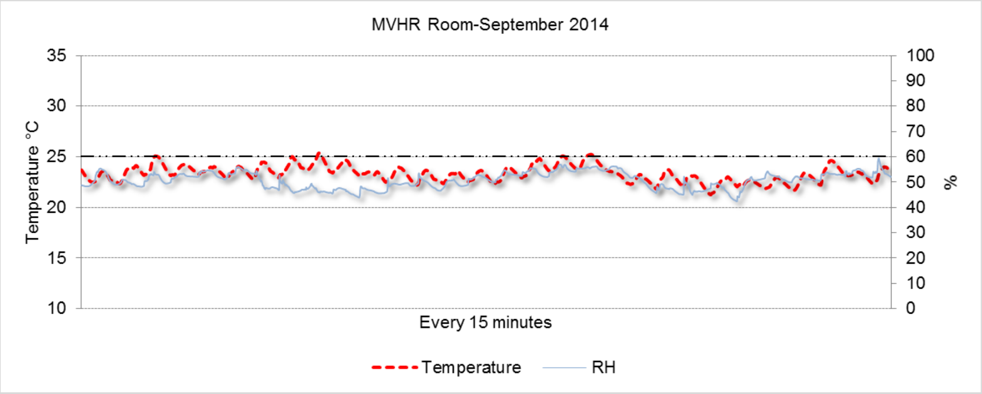
Measured temperature & RH (Second floor shower - May 2014)



Measured temperature & RH (Second floor shower - September 2014)

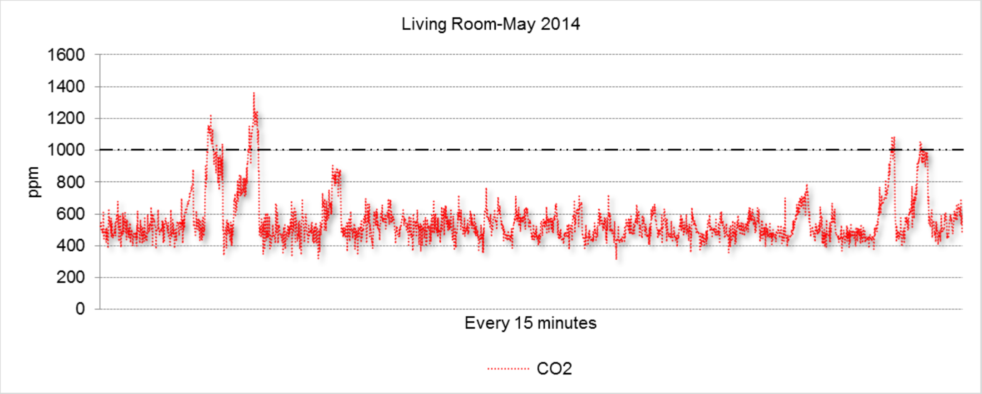


Measured temperature & RH (MVHR room - May 2014)

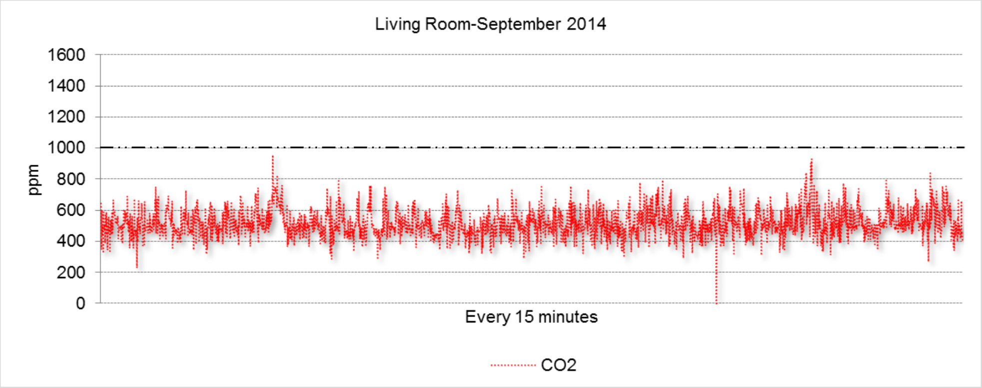


Measured temperature & RH (MVHR room - September 2014)

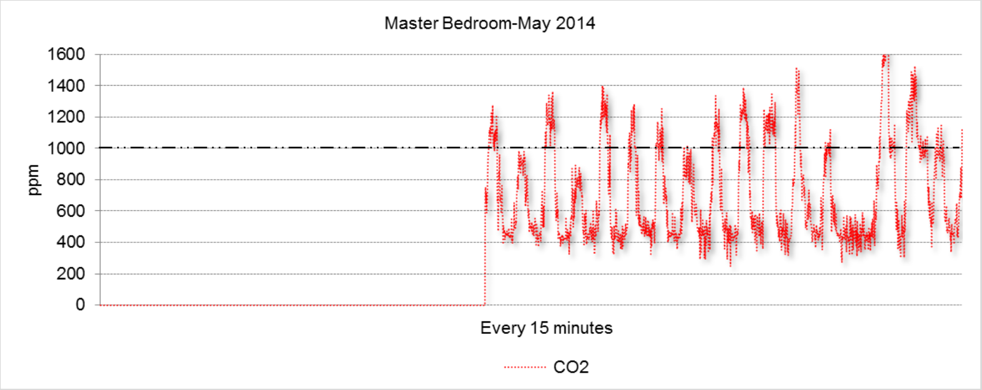
Indoor CO_2 for May and September – Building One:



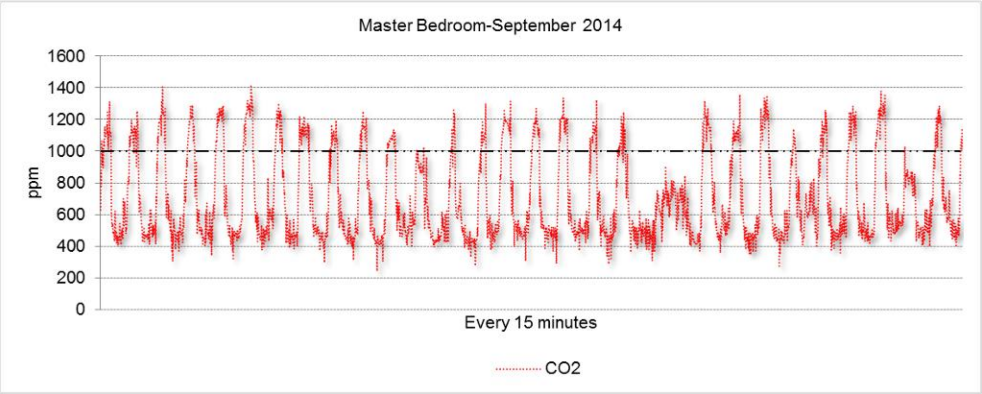
Measured indoor CO_2 level for Living room - May 2014



Measured indoor CO_2 level for Living room - September 2014



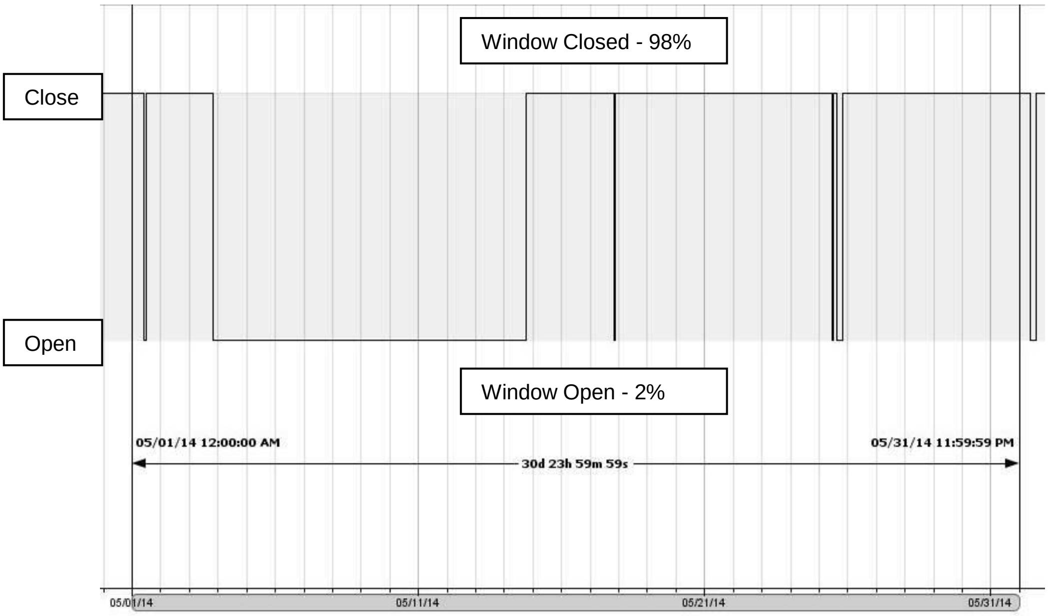
Measured indoor CO_2 level for Master Bedroom - May 2014



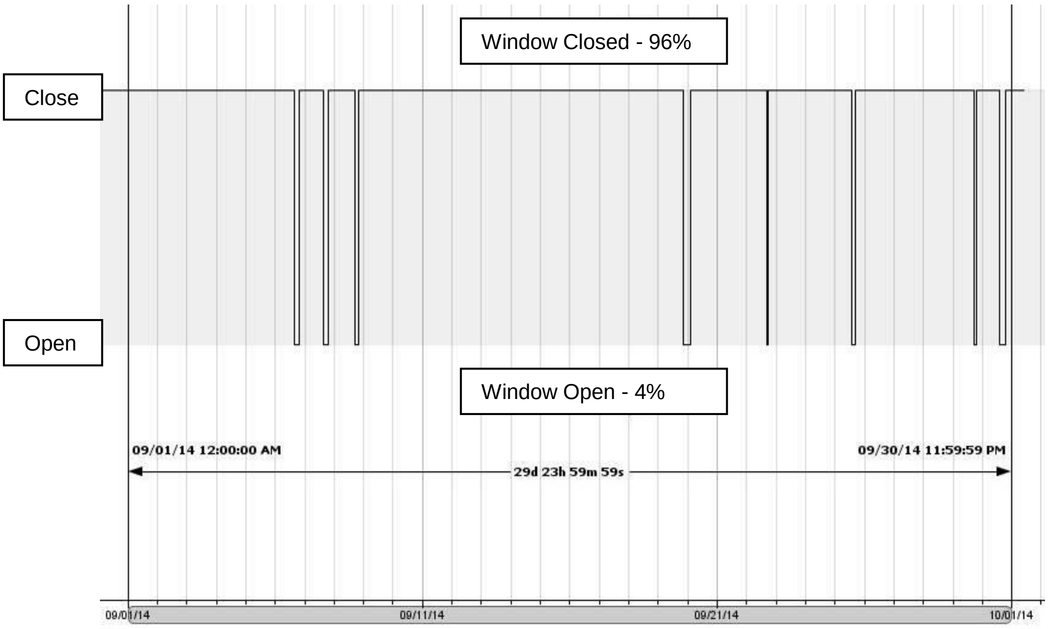
Measured indoor CO_2 level for Master Bedroom – September 2014

Window monitor data – Building One:

Dining room

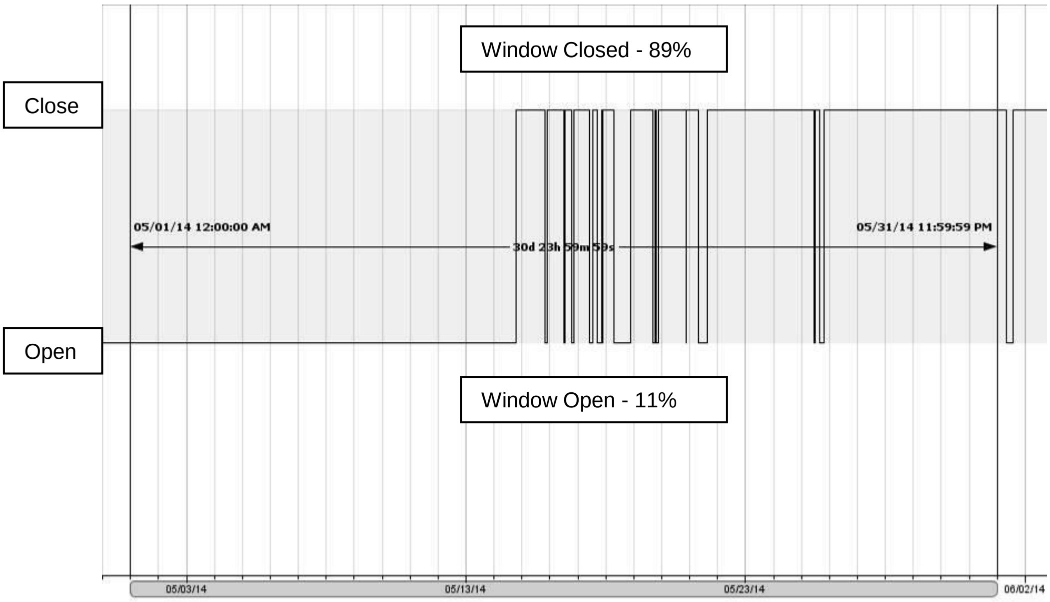


Monitored window operation - W1 - May 2014

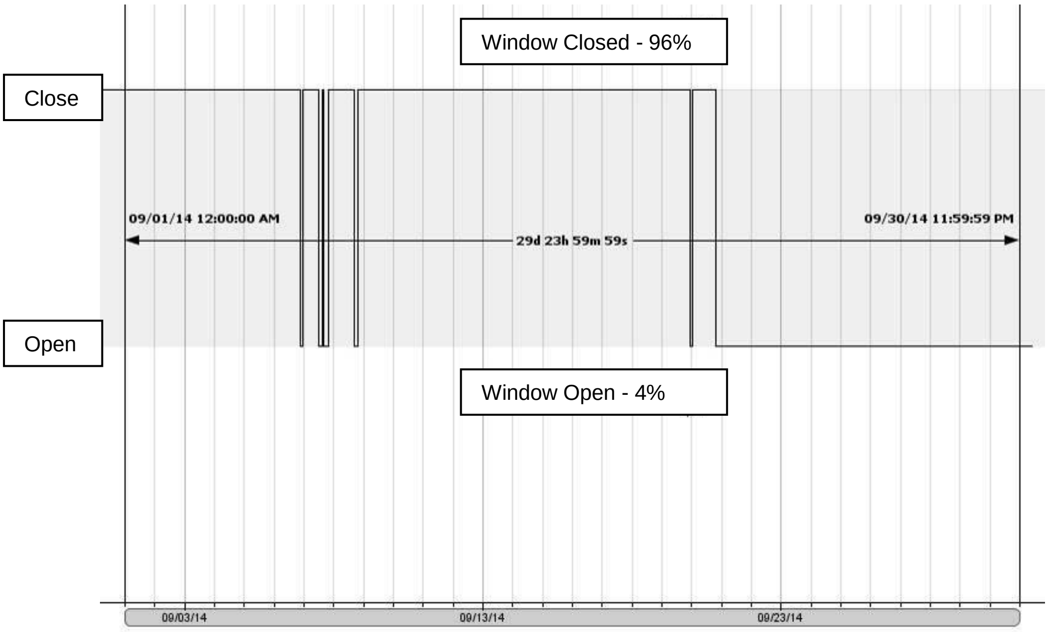


Monitored window operation - W1 - September 2014

Living room

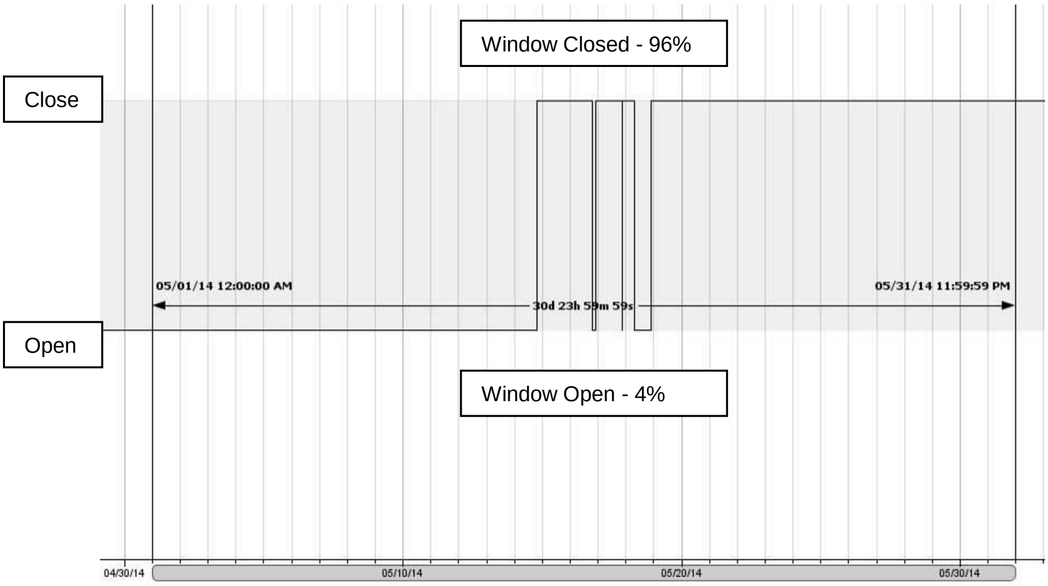


Monitored window operation – W2 - May 2014

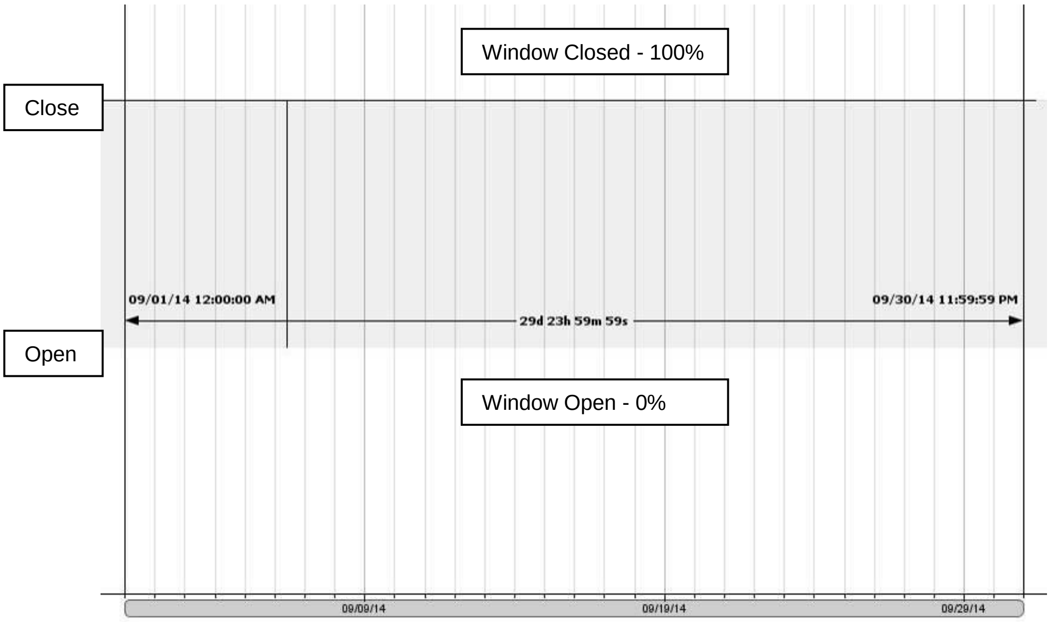


Monitored window operation – W2 - September 2014

Kitchen

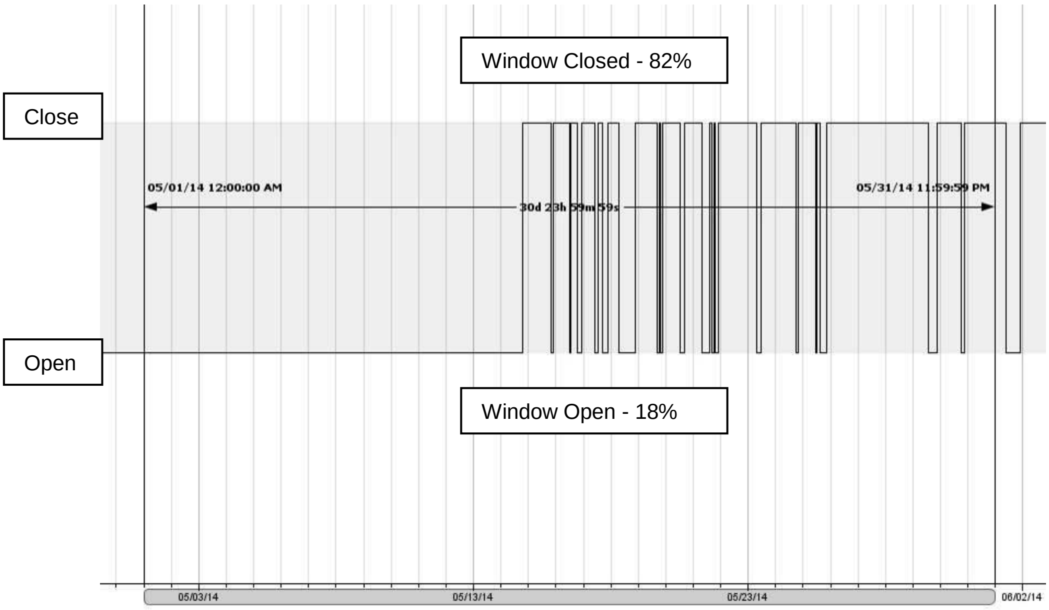


Monitored window operation – W8 - May 2014

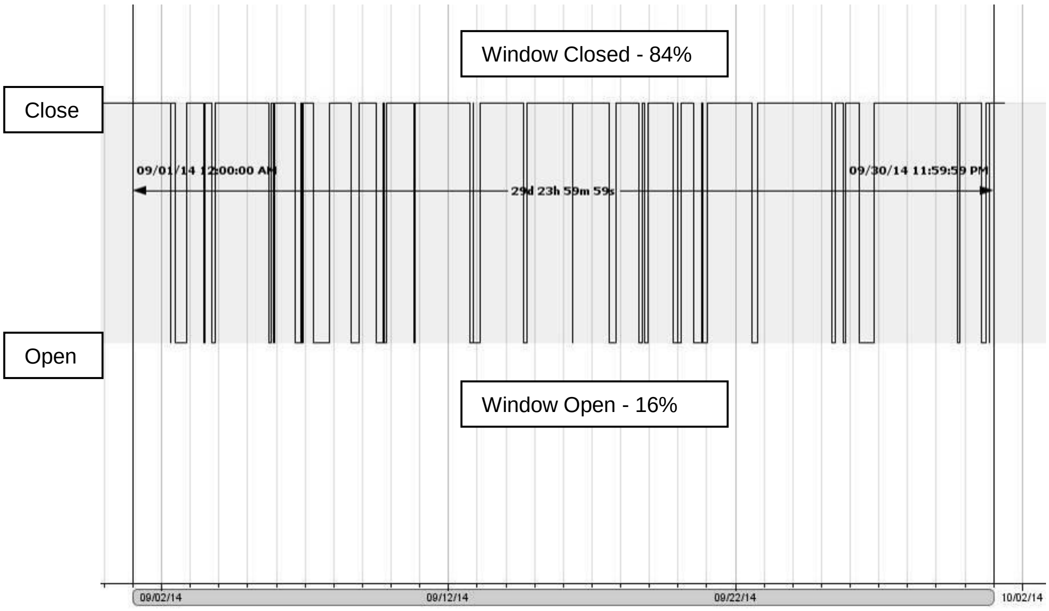


Monitored window operation – W8 - September 2014

Living room/ office area

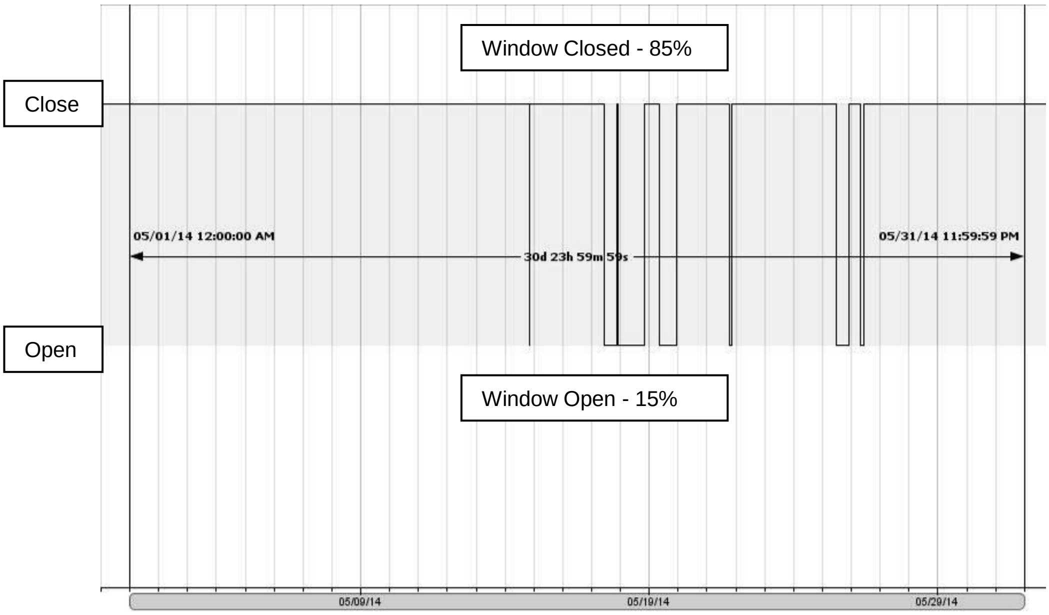


Monitored window operation – W5 - May 2014

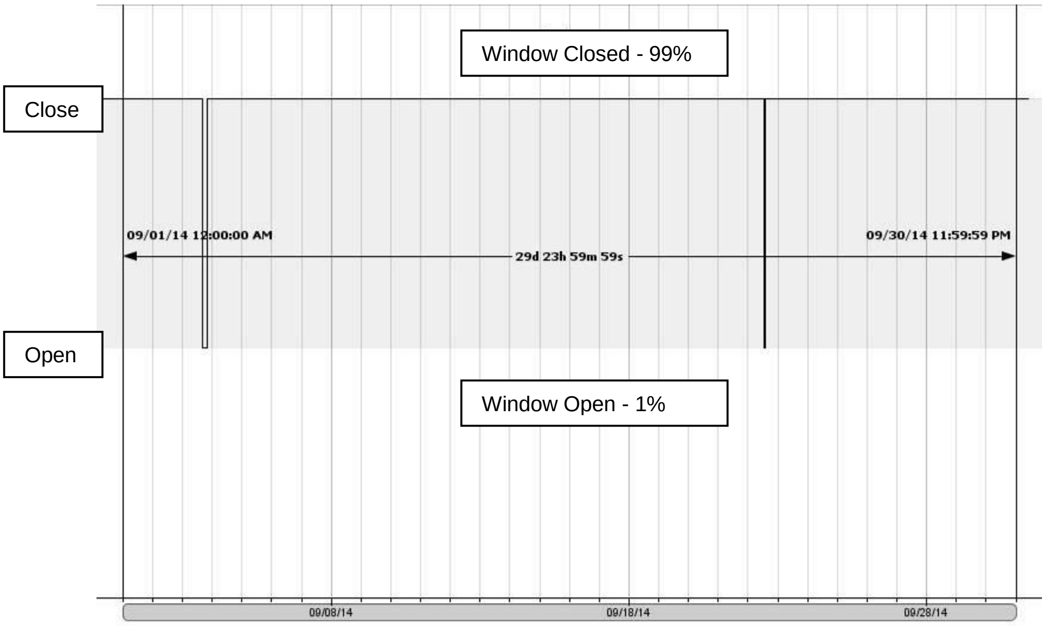


Monitored window operation – W5 - September 2014

Master bedroom

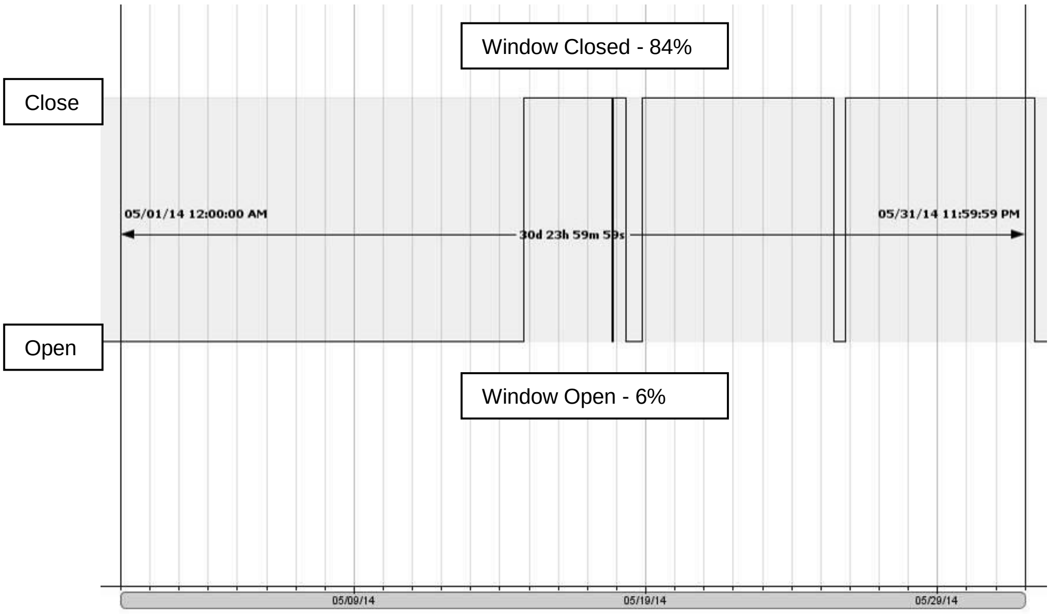


Monitored window operation – W10 - May 2014

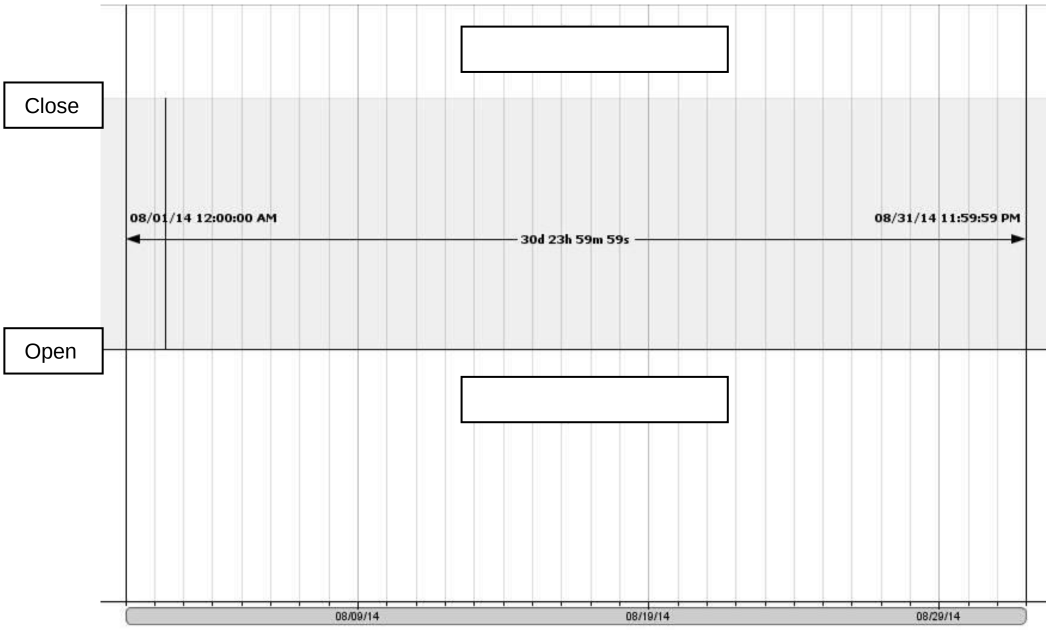


Monitored window operation - W10 - September 2014

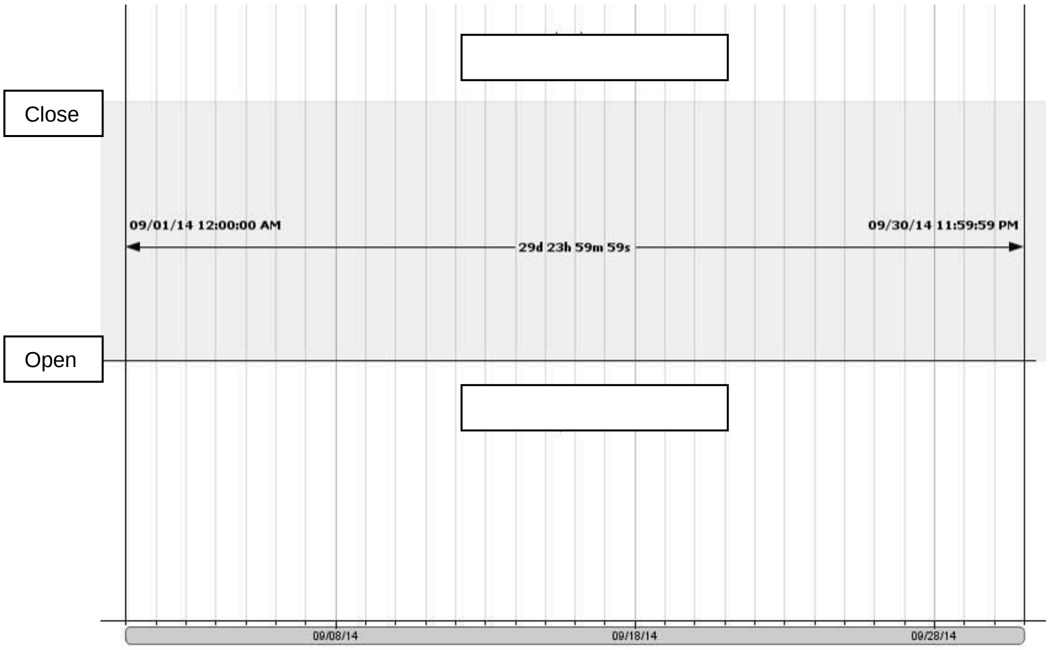
Bedroom 5



Monitored window operation - W12 - May 2014

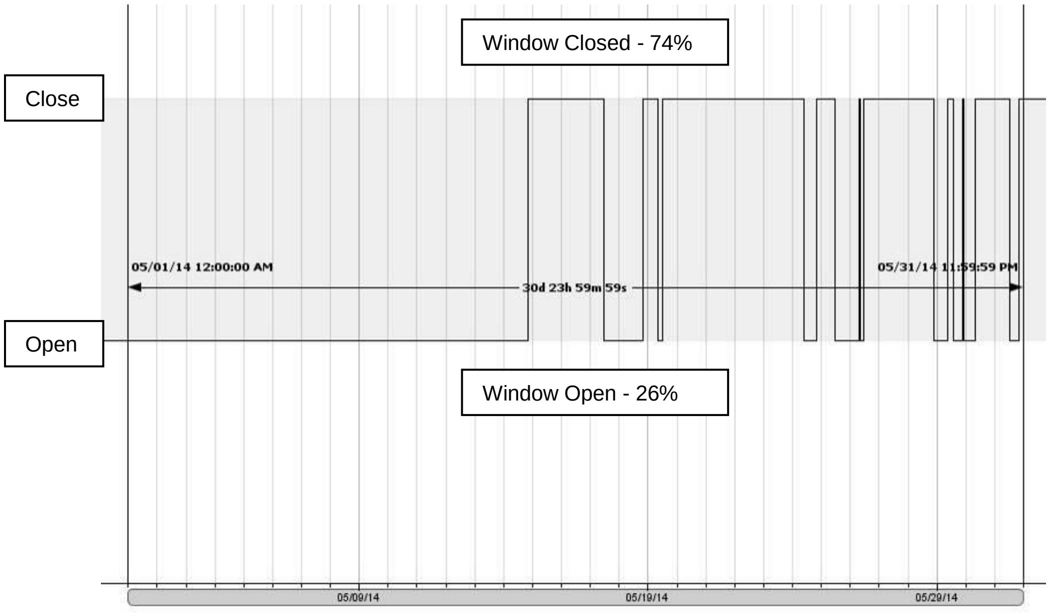


Monitored window operation - W12 - August 2014

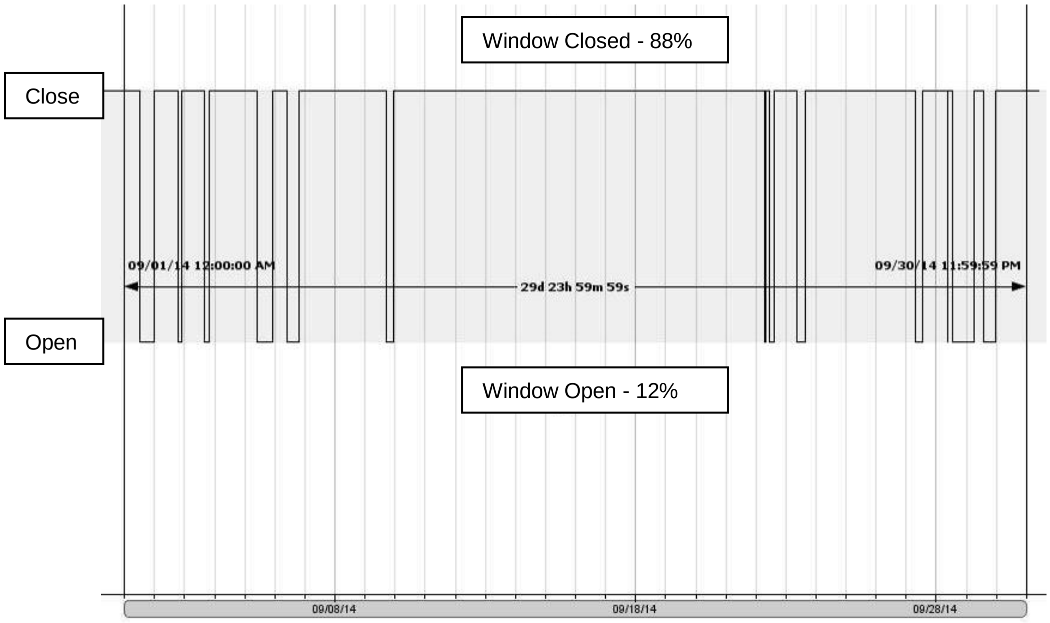


Monitored window operation - W12 - September 2014

Master bathroom

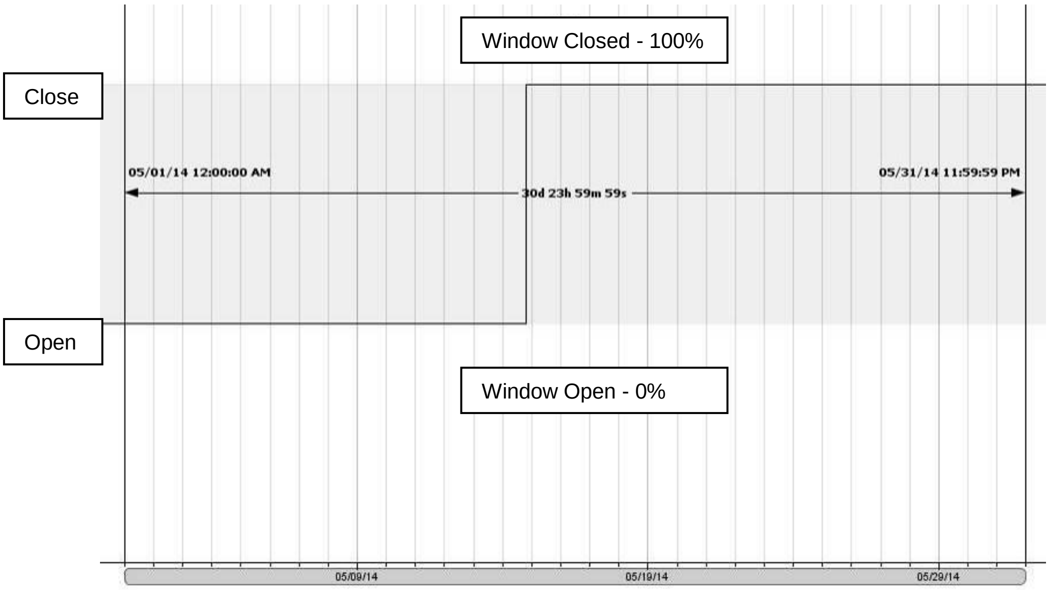


Monitored window operation - W18 - May 2014

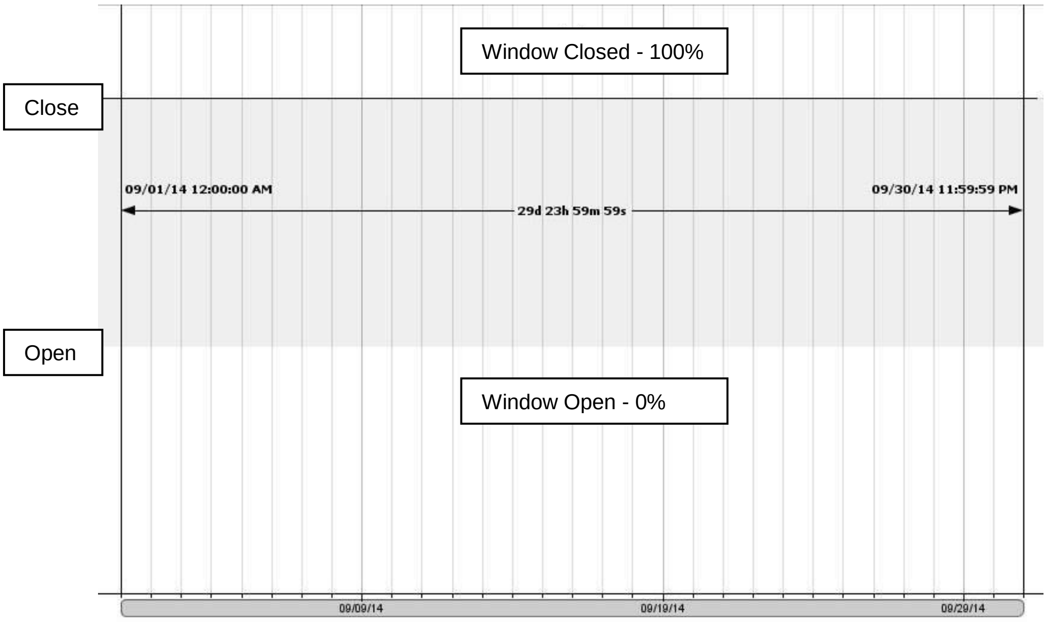


Monitored window operation - W18 - September 2014

Bedroom 3

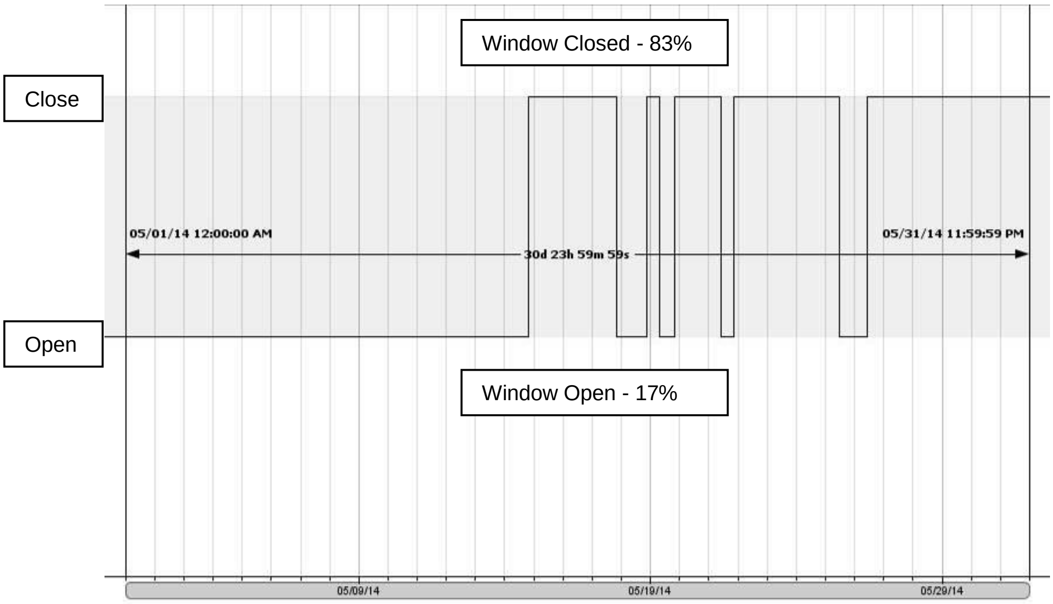


Monitored window operation - W24 - May 2014

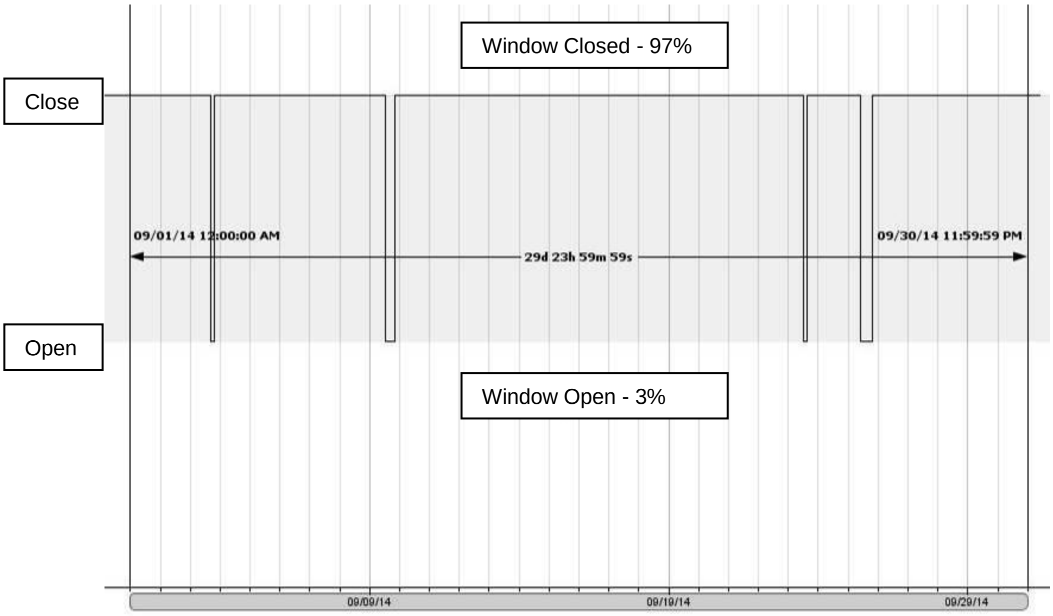


Monitored window operation - W24 - September 2014

Bedroom 4



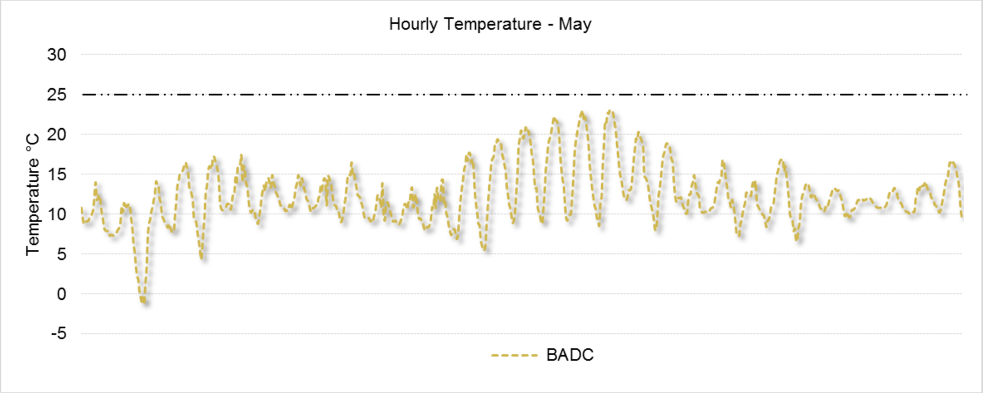
Monitored window operation - W21 - May 2014



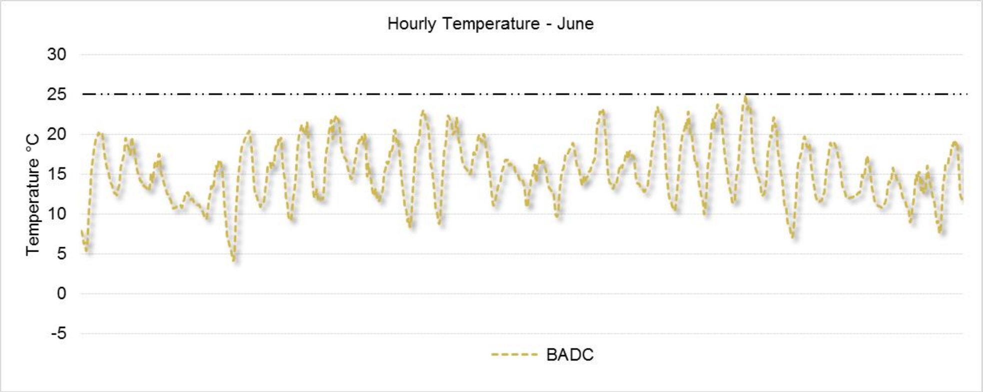
Monitored window operation - W21 - September 2014

APPENDIX D

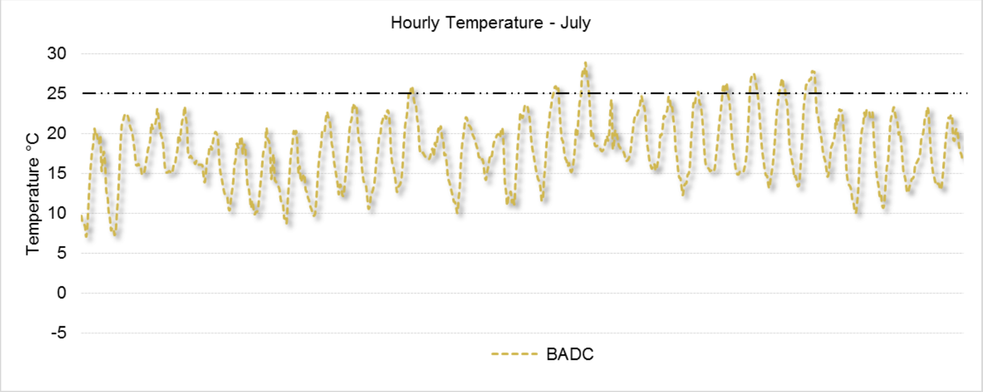
Ambient temperatures – Building Two:



Ambient temperature May 2014 (BADC)

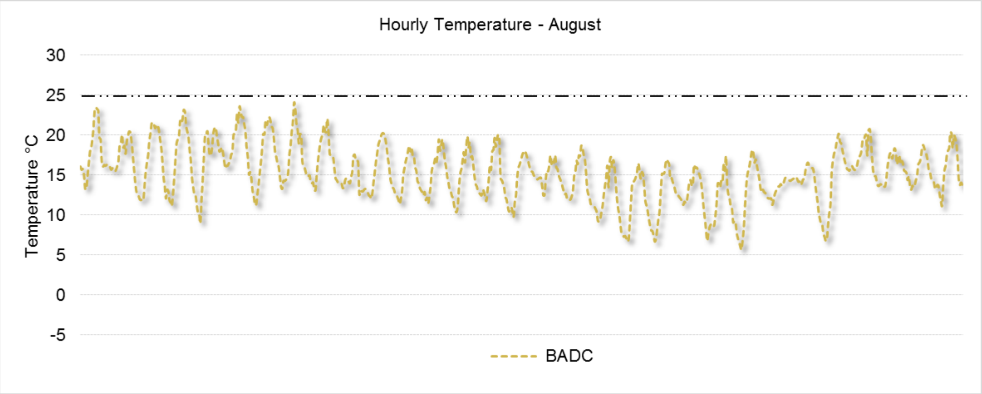


Ambient temperature June 2014 (BADC)

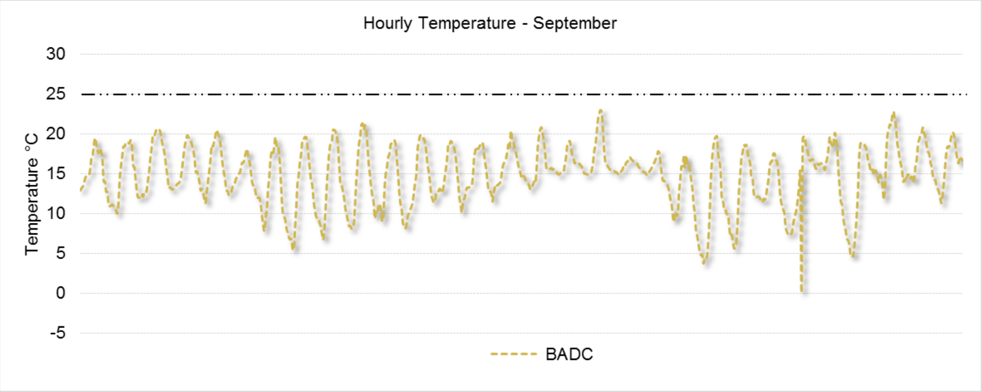


Ambient temperature July 2014 (BADC)

Ambient temperature September 2014 (BADC)

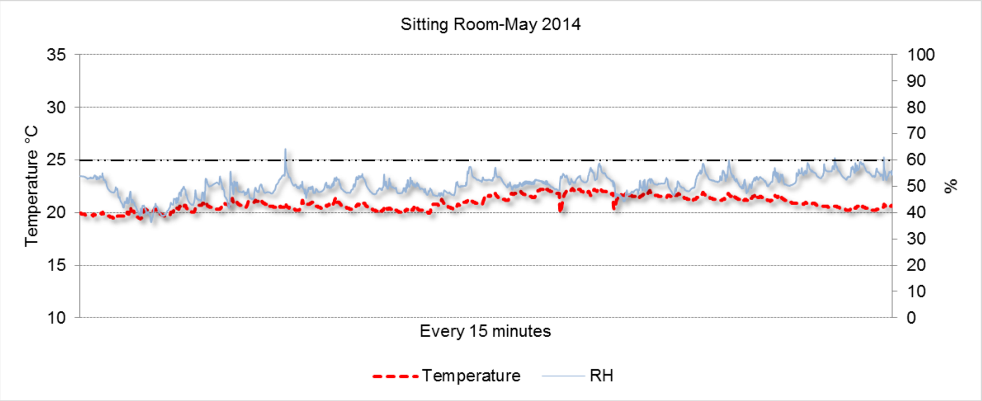


Ambient temperature August 2014 (BADC)

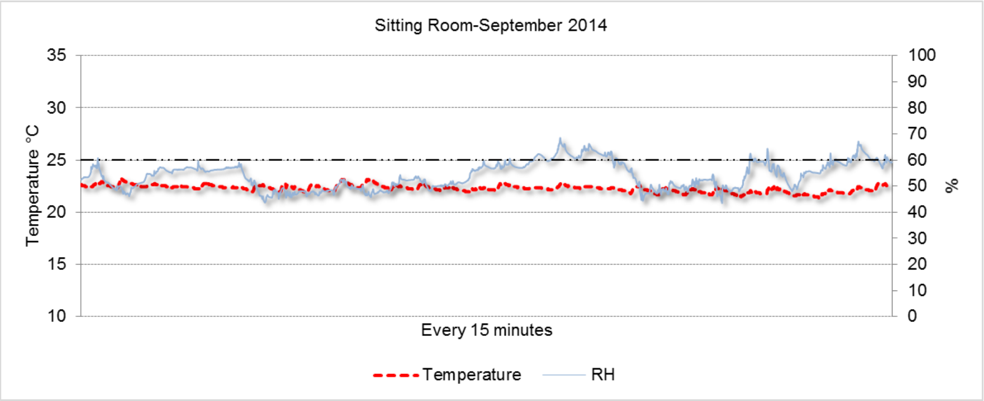


Ambient temperature September 2014 (BADC)

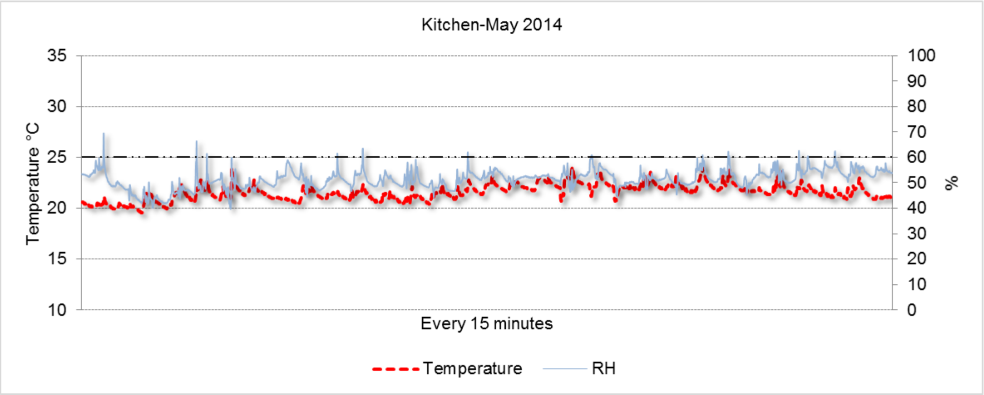
Indoor temperatures for May and September – Building Two:



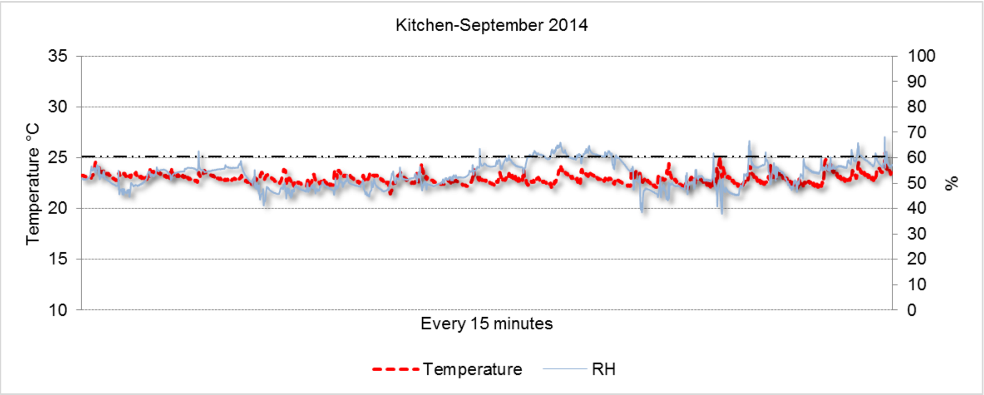
Measured temperature & RH (Sitting room - May 2014)



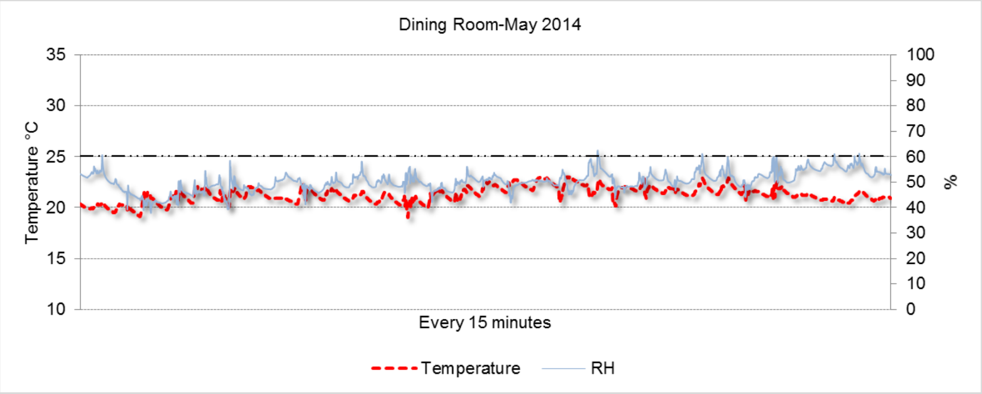
Measured temperature & RH (Sitting room - September 2014)



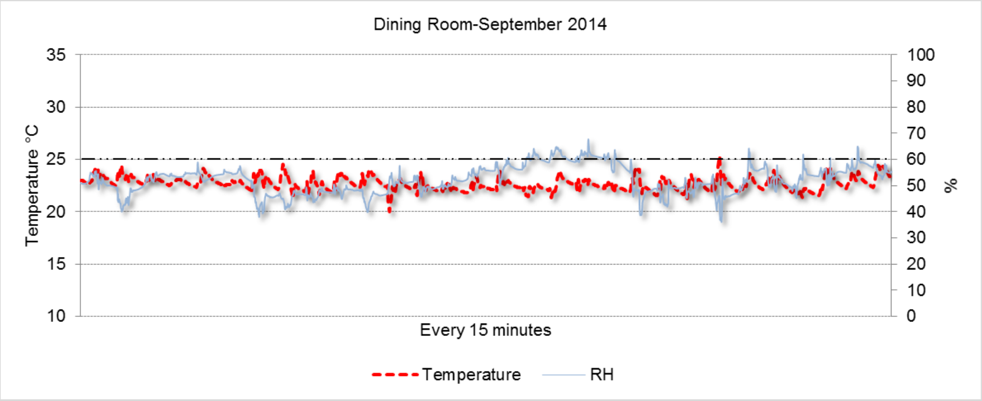
Measured temperature & RH (Kitchen - May 2014)



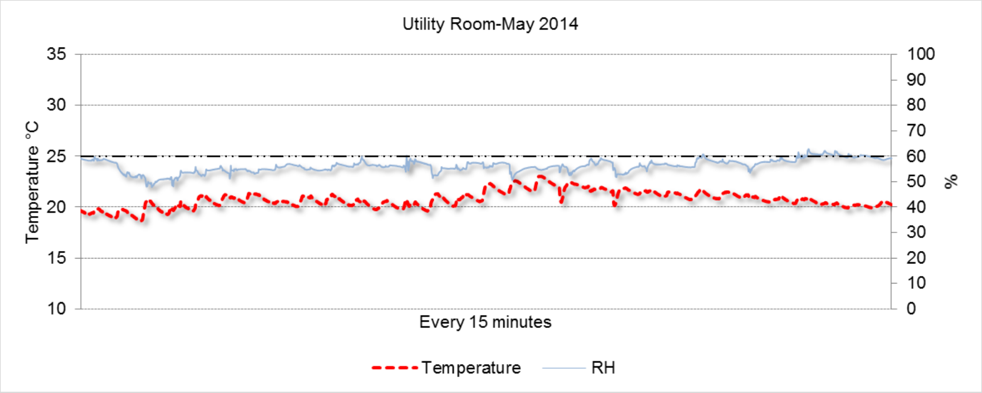
Measured temperature & RH (Kitchen - September 2014)



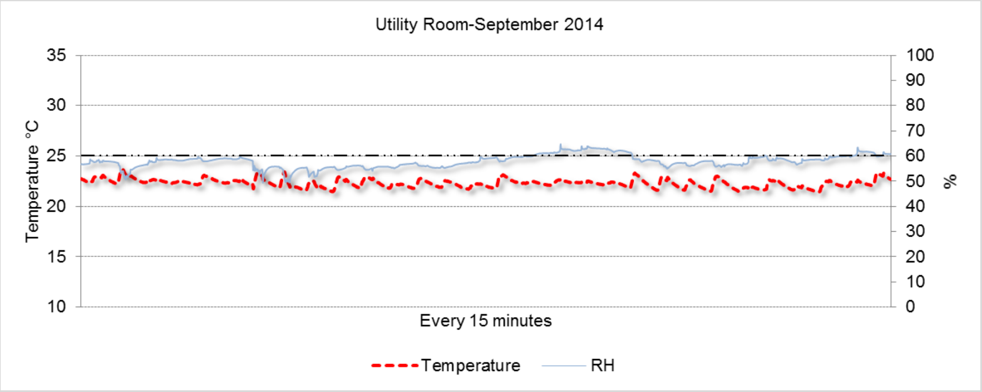
Measured temperature & RH (Dining room - May 2014)



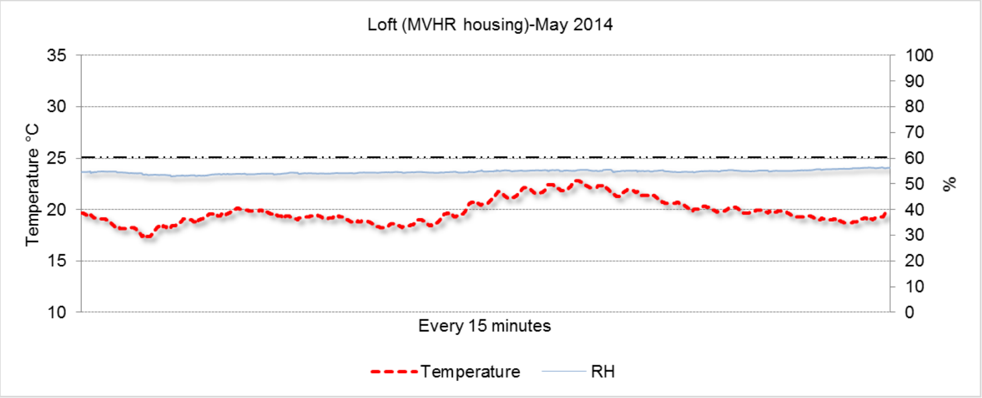
Measured temperature & RH (Dining room - September 2014)



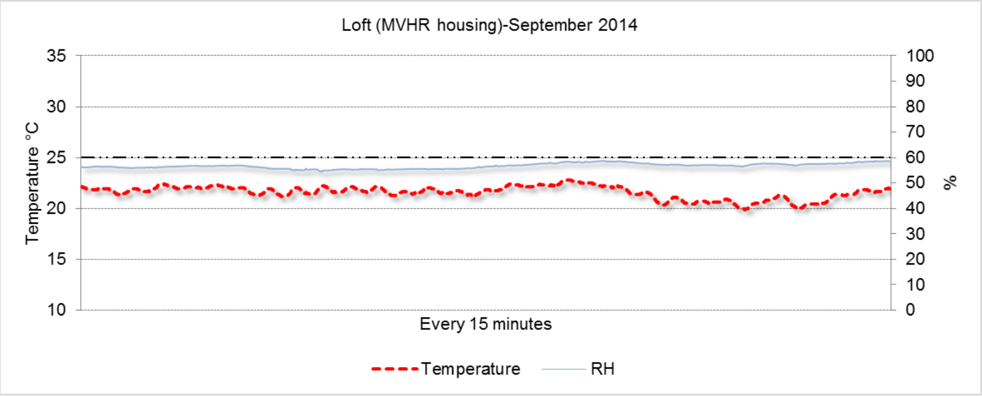
Measured temperature & RH (Utility room - May 2014)



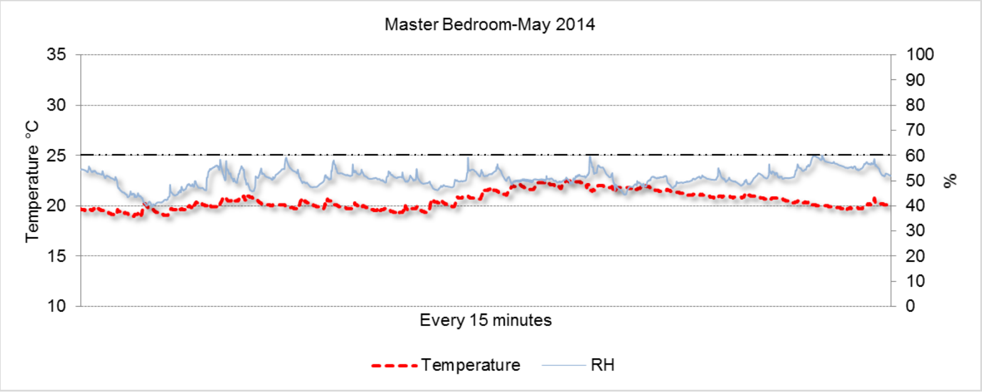
Measured temperature & RH (Utility room - September 2014)



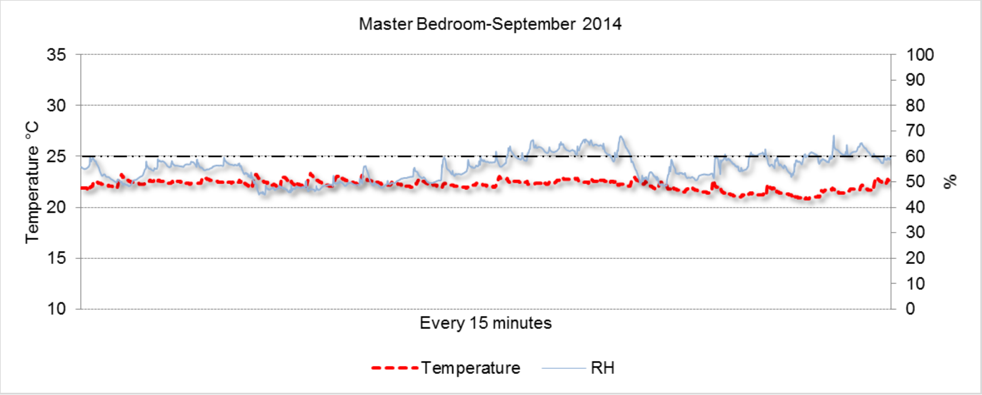
Measured temperature & RH (Loft - May 2014)



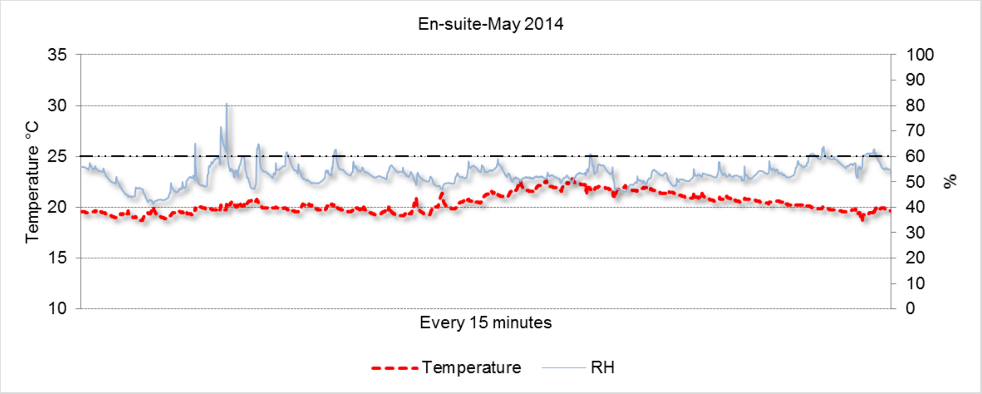
Measured temperature & RH (Loft - September 2014)



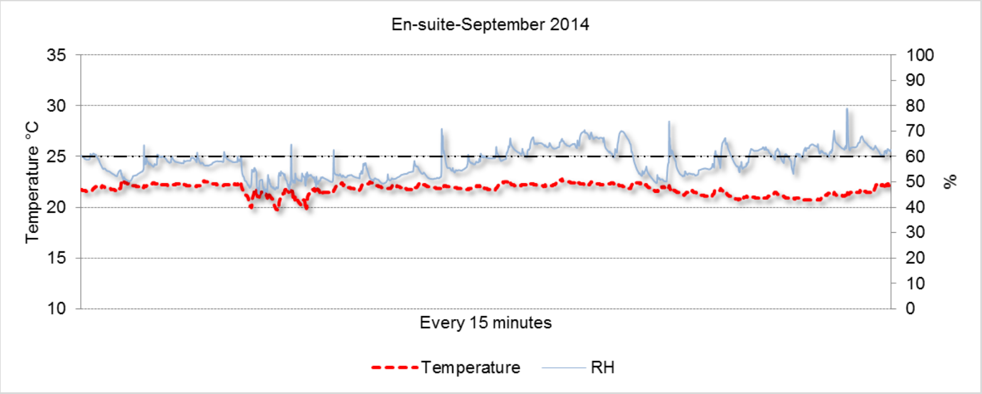
Measured temperature & RH (Master bedroom - May 2014)



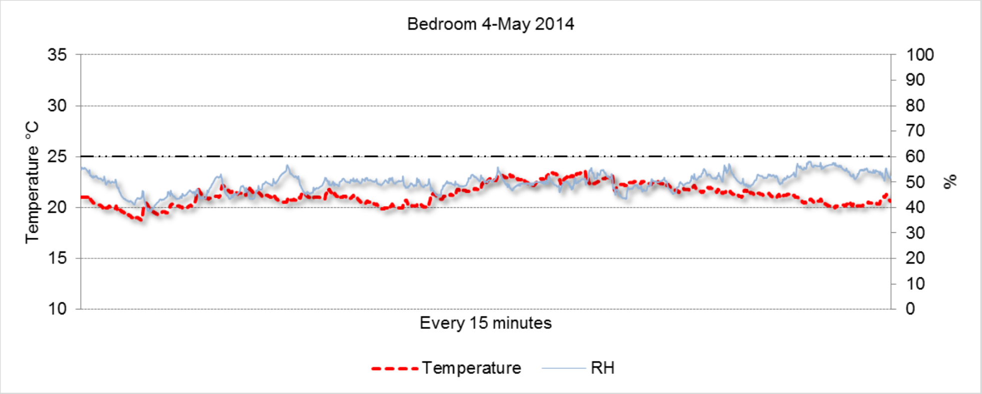
Measured temperature & RH (Master bedroom - September 2014)



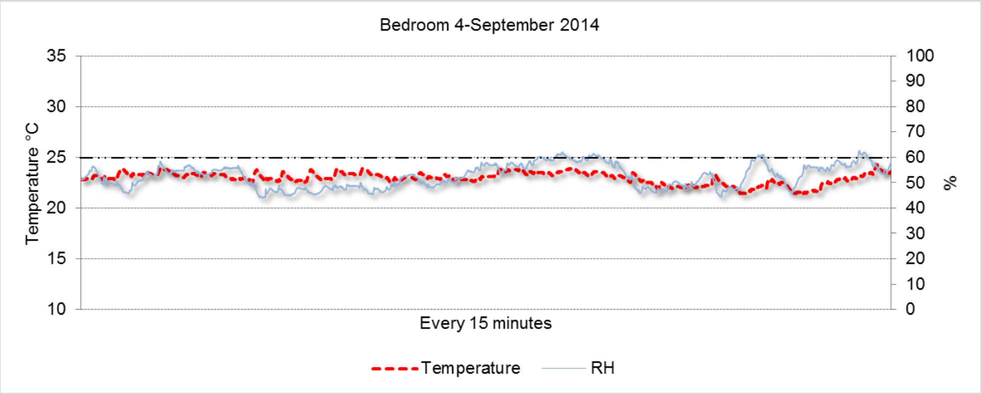
Measured temperature & RH (Master En-suite - May 2014)



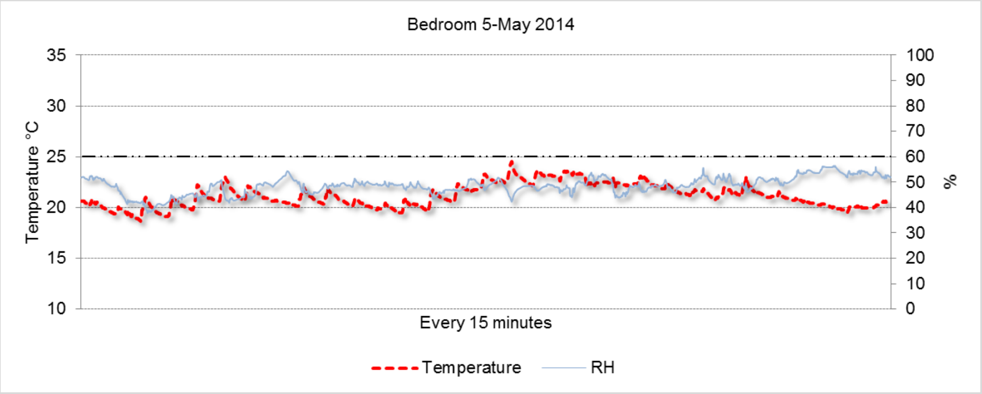
Measured temperature & RH (Master En-suite - September 2014)



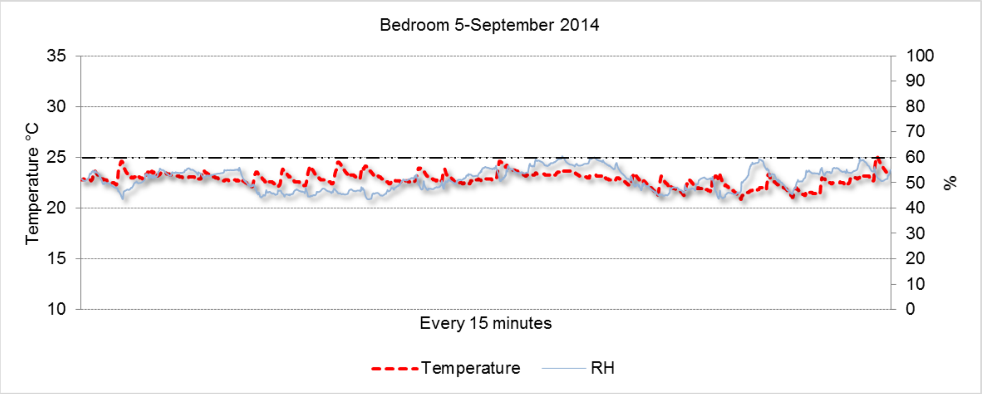
Measured temperature & RH (Bedroom 4 - May 2014)



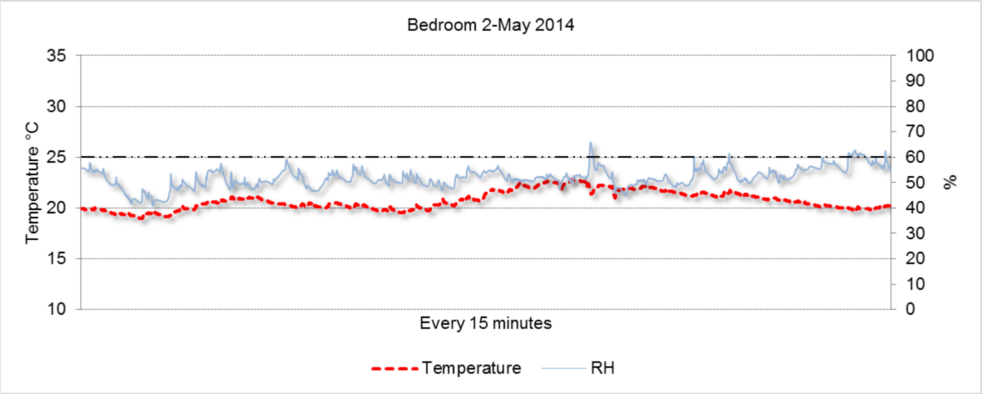
Measured temperature & RH (Bedroom 4 - September 2014)



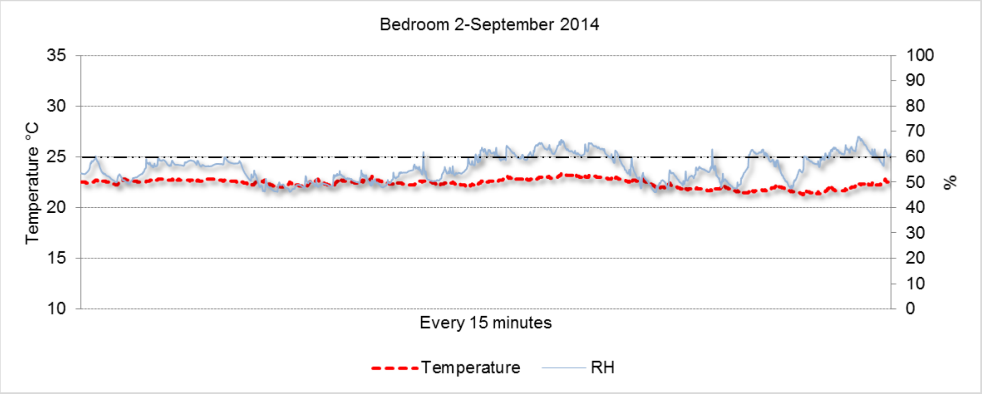
Measured temperature & RH (Bedroom 5 - May 2014)



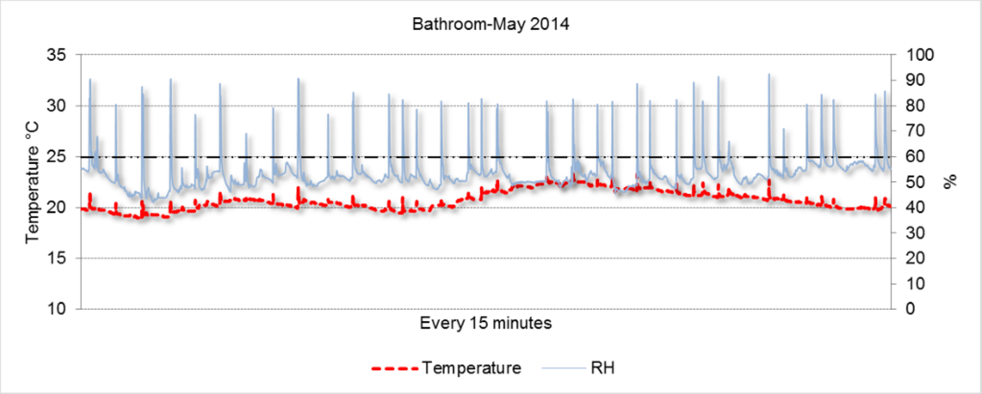
Measured temperature & RH (Bedroom 5 - September 2014)



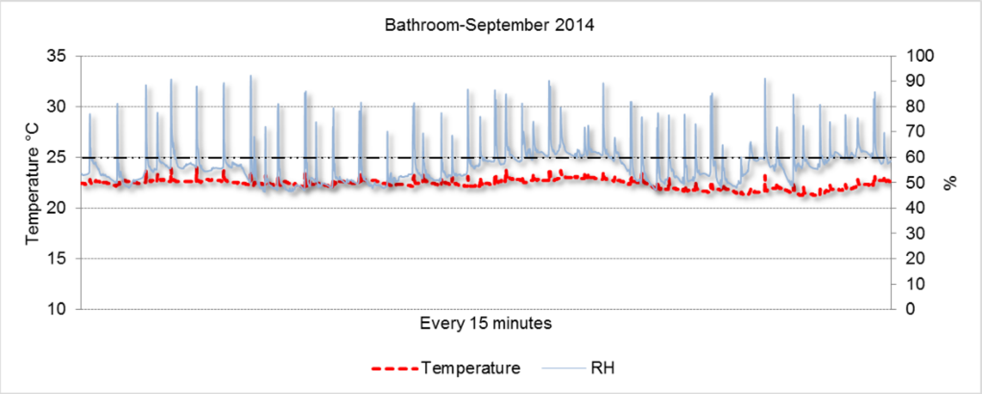
Measured temperature & RH (Bedroom 2 - May 2014)



Measured temperature & RH (Bedroom 2 - September 2014)

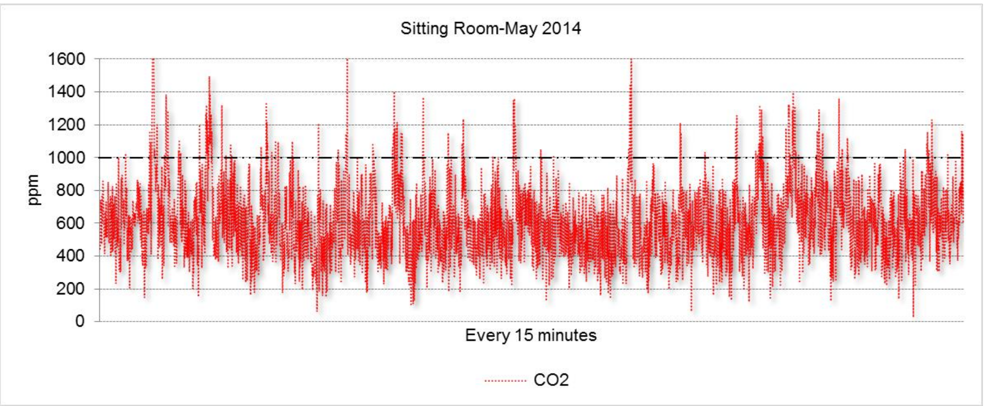


Measured temperature & RH (Bathroom - May 2014)

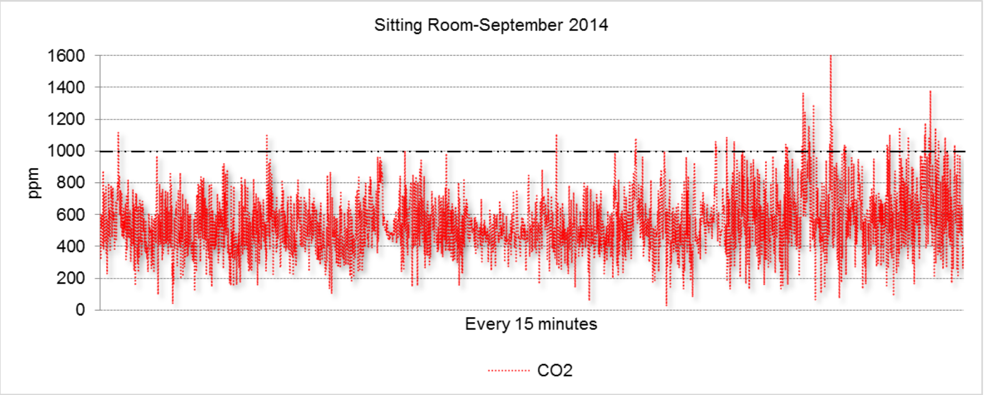


Measured temperature & RH (Bathroom - September 2014)

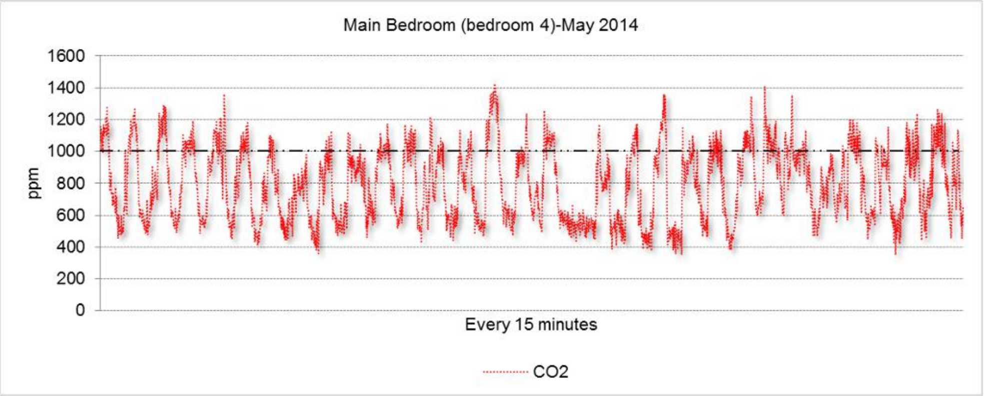
Indoor CO_2 for May and September – Building One:



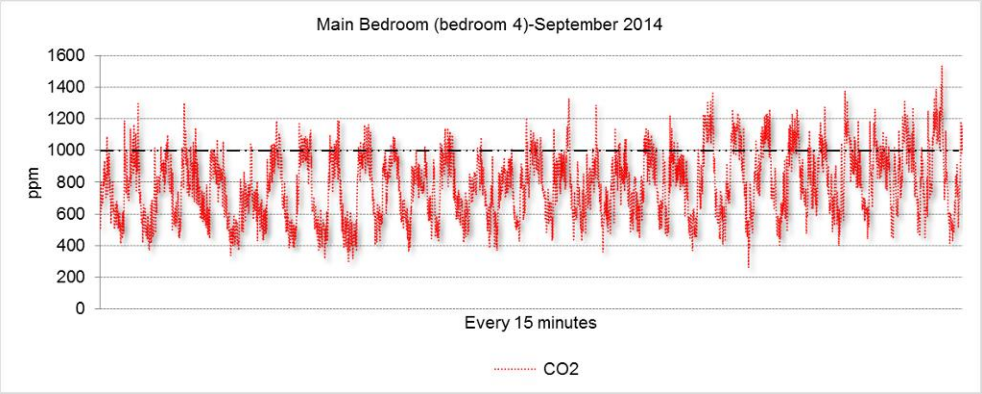
Measured CO_2 level for Sitting room - May 2014



Measured CO_2 level for Sitting room - September 2014



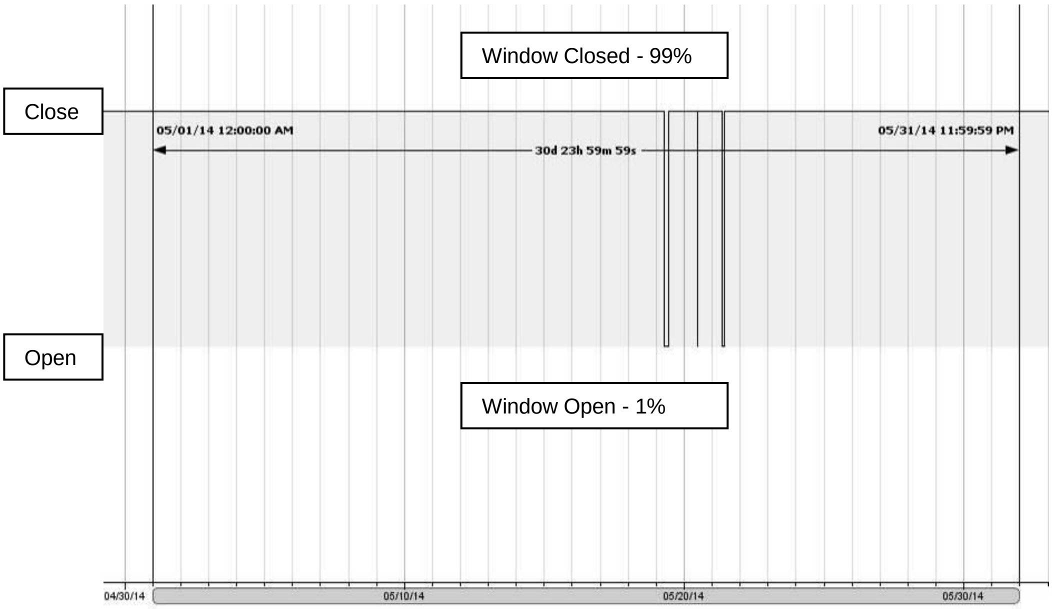
Measured CO_2 level for bedroom 4 - May 2014



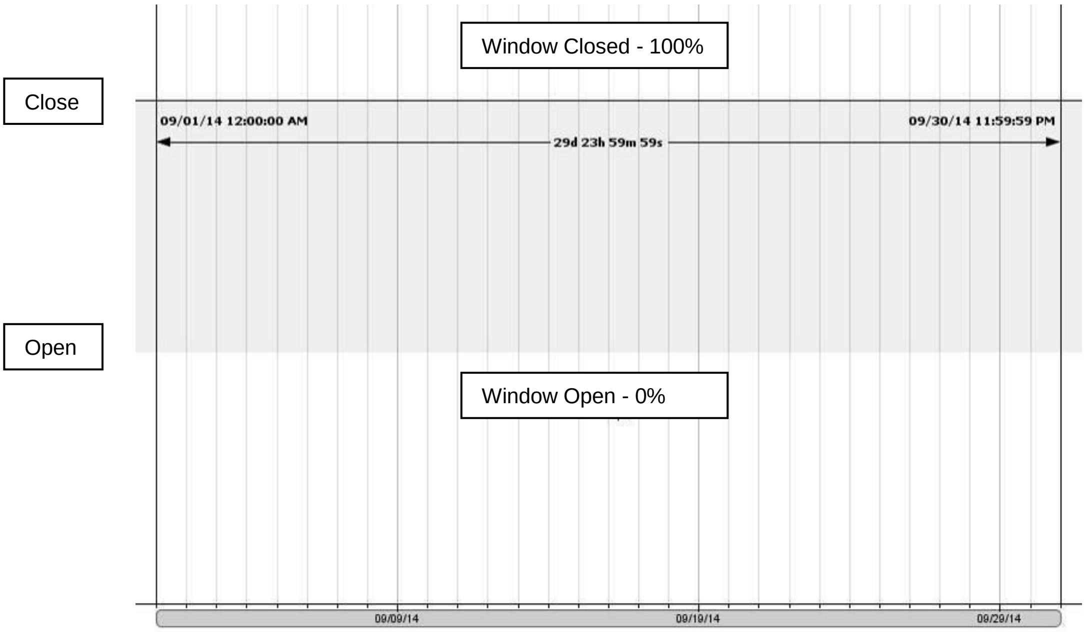
Measured CO_2 level for bedroom 4 - September 2014

Window monitor data – Building Two:

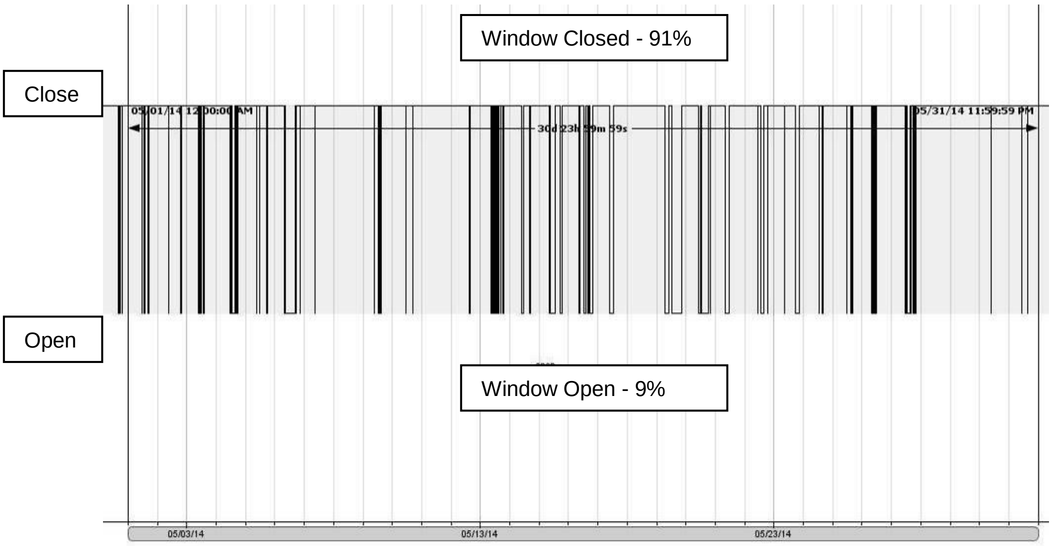
Sitting room



Monitored window operation - W2 - May 2014

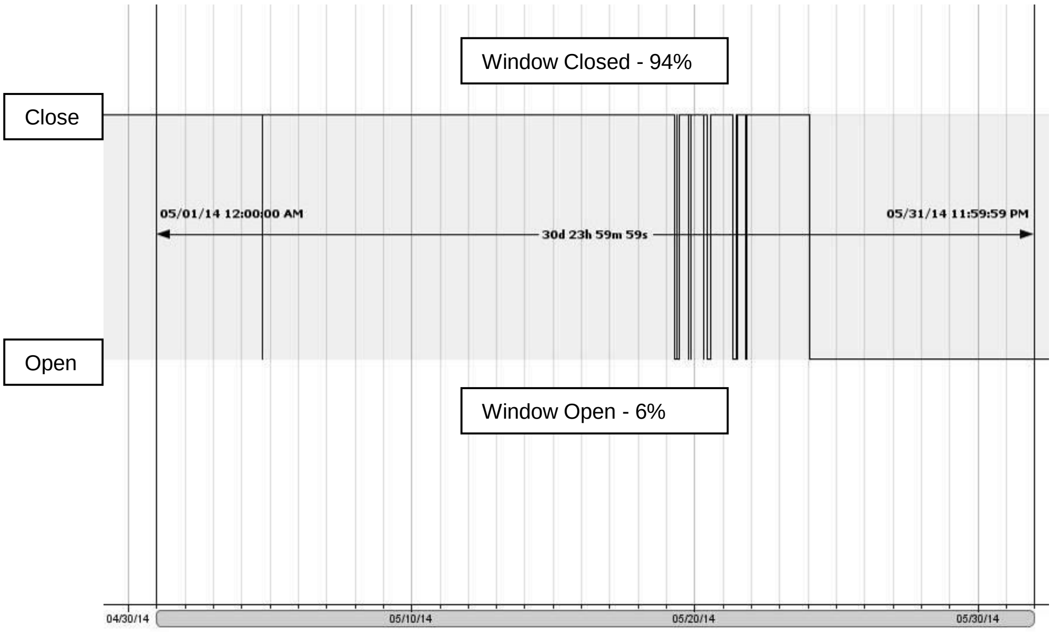


Monitored window operation - W2 - September 2014

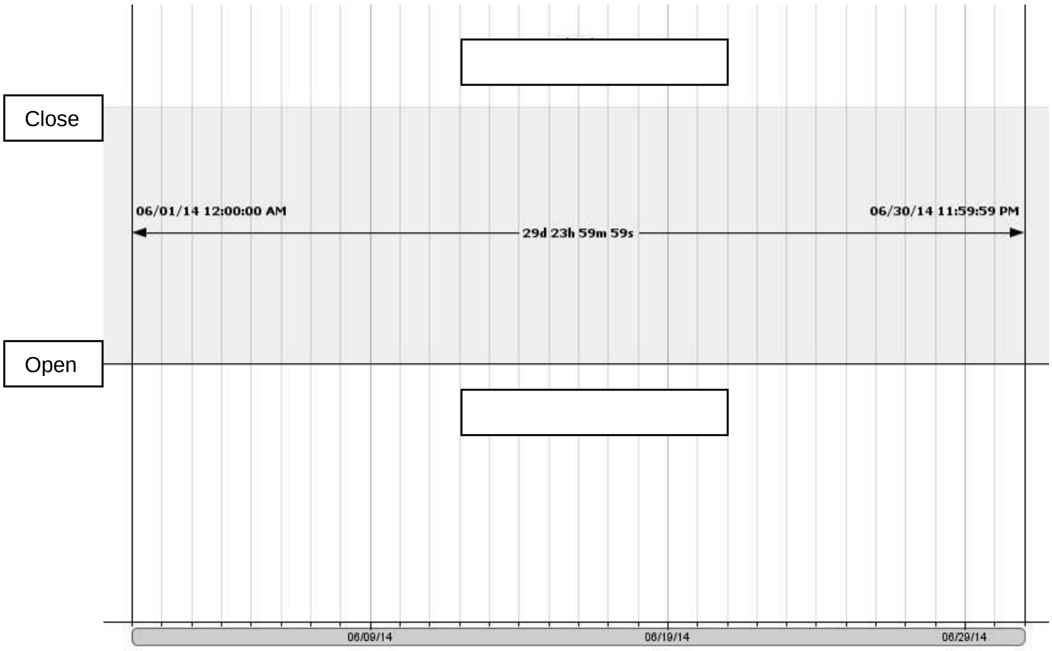


Monitored window operation – D7 - May 2014

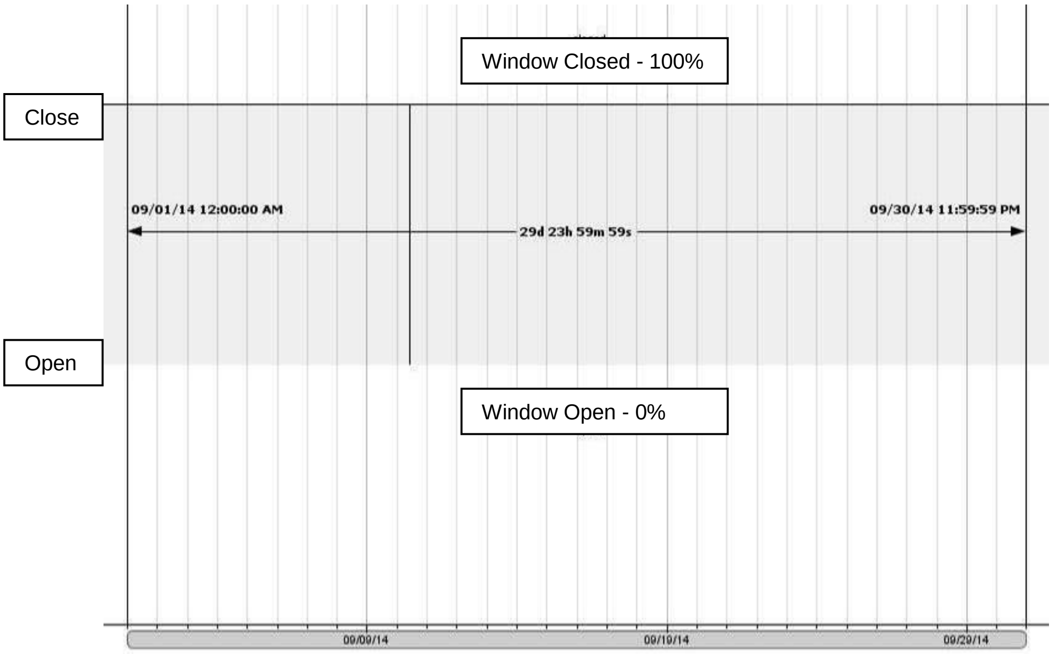
Dining room



Monitored window operation – D4 - May 2014

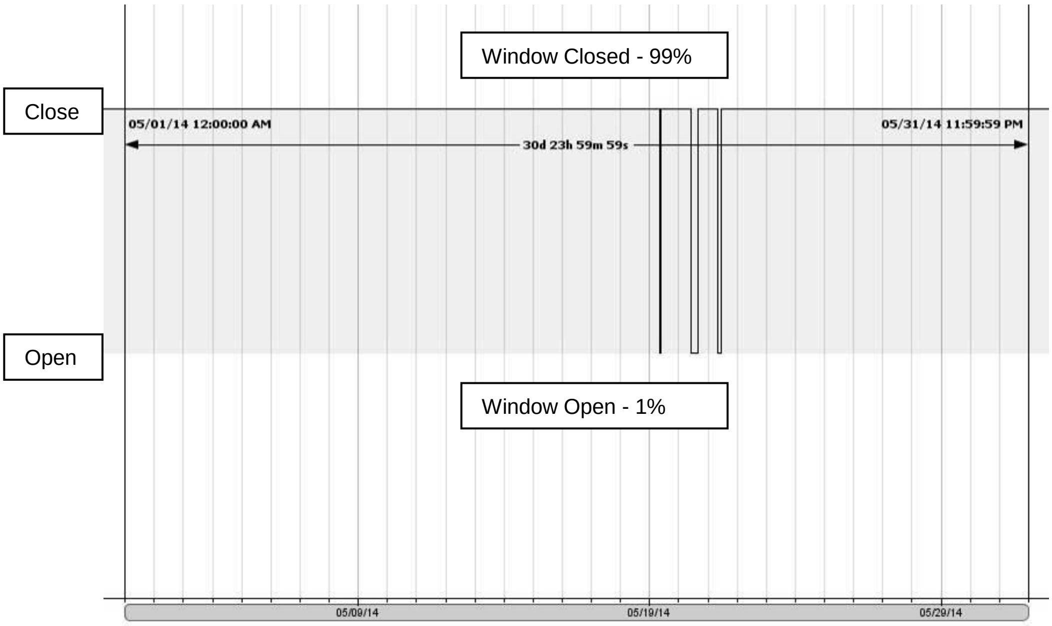


Monitored window operation – D4 - June 2014

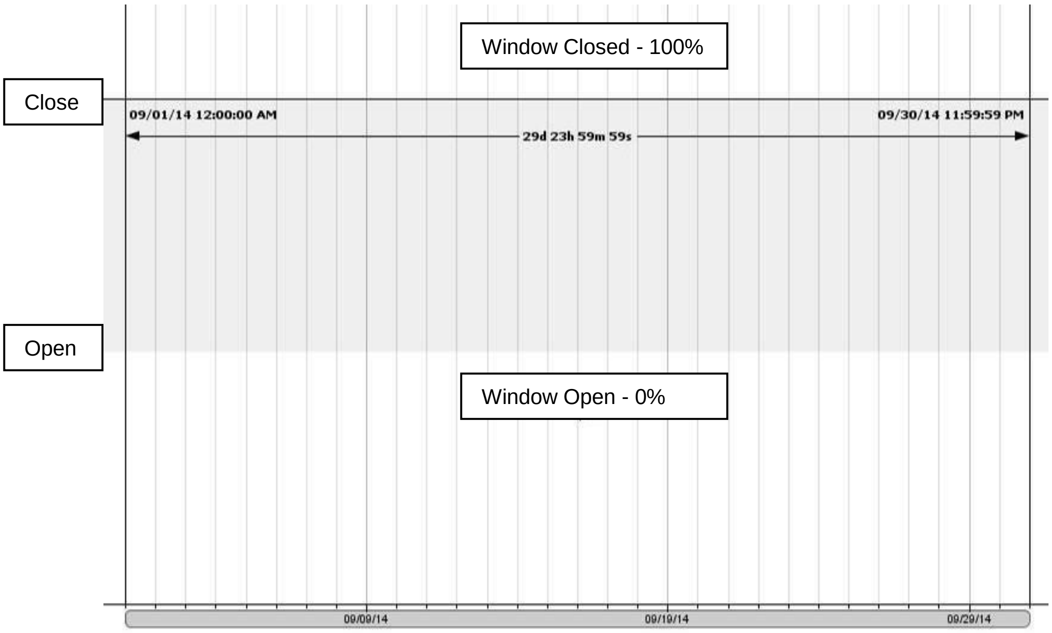


Monitored window operation – D4 - September 2014

Bedroom 1

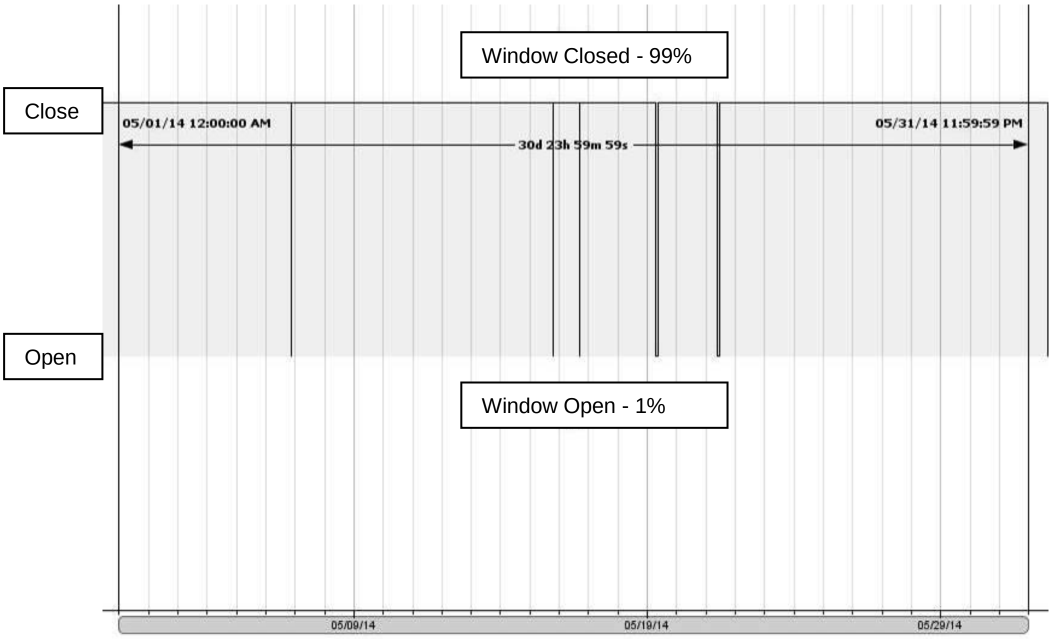


Monitored window operation – W13 - May 2014

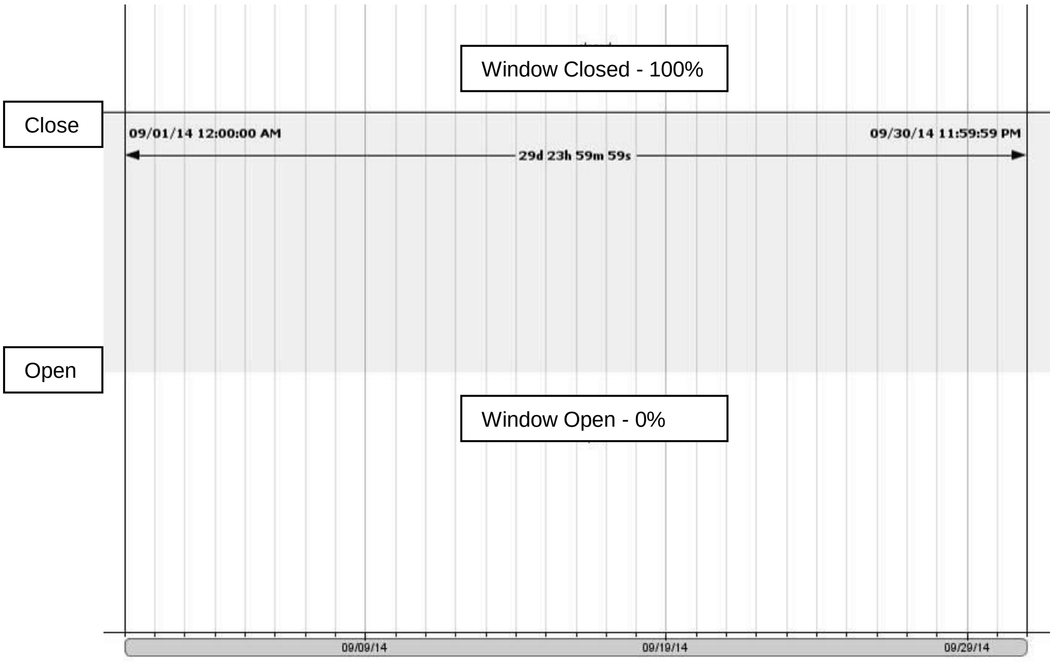


Monitored window operation – W13 - September 2014

Bathroom

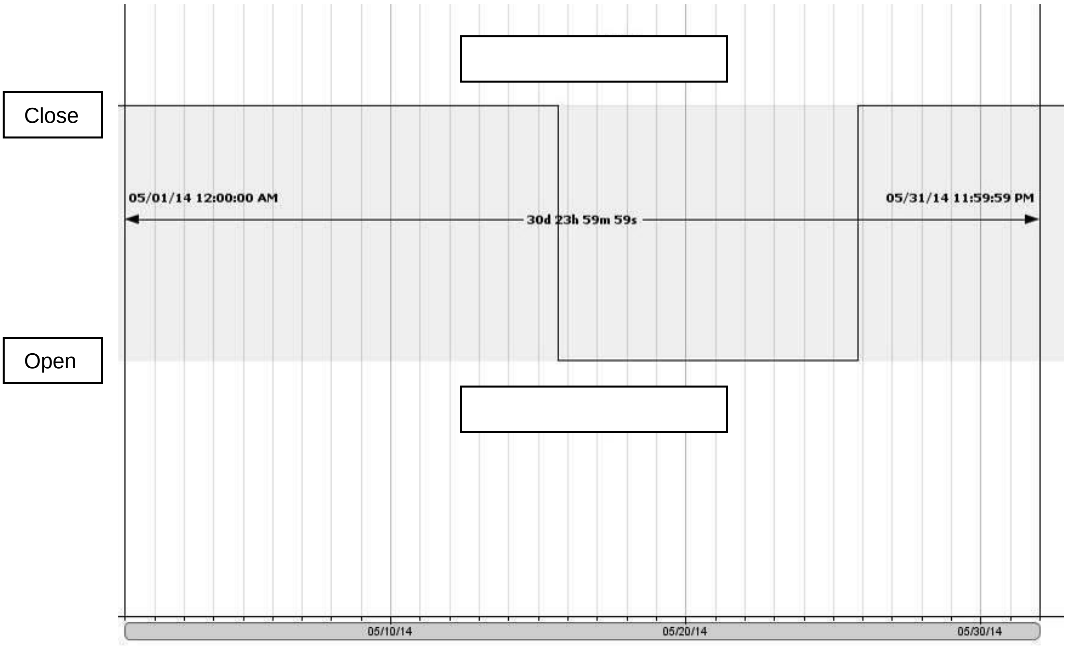


Monitored window operation – W17 - May 2014

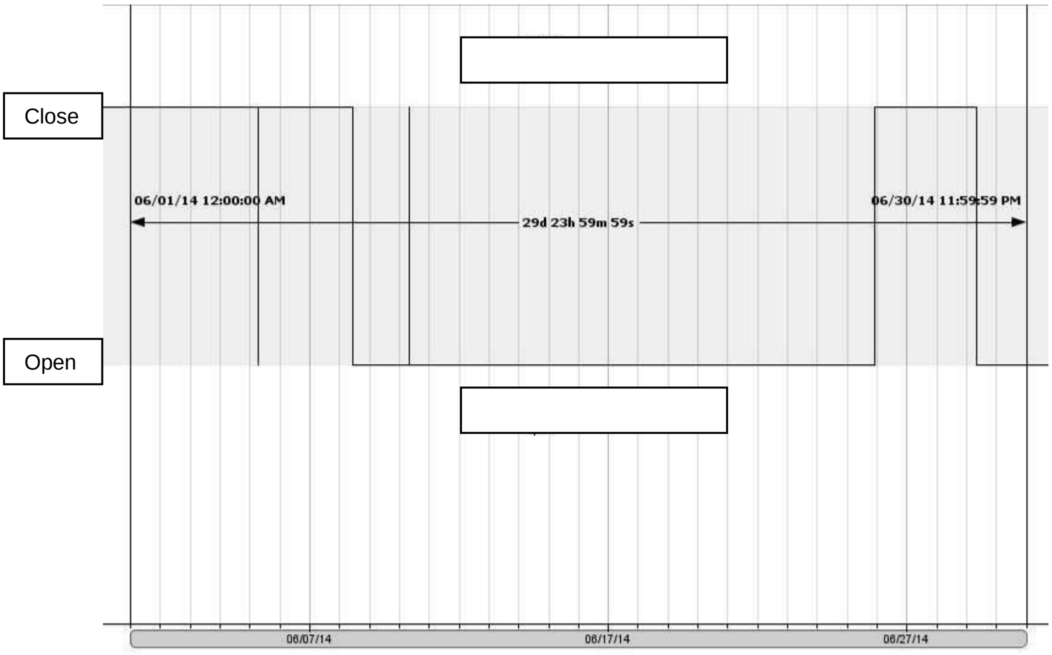


Monitored window operation – W17 - September 2014

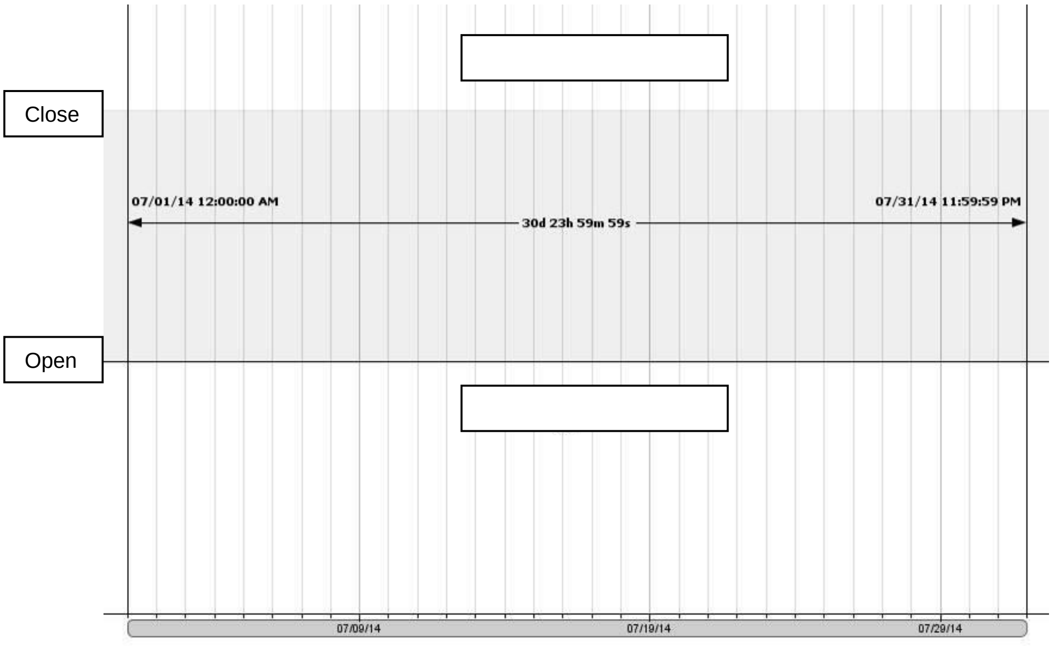
Bedroom 4



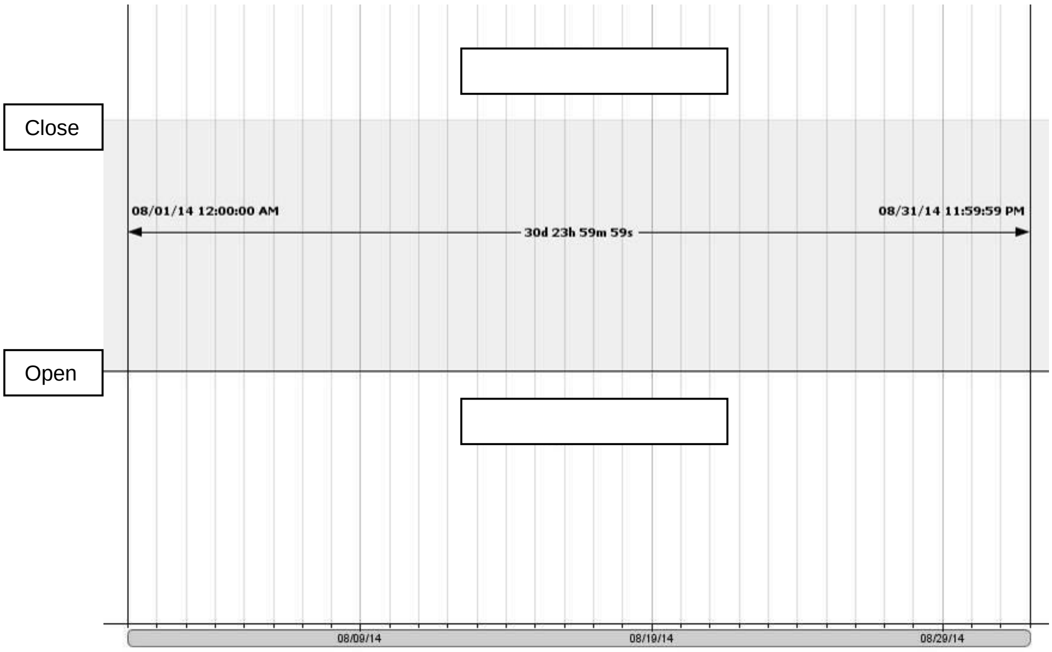
Monitored window operation – W16 - May 2014



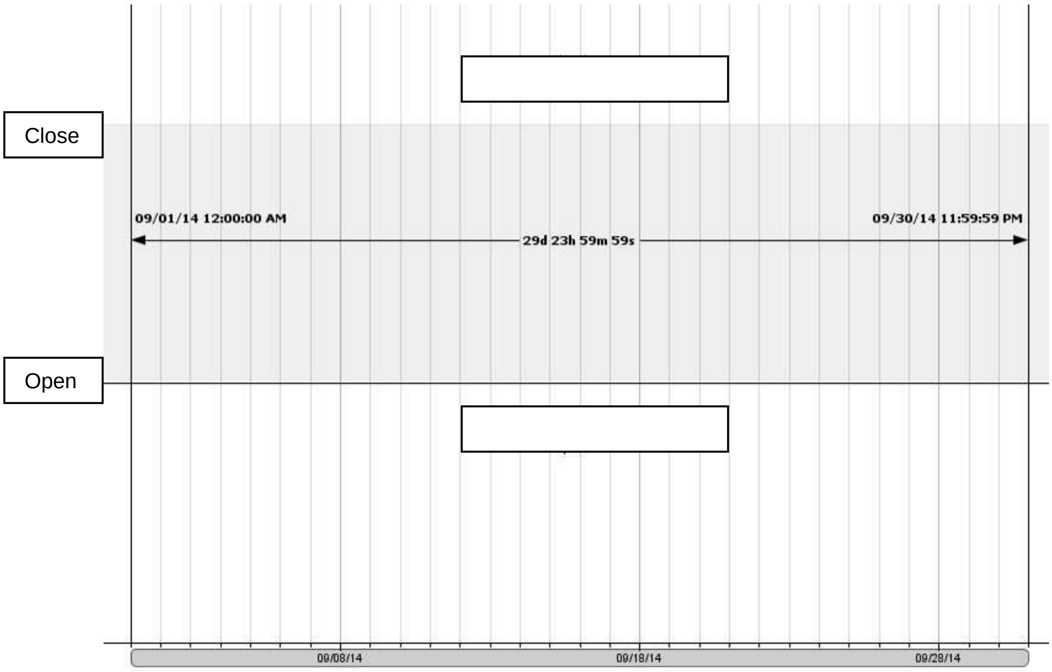
Monitored window operation – W16 - June 2014



Monitored window operation – W16 - July 2014

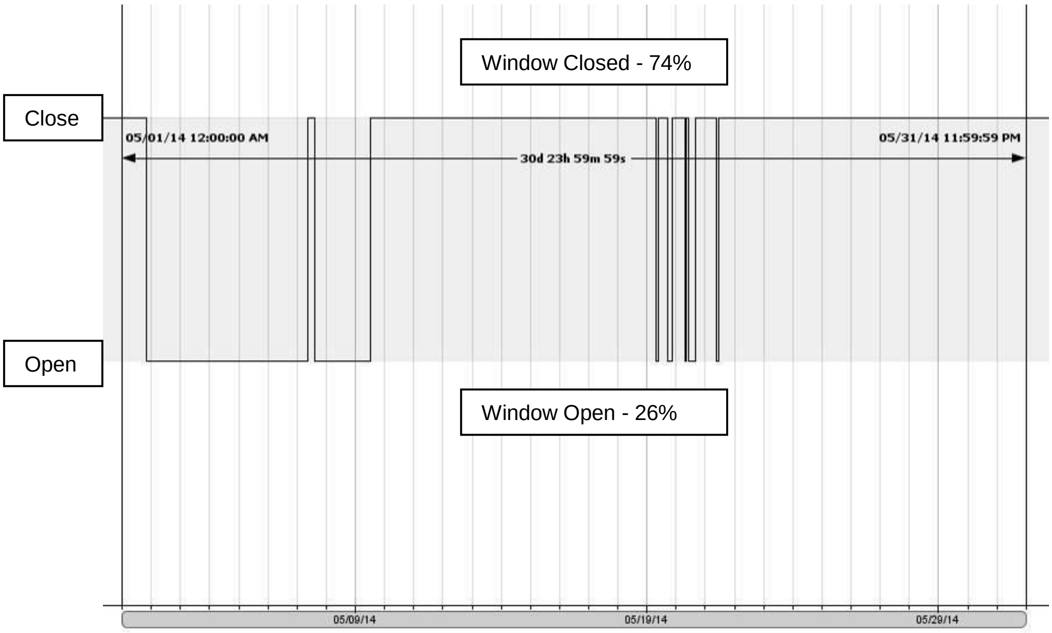


Monitored window operation – W16 - August 2014

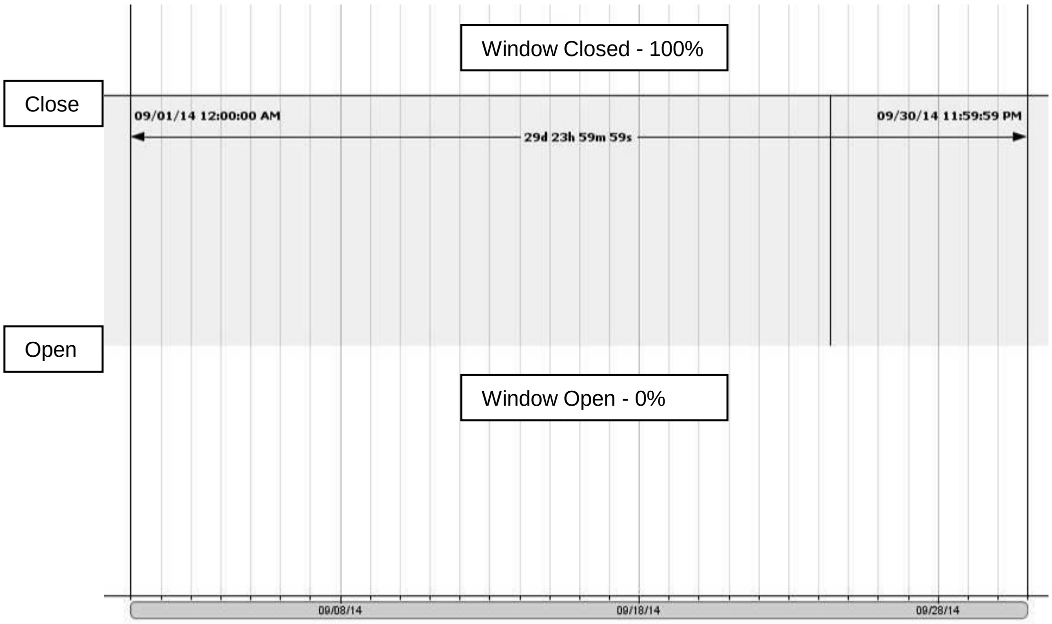


Monitored window operation – W16 - September 2014

Bedroom 5



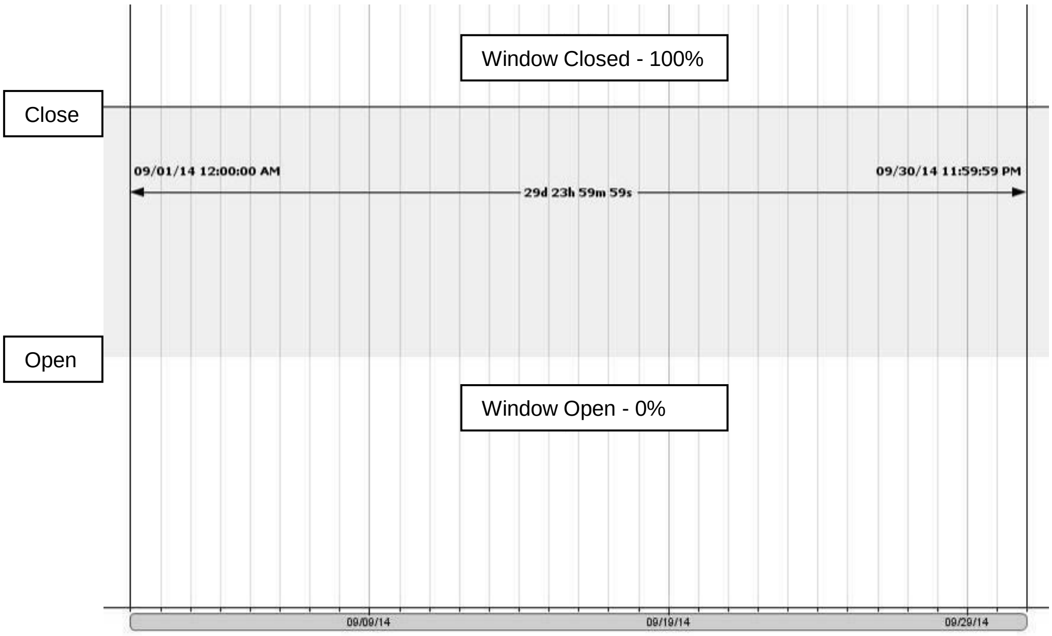
Monitored window operation – W15 - May 2014



Monitored window operation – W15 - September 2014

Bedroom 2

Monitored window operation – W16 - May 2014

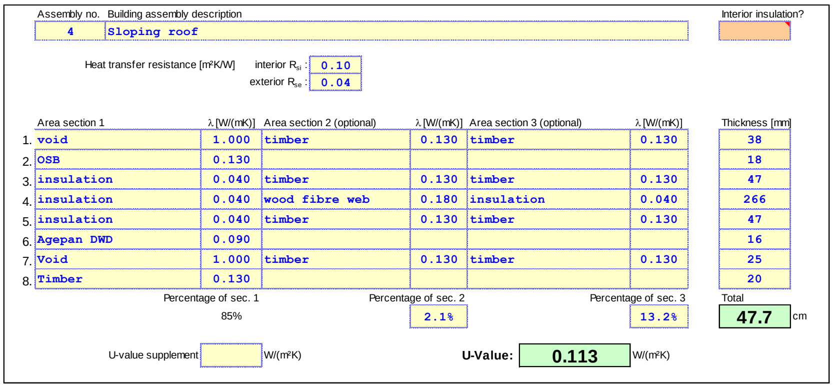


Monitored window operation – W16 - September 2014

APPENDIX E

Building One:

Roof



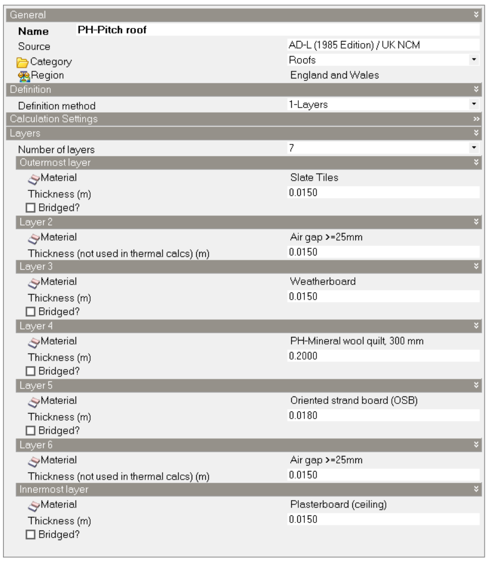
Assembly no.	Building assembly description	Interior insulation?
4	Sloping roof	

Heat transfer resistance [m²K/W] interior R_{si} : 0.10
exterior R_{se} : 0.04

	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	void	1.000	timber	0.130	timber	0.130	38
2.	OSB	0.130					18
3.	insulation	0.040	timber	0.130	timber	0.130	47
4.	insulation	0.040	wood fibre web	0.180	insulation	0.040	266
5.	insulation	0.040	timber	0.130	timber	0.130	47
6.	Agepan DWD	0.090					16
7.	Void	1.000	timber	0.130	timber	0.130	25
8.	Timber	0.130					20
	Percentage of sec. 1	85%	Percentage of sec. 2	2.1%	Percentage of sec. 3	13.2%	Total 47.7 cm

U-value supplement W/(m²K)

U-Value: 0.113 W/(m²K)



General

Name	**PH-Pitch roof**
Source	AD-L (1985 Edition) / UK NCM
Category	Roofs
Region	England and Wales

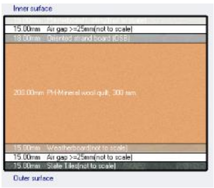
Definition

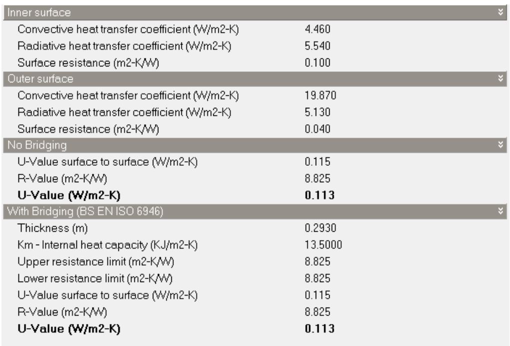
Definition method	1-Layers

Calculation Settings

Layers

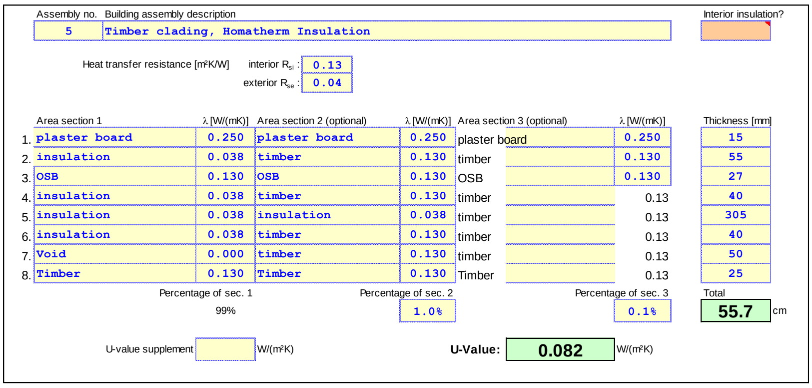
Number of layers	7
Outermost layer	
Material	Slate Tiles
Thickness (m)	0.0150
☐ Bridged?	
Layer 2	
Material	Air gap >=25mm
Thickness (not used in thermal calcs) (m)	0.0150
Layer 3	
Material	Weatherboard
Thickness (m)	0.0150
☐ Bridged?	
Layer 4	
Material	PH-Mineral wool quilt, 300 mm
Thickness (m)	0.2000
☐ Bridged?	
Layer 5	
Material	Oriented strand board (OSB)
Thickness (m)	0.0180
☐ Bridged?	
Layer 6	
Material	Air gap >=25mm
Thickness (not used in thermal calcs) (m)	0.0150
Innermost layer	
Material	Plasterboard (ceiling)
Thickness (m)	0.0150
☐ Bridged?	





Inner surface	
Convective heat transfer coefficient (W/m2-K)	4.460
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.100
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.115
R-Value (m2-K/W)	8.825
U-Value (W/m2-K)	**0.113**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.2930
Km - Internal heat capacity (KJ/m2-K)	13.5000
Upper resistance limit (m2-K/W)	8.825
Lower resistance limit (m2-K/W)	8.825
U-Value surface to surface (W/m2-K)	0.115
R-Value (m2-K/W)	8.825
U-Value (W/m2-K)	**0.113**

Wall



Assembly no.	Building assembly description	Interior insulation?
5	Timber cladding, Homatherm Insulation	

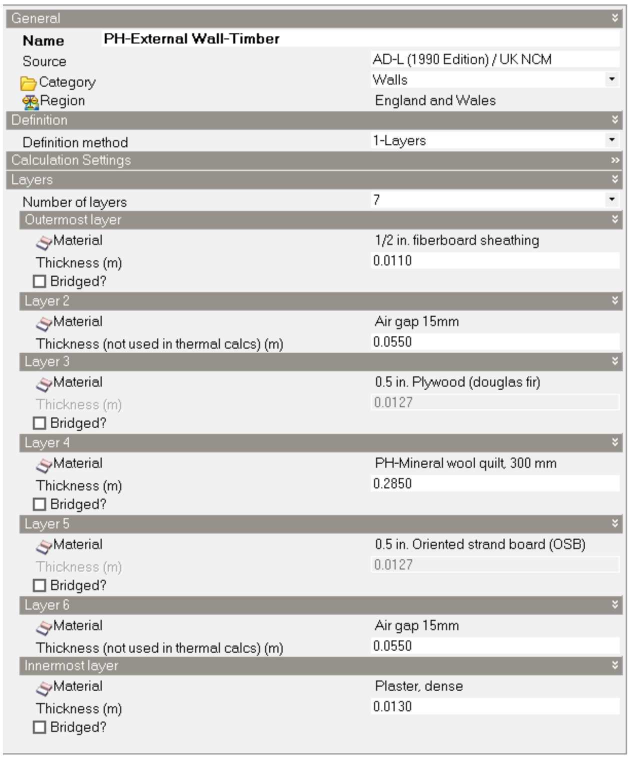
Heat transfer resistance [m²K/W] interior R_{si} : 0.13

exterior R_{se} : 0.04

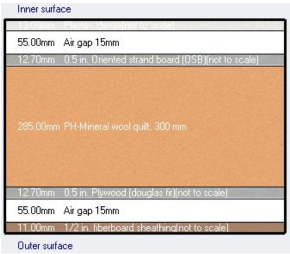
	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	plaster board	0.250	plaster board	0.250	plaster board	0.250	15
2.	insulation	0.038	timber	0.130	timber	0.130	55
3.	OSB	0.130	OSB	0.130	OSB	0.130	27
4.	insulation	0.038	timber	0.130	timber	0.13	40
5.	insulation	0.038	insulation	0.038	timber	0.13	305
6.	insulation	0.038	timber	0.130	timber	0.13	40
7.	Void	0.000	timber	0.130	timber	0.13	50
8.	Timber	0.130	Timber	0.130	Timber	0.13	25
		Percentage of sec. 1		Percentage of sec. 2		Percentage of sec. 3	Total
		99%		1.0%		0.1%	55.7 cm

U-value supplement W/(m²K)

U-Value: 0.082 W/(m²K)



General	
Name	PH-External Wall-Timber
Source	AD-L (1990 Edition) / UK NCM
Category	Walls
Region	England and Wales
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	7
Outermost layer	
Material	1/2 in. fiberboard sheathing
Thickness (m)	0.0110
☐ Bridged?	
Layer 2	
Material	Air gap 15mm
Thickness (not used in thermal calcs) (m)	0.0550
Layer 3	
Material	0.5 in. Plywood (douglas fir)
Thickness (m)	0.0127
☐ Bridged?	
Layer 4	
Material	PH-Mineral wool quilt, 300 mm
Thickness (m)	0.2850
☐ Bridged?	
Layer 5	
Material	0.5 in. Oriented strand board (OSB)
Thickness (m)	0.0127
☐ Bridged?	
Layer 6	
Material	Air gap 15mm
Thickness (not used in thermal calcs) (m)	0.0550
Innermost layer	
Material	Plaster, dense
Thickness (m)	0.0130
☐ Bridged?	



Inner surface

13.00mm Plaster, dense(not to scale)

55.00mm Air gap 15mm

12.70mm 0.5 in. Oriented strand board (OSB)(not to scale)

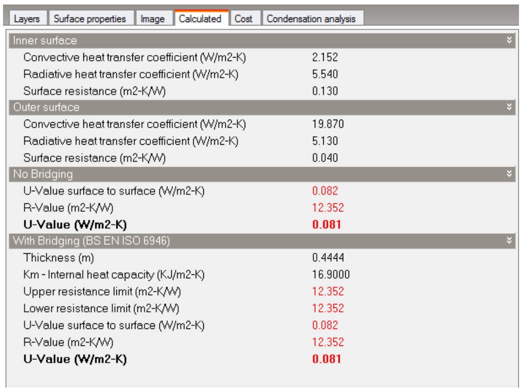
285.00mm PH-Mineral wool quilt, 300 mm

12.70mm 0.5 in. Plywood (douglas fir)(not to scale)

55.00mm Air gap 15mm

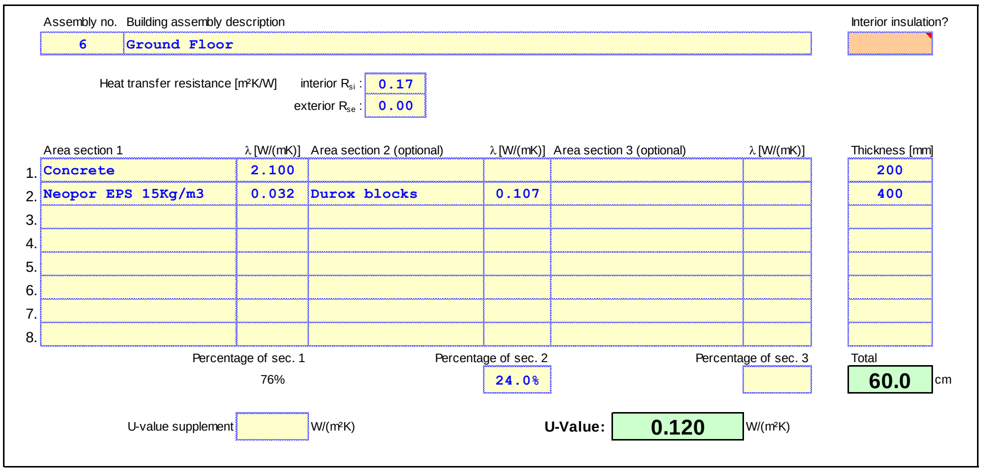
11.00mm 1/2 in. fiberboard sheathing(not to scale)

Outer surface



Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.082
R-Value (m2-K/W)	12.352
U-Value (W/m2-K)	**0.081**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.4444
Km - Internal heat capacity (KJ/m2-K)	16.9000
Upper resistance limit (m2-K/W)	12.352
Lower resistance limit (m2-K/W)	12.352
U-Value surface to surface (W/m2-K)	0.082
R-Value (m2-K/W)	12.352
U-Value (W/m2-K)	**0.081**

Floor



Assembly no. 6 Building assembly description **Ground Floor**

Interior insulation?

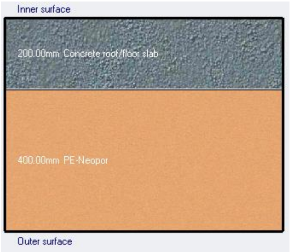
Heat transfer resistance [m²K/W] interior R_{si} : 0.17

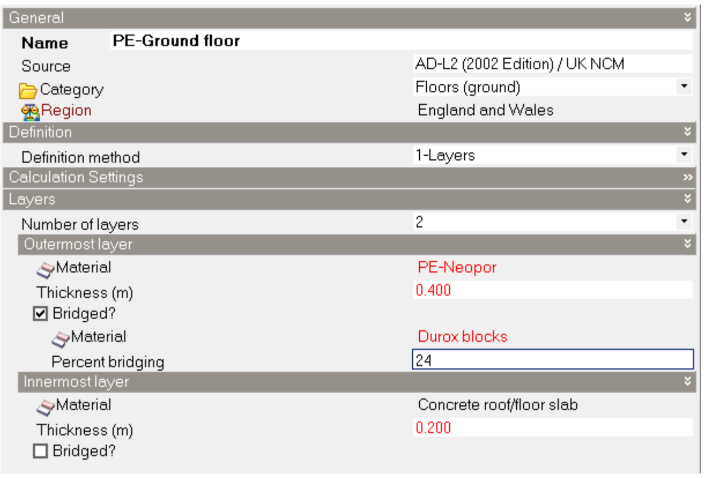
exterior R_{se} : 0.00

	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Concrete	2.100					200
2.	Neopor EPS 15Kg/m3	0.032	Durox blocks	0.107			400
3.							
4.							
5.							
6.							
7.							
8.							
	Percentage of sec. 1	76%	Percentage of sec. 2	24.0%	Percentage of sec. 3		Total 60.0 cm

U-value supplement W/(m²K)

U-Value: 0.120 W/(m²K)





General

Name **PE-Ground floor**

Source: AD-L2 (2002 Edition) / UK NCM

Category: Floors (ground)

Region: England and Wales

Definition

Definition method: 1-Layers

Calculation Settings

Layers

Number of layers: 2

Outermost layer

Material: PE-Neopor

Thickness (m): 0.400

☑ Bridged?

Material: Durox blocks

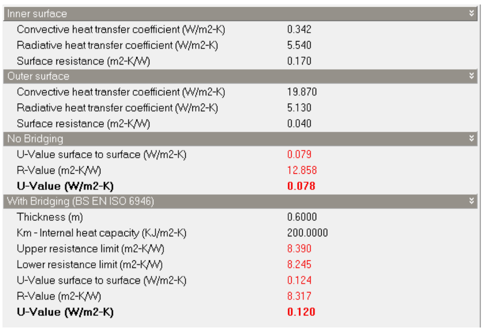
Percent bridging: 24

Innermost layer

Material: Concrete roof/floor slab

Thickness (m): 0.200

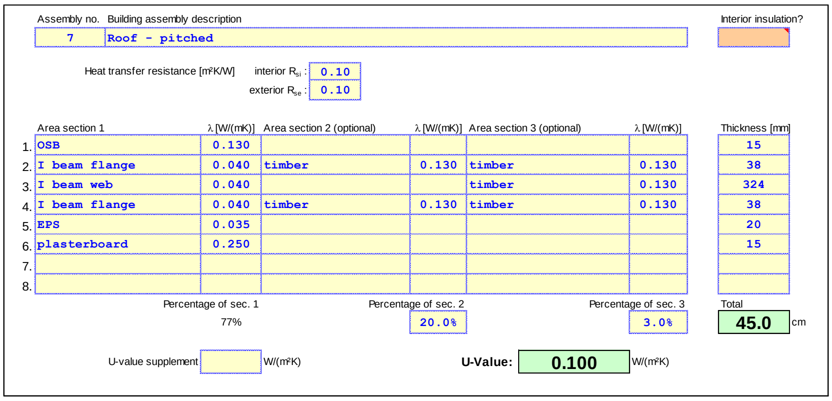
☐ Bridged?



Inner surface	
Convective heat transfer coefficient (W/m2-K)	0.342
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.170
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.079
R-Value (m2-K/W)	12.858
U-Value (W/m2-K)	**0.078**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.6000
Km - Internal heat capacity (KJ/m2-K)	200.0000
Upper resistance limit (m2-K/W)	8.390
Lower resistance limit (m2-K/W)	8.245
U-Value surface to surface (W/m2-K)	0.124
R-Value (m2-K/W)	8.317
U-Value (W/m2-K)	**0.120**

Building two:

Roof pitched



Assembly no. 7

Building assembly description: Roof - pitched

Interior insulation?

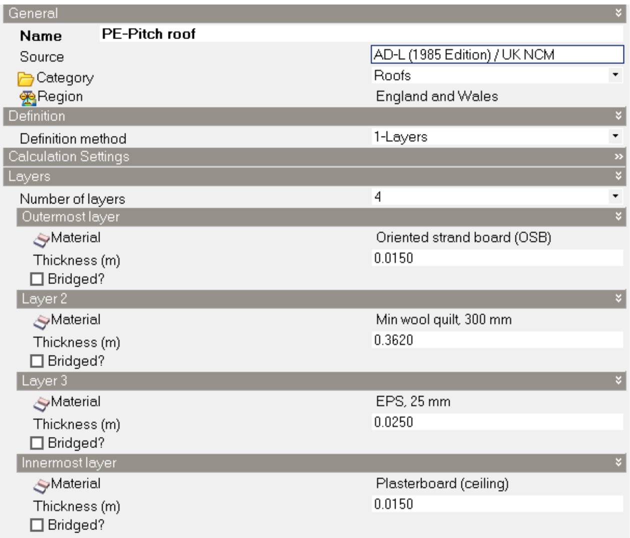
Heat transfer resistance [m²K/W] interior R_{si} : 0.10

exterior R_{se} : 0.10

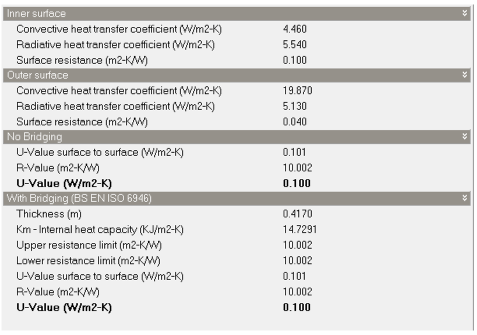
	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	OSB	0.130					15
2.	I beam flange	0.040	timber	0.130	timber	0.130	38
3.	I beam web	0.040			timber	0.130	324
4.	I beam flange	0.040	timber	0.130	timber	0.130	38
5.	EPS	0.035					20
6.	plasterboard	0.250					15
7.							
8.							
	Percentage of sec. 1	77%	Percentage of sec. 2	20.0%	Percentage of sec. 3	3.0%	Total 45.0 cm

U-value supplement W/(m²K)

U-Value: 0.100 W/(m²K)

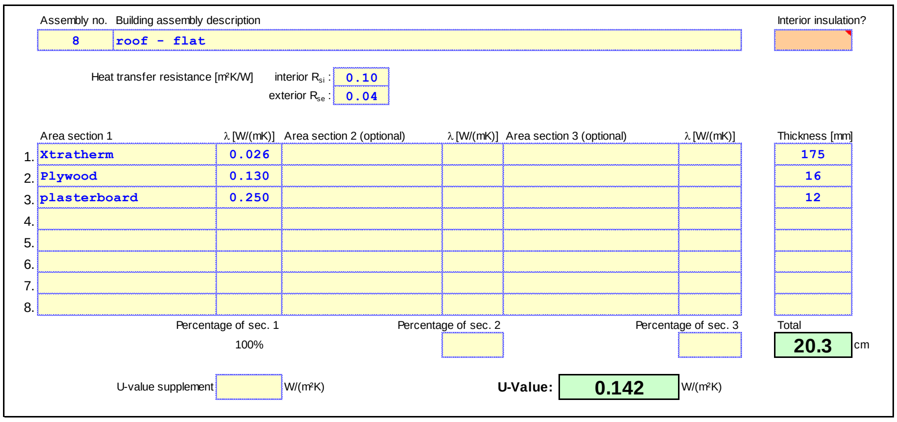


General	
Name	**PE-Pitch roof**
Source	AD-L (1985 Edition) / UK NCM
Category	Roofs
Region	England and Wales
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	4
Outermost layer	
Material	Oriented strand board (OSB)
Thickness (m)	0.0150
☐ Bridged?	
Layer 2	
Material	Min wool quilt, 300 mm
Thickness (m)	0.3620
☐ Bridged?	
Layer 3	
Material	EPS, 25 mm
Thickness (m)	0.0250
☐ Bridged?	
Innermost layer	
Material	Plasterboard (ceiling)
Thickness (m)	0.0150
☐ Bridged?	



Inner surface	
Convective heat transfer coefficient (W/m2-K)	4.460
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.100
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.101
R-Value (m2-K/W)	10.002
U-Value (W/m2-K)	**0.100**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.4170
Km - Internal heat capacity (KJ/m2-K)	14.7291
Upper resistance limit (m2-K/W)	10.002
Lower resistance limit (m2-K/W)	10.002
U-Value surface to surface (W/m2-K)	0.101
R-Value (m2-K/W)	10.002
U-Value (W/m2-K)	**0.100**

Roof Flat



Assembly no.	Building assembly description	Interior insulation?
8	roof - flat	

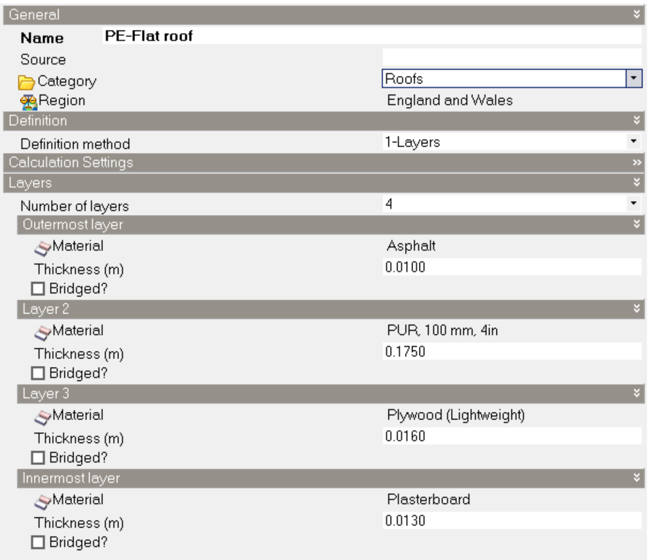
Heat transfer resistance [m²K/W] interior R_{si} : 0.10

exterior R_{se} : 0.04

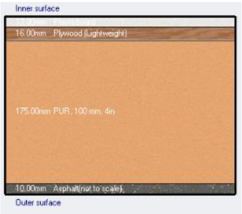
	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Xtratherm	0.026					175
2.	Plywood	0.130					16
3.	plasterboard	0.250					12
4.							
5.							
6.							
7.							
8.							
	Percentage of sec. 1	100%	Percentage of sec. 2		Percentage of sec. 3		Total 20.3 cm

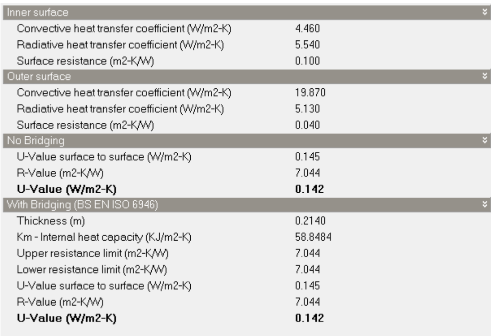
U-value supplement W/(m²K)

U-Value: 0.142 W/(m²K)



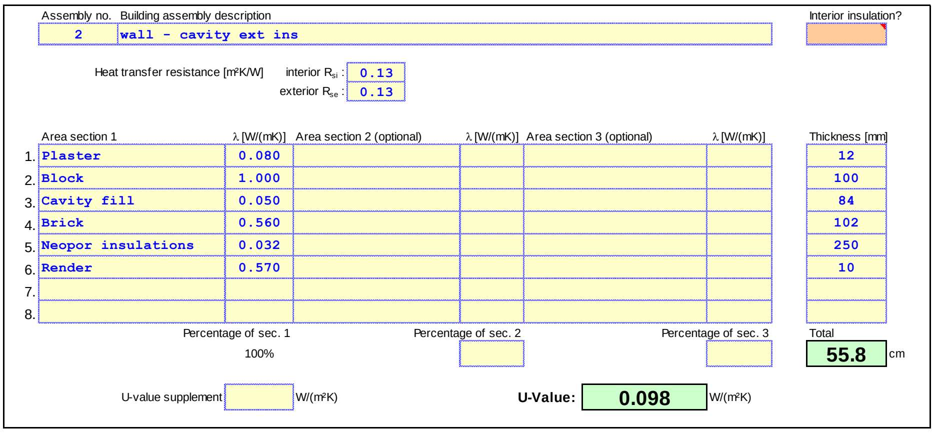
General	
Name	PE-Flat roof
Source	
Category	Roofs
Region	England and Wales
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	4
Outermost layer	
Material	Asphalt
Thickness (m)	0.0100
☐ Bridged?	
Layer 2	
Material	PUR, 100 mm, 4in
Thickness (m)	0.1750
☐ Bridged?	
Layer 3	
Material	Plywood (Lightweight)
Thickness (m)	0.0160
☐ Bridged?	
Innermost layer	
Material	Plasterboard
Thickness (m)	0.0130
☐ Bridged?	





Inner surface	
Convective heat transfer coefficient (W/m2-K)	4.460
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.100
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.145
R-Value (m2-K/W)	7.044
U-Value (W/m2-K)	**0.142**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.2140
Km - Internal heat capacity (KJ/m2-K)	58.8484
Upper resistance limit (m2-K/W)	7.044
Lower resistance limit (m2-K/W)	7.044
U-Value surface to surface (W/m2-K)	0.145
R-Value (m2-K/W)	7.044
U-Value (W/m2-K)	**0.142**

Wall existing



Assembly no. 2

Building assembly description: wall - cavity ext ins

Interior insulation?

Heat transfer resistance [m²K/W]

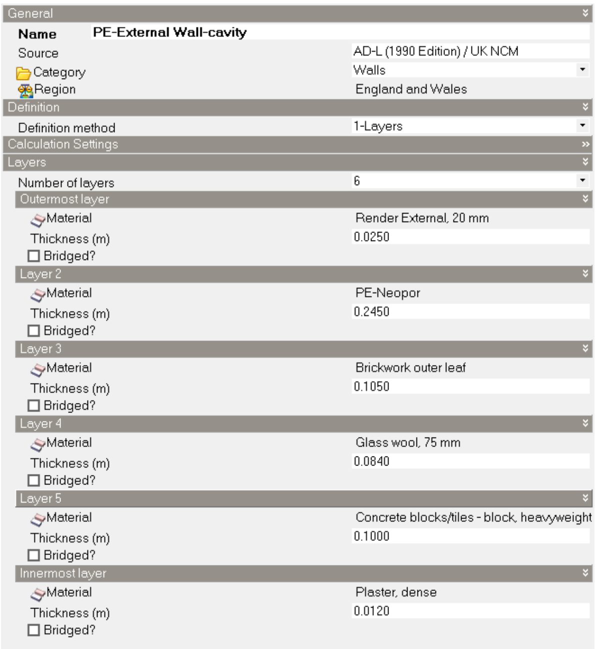
interior R_{si} : 0.13

exterior R_{se} : 0.13

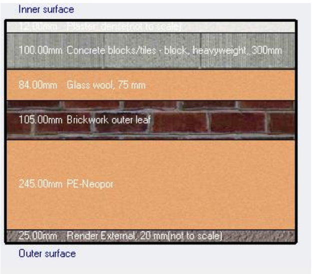
	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Plaster	0.080					12
2.	Block	1.000					100
3.	Cavity fill	0.050					84
4.	Brick	0.560					102
5.	Neopor insulations	0.032					250
6.	Render	0.570					10
7.							
8.							
	Percentage of sec. 1		Percentage of sec. 2		Percentage of sec. 3		Total
	100%						55.8 cm

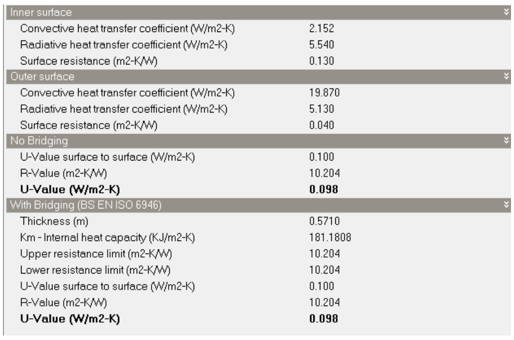
U-value supplement W/(m²K)

U-Value: 0.098 W/(m²K)



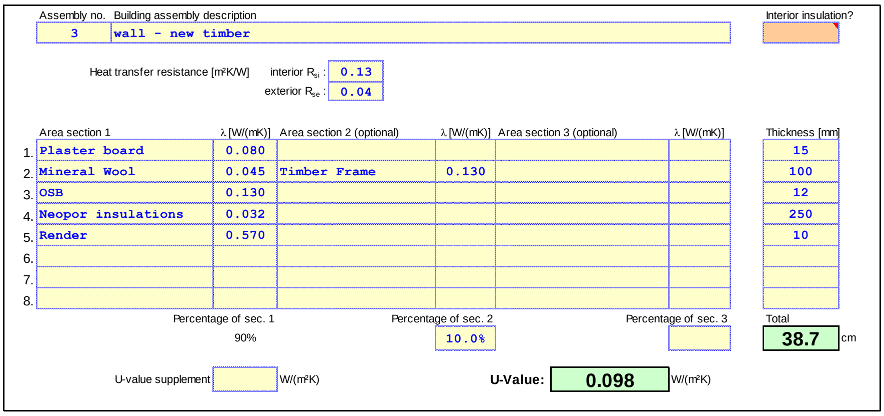
General	
Name	**PE-External Wall-cavity**
Source	AD-L (1990 Edition) / UK NCM
Category	Walls
Region	England and Wales
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	6
Outermost layer	
Material	Render External, 20 mm
Thickness (m)	0.0250
☐ Bridged?	
Layer 2	
Material	PE-Neopor
Thickness (m)	0.2450
☐ Bridged?	
Layer 3	
Material	Brickwork outer leaf
Thickness (m)	0.1050
☐ Bridged?	
Layer 4	
Material	Glass wool, 75 mm
Thickness (m)	0.0840
☐ Bridged?	
Layer 5	
Material	Concrete blocks/tiles - block, heavyweight
Thickness (m)	0.1000
☐ Bridged?	
Innermost layer	
Material	Plaster, dense
Thickness (m)	0.0120
☐ Bridged?	





Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.100
R-Value (m2-K/W)	10.204
U-Value (W/m2-K)	**0.098**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.5710
Km - Internal heat capacity (KJ/m2-K)	181.1808
Upper resistance limit (m2-K/W)	10.204
Lower resistance limit (m2-K/W)	10.204
U-Value surface to surface (W/m2-K)	0.100
R-Value (m2-K/W)	10.204
U-Value (W/m2-K)	**0.098**

New Wall



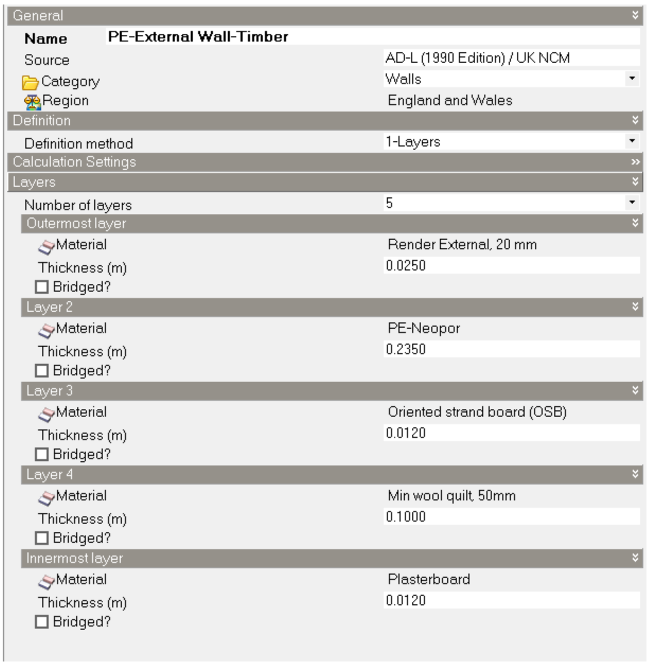
Assembly no.: 3
Building assembly description: wall - new timber
Interior insulation?

Heat transfer resistance [m²K/W] interior R_{si} : 0.13
exterior R_{se} : 0.04

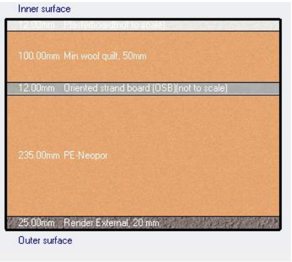
	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Plaster board	0.080					15
2.	Mineral Wool	0.045	Timber Frame	0.130			100
3.	OSB	0.130					12
4.	Neopor insulations	0.032					250
5.	Render	0.570					10
6.							
7.							
8.							
	Percentage of sec. 1	90%	Percentage of sec. 2	10.0%	Percentage of sec. 3		Total 38.7 cm

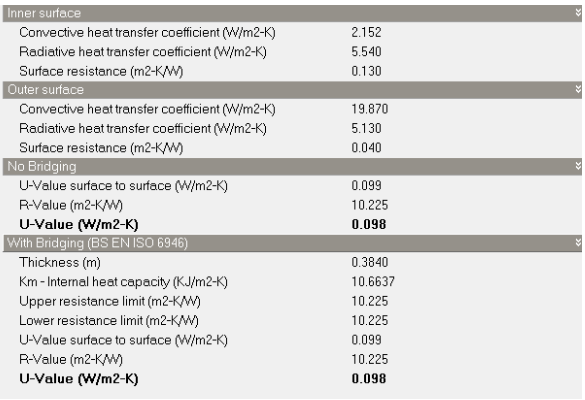
U-value supplement W/(m²K)

U-Value: 0.098 W/(m²K)



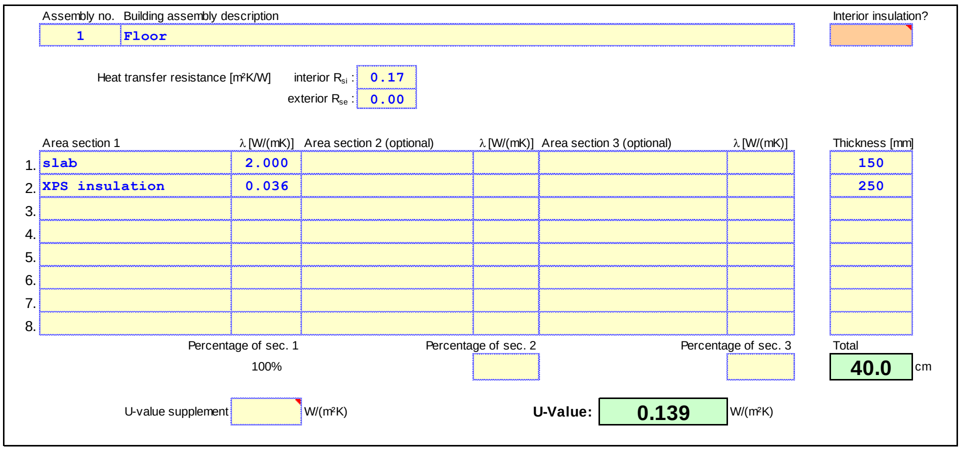
General	
Name	**PE-External Wall-Timber**
Source	AD-L (1990 Edition) / UK NCM
Category	Walls
Region	England and Wales
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	5
Outermost layer	
Material	Render External, 20 mm
Thickness (m)	0.0250
☐ Bridged?	
Layer 2	
Material	PE-Neopor
Thickness (m)	0.2350
☐ Bridged?	
Layer 3	
Material	Oriented strand board (OSB)
Thickness (m)	0.0120
☐ Bridged?	
Layer 4	
Material	Min wool quilt, 50mm
Thickness (m)	0.1000
☐ Bridged?	
Innermost layer	
Material	Plasterboard
Thickness (m)	0.0120
☐ Bridged?	





Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.099
R-Value (m2-K/W)	10.225
U-Value (W/m2-K)	**0.098**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.3840
Km - Internal heat capacity (KJ/m2-K)	10.6637
Upper resistance limit (m2-K/W)	10.225
Lower resistance limit (m2-K/W)	10.225
U-Value surface to surface (W/m2-K)	0.099
R-Value (m2-K/W)	10.225
U-Value (W/m2-K)	**0.098**

Floor



Assembly no. 1 | Building assembly description: Floor | Interior insulation?

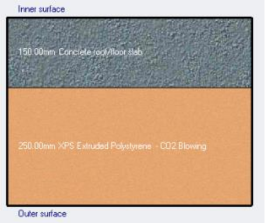
Heat transfer resistance [m²K/W] interior R_{si} : 0.17

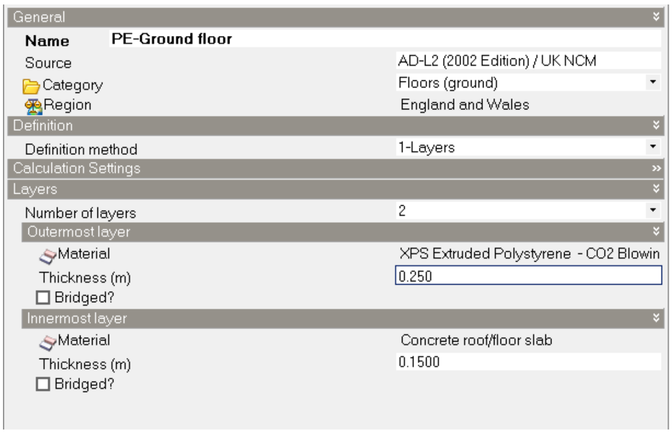
exterior R_{se} : 0.00

	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	slab	2.000					150
2.	XPS insulation	0.036					250
3.							
4.							
5.							
6.							
7.							
8.							
	Percentage of sec. 1		Percentage of sec. 2		Percentage of sec. 3		Total
	100%						40.0 cm

U-value supplement W/(m²K)

U-Value: 0.139 W/(m²K)





General

Name **PE-Ground floor**

Source	AD-L2 (2002 Edition) / UK NCM
Category	Floors (ground)
Region	England and Wales

Definition

Definition method	1-Layers

Calculation Settings

Layers

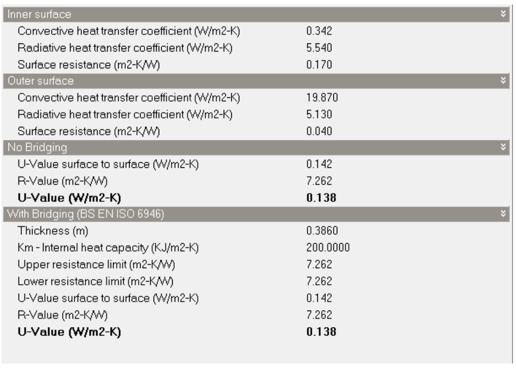
Number of layers	2

Outermost layer

Material	XPS Extruded Polystyrene - CO2 Blowin
Thickness (m)	0.250
☐ Bridged?	

Innermost layer

Material	Concrete roof/floor slab
Thickness (m)	0.1500
☐ Bridged?	



Inner surface

Convective heat transfer coefficient (W/m2-K)	0.342
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.170

Outer surface

Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040

No Bridging

U-Value surface to surface (W/m2-K)	0.142
R-Value (m2-K/W)	7.262
U-Value (W/m2-K)	**0.138**

With Bridging (BS EN ISO 6946)

Thickness (m)	0.3860
Km - Internal heat capacity (KJ/m2-K)	200.0000
Upper resistance limit (m2-K/W)	7.262
Lower resistance limit (m2-K/W)	7.262
U-Value surface to surface (W/m2-K)	0.142
R-Value (m2-K/W)	7.262
U-Value (W/m2-K)	**0.138**