Department of Mechanical Engineering

TOWARDS NET ZERO ENERGY BUILDINGS: PASSIVE HOUSE PERFORMANCE WITH PV INSTALLATION AND ADVANCED VENTILATION CONTROL IN TWO DIFFERENT CLIMATES

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Signed: Álvaro Corral González Date: 9th September 2011

Abstract

In 2010, within the EU's new strategy for sustainable growth and jobs named 'Europe 2020', the European Commission defined the necessity of mitigate the climate change and make a sustainable use of the energy as one of the main headline targets. Objectives of reducing the greenhouse gas emissions by 20%, to obtain 20% of EU's energy requirements from renewable sources and to obtain another 20% of increase in energy efficiency were set. European Union countries use an average of about 40% of their total energy needs in residential and commercial buildings. The expansion of Passive Houses could be a perfect way to meet these objectives since the PassivHaus criteria establishes a maximum space heating use of 15 kWh/(m^2a), which may lead to a saving up to 90% compared with standard houses. This huge decrease could even open the possibility of achieving Zero Carbon Energy buildings if appropriate renewable energy schemes are integrated in these dwellings.

The PassivHaus concept is seeking for a high thermal comfort and indoor air quality with a minimal energy use. It was developed about 20 years ago mainly in Germany and Austria and more recently in the UK, although nowadays new projects are appearing in other EU countries and in the USA with the aim to adapt these highly efficient energy buildings to another different climates.

Within this background context, this thesis carries out an exploration of Passive House performance in two completely different climates using high resolution dynamic simulation. In order to do that, a highly detailed model of a Scottish certified Passive House was designed in ESP-r using all the accurate construction details from the available PHPP spreadsheet. Then, performance of this dwelling was evaluated for a Scottish climate and results were compared with the PHPP spreadsheet, identifying the differences between both approaches. Results showed that ESP-r space heating prediction was about 300 kWh larger than PHPP prediction. Different reasons were founded as origin of this difference being the more precise climate database used in ESP-r the main cause.

This research also explores the performance of this dwelling when the model is transferred to a warmer location such as Madrid. It studies the great importance that

the implementation of a mechanically controlled night ventilation system could have in the reduction of the high cooling demand obtained as a consequence of the high ambient temperatures. As the main aim of this section is to evaluate the power of the aforementioned system and the length of this project was highly time constrained, Scottish vernacular architecture was not modified when the model was transferred to the new location. Therefore, this study could also be considered as a method to mitigate the coming global warming in cold climates. Results showed the great advantages obtained from the installation of this type of night ventilation system since a saving of more than 50% in cooling demand was achieved and PassivHaus criteria in terms of energy demand was met just by implementing this scheme. Further work will be suggested regarding the application of this type of systems in Passive Houses totally adapted to these climates (shading devices, building techniques, etc.).

The last part of this thesis elaborates a brief preliminary study of the possibility of achieving a Net Zero Energy building. It explores to what extent the installation of a PV array covering the entire roof in a Passive House could contribute in obtaining this type of buildings. MERIT software was used for this purpose and results showed that it was possible to achieve it in a warm climate such as Madrid but not in a cold climate such as Dunoon, Scotland.

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1. Introduction

As a consequence of the high impact of the current economic and financial crisis, economic realities are moving faster than political realities and the European Commission believes that it is necessary to accept that “the increased economic interdependence demands a more determined and coherent response at the political level” (European Commision, 2010). Replacing the failed Lisbon Agenda adopted in 2000, which main aim was to make the EU "the most competitive and dynamic knowledge-based economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion" by the end of 2010 (European Council), the European Union launched in the past year the called ‘Europe 2020’, a new strategy for sustainable growth and jobs. Innovation and sustainable growth were set as the centre of its proposal, being to reduce the climate change and energy use one of the main aims of this plan. Within this objective, three targets were agreed to meet for the whole EU by 2020: to reduce the greenhouse gas emissions by 20% compared with the levels of 1990, to increase the contribution of renewables in its total energy needs to 20% and to obtain another 20% of increase in energy efficiency.

Moreover, the European Commission stated that the fact of reaching the goals of this sustainable growth proposal could lead the EU to improve its productivity and competitiveness maintaining itself as the world’s heart of green solutions regarding the growing competition from China and the USA. In numbers, it was estimated that by reaching these energy goals the EU could save €60 billion for oil and gas imports, the GDP could boost by 0.6% to 0.8% and it would be created about a million of new jobs by 2020 (European Commision, 2010). Also, the European Commission encouraged the EU countries to meet the ‘Europe 2020’ strategy maximising benefits and minimizing costs supporting the introductions and spread of innovative technological solutions.

Few months after the implementation of the ‘Europe 2020’ strategy, the European Commission elaborated on May 2010 a recast of the Directive on energy performance of buildings (2002/91/EC) in order to clarify the minimum requirements regarding the energy performance of new and existing buildings. As EU countries use an average of about 40% of their total energy needs in residential and commercial buildings, fact which makes buildings responsible for 36% of the total EU CO_2 emissions, it was believed that a new Directive was necessary in order to improve the building's energy performance with the aim to achieve the previous climate change and energy objectives (European Parlament, 2010,a). This new Directive (2010/31/EU), expressed that in order to calculate the energy performance of buildings it was necessary to consider not only the space heating demand and the thermal characteristics of the building's envelop, but also the energy demand associated with a typical use of the building regarding the hot water supply, the air-conditioning and lighting installations or the indoor climatic conditions. One of the main objectives of this Directive, as stated in its article 9 was that "the Member States shall ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings" (European Parliament, 2010,b).

With the purpose of determining the level of ambition set in this recast of the Directive, the European Commission decided to carry out an Impact Assessment (European Commission) which assessed the possibility of "*setting up EU–wide low or zero energy/carbon buildings/passive house requirements*" as one of the main options to be considered. Many other options regarding the improvement of the energy performance in a building were assessed but the results expressed that this option caused the greatest energy savings and also the largest number of jobs created.

According to the PassivHaus Institute (PHI): "Passive Houses are buildings which assure a comfortable indoor climate in summer and in winter without needing a conventional heat distribution system. To permit this, it is essential that, under climatic conditions prevailing in Central Europe, the building's annual space heating requirement does not exceed 15 $kWh/(m^2a)$". PHI also considers the PassivHaus standard as a "refinement of the low-energy house (LEH) standard" and states that the energy savings achieved following this criteria could rise up to 90% of the space heating demand and 75% of the total energy demand compared with the standards of the 1995 German Thermal Insulation Ordinance (Wärmeschutzverordnung).

Therefore, the implementation of the PassivHaus standard in new buildings could be the optimum way to reduce its energy demand achieving high values of both thermal comfort and indoor air quality at the same time. Moreover, the sensitive decrease in the space heating demand would open the possibility of meeting the entire energy demand only by using renewable sources facilitating in this way to the achievement of a Zero-Carbon building in accordance with the European Parliament Directives regarding the 'Europe 2020' strategy towards the reduction of the greenhouse gas emissions, the increase of the use of renewables and the increase in energy efficiency.

PassivHaus concept was originally developed some years ago mainly in Germany and Austria and more recently in the UK, although nowadays new projects are appearing in other EU countries and in the USA with the aim to adapt these highly efficient energy buildings to other different climates. Actually, the 15th International Passive House conference held on the 25th of May of 2011 counted with participants from 50 different countries (PHI, 2011a). In northern Europe, a careful design of the building envelope considering aspects such as thermal properties, building orientation or solar shading might be enough to often remove the need for additional cooling in summer. However, in southern Europe with climate change and with expectations of a high quality internal environment throughout the year, the opportunity of additional cooling need to be considered (Passive-On project, 2007a). But as the implementation of these low-energy buildings in warm locations is a very recent issue, very few researches have been published about the performance in these types of climate.

The main purpose of this thesis will be to explore the performance of a Passive House in Scotland throughout dynamic simulation and also to transfer this dwelling to a warmer location such as Madrid. Study of the importance that a mechanically controlled night ventilation system could have in reducing the high cooling demand obtained as consequence of the high ambient temperatures will be carried out. To conclude, it undertakes a preliminary study about the contribution towards a Net Zero Energy building by installing a PV array.

2. Literature Review

2.1 Origin of Passive House concept

Techniques of passive building design have been practised since many years ago. There is evidence that ancient cultures such as the Greek and the Chinese started to develop its own solar architecture design more than 2000 years ago considering in their construction projects some elements such as solar orientation, thermal mass or ventilation (Bulti, 1980). But it was not until the 1930s when the modern term 'solar house' started to be used after the design of the called 'House of Tomorrow' for the 1933 Century Progress Exposition in Chicago (Collins & Nash, 2002). After this date, during the 1940s a big number of passive solar houses were build in the USA and the interest in solar building design was exponentially increasing until the 1970s; when as a consequence of the 1973 oil crisis, numerous patterns were published about the regarded topic (Borasi & Zardini, 2008).

However, this conception of passive solar houses was not conceived as a Passive House in the same sense as it is known today. The first idea about the current Passive House concept was developed by Professor Bo Adamson. During the 1980s, when he was working for the Department of Building Science at Lund University, Sweden, he undertook a feasibility study of Passive Houses in Beijing (Adamson, 1989) in which he proposed to improve the passive design with the idea of avoid any auxiliary heating system. After this study, Professor Bo Adamson continued researching this field in his office at Lund University until the arrival of Wolfgang Feist as visiting PhD student (Feist W. , From Low-Energy Buildings to the Passive House., 2006b). Together, they developed further the idea of Passive House carrying out diverse projects until 1990, when the first official Passive House was built in Darmstadt Kranichstein, Germany. Thermal insulation, airtightness and heat recovery ventilation were the crucial components. A blower door test resulted in a value lower than 0.30 ac/h at a pressure of 50 Pa and the mechanical ventilation system was composed by a heat exchanger with an efficiency of about 80% (Feist W. , 15th Anniversary of the Darmstadt - Kranichstein Passive House, 2006).

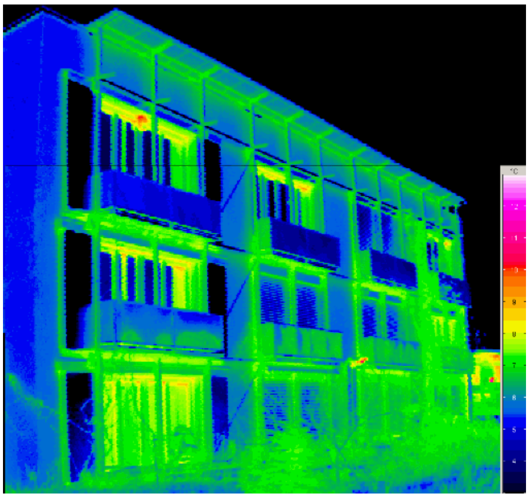

Figure 1: External thermographic photo of the first Passive House. (Source: Feist)

2.2 Passive House definition and PassivHaus criteria

After numerous researches, Wolfgang Feist founded the PassivHaus Institut in 1996 with the aim to promote the aim to promote and control the standards. This group developed the Passive House Planning Package (PHPP) as an excel spreadsheet based planning tool with the objective of assisting the design of a building following the Passivhaus standard providing all the instruments necessary for the design of a well performing low energy building. Since then, it is estimated that more than 25,000 Passive Houses have been built and certified around the world, mainly in Austria and Germany, although recently the concept is being quickly spread to other places such as the UK, the USA or the Scandinavian countries.

The PassivHaus Institut defined the concept of Passive House as "a building for which thermal comfort (ISO 7730) can be achieved solely by postheating or postcooling of the fresh air mass, which is required to fulfil sufficient indoor air quality conditions (DIN 1946) – without a need for recirculated air" (PHI, Passipedia, 2011).

Besides this definition, the PHI stated that a consideration had to be done to this definition. In a Passive House, it would be required to install a ventilation system equipped with a highly efficient heat recovery system with the aim of using the fresh ventilation air for heating purposes without the necessity of installing an auxiliary heating system.

For reasons of quality approval, the PHI set a group of features to be met in order to certify a Passive House. The certification criteria applicable to residential buildings is (Feist W. , 2009):

Specific space heating demand	≤ 15kWh/(m^2yr)
OR peak space heating load	≤ 10W/m^2
Specific space cooling demand	≤ 15kWh/(m^2yr)
Annual overheating hours (indoor temperature over 25°C)	≤ 10%
Airtightness test result (n50)	≤ 0.6 air changes/h
Entire specific primary energy demand	≤ 120kWh/(m^2yr)

Table 1: Passive House certification criteria.

It must be specified that in warm locations in which there is also a specific space cooling demand, the total primary energy demand requirement remains the same and hence this cooling requirement must be compensated in some way. Moreover, it must be highlighted that the reference value for the area is the so-called Treated Floor Area (TFA), which is "the net living area inside of the thermal envelope according to the German 'Wohnflächenverordnung' (Feist, Pfluger, Kaufmann, Schnieders, & Kah, 2007).

The principle behind the PassivHaus standard is the aim to reduce the investment as much as possible by increasing the energy efficiency of the dwelling. According to the PHI (Feist W.), space heating demand is the responsible for most of the energy consumption in a house. This space heating demand can be reduced increasing the efficiency of insulation, heat recovery or passive solar gains. By means of all this improvements, when the peak heating load decreases until 10 W/m^2, the ventilation system is able to distribute all the heating requirements throughout the building and it can be used as space heating system without the necessity of installing an auxiliary heating system. This suppression of the auxiliary system will produce a significant decrease in the construction costs of the dwelling.

However, it would not be wise to increase the efficiency of the building beyond this point of 10 W/m^2 since no extra benefits will be obtained, fact which makes this value the optimum one. This is because of the exponential increase of the construction costs from this point. The next figure illustrates this effect (Feist W.):

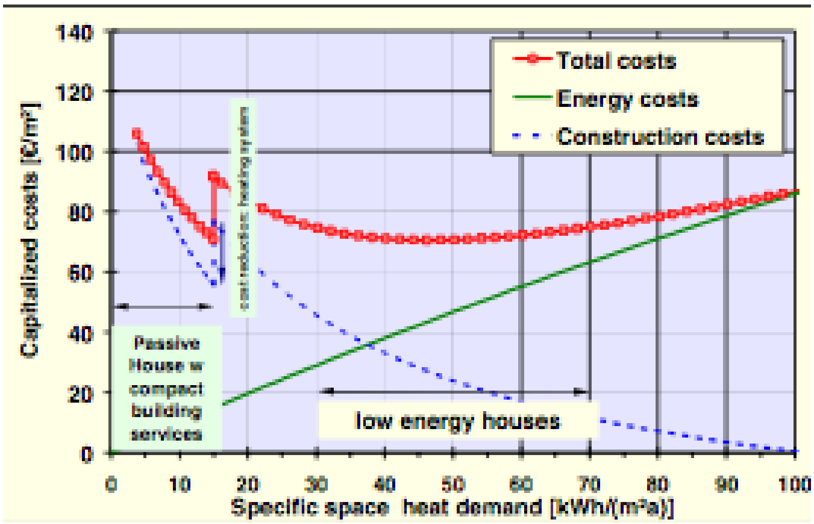

Figure 2: Cost-energy analysis (source: Feist)

Summarizing, the PassivHaus standard can be considered as "a refinement of the low-energy house (LEH) standard" (PHI, 2011b) and if besides the low space heating requirement, a responsible use of hot water and electricity demand is made, it will be easy to reduce significantly the total primary energy demand to values significantly below 120 kWh/(m^2yr).

The next figure compares the specific energy consumption level of dwellings and shows a predicted 75% energy saving comparing the Passive House standard with the German standard of 1995 (PHI, 2011b).

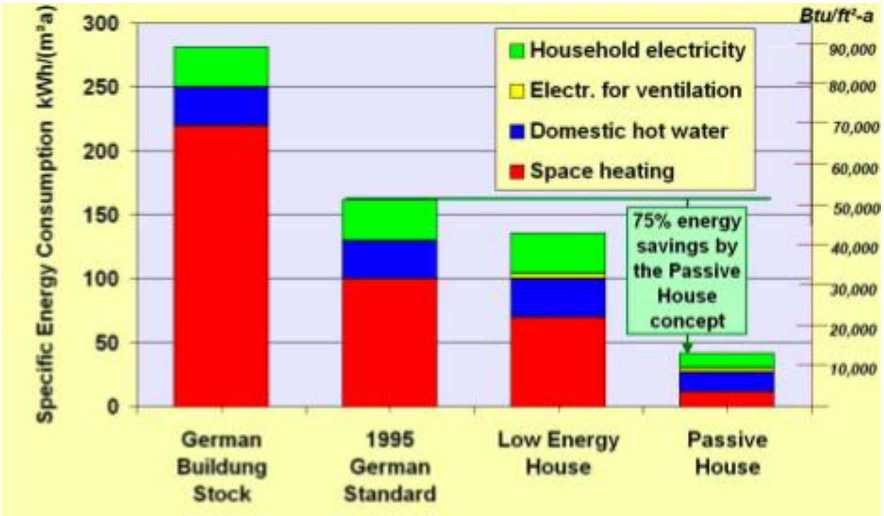

Figure 3: Comparison of energy consumption. Source: PHI

2.3 Passive House design strategy

In order to meet the before mentioned criteria, certain construction requirements are necessary for its concept of PassivHaus: (Laustsen, 2008), (Janson, 2010), (PassiveHaus UK) and (Feist W. , 2009)

- ***Super insulation.*** All the building parts must have a very high level of insulation preventing thermal bridging and air leakage. U-values of housing envelopes must be lower than 0.15 W/(m^{2}K).

- ***Highly insulated windows.*** Windows must be very efficient and have three layers of glass with low-e coating on multiple sides and filled with argon. It is also required to have energy efficient frames. The overall U-value for the windows including both glazing and frames should not exceed 0.80 W/(m^{2}K) with a solar-gain heat coefficient of about 50%.

- ***Thermal bridge free design.*** Thermal bridges must be avoided as they are the break of the thermal insulation surrounding the building and they can cause massive heat losses. Thermal bridges must be lower than 0.01 W/(mK).

- ***Airtight construction.*** High level of airtightness is necessary to assure a uniform indoor temperature without draughts and to avoid infiltration that does not pass through the heat exchanger of the ventilation system, which would lead to an increase in the space heating demand.

- ***Orientation.*** Windows must be orientated to the south to maximise the solar heat gains. Moreover, window area must be optimised to avoid an extreme increase in the indoor temperatures during the summer but also to avoid a large space heating demand due to the heat losses through them during the winter. Consideration must be done regarding the low surface temperatures and the discomfort of the occupants.

- ***Efficient mechanical ventilation.*** In order to ensure appropriate ventilation and to achieve a good level of indoor climate, efficient mechanical air ventilation must be provided. Fresh air demand should be 30 m^3/h person and typical air flow exchange is between 0.3 and 0.4 ac/h. Fresh air is brought from outside into the dwelling and stale air is blown out through the central ventilation system. Temperatures inside the dwelling must be homogeneous.

- ***Highly efficient heat recovery system.*** Installation of a heat exchanger is required. Most of the heat in the exhaust air has to be transferred to the incoming fresh air achieving an efficiency greater than 80%. The unit must be very quiet and the energy used for the fans must be very low. The ventilation system will have to be equipped with a bypass for the heat exchanger to avoid high temperatures during summer. Ducts must be insulated as well. Moreover, it exist the possibility of using the ground as a heat or cold buffer.

- ***Extra energy savings.*** Use the solar energy as a source of savings for both hot water supply and electricity using solar thermal collectors and PV panels. Use also low energy appliances.

However, Passive House design will depend on the climatic location of the dwelling and some corrections and adaptations might be done to these suggestions. For instance, Central and North Europe designs will usually meet all the aforementioned features but in the case of warm locations a modification in the design will be needed towards the field of passive cooling.

2.4 Expansion of the Passive House and Low-Energy House concept

As a consequence of the success that the first Passive House projects had had, several new projects started to appear in the late 1990s with the aim of exploring the conditions for a broad introduction of the PassivHaus concept.

2.4.1 CEPHEUS project

CEPHEUS project (Cost Efficient Passive Houses as EUropean Standards) was undertaken from 1998 to 2001 and it was a program supported by the Thermie-Program of the European Commission (BU/0127/97). The project consisted on the testing and proving of 221 housing units (within 14 projects) built following the PassivHaus standard in five different European countries: Germany, Austria, Sweden, Switzerland and France.

Figure 4: CEPHEUS sites. Source: PHI

The Passive Houses built were monitored and closely evaluated with the main aim of "demonstrate the technical feasibility (in terms of achieving the targeted energy performance indexes) at low extra cost (target: compensation of extra investment cost by cost savings in operation) for an array of different buildings, constructions and designs implemented by architects and developers in a variety of European countries" (PHI, 2011b). Moreover, the project was also carried out "to study the investor-purchaser acceptance" and "to create the preconditions for broad market introduction".

Based on the results obtained, it was considered that the CEPHEUS project was a total success due to the correct functionality of the dwellings in all the locations using different building styles, space heating savings of more than 80% and overall satisfaction of the occupants. Moreover, by the end of the project the number of Passive-House-compliant window products, heat recovery units and heat pump units available in the market had considerably increased.

2.4.2 IEA SHC Task 28 project

This project was undertaken from April 2000 to April 2005 with the aim of achieving a large penetration of the solar houses in the housing market of the 18 participating countries. This project was not only focus in the spread of the PassivHaus concept but also in the penetration of other low-energy building standards such as Factor-Four Plus Housing. The results of the project illustrated a wide range of strategies for designing these ecological buildings with all the construction details available to promote the integration into the market (Hastings & Wall, 2007).

2.4.3 PEP project

Promotion of European Passive Houses project (PEP) was completed in December 2007 with the objective of "to promote the potential of the European Passive House concept in Europe by the development of information packages and design tools for passive houses, the organization of (inter)national workshops, symposia and conferences and the set up of an international passive house website" (PEP Consortium). The project was partially supported by the European Commission under the Intelligent Energy Europe Programme and it prepared a certification scheme for Passive House certification in relation to the European Performance Building Directive. Participants of this project were Austria, Finland, Norway, Belgium, Germany, the UK, Denmark, Ireland and the Netherlands. It identified the general barriers towards the implementation of Passive Houses in the partner countries of the project (e.g. local building techniques or limited know-how and construction skills) giving suggestions to overcome these barriers (Strom, Joosten, & Boonstra, 2006).

2.4.4 NorthPass project

More recently, the NorthPass project was carried out supported by the EU's Intelligent Energy Europe programme. It was set in May 2009 and is still under development with a closing date in May 2012. The main aim of the project is to increase the awareness and to promote the market acceptance of very low energy buildings such as Passive Houses in Northern Europe countries. Member countries of this project are Denmark, Finland, Norway, Sweden, Estonia, Lithuania, Latvia and Poland. The outcome of the project will be an evaluation of the application of local criteria to these buildings and its applicability throughout the EU. Also, to give guidelines for the design of very low-energy houses in cold climates (VTT Technical research centre).

2.4.5 Passive-On project

This project was a research funded within the Intelligent Energy for Europe SAVE programme and it was run from January 2005 to September 2007. Unlike the previous projects, the partner countries were not located in North and Central Europe but they were countries of Southern Europe. The objective of this research was to examine how to take the concept of Passive House in these locations and to explore not only the necessity of providing warm houses in winter but also cool houses in summer. Specifically, the project addressed the question of this applicability in Italy, Spain and Portugal although also related to France and the UK as 'warm climates'.

The main innovation that this project carried out was the formulation of a revised proposal towards the application of the PassivHaus concept in these warm climates.

This was because in these locations, most architects associated a passive house to a dwelling built in accordance to the principles of passive solar design rather than to the PassivHaus standard. The recast proposed took into account these considerations and also the climatic conditions. The new points of the proposed PassivHaus Standard for Warm European Climates were (Passive-On project, 2007a):

- **Cooling criterion**. If cooling is provided by mainly passive means the indoor comfort requirements are defined by the Adaptive Model of the Annex A.2 of the EN 15251. Moreover, heating and cooling demand must be lower than 15 kWh/m^{2}a and total primary energy lower than 120 kWh/m^{2}a. On the other hand, if cooling is provided by mainly active systems the indoor comfort requirements are defined by the Fanger Model of the EN 15251. In addition, heating and cooling demand must be lower than 15 kWh/m^{2}a *each one* and total primary energy lower than 120 kWh/m^{2}a.

- **Air tightness.** "If good indoor air quality and high thermal comfort are achieved by means of a mechanical ventilation system, the building envelope should have a pressurization test (50 Pa) result according to EN 13829 of no more than 0.6 ac/h. For locations with winter design ambient temperatures above 0°C, *a pressurization test result of 1.0 ac/h is usually sufficient* to achieve the heating criterion".

- **Comfort criterion room temperature summer.** "In warm and hot seasons, operative room temperatures remain within the comfort range defined in EN 15251. Furthermore, if an active cooling system is the major cooling device; operative room temperature can be kept below 26 °C".

Moreover, the new proposal stated that the modified standard let the designer to choose from a wide range of alternative passive designs with the only requirement of guaranteeing the energy and comfort requisites set out in the standard.

One of the most relevant outcomes regarding this thesis was the elaboration of a table which associated the average cooling demand and heating demand of several locations within the project, with the values obtained for Madrid, city chosen in this thesis as a case study. Passive-On project established a relationship between the energy demand of these locations by setting two parameters called 'Winter Climatic Severity' and 'Summer Climatic Severity', obtained by dividing all the heating and cooling demands of the diverse sites by Madrid values. The advantage of using these Climatic Severity Indexes with respect to using the typical heating and cooling degree days was the fact that, apart from taking into consideration the climatic data, it also considered the building characteristics used.

The next table summarise the coefficients obtained with respect to Madrid:

Location	Winter Climatic Severity (WCS)	Summer Climatic Severity (SCS)
Germany (Dresden)	3.31	0.00
Germany (Braunschweig)	2.56	0.05
Germany (Freiburg)	2.14	0.10
United Kingdom (Brighton)	1.83	0.01
United Kingdom (Glasgow)	2.59	0.00
United Kingdom (London)	2.22	0.01
United Kingdom (Newcastle)	2.59	0.00
United Kingdom (Nottingham)	2.36	0.00
France (Agen)	1.44	0.19
France (Carcassonne)	1.24	0.37
Italy (Milan)	1.81	0.46
Italy (Rome)	0.83	1.19
Italy (Trapani)	0.32	1.87
Portugal (Lisbon)	0.37	1.05
Spain (Seville)	0.32	2.56
Spain (Madrid)	1.00	1.00
Spain (Granada)	0.81	1.11
Spain (Burgos)	1.96	0.05

Table 2: Climatic Severity Indexes in European locations. Source: Passive-On project

In addition, a correlation was found to get the ratio heating demand saving/insulation level in function of the orientation and climate.

Finally they propose several techniques to overcome the summer overheating through passive cooling. One of the main methods they suggested was to make use of an effective night ventilation taking advantage of the large summer diurnal swings in air temperature, in which the ambient temperature dropped below the room temperature. A well distributed airflow path and an automatic vent opening were considered vital to achieve an appropriate cooling.

The only specific data available regarding Spanish locations (Seville and Granada) shows that summer night ventilation strategy was scheduled. It worked "from 0 am to 7 am when, typically the outdoor air is colder that the indoor" and airflow rates of 4, 8 and 12 ac/h were assumed (Passive-On project, 2007b).

	Seville	Granada
Heating	2.8	8.7
Cooling	21.7	7.9

Table 3: Energy demand for Spanish locations (kWh). Source: Passive-On project

The fact that in Seville the cooling demand was very large due to the high temperatures, together with the fact that during winter in Granada the indoor resultant temperature drops until values about 17ºC (see next figure), suggest that both the temperature control and the night ventilation system used are not sensitive and effective enough to obtain results that could meet the PassivHaus criteria for warm climates.

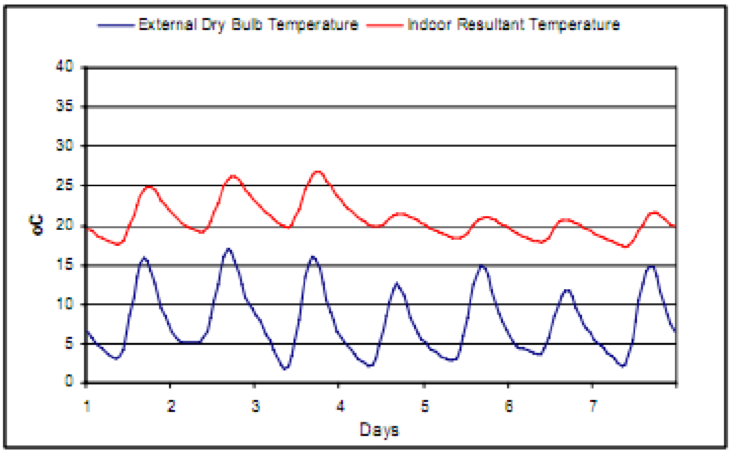

Table 4: Temperatures during one winter week in Granada. Source: Passive-On project

Furthermore, this thesis will try to research within this gap and to assess to what extent a mechanically controlled night ventilation system is able to reduce the cooling demand in a Spanish location such as Madrid. Also, it will be set a temperature control at the same time in order to maintain the temperatures between the comfortable range of 20ºC and 25ºC.

2.4.6 Passive Houses in South West Europe

This investigation carried out by Jürgen Schnieders and published in 2009 (2nd corrected edition) was originally a PhD dissertation at the University of Kaiserslautern. The study basically explore if the PassivHaus concept can be extended to South West Europe expanding the work carried out in the Passive-on project, research in which Jürgen Schnieders was main subcontractor and hence significant part of it was derived from him.

Regarding night ventilation, he states that a saving up to 3.8 kWh/m^2 in cooling demand may be achieved by combining the use of night ventilation with open windows with a ventilation heat recovery bypass (Schnieders, 2009). Moreover, in most of the climates the implementation of this passive cooling would be outweighed by a significant increase in the dehumidification demand but the Spanish case will be the exception due to its semi-arid climate. This circumstance suggest that in Madrid, place with a more continental climate than most of the Spanish cities due to its location in the middle of the Iberian Peninsula, dehumidification will be either not required or very small.

Between all the locations of this research, night ventilation rates worked better in Seville and Madrid providing a significant sensible cooling. Moreover, it was predicted a very slightly increase in the heating demand as a consequence of this night ventilation.

Taking in consideration the results of this research and also the ones of the Passive-On project, this thesis will undertake a study about the importance of installing a mechanically controlled night ventilation system in order to reduce the cooling demand in warm climates as it was explained in the previous page. A first evaluation of Passive House performance will be carried out in Scotland. Then, the model used in this location will be transferred to Madrid.

2.5 PHPP and ESP-r approaches

ESP-r was originated and developed at the University of Strathclyde in Glasgow by Professor Joe Clarke with the ambition of trying to involve as much as possible of the system, the building and its subsystems (Clarke, 2001). According to the Energy Systems Research Unit of the University of Strathclyde (ESRU, 2011), ESP-r is a general purpose energy modelling tool based on a finite volume conservation approach which the objective of simulating the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with associated environmental control systems. It allows the designer to explore the relationships between a building's form, fabric, air flow, plant and control and its response to climate, occupancy and control system influences. ESP-r has been validated and compared to other tools (Strachan, 2000) in diverse studies in both intermodal comparison against other simulation and to measured data.

On the other hand, the Passive House Planning Package (PHPP) is an excel spreadsheet based planning tool with the aim of assisting the design of a Passive House following the Passivhaus standard providing all the instruments necessary for the design of a well performing low energy building. It is a simplified stationary calculation method which treats the whole building as a single zone for purposes of energy calculations and shows the final results in terms of monthly energy balances (in accordance with EN 13790) rather than carrying out a dynamic simulation with short time-steps. It has identified the critical factors to obtain reliable results and its usage is more straightforward than most of the dynamic simulation software (PHI, 2011c). More information and detailed calculation system approach followed in PHPP is available in its manual (PHI, 2007).

In this thesis, a use of high resolution dynamic simulation is required in order to get enough accurate data about the mechanically controlled night ventilation system that was used. Hence, a very detail model of a specific Scottish Passive House will be designed in ESP-r following the specifications of the available PHPP. Comparison of between the results obtained using ESP-r and PHPP will be carried out. Finally, the ESP-r model will be transferred to a warmer climate to explore the importance of the abovementioned night ventilation system.

Moreover, in comparison with a full scale experiment, which requires much more time and expenses, the use of a dynamic simulation approach by means of ESP-r, will let to undertake a parametric study on how certain changes in some boundary conditions might affect to the final results. Another reason of using this dynamic simulation approach is to obtain a completely reproducible model with high resolution and reliability in which many others experiments and changes could be implemented in the future.

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3. Objectives, methodology and outcomes

3.1 Objectives

The first purpose of this thesis is to explore in detail the performance of a specific certified Passive House located in Dunoon (Scotland) by means of a dynamic simulation designing an ESP-r model of the building. Also, it explores the performance when the dwelling is transferred to a much warmer climate such as Madrid. In this location, the main objective is to study the great importance that the implementation of an adequate airflow control has in a Passive House. Specifically, it investigates the large benefits that the installation of a mechanically controlled night ventilation system has in reducing the cooling demand obtained as consequence of the high ambient temperatures. Secondary objective is a preliminary exploration of the amount of energy that could be obtained by installing a PV array contributing towards the possibility of achieving a Net Zero Energy building.

3.2 Methodology and outcomes

Methodology followed in this thesis is very linked with the outcomes obtained, as almost every step of it produces a different outcome.

1. Creation of a highly detailed model of Dunoon's Passive House in ESP-r.

All the construction details specification of the available PHPP certified spreadsheet will be introduced in the ESP-r database. This cover walls, roof, floor and windows composition and thermal characteristics. Windows reveals, external shading and infiltration and ventilation patterns are considered as well. Also, to make this model available as exemplar since currently there is not a default model of Passive House in ESP-r (it will also be available the model with night ventilation implemented).

2. Detailed exploration of Passive House in Dunoon, Scotland. Benefits of dynamic simulation.

Using the previous dynamic simulation approach, high resolution data of parameters such as climate data, zone temperatures, heating demand, heat gains and losses (through surfaces, casual gains, infiltration, ventilation and solar radiation) or thermal comfort will be analysed.

Apart from allowing the user to get very high resolution data, dynamic simulation permits to implement some modifications in the model with the aim of obtaining a better simulation of the occupants' behaviour. Using the power of this approach, modifications such as sensing the Zone Resultant Temperature instead of the Dry Bulb Temperature were carried out.

3. ESP-r – PHPP results comparison.

Results obtained using dynamic and simplified stationary approaches were analysed identifying and discussing the differences between them.

4. Exploration of Passive House performance in warm climates. Importance of mechanically controlled night ventilation system.

Performance of the model when it is transferred to a warmer location such as Madrid was explored obtaining a significant overheating with respect to the Scottish location. It was analysed the importance of having an appropriate airflow network in a Passive House and studied to what extent a mechanically controlled night ventilation system modelled in ESP-r could be able to mitigate the high cooling demand obtained as consequence of the high ambient temperatures. As the main aim of this section was to evaluate the power of the aforementioned system and the length of this project was highly time constrained, Scottish vernacular architecture was not modified when the model was transferred to the new location. Therefore, this study could also be considered as a method to mitigate the coming global warming in cold climates. Results show the great advantages of the installation of this type of night ventilation system since a saving of more than 50% in cooling demand was achieved and PassivHaus criteria in terms of energy demand was met just by implementing this scheme. Further work will be suggested regarding the application of this scheme in a Passive House adapted to this type of climates (shading devices, building techniques, etc.).

5. Adaptation of Passive House towards Net Zero Energy buildings.

To conclude this research, a brief preliminary study of the possibility of achieving a Net Zero Energy building is undertaken. A PV system was carefully designed and installed evaluating the total energy that could be supplied from this scheme. MERIT software was used for this purpose.

4 Description and modelling of a specific Passive House in Dunoon, Scotland

This project explores in detail the performance of a particular Passive House situated in Dunoon (Scotland). A very detailed model of this dwelling will be designed using ESP-r and a set of simulations will be done for the actual location of the building. Results will be compared with the available Passive House Planning Package (PHPP).

The first step of this project is to describe in detail the situation and characteristics of the dwelling as it was necessary to introduce in the ESP-r database all its construction details specifications. This was done using the information of the available PHPP certified spreadsheet (Dunoon's PHPP, 2011) regarding walls, roof, floor and windows composition and thermal characteristics.

4.1 Dunoon's Passive House

Dunoon is a little city situated around 20 miles on the west with respect to Glasgow. This location suggests that the climate of the Passive House will be more moderate than the Glaswegian climate due to it is situated just by the sea.

Figure 5: Google Maps snapshot of Dunoon and surroundings.

The building under study is the first of the 10 semi-detached houses of the next figure:

Figure 6: Google Maps snapshot of the Passive House in Dunoon.

Drawings of the Passive House for the South elevation and West and East elevation respectively are detailed below:

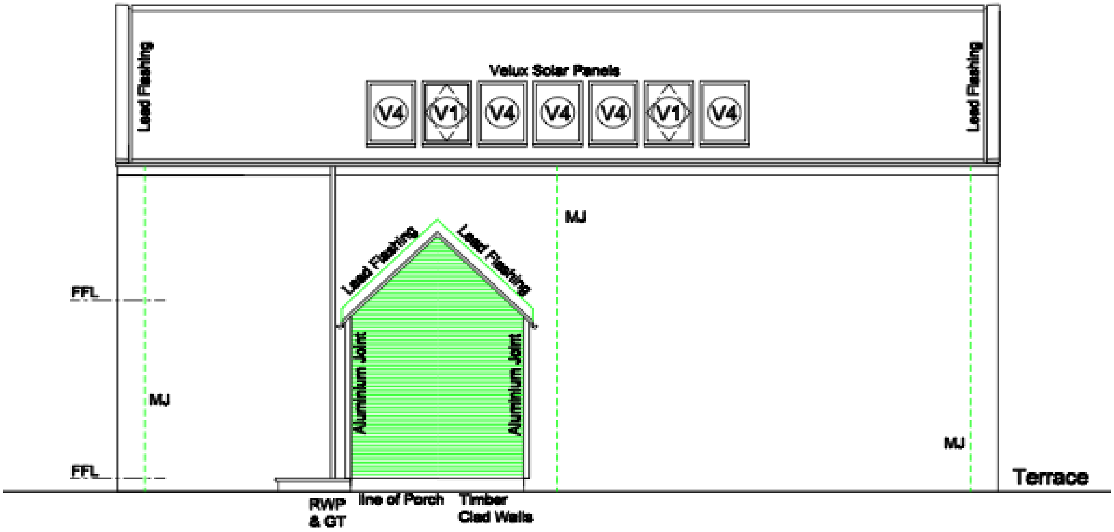

Figure 7: South elevation. Source: thesis supervisor

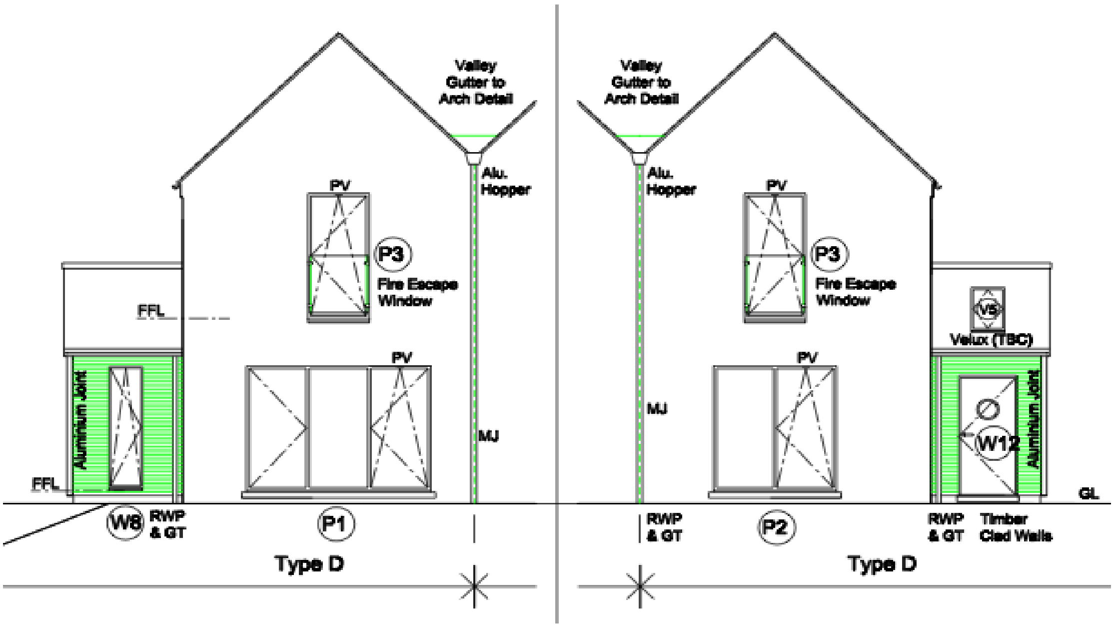

Figure 8: West and East elevation. Source: thesis supervisor

By inspection we can realise about some major problems regarding the shape of the building. It is shown that there are no south facing windows apart from two rooflights V1 (the other five stated as V4 are solar thermal panels) which means that the solar heating gains during the year will not be very high. Moreover, it is a long and tall house with a small floor area resulting in a very large exterior surface and hence the heat losses throughout the walls will be considerable being in that way a parameter to take into account regarding the total heating demand.

It seems clear then, that one of the main issues to be aware when looking at a low energy building is the insulation of its thermal envelope. The Passive House standard allows a maximum U-value of are 0.15 W/(m^{2}K) for opaque elements like walls, ground floor and roof, and a maximum of 0.8 W/(m^{2}K) for windows and doors.

4.2 Envelop construction information

The next section describes the specification of the building's thermal envelop as stated in the certified PHPP spreadsheet supplied by the thesis supervisor:

4.2.1 Walls

The walls of the house are made of a typical construction for Passive House including (from the inside to the outside) layers of plasterboard, polyurethane insulation, OSB, mineral wool with I-studs, softwood and OSB again. The total thickness of these ambient walls is 38.1 cm and the overall U-value is 0.086 W/(m^{2}K). Details of this construction are shown in the next table.

Assembly No.: 1 — Building Assembly Description: Ambient wall

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)]	Total Width Thickness [mm]
1.	Plasterboard	0.210					13
2.	PU insulation TW55	0.021					50
3.	OSB	0.130					9
4.	Mineral wool/I-studs	0.032	softwood	0.130			50
5.	Mineral wool/I-studs	0.032			softwood	0.130	200
6.	Mineral wool/I-studs	0.032	softwood	0.130			50
7.	OSB	0.130					9
8.							

Percentage of Sec. 2: 8.3% — Percentage of Sec. 3: 1.6% — Total: 38.1 cm

U-Value: 0.086 W/(m²K)

Table 5: Wall construction.

4.2.2 Roof

The composition of the roof is basically the same than the one for the walls with a different in the material of the external layer; it uses 22 mm of sarking boards instead of 9 mm of OSB (note that both materials have the same thermal conductivity). Then, the total thickness for the roof is 39.4 cm and the overall U-value will be almost the same than for the walls, 0.087 W/(m^{2}K). See next table for further details.

Assembly No.	Building Assembly Description
2	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)]	Total Width Thickness [mm]
1.	Plasterboard	0.210					13
2.	PU insulation TW55	0.021					50
3.	OSB	0.130					9
4.	Mineral wool/I-studs	0.032	softwood	0.130			50
5.	Mineral wool/I-studs	0.032			softwood	0.130	200
6.	Mineral wool/I-studs	0.032	softwood	0.130			50
7.	Sarking boards	0.130					22
8.							
			Percentage of Sec. 2	8.3%	Percentage of Sec. 3	1.6%	Total 39.4 cm

U-Value: 0.087 W/(m²K)

Table 6: Roof construction.

4.2.3 Floor

For the floor it was used a first layer of concrete slab and then a second layer of extruded polystyrene insulation. The total thickness of the floor is 32.5 cm and the overall U-value is 0.154 W/(m^{2}K). Details of this construction are shown in the next table.

Assembly No.	Building Assembly Description
3	Floor slab

Heat Transfer Resistance [m²K/W] interior R_{si} : 0.17

exterior Rse: 0.00

	Area Section 1	λ[W/(mK)]	Area Section 2 (optional)	λ[W/(mK)]	Area Section 3 (optional)	λ[W/(mK)]	Total Width Thickness [mm]
1.	Concrete slab	2.100					125
2.	Insulation XPS	0.032					200
3.							
4.							
5.							
6.							
7.							
8.							
			Percentage of Sec. 2		Percentage of Sec. 3		Total 32.5 cm

U-Value: 0.154 W/(m²K)

Table 7: Floor construction.

4.2.4 Windows

As we can see in the layout of the house, there are a total of ten windows distributed within the two floors. It is important to highlight that the whole porch was neglected for this project (and hence the window of the porch) due to it was unheated and thus there is not energy requirement for it. By inspection of the plans, three different types of windows can be found: three small Velux rooflights stated as V1 (two South facing and one North facing), two big fixed windows and five big operable windows (represented with dotted lines). The next table stated the dimension of the windows and their g-value. It also contains the U-value and Ψ-value for the glazing and the frames. Note that it was the only available information and it was not possible to find the details of the specific composition of each type of window.

			Window Rough Openings		g-Value	U-Value		Ψ–Value	
Quan-tity	Description	Orientation	Width	Height	Perpen-dicular Radiation	Glazing	Frames	YSpacer	Y Instal
			m	m	-	W/(m2K)	W/(m2K)	W/(mK)	W/(mK)
1	Living room	East	0.993	2.180	0.51	0.80	0.87	0.075	0.025
1	Living room	East	0.993	2.180	0.51	0.80	0.87	0.075	0.025
1	Living room	East	0.994	2.180	0.51	0.80	0.75	0.075	0.025
1	Kitchen	West	1.028	2.150	0.51	0.80	0.87	0.075	0.030
1	Kitchen	West	0.952	2.150	0.51	0.80	0.75	0.075	0.030
1	Bed 1	West	0.980	2.150	0.51	0.80	0.87	0.075	0.030
1	Bed 2	East	0.980	2.150	0.51	0.80	0.87	0.075	0.030
2	Velux 3065 M08	South	0.780	1.400	0.45	0.63	1.50	0.029	0.079
1	Velux 3065 M04	North	0.780	0.980	0.45	0.63	1.50	0.029	0.079

Table 8: Windows details.

4.3 ESP-r initial model

As part of the outcome of this dissertation, an initial ESP-r model of a Passive House will be designed *based on the information provided in the drawings and PHPP* of the Passive House located in Dunoon. This model will be available for next researches that would like to continue with this study further away. As the current downloadable version of ESP-r does not contain a specific model of this type of low energy building, it will be necessary to build the house from scratch. Not only does this include the design of the envelope but also to create a new set of databases for the diverse materials, constructions and optical properties used as well as bearing in mind other parameters such as the shading of the building or the casual heat gains. With the objective of having a clear view about all the boundary conditions and specification of the model and to fully understand the simulations of the next sections, details of all the design of the model will be given in this chapter. Note that this section only shows the details of the design of the ESP-r model that will be used as starting point and initial model for the simulations. In further sections, several modifications will be done to the initial model in order to study the performance of the Passive House with respect to these changes. Details of these modifications will be provided.

4.3.1 Building location and orientation

It is important to consider the climate in which the building is going to perform as it will be the most sensitive parameter in the simulation. ESP-r offers the possibility of either choosing a climate data from its wide database or importing the desired climate from other external sources. For the purpose of this project, the default ESP-r climate database will be used. A set of simulations will be run for Oban first (as it has a similar climate as Dunoon), and Madrid afterwards, in order to study the performance of the Passive House in different climates. Note that Oban's climate data description is available in section 5.1.1 and note also that ambient temperature comparison between ESP-r approach using Oban's data and PHPP approach using Glasgow's data is available in section 5.2.2.

The orientation of the building is a parameter to consider as it will influence in the amount of solar heat gains that the dwelling will receive. In the next figure, it may be identified that the deviation from the North of the South elevation is 163º rather than 180º. Then, a shift of 17º will be needed to consider when building the envelope of the house.

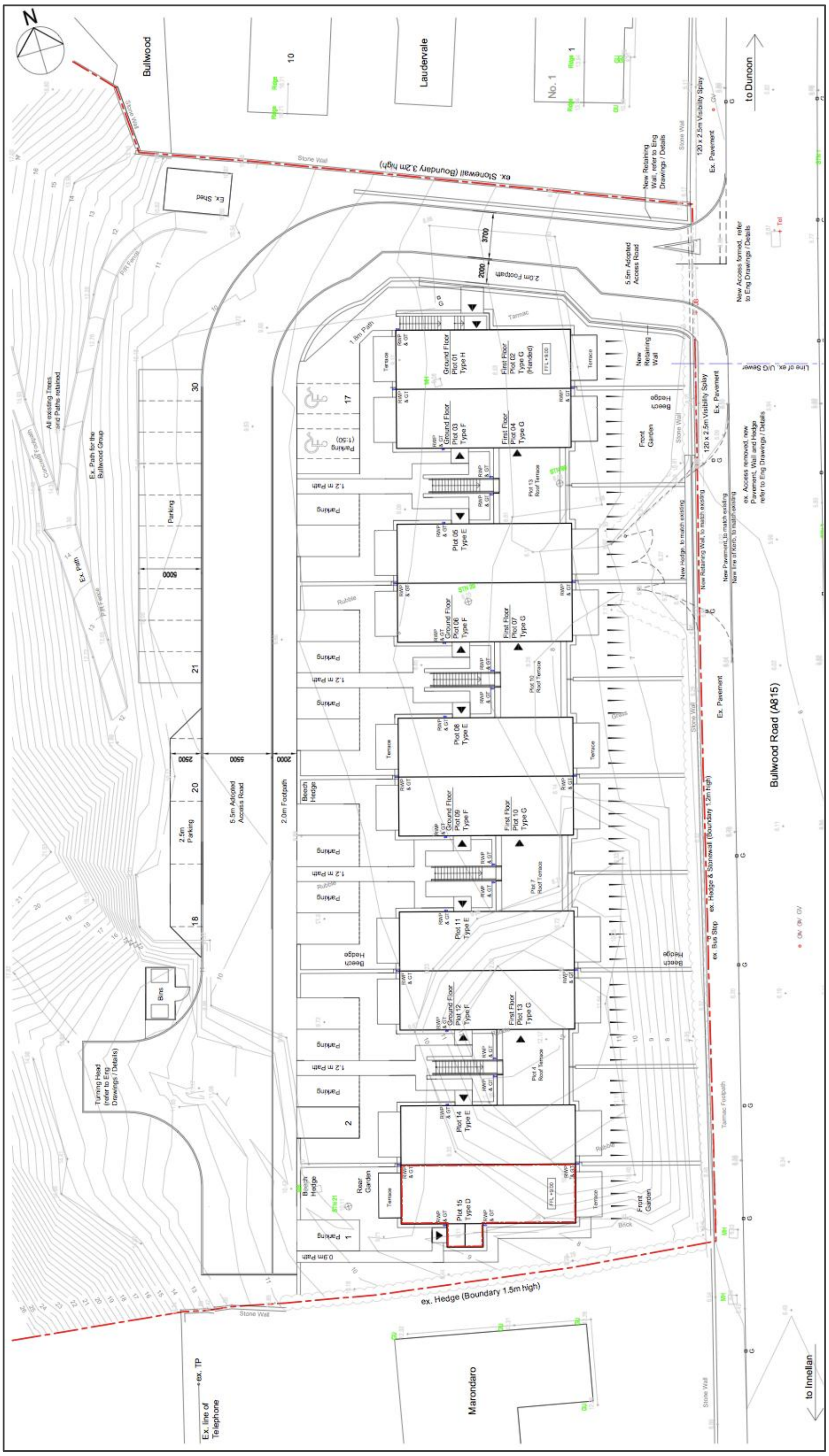

Figure 9: Building orientation

4.3.2 Building envelope construction

The first step is to have a look to the plans of the building and to choose how to build the building envelope. In order to simplify the model, it was decided to divide it in two different zones; one for the ground floor and another for the first floor, avoiding in that way the construction of each of the rooms of the house and making the model more complex. Also, it will not be necessary to design a connection between both zones (i.e. stairs space) as in ESP-r it is possible to specify the ventilation air change rate from one zone to the other. As it was mentioned before, the porch was neglected due to it is unheated. Furniture and equipment effects were neglected as well.

4.3.2.1 Walls, roof and floor

Once that the dimensions of each of the zones have been identified and the envelope of the building has been created, it is time to specify the composition of each surface. As the default database does not include the composition of the actual Passive House we are modelling it was necessary to create a new set of constructions based on the specification mentioned in the previous section (see Table 5, Table 6 and Table 7). The next tables show the building envelop construction for each surface:

```
Details of opaque construction: Wall_PH and overall thickness  0.381

Layer|Matr|Thick |Conduc-|Density|Specif|IR  |Solr|Difful R    |Descr
     |db  |(mm)  |tivity |       |heat  |emis|abs |resis|m^2K/W
Ext   112   13.0    0.210   900.  1000. 0.91 0.70    11.  0.06 Plasterboard (UK code) : Plasterboard (UK co
   2  234   50.0    0.021    30.   837. 0.90 0.50    90.  2.38 PU PH : Polyurethane insulation TW55
   3   79    9.0    0.130   650.  1700. 0.90 0.70  1200.  0.07 OSB : OSB wood based on the SBEM database
   4  307  288.5    0.032    12.  1000. 0.90 0.70    30.  9.02 Min wool PH : Insulation Mineral wool with I
   5   71   11.5    0.130   630.  2760. 0.90 0.65    12.  0.09 softwood : Softwood (generic)
Int    79    9.0    0.130   650.  1700. 0.90 0.70  1200.  0.07 OSB : OSB wood based on the SBEM database
ISO 6946 U values (horiz/upward/downward heat flow)=  0.084  0.085  0.084 (partition)  0.084
Total area of Wall_PH is    161.79
```

Table 9: ESP-r wall construction details.

```
Details of opaque construction: Roof_PH and overall thickness  0.394

Layer|Matr|Thick |Conduc-|Density|Specif|IR  |Solr|Difful R    |Descr
     |db  |(mm)  |tivity |       |heat  |emis|abs |resis|m^2K/W
Ext   112   13.0    0.210   900.  1000. 0.91 0.70    11.  0.06 Plasterboard (UK code) : Plasterboard (UK co
   2  234   50.0    0.021    30.   837. 0.90 0.50    90.  2.38 PU PH : Polyurethane insulation TW55
   3   79    9.0    0.130   650.  1700. 0.90 0.70  1200.  0.07 OSB : OSB wood based on the SBEM database
   4  307  288.5    0.032    12.  1000. 0.90 0.70    30.  9.02 Min wool PH : Insulation Mineral wool with I
   5   71   11.5    0.130   630.  2760. 0.90 0.65    12.  0.09 softwood : Softwood (generic)
Int    91   22.0    0.130   650.  1700. 0.90 0.70  1200.  0.17 Sarking board PH : Sarking board for a PH
ISO 6946 U values (horiz/upward/downward heat flow)=  0.084  0.084  0.083 (partition)  0.083
Total area of Roof_PH is     69.35
```

Table 10: ESP-r roof construction details.

```
Details of opaque construction: Floor_PH and overall thickness  0.325

Layer|Matr|Thick |Conduc-|Density|Specif|IR  |Solr|Diffu| R    |Descr
     |db  |(mm)  |tivity |       |heat  |emis|abs |resis|m^2K/W
Ext    50  125.0     2.100  2400.  1000. 0.90 0.70    13.  0.06 Concrete slab PH : Concrete slab high densit
Int   235  200.0     0.032    38.  1450. 0.90 0.30   350.  6.25 XPS insulation PH : XPS extruded polystyrene
ISO 6946 U values (horiz/upward/downward heat flow)=  0.154  0.155  0.153 (partition)  0.152
Total area of Floor_PH is     52.07
```

Table 11: ESP-r floor construction details.

As it can be seen, despite the composition and thickness of each layer is the same than the ones specified in the PHPP spreadsheet, the U-values obtained could be slightly different due to ESP-r does not use this value for the simulation, but it calculates it based on all the other properties of the materials used. For instance, the PHPP U-value for the walls is 0.086 and the ESP-r U-value is 0.084. However, this little difference will not make a big difference in the simulations.

But what it is important to highlight is that a new construction had to be built with respect to the PHPP spreadsheet. As two different floors are being considered, it is required to detail the composition of the construction which separates the ground floor and the first floor. A typical construction made of plasterboard, mineral wood, air cavity and OSB was used:

```
Details of opaque construction: Ceiling-floo and overall thickness  0.102

Layer|Matr|Thick |Conduc-|Density|Specif|IR  |Solr|Diffu| R    |Descr
     |db  |(mm)  |tivity |       |heat  |emis|abs |resis|m^2K/W
Ext   112   13.0     0.210   900.  1000. 0.91 0.70    11.  0.06 Plasterboard (UK code) : Plasterboard (UK co
   2  307   50.0     0.032    12.  1000. 0.90 0.70    30.  1.56 Min wool PH : Insulation Mineral wool with I
   3    0   22.0     0.000     0.     0. 0.99 0.99     1.  0.17 air  0.17 0.17 0.17
Int    79   17.0     0.130   650.  1700. 0.90 0.70  1200.  0.13 OSB : OSB wood based on the SBEM database
ISO 6946 U values (horiz/upward/downward heat flow)=  0.477  0.484  0.468 (partition)  0.458
Total area of Ceiling-floo is     52.07

Details of transparent construction: PH_Wind_Air with PH_3_Arg-e optics and overall thickness  0.037
```

Table 12: ESP-r ceiling-floor construction details.

Note that as ESP-r runs the simulations zone by zone, this construction was placed in the ground floor and another similar construction but inversed was required to be built for the first floor.

Therefore, this two zones consideration will be *one of the first differences when comparing PHPP with ESP-r*. South facing windows are located just in the first floor and hence the temperature of this zone will tend to be higher than the temperature of the ground floor because of the solar heat gains. Also it must be taken into account that the overall glazing surface is less for the first floor which means less heat losses. Then, the fact of setting an air change rate from one floor to the other later on will create heat transfer from the warmest room (first floor) to the coldest room (ground floor). However, this effect will be slightly minimised due to the tendency of warm air to rise. Further details can be found in the discussion section.

The next figure shows the Passive House design so far:

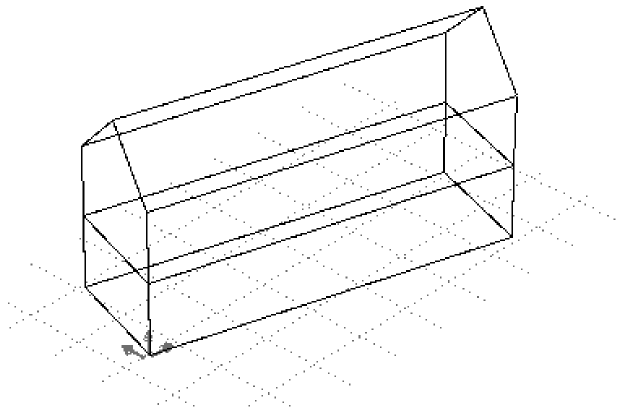

Figure 10: Passive House model.

As PHPP spreadsheet does, in order to get reliable results it is necessary to specify the environment of each surface in ESP-r, i.e. either it is facing the exterior, to another zone, etc. In this model all the surfaces will be facing the exterior except the floor which will be facing the ground and the North walls that will be facing another similar building due to we are dealing with a semi-detached house.

4.3.2.2 <u>Windows: glazing and frames</u>

Next step is to create the windows and doors of the building. As it was already mentioned, the door of the house was neglected to simplify the model. Although it was a crystal door, solar heat gains may be neglected due to it led to the porch which acts as shading. Moreover, U-value of the door will be reduced by sheltering, which makes door's U-value to approximate to walls' U-value.

Again, it was necessary to add new constructions to the database as it did not contain the assembly required.

In order to obtain a model properly bounded and without any edge problem, frame design must be done prior to glazing design using for both components the option 'insert within a surface' and choosing the appropriate wall. In this way, glazing will be child of the frame and the frame child of the wall. After having created these new components, it is also important to make sure that the vertexes of the wall which contains the surfaces are correctly specified taking into account the new creations.

It is also need to mention that the drawings of the Passive House did not show much details of the materials used in the construction of both glazing and frames (it only said that windows were triple glazed with argon in between). Hence the only data available to create the new database was the specified in the PHPP spreadsheet: U-value and g-value for the glazing and U-value for the frames (also lengths and widths). Typical Passive House constructions for glazing and frames were carried out to fulfilling these U-values and g-values. Moreover, although ESP-r shows both of these parameters in the user's interface, it does not use either of them in the simulations. The software, however, uses other variables associated with these values that it can be input and hence a new approach will be needed to create the specific construction database required.

- *Frames*:

According to PHPP spreadsheet, three different types of frames are needed in the model. One for the small windows of the roof (Frame_PH_PV) with a U-value of 1.50 $W/(m^2K)$, another one for the big operable windows (Frame_PH_Sas) with a U-value of 0.87 $W/(m^2K)$ and a last one for the big fixed windows (Frame_PH_Fix) with a U-value of 0.75 $W/(m^2K)$. See drawings to differentiate the location of operable windows (with dotted lines) and fixed windows. Note that PassivHaus criteria states that windows should have U-values lower than 0.8 $W/(m^2K)$ and then these windows does not meet it. However, the Passive House was verified due to the overall heating load was lower than 10 W/m^2.

Regarding frames composition, it was thought that a typical frame composition of three layers made of softwood, expanded polystyrene (EPS) and softwood again would fit quite well within the PassivHaus concept. A default value of 12 mm was set for the softwood layers and different thicknesses of EPS were tested until the U-value of each of the frame composition was satisfied. As it is shown in the table below, thicknesses of 9 mm, 24 mm and 29 mm were required to meet the U-value specification of each type of frame:

```
This surface probably wraps around another surface.

Surface|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
layer  |db | (mm)  |tivity |        |heat  |emis|abs |
Frame_Wind_2 is composed of Frame_PH_PV and is opaque:
    1   71   12.0     0.130   630.0  2760.0 0.90 0.65  softwood
    2  214    9.0     0.030    25.0  1000.0            EPS
    3   71   12.0     0.130   630.0  2760.0 0.90 0.65  softwood
 ISO 6946 U values (hor/up/dn heat flow) for Frame_PH_PV is  1.528  1.601  1.440 (partn)  1.343
-------------------------------------------------------
This surface probably wraps around another surface.

Surface|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
layer  |db | (mm)  |tivity |        |heat  |emis|abs |
Frame_2 is composed of Frame_PH_Sas and is opaque:
    1   71   12.0     0.130   630.0  2760.0 0.90 0.65  softwood
    2  214   24.0     0.030    25.0  1000.0            EPS
    3   71   12.0     0.130   630.0  2760.0 0.90 0.65  softwood
 ISO 6946 U values (hor/up/dn heat flow) for Frame_PH_Sas is  0.866  0.889  0.837 (partn)  0.803
-------------------------------------------------------
This surface probably wraps around another surface.

Surface|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
layer  |db | (mm)  |tivity |        |heat  |emis|abs |
Frame_2 is composed of Frame_PH_Fix and is opaque:
    1   71   12.0     0.130   630.0  2760.0 0.90 0.65  softwood
    2  214   29.0     0.030    25.0  1000.0            EPS
    3   71   12.0     0.130   630.0  2760.0 0.90 0.65  softwood
 ISO 6946 U values (hor/up/dn heat flow) for Frame_PH_Fix is  0.757  0.774  0.735 (partn)  0.709
-------------------------------------------------------
```

Table 13: Frame composition for reaching the U-value required.

- *Glazing*:

A similar approach was carried out in order to create the glazing of the windows. This time, only two types of glazing were required. One for the small windows of the roof (PH_Velux_Win) with a U-value of 0.63 W/(m^{2}K), and another one for the big operable and fixed windows (PH_Wind_Air) with a U-value of 0.80 W/(m^{2}K).

Regarding glazing composition, it was used triple glazing filled with argon as stated in the PHPP spreadsheet. Also it was specified the thickness of each layer: 6 mm, 5 mm and 6 mm for the glazing, filled with 10 mm of argon. Plate glass and air were used for the construction but then, in order to simulate the presence or argon and hence to reduce the overall U-value, the R value of the gas had to be adjusted. The next calculation shows, as example, the method used to reach the required U-value of 0.63 W/(m^{2}K) for the small windows of the roof:

$$A\ couple\ of\ basic\ heat\ transfer\ equations\ through\ a\ wall\ are:$$

$$\Sigma R = \frac{1}{U_T \cdot A} \quad and\ R_i = \frac{L_i}{K_i \cdot A}$$

$$For\ the\ glazing\ construction:$$

$$\Sigma R = R_{s1} + R_{s2} + R_1 + R_2 + R_3 + 2R_{gas}$$

$$where\ R_{s1}\ and\ R_{s2}\ are\ the\ surface\ resistances.$$

$$And\ taking\ out\ the\ areas\ in\ both\ sides\ we\ obtain:$$

$$\frac{1}{U} = 0.13 + 0.04 + \frac{0.006}{0.760} + \frac{0.005}{0.760} + \frac{0.006}{0.760} + 2R_{gas}$$

$$where\ 0.760\ is\ the\ thermal\ conductivity\ of\ the\ glass.$$

$$And\ then\ substituting\ U\ for\ the\ U\ value\ of\ the\ glazing, i.e.\ 0.63\,\frac{W}{m^2K}$$

$$R_{gas} = 0.698 \cong \boxed{0.700\ \frac{m^2K}{W}}$$

Thus, it will be required an R value of about 0.700 (m^2K)/W to reach the U-value specified of 0.63 W/(m^2K). Note that for the other glazing construction the R value was calculated in the same way. The next table shows a summary of both glazing constructions:

```
Surface|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
layer  |db | (mm)  |tivity |        |heat  |emis|abs |
Wind_1 is composed of PH_Velux_Win & optics PH_3_Arg-e
    1  242    6.0    0.760  2710.0   837.0 0.83 0.05  plate glass
    2    0   10.0    0.000     0.0     0.0            air gap (R= 0.700)
    3  242    5.0    0.760  2710.0   837.0            plate glass
    4    0   10.0    0.000     0.0     0.0            air gap (R= 0.700)
    5  242    6.0    0.760  2710.0   837.0 0.83 0.05  plate glass
 ISO 6946 U values (hor/up/dn heat flow) for PH_Velux_Win is  0.628  0.640  0.613 (partn)  0.594

Surface|Mat|Thick  |Conduc-|Density |Specif|IR  |Solr| Description
layer  |db | (mm)  |tivity |        |heat  |emis|abs |
Liv_win_sash is composed of PH_Wind_Air & optics PH_3_Arg-e
    1  242    6.0    0.760  2710.0   837.0 0.83 0.05  plate glass
    2    0   10.0    0.000     0.0     0.0            air gap (R= 0.530)
    3  242    5.0    0.760  2710.0   837.0            plate glass
    4    0   10.0    0.000     0.0     0.0            air gap (R= 0.530)
    5  242    6.0    0.760  2710.0   837.0 0.83 0.05  plate glass
 ISO 6946 U values (hor/up/dn heat flow) for PH_Wind_Air is  0.798  0.818  0.774 (partn)  0.745
```

Table 14: Glazing constructions.

But as far as the glazing concerned, this is not the whole story. Besides the necessity to meet the U-value specified, it is also required that the window construction meets the g-value (solar total energy transmittance) stated in the PHPP spreadsheet in order to get an accurate model.

4.3.2.3 *Optical properties*

Glazing must optimize the entry of solar radiation. This is measured using the g-value, which is the total solar energy transmittance and it is calculated using the sum of the primary solar transmittance (solar radiation that directly enters a building through a window) and the secondary transmission (solar radiation absorbed by the glazing and transferred into the room).

In ESP-r is not possible to create a window with a specific g-value straight away. Moreover, it does not use this value for the calculations but it uses another variables associate with this parameter. The only method to meet at the same time the g-value and the U-value stated in PHPP, will be to use an external software as WINDOW 6 in order to create a triple glazing window filled with argon with the desired g-value and U-value. Then, all the rest of the parameters obtained associated with these values (direct transmission and absorption at different angles, etc.) will be imported to the ESP-r optical database, creating in that way a set of optical properties linked with the available PHPP g-value.

WINDOW 6 is a program to model products for National Fenestration Rating Council (NFRC) certified simulations. For the purpose of this research, it was only necessary to use the 'Glazing System Library', where the user must look for a specific glazing composition selecting as well the gas filling. The difficulty of this process lies in selecting the correct type of glass which gives at the same time the U-value and g-value we are looking for and hence, the unique method to reach both values is the trial and error approach. Note also that it is needed to bear in mind that in order to meet the PassivHaus standard it is necessary to use windows with low-E coating in both sides.

The selection made for the big windows of the Passive House was two glasses ID 5142 and one glass ID 884 filling the both gaps with argon. The U-value and g-value obtained for the construction was approximately the same as the target values (0.80 $W/(m^2K)$ and 0.51 respectively). The last step was to fill the optical database with the values obtained from WINDOW 6.

Note that the use of WINDOW 6 is beyond the scope of this project and not further details of how to use this software and obtain the desired results will be provided. For the other type of window construction (rooflights), the method followed was the same. Further explanations of this program can be found in its *Simulation Manual* available online as a PDF document. (Mitchell, Kohler, Zhu, & Arasteh, 2011)

After all these modifications regarding the glazing, the frames and the optical properties the envelope of the Passive House design is done and looks like that:

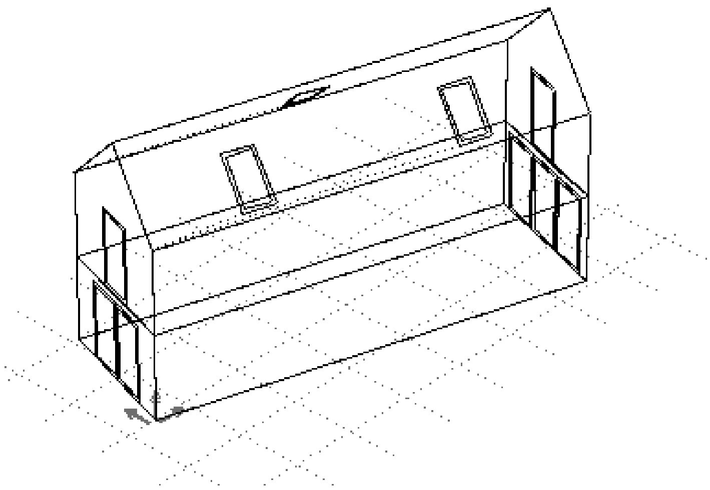

Figure 11: Passive House model.

4.3.2.4 Thermal bridges

ESP-r let the user to define linear thermal bridges in each zone of the model. In order to meet the Passivhaus standard it is highly recommended to obtain a thermal bridge free construction; i.e. with a thermal bridge coefficient (Ψ) lower than 0.01 W/(mK). (PHI, Design avoiding thermal bridges, 2011) As the available data suggests, all the junctions between walls, ground and roof will be considered as thermal bridge free and then only the junctions regarding the windows will be specified as thermal bridges.

Thermal bridge heat loss coefficients for the windows were available in the PHPP spreadsheet supplied. There were two different Ψ values: Ψ_{spacer} and $\Psi_{installation}$. The total Ψ was assumed to be the addition of both thermal bridge coefficients due to the small width of the frames. First of all, it was necessary to study the geometry of each zone of the model and to calculate the length of the thermal bridges for the lintel above the windows, for the sill below the windows and for the jamb at the windows.

The ground floor comprises five big windows and the length of the thermal bridges calculated were 5.96 m for both the lintels and the sills, and 23.80 m for the jamb. The total Ψ-value was estimated as 0.100 W/(mK) and then the total losses of the ground floor due to thermal bridges are:

$$(5.96 * 0.100) + (5.96 * 0.100) + (23.80 * 0.100) = 3.572\ W/K$$

As far as the first floor is concerned, it comprises two big windows and three small skylights. The length of the thermal bridges calculated were 5.30 m for both the lintels and the sills, and 17.32 m for the jambs. The total Ψ-value was estimated as 0.106 W/(mK) and then the total losses of the first floor due to thermal bridges are:

$$(5.30 * 0.106) + (5.30 * 0.106) + (17.32 * 0.100) = 2.792\ W/K$$

It can be seen then how the ground floor has more thermal bridge losses due to its larger glazing area.

4.3.3 Shading

The next issue to consider is the shading of the building, which will contribute to reduce the overall solar heat gains within the year. For this model it will be considered two different types of shading; shading by external objects such as row houses or nearby hills, and shading by window reveals (note that the building does not have balcony slabs). Again, all the data was obtained from the PHPP spreadsheet. In ESP-r, the shading of the building may be defined in the submenu *solar obstruction*.

4.3.3.1 External objects

In order to run a set of simulations and to make a discussion of the results for a general model of a Passive House, the creation of these shading details by external objects will not be necessary due to the dwelling is not placed in a specific location.

However, as this project is focused on a particular Passive House located in Dunoon, it will be required to specify all the types of shading that might affect to the thermal performance of the building.

As the ESP-r model had not got any shading element either in the North nor the South that could affect to the north and south facing rooflights (the south-glazed door was neglected due to it led to a porch), it will be only necessary to consider the shading in the East and West façades. Two main elements were identified as external objects: first, a hill/cliff to the West of 25 m high at a distance of 20 m from the house. Second, a large fence to the East of 1.20 m at a distance of 10 m from the house. As it was mentioned in previous sections, the North façade was shifted 17º clockwise which made much more complicated the creation of both external objects. It was required to input the origin coordinates (X, Y, Z) of the shading and then the dimensions and the rotation of the block. The problem lied in finding the origin coordinates of the shading block bearing in mind the 17º shifting of the building and the block-house horizontal distance. Trigonometry calculation was required to find the origin point.

4.3.3.2 <u>Window reveals</u>

It was assumed a window reveal depth of 0.15 m for each of the windows of the building.

After having included all the solar obstructions mentioned, the model of the Passive House looked as follows:

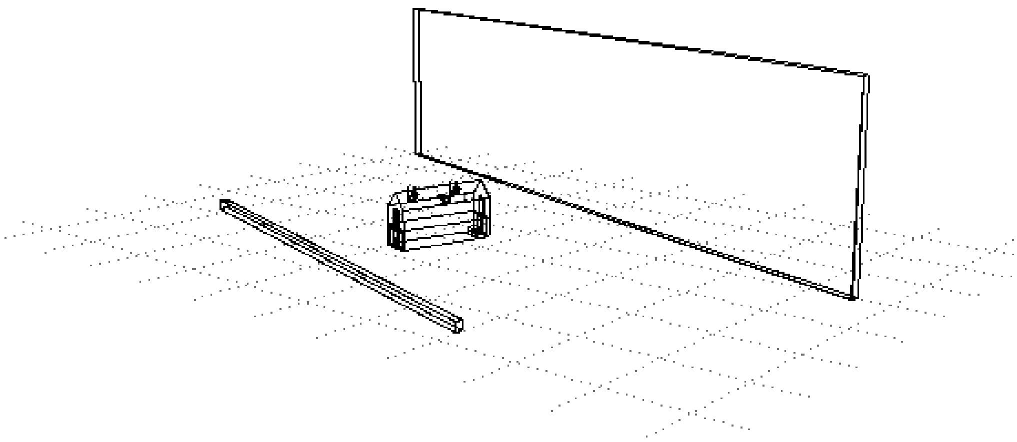

Figure 12: Passive House model and obstructions. Eye point (X,Y,Z): 120, 110, 40. Angle of view 40º.

4.3.4 Operational details

The operational details of a building are one of the most important parameters when evaluating the energy performance of a model in ESP-r. By defining these operational details it is possible to assess the performance of a building and to take some patterns that give enough hints to imagine the circumstances where the building would perform better or worst. ESP-r allows setting zone operational details in terms of three groups of days: weekdays, Saturday and Sunday. Moreover, it is also possible to implement more day types if it is required but for this model it will be used the default day types.

The software divides the operational details in two main submenus: scheduled air flows and casual gains.

4.3.4.1 Scheduled air flows

There are two different parameters to be set within the scheduled airflows: infiltration rate and ventilation rate. For the initial ESP-r model, the input data was taken from the PHPP spreadsheet.

Ventilation rate of 0.30 ac/h from the first floor to the ground floor and vice versa was set. ESP-r considers ventilation just as the amount of air transferred from zone to zone and put the ventilation coming from the Heat Recovery Ventilation System into the infiltration group.

Moreover, a total effective air exchange of 0.086 ac/h was input, as a consequence of using a HVRS with 82% efficiency and an average air change rate in the building of 0.30 ac/h, plus an infiltration air change rate of 0.032 ac/h.

Both parameters were assumed to be constant during the whole day.

4.3.4.2 Casual gains

Casual gains in ESP-r are divided into three groups depending on the origin of the heat gains: occupancy, lighting and equipment. When setting each heat gain type, it is necessary to specify the sensible and latent magnitude of the gain, and for the sensible portion also the fraction of the gain which is radiant and the fraction which is convective. As starting point for the initial model, heat gains were distributed following the worst case scenario stated in the PHPP spreadsheet which led to a peak in the heating load. It was found that in this dwelling, the total internal heat gains for this scenario were 124 W mainly caused by the occupants presence. 64 W were distributed in each floor. All the gains were assumed to be sensible and the default values of 50% convective and 50% radiant were kept. As this heat gains were assumed constant and no changes will be done regarding the occupants behaviour, it was considered that it was a better option to make the design for the worst case scenario having an extra heating demand as a consequence of the lower casual gains. In this case the model covers the possibility of having lower occupancy or lower equipment usage without causing an underestimation of the space heating demand.

4.3.5 Control Systems

A wide range of environmental control systems can be set in ESP-r. In order to create a control loop it will be necessary to specify some variables: what is sensed, where the sensor is, what control logic is applied to the sensor at different times of the day, what action is taken and where the point of interaction is. (Hand, 2010)

For the initial model, a simple temperature control was created. It sensed the dry bulb temperature of the current zone and the actuator was placed in an air point of the current zone as well (very high insulation assumed for this aspect). The control was valid for the whole year and it was working the entire day. The control law was a basic control with a maximum heat capacity of 1500 W and also a maximum cooling capacity of 1500 W. The heating setpoint was 20ºC and the cooling setpoint was 25ºC which follows the Passivhaus standard concept of range of comfortable indoor temperature.

Note that in Scotland, cooling demand is not necessary as natural ventilation is enough to cool down the rooms. However, a cooling system was required to be applied. If no cooling setpoint is stated, temperatures during summer will rise above

35ºC because of the highly insulated dwelling. But in reality, this will not occur since the occupants would open the windows when the temperature surpassed their comfort thermal level. 25ºC was assumed to be this boundary temperature and then, temperatures will not rise over this value. Moreover, if cooling is not designed, a quick large drop in the ambient temperature when the indoor temperature is very high could lead to an underestimation of the heating demand since it would take longer to reach the heating setpoint of 20ºC.

5 Passive House Performance in Dunoon, Scotland

This section details all the simulations and that were carried out using the initial Passive House model of ESP-r as starting point. The aim is to provide a wide set of data regarding the performance of the model in order to be able to compare the results later with the available PHPP spreadsheet data analysing both approaches and identifying the differences between them. Moreover, getting the most out of the ESP-r dynamic simulation, some modifications were undertaken in the temperature control of Dunoon's model that PHPP does not considered (e.g. to sense the Zone Resultant Temperature) in order to better simulate the behaviour of the occupants regarding thermal comfort.

5.1 <u>Initial Passive House model results for ESP-r</u>

5.1.1 Climate data

The climate data will be the parameter that influences the most in the next simulation results. As Dunoon is a very small Scottish city, it was not found a climate database file to import to ESP-r for this specific location. However, the default ESP-r database contained climate data of two nearby cities such as Glasgow and Oban.

The distance between Dunoon (55º 57' N) and Oban (56º 42' N) is 37.87 miles meanwhile the distance between Dunoon and Glasgow (55º 50' N) is 28.29 miles. Despite Oban being further away from Dunoon and also situated more in the north, its climate database was used due to its location beside the sea, an attribute shared with Dunoon, and hence their climates will be more similar.

The next figure shows the annual variation of the ambient temperature:

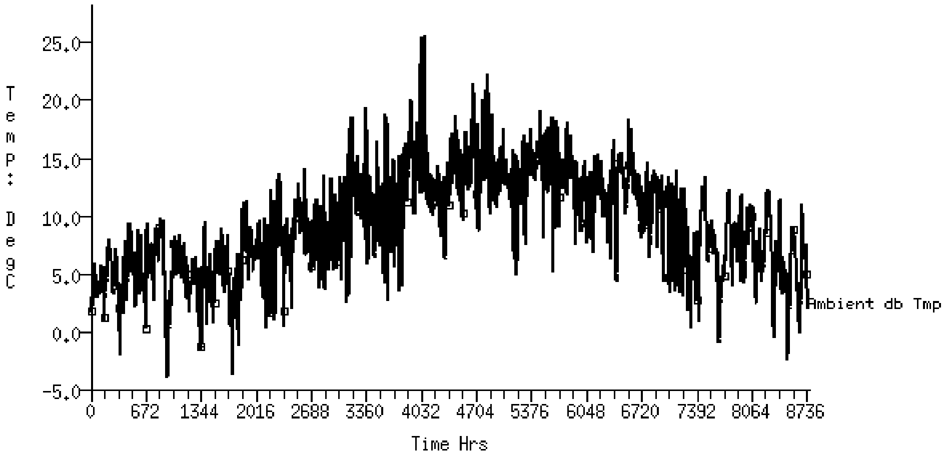

Figure 13: Annual ambient temperature.

ESP-r allows calling for the maximum and minimum value for a variable within a specific period and also it is possible to know the amount of hours that this variable is above or below certain value. For instance, the maximum annual temperature for the database chosen is 25.5ºC and it occurs on the 19th of June whereas the minimum annual temperature is -3.9ºC and it occurs on the 9th of February. The ambient temperature will be below -2ºC only during 24.0 h over the entire year, fact that gives a good prospect towards the possibility of achieving a very low space heating demand. Also, it can be seen how the temperature hardly ever goes above 20ºC, only during 50 h over the year.

Apart from the temperature data, the ESP-r climate database also contains information about the solar direct and diffuse radiation, the wind speed, the wind direction, the ambient relative humidity and the sky illuminance.

Comparison between ESP-r and PHPP climate databases used for Dunoon is available in section 5.2.2.

5.1.2 Simulation results

5.1.2.1 *Overview*

The simulation was run from the entire year assuming a start-up period duration (days preceding the user defined simulation period) of five days in order to start getting reliable results since the beginning of the simulation. It was used a one hour time-step period. The next table shows the total heating and cooling requirements for the year:

Zone total sensible and latent plant used (kWhrs)

id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd
1	Ground_floor	1097.06	4623.0	-250.37	960.0
2	First_Floor	989.90	4332.0	-275.50	1064.0
	All	2086.96	8955.0	-525.86	2024.0

Table 15: Annual heating and cooling demand

The total annual heating demand is about 2087 kWh. In order to know if the model meets the PassivHaus criteria it is necessary that the heating requirement is lower than 15 kWh/m^2. Treated Floor Area (TFA) of the dwelling was considered as 88m^2 following the PH definition of TFA for a house: "the sum of the TFA of the living spaces belonging to it" (PHI, Passipedia, 2011).

Therefore, for the moment it will not meet the PassivHaus standard criteria. However, PHPP spreadsheet states that its heating peak load is less than 10 W/m^2 and the dwelling will meet the criteria. Cooling demand will be neglected due to the Passive House is situated in Scotland and natural ventilation will be enough to cool down the building when required as it was already explained.

5.1.3.2 Zone temperature – ambient temperature – direct solar radiation correlation

First step was to compare the dry bulb temperature of both zones with the ambient temperature and then with the direct solar radiation. Note that due to the control system used the zone temperatures will be situated between 20ºC and 25ºC.

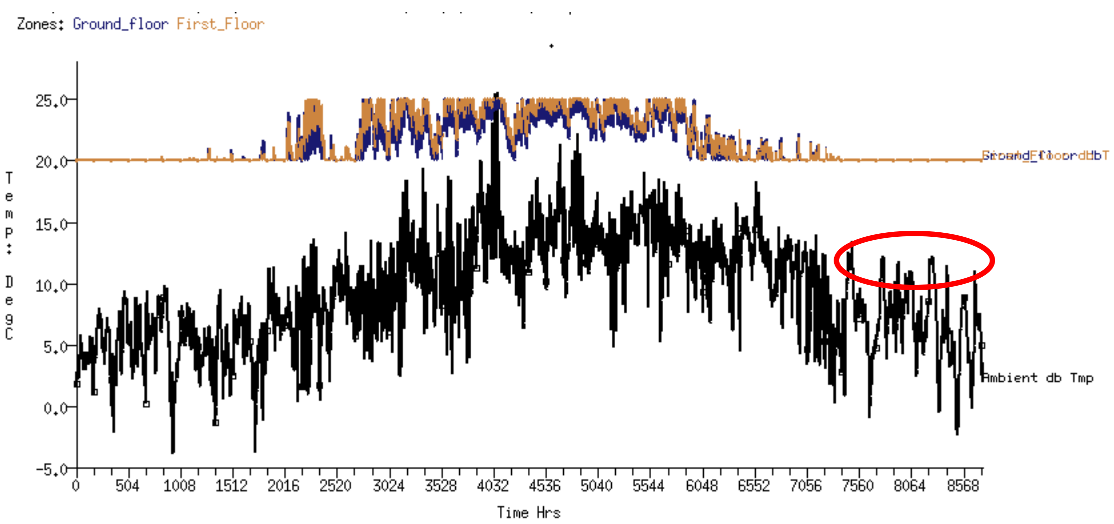

Figure 14: Zones dry bulb temperature vs. ambient temperature.

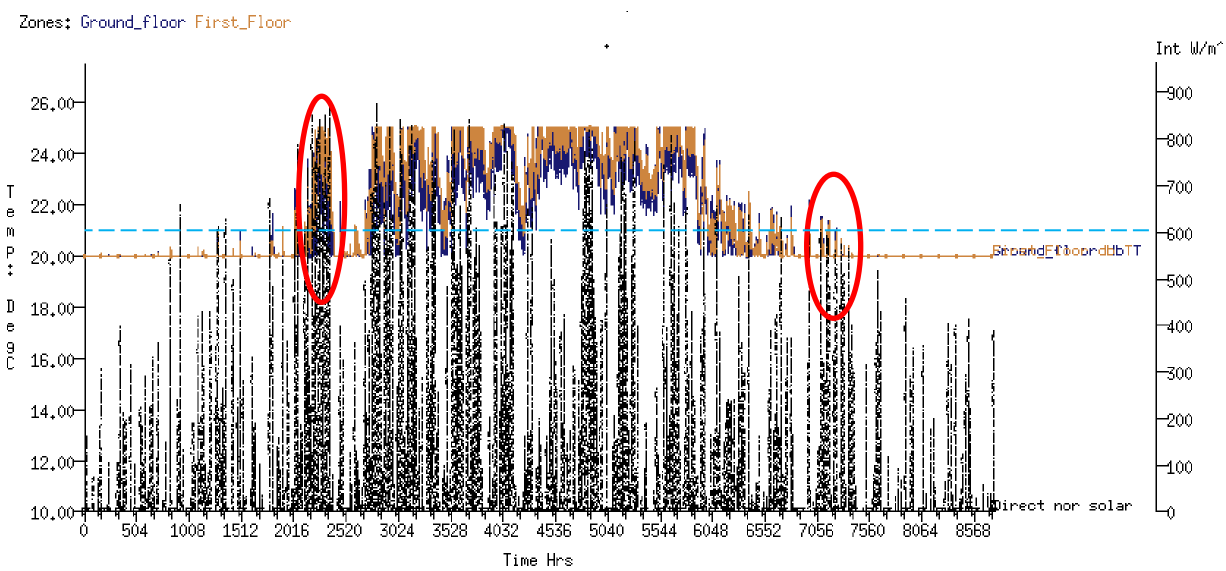

Figure 15: Zones dry bulb temperature vs. direct solar radiation.

It exists a correlation between the temperatures of the ground floor and first floor and the ambient temperature as in the warmer months of the year the zone temperature will be higher than in winter. However, it is important to notice that due to the Passive House is very well insulated and it has much less heat losses than a standard house, the contribution of the ambient temperature to the actual inside temperature of the dwelling will be *less important* than the typical contribution for a house with standard insulation. Therefore, the importance of the direct solar radiation and then solar heat gains with respect to the indoor temperature of a Passive House will *increase*.

This fact may be checked looking at the previous figures. First of all, Figure 14 shows that in the first half of the year the zone temperature goes above 20ºC as soon as the ambient temperature is about 10ºC or greater. However, in the second half of the year the pattern is not the same as the ambient temperature exceeds 10ºC several times and the zone temperature keeps at 20ºC. Moreover, Figure 15 shows how the variation in the solar direct radiation fits better with the zone temperature than the variation in the ambient temperature. It can be considered that the zone temperature will exceed 20ºC whenever the direct radiation is greater than 600 W/m^2 (see dotted line of Figure 15).

5.1.3.3 Annual heating demand analysis

It was already shown in Table 15 that the total annual heating demand for the Passive House was 2087 kWh with a distribution of 1097 kWh for the ground floor and 990 kWh for the first floor.

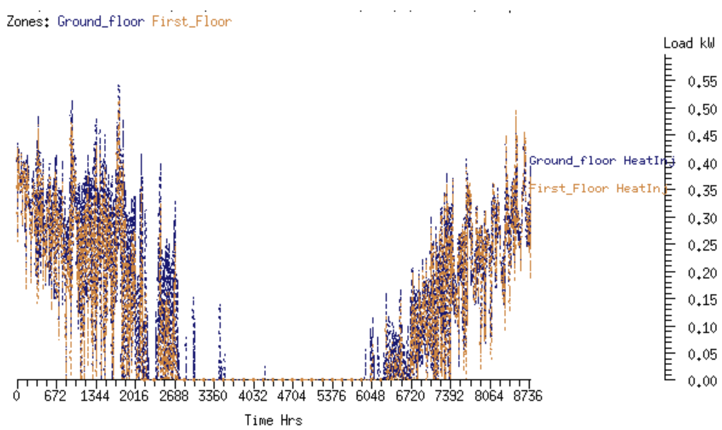

Figure 16: Annual heating demand.

The figure above is the annual heating demand on an hourly time-step basis. It shows that, despite having a different geometry and glazed area, both floors have approximately the same annual heating demand (being the ground floor requirement slightly higher) and also that the energy demand distribution throughout the year for both floors is approximately the same.

Cooling demand was neglected because the house is located in Dunoon, where natural ventilation during summer is enough to cool down the rooms. Section 5.3 will carry out a study about the sensitivity of the temperature control assumed, changing the setpoints and also sensing the zone resultant temperature instead the zone dry bulb temperature.

Moreover, this energy demand will be highly influenced for a wide range of variables and further study will be necessary in order to know the actual heat gains and losses of each floor.

5.1.3.4 <u>Heat gains and losses analysis</u>

The table below contains the monthly heat gains and losses (in kWh) for each of the zones of the Passive House and also the overall values for the whole building.

Zone	Period	Transparent surfaces		Opaque surfaces		Casual gains		Infiltrat	Ventilat	Plant		Solar radiation	
		Extern facing	Other facing	Extern facing	Other facing	Convec	Radiant			Heating	Cooling	Absor inside	Entering zone
Ground													
	Jan	-32.6	0	-52.9	-97.3	23.1	23.1	-43.4	0	243.5	0	25	25.5
	Feb	-25	0	-38.6	-70.5	20.8	20.8	-38.6	0	187.7	0	49.9	51
	Mar	-21.8	0	-30.1	-53	23.1	23.1	-42	-0.4	163.4	0	98.8	101.2
	Apr	-4.9	0	4.4	12.2	22.3	22.3	-37.1	2.8	43	-8.3	169.3	173.5
	May	4.5	0	24.4	51.4	23.1	23.1	-35.2	5.4	2.5	-43	217.5	222.9
	Jun	8.5	0	32.2	67.3	22.3	22.3	-29.9	4.6	0.1	-77.4	206.5	211.7
	Jul	6.2	0	26.5	55.8	23.1	23.1	-27.8	4	0	-62	183.4	188.2
	Aug	5.2	0	25	56.8	23.1	23.1	-28.9	3.2	0	-57.5	179	183.5
	Sep	-3.7	0	4.7	14.3	22.3	22.3	-25.1	1.4	11.3	-2.2	96.6	99
	Oct	-11.5	0	-11.4	-16	23.1	23.1	-27.6	0	68.9	0	64.9	66.5
	Nov	-22.6	0	-32.8	-57.1	22.3	22.3	-35	0	157.8	0	32.3	33
	Dec	-29.9	0	-48	-87.9	23.1	23.1	-39.5	0	218.9	0	16.7	17.1
	Total	**-127.6**	**0**	**-96.6**	**-124**	**271.7**	**271.7**	**-410.1**	**21**	**1097.1**	**-250.4**	**1339.9**	**1373.1**
First Floor													
	Jan	-19.1	0	-115.5	-26.8	23.1	23.1	-59.7	0	229.6	0	26.3	26.6
	Feb	-13.6	0	-74.8	-14.5	20.8	20.8	-53	0	163.1	0	49.5	50.1
	Mar	-11.4	0	-56.9	-5	23.1	23.1	-57.6	0.5	137.9	0	86.6	87.7
	Apr	-0.3	0	16.7	29.8	22.3	22.3	-52.1	-3.9	23.3	-8.2	148.9	150.9
	May	4.8	0	48.1	53.4	23.1	23.1	-50.6	-7.5	0	-44.3	187.1	189.6
	Jun	7.3	0	66.7	66.9	22.3	22.3	-43	-6.3	0	-91.4	179.1	181.5
	Jul	5.9	0	54.9	56.7	23.1	23.1	-39.8	-5.5	0	-74.2	163	165.1
	Aug	4.6	0	45.1	49.1	23.1	23.1	-41	-4.4	0	-54.7	154.6	156.7
	Sep	-0.9	0	11.7	19.4	22.3	22.3	-35.1	-1.9	5.3	-2.6	90.5	91.7
	Oct	-5.9	0	-24	1.6	23.1	23.1	-37.9	0	63.2	0	64.5	65.3
	Nov	-13.3	0	-75.1	-15.7	22.3	22.3	-48.2	0	155.5	0	35.5	36
	Dec	-17.9	0	-108.8	-25.5	23.1	23.1	-54.3	0	212.1	0	20	20.3
	Total	**-59.8**	**0**	**-211.9**	**189.4**	**271.7**	**271.7**	**-572.3**	**-29**	**990**	**-275.4**	**1205.6**	**1221.5**
All zones													
	Jan	-52	0	-168	-124	46	46	-103	0	473	0	51	52
	Feb	-39	0	-113	-85	42	42	-92	0	351	0	99	101
	Mar	-33	0	-87	-58	46	46	-100	0	301	0	185	189
	Apr	-5	0	21	42	45	45	-89	-1	66	-16	318	324
	May	9	0	72	105	46	46	-86	-2	2	-87	405	413
	Jun	16	0	99	134	45	45	-73	-2	0	-169	386	393
	Jul	12	0	81	112	46	46	-68	-2	0	-136	346	353
	Aug	10	0	70	106	46	46	-70	-1	0	-112	334	340
	Sep	-5	0	16	34	45	45	-60	0	17	-5	187	191
	Oct	-17	0	-35	-14	46	46	-65	0	132	0	129	132
	Nov	-36	0	-108	-73	45	45	-83	0	313	0	68	69
	Dec	-48	0	-157	-113	46	46	-94	0	431	0	37	37
	Annual	**-188**	**0**	**-309**	**66**	**544**	**544**	**-983**	**-8**	**2086**	**-525**	**2545**	**2594**

Table 16: Heat gains and losses in the building (kWh).

A) Transparent surfaces:

All the transparent surfaces are extern facing. The ground floor has an overall total loss of 127.6 kWh which is more than the double of the loss for the first floor (59.8 kWh). This is due to the glazing area is larger for the ground floor and then the heat losses during winter through those windows will be higher. Moreover, despite the first floor is the only with south facing windows, the heat gains in the summer will be again slightly higher for the ground floor because of the same reason, e.g. in July 6.2 kWh in contrast with 5.9 kWh. However, these gains will be very short in comparison with the losses.

B) Opaque surfaces:

The building has more external facing opaque surfaces in the first floor (roof and walls) than in the ground floor (just the walls). Moreover, it is important to notice that the north walls are not facing the exterior but they are facing the other semi-detached dwelling. In the same way that for the transparent surfaces the larger zone will have more heat losses in winter and more heat gains in summer, which in this case will be the first floor. Moreover, heat gains will be obtained during the months of April and September whereas in the previous case heat losses were found for these months regarding transparent surfaces. The reason of this fact is that the U-value for the opaque surfaces is higher and also that they have much greater mass thermal capacity.

Regarding the opaque surfaces that are not facing the exterior, the main difference between both zones is that the ground floor has a floor which is facing the ground. Both zones have a north wall that is facing another similar semi-detached house. As the results table shows, the values for the autumn and winter are greater for the first floor as consequence of the lower temperature of the earth surface in those months. During spring and summer months, when the earth surface temperature is higher, the values for both zones will be almost the same compensating in that way the small losses though the ground for the heat gains that the ground floor has from the first floor due to the higher temperature of the latter (see Figure 14 and Figure 15).

C) Casual gains:

Occupancy, lighting and equipment casual gains were assumed to be constant throughout the year using the values from PHPP (for further details see section 4.3.4.2).

D) Infiltration and ventilation:

Infiltration losses are greater for the first floor as it has larger surface area and also higher for winter months when the ambient temperature is lower than for summer months when it is higher.

ESP-r considers ventilation just as the amount of air transferred from zone to zone and put the ventilation coming from the HRVS inside the infiltration group. Because of this consideration, it is shown there are not either heat gains or losses during the autumn and winter months. The ambient temperature is very low for that period and the heating control works constantly to maintain the temperature of both zones at 20ºC (see Figure 14). Therefore, although a ventilation rate was set, air changes between two zones at the same temperature will not produce either heat gains or heat losses. However, in spring and summer months when the temperature of the first floor is higher than the ground floor, there will be heat transfer from the first to the latter.

For further information about infiltration and ventilation air changes rates see section 4.3.4.1.

E) Plant heating and cooling:

Discussed in the previous section.

F) Solar radiation:

The table shows that there is more solar radiation entering into the ground floor than the first floor due to the larger glazing area for the ground floor. Only the first floor has south facing windows, however, their size is not big enough to received a large amount of radiation.

5.1.3.5 *Thermal comfort assessment*

According to (ASHRAE 55, 2004), thermal comfort is "that condition of mind that expresses satisfaction with the thermal environment". This definition already expresses that thermal comfort may be subjective and it can varies from individual to individual even when they are exposed to the same ambient conditions.

In order to study the thermal comfort of the people in the model, four typical seasonal days were chosen (1^{st} January, 1^{st} April, 1^{st} July and 1^{st} October) and the results of the assessment are shown in the next tables.

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	20.0	18.7	22.	21.4	-0.60	-0.40	8.	comfortable, pleasant
1.5	20.0	18.6	22.	21.4	-0.60	-0.40	8.	comfortable, pleasant
2.5	20.0	18.6	22.	21.4	-0.60	-0.40	8.	comfortable, pleasant
3.5	20.0	18.6	22.	21.4	-0.60	-0.40	8.	comfortable, pleasant
4.5	20.0	18.6	23.	21.4	-0.60	-0.40	8.	comfortable, pleasant
5.5	20.0	18.6	23.	21.4	-0.60	-0.40	8.	comfortable, pleasant
6.5	20.0	18.6	23.	21.4	-0.60	-0.40	8.	comfortable, pleasant
7.5	20.0	18.6	23.	21.4	-0.60	-0.40	8.	comfortable, pleasant
8.5	20.0	18.6	24.	21.4	-0.60	-0.40	8.	comfortable, pleasant
9.5	20.0	18.6	24.	21.4	-0.60	-0.40	8.	comfortable, pleasant
10.5	20.0	18.6	24.	21.4	-0.59	-0.39	8.	comfortable, pleasant
11.5	20.0	18.8	25.	21.5	-0.57	-0.37	8.	comfortable, pleasant
12.5	20.0	19.1	25.	21.6	-0.56	-0.35	8.	comfortable, pleasant
13.5	20.0	19.1	25.	21.6	-0.55	-0.35	8.	comfortable, pleasant
14.5	20.0	19.1	25.	21.6	-0.55	-0.35	8.	comfortable, pleasant
15.5	20.0	19.1	25.	21.6	-0.55	-0.35	8.	comfortable, pleasant
16.5	20.0	19.0	25.	21.6	-0.56	-0.36	8.	comfortable, pleasant
17.5	20.0	18.9	25.	21.5	-0.57	-0.37	8.	comfortable, pleasant
18.5	20.0	18.8	25.	21.5	-0.57	-0.37	8.	comfortable, pleasant
19.5	20.0	18.8	25.	21.5	-0.57	-0.38	8.	comfortable, pleasant
20.5	20.0	18.8	25.	21.5	-0.58	-0.38	8.	comfortable, pleasant
21.5	20.0	18.7	25.	21.5	-0.58	-0.38	8.	comfortable, pleasant
22.5	20.0	18.7	25.	21.5	-0.58	-0.38	8.	comfortable, pleasant
23.5	20.0	18.7	25.	21.5	-0.58	-0.38	8.	comfortable, pleasant

Table 17: Comfort assessment for a winter day.

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	21.0	21.4	32.	23.1	-0.22	-0.01	5.	comfortable, pleasant
1.5	20.7	21.1	32.	22.8	-0.28	-0.07	5.	comfortable, pleasant
2.5	20.4	20.8	33.	22.5	-0.33	-0.13	5.	comfortable, pleasant
3.5	20.1	20.4	34.	22.3	-0.38	-0.18	6.	comfortable, pleasant
4.5	20.0	20.1	34.	22.1	-0.41	-0.22	6.	comfortable, pleasant
5.5	20.0	19.9	35.	22.0	-0.43	-0.24	6.	comfortable, pleasant
6.5	20.0	19.7	35.	22.0	-0.45	-0.25	6.	comfortable, pleasant
7.5	20.0	19.9	35.	22.1	-0.43	-0.23	6.	comfortable, pleasant
8.5	20.3	20.9	34.	22.5	-0.33	-0.12	5.	comfortable, pleasant
9.5	21.0	21.7	33.	23.2	-0.20	0.02	5.	comfortable, pleasant
10.5	21.5	21.9	32.	23.5	-0.13	0.09	5.	comfortable, pleasant
11.5	21.6	22.1	32.	23.6	-0.10	0.12	5.	comfortable, pleasant
12.5	21.8	22.3	31.	23.7	-0.07	0.15	5.	comfortable, pleasant
13.5	21.9	22.4	31.	23.8	-0.05	0.17	6.	comfortable, pleasant
14.5	22.0	22.4	31.	23.8	-0.05	0.17	6.	comfortable, pleasant
15.5	21.9	22.4	31.	23.8	-0.05	0.17	6.	comfortable, pleasant
16.5	22.0	22.5	31.	23.8	-0.05	0.18	6.	comfortable, pleasant
17.5	21.9	22.4	31.	23.8	-0.05	0.17	6.	comfortable, pleasant
18.5	21.8	22.2	31.	23.7	-0.09	0.13	5.	comfortable, pleasant
19.5	21.5	21.9	31.	23.4	-0.14	0.07	5.	comfortable, pleasant
20.5	21.1	21.5	32.	23.1	-0.21	0.00	5.	comfortable, pleasant
21.5	20.6	21.1	33.	22.7	-0.28	-0.07	5.	comfortable, pleasant
22.5	20.2	20.7	33.	22.4	-0.35	-0.15	5.	comfortable, pleasant
23.5	20.0	20.3	33.	22.2	-0.40	-0.20	6.	comfortable, pleasant

Table 18: Comfort assessment for a spring day.

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	20.0	19.5	45.	22.0	-0.40	-0.23	6.	comfortable, pleasant
1.5	20.0	19.5	46.	22.0	-0.39	-0.23	6.	comfortable, pleasant
2.5	20.0	19.4	47.	22.1	-0.38	-0.22	6.	comfortable, pleasant
3.5	20.0	19.4	49.	22.1	-0.37	-0.22	6.	comfortable, pleasant
4.5	20.0	19.4	50.	22.1	-0.36	-0.21	6.	comfortable, pleasant
5.5	20.0	19.4	52.	22.1	-0.35	-0.20	6.	comfortable, pleasant
6.5	20.0	19.4	53.	22.2	-0.34	-0.20	6.	comfortable, pleasant
7.5	20.0	19.5	55.	22.2	-0.32	-0.19	6.	comfortable, pleasant
8.5	20.0	19.5	56.	22.2	-0.31	-0.18	6.	comfortable, pleasant
9.5	20.0	19.6	57.	22.3	-0.29	-0.16	6.	comfortable, pleasant
10.5	20.1	19.9	59.	22.4	-0.26	-0.13	5.	comfortable, pleasant
11.5	20.2	20.2	59.	22.7	-0.20	-0.08	5.	comfortable, pleasant
12.5	20.4	20.4	60.	22.9	-0.16	-0.04	5.	comfortable, pleasant
13.5	20.6	20.5	60.	23.0	-0.12	-0.01	5.	comfortable, pleasant
14.5	20.7	20.6	61.	23.2	-0.09	0.02	5.	comfortable, pleasant
15.5	20.8	20.7	61.	23.2	-0.07	0.03	5.	comfortable, pleasant
16.5	20.8	20.7	62.	23.3	-0.06	0.04	5.	comfortable, pleasant
17.5	20.7	20.7	63.	23.2	-0.07	0.03	5.	comfortable, pleasant
18.5	20.6	20.6	64.	23.1	-0.08	0.01	5.	comfortable, pleasant
19.5	20.5	20.4	65.	23.1	-0.10	-0.00	5.	comfortable, pleasant
20.5	20.4	20.4	66.	23.0	-0.11	-0.02	5.	comfortable, pleasant
21.5	20.3	20.3	66.	22.9	-0.13	-0.04	5.	comfortable, pleasant
22.5	20.2	20.2	67.	22.8	-0.15	-0.05	5.	comfortable, pleasant
23.5	20.1	20.1	67.	22.7	-0.17	-0.07	5.	comfortable, pleasant

Table 19: Comfort assessment for an autumn day.

Time (hrs)	t-air (deg.C)	t-mrt (deg.C)	rel.h (%)	SET (deg.C)	PMV* (-)	PMV (-)	PPD (%)	Comfort assessment based on PMV
0.5	21.8	22.1	41.	23.9	0.00	0.18	6.	comfortable, pleasant
1.5	21.7	21.9	42.	23.7	-0.03	0.14	5.	comfortable, pleasant
2.5	21.5	21.7	43.	23.6	-0.06	0.11	5.	comfortable, pleasant
3.5	21.3	21.5	44.	23.4	-0.09	0.08	5.	comfortable, pleasant
4.5	21.1	21.3	44.	23.3	-0.12	0.05	5.	comfortable, pleasant
5.5	21.0	21.2	45.	23.2	-0.14	0.03	5.	comfortable, pleasant
6.5	21.0	21.2	45.	23.2	-0.14	0.03	5.	comfortable, pleasant
7.5	21.1	21.4	45.	23.3	-0.11	0.06	5.	comfortable, pleasant
8.5	21.4	21.8	45.	23.6	-0.04	0.13	5.	comfortable, pleasant
9.5	22.0	22.4	44.	24.1	0.06	0.23	6.	comfortable, pleasant
10.5	22.6	23.0	42.	24.6	0.17	0.34	7.	comfortable, pleasant
11.5	23.1	23.5	41.	25.0	0.27	0.44	9.	comfortable, pleasant
12.5	23.6	24.0	40.	25.4	0.35	0.53	11.	slightly warm, acceptable
13.5	24.0	24.4	39.	25.7	0.42	0.61	13.	slightly warm, acceptable
14.5	24.4	24.8	38.	26.0	0.49	0.68	15.	slightly warm, acceptable
15.5	24.7	25.2	37.	26.3	0.54	0.74	17.	slightly warm, acceptable
16.5	24.9	25.4	36.	26.5	0.57	0.78	18.	slightly warm, acceptable
17.5	25.0	25.6	36.	26.5	0.59	0.80	19.	warm, unpleasant
18.5	25.0	25.5	36.	26.5	0.59	0.80	18.	slightly warm, acceptable
19.5	24.9	25.3	37.	26.4	0.57	0.77	18.	slightly warm, acceptable
20.5	24.7	25.0	37.	26.2	0.52	0.72	16.	slightly warm, acceptable
21.5	24.4	24.7	38.	26.0	0.47	0.67	14.	slightly warm, acceptable
22.5	24.1	24.4	39.	25.8	0.42	0.61	13.	slightly warm, acceptable
23.5	23.8	24.1	39.	25.5	0.37	0.56	11.	slightly warm, acceptable

Table 20: Comfort assessment for a summer day.

Note that these results are based on a thermal comfort assessment with cooing setpoint at 25ºC. Default ESP-r boundary conditions were chosen for the assessment, i.e. activity level of 90.0 clothing level of 0.70 and air speed of 0.10.

Different set of variables are shown in the tables: temperature of the air in the room, Mean Radiant Temperature, Relative Humidity. Standard Effective Temperature, Fanger Predicted Mean Vote, Predicted Mean Vote based on ET and Predicted Percentage of Dissatisfied respectively. Comfort assessment in ESP-r is based on PMV, which represents the comfort of a large group of people exposed to a particular environment conditions according to the ASHRAE thermal sensation scale.

The results show that for winter, spring and autumn days the occupants of the Passive House feels comfortable. Only during the summer day they feel slightly warm during the second half of the day and even warm from 5.30 pm to 6.30 pm. This is due to the PMV value for that periods is greater than 0.5. Also it can be seen that the MRT and SET values at some points of the day are higher than 25ºC. However, this fact should not be an important issue and it could be solved just by increasing the natural ventilation opening the windows.

The temperature control system designed for the model senses the dry bulb temperature of the room with a heating setpoint of 20ºC and a cooling setpoint of 25ºC following the PassiveHaus standard for thermal comfort. However, it was considered that in order to increase the comfort of the occupants the control should sense instead the ZRT (average of DBT and MRT) and then a modification in the control will be carried out in next sections to check the difference in the performance.

All of the parameters of the tables depend in some extend on the dry bulb temperature which is being controlled. Then, due to this fact, these variables will keep in good values in terms on thermal comfort and occupants will tend to feel comfortable whenever the relative humidity is not extremely high or low. However, as the humidity is relative to the temperature, it seems not to have much significance for thermal comfort by its own. Moreover, several experiments have shown that individuals cannot judge the humidity when it relies on a range between 20% and 70% if the room temperature is comfortable enough (Schnieders, 2009). Also, (Rasmussen, 1971) carried out an experiment exposing a large group of people to temperatures from 21.1ºC to 27.8ºC and RH from 25% to 70% and found a weak correlation between the subjects' warmth votes and the vapour pressure of the air.

The next figure shows that the relative humidity throughout the year ranges from about 20% to 60%, which based on the previous studies should not influence in big extent to achieve a good level of thermal comfort.

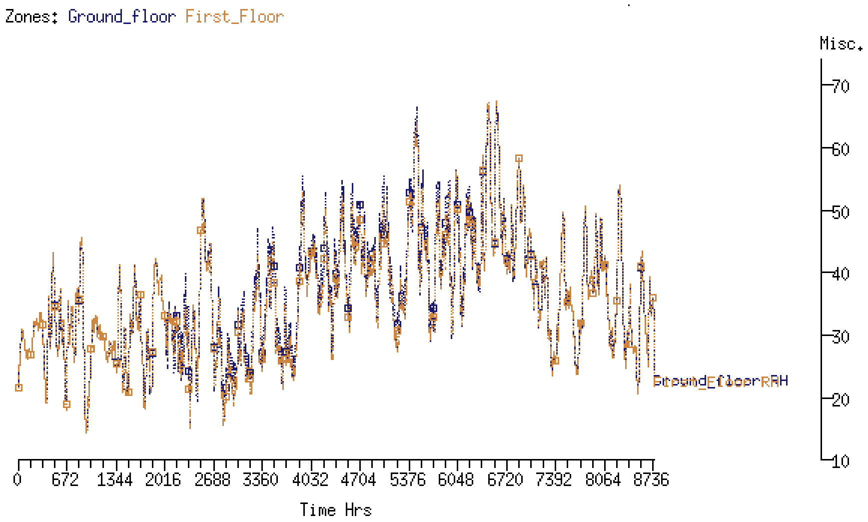

Figure 17: Relative humidity.

5.2 PHPP – ESP-r comparison

In previous sections, an initial model of the Passive House has been used in ESP-r to run dynamic simulations with short time-steps in order to study the performance of this type of buildings in cold climates such as Scotland. However, in order to get the distinction of 'Certified Passive House', the dwelling has to meet some specific PassivHaus Standard certification criteria that need to be assessed using a simplified stationary calculation method by means of PHPP. PHPP spreadsheet for the under researched building was available and it was used to obtain some information for the designing of the ESP-r model such as the U-values of the constructions used, the shading components or the thermal bridges within the building envelop. This section explores the differences between the set of results obtained using both tools. This comparison will be used to see whether or not the model created in ESP-r behaves properly comparing it against PHPP.

5.2.1 Annual space heating demand

According to the Passive House Institute (Feist W. , 2009), the certification criteria applicable to residential buildings is:

Specific space heating demand	≤ 15kWh/(m²yr)
OR Heating load	≤ 10W/m²
Specific space cooling demand	≤ 15kWh/(m²yr)
Annual overheating hours (indoor temperature over 25°C)	≤ 10%
Airtightness test result (n50)	≤ 0.6 air changes/h
Total specific primary energy demand	≤ 120kWh/(m²yr)

Table 21: Passive House certification criteria.

And the PHPP verification sheet looked as follows:

Specific Demands with Reference to the Treated Floor Area						
Treated Floor Area:	88.4	m^2				
	Applied:	Monthly Method		PH Certificate:		Fulfilled?
Specific Space Heat Demand:	20	$kWh/(m^2a)$		15	$kWh/(m^2a)$	No
Pressurization Test Result:	0.4	h^{-1}		0.6	h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	93	$kWh/(m^2a)$		120	$kWh/(m^2a)$	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	54	$kWh/(m^2a)$				
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	0	$kWh/(m^2a)$				
Heating Load:	10	W/m^2				
Frequency of Overheating:	3	%	over	25	°C	
Specific Useful Cooling Energy Demand:		$kWh/(m^2a)$		15	$kWh/(m^2a)$	
Cooling Load:	8	W/m^2				

Table 22: PHPP verification

The previous tables show that effectively the Passive House under study meets the criteria. It can be noticed that it does not meet the specific space heating demand although it does meet the heating load and thus it can be certified.

ESP-r is an energy modeling tool and it was used to estimate the space heating demand and to evaluate the performance of the building regarding parameters that could have an influence in the thermal comfort of the occupants. Therefore, its comparison with PHPP will be based on the space heating requirements. Space cooling demand was neglected due to the Passive House is located in Scotland, where natural window ventilation is enough to cool down the building temperature when it is required.

	ESP-r (kWh)	PHPP (kWh)
TOTAL	2087	1766

Table 23: ESP-r vs. PHPP

The annual space heating demand estimated by PHPP is 1766 kWh. On the other hand, the ESP-r estimation was 2087 kWh. Next sections will study the differences and assumptions made for each approach in order to explain these difference.

5.2.2 Monthly space heating demand

It was considered that the overall annual values for the space heating demand did not offer enough details about the heating requirements in the building throughout the year and taking adventage of the fact that PHPP also shows the montly energy demand profile and that ESP-r is a dynamic simulation software and it is possible to set the desired time-step, a comparison of the two approaches was made in a monthly basis. The next figure shows the results.

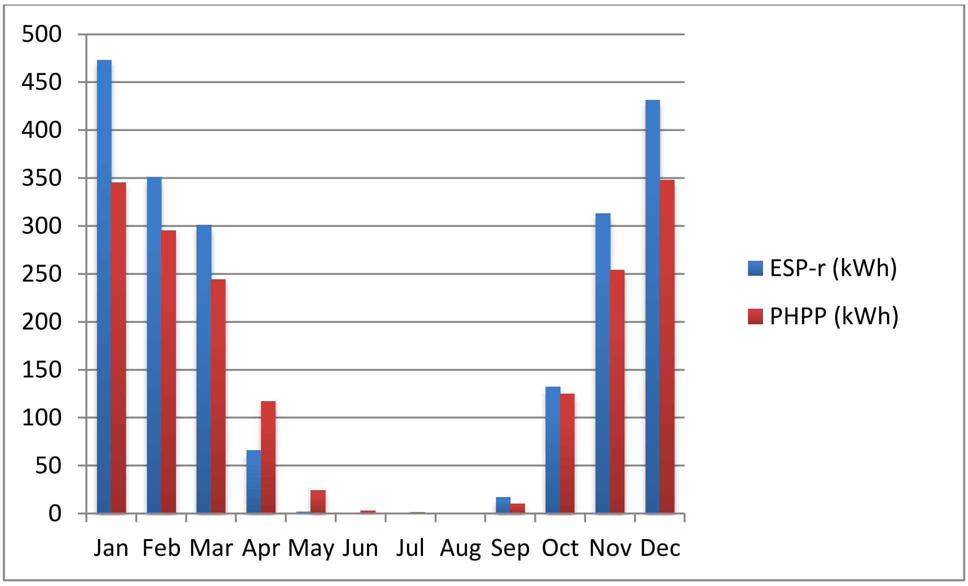

Figure 18: Monthly comparison in kWh

Figure 18 shows that the total space heating demand in kWh is larger for ESP-r. It is noticeable that in January and December the demand in ESP-r is between 80 – 120 kWh greater. Moreover, the overall difference in space heating demand between both approaches is about 300 kWh, note also that the difference considering just these two months is already about 200 kWh. This ESP-r – PHPP monthly difference decrease little by little in the months near these dates until summer where there is not heating demand. However, there is an exception to this decreasing tendency; in April, May and June the demand in PHPP is larger than in ESP-r.

There are several reasons that could explain this fact. First of all it is necessary to consider that different climate databases were used. PHPP uses a climate database from Glasgow whereas in ESP-r it was decided to use a database from Oban because the actual location of the Passive House (Dunoon) is nearby the sea as also Oban is. Moreover, ESP-r uses climate database of 1994 for Oban meanwhile PHPP does not state the year for the climate database that is using. Monthly average temperature data for both locations is available below.

Temp (ºC)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PHPP (Glasgow)	6.9	6.3	6.9	8.0	10.7	12.7	14.8	15.4	14.0	11.0	8.6	6.9
ESP-r (Oban)	4.8	5.1	5.5	8.1	10.7	12.7	14.3	13.7	12.1	10.6	7.3	6.2

Table 24: Monthly average dry bulb temperature comparison.

Analyzing the data, an interesting aspect was found. The average temperature in Glasgow is always higher than in Oban (and then more heating demand is expected for Oban) except in three months in which it is the same or one tenth lower. These months are April, May and June; exactly the points where the heating demand changed its tendency and higher values were obtained for Glasgow (PHPP). Then, the different database used will be one of the reasons that could explain the change in the aforementioned tendency.

5.2.3 Comparison of input data for both approaches

The previous section has already investigated that one of the factors that have an influence over the results obtained is the different climate database used. However, a broader review to the input data for ESP-r and PHPP will be necessary in order to find any other element that could influence on the final results obtained in both models.

It is important to highlight again that the ESP-r model was created based on the specification of the PHPP certified spreadsheet available for the Passive House under study and then almost all of the input values will be the same.

Apart from the climate, a large set of building characteristics have to be analyzed. The orientation of the building with a shift of 17º was considered in both models. Moreover, all the values input in ESP-r regarding the envelop construction of the walls, roof, floor, windows, window reveals and thermal bridges (U-values, thickness, etc.) were entered in concordance with the PHPP spreadsheet and hence no difference it should make in the results. The same happens with the scheduled air flows. However, the casual heat gains input were referred to the worst case scenario for the heating load in order to provide the model with the flexibility of having lower occupancy or lower equipment usage without causing an underestimation of the space heating demand (see section 4.3 for further details about all the input data). Simulations were done and the results showed a constant increase in the ESP-r heating demand with respect to PHPP of about 20 kWh/month regarding casual gains. Then, this is one of the reasons of the greater ESP-r overall space heating demand estimation, although, as this difference was a constant monthly value, this will not be the reason of the changes in the month-to-month heating demand variation regarding both approaches.

Additionally, there is another difference in the input data. PHPP assumes a constant temperature of 20ºC in the building throughout the year for its energy calculations. But the PassivHaus standard states that the range of comfortable indoor temperature is 20ºC – 25ºC and then these temperatures were used as heating and cooling setpoint for the mentioned control.

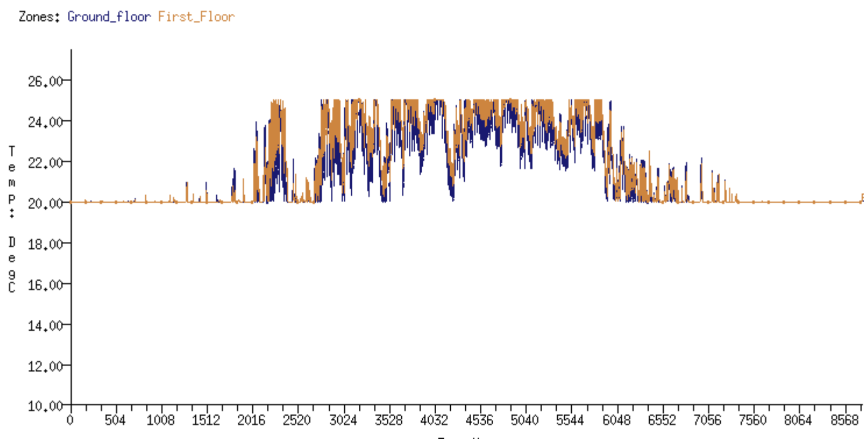

Figure 19: Annual zone temperature.

As the figure shows, the ESP-r control makes the dry bulb temperature of the house to be maintained at 20ºC in the coldest months of the year when the ambient temperature is lower, which means that heating will be constantly needed during these months to avoid the temperature going below its setpoint of 20ºC. The figure also shows how from April this temperature starts to swing between the comfortable temperature range (20ºC – 25ºC), fact which supposes a difference in the room temperature of both approaches since in PHPP the temperature is maintained at 20ºC.

5.2.4 Comparison conclusions

Passive House Planning Package (PHPP) is an excel spreadsheet based planning tool with the aim of assisting the design of a Passive House following the Passivhaus standard providing all the instruments necessary for the design of a well performing low energy building. It is a simplified stationary calculation method which treats the whole building as a single zone for purposes of energy calculations and shows the final results in terms of monthly energy balances rather than carrying out a dynamic simulation with short time-steps as ESP-r does.

A Passive House located in Dunoon, Scotland, was modeled in ESP-r following building specifications provided by an official PHPP spreadsheet. The overall space heating demand in kWh obtained in ESP-r was about 15% higher than in PHPP. It was found that the main reason for the difference between both approaches was the different climate database used (Oban in ESP-r and Glasgow in PHPP) being the Glaswegian climate colder and hence causing more overall heating demand.

Regarding the monthly demand (see Figure 18), ESP-r estimation was especially higher in January and December due to colder average temperatures than PHPP. This monthly demand difference decreases from February and starts to grow again in the end of the summer. However, for the PHPP model the reduction and subsequent increase of the demand is smoother than for the ESP-r model, in which the reduction is a huge in April and May.

Therefore, it has been shown that the ESP-r model behaves properly and all the set of results obtained seem to be realistic when comparing with PHPP taking into account the different approaches carried out by both tools. Then, this ESP-r model will be used in the next sections since a dynamic approach will be necessary due to the need to implement a night ventilation control using a very short time-step period when the dwelling is transferred to a warmer place.

5.3 ESP-r Dunoon’s model modifications

All the simulations and results obtained so far have been based on the *initial ESP-r model* created in accordance with the PHPP spreadsheet available for the Passive House. Although the performance of Dunoon’s Passive House has been already studied, it was decided to see how the model reacted when some modifications are implemented now that the results obtained in ESP-r seem to be realistic when comparing with PHPP. These changes implemented in the model will be done with the purpose of obtaining better simulation of the behaviour of the occupants regarding the thermal comfort and associated manipulations in the temperature control system. Then building’s envelop characteristics and composition will not be modified.

5.3.1 Mean Radiant Temperature concept

The mean radiant temperature (MRT) is defined as “the uniform surface temperature of a radiantly black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space” (Watson, 2002). It is the area weighted mean temperature of the objects surrounding the body. Then, the radiant heating or cooling ability of any surface must be evaluated in the context of its area in proportion to the area and temperature of other surfaces in the room. This fact will convert the MRT into a very important parameter regarding the thermal comfort in a Passive House and it must be considered in the ESP-r model although PHPP does not consider it.

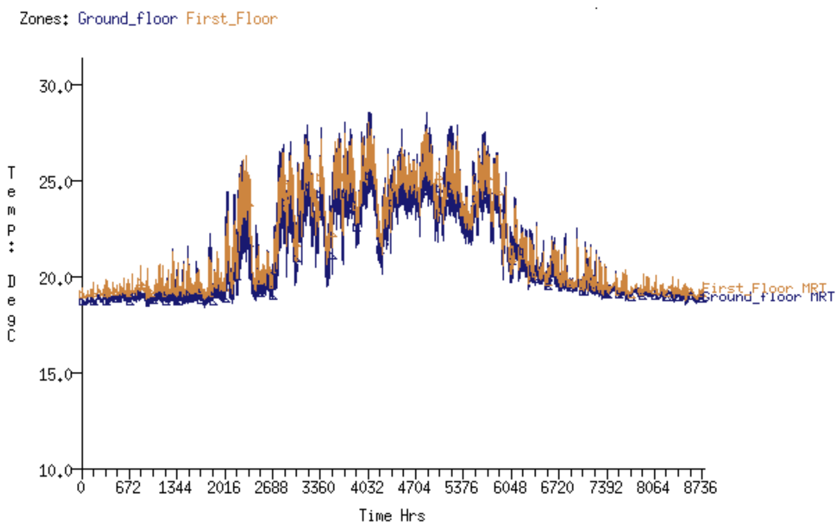

Figure 20: MRT in the building's zones.

The figure above illustrates that the MRT varies with respect to the zone dry bulb temperature (DBT) (shown in Figure 19). The basic temperature control set in ESP-r senses the latter which swings from 20ºC to 25ºC but the MRT has a maximum value of 28.5ºC and a minimum value of 18.3ºC due to the surface temperature of the walls and windows of the building are not the same than the room temperature. This increase in the range of MRT sensed compared with the room dry bulb temperature could cause a reduction in the level of comfort of the occupants and it will be necessary to modify the model to assure a good thermal comfort of the occupants throughout the entire year.

5.3.2 First model modification – Zone Resultant Temperature (ZRT)

As consequence of the differences between the zone DBT and the MRT, the temperature control set in ESP-r will need to be modified. It was decided to use a control which sensed the resultant temperature instead of the DBT. The resultant temperature (or operative temperature) is the average between the dry bulb temperature (DBT) and the area weighted mean radiant temperature (MRT) in the middle of the zone and it expresses the real temperature that an individual feels inside a room. This change will make the occupants to feel more comfortable than in the previous model because the control now will sense the temperature they feel instead of the actual temperature of the room. Therefore, the first model modification will consist of changing the control to sensing the ZRT keeping the same heating and cooling set points and the results are shown below:

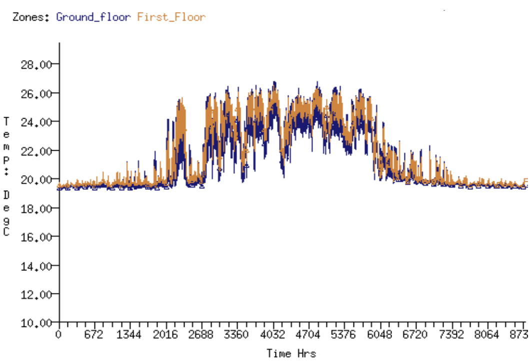

Figure 21: ZRT before modification

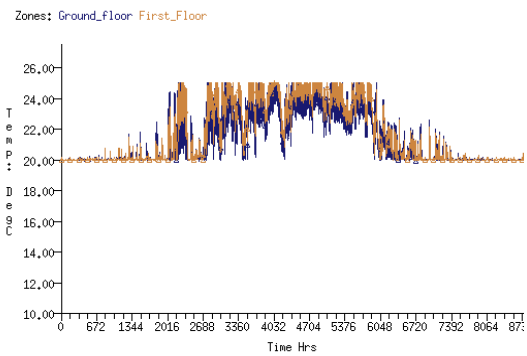

Figure 22: ZRT after modification

It can be seen how before implementing the new control, the ZRT keeps below the heating setpoint of 20ºC a long time over the year and it also goes above the cooling setpoint of 25ºC during the warmest months even surpassing the barrier of 26ºC. Hence, after the modification, the ZRT will swing between 20-25ºC and the thermal comfort of the occupants will increase.

The last step is to assess the change in the heating demand that the change in the type of temperature sensed will make. In previous sections it was calculated that the space heating demand for the initial model was 2087 kW whereas for this modification the total value rises until 2189 kWh. It means that this increase in the thermal comfort level of the occupants will lead to a *growth of 4.9%* in the space heating demand.

5.3.3 Second model modification – Control temperature range

In the initial model, heating and cooling setpoints were adjusted to 20ºC and 25ºC respectively following the PassivHaus standard of indoor thermal comfort. However, thermal comfort is a subjective area and results from laboratory have shown that there is always an inter-individual difference in the temperature preferred for a house resulting in a minimum of 5% dissatisfied under any given set of conditions. Moreover, practical experience from measurements of a large number of Passive Houses in Germany, Austria and Switzerland have shown that the actual desired temperature can vary in large extent but it has been found a tendency in setting the heating point at 19ºC (Schnieders, 2009). Also, the new standard [DIN 4108-6] has reduced the indoor temperature to a value of 19ºC.

Because of these facts, the performance of the Passive House was studied when it is adapted to a new temperature range adjusting the heating point to 19ºC but keeping the control to sense the ZRT for a better thermal comfort.

The space heating demand obtained for this modification of the model was <u>*1915 kWh*</u>, which supposes a reduction of *8.2%* with respect to the initial model and a reduction of *12.5%* with respect to the second model. It shows the possibility of decreasing the overall heating demand even when the control is sensing the ZRT, which has the handicap of increasing in the energy used. Thus, the model suggests that it will be possible to save energy and to improve the thermal environment of the occupants at the same time assuming that the occupants will react to the ZRT according to the comfortable temperature ranges previously detailed.

6. Passive House Performance in warm climates. Importance of the implementation of an appropriate night ventilation control

6.1 Background

In the previous section it has been seen how the concept of Passive House, which was launched in Central Europe, may be applied to colder environments such as Dunoon (Scotland), leading to a considerable reduction in the space heating with respect to standard Scottish dwellings due to the building's good thermal insulation and good airtightness. This section will explore the importance that the installation of a mechanically controlled night ventilation system modelled in ESP-r might have in the performance of the dwelling, when a much warmer climate is applied to it. Madrid, capital and more populated city of Spain, and main center of industrial activity within the country was chosen as the place for the implementation of this scheme.

The main difference with respect to the previous case study of Passive House's performance in Scotland will be the reduction in the heating demand and the apparition of a huge cooling demand needed to be met as a consequence of the warmer climate.

Previous documents on performance of these buildings suggest that original PassivHaus building techniques will not be directly transferable to other climates and a boundary condition such as the local building traditions regarding the specific climatic conditions must be considered (SPHC, Scottish Passive House Centre). However, as the main aim of this section was to evaluate the capacity of the aforementioned system in reducing the cooling demand and the length of this project was highly time constrained, Scottish vernacular architecture was not modified when the model was transferred to the new location. Therefore, apart from seeing this study as an evaluation of the importance of setting an adequate night ventilation system in warm climates, it also could be seen it as a strategy to follow in cold climates in order to mitigate the coming global warming. It explores whether or not the fact of using an appropriate mechanically controlled night ventilation system would be enough to reduce the cooling demand until values admitted by the PassivHaus criteria. A wide range of airflow networks and different night ventilation setpoints will be considered. High-resolution dynamic simulation using short time-step intervals will be necessary in order to correctly recreate all the issues regarding night ventilation. ESP-r model designed for Dunoon will be used as starting point with the subsequent change in the climate data.

6.2 Climate

The first step taken in this study was to apply Madrid's climate database to the ESP-r initial model used formerly for Scotland. Climate data from the ASHRAE's International Weather for Energy Calculations (IWEC) database was used. The IWEC files contain hourly weather observations such as dry bulb temperature, dew point temperature, wind speed, wind direction, and hourly solar radiation and illuminance data that is calculated from earth-sun geometry and cloud cover. 2001 was identified as a typical year in terms of climate for Madrid and then data for this year was used.

Madrid is situated in the center of the Iberian Peninsula and it is part of the Meseta Central with an elevation of about 600 m above sea level. This situation results in a more continental climate than most of the Spanish cities and sensitive fluctuations in the temperature throughout the year.

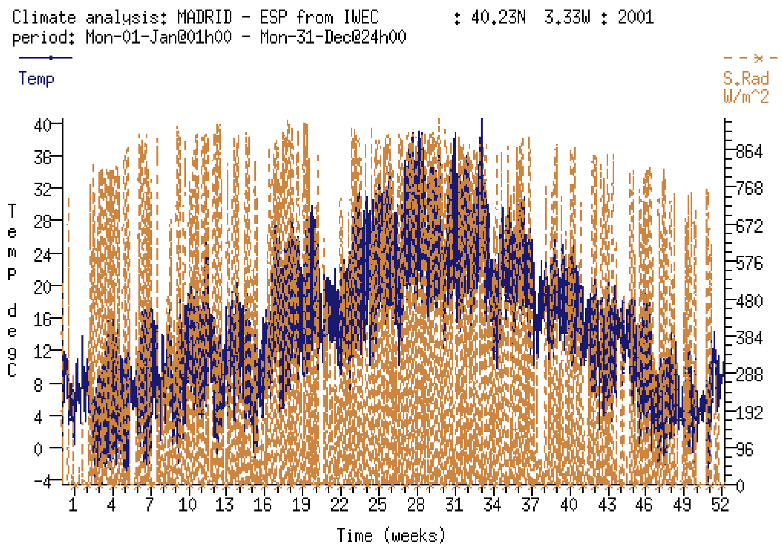

Figure 23: Madrid's ambient temperature and direct solar radiation.

Two main facts must be noticed in the previous figure. In summer, Madrid rises temperatures about 40ºC (and they also may exceed 20ºC during the night) although in winter temperatures may descend until values of approximately -3ºC. This fact implies cooling and heating requirements within the year. Heating demand for Madrid will be lower than for Dunoon because it is warmer winter. Moreover, values of direct solar radiation of about 900W/m^2 are reached almost during the entire year, which will cause a sensitive increment in the solar gains with respect to Dunoon and together with the high temperatures in summer would probably cause a problem of overheating in the dwelling resulting in a higher cooling demand. Thus, due to all of these differences in the climate, modification of the ESP-r initial model will be necessary in order to reduce as much as possible the energy demand. Importance of the implementation of an adequate mechanically controlled night ventilation system will be studied.

6.3 ESP-r initial model transferred to a warmer location

A first simulation will be run just using the ESP-r initial model built for Scotland and changing the climate database to Madrid. After that, several modifications in the model will be carried out with the purpose of creating a strategy for decreasing the space energy demand.

6.3.1 Performance of initial ESP-r model in Madrid

The first step was to select Madrid's climate database. After considering the characteristics of this climate, it seemed clear that during summer nights ventilation would be required in order to decrease the cooling demand for this period. Then, if the user wants to implement any type of airflow control system to the model later, it will be necessary to create an airflow network that simulates the infiltration and ventilation patterns of the dwelling rather than inputting the total infiltration and ventilation rates into the scheduled air flow menu of the model. This is necessary in order to be able to run the simulations properly, as in ESP-r it is necessary to have air flowing at each instant if an airflow network has been established.

Last version of ESP-r has an option which allows creating from the input scheduled airflows the equivalent airflow network associated to these values. When using this option the software scans the existing zone operational details and creates one node for each zone and fixed volume flow rate components to represent infiltration and ventilation patterns. Moreover, it also creates a source boundary wind pressure node and a sink boundary wind pressure node as a set of orifices from each zone to the sink to allow exfiltration. After using this option a first simulation of the equivalent initial model with airflow network was run and the results are expressed in the next table:

Zone total sensible and latent plant used (kWhrs)

Zone id	Zone name	Sensible heating Energy (kWhrs)	Sensible heating No. of Hr rqd	Sensible cooling Energy (kWhrs)	Sensible cooling No. of Hr rqd
1	Ground_floor	691.65	2839.0	-906.16	2676.0
2	First_Floor	387.38	1938.0	-1630.12	3830.0
	All	1079.03	4777.0	-2536.28	6506.0

Table 25: Heating and cooling demand.

Note that for this first simulation the so called 'ESP-r initial model' was used (see section 4.3 for boundary conditions) i.e. modifications of section 5.3 were not used (the only control used was a simple temperature control of 20-25ºC) due to the first aim was to compare the performance of the actual Passive House in different climates without implementing any improvement to the model.

The table shows that in comparison with the model's performance in Dunoon, the heating demand was almost half (1079 kWh for 2087 kWh) and cooling demand of 2536 kWh would need to be considered in Madrid whereas in Dunoon natural ventilation is enough to cool down the temperature until the desired value. Also, it is noticeable that in Dunoon the requirements for both floors were approximately the same meanwhile in Madrid the *ground floor requires much more heating and much less cooling* than the first floor. This would probably be a consequence of the greater amount of solar gains in Madrid and the window location since the first floor is the only one with south facing windows.

6.3.2 Adapting the model. Night ventilation control implementation

After analyzing the results when the new climate has been used in the initial ESP-r model it was identified that, as it was expected, for this new location the main issue would be trying to find a strategy in order to reduce the high values of cooling demand. On the other hand, initially, the heating requirements would not be a big problem since the total value was considerably lower than for the Dunoon's case study. It was found a large summer diurnal swings in air temperature, in which the ambient temperature dropped below the room temperature. Because of these facts, a night ventilation control was established with the purpose of reducing the cooling demand.

6.3.2.1 Basic airflow network and airflow control scheme

In ESP-r, before introducing any new type of airflow control into the model it is necessary to create an appropriate airflow network which is able to support the desired control.

Night ventilation has to satisfy two conditions: the ambient temperature needs to be less than the zone temperature and the zone temperature needs to be higher than the desired setpoint e.g. 25ºC. In order to create a control for these conditions it is required to design a mass flow network with three nodes and two controlled connections as follows (note that the figure does not show the previously created equivalent airflow network associated to the input ventilation and infiltration):

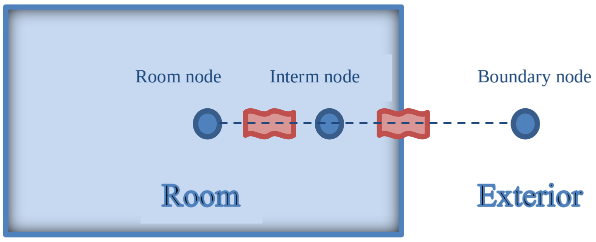

Figure 24: Airflow network for night ventilation.

There is one boundary node (wind pressure drive) on the exterior of the room which is connected to a second indoor intermediate node (unknown pressure) via a component that represents the window (air flow door opening). This node is connected to the room node which is situated in the middle of the room via a second component (slightly bigger air flow door opening). Note that this partial airflow network was added to the original network designed in section 6.3.1 which already contained fixed volume flow rate components to represent infiltration and ventilation patterns. This is needed for the solver so that when the control associated to this airflow network is active there is still a minor path for the air to go from the room to the outside node. As far as the components are concerned, air flow door openings were selected because the windows of the dwelling were actually a type of patio door that let the air flow from the inside to the outside and vice versa. Dimensions of these components were input following the data shown in section 4.2.4 and a typical discharge factor of 0.60 was assumed.

Regarding the airflow control, a double flow control was necessary to set. The first one acts on the connection between the boundary node and the intermediate node and it senses *the temperature difference* between the boundary node and the zone node. To achieve that is it necessary to state in the airflow network that the internal intermediate node is not associated with a zone but it senses the temperature of the room node, which obviously is associated with the room zone. In this way we manage to compare both the indoor and outdoor temperature. Then, the last step is to state some premises: the control must be an on/off control valid during the entire year, the setpoint is 0 (for sensing when one temperature is higher than the other) and the opening capacity fraction is 1 (window fully opened). Moreover, as the temperature difference selection subtracts the value of the first node of the connection from the value of the second one, it is necessary to have an inverse action in order to open the window when the ambient temperature is less than the room temperature.

The second flow control acts on the connection between the intermediate node and the room node and senses the *room temperature*. It is also an on/off control valid during the entire year and opening capacity fraction 1. The action this time is direct with an initial setpoint of 24.5ºC, i.e. the window will open when the room temperature is higher than 24.5ºC.

Then, air will flow from the exterior to the room only when both of these controls are satisfied, i.e. $T_{room} > 24.5ºC$ and $T_{ambient} < T_{room}$. Setpoint of 24.5ºC was chosen as initial value although it will be changed later to find the optimum control regarding night ventilation.

Note that apart from this double airflow control, the original temperature control with setpoints of 20ºC and 25ºC used in previous section is still working.

6.3.2.2 Night ventilation strategy

The purpose of this section is to find the best night ventilation strategy that leads to the lowest energy consumption in terms of total energy demand. In order to meet the PassivHaus standard the dwelling should not surpass an annual heating and cooling consumption of 15 kWh/m^2 for each one, which assuming a treated floor area of 88 m^2 (as PHPP does) leads to a total of 1320 kWh. This section will study the possibility of achieving those figures by modifying the control airflow designed. Dunoon's building techniques will be kept and importance of installing a mechanically controlled night ventilation system will be explored.

As under study dwelling has three operable patio windows/doors in the ground floor (the other two are fixed) and in the first floor it counts with another two plus three more rooflights, then a lot of different combinations of opened and closed windows could be implemented in order to find the optimum match. Moreover, the possibility of changing the setpoints in the abovementioned controls could increase extremely the number of these combinations.

Because of this fact, a sensible approach must be carried out. It was decided to keep the setpoints of the basic temperature control at 20ºC and 25ºC following the recommendation of the PassivHaus standard in order to be able to compare the results obtained with the initial model used for Dunoon. However, the temperature setpoint of the airflow control that sensed the room temperature will be modified trying to find what temperature between the range of 20ºC and 25ºC is the optimal for opening the windows in terms of total energy use.

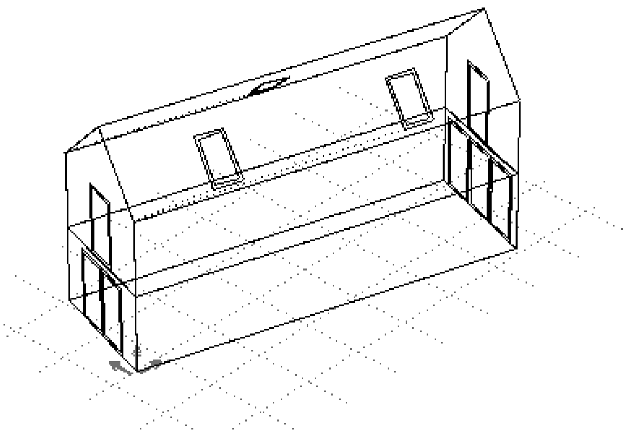

Figure 25: Passive House model

Based on the results obtained in Table 25 regarding the heating and cooling demand required for the initial model in Madrid without implementing any airflow control, it was found that both floors would need night ventilation to reduce its values of cooling demand. However, it was decided to open the windows one by one and see the performance of the house to each change.

Three representative window opening combinations and three temperature setpoints for opening the windows were chosen. This led to design three different airflow networks (one per window opening combination) and three different airflow controls (one per opening temperature setpoint), which finally resulted in nine sets of different simulations to complete.

6.3.2.3 Airflow network and airflow control specification

It is obvious that the more windows open, the more savings in the cooling demand will be achieved. However, due to security reasons night ventilation must be restricted. This was the reason why it was considered that the windows of the main façace should not be opened during the night in order to avoid any type of robbery and only windows of the back of the house (west) and rooflights could be opened (see Figure 25). Then, the two first window opening combinations chosen were; on one hand, the ground floor west window and on the other hand, the ground and first floor west windows. As these windows were quite big, it might be enough with using this configuration of ventilation to achieve the desired reduction in the cooling demand. However, as the first floor needed more cooling than the first floor because it had more solar gains since it contained two south facing rooflights, an extra airflow control network was designed adding the opening of the north rooflight to the second window combination.

Regarding the control used, temperature setpoints for opening and closing the windows were required to rely on the range between 20ºC and 25ºC as this values were the setpoints of the basic temperature control. Hence, values of 20.5ºC, 22.5ºC and 24.5ºC were chosen for the simulation in order to study how these different setpoints affected to the performance of the Passive House. For instance, a setpoint of 22.5ºC will mean in the next sections that the windows are opened when the room temperature is higher than the ambient temperature and also higher than 22.5ºC.

6.3.3 First set of results. Extra heating demand discrepancies

The next table summarizes the heating and cooling requirements calculated for each of the nine simulations comparing them with the results without any type of night ventilation. Note that for these simulations the one hour time-step period used so far is not enough due to the constant fluctuations of the indoor temperature as consequence of the new airflow controls set. Then, higher resolution will be needed and a time-step interval of 15 min was selected (if more resolution were required, the time needed for the simulations would increase considerably).

Windows opened	Opening/closing setpoint (ºC)	Zone	Heating (kWh)	Cooling (kWh)
No	_	Ground	691.65	906.16
		First	387.38	1630.12
		All	1079.03	2536.28
One (Ground Floor)	20.5	Ground	1343.21	474.75
		First	389.11	1447.21
		All	1732.32	1921.96
	22.5	Ground	787.6	520.33
		First	386.34	1489.95
		All	1173.94	2010.28
	24.5	Ground	698.01	640.11
		First	386.32	1555.71
		All	1084.33	2195.82
Two (Ground Floor & First Floor)	20.5	Ground	1331.86	465.71
		First	1693.87	675.06
		All	3025.73	1140.77
	22.5	Ground	777.71	514.01
		First	472.44	736.25
		All	1250.15	1250.26
	24.5	Ground	699.19	634.82
		First	394.38	944.9
		All	1093.57	1579.72
Three (Ground Floor, First Floor & rooflight)	20.5	Ground	793.68	509.35
		First	2233.68	590.93
		All	3027.36	1100.28
	22.5	Ground	777.18	510.27
		First	846.7	617.22
		All	1623.88	1127.49
	24.5	Ground	779.02	513.42
		First	472.83	699.37
		All	1251.85	1212.79

Table 26: Energy demand with and without night ventilation.

Having a quick look at the table, it is easy to realise that despite night ventilation reduces the cooling demand as it was expected; it also increases the heating demand. It is shown that this heating demand is even tripled in some cases, fact which seems to be a huge overestimation of the energy demand and that will be studied and explained later.

As a consequence of the window opening control established, the heating demand could only increase slightly, especially for the low temperature closing setpoints (20.5ºC). This circumstance would take place in the case of a warm summer evening/night in which the temperature falls suddenly (e.g. from 30ºC to 10ºC). In the model with low temperature opening set point, the windows would open until the room reaches the value of 20.5ºC, temperature at which the windows would be closed again. However, as the ambient temperature decreases more, the building would need extra heating requirements if this ambient temperature does not rise soon letting the room temperature to fall below 20ºC.

On the other hand, in the model without night ventilation, this circumstance would be unlikely to happen since during the day the temperature easily reaches the cooling setpoint of 25ºC and stays there. Even if during the night the ambient temperature drops to 10ºC, the indoor temperature will not fall below 20ºC before the sun starts to heat the ambient again during the morning, due to the very good insulation of this type of very low energy buildings.

The next figure illustrates this effect as example:

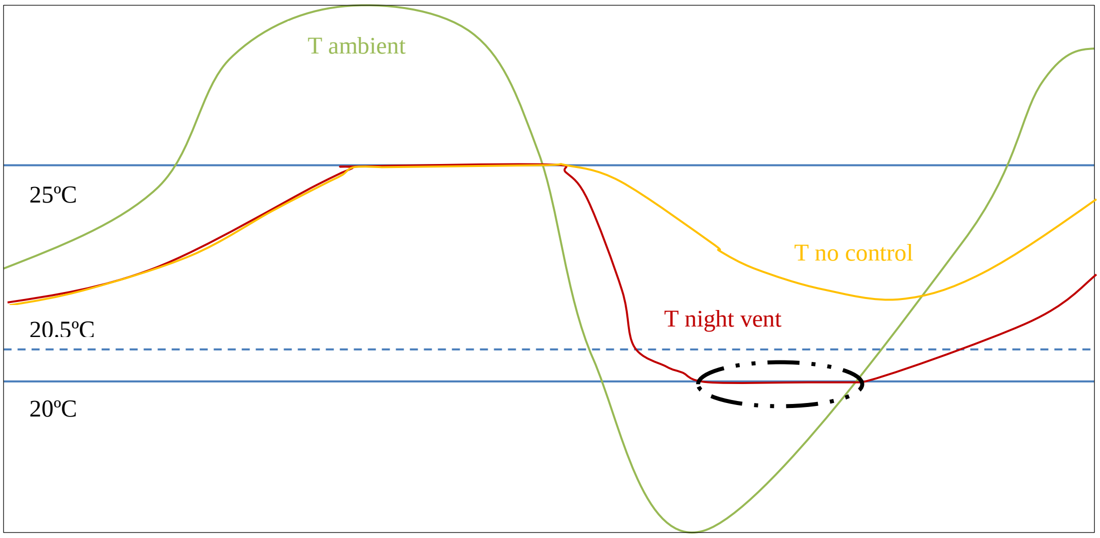

Figure 26: Example of possible extra heating demand for night ventilation.

However, this extra heating demand predicted will not occur very often because in Madrid the temperature normally does not fall until such a low values during the night. Hence, it is impossible to obtain an increment of 300% for the heating demand as result of the night ventilation implementation as the previous table shows for the second and third cases with a setpoint of 20.5ºC. The reason of this huge increment in explained in the next section.

6.3.3.1 Time-step period as origin of the discrepancies

In dynamic thermal simulation studies it is important to find an adequate balance between high resolution results and sufficiently fast calculation.

The discrepancy related to the massive extra heating showed in Table 26 will be mainly cause by the time-step increment chosen for the simulations. A time-step increment of 15 min was used but a much higher resolution simulation will be required to carry out and ESP-r is able to run simulations with much shorter time-steps. The current conflict is that if measurements are taken each 15 min, it is being assumed that each time that the abovementioned extra heating demand is required, the heating system works for the next 15 min when in reality this working period could be much less. This fact will cause an over-estimation of the heating demand and careful consideration must be taken. This issue was identified to occur for instance, during the night of the 3rd of June for the airflow control with 3 windows opened and with a setpoint of 20.5ºC for the night ventilation. Simulation with a time-step period of 1 min was run for that night in order to see until what extent the 15 min time-step simulation was inaccurate. The next figures compare both approaches:

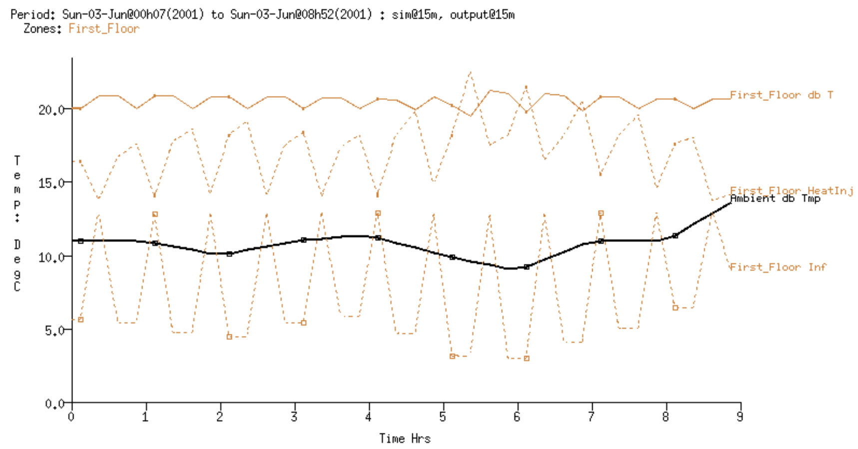

Figure 27: Extra heating with 15 min time-step period.

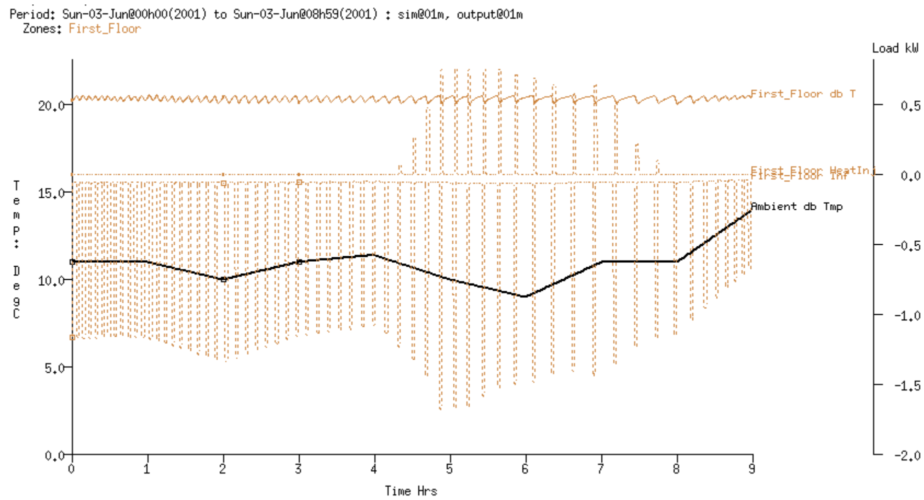

Figure 28: Extra heating with 1 min time-step period.

Four variables are shown: ambient temperature, dry bulb temperature, infiltration and heating; the three last referred to the first floor. Note that when the windows are closed, the zone temperature tends to increase due to the radiant and the other zone temperatures were slightly higher (variables not shown in the figure in order to see clearer the others). As the temperature setpoint for closing the windows were 20.5ºC and the ambient temperature reflects a chilly night, it does not take long to cool down the room temperature from 20.5ºC to 20ºC if the windows are still open even when they should have closed at 20.5ºC as consequence of a large time-step interval simulation. Then, the entire heating demand correspondent to this period will not be necessary in an ideal model which senses the temperature at every moment since as soon as the temperature fall below 20.5ºC, the windows would be closed and the temperature would not drop until 20.Cº.

Now, having a look at the first figure, it is seen that heating is required within the entire period. However, in the second figure heating is required just from 4am to 8am when the infiltration is higher and the power and length of the heating interval is much less than for the first simulation. Calling for the values of heating demand in both approaches, values of 5.33 kWh with 9.0 h of heating required and 0.29 kWh with 0.5 h of heating required were obtained for Figure 27 and Figure 28 respectively. The difference between one to another is extremely high and then 15 min time-step approach will not be used as a sensible approach for evaluating the effects of night ventilation as it would result in a huge overestimation of heating demand (see Table 26). It has been proved that the overestimation calculated using 1 min time-step period is quite low and then *this approach will be taken as the correct one*. Note that the ideal method would be to sense and respond to the variables each second but this huge amount of time-steps would lead ESP-r to have a simulation duration of days and also it would negatively impact the airflow control lifetime due to the constant opening/closing operation. Therefore, in order to properly implement this night ventilation scheme a high resolution dynamic approach via ESP-r must be followed. PHPP monthly methodology would not be then very accurate for this purpose.

6.3.3.2 <u>From high resolution data (15 min) to very high resolution data (1 min)</u>

It has been seen that an approach with a time-step period of 1 min is required in order to get enough accurate data about what is actually happening in the dwelling regarding night ventilation and heating demand. Figure 28 showed the benefits of using a simulation with this time-step period during a morning of June regarding the extra heating requirements. However, due to the location of Madrid and the big fluctuation of the temperatures, this circumstance will not occur only during summer months but it will happen also several days during spring and autumn. Then, an annual simulation with a time-step of 1 min will be necessary to run to avoid inaccuracy in the predicted heating demand.

As Table 26 showed, a total of nine different simulations with different airflow control were decided to be run in order to compare the model performance between them. Moreover, if any improvement wants to be added to the model later, a new simulation for each of the previous airflow control used should be run increasing quickly the total number of simulations for each new modification applied.

Thus, this need to run a large number of annual simulations could cause issues with the time required to carry out them. Due to the different controls set (one temperature control, one airflow control for each window to be opened), the airflow network designed and all the fully detailed construction of the Passive House input in ESP-r (envelop composition, thermal bridges, internal and external shading, operational details, etc.), a simple annual simulation could need a lot of time to be done. Then, is it necessary to find a strategy for passing from high resolution data simulations (15 min) to very high resolution data (1 min) without running each one of the different simulations. The method will be to assess which of the 9 combinations of airflow controls simulated with a time-step of 15 min lead to the best result in terms of both energy demand and thermal comfort. Once the best couple of combinations has been found, they can be simulated using 1 min time-step reducing in this way the total amount of very high resolution simulations needed to be run.

6.3.3.3 How to find the best airflow control combination

This chapter explains how to find the airflow control combination that gives better energy usage results running a 15 min time-step simulation. It is necessary to have a look at Table 26 and to examine the heating and cooling demand.

It has been explained that the heating demand calculated using this 15 min approach will be highly overestimated due to the time-step interval used (see Figure 27 and Figure 28) and then it will not be reliable at all.

However, it is important to realize that night ventilation implementation actually implies not a big growth of the heating demand as the 15 min approach suggested, but *a slightly increase* with respect to the initial case where the windows were shut all the day. This is due to the effect described in Figure 26, where a quick drop of the ambient temperature during a summer night leads to an increase in the heating requirement. But as this effect does not happen very often throughout the year (and if it does the extra energy required is not very high), this increase will not be very large.

Then, as Table 26 shows a big increase in the heating demand using a 15 min time-step (especially for airflow controls with more than one window to open and lower closing temperature setpoints), this interval approach will not be reliable enough to be considered. In order to find the optimum airflow control in terms of heating demand a more high resolution simulation will need to be done.

On the other hand is the cooling demand prediction, with which a 15 min time-step approach will be enough to get accurate data. Regarding heating demand, night ventilation was switched on and off creating a lot of oscillations in the room temperature and if the time-step period was large enough, heating overestimation appeared (see Figure 27). But in this case, as night ventilation is deactivated when cooling is required (due to the high ambient temperatures), it will make the room temperature profile to be flat without oscillations at 25ºC during the cooling time. Therefore, contrary to what happened with heating demand, cooling demand will be constantly needed during the warmest hours of the day and energy predictions will be very precise using any of the two different time-step approaches. The next figures show a comparison of the performance of the model for both approaches.

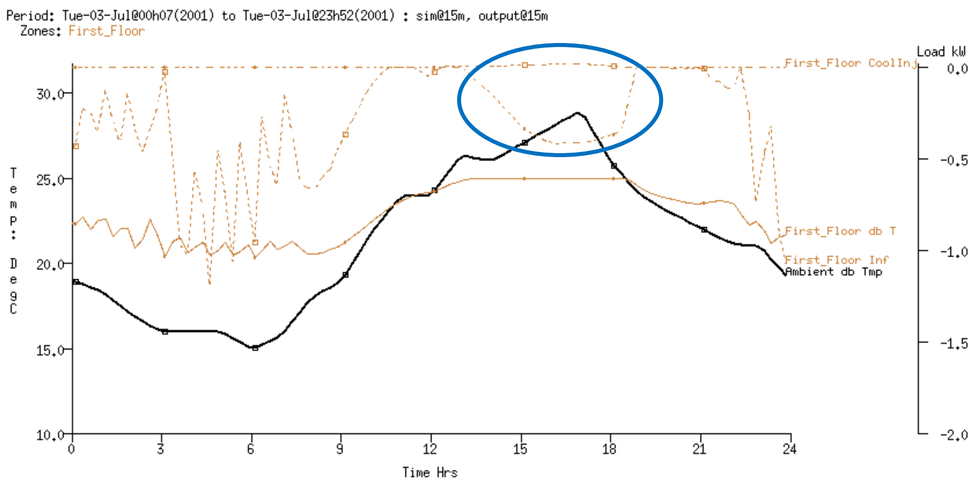

Figure 29: 15 min time-step approach

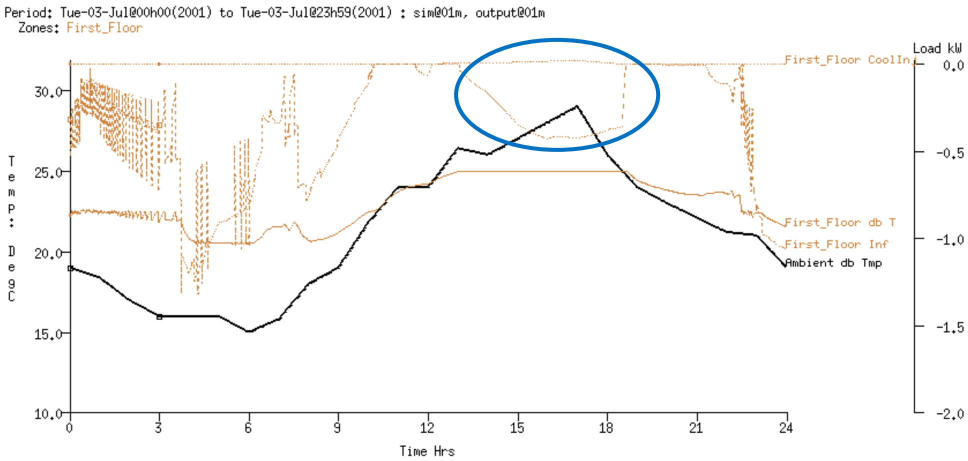

Figure 30: 1 min time-step approach

Simulation for a single day was run and the airflow network control used was three windows opened and closing temperature setpoint of 22.5ºC. The results match with all the expectations previously detailed. Cooling demands (rounded in blue) obtained for this day were 1.72 kWh using a 15 min time-step period and 1.75 kWh using a 1 min time-step period. Thus, it has been shown that in terms of cooling prediction a 15 min time-step approach is enough to get results with a high accurate level. Note that similar daily simulations using different airflow controls were run and similar patters were found.

In conclusion, analysis of *cooling demand predictions using a time-step period of 15 min* must be done in order to find the best airflow control combinations in terms of energy usage. Then, once the best of them have been identified, a more high resolution simulation using a *time-step period of 1 min* must be carried out with the purpose of predicting with a high level of accuracy the *heating demand*. Following this approach, a lot of time will be saved by avoiding the very long duration of a large group of 1 min time-step annual simulations.

6.3.3.4 Cooling demand data analysis

(Note that all of this analysis is referred to the cooling demand predictions of Table 26)

The first case shows the energy demand for a simple airflow network without night ventilation scheme and just considering the ventilation and infiltration patterns of the initial ESP-r model.

In the first airflow network a big window of the ground floor is opened. It can be seen that this opening causes a sensitive reduction in the cooling demand of the ground floor and also a slight decrease in the first floor as consequence of the ventilation between floors set in the airflow network. Also, the data shows that the difference in the total cooling demand for this airflow network from setting the windows to be opened when the room temperature is higher than 20.5ºC or to be opened at 24.5ºC is about 275 kWh, figure quite significant that must be considered.

In the third airflow configuration a big window of the first flow is also opened. It causes a large reduction in the cooling demand for the first floor and a small one for the ground floor due to the ventilation pattern between floors. The demand difference between the temperature setpoints (20.5 – 24.5ºC) is about 440 kWh and again needs to be considered.

At this point, it was evaluated whether or not was necessary to open an extra window in the first floor. It was identified that this floor had an average of about 40% extra cooling demand than the ground floor as consequence of the larger solar gains received. Then, it was decided to create a new airflow network control adding the north rooflight to the previous opening windows. Note that this rooflight was not situated in any bedroom and hence opening/closing night ventilation mechanism will not affect occupants' sleeping comfort in terms of noise. The results for this combination of three windows opened show the same patter that in the previous cases regarding the reduction of the cooling demand but in this case that decrease is smaller. Moreover, two important facts must be highlighted now: first, the total cooling demand for the ground floor is almost the same for each of the window opening/closing temperature setpoints and only a small different will appear in the cooling demand for the first floor. Second, comparing the total demand of both floors to the previous two windows airflow control, it can be seen that the values obtained are not very different with the exception of the 24.5ºC setpoint. These two facts suggest that a high level of night ventilation has been reached and the opening of new windows would not produce a significant improvement anymore. Additionally, as it was mentioned in previous sections, it was decided not to open any main façade window for security reasons and then no more operable windows were available in the back of the house. Also, none of the south facing rooflights wanted to be opened because they were located very near to rooms and they could cause noise discomfort (due to the opening/closing) to the occupants during the night.

In conclusion, a three windows opening system will be enough to obtain effective night ventilation and no more windows are needed to be open. The difference between selecting one or another opening/closing setpoint for the schemes with either one or two windows to be open is quite large (about 275 and 440 kWh respectively). However, the effective ventilation obtained with a three-windows scheme makes this difference reduce to 112 kWh. This fact *plays down the importance of setting the opening/closing windows setpoint to one or another value in terms of cooling demand*, increasing in this way the flexibility of the occupants to select their own preferred value according to their thermal comfort perception or state.

Therefore, based on these findings, only three high resolution simulations with 1 min time-step increment will be run. One for each of the temperature opening setpoints (20.5, 22.5 and 24.5ºC) of the three-windows scheme airflow network.

6.3.4 Second set of results. Very high resolution time-step data (1 min). Validation of the approach

The abovementioned simulations were run with a time-step period of 1 min. In order to know if the approach followed in the previous section is valid, two facts have to be checked.

First thing to do is to compare the results obtained using 1 min and 15 min time-step increments for the simulations. The next table shows the results obtained:

Windows opened	Opening/closing setpoint (ºC)	Zone	15 min time-step Cooling (kWh)	1 min time-step Cooling (kWh)
3 (Ground Floor, First Floor & rooflight)	20.5	Ground	509.35	505.85
		First	590.93	589.9
		All	1100.28	1095.75
	22.5	Ground	510.27	508.04
		First	617.22	631.19
		All	1127.49	1139.23
	24.5	Ground	513.42	510.51
		First	699.37	699.42
		All	1212.79	1209.93

Table 27: Comparison of cooling demand simulations with different time-step period.

As previous sections expected, cooling demand results using a time-step period of 15 min were accurate enough and its values are almost the same for both approaches.

Also, it is needed to check whether or not using the 1 min time-step approach, the huge heating demand overestimation issue is fixed. According to previous expectations, night ventilation implementation will not extremely rise the heating demand but it should actually lead to a slightly increase as a consequence of the fact described in Figure 26 (quick drop in the ambient temperature during a summer night). The following table compares the effect of night ventilation implementation with respect to the initial ESP-r model which did not count with it.

Windows opened	Opening/closing setpoint (ºC)	Zone	Heating (kWh)	Cooling (kWh)	Total (kWh)
No	_	Ground	691.65	906.16	
		First	387.38	1630.12	
		All	1079.03	2536.28	3615.31
3 (Ground Floor, First Floor & rooflight)	20.5	Ground	733.7	505.85	
		First	522.61	589.9	
		All	1256.31	1095.75	2352.06
	22.5	Ground	713.27	508.04	
		First	393.1	631.19	
		All	1106.37	1139.23	2245.6
	24.5	Ground	712.09	510.51	
		First	383.9	699.42	
		All	1095.99	1209.93	2305.92

Table 28: Overall effect of night ventilation using 1 min time-step approach.

Again, as previous sections predicted, that small heating increase was found. This growth was larger for lower temperature setpoints due to for a setpoint of 20.5ºC the temperature only needed to drop 0.5ºC whereas for 24.5ºC it needed to drop 4.5ºC. Moreover, the overall cooling demand was reduced by more than 50% for all of the cases, reaching a reduction of almost 60% for a temperature setpoint of 20.5ºC.

Hence, all the results fit with the expectations described before and the approach of going from a high resolution simulation to a very high resolution simulation will be considered as valid.

6.3.4.1 Selection of the best airflow control scheme. Thermal comfort considerations

Looking again at the previous table, it can be seen that the lower the opening/closing temperature setpoint selected, the higher the heating demand and the lower the cooling demand or vice versa. But looking deeply, it is found that these differences are not very large. Actually the overall heating values as well as the overall cooling values are quite similar between them (maximum differences of about 100 kWh) with independency of the airflow control scheme chosen. This suggests that the fact of using this airflow control with three windows being opened, not only plays down the importance of setting the opening/closing windows setpoint to one or another value in terms of cooling demand as section 6.3.3.4 stated, *but also plays it down in terms of heating demand*.

Then, any of the previous airflow control scheme could be chosen with a result of a good performance in both heating and cooling demand, increasing in this way the flexibility of the occupants to select their own preferred value according to their thermal comfort perception. Moreover, considering the treated floor area of the house as 88 m^2 following the PHPP spreadsheet specification, the maximum of both heating and cooling demand needed in order to meet the PassivHaus standard (15 kWh/m^2) would be 1320 kWh. All of simulations for these airflow control schemes meet this requirement, fact which shows the huge importance of setting an appropriate mechanically controlled night ventilation system in a warm climate. Note that if there is no setpoint preference by the occupants, it would be suggested to use a setpoint of 22.5ºC since the total energy consumption is a bit less.

But this is not the whole story. In order to assure high levels of thermal comfort in the dwelling, it is also necessary to check another two variables. First, values of indoor relative humidity. Second, whether or not there is any point during the year in which the heating or cooling system capacity of the Passive House (1500 W) is not enough to keep the indoor temperature between the setpoints of 20ºC and 25ºC.

A) Indoor relative humidity:

As section 5.1.3.5 described, several experiments have shown that individuals cannot judge the humidity when it relies on a range between 20% and 70% if the room temperature is comfortable enough (Schnieders, 2009), and these level will be taken as limits for thermal comfort.

The main problem regarding relative humidity in warm climates could be the possibility of needing a dehumidification system if the RH is very high during the summer months. However, Madrid is situated in the center of the Iberian Peninsula with an elevation of about 600 m above sea level. This situation results in a more continental climate than most of the Spanish cities, having dryer summers than them. The next table shows that RH during the summer months will not be that high.

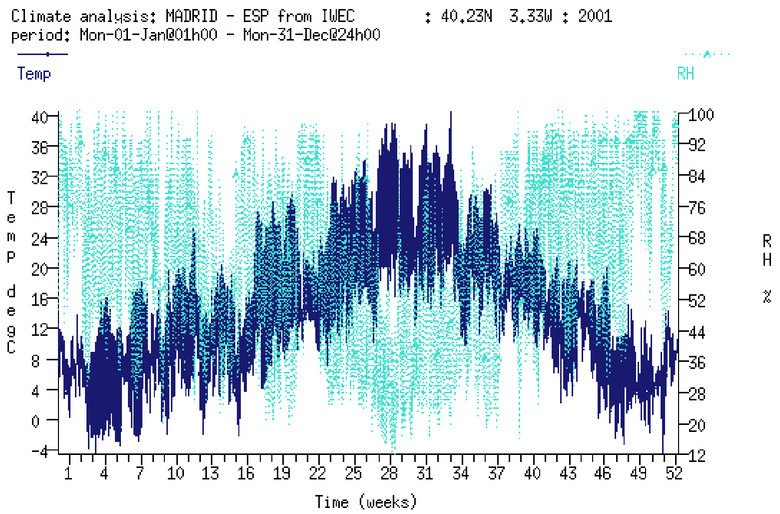

Figure 31: Madrid's ambient relative humidity and temperature.

Then, it is not expected to have very high values of RH inside the dwelling and only few peaks could be found during short periods.

Analyzing the results of the ESP-r simulation, it is possible to obtain the amount of hours and the percentage of time in which the values of the zone RH were situated outside of the comfortable range of 20% and 70%. The next table summarises these findings:

Windows opened	Opening /closing setpoint (ºC)	Zone	RH 70% hours above	RH 70% % above	RH 20% hours below	RH 20% % below
3 (Ground Floor, First Floor & rooflight)	20.5	Ground	25.97	0.3	315.72	3.6
		First	55.45	0.6	271.45	3.1
		All	81.42	0.5	587.17	3.4
	22.5	Ground	25.97	0.3	312.45	3.6
		First	27.93	0.3	371.93	4.2
		All	53.90	0.3	684.38	3.9
	24.5	Ground	26.07	0.3	312.65	3.6
		First	20.98	0.2	390.07	4.5
		All	47.05	0.3	702.72	4.0

Table 29: Relative humidities outside the comfortable range for each airflow control.

It is shown that actually, high values of RH will not be a problem for this model in any of the cases as the maximum percentage of RH > 70% obtained was 0.6%. Moreover, the maximum percentage in which the RH < 20% only was 4.5% and this fact will not cause many problems either. In any case, as if the occupants feel the ambient a bit dry, they could manually open a window for a short period to increase the RH, although this action could lead to an extra energy demand if the window is kept open more time than enough.

B) Temperatures outside the range of 20ºC and 25ºC:

Also, it is necessary to know the amount of hours and the percentage of time in which the values of the zone dry bulb temperature were situated outside of the heating and cooling setpoints of 20ºC and 25ºC due to the heating or cooling system capacity of the Passive House (1500 W) was not enough to keep the indoor temperature between this range.

The next table shows the frequency in which the temperatures are outside of the comfortable range:

Windows opened	Opening /closing setpoint (ºC)	Zone	Temp 25ºC hours above	Temp 25ºC % above	Temp 20ºC hours below	Temp 20ºC % below
3 (Ground Floor, First Floor & rooflight)	20.5	Ground	0.00	0.0	0.02	0.0
		First	0.00	0.0	40.35	0.5
		All	0.00	0.0	40.37	0.2
	22.5	Ground	0.00	0.0	0.05	0.0
		First	0.00	0.0	4.77	0.1
		All	0.00	0.0	4.82	0.0
	24.5	Ground	0.00	0.0	0.05	0.0
		First	0.00	0.0	0.02	0.0
		All	0.00	0.0	0.07	0.0

Table 30: Temperatures outside the comfortable range for each airflow control.

It is shown that there is not overheating at all and the maximum percentage of time in which the temperature is below 20ºC is 0.5 %, which is a very low value and it does not cause any problem.

6.3.4.2 *Selection of the best airflow control scheme. Suggestions*

Summarizing, indoor relative humidity and indoor temperature will not cause any problem regarding the thermal comfort of the occupants in any of the three different airflow controls used (ventilation system using three windows and with three different setpoints) and any of them could be chosen as a good control system. However, if it is necessary to choose one as the optimum, it is suggested to select the airflow control with setpoint at 22.5ºC since its values of RH and temperatures oscillate around more comfortable values.

Same suggestion would be made for the optimum control system regarding the heating and cooling demand. Looking again at Table 28, it can be seen that all of the overall values for both annual heating and cooling demand meet the PassivHaus criteria (less than 15 kWh/m^2 for each one), showing the importance of the night ventilation scheme in warm climates. Actually, the cooling demand in all of the cases was reduces by more than 50% only by using an appropriate night ventilation.

The values obtained were 2352 kWh, 2245 kWh and 2305 kWh for setpoints of 20.5ºC, 22.5ºC and 24.5ºC respectively. Then, apart from having the less energy requirements, the airflow control system with a setpoint at 22.5ºC will make the temperature of the zones oscillate around that temperature (see figure below) instead of oscillating around 20.5ºC or 24.5ºC as the other setpoints would make. These temperatures are quite comfortable but were considered to be a bit less comfortable than 22.5ºC. The next figure shows the profile for the airflow control chosen:

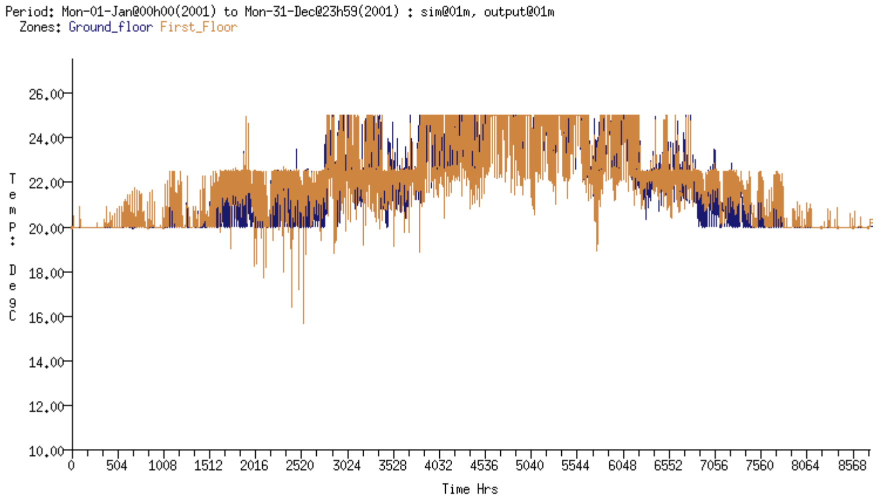

Figure 32: Simulation results for a setpoint of 22.5ºC. Zone temperatures.

6.4 ESP-r Madrid's model modification

In the same way that section 5.3 did for Dunoon, this section carries out a short analysis when modifications are implemented in the model for warmer climates. Again, these changes will be done with the only purpose of obtaining a better simulation of the behaviour of the occupants regarding thermal comfort throughout manipulations in the temperature control system. This time building's envelop characteristics and composition will not be modified either.

It was identified that the RH in Madrid's model oscillated more than in Dunoon's model and then the temperature control setpoints of 20ºC and 25ºC will not be changed. Most Spanish citizens say to feel uncomfortable with temperatures less than 20ºC. Also, ISO 7730:2006 states that during summer, in order to reach a 'Class A' level of comfort, with a room temperature of 25ºC the RH acceptable value is about 80%, but if the room temperature is 26ºC the RH acceptable value drops until less than 40%. Hence, it was decided to keep the temperature control setpoints as 20ºC and 25ºC and no modifications will be done regarding this aspect.

Then, the only modification carried out for this model will be a change in the temperature sensed. As section 5.3.2 clearly explained, zone resultant temperature (ZRT) expresses the real temperature that an individual feels inside a room and a control over this variable will lead the occupants to a higher level in comfort than if the zone dry bulb temperature is controlled. In order to implement this modification, all the control systems (temperature and airflow controls) were set to sense the ZRT.

The next table expresses the difference in the energy demand when controlling the DBT or the ZRT.

Temperature sensed	Zone	Heating (kWh)	Cooling (kWh)	Total (kWh)
Dry Bulb Temperature	Ground	713.27	508.04	
	First	393.1	631.19	
	All	1106.37	1139.23	2245.6
Zone Resultant Temperature	Ground	728.44	576.11	
	First	395.19	715.37	
	All	1167.63	1291.48	2459.11

Table 31: DBT - ZRT sensing comparison.

As it occurred for Dunoon's model, the change in sensing the ZRT instead of the DBT implies an increase in the energy demand. However, the values obtained still meet the PassiveHaus criteria with values of heating and cooling demand less than 15 kWh/m^2.

6.5 Madrid's model findings and conclusions

As consequence of the change to a warmer climate, initial performance of Dunoon's Passive House model transferred to Madrid, results in a heating demand of 1079 kWh, which means a reduction of about 50%. However, the main problem regarding the performance of the dwelling in this new location is the huge cooling demand that comes into play with a value of 2536 kWh. Hence, improvements are needed in order to make an effective energy use and to meet the Passive House criteria.

The few studies undertaken about performance of Passive Houses in warm climates suggest that original building techniques will not be directly transferable to other climates. However, this project decided to keep the Scottish vernacular architecture when the ESP-r model was transferred to Madrid, in order to evaluate the importance of setting an adequate mechanically controlled night ventilation system and also in which extend this scheme would be able to reduce the overheating obtained.

Performance of nine diverse airflow temperature controls was evaluated by combining the operability of some windows within the house with three different temperature setpoints for night ventilation. These setpoints were ranged between the interval of 20ºC and 25ºC, values which were used as heating and cooling setpoints for a constant temperature control.

It was found that the implementation of this night ventilation control produced a great overestimation in the heating demand results if not short enough time-step periods were used for the simulations (1 min). However, cooling demand results were very accurate even using long time-steps. Duration of annual simulations with a time-step period of 1 min was found to be extremely long. Due to the large amount of simulations needed to run, it was needed to reduce these 1 min simulations as much as possible. Then, in order to correctly evaluate the performance of the house, it was necessary to find a strategy to identify the most effective airflow temperature controls when using a large time-step period, finding a way to overcome this heating demand overestimation and reducing at maximum the number of short time-step simulations needed to be run. Once this was found, annual simulation using 1 min time-step period was run to obtain high accurate data.

Results suggest that airflow control with three-window opening system will be enough to obtain effective night ventilation and no more windows are needed to be open. For this system, night ventilation temperature setpoint will not influence in large extent on both energy demand and occupants' comfort in terms of indoor temperature and relative humidity. Then, the three-window night ventilation model is versatile enough to let the users select their own preferred temperature setpoint. Each of the results obtained from the selection of any setpoint has both heating and cooling demand lower than 15 kWh/m^2. If no preference is identified in the setpoint selection, it is suggested to use 22.5ºC due to it will lead to a slightly better results in terms of energy demand and thermal comfort.

Therefore, it has been shown the great importance that the implementation of a mechanically controlled night ventilation system has in the adaptation of these low-energy buildings to a warmer climate such as Madrid. Then, when building a Passive House in this type of climates, full attention must be paid to the night ventilation system installed. The results of this thesis prove that this parameter is as important as other considerations such as the building techniques, component which previous studies seem to give much more importance. Moreover, this study has proved as well that Scottish building techniques could be transferable to a total different climate such as Madrid, still meeting the PassivHaus criteria in terms of energy demand (according to ESP-r results) if an appropriate mechanical airflow temperature control is applied. Thus, this system has the capacity to reduce the cooling demand to values lower than 15 kWh even when the dwelling has not been totally adapted to a warm climate (shading devices and local building traditions were not considered). This fact suggests the idea that this project could also be seen as a methodology to follow towards the mitigation of the global warming in cold climates by using an adequate night ventilation system.

Using the features of the ESP-r dynamic simulation, it was showed that PassivHaus space heating and cooling demand criteria would still be met when the controls senses the zone resultant temperature instead of the zone dry bulb temperature. This results in a more accurate simulation of the behaviour of the occupants regarding thermal comfort, as the people will feel and react to the changes of the ZRT rather than the DBT.

To conclude, an interesting fact must be highlighted as consequence of the PassivHaus criteria vision regarding energy demand. Dunoon's model did not meet the energy demand criteria because it had a total heating demand greater than 15 kWh/m^2 even when there was not cooling required (although it met the 10 W/m^2 heating load requirement). However, Madrid's model has values of both heating and cooling demand lower than 15 kWh/m^2, even when the total amount of energy used (heating + cooling) is higher than Dunoon's.

From the previous considerations it could be extracted that, as (Schnieders, 2009) predicted, it is usually much easier to compensate all the shortcomings created by boundary conditions or design issues in warm climates than in colder climates. This is due to both the low heating demand and the possibility of exceptionally reduce the cooling demand in warm places using schemes such as the aforementioned night ventilation system or other systems such as roller shutters or other shading devices. However, in cold locations will be more difficult to meet the heating requirements even when the building has been completely designed to reduce its heating demand as much as possible. Example of this case is the Dunoon's Passive House. Previous sections showed that the total space heating demand of the dwelling was greater than 15 kWh/m^2 when a Scottish climate was applied. Then, in order to meet the PassivHaus criteria, it was necessary to satisfy the 10 W/m^2 peak heating load requirement instead.

7 From Passive House to Net Zero Energy buildings via PV array. Preliminary study.

7.1 <u>Background and purpose of the study</u>

As it has been explained in the literature review section, the PassivHaus concept was originated in Germany and it was developed around Central Europe. Few years ago some projects contributed towards its expansion to the northern Europe countries and more recently an adaptation of the original PassivHaus criteria was carried out by the PHI (see section 2.4.5) in order to spread the concept throughout warm climate countries.

The new ‘Europe 2020’ strategy set by the European Commission defined the necessity of make a sustainable use of energy by reducing the greenhouse gas emissions and increasing both the energy obtaining from renewable sources and the energy efficiency (European Commision, 2010). Being aware of this fact and also of the subsequent new Directive on Energy Performance of Buildings which stated that by the end of 2020 all the new buildings had to be nearly zero-energy buildings (2010/31/EU), the PHI considers the adoption of its PassivHaus concept in dwellings as one of the most effective strategies towards the achievement of these nearly zero-energy buildings.

During the last International Passive House Conference celebrated in Innsbruck on May 2011 (PHI, 2011a), several presentations showed that the cost associated to the renewables schemes necessary to reach this Net Zero level would be prohibitive unless the building envelope matches with PassivHaus requirements. Also, based on this building construction criteria and encouraging the massive use of renewables, some demonstrators suggested the idea of moving to a further level: the Energy Plus House. This type of houses produces more energy from renewables than they import from the grid in an annual basis. Currently, projects such as *Zero:e Park* are developing this concept (Zero:e Park, 2011).

In addition, during the conference it was encouraged the use of PV over the use of solar thermal even for solar hot water purposes due to the following reasons (Peabody, 2011):

- *"PV panels maintain the same efficiency relative to solar exposure year round, while solar thermal efficiency drops significantly in winter months.*
- *Solar thermal panels become decreasingly efficient as the array grows larger due to increasing system temperatures and storage areas. There is no comparable drop-off of efficiency for PV.*
- *PV panels can be much more efficient at making hot water when tied to heat pumps, which have the added versatility of providing air conditioning in the summer months.*
- *Over time solar PV panels will continue to improve in efficiency, yet solar thermal panels will remain more or less at present levels. This should be a consideration in long-term planning."*

Therefore, a preliminary study of the performance of the Passive House modelled in previous sections will be undertaken when the roof is covered by PV panels with the aim of assess to what extent is possible to achieve a Net Zero Energy building. However, further work will be suggested regarding the application of hybrid systems composed of PV's and other renewable schemes such as heat pumps or solar thermal in order to find the best strategy towards obtaining these Net Zero Energy buildings.

7.2 Methodology

This section carries out a study in both of the locations in which the performance of the Passive House was analysed (Dunoon and Madrid). First of all, a design of the PV system used will be carried out with the aim of obtaining a system with a good performance. Then, total energy demand will be calculated breaking down this concept into three different groups such as space heating and cooling demand, domestic hot water demand and electricity demand. Finally, energy supply from the previously designed PV system will be assessed using MERIT software and it will be explored whether or not is possible to achieve a Net Zero Energy building in any of these locations.

7.3 PV system design

The next selection of PV system design was carried out based on the considerations of the PV Domestic Field Trial report part II towards a good PV performance. It was made by DTI as part of the DTI New and Renewable Energy Programme managed by Future Energy Solutions (DTI, 2006).

7.3.1 PV module

When choosing a PV module, a set of parameters such as available roof area, desired power output or panel cost and availability are necessary to consider taking into account the requirements of the site. For the purpose of this study, it was decided to fully cover the roof of the dwelling in order to get the maximum possible power output and to explore the possibility of achieving a Net Zero Energy building.

Exploring the market, it was seen that polycrystalline panels were cheaper than monocrystalline panels. This is because polycrystalline cells are more cost-efficient to produce. They are produced pouring silicon into blocks that are subsequently sawed into plates forming crystal structures of different sizes in multiple directions during the solidification of the material. This fact makes that this type of cells have a slightly lower efficiency than monocrystalline cells with larger individual cells and slightly larger module. On the other hand, monocrystalline cells are extracted from melted silicon and then sawed into thin plates and then the crystal obtained has grown in only one plane.

The market indeed shows that because of its higher efficiency, monocrystalline panels are more expensive than polycrystalline panels when both have the same peak power. However, maximum peak power of the commercially available panels is normally lower for the former than for the latter. Due to this consideration, it was decided to find in the market one PV panel of each type in order to run diverse simulations and to find out which type of PV module is the most appropriate for this study. Price must evidently be considered.

As there are hundreds of different PV panels commercially available, the selection of panels was based on the large list of *www.wirefreedirect.com/solar_panels_and_modules.asp* taking into account all the previous concerns. PV panels with high peak power and reasonably price were selected:

- Kyocera KD240GH-2PB *polycrystalline* solar panel with peak power of 240 W and V_{oc} of 36.9 V. Dimensions: 1662x990x46 mm. Price: £524.00.

- Sharp NU-180E1 *monocrystalline* solar panel with peak power of 180 W and V_{oc} of 30.0 V. Dimensions: 1318x994x46 mm. Price: £495.00.

Full description of the characteristics and properties of these PV panels is available in *Appendix II*. Note that both PV modules fulfil the test conditions according to the standard IEC 61215 for PV module qualification as it is recommended in the *PV Domestic Field Trial report*. It guarantees power rating at STC to within 90% of its original performance for 10 years and preferably 80% for 20 years.

At the beginning of this section it was said that one of the main parameters to be considered when installing a PV module is the available roof area. As the aim of this study is to obtain the maximum energy possible from PV it, it was tried to completely cover the roof with PV panels. It was necessary to realise that the southern facing roof contained two rooflights with dimensions of 1.6x1.0 m and this area was not available to install new devices. It originally also contained five solar thermal panels but since this study only considers the installation of PV panels, they were neglected with the purpose of enlarging the surface available for PV panels.

An important issue was found when calculating the number of panels of each type that could be installed on the roof: the dimensions of the surface of the southern facing roof were 12.70x2.95 m. This fact caused that it was impossible to install two rows of Kyocera's polycrystalline PVs as its length was 1.662 m. However, it was possible to install two rows of Sharp's monocrystalline PVs as its length was 1.318 m. This circumstance made that a total amount of 22 Sharp's panels were able to be installed whereas the amount of Kyocera's panels was only 10. Therefore, Kyocera's polycrystalline panels were neglected and the study was undertaken only considering the Sharp ones. Moreover, even without considering the price, none of the polycrystalline panels of the list with peak power greater than Sharp's monocrystalline panel (180 W) has a length short enough to be able to install a double row of them on the roof.

At this point one important issue must be highlighted. The main aim towards the achievement of a Net Zero Energy building is to supply as much energy as possible. Then, as it has been shown, consideration of the PV system design must be done prior building the dwelling to maximise the percentage of roof area that can be covered by panels. In this way, the PV panel selection would not be restricted by the roof dimensions and it will be possible to fully cover the roof with the ideal PV panel previously selected.

According to the DTI report, the final step when choosing a PV module would be "to consider the request of performance data on modules supplied to ensure that they fall within the nominal range".

Summarizing, 22 Sharp NU-180E1 monocrystalline PVs with a total peak power of 3960 W and total price of £10890.00 will be used.

7.3.2 Support structure, array tilt angle and orientation

To ensure a high level of performance, the PV system must be designed using a support structure that allows ventilation beneath the modules with the purpose of decreasing the operating temperature and hence keeping high efficiencies. Also, it must be avoided any type of cell shading and dirt build-up by having a low enough support structure profile.

Regarding the array tilt angle, high efficiencies are expected as long as the roof is tilted between 25 and 60º. The optimum tilt angle would be about 45º, exactly the inclination of the roof of the Passive House under study and then maximum output regarding tilt angle is expected.

Concerning array orientation DTI report states that, despite what it commonly though, it is not totally necessary that the system faces the south giving more importance to the fact of reducing the system losses. An orientation between southeast and southwest still gives high levels of efficiency and output. As section 4.3.1 described the south facing wall was deviated 17º to the east, fact that will need to be considered in the simulations. Due to this shift of 17º, losses in energy production slightly higher than 3% are expected according to the report.

7.3.3 Inverter

When selecting the inverter, it is necessary to consider the possibility that the inverter intermittently turns off as a consequence of the grid voltage being higher than the allowed maximum level. Hence, its maximum input voltage should be a bit higher than the nominal grid voltage in order to avoid this issue. In the case of the UK, the grid voltage is 230V and due to the UK-Europe grid voltage harmonization (CENELEC Harmonization Document HD 472 S1) it is allowed to vary from -6% to +10%, fact which requires an inverter able to operate at least at 253V. In the case of Spain, it would be enough with 242V since the grid voltage is 220V.

In relation to the inverter power capacity, DTI report says that the recommended value for the UK is around 75% of the array capacity due to the relative low proportion of time in which the sunlight level is high enough to achieve great levels of production. However, as this research also considers the implementation of PVs in Spain where the sunlight level is much higher, the percentage will be increased and an inverter of nearly the array capacity (3960W) would be needed. Exploring the market it was noticed that an inverter with capacity of about 4000W would be used since there was not found inverters commercially available with capacity in the range of 3500 and 4000W.

Finally, on the PV array side of the inverter it is important to use cabling and switching suitable for DC electricity at adequate levels of voltage and current in order to avoid a voltage drops higher than 3%.

Considering the previous issues, a Sunny Boy 4000TL inverter from SMA Solar Technology was chosen. It has maximum DC power of 4200W, with maximum input voltage of 550V, nominal AC voltage range of 180-280V and maximum efficiency of 97.0%. Full specification of the inverter selected is available in *Appendix III*.

7.3.4 Other considerations

Apart from the inverter losses, shading can be a major source of losses in the PV system and it is necessary to consider and reduce all the potential shading sources that may interact with the system such as trees, neighbouring buildings or building self-shading. Following the indications of the available PHPP, it will be assumed that there is not any type of external shading that could affect to the south-facing façade and then a perfect location of the Passive House leading to zero shading losses.

Also, it is suggested to minimise the cable length and to ensure good cable connections to avoid a reduction in the long-term performance. Similarly, it is encouraged the installation of display units in an accessible position to allow the user see whether or not the system is operating. Additionally, to ensure that the user has an overall understanding of how the system installed works in order to correctly react to a possible problem ant to avoid extra losses.

7.4 Energy demand

The total energy demand is break down into three different groups: space heating and cooling demand, domestic hot water demand and electricity demand.

7.4.1 Space heating/cooling demand

In previous sections, performance of the case study Passive House was explored in two different locations such as Dunoon and Madrid. As outcome of this research it was obtained the space heating/cooling requirements for each location running dynamic simulation by means of ESP-r. After implementing some improvements, Dunoon had a space heating demand of 1.91 MWh/yr (see section 5.3.3). On the other hand, when the dwelling was transferred to a warmer climate such as Madrid, it was obtained a lower space heating demand (1.11 MWh/yr) although there was also a cooling demand required (1.14 MWh/yr). Then, the total demand for Madrid was 2.24 MWh/yr (see section 6.3.4).

7.4.2 Domestic hot water demand

Domestic hot water demand for Dunoon's Passive House was available in the PHPP spreadsheet. It assumed an average occupancy of 2.5 persons for the under study Passive House, a consumption of 25 l/person/day at 60ºC and an average cold water temperature supply of 10ºC. This resulted in a useful heat demand for domestic hot water of 1520 kWh/yr. However, the PHPP also considered the heat losses through the individual pipes (321 kWh/yr) under the assumption that each inhabitant uses each hot water tap of his dwelling three times a day. Also, the heat losses from storage (323 kWh/yr). Then, the total heat demand of the DHW system is *2164 kWh/yr*, which leads to a utilization factor of 70.2%.

Domestic hot water for Madrid's Passive House was not available since there was not PHPP spreadsheet for this model. Hence, it was calculated using the same values with the exception of a different average cold water temperature supply as consequence of the higher ambient temperatures. Average value of 18.35ºC was used as it is stated in (Freire, Soler, & Fernández, 2008). The final consumption was estimated as *1940 kWh/yr*.

7.4.3 Electricity demand

Electricity demand was assumed to be the same for Dunoon than for Madrid since no major difference in the use of appliances, electronics, etc. was considered. Auxiliary electricity demand from the ventilation system and from the inverter was neglected.

Therefore, taking into account these aspects, Dunoon's PHPP was used to predict the electricity demand for both locations, obtaining a value of *1203 kWh/yr* as it is shown in the next figure.

Column Nr.	1	2	3			4	5		6		7	8	8a	9
Application	Used ? (1/0)	Within the Thermal Envelope? (1/0)	Norm Demand			Utilization Factor	Frequency		Reference Quantity		Useful Energy (kWh/a)	Electric Fraction	Non-Electric Fraction	Electricity Demand (kWh/a)
Dishwashing	1	1	1.05	kWh/Use		1.00	65	/(P*a)	2.5	P	172	50%		86
DHW Connection													50%	
Clothes Washing	1	1	1.03	kWh/Use		1.00	57	/(P*a)	2.5	P	148	55%		82
DHW Connection													45%	
Clothes Drying with:	1	1	0.00	kWh/Use	Residual dampness	0.88	57	/(P*a)	2.5	P	0	0%		0
Clothesline			0.00		0.60						0		0%	
Energy Consumed by Evaporation	1	1	3.13	kWh/Use		0.60	57	/(P*a)	2.5	P	270		100%	
Refrigerating	0	1	0.78	kWh/d		1.00	365	d/a	1	HH	0	100%		0
Freezing	0	1	0.88	kWh/d		1.00	365	d/a	1	HH	0	100%		0
or Combined Unit	1	1	1.00	kWh/d		1.00	365	d/a	1	HH	365	100%		365
Cooking with:	1	1	0.25	kWh/Use		1.00	500	/(P*a)	2.5	P	316	100%		316
Electricity					Percentage CFLs								0%	
Lighting	1	1	16	W	90%	1.00	2.90	kh/(P*a)	2.5	P	117	100%		117
Consumer Electronics	1	1	80	W		1.00	0.55	kh/(P*a)	2.5	P	111	100%		111
Small Appliances, etc.	1	1	50	kWh		1.00	1.00	/(P*a)	2.5	P	126	100%		126
Total Aux. Electricity											0			0
Other:														
											0			0
											0			0
											0			0
Total											1626 kWh			1203 kWh

Figure 33: Electricity demand prediction according the available PHPP.

7.4.4 Overall demand

To conclude, the next table expresses the total energy demand prediction for both locations.

	Dunoon (kWh)	Madrid (kWh)
Heating/Cooling	1910	2250
Hot water	2164	1940
Electricity	1203	1203
Total	5277	5393

Table 32: Total annual energy demand.

One last point is necessary to consider here. It must be noticed that the heating/cooling demand prediction for Madrid was obtained in previous sections trough a dynamic simulation with the aim of showing the importance of implementing a mechanically controlled night ventilation system in a warm climate towards a reduce in the cooling demand. Thus, the demand of a Passive House which has been totally adapted to a warm climate by installing appropriate shading devices would be considerably less.

7.5 Energy supply. Results and conclusions

In order to assess the energy supply from the previously designed PV system, MERIT software was used.

With the purpose of running simulations consistent with the previous Passive House performance studies (Dunoon and Madrid), ESP-r climate database of both locations was transferred to MERIT. Then, design of the PV system was undertaken following the previous specification regarding the PV modules and the inverter. As it was already mentioned, 22 Sharp NU-180E1 monocrystalline PV modules were installed using a Sunny Boy 4000TL inverter from SMA Solar Technology.

Results of *3520 kWh/yr* and *6320 kWh/yr* were obtained for Dunoon and Madrid respectively. As it was expected, energy supply in Madrid was much larger than in Dunoon as a consequence of the greater solar radiation.

Comparing these results with the overall demand prediction shown in Table 32, it can be noticed that according with this study it would not be possible to achieve a Net Zero Energy building in Dunoon by using only PVs since the energy demand surpasses the energy supply in about 1700 kWh/yr. Installation of hybrid systems composed of PV's and other renewable schemes such as heat pumps or micro wind turbines could make possible this objective. Further investigation on this area is suggested.

On the other hand, it seems that in the case of Madrid it would be possible to achieve this aim. The total energy demand was calculated as 5393 kWh/yr and the energy supply from the PV system was 6320 kWh/yr. However, further considerations are necessary here. It was already mentioned that auxiliary electricity demand from the ventilation system and from the inverter was neglected and also the losses through the cables of the PV system but in any of the cases this aspects could compensate the difference of about 1000 kWh/yr that exists between supply in demand. Moreover, it must be realised the type of dwelling that we are dealing with. Dunoon's Passive House was directly transferred to Madrid and the only modification carried out (besides the different climate database used) was the implementation of a mechanically controlled night ventilation system as the main aim of the thesis was to show the importance of this scheme in the reduction of cooling demand in warm climates. Therefore, if the dwelling is totally adapted to the new warm climate by installing shading devices, the cooling demand would decrease more making even easier the achievement of a Net Zero Energy building and without the necessity of entirely cover the roof with PV modules of high power capacity.

Summarising, according to this preliminary study it would not be possible to achieve a Net Zero Energy building in a cold climate such as Dunoon just by covering the roof of a Passive House with PV panels of high capacity due to the low solar radiation received. However, it has been showed that as (Schnieders, 2009) predicted, it is usually much easier to compensate all the shortcomings created by boundary conditions or design issues in warm climates than in cold climates. Actually, the concept of Passive House adapted to a warm climate such as Madrid could be extended to the concept of Energy Plus House, i.e. combining the great savings in space heating and cooling demand with the installation of highly efficient PV's it would be possible to obtain a Net Zero Energy building. However, carefully consideration must be done when designing the PV system and it is suggested to follow the considerations of a PV Domestic Field Trial in order to obtain a PV system with high level of performance.

Future Work

This thesis is mainly focused in the evaluation of the performance of Passive Houses regarding the total energy use and thermal comfort. The model is not sensitive to occupant's behaviour since heat gains regarding occupancy, lighting and use of appliances were assumed to be constant throughout the year. It is suggested to undertake a research about the influence that the behavior of the occupants might have in the performance of these dwellings.

Moreover, as this thesis was concentrated on the exploration of the importance of a mechanically controlled night ventilation system regarding cooling demand reduction Scottish vernacular architecture was not modified when the ESP-r model was transferred to Madrid. Suggestion is made to explore the performance of the dwelling when, apart from adding this night ventilation system, building techniques are adapted to this location (i.e. implementation of shading devices, optimum situation of the windows regarding solar gains, construction materials, etc.) in order to see to what extent this cooling demand could be reduced in a optimised Passive House for warm climates. After studying this aspect, a more accurate assessment towards the achievement of a Net Zero Energy building in a warm climate by installing a PV array could be done.

It is also suggested to undertake a deeply study in the designing of the optimum PV system considering aspects such as axis and tilt tracking.

Finally, an economic analysis is proposed to carry out regarding capital costs, maintenance costs and payback period of these Net Zero Energy buildings.

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Appendix I. Passive House platforms around the world

ProKlima Hannover	Germany
PIG Passivhaus Deutschland	Germany
IG Passivhaus Österreich	Austria
IG Passivhaus Schweiz	Switzerland
Passiefhuis Platform Belgium	Belgium
Passiefbouwen Holland	The Netherlands
Centrum pasivnho domu	Czech Republic
Inštitút pre energeticky pasívne domy	Slovakia
NZ Passive House	New Zealand
Das Erste Passivhaus in Slowenien	Slovenia
Minergie Schweiz	Switzerland
Ecological Construction Laboratory	USA
Passive House UK	United Kingdom
Promotion of european Passive Houses	Ireland
Austrian Energy Agency	Austria
Der Okobau Cluster Niederösterreich	Austria
Österreichs Internetportal für Nachhaltige Entwicklung	Austria
Holzkonstruktionen und Bauteilanschlüsse	Germany
Energieinstitut Vorarlberg	Austria
The Platform for Innovative Technologies	Austria
Klimabündnis Österreich	Austria
Internationale Passivhaustagung	Austria
Energieeffiziente Haustechniksysteme	Austria
Niedrig Energie Institut	Germany
Sole-Erdwärmetauscher für Lüftungsanlagen	Germany
Passivhaus Institut	Germany
Informationen zum Passivhaus	Germany
Passive House projects in Europe	Germany
Annual Passive House Conference	Germany
Passivhaus Dienstleistung GmbH	Germany
Alt Om Passivhuse	Denmark
Polski Instytut Budownictwa Pasywnego	Poland

Appendix II. PV modules specification

THE NEW VALUE FRONTIER

KYOCERA

KD240GH-2PB

High efficiency multicrystal photovoltaic module

EXAMPLES OF APPLICATION

- Grid-connected systems, for e.g.
  - Residential solar power systems
  - Public and industrial solar power systems
- Solar power stations

CUTTING-EDGE TECHNOLOGY

Exhaustive research work and continuous further development of production processes enable the integrated Kyocera high-performance solar cells with a standard size of 156 mm x 156 mm to achieve over 16 % efficiency, guaranteeing an extremely high annual yield of energy from the photovoltaic system.

To protect against the harshest weather conditions, the cells are embedded between a reinforced glass covering and EVA foil, and are sealed with a PET foil backing. The laminate is set in a sturdy aluminium frame which is easy to assemble. The module fulfils test conditions according to IEC 61215 ed. 2 for a surface load of 5,400N/m².

The junction box on the module backside is equipped with bypass diodes that eliminate the risk of the individual solar cells overheating (hot spot effect). Many series-connected photovoltaic modules can be easily wired using pre-assembled solar cables and multi-contact plugs.

Kyocera manufactures all the components at its own production sites – without buying in semi-finished products – to ensure consistently high product quality.

Free-field installation, Italy

TUVdotCOM Service: Internet platform for tested quality and service
TUVdotCom-ID: 0000023299
IEC 61215 ed. 2, IEC 61730 and Safety Class II
Kyocera is ISO 9001 and ISO 14001 certified and registered.

TÜV

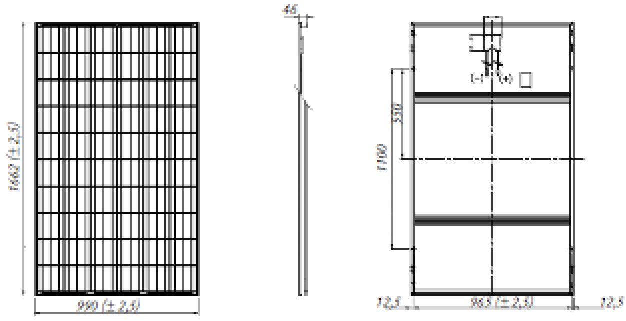
www.tuv.com

KYOCERA SOLAR

We care!

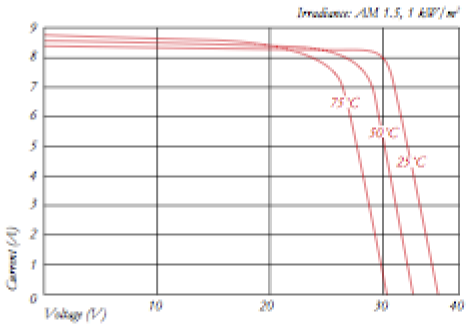
SPECIFICATIONS

in mm

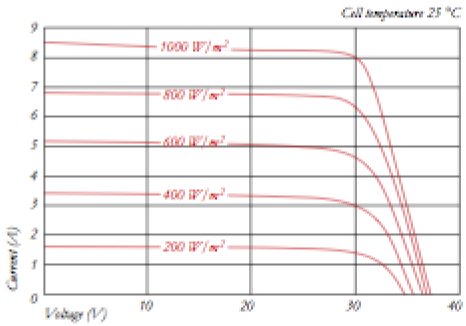


ELECTRICAL CHARACTERISTICS

Current-Voltage characteristics at various cell temperatures



Current-Voltage characteristics at various irradiance levels



ELECTRICAL PERFORMANCE

PV Module Type		KD240GH-2PB
At 1000 W/m² (STC)*		
Maximum Power	[W]	240
Maximum System Voltage	[V]	1000
Maximum Power Voltage	[V]	29.8
Maximum Power Current	[A]	8.06
Open Circuit Voltage (V_{OC})	[V]	36.9
Short Circuit Current (I_{SC})	[A]	8.59
At 800 W/m² (NOCT)**		
Maximum Power	[W]	172
Maximum Power Voltage	[V]	26.7
Maximum Power Current	[A]	6.45
Open Circuit Voltage (V_{OC})	[V]	33.7
Short Circuit Current (I_{SC})	[A]	6.95
NOCT	[°C]	45.0
Power Tolerance	[%]	+5 / -3
Maximum Reverse Current I_R	[A]	15
Series Fuse Rating	[A]	15
Temperature Coefficient of V_{OC}	[V/°C]	-1.33×10^{-1}
Temperature Coefficient of I_{SC}	[A/°C]	5.15×10^{-3}
Temperature Coefficient of Max. Power	[W/°C]	-1.10
Reduction of Efficiency (from 1000 W/m² to 200 W/m²)	[%]	7.3

DIMENSIONS

Length	[mm]	1662 (±2.5)
Width	[mm]	990 (±2.5)
Depth / incl. Junction Box	[mm]	46
Weight	[kg]	21
Cable	[mm]	(+)1030 / (–)830
Connection Type		MC PV-KBT3 / MC PV-KST3
Junction Box	[mm]	112x82x15
IP Code		IP65

GENERAL INFORMATION

Performance Guarantee	10*** / 20 years****
Warranty	5 years*****

CELLS

Number per Module		60
Cell Technology		polycrystalline
Cell Shape (square)	[mm]	156x156
Cell Bonding		3 busbar

* *Electrical values under standard test conditions (STC): irradiation of 1000 W/m², airmass AM 1.5 and cell temperature of 25 °C*

** *Electrical values under normal operating cell temperature (NOCT): irradiation of 800 W/m², airmass AM 1.5, wind speed of 1m/s and ambient temperature of 20 °C*

*** *10 years on 90% of the minimally specified power P under standard test conditions (STC)*

**** *20 years on 80% of the minimally specified power P under standard test conditions (STC)*

***** *In the case of Europe*

Your local Kyocera dealer:

KYOCERA SOLAR

We care!

KYOCERA Fineceramics GmbH
Solar Division
Fritz-Mueller-Straße 27
73730 Esslingen/Germany
Tel: +49 (0)711-93 93 49 99
Fax: +49 (0)711-93 93 49 50
E-Mail: solar@kyocera.de
www.kyocerasolar.de

SHARP

NU series
185 W | 180 W
175 W | 170 W

Monocrystalline silicon photovoltaic modules

say yes to solar power!

Because it protects the climate.

Innovation from the photovoltaic pioneer

Sharp, as a solar specialist with 50 years of experience in photovoltaics (PV), makes an essential contribution towards groundbreaking advancements in solar technology.

The NU Sharp series of photovoltaic modules are designed for applications with a high power requirement. These monocrystalline quality modules produce a sustained, reliable yield even under demanding deployment conditions.

All Sharp NU series modules offer optimal system integration – both technically and economically – and are suitable for installation in grid-coupled systems.

Brief information for the installer

- 155.55 mm x 155.55 mm monocrystalline solar cell
- 48 cells in series
- 2,400 N/m^2 mechanical load-bearing capacity (245 kg/m^2)
- 1,000V DC maximum system voltage
- CE tested for your safety

Product features

- High performance photovoltaic modules made of monocrystalline (155.55 mm^2) silicon solar cells with module efficiency of up to 14.1 %.
- Bypass diodes to minimise power loss with shading.
- Textured cell surface for especially high current yields.
- BSF structure (Black Surface Field) for optimising cell efficiency.
- Use of annealed glass, EVA plastic and weather-protection foil, as well as an anodised aluminium frame with water drainage holes for prolonged use.
- Output: connection cable with water-protected plug connector.

Quality from Sharp

Sharp Solar quality sets standards. Permanent monitoring guarantees consistent high quality. Each module is optically, mechanically and electrically tested. You recognise it from the Original Sharp label, the serial number and the Sharp guarantee:

- 2 year product guarantee
- 10 year performance guarantee for a 90 % power output
- min. 20 year performance guarantee for a 80 % power output

The detailed guarantee conditions and further information is available at www.sharp-world.com.

Mechanical data

Cell	Monocrystalline (155.55 mm)[2] Sharp silicon solar cells
Number and connection of cells	48 in series
Dimensions	1,318 x 994 x 46 mm (1.31 m²)
Weight	16 kg
Connection type	Cable with plug connector (MC-3)

Limit values

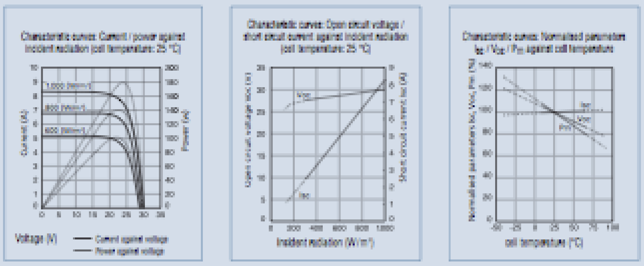
Storage humidity	up to 90	%
Operating temperature (cell)	–40 to +90	°C
Storage temperature	–40 to +90	°C
Maximum system voltage	1,000	V DC
Maximum mechanical load	2,400	N/m²

Electrical data

Module production in the EU Module production in Japan		NU-185 (E1) NU-S5 (E3E)	NU-180 (E1) NU-S0 (E3E)	NU-S0 (E3Z)	NU-R5 (E3Z)	NU-R0 (E3E)	
Rated power		185 W_p	180 W_p	180 W_p	175 W_p	170 W_p	
Open circuit voltage	V_{oc}	30.2	30.0	30.0	29.8	29.4	V
Short circuit current	I_{sc}	8.54	8.37	8.23	8.29	8.37	A
Voltage at maximum power	V_{pm}	24.0	23.7	23.7	23.2	22.4	V
Current at maximum power	I_{pm}	7.71	7.6	7.6	7.55	7.60	A
Module efficiency	η_m	14.1	13.7	13.7	13.4	13.0	%
Temperature coefficient - open circuit voltage	αV_{oc}	-104	-104	-104	-104	-104	mV / °C
Temperature coefficient - short circuit current	αI_{sc}	+0.053	+0.053	+0.053	+0.053	+0.053	% / °C
Temperature coefficient – power	αP_m	-0.485	-0.485	-0.485	-0.485	-0.485	% / °C

The electrical data apply under standard testing conditions (STC): Incident radiation 1.000 W/m² mit Lichtspektrum AM 1.5 with AM 1.5 light spectrum at a cell temperature of 25 °C. The power output is subject to a manufacturing tolerance of – 5 % and + 10 %. The modules manufactured in Europe and Japan are identical.

Characteristic curves

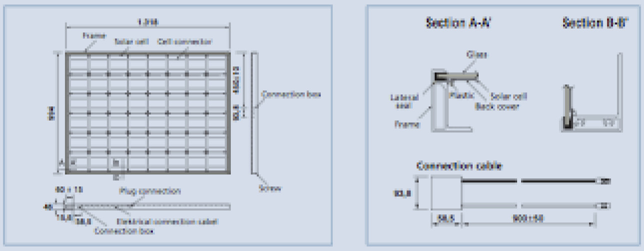


Applications

- Grid-coupled PV systems
- Grid-independent systems
- On-roof PV systems (roof parallel)
- On-roof PV systems (on stilts)
- Open air PV systems

Please read our extensive installation guide carefully prior to installing the photovoltaic modules.

External dimensions



Note

Modifications to technical data are possible without prior notice. Please request the current datasheets from Sharp before using Sharp products. Sharp assumes no responsibility for damage caused to equipment fitted with Sharp products based on unverified information.

The specifications may deviate slightly and are not guaranteed. Installation and operating instructions are to be obtained from the relevant manuals or can be downloaded from www.sharp-world.com.

This module should not be connected directly to a load.

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Appendix III. Inverter specification

Inverter used: Sunny Boy 4000TL

	Sunny Boy 3000TL	Sunny Boy 4000TL	Sunny Boy 5000TL
Input (DC)			
Max. DC power (@ cos φ=1)	3200 W	4200 W	5300 W
Max. input voltage	550 V	550 V	550 V
MPP voltage range / rated input voltage	188 V – 440 V / 400 V	175 V – 440 V / 400 V	175 V – 440 V / 400 V
Min. input voltage / initial input voltage	125 V / 150 V	125 V / 150 V	125 V / 150 V
Max. input current input A / input B	17 A / —	15 A / 15 A	15 A / 15 A
Max. input current per string input A / input B	17 A / —	15 A / 15 A	15 A / 15 A
Number of independent MPP inputs / strings per MPP input	1 / 2	2 / A:2; B:2	2 / A:2; B:2
Output (AC)			
Rated output power (@ 230 V, 50 Hz)	3000 W	4000 W	4600 W
Max. apparent AC power	3000 VA	4000 VA	5000 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V – 280 V	220 V, 230 V, 240 V / 180 V – 280 V	220 V, 230 V, 240 V / 180 V – 280 V
AC power frequency / range	50 Hz, 60 Hz / -5 Hz ... +5 Hz	50 Hz, 60 Hz / -5 Hz ... +5 Hz	50 Hz, 60 Hz / -5 Hz ... +5 Hz
Rated power frequency / rated power voltage	50 Hz / 230 V	50 Hz / 230 V	50 Hz / 230 V
Max. output current	16 A	22 A	22 A
Power factor at rated power	1	1	1
Adjustable displacement factor	—	—	—
Feed-in phases / connection phases	1 / 1	1 / 1	1 / 1
Efficiency			
Max. efficiency / European efficiency	97 % / 96.3 %	97 % / 96.4 %	97 % / 96.5 %

Protection			
Input-side disconnection device	yes	yes	yes
Ground-fault monitoring / grid monitoring	yes / yes	yes / yes	yes / yes
DC surge arrester Type II, can be integrated	—	—	—
DC reverse-polarity protection / AC short-circuit current capability / galvanically isolated	yes / yes / —	yes / yes / —	yes / yes / —
All-pole sensitive residual current monitoring unit	yes	yes	yes
Protection class (according to IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III	I / III	I / III
General Data			
Dimensions (W / H / D)	470 / 445 / 180 mm (18.5 / 17.5 / 7.1 inch)	470 / 445 / 180 mm (18.5 / 17.5 / 7.1 inch)	470 / 445 / 180 mm (18.5 / 17.5 / 7.1 inch)
Weight	22 kg / 48.5 lb	25 kg / 55.12 lb	25 kg / 55.12 lb
Operating temperature range	-25 °C ... +60 °C / -13 °F ... +140 °F	-25 °C ... +60 °C / -13 °F ... +140 °F	-25 °C ... +60 °C / -13 °F ... +140 °F
Noise emission (typical)	25 dB(A)	29 dB(A)	29 dB(A)
Self-consumption (night)	0.5 W	0.5 W	0.5 W
Topology	Transformerless	Transformerless	Transformerless
Cooling concept	Convection	Convection	OptiCool
Degree of protection (according to IEC 60529)	IP65	IP65	IP65
Degree of protection of connection area (according to IEC 60529)	IP54	IP54	IP54
Climatic category (according to IEC 60721-3-4)	4K4H	4K4H	4K4H
Maximum permissible value for relative humidity (non-condensing)	100 %	100 %	100 %