Simulation and study of a prefabricated NZEB housing system: Zero Bills Home

ZEDfactory

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"Your attitude, not your aptitude, will determine your altitude."

Zig Ziglar

Abstract

As the world experiences aggravating climate changes and a sustainable development seems to be at risk, society finds itself in a crisis that goes beyond financial or social causes. We are now facing what can be referred to as an environmental crisis, mainly due to the depletion of the world’s finite natural resources and the destruction of the ozone layer. This could have catastrophic consequences as we are hindering future generations from meeting their own needs.

In order to prevent implications of this magnitude, worldwide governmental policies are starting to be enforced, mainly in the energy sector. The target is to reduce greenhouse gas emissions by means of an increase in the share of renewable energy sources in the total energy consumption.

The building industry plays an important role in this change, as it is linked with approximately one third of energy related carbon emissions. In this field, the world turns its attentions towards Net-Zero Energy Buildings.

This work focuses on a detailed energy analysis of a residential house designed to consume a minimum amount of energy throughout its lifespan, while generating an annual electrical surplus due to a building integrated photovoltaic system. This analysis is based on a dynamic thermal simulation performed in TRNSYS, which consists in two parts: determining the energy demands of the building and its annual electrical production.

By comparing these parameters, it was possible to validate the concepts inherent to this housing system which therefore achieves a “zero carbon” and “zero bills” status.

Resumo

Numa altura em que o mundo se encontra perante alterações climatéricas cada vez mais agravantes e um desenvolvimento sustentável parece estar em risco, a sociedade atual encontra-se numa crise que vai para além de causas meramente financeiras ou sociais. Enfrentamos agora o que pode ser designado como uma crise ambiental, devido principalmente à depleção dos recursos naturais finitos numa escala global e à destruição da camada de ozono. Tal facto poderá ter consequências catastróficas, já que estamos a criar entraves para que gerações futuras consigam satisfazer as suas próprias necessidades.

A fim de prevenir implicações desta magnitude, diversas políticas governamentais estão a começar a ser aplicadas em todo o mundo, principalmente no setor da energia. O seu propósito é reduzir as emissões dos gases de efeito de estufa por meio de um aumento da participação de fontes renováveis de energia no consumo energético global.

A indústria da construção tem um papel preponderante nesta mudança, uma vez que está aliada a cerca de um terço das emissões de carbono relacionadas com a energia. Nesta área, o mundo vira as suas atenções face aos Net-Zero Energy Buildings.

Esta dissertação concentra-se numa análise energética detalhada de um edifício residencial, projetado para consumir uma quantidade mínima de energia ao longo do seu período de vida, gerando um superávit anual de eletricidade por meio de um sistema fotovoltáico integrado no edifício. Esta análise foi realizada tendo como base simulações térmicas desenvolvidas no software TRNSYS, consistindo em duas componentes principais: a determinação das necessidades energéticas do edifício e a sua produção anual de eletricidade.

Ao comparar estes parâmetros foi então possível validar os conceitos inerentes ao presente sistema de habitação, que, por conseguinte, atinge um estatuto de “zero carbon” e “zero bills”.

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Nomenclature

List of symbols

A	Area [m^2]
c	Specific heat capacity [kJ/kg·K]
cp	Pressure coefficient [-]
G-Value	Solar factor of glass [-]
I_{sc}	Short-Circuit Current [A]
P_{ann}	Accumulated annual precipitation [mm]
P_{min}	Mean precipitation of the driest month [mm]
P_{smax}	Mean precipitation of the wettest summer month [mm]
P_{smin}	Mean precipitation of the driest summer month [mm]
P_{th}	Annual precipitation value representing the dryness threshold [mm]
P_{wmax}	Mean precipitation of the wettest winter month [mm]
P_{wmin}	Mean precipitation of the driest winter month [mm]
R-Value	Thermal resistance [m^2·K/W]
R_j	Thermal resistance of a material [m^2·K/W]
R_{si}	Interior superficial thermal resistance [m^2·K/W]
R_{se}	Exterior superficial thermal resistance [m^2·K/W]
t	Thickness [m]
T	Absolute temperature [K]
T_{ann}	Mean annual temperature [°C]
T_{max}	Monthly mean temperature of the warmest month [°C]
T_{min}	Monthly mean temperature of the coldest month [°C]
T_{mon}	Monthly mean temperature [°C]
U-Value	Thermal transmittance [W/m^2·K]
v	Velocity [m/s]

V_{oc}	Open-Circuit Voltage [V]
λ	Thermal conductivity [W/m·K]
Ψ	Linear thermal transmittance [W/m·°C]
Φ	Wind angle [°]
ρ	Volumetric mass [kg/m^3]
ρ_a	Air volumetric mass at ambient conditions [kg/m^3]
ρ_i	Air volumetric mass at indoor conditions [kg/m^3]
ΔP_g	Global pressure loss [Pa]
ΔP_s	Pressure loss due to stack effect [Pa]
ΔP_w	Pressure loss due to the effect of the wind [Pa]
ΔTh	Logarithmic temperature difference [°C]

List of abbreviations

ACH	Air Changes per Hour
ADPI	Air Diffusion Performance Index
AHU	Air Handling Unit
BRE	Building Research Establishment
CIRIA	Construction Industry Research and Information Association
COP	Coefficient of Performance
DCLG	Department for Communities and Local Government
EER	Energy Efficiency Ratio
EPS	Expanded Polystyrene
EU	European Union
FIT	Feed-In Tariffs
HBM	Heat Balance Method
ICE	Inventory of Carbon and Energy
IET	Institute for Energy and Transport

LNEC	Laboratório Nacional de Engenharia Civil
MDF	Medium Density Fibreboard
MVHR	Mechanical Ventilation Heat Recovery
NZEB	Net Zero Energy Building
OECD	Organization for Economic Co-Operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OSB	Oriented Strand Board
PEX	Cross-Linked Polyethylene
PVGIS	Photovoltaic Geographical Information System
REHVA	Federation of European Heating, Ventilation and Air-conditioning associations
TER	Target Emission Rate
TESS	Thermal Energy System Specialists
TRNSYS	Transient System Simulation Tool
UAE	United Arab Emirates
UK	United Kingdom
WCED	World Commission on Environment and Development
ZBH	Zero Bills Home
ZEB	Zero Energy Building

1. Introduction

1.1 Background

Energy is the life blood of our society. The well-being of the world’s population, industry and economy depends on safe, secure, sustainable and affordable energy. However, it will take decades to steer energy systems onto this path. Nevertheless, decisions have to be made immediately and the urgent task is to implement solutions which will make the necessary shift possible allowing the world to mature in a competitive and sustainable way [1].

The European Council in 2007 adopted ambitious energy and climate change objectives for 2020 - to reduce greenhouse gas emissions by 20% when compared to the 1990 levels, to increase to 20% the share of renewable energy in the total energy consumption and to increase the energy efficiency by 20%. A long-term commitment to the decarbonisation path was also established, with a target for the European Union (EU) and other industrialised countries, consisting in a reduction of 80 to 95% in greenhouse gas emissions by 2050. To achieve these goals, special attention should be given to the sectors with the largest potential to make energy efficiency gains, namely the existing building industry [1].

The construction sector plays an important role in the European economy as it generates almost 10% of the Gross Domestic Product and provides 20 million jobs. Due to its economic importance, an increase in the performance of the construction sector can significantly influence the development of the overall economy. The energy performance of buildings and resource efficiency in manufacturing, transport and construction of these infrastructures has an important impact on energy, climate change and sustainable growth. Therefore, higher energy efficiency in new and existing buildings is essential for the transformation of the European Union’s energy system [2].

The uprising of Nearly Zero Energy Buildings (NZEB) represents a major challenge in the construction sector. While the number of low-energy buildings is growing, they are still far from what was expected. In addition, efforts to improve energy efficiency and to integrate renewable energy sources are progressing slowly. In order to achieve these goals and to ensure a global sustainable development, there is a great need for more action in the field of energy efficient buildings [2].

1.2 ZEDfactory – Company presentation

ZEDfactory is an architectural practice whose designs for zero carbon building projects are sought out by clients around the world. Founded by Bill Dunster, prestigious British architect and appointed Officer of the Order of the British Empire, ZEDfactory firstly started in 1998 as Bill Dunster Architects. Since the first day, the company has been exclusively committed to low carbon design and development, being leaders in this field with a unique track record of delivering Zero (fossil) Energy Development (ZED) buildings in the UK.

ZEDfactory works closely with leading UK academics and consultants to model predicted energy consumption and production, fluid dynamics and whole life cycle carbon costs of their designs to ensure they achieve the lowest environmental impact possible. As a practice, ZEDfactory demonstrates in its projects a step change reduction in carbon footprint can be achieved at the same time as an increase in overall quality of life.

Renewable energy devices and passive energy features are an inherent part of the design thinking. The practice keeps up-to-date with both the technologies and performance parameters that influence building design, thus enabling an appropriate use of energy-saving and low-environmental impact devices [3].

Figure 1 - ZEDfactory's emblematic project: BedZED [4]

ZEDfactory's main belief is that in the struggle against global climate change and in order to reduce carbon emissions, society needs more than energy efficient buildings. The aim is a zero carbon / zero waste society capable of running off the limited supplies of renewable energy available within national boundaries [4].

1.3 The “Zero Bills Home” project

“The Zero Bills Home is a prefabricated Zero Carbon and Zero Bills housing system that benefits from the affordability of a kit house, but the flexibility of a bespoke, architect designed home.” [5]

Figure 2 - “Zero Bills Home” AX4 model

The “Zero Bills Home” (ZBH), which is the designation of each one of these specific housing units, is able to generate more income than bills over the course of a year, based on typical UK solar and household energy consumption data. These buildings are designed to meet the Government’s Code 6 energy standard from the Code for Sustainable Homes [6]. This is done through high building fabric efficiency and offsetting the regulated carbon emissions with photovoltaic panels that form the waterproof finish on the south facing roof of each property. The “zero bills” concept means that it is possible to generate an annual income on energy bills, thus progressively offsetting the cost of the building, whereas a “zero carbon” building is able to overcome its total energy demands with on-site generation via renewable sources.

These houses are made using a hybrid heavyweight timber frame prefabricated kit, using standardised processes that have been upgraded to meet the high performance thermal requirements to achieve a zero carbon and zero bills specification. In order to increase the speed and effectiveness of the construction, in large developments of the “Zero Bills Home”, local suppliers and contractors work together with locals in an on-site assembly unit [7].

In order to achieve a high specification building, such as the “Zero Bills Home”, several strategies have to be merged together. These houses embody the following ingredients:

- Low-embodied-energy building structure;
- High levels of insulation, which reduces the thermal demands of the building;
- Airtight construction, as the building should have as little uncontrolled ventilation as possible, mainly during the heating season;
- High thermal mass, which helps to stabilise the internal temperature by storing energy during the day and re-radiating it during the night;
- Optimized solar orientation, with south facing glazing;
- A heating and ventilation system using:
    - An efficient mechanical ventilation system with heat recovery;
    - A small air source heat pump4;
    - A compact hot water cylinder;
    - An underfloor heating system for space heating;
- High efficiency LED lighting and energy saving appliances;
- Water saving strategies, such as aerated shower heads, low-flow taps and integrated shower heat recovery units.
- The “ZEDroof”, which is the south-facing building integrated photovoltaic system used to generate all net electricity demands on site. This integrated energy roof is the core of the “Zero Bills Home”, as it generates electricity whilst letting daylight into a loft to create a modern and comfortable room in the south-facing roof space [7].

All these elements improve this building’s performance and reduce the annual energy demands which in the course of a year are offset by the total energy produced by the photovoltaic system. As this system is directly connected to the grid at all times, the energy surplus can be sold to the national grid, therefore generating monthly revenues, instead of monthly bills.

1.4 Objectives

The main purpose of the developed work was to validate the “Zero Bills Home” concept as a low-energy consumption building which is able to offset its annual demands with on-site electric energy production. In order to do so, more specific objectives were outlined and they are stated as follows:

- Detailed study of the building’s physics and its constructive elements;
- Thermal simulation of the building using TRNSYS software;
- Integrated modelling of the photovoltaic roofing system using TRNSYS software;
- Annual energy analysis of the “Zero Bills Home”, including:
    - Heating demands;
    - Hot water demands;
    - General electric energy consumption;
    - Electric energy production;
- Design of an HVAC system according to the building’s requirements;
- Dynamic simulation of the exact same construction in different conditions, with the purpose of studying its adaptability and verification of the “Zero Bills Home” concept. The chosen location was Porto, Portugal.

After completing these objectives, an additional goal was self-proposed: to perform a carbon footprint analysis, in order to determine how many years it would take the “Zero Bills Home” to overcome its embodied carbon emissions.

1.5 Thesis outline

The outline of this thesis consists of five main chapters: (1) introduction, (2) literature review, (3) study case: “Zero Bills Home”, (4) data analysis and developed work and (5) conclusions and future work.

The first chapter encompasses a general background to the developed project, underlining its objectives, together with a brief presentation of the company and the “Zero Bills Home” project.

Followed by the literature review, an overview regarding the current world energy consumption and the share that each fuel represents is analysed in this second chapter. In addition, increasingly important concepts such as “sustainable development” and “Net Zero Energy Building” are referred, together with general aspects on prefabricated buildings, HVAC systems and thermal simulation software. Lastly are referenced the main British energy performance regulations in the residential building industry.

The third chapter refers to the developed case study in this project. Starting with a brief description on the studied house type, it is followed by a thorough characterization of the constructive elements of this building. Subsequently to a transitory climatic description of the two proposed locations, the methodology behind the developed thermal simulation is explained. A detailed overview on the interfaces used in this software are also discussed in this chapter, where both the photovoltaic and the building model are described.

In the following chapter, the results of all the developed models are presented. Because the “Zero Bills Home” is meant to be built in the United Kingdom, a full study and analysis was done as if this building was located in London. This includes an analysis on the heating demands, the hot water demands and the general electric energy consumption for all the different case scenarios considered. The annual energy demands of this house are then compared with the annual photovoltaic energy production, which was obtained from TRNSYS software. Subsequently, the HVAC system was designed and each unit was specified in detail. In addition, the self-proposed embodied carbon analysis was developed and finally, an energy analysis was made considering that the same building was constructed in Porto.

Finally, in the fifth chapter, the most important conclusions of this work are outlined together with suggestions for future work.

2. Literature Review

2.1 World energy consumption

According to the “BP Statistical Review of World Energy 2013” published in June of 2013 by one of the world’s largest oil and gas companies, British Petroleum (BP), the year 2012 highlighted the flexibility of the world’s energy markets [8].

This study states that during the year of 2012 a global slowdown in the growth of energy consumption was verified, which was partly a result of the North American and European economic recession. On the supply side, increasingly diverse sources of energy are being used, contributing to the innovation and evolution of the world’s energy market. The American shale revolution continues to be the most relevant phenomenon of the last few years as in 2012 the largest increase in oil and natural gas production in the world were seen in the United States, combined with the largest growth in oil production in its history [8].

The oil industry has seen some disruptions regarding the oil supply in Africa and in the Middle East, but they were successfully counterbalanced by the recent production growth if the Organization of the Petroleum Exporting Countries (OPEC). Countries like Libya have strongly recovered from previous drops, while countries like the United Arab Emirates (UAE), Saudi Arabia and Qatar, saw their production reaching record levels. Nevertheless, this positive scenario was overshadowed by the increasing oil prices which have reached another record high [8]. Coal continues to be the fastest-growing form of fossil fuel, but in relative terms, it has seen the lowest growth in its history. However, China alone is now, for the first time, consuming nearly as much coal as the rest of the world combined. As well as its counterparts, natural gas also saw a below-average growth in 2012. Yet, mainly due to its increasingly competitive price regarding coal, it was the only fossil fuel whose growth increased in 2012. As a result of the Fukushima incident, global nuclear power faced the major decline in its history, as Japan faced a drastic decrease in its production. Renewable energy power generation is becoming an increasingly important energy supply, as it helps to avoid the depletion of natural finite resources. Despite this slowdown in the growth of energy consumption, with the exception of nuclear power and biofuels, all remaining fuels reached record levels in their production and consumption [8].

As expected, the energy market expanded in countries with emerging economies such as China and India, who combined account for nearly 90% of the net increase in global energy consumption. On the other hand, the energy consumption in the Organization for Economic Co-Operation and Development (OECD) countries, particularly in the United States, has declined once more. In 2012, the world primary energy consumption grew by 1,8%, but still remained below the 10-year average of 2.6%. Mainly due to the recession in the US, the energy consumption in the OECD saw a decline of 1.2%, but in global terms managed to be offset by the 4.2% growth in the non-OECD consumption. However this growth is also well below the 10-year average of 5.3%. Africa was the only region in the world where this scenario was not verified [8].

As can be seen in Figure 3, with the exception of Saudi Arabia and Oceania, the highest energy consumption per capita in 2012 was verified in the northern hemisphere, mainly in countries like the United States of America and Canada. This is due to the fact that the main industrialized countries are located there. It is predicted that developing countries with growing industries like China and India increase their consumption per capita in the next years, thus matching the countries that currently are in the top position.

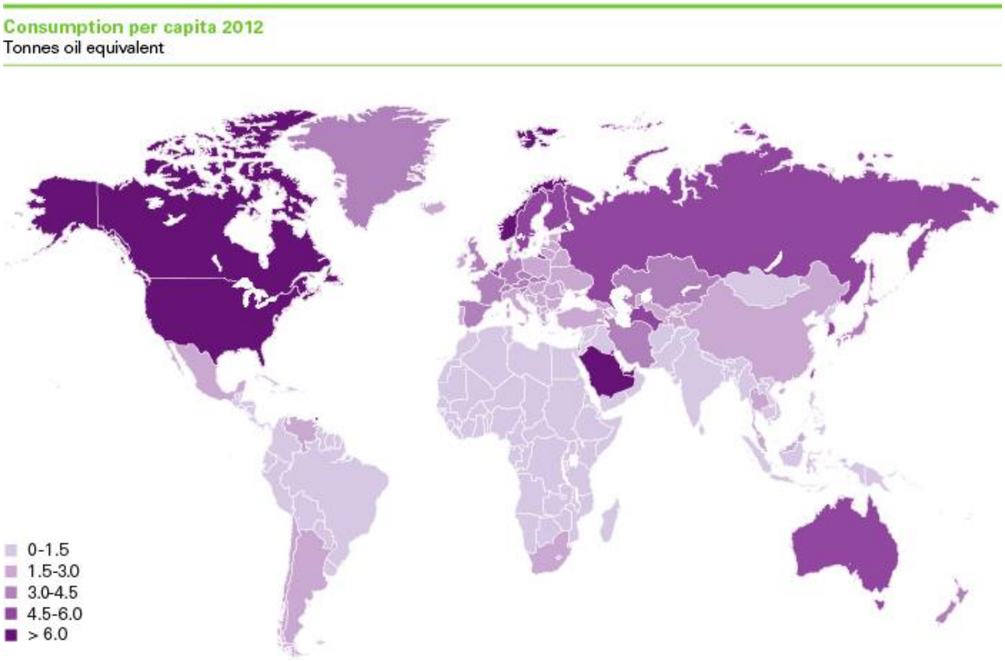

Figure 3 - World energy consumption per capita in 2012 (TOE) [8]

As reported by the International Energy Agency (IEA), in the 2013 edition of their yearly review “Key World Energy Statistics” much has changed in the way that energy is consumed globally. Forty years ago, fossil fuels had a share of almost 90% in the total primary energy supply, where oil was leading with 46%, followed by coal and subsequently by natural gas. Even though fossil fuels still contribute in a large scale to the worldly energy supply, now with a share of 80%, this tendency seems change, as renewable energies start to emerge. From 1973 until 2011 the main changes were verified in the oil industry that dropped its share from 46% to 31.5%. As for natural gas and coal, they have increased their share in

5% and 4% respectively, thus becoming an important alternative to oil as the leading industry in the energy market. There was a substantial increase in the energy produced by nuclear power, especially in countries like France, the United States and Japan, contributing to its growth from 0.9% to 5.1%. Enclosed in the charts below as “Other” are sources of renewable energy such as geothermal, solar and wind, which together have grown about 1% in their share of primary energy supply. The renewable energy industry has matured in the last decades and it plays an important role in the future of the sustainable development of the world [9].

In the last forty years, twice as much energy needed to be supplied in order to follow the world’s energy demands. Where once in 1973 the OECD would supply over 60% of the total primary energy, in 2011 its share reduced to 40.5% mostly due to the industrial and economic growth of Asian countries, with China in particular representing now a share of 21%.

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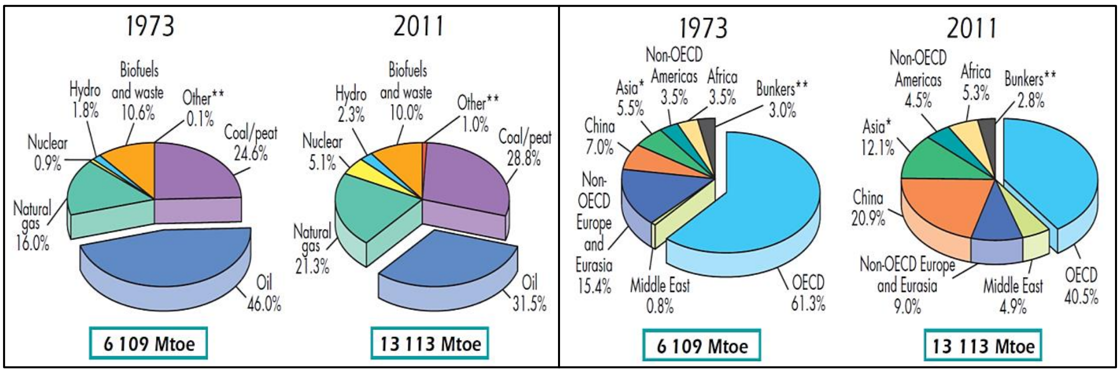

Figure 4 - 1973 and 2011 fuel (left) and regional (right) shares of total primary energy supply. [9]

In terms of shares of electricity generation, the scenario remains similar to the previous case regarding the regional distribution, where the OECD has lost a share of nearly 25% to China and the remaining Asian countries.

It is also interesting to understand how energy is consumed worldwide in the major energy end-use sectors: industrial, transportation, residential and commercial. Besides the electricity that is used by each sector it is also necessary to consider the losses in electricity generation, transmission and distribution before it can be consumed by the end-use sectors.

According to the U.S. Energy Information Administration (EIA), in 2011, more than half of the energy used worldwide is being consumed by the industrial sector, with a share of 50.8%, mostly driven by the industrial revolution in countries like China. Approximately 25% of the energy consumed by the industrial sector is accounted as electric losses [10], which means that roughly 12.5% of the energy consumed in the world is lost in this process. The transportation sector, using almost 20% of the total energy, has the lowest percentage of losses when compared with its counterparts, with only 1.9%. Both the residential and the commercial sectors have high electricity losses, accounting for virtually half of the energy that is used to satisfy their demands. Respectively they contribute to 17.6 and 11.9% of the total energy use [10].

Table 1 - World energy use per sector [10]

End-use Sectors	Share of Total Energy Use (%)	Share of Electricity Losses (%)
Industrial	50.8	24.8
Transportation	19.7	1.9
Residential	17.6	43.5
Commercial	11.9	54.8

As shown in the subsequent figure, over the past forty years, the electricity demands have increased from 6115TWh to 22126TWh but the fuel shares are slightly different. Coal remains the first choice with a share of 40%, but its main alternative has changed. Oil is no longer the second option, as it has been replaced by natural gas, which used to be the fourth most used fuel in electrical generation after hydro power, oil and coal. In 2011 oil represented a share of 4.8%, approximately the same as renewable energy sources, with the exception of hydro power, which alone accounts for 15.8%.

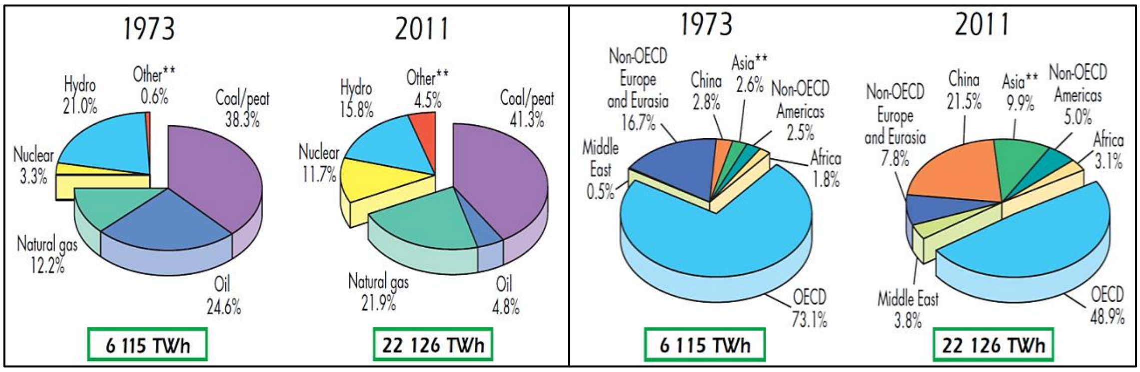

Figure 5 - 1973 and 2011 fuel (left) and regional (right) shares of electricity generation [9]

Even though fossil fuels still represent the major share in electricity generation, low carbon power production energy sources, such as nuclear power and renewables are becoming increasingly important and changing the way the world looks the energy industry.

2.2 Sustainable development

The importance of the term "sustainable development" has been growing since 1987 due to a report published that year, to the United Nations by the World Commission on Environment and Development (WCED) chaired by the Norwegian Prime Minister Gro Harlem Brundtland, hereafter known as "The Brundtland Report" which states that:

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." [11]

This organizing principle is the basis of sustainability, and its goal is to interconnect the economic, ecological, political and cultural domains [12], thus linking the world as an integrated dynamic system. It supports strong economic and social development, mainly for people with a low standard of living and emphasizes the importance of protecting the environment and its natural resources. In order to improve social and economic well-being, measures that destroy the environment and endanger it for future generations must not be considered [13]. However, in order to achieve an economic development changes will have to be made in the ecosystems, as they cannot be preserved intact. But this is not necessarily a dramatic scenario: provided the rate of use is within the limits of regeneration and natural growth, renewable resources like forests and fish stocks do not have to be completely depleted. On the other hand, the use of non-renewable resources will obviously reduce the available stock for future generations. Nonetheless, this does not necessarily mean that such resources should be cast aside and not used at all. As long as the rate of depletion, the economy of use and the emphasis on recycling are calibrated to ensure that the resource does not run out before acceptable substitutes are available, they still have an important role to play in the energy industry [11].

Over the past 20 years society has accepted sustainable development as a guiding principle, however this concept remains elusive and its implementation has been challenging [14]. The strategy for sustainable development aims to promote harmony among human beings and between humanity and nature, and in order to achieve it, it is required:

- a political system in which citizens can effectively participate in decision making;
- an economic system able to generate surpluses on a independent and sustained basis;

- a social system responsible for implementing solutions for the tensions arising from a disharmonious development;
- a production system that preserves an ecological development;
- a technological system that can constantly search for new solutions;
- an international system that nurtures sustainable patterns of trade and finance;
- an administrative system that is flexible and capable of self-correction. [11]

These are the goals that should underlie a worldwide sustainable development. It is vital that they are pursued effectively and that every country, every governmental agency and every citizen can provide their contribution. Sustainable development requires a fundamental and revolutionary change in the way economies and societies are developed and managed. This concept argues the need for an action now in order to defend the future [15]. Amongst the different sectors, the building industry plays a crucial role in this change, as new buildings have the potential to reduce worldwide energy demands. A new concept referred to as Net-Zero Energy Building (NZEB) seems to be the next step.

2.3 Understanding the concept: Net Zero Energy Building (NZEB)

“Net Zero-Energy Building” is a concept whose definition still needs clarification and is yet to become universal. Nonetheless, this term usually refers to a high specification construction type with a sustainable basis. It is widely expected that in the coming years this concept spreads throughout the globe, as approaches towards the 2020 goals are planned in most countries the European Union.

Even though this term has been used commercially as a highlighted marketing strategy as well as appearing in several governmental documents, a standardised definition and energy calculation methodology is still required [16]. Associated is the fact that contemporary literature has introduced distinct terminologies in attempt to explain this concept. Amongst these, the most widely used would be:

- ZEB – Zero Energy Building or Zero Emission Building
- NZEB – Net Zero Energy Building or Nearly Zero Energy Building

In order to reach an agreement in the definition of this concept there are some important aspects that need to be clarified, in particular the metric of the balance and the balancing period. Several parameters can be measured in the definition of the “zero” balance of the building, such as the end-use energy, the primary energy, carbon dioxide emissions, exergy, amongst others. It is therefore crucial for the understanding of this concept the existence of a universal measure system, in order to define this balance. The time period in which this analysis is made can vary from an extensive full life cycle of a building to a very commonly used annual balance or can correspond, in some particular cases, to a seasonal or monthly balance [17]. Because energy prices vary over time and since it is not always simple to estimate how they will float, if the time standard was to be a full life cycle, it would be possible that a building would only achieve this definition at the time of its design. Therefore a yearly balance seems to be a simpler and more generally accepted time period to evaluate the “zero” balance of a building. In relation to the metric of the balance, the end-use energy seems to be the easiest unit to implement and understand, thus linking this concept with the term “Zero Energy Building”. Reaching a net value of zero carbon dioxide emissions over time is another interesting approach, but it should be analysed as a separate definition of “Zero Emission Building” [17].

According to the Federation of European Heating, Ventilation and Air-conditioning associations, REHVA, “*a ZEB is understood as a grid-connected, energy-efficient building that balances its total annual energy consumption by on-site generation and associated feed-in credits*” [18]. When looking at the terms linked with energy, a “Zero Energy Building” seems to be a utopic approach to this definition, as a building will always need to consume energy for household appliances, hot water demands, etc. When referring to this term, some authors consider a ZEB to be a building that can produce enough energy to counterbalance its energy demands. This is, in fact, when the term “Net” comes into play, as it is set to emphasize a balance between energy consumption and production over a time period. A “Net Zero Energy Building” would then equal these two parameters over time, resulting in a net “zero” balance. With the introduction of this term, one can now speak of NZEB and its variants, as can be seen in the following figure:

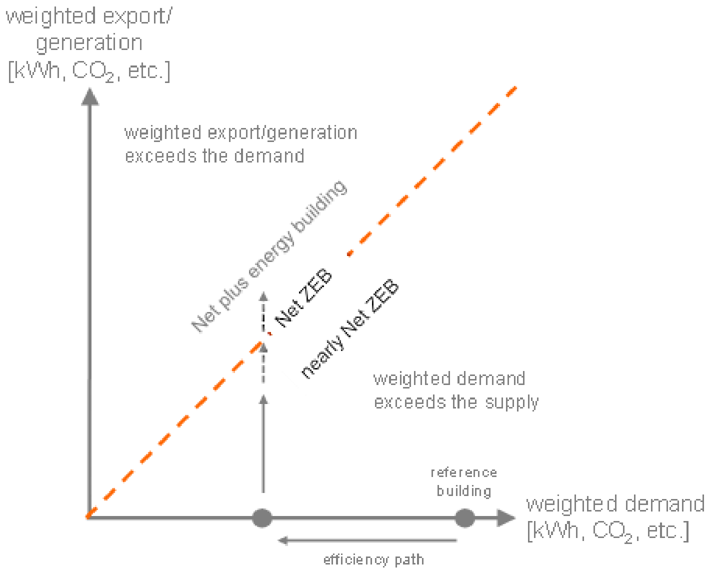

Figure 6 - Net ZEB Variants [18]

In addition to the NZEB concept, which can be referred to as a building that will be able to generate the same amount of energy as it needs over time, two new terms arise: The “Nearly Net Zero Energy Building” and the “Net Plus Energy Building”. They are basically a mirrored image of one another over the NZEB concept – While the “Nearly Net Zero Energy Building” is not fully able to match its demands with its total production, thus approaching the NZEB line, the “Net Plus Energy Building” is able generate an energy surplus over time.

In order to achieve these concepts, a universally accepted set of standards needs to be implemented. The NZEB concept has been a step-by-step evolution of other forms of low energy buildings, in particular the German “PassivHaus”, whose standards are well defined and have been used as guidelines for these constructions. This standard was developed in the early 1990s, in Germany, by Professors Bo Adamson of Sweden and Wolfgang Feist of Germany and the first dwellings to be completed to the Passivhaus Standard being constructed in Darmstadt in 1991.The principles behind these standards lie on achieving a building with an excellent thermal performance and exceptional airtightness with efficient mechanical ventilation with heat recovery [20]

The PassivHaus standard requires that all constructive elements, such as walls, floors, roofs and windows, have very good thermal properties (low U-Values), reason for which insulation is fundamental. In addition to this, in order to avoid unnecessary heat loss thermal bridging should be minimized. In order to reduce the amount of air entering the fabric, the building must have very good airtightness levels which can only be achieved by using air tight membranes or barriers within each of the constructive elements, guaranteeing that air leakage at 50 Pascal pressure does not exceed 0.6 air changes per hour (ACH). This is usually one of the main problems in this type of construction, as it is widely affected by workmanship of the site operatives. In such an airtight building a mechanical ventilation system is needed to assure indoor air quality for the occupants. Efficient Mechanical Ventilation Heat Recovery systems, where the exhaust air is used to heat the outdoor supply air, are used in these buildings, thus guaranteeing air quality and reducing heating demands [20].

In regard to what was done in the evolution of the PassivHaus concept, it is crucial that a clear definition, calculating methodology and standards for the NZEB concept are adopted worldwide.

2.4 Modular buildings

Modular buildings, also known as prefabricated buildings, are structures that are built by manufacturers and subsequently installed on-site. Since the majority of the building is prepared offsite, construction time and cost can be widely reduced. They can be built for many purposes; however this type of construction has been mostly used in locations requiring temporary structures, short construction time, or inexpensive construction costs, with the aim of providing social housing and shelter after natural catastrophes. Unlike traditional buildings, which can take months in their constructions, modular buildings can be assembled in few weeks.

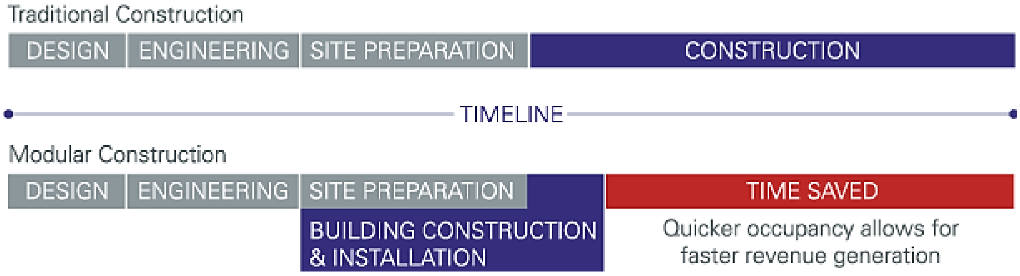

Figure 7 - Comparative time chart between traditional and modular construction [21]

Their popularity increased after the Second World War, due to the increasing need to hastily build new dwellings in order to replace all those who were destroyed by the war. At that time, prefabricated buildings were aesthetically less attractive than traditional ones; however, their rapid construction was enough to fit the purpose. In recent years, the interest in modular buildings has grown as they can evenly compete with traditional buildings in aesthetics, but also because they can be both long lasting and sustainable, while delivering a high building quality. They can have various designs and can use different types of materials in their construction, thus allowing for customized specifications. Prefabricated residential houses, military bases, schools, churches, etc. have been built in several locations throughout the world [22].

As a sustainable construction method, prefabricated construction is increasingly being adopted worldwide to enhance productivity and to alleviate the adverse environmental and social effects as a result of conventional construction activities. Prefabrication is becoming increasingly important to the entire construction industry [23].

The main difference between modular buildings used for emergency sheltering and residential buildings lies on the occupant's comfort. In a residential housing system it is crucial to ensure thermal comfort; therefore HVAC systems have to be implemented and designed accordingly to the requirements of each building.

2.5 General aspects of HVAC systems

"Heating, Ventilation and Air Conditioning" - HVAC systems can be characterized according to how the energy distribution is made, with local or central systems. While there are many options, most centralized systems fall within one of these three main categories based on the distribution of the working fluid:

- All-air systems;
- Air-water systems;
- All-water systems;

A local HVAC system is an isolated system that will independently serve only a single thermal zone. The most typical solution is the split system, which generally consists of an exterior unit, encompassing a compressor and a condenser, and an interior unit, which incorporates an evaporator and an expansion valve. They are collectively more reliable than centralized systems, since if one local unit would fail it would only cause discomfort in one room, while the remaining would continue to operate at normal conditions. When compared to a centralized system, they are also more flexible as they can provide individualized control, thus greatly contributing to occupant comfort. These systems may also be shut off if the zone becomes unoccupied, thus generating energy savings. On the other hand, these units do not allow for centralized energy management operations and their controls are usually much more limited. Their lifespan is lower in comparison with a central system and they also have higher energy consumptions [24].

The purpose of a central HVAC system is to serve, from one base location, as many thermal zones as needed, thus having as many control points as there are zones. The main advantages of centralized HVAC system, when compared to local systems, are that it provides a wider control of comfort conditions, its energy efficiency is much higher, it has a greater load-management potential the equipment has higher quality, efficiency and durability. On the downside, because the technology involving these systems is more sophisticated, they are more expensive to install and require more skill to operate and maintain [25].

In an all-air system heated or cooled air is delivered to each zone through a duct distribution network. The outside air is conditioned in an Air Handling Unit (AHU) and then supplied into the spaces, thus renewing the inside air and setting it to chosen conditions. All water systems are based on the distribution of hot or cold water to individual heat transfer devices, thus controlling the temperature inside each zone. These systems are unable to control relative humidity and outdoor air content, thus requiring a separate ventilation system is required for quality installations. Air-water systems use both fluids to provide the required conditions for each zone. They benefit from the combined advantages of both all-air and all-water systems, as the latent energy primarily from outside air is removed in the air handling unit, which is then ventilated to indoor space, and indoor sensible energy is carried in the water, due to its superior specific heat and density, thus reducing space requirements [26].

2.6 Thermal simulation software

Thermal simulation programs are powerful tools used to create virtual simulations of real models, for the most diverse applications, without material or monetary costs. Over the years, they became a popular technique of reducing the energy demands in buildings as these can be properly planned and optimized to reduce the amount of energy that is spent during their life-cycle.

Today, these software tools fall into two categories: design tools and simulation tools. Design tools are used to dimension HVAC equipment, basing their calculations on summer and winter design days, which define the worst case scenario enabling to size the HVAC equipment. On the other hand, simulation tools are used to predict the energy performance of the building during the course of a year, thus including dynamic calculations based on various thermodynamic equations [27].

Over the last years, multiple energy simulation programs have been developed, but it is important to understand the differences between them. Before choosing between these tools, it is important to understand the different thermodynamic models that are used behind their calculations, their purpose of use, their life-cycle applicability, amongst many other characteristics. Nevertheless, the enabled access to these tools does not mean that energy simulation is available to everyone; without knowledge of the limitations of the programs and understanding the thermal processes that are being used, it is impossible to generate and interpret realistic and reliable results [27]. In this research, TRNSYS was the main software to be used and it is described in detail in the following sub-chapter.

2.6.1 TRNSYS software

TRNSYS (TRaNsient SYstem Simulation Program) is an energy simulation software whose open modular system approach makes it one of the most flexible tools available and it has been one of the key factors in this software's success throughout the years. It includes a graphical interface, a simulation engine, and a library of components that range from various building models to standard HVAC equipment to renewable energy and emerging technologies, while also including a method for creating new components [28].

It has an extensive cross section of users worldwide that spans from researchers to consultants, engineers to building simulation experts, and students to architects. Because of the wide user-base, the tool's long history, and its inherent flexibility, it is actively being used in many of the following applications [29]:

- Building Simulation (including LEED Energy Modelling)
- Solar Thermal Processes
- Ground Coupled Heat Transfer
- High Temperature Solar Applications
- Geothermal Heat Pump Systems
- Coupled Multizone Thermal/Airflow Modelling
- Optimization
- Energy System Research
- Emerging Technology Assessment
- Power Plants (Biomass, Cogeneration)

- Hydrogen Fuel Cell Systems
- Wind and Photovoltaic Systems
- Data and Simulation Calibration

This software was developed and it is currently maintained by the University of Wisconsin-Madison College of Engineering's Solar Energy Laboratory (SEL) and it has been commercially available since 1975. Together with several other American and European institutions, such as TRNSYS distributor and content developers Thermal Energy System Specialists (TESS), or German distributors and TRNBuild designers Transsolar, TRNSYS has evolved over the years. While originally created to simulate the performance of solar water heating systems, it now accounts for multiple purposes, including the thermal simulation of buildings. In this project, TRNSYS 16 was the version of this software that was used to develop the simulation, but there is already one newer version available in the market called TRNSYS 17. With the release of version 17, TRNSYS included TRNSYS3D, which is a plugin for Google SketchUp™ that allows the user to actually draw the building and import its geometry directly from SketchUp into TRNBuild, thus making the whole geometric building simulation much simpler and more visual.

TRNSYS is a software package consisting of several programs: A graphical interface for creating input files called TRNSYS simulation Studio, shown in Figure 8, the simulation engine (TRNDll.dll) and its executable (TRNExe.exe), the Building input data visual interface (TRNBuild.exe), and the Editor used to create stand-alone redistributable programs known as TRNSED applications (TRNEdit.exe) [30].

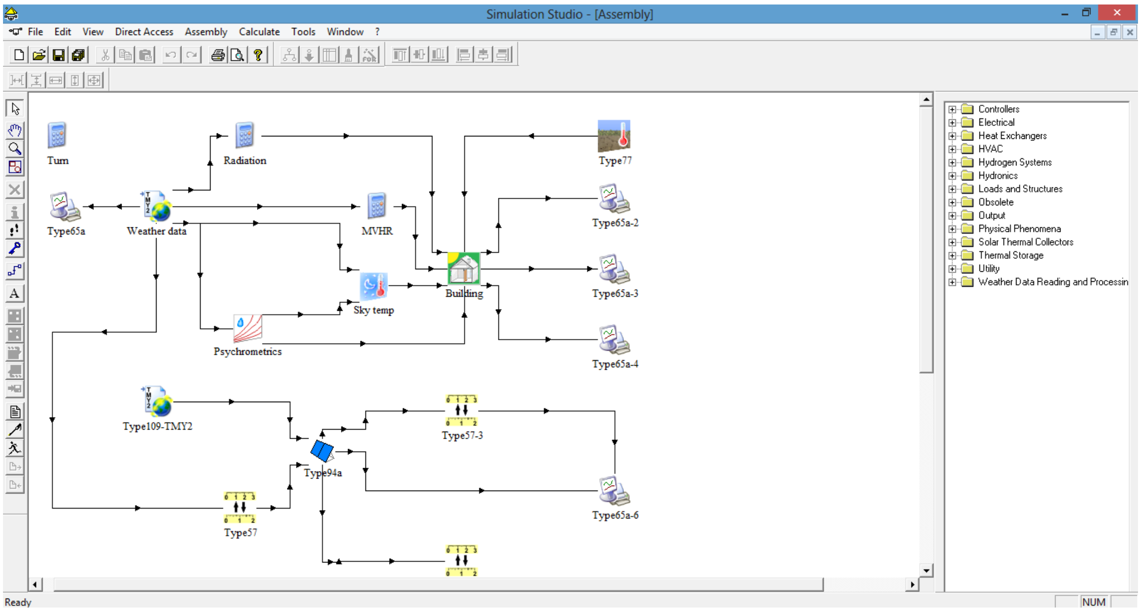

Figure 8 - TRNSYS Simulation Studio Interface

2.7 Building Regulations in the United Kingdom

2.7.1 Part L Regulations

"The Building Regulations" is a set of national building standards for England and Wales concerning the design and construction of new buildings and alterations to existing ones. According to the Department for Communities and Local Government (DCLG), their main purpose is to "ensure that buildings are safe, healthy, accessible and sustainable for current and future generations" [31].

In 1965, the first set of standards was introduced in the Building Regulations. Since 2010, at the date of its last revision, it consisted of 14 technical parts, which include Part L "Conservation of fuel and power" that specifically covers energy efficiency requirements, and it is composed by four parts:

- Part L1A for new dwellings;
- Part L1B for existing dwellings;
- Part L2A for new buildings other than dwellings;
- Part L2B for existing buildings other than dwellings.

Since its first edition in 1990, Part L has been amended in 1995, 2002, 2006, and lately in 2010. This specific set of rules was issued with the aim of decreasing fossil fuel usage by reducing space heating, but with the 2006 and 2010 editions, the focus has changed towards reducing CO_2 emissions. [32]

Part L, being the document which covers fuel and power, is also where the energy efficiency information on ventilation is covered. In the latest edition, the document has improved the energy efficiency targets for buildings by 25%, which affects ventilation equipment. It is also set to deliver an improvement of 25% when compared with previous regulations, on the Target Emission Rate (TER). According to the latest review on this document, the standards for new buildings are linked with the Level 3 standard of the Code for Sustainable Homes (CSH) [33].

2.7.2 Code for Sustainable Homes

According to the DCLG [6], *"The Code for Sustainable Homes has been developed to enable a step change in sustainable building practice for new homes"*. Its main purpose is to rate and certify the performance of new built homes and it is intended to become a single standard in the development of sustainable buildings.

This is a governmental document that was developed in close work with the Building Research Establishment (BRE) and the Construction Industry Research and Information Association (CIRIA), being firstly issued in December 2006 with the publication of “Code for Sustainable Homes: A step-change in sustainable home building practice” and becoming operational in April 2007. Although the Code for Sustainable Homes is not yet a mandatory document, its importance is increasingly growing in the building industry and the Government is planning to officialise it in the near future. For now, Code compliance is voluntary but it is recommended that new buildings are built in accordance with these standards [6]:

The Code for Sustainable Homes covers nine key issues in sustainable housing development, which are divided into the following categories:

- Category 1 – Energy/CO_2;
- Category 2 – Water;
- Category 3 – Materials;
- Category 4 – Surface Water Run-off;
- Category 5 – Waste;
- Category 6 – Pollution;
- Category 7 – Health and well-being;
- Category 8 – Management;
- Category 9 – Ecology.

The major focus of this document is energy efficiency and CO_2 emissions, which minimum standards must be met to ensure the accreditation of the building. One remarkable characteristic of the CSH is that it goes beyond other international standards such as Canada’s R-2000 and Germany’s PassivHaus, as it specifies that, in order to achieve a “Zero Carbon Home”, domestic energy must be generated by renewable sources, which is not complied in these other international standards. While the PassivHaus standard sets a maximum energy usage level of 15kWh/m2 per year for space heating and cooling, it does not specify the required energy sources to achieve so. As such, when combined with the other categories required, the Code for Sustainable Homes is amongst the most challenging and demanding international housing standards [34].

The Code for Sustainable Homes uses a star (*) rating system, to characterize the overall sustainability performance of a home, with direct correspondence to the Code Level it achieves. One star (*) is the rating achieved by Level 1 houses and it is the entry level of the Code. On the other edge, with a star rating of six (******), there is the Code Level 6 house, which refer to a “Zero Carbon Home”.

Because it is intended that the CSH will signal the future of Building Regulations, the highest standards of the Code represent a larger improvement over Part L of the Building Regulations. After the 2010 revision of Part L, new buildings are now considered to be Level 3 equivalent. Nevertheless in order to achieve higher levels, improvements have to be made, has can be seen in Table 2.

Table 2 - Code Levels for Mandatory Minimum Standards in CO_2 Emissions [6]

Code Level	**Minimum Percentage Improvement in Dwelling Emission Rate over Target Emission Rate**
Level 1 (*)	0% (Compliance with Part L 2010 only is required)
Level 2 (**)	0% (Compliance with Part L 2010 only is required)
Level 3 (***)	0% (Compliance with Part L 2010 only is required)
Level 4 (****)	25%
Level 5 (*****)	100%
Level 6 (******)	Net Zero CO_2 Emissions

2.7.3 UK Feed-In Tariffs

A Feed-In Tariff (FIT) is an economical strategy introduced to promote the deployment of small-scale renewable and low-carbon electricity generation technologies [35]. As of 2013, some form of the Feed-In Tariffs policy has been implemented in 71 countries and 28 states [36].

The United Kingdom (UK) started implementing a national Feed-In Tariff (FIT) mechanism in 2010, which included specific payment tariffs for solar photovoltaic installations. A revised FIT rate has been put in place starting two years later, applicable to any installations with an eligibility date of on or after March 2012 [37].

In order to enable a greater number of investors, the FIT scheme provides three financial incentives:

1. The generation tariff, where the energy supplier will pay a set rate for each kWh of electricity generated. This tariff is dependent on the technology used and on the size of the installation.

2. The export tariff, where all technologies receive a supplementary fixed rate for each unit of electricity exported to the grid, in addition to the generation tariff.

3. And electricity bill savings, as on-site generation will reduce the amount of electricity required from the grid resulting in reduced energy bills [35].

3. Case Study: “Zero Bills Home”

3.1 “Zero Bills Home” AX4 Model

The work developed in this project was carried out for the “Zero Bills Home” AX4 model, which was the housing system proposed to be simulated and studied in detail as shown in Figure 2 in the first chapter.

This building consists of 3 storeys, each having a floor area of 47m^2 together with a height of 2.5 meters for both the ground floor and the first floor. On the other hand, the height of the second floor varies by virtue of the sloped roof on the north façade and the ZEDroof facing south. Figure 9 shows a floor overview of the three storeys.

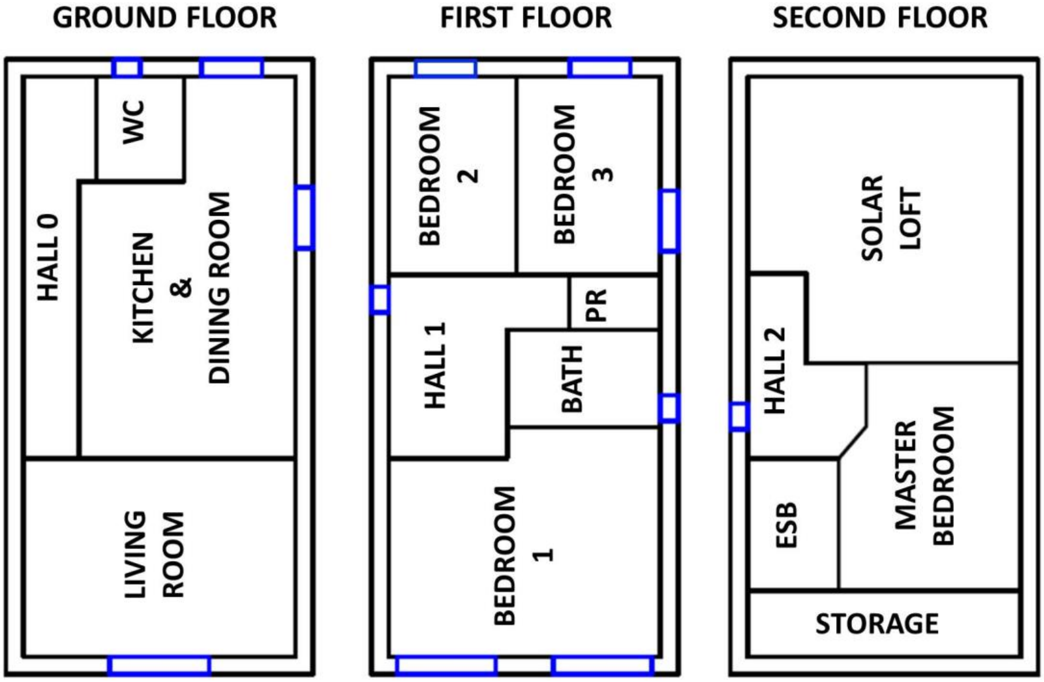

Figure 9 - “Zero Bills Home” AX4 simplified floor plants

The ground floor comprises a living room with 16.1m^2, a 6.9m^2 hallway, a small water closet with 2.7m^2 (WC) and a 21.3m^2 room with a kitchen and an incorporated dining room.

The first floor contains a small 1.5m^2 power room (PR) where the equipment is stored, one bathroom with 4.5m^2 (BATH) and a hallway with 7.5m^2, alongside with 3 bedrooms - Bedroom 1, Bedroom 2 and Bedroom 3 – with a respective floor area of 17.5m^2, 7.5m^2 and 8.5m^2.

As for the third floor, it encompasses a storage room with a floor area of 5.4m^2, a 11.4m^2 bedroom with a 3.6m^2 en-suite bathroom (ESB), a 4.9m^2 hallway and a Solar Loft area with 21.7m^2 covered by the ZEDroof.

Table 3 - "Zero Bills Home" AX4 areas

Total Floor Area [m^2]	141
Gross Internal Floor Area [m^2]	120
Insulated Envelope Area [m^2]	185
Glazed Envelope Area [m^2]	18

In the subsequent chapter, the constructive elements that assemble this building are explained in detail.

3.2 Envelope analysis

The thermal behaviour of a building is characterized by fundamental thermal properties of the envelope and additional parameters. The main parameters that quantify the thermal behaviour are the thermal transmission coefficients of the envelope, such as:

- Thermal conductivity - λ;
- Thermal resistance - R-Value;
- Thermal transmittance - U-Value.

In physics, thermal conductivity, λ, is the property of a material's ability to conduct heat through a specific type of material, regardless of its thickness. It appears primarily in Fourier's Law for heat conduction. It is measured in Watts per meter-Kelvin (W/m·K).

The thermal resistance of a material, also known as the R-Value is a measure of resistance to heat flow through a given thickness of material. So the higher the R-Value, the more thermal resistance the material has and therefore the better its insulating properties [38].

The R-Value (m^2·K/W) can easily be calculated with the material's thickness, t, and its thermal conductivity, λ, using the following equation:

$$R\text{-}Value = \frac{t}{\lambda}$$

The third term, thermal transmittance, commonly known as the U-value, is a measure of the rate of heat loss of a building component (W/m^2·K). The U-value is calculated from the reciprocal of the combined thermal resistances of the materials in the element, air spaces and surfaces, also taken into account is the effect of thermal bridges, air gaps and fixings [38].

This parameter can be calculated by:

$$U = \frac{1}{R_{si} + \sum R_j + R_{se}},$$

where R_{si} and R_{se} are the interior and exterior superficial thermal resistance, respectively, and R_j is the thermal resistance of each internal material.

The values for the superficial thermal resistances can be found in a table obtained from Laboratório Nacional de Engenharia Civil's (LNEC) publication "ITE 50 - Coeficientes de transmissão térmica de elementos da envolvente de edifícios", which intends to support studies in the scope of thermal performance of buildings and the application of the Portuguese building thermal regulations [39].

Table 4 - Superficial thermal resistances [39]

Heat Flow		**Superficial thermal resistance** $(m^2 \cdot °C/W)$		
		Exterior (R_{se})	Unheated Zone (R_{se})	Interior (R_{si})
Horizontal		0.04	0.13	0.13
Vertical	Ascending	0.04	0.10	0.10
	Descending	0.04	0.17	0.17

Also, it is important to know other properties of the material in use, such as its specific heat capacity, c, which alongside its volumetric mass, ρ, and thickness, t, provide the value of the thermal mass, given in kJ/m^2·K, by multiplying those three terms.

Because the case study's building is a modular one, for every wall type that supports a different purpose there is normally one single kind of construction used. In total, this building has seven different construction types, alongside with five fenestration elements that include windows and glass doors.

The "Zero Bills Home" incorporates in its structure some very common materials that are often used in construction, together with unique materials, whose properties define the thermal envelope of this building.

All the external walls, ground floor and external roof are highly insulated, thus creating an extremely tight super-insulated shell that keeps the air inside the house sealed from the outside weather conditions. This way, the external envelope of the building will have very low U-Values (around 0.11W/m^2·°C), which means that the energy exchanged with the outside will be reduced, accounting for low heat loss and gains. The entire building frame is made of structural timber beams that will work as cold bridges from where heat transfer will more easily occur. The thermal properties of the walls in which this particular situation occurs where calculated bearing this fact in mind. As for the remaining thermal bridges, they were analysed in particular, according to their specific constructive display.

In contrast, the internal constructive elements have fewer insulation and higher thermal mass, therefore being able to store more heat energy, working as a thermal battery.

As for the fenestration, the usage of double glazed windows allows a better insulation (around 1.4 W/m^2·°C), thus increasing the building's thermal performance while maintaining it affordable.

Figure 10 shows the different constructive elements that together assemble the "Zero Bills Home".

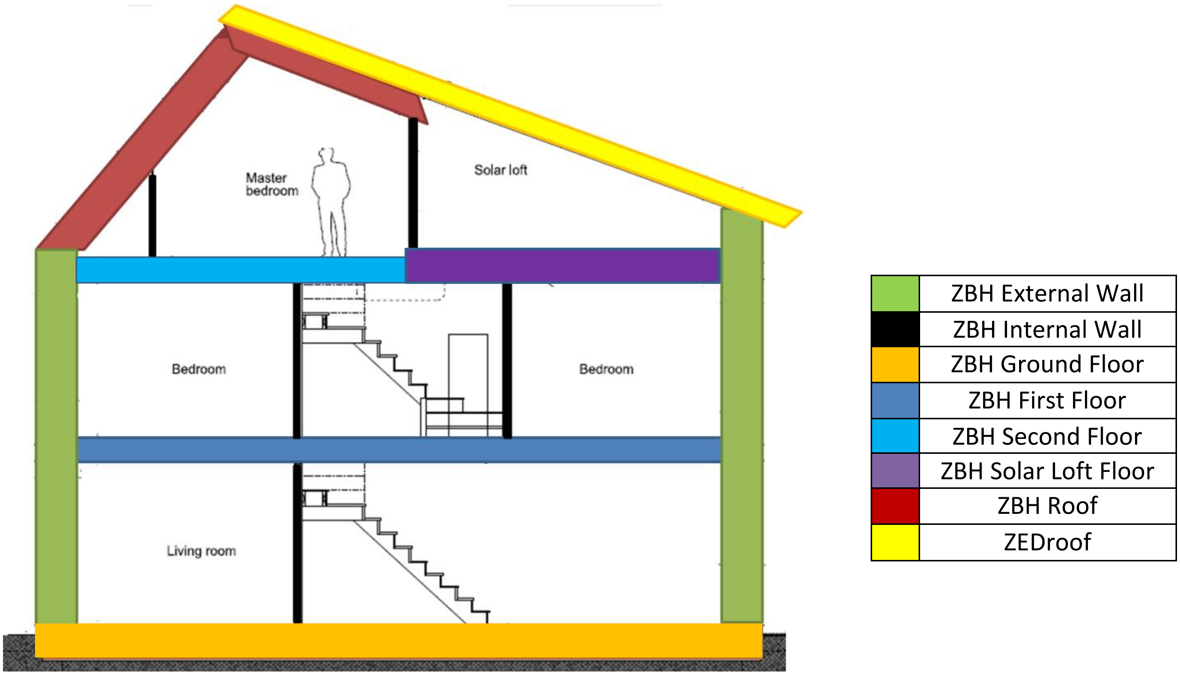

Figure 10 - Constructive elements of the "Zero Bills Home"

The following values used for the thermal characterization of this building were based on data from manufacturers and suppliers of ZEDfactory and typical properties of standard materials. They will be presented using Celsius (°C) instead of Kelvin (K) as the temperature measuring unit. For the thermal properties below this change will have no effect, since it is in fact a temperature difference that is used to define them.

3.2.1 External walls

The external walls that enclose the building are highly insulated, having a U-Value of 0.14 W/m^2·°C. One of its main layers is composed of structural timber filled with a particular kind of glass and rock mineral wool, known as Earthwool. This layer will be henceforth referred to as “inhomogeneous material”. For the inhomogeneous material layer, properties such as heat capacity, volumetric mass and thermal storage were calculated based on the timber/insulation ratio.

Table 5 - “Zero Bills Home” External Wall details

	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
ZBH External Wall	Rse	-	-	0.0400	0.14	-	-	-
	Water-proof Membrane	0.0003	0.100	0.0030		1.45	416.0	0.2
	Inhomogeneous Material	0.0500	0.048	1.0382		0.93	89.0	1.6
	Earthwool	88.00%	0.037	-		0.84	33.0	1.2
	Softwood Timber	12.00%	0.130	-		1.60	500.0	4.8
	MDF	0.0180	0.180	0.1000		1.70	800.0	24.5
	Inhomogeneous Material	0.2000	0.044	4.5005		0.90	70.36	5.7
	Earthwool	92.00%	0.037	-		0.84	33.0	5.1
	Softwood Timber	08.00%	0.130	-		1.60	500.0	12.8
	Inhomogeneous Material	0.0500	0.048	1.0382		0.93	89.0	1.6
	Earthwool	88.00%	0.037	-		0.84	33.0	1.2
	Softwood Timber	12.00%	0.130	-		1.60	500.0	4.8
	Plasterboard	0.0125	0.190	0.0658		1.00	680.0	8.5
	Rsi	-	-	0.1300		-	-	-
		0.3308		**6.9157**				**8.5**

3.2.2 Internal walls

The internal walls are used to separate each division amongst the others, so their construction is simple, not accounting for any specific isolative properties or thermal mass.

Table 6 - “Zero Bills Home” Internal Wall details

ZBH Internal Wall	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
	Rsi	-	-	0.13	1.03	-	-	-
	Plasterboard	0.0125	0.190	0.0658		1.00	680.0	8.5
	Softwood Timber	0.0750	0.130	0.5769		1.60	500.0	20
	Plasterboard	0.0125	0.190	0.0658		1.00	680.0	8.5
	Rsi	-	-	0.13		-	-	-
		0.0500		**0.9685**				**37**

3.2.3 Ground floor

The ground floor is highly insulated, with a U-Value of 0.11 W/m^2·°C and has a high thermal storage due to its two internal layers, the screed slab and the Terra Cotta tiles.

Table 7 - “Zero Bills Home” Ground Floor details

ZBH Ground Floor	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
	EPS	0.3500	0.040	8.7500	0.11	1.55	15.0	8.1
	Screed	0.0650	1.150	0.0565		1.05	2100.0	143.3
	Terra Cotta Tile	0.0180	1.200	0.0150		0.80	2000.0	28.8
	Rsi	-	-	0.1700		-	-	-
		0.4330		**9.0315**				**172.1**

3.2.4 Exposed floors

The Solar Loft is a division that is treated as being exterior because there is an air gap between the room and its roof, the ZEDroof, keeping this space ventilated at all times and allowing heat transfers. Therefore, the floor is highly insulated, having similar U-Values to the ground floor and the external roof.

Table 8 - “Zero Bills Home” Solar Loft Floor details

ZBH Solar Loft Floor	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
	Rsi	-	-	0.1700	0.11	-	-	-
	Plasterboard	0.0125	0.190	0.0658		1.00	680.0	8.5
	OSB	0.0150	0.130	0.1154		1.70	650.0	16.6
	EPS	0.3500	0.040	8.7500		1.55	15.0	8.1
	OSB	0.0150	0.130	0.1154		1.70	650.0	16.6
	Rsi	-	-	0.1700		-	-	-
		0.3925		**9.3866**				**16.6**

3.2.5 Internal floors

Within the materials that compose the first storey's floor, both the fired Terra Cotta bricks and the screed account for its high thermal mass, which will work as a thermal battery where heat will stack during the day.

Table 9 – "Zero Bills Home" First Floor details

	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
ZBH First Floor	Rsi	-	-	0.1700	1.30	-	-	-
	Terra Cotta Brick	0.1350	1.100	0.1227		0.92	1430.0	177.6
	Plywood	0.0180	0.120	0.1385		1.215	545.0	11.9
	Screed	0.0650	1.150	0.0565		1.05	2100.0	143.3
	Hardwood	0.0180	0.160	0.1125		1.700	500.0	15.3
	Rsi	-	-	0.1700		-	-	-
		0.2360		**0.7702**				**348.1**

As for the second storey, the layer made of 200mm thick timber beams has the same construction as one of the inhomogeneous layers used in the external walls, except that the insulation was removed, thus having only 12% of softwood timber. Its thermal properties were calculated considering a uniform distribution of 24mm timber across the floor.

$$200 \times 0.12 = 24mm$$

Table 10 - "Zero Bills Home" Second Floor details

	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
ZBH Second Floor	Rsi	-	-	0.1700	1.32	-	-	-
	Plasterboard	0.0125	0.190	0.0658		1.00	680.0	8.5
	Softwood Timber	0.2000*	0.130	0.1846		1.60	500.0	19.2
	Screed	0.0650	1.150	0.0565		1.05	2100.0	143.3
	Hardwood	0.0180	0.160	0.1125		1.700	500.0	15.3
	Rsi	-	-	0.1700		-	-	-
		0.2955		**0.7594**				**186.3**

3.2.6 External roof

The external roof that covers the north façade of the studied building is highly insulated, with a U-Value of 0.11 W/m^2·°C, which reduces the amount of heat that the building envelope exchanges with the outside.

Table 11 - "Zero Bills Home" Roof details

	Layer	t [m]	λ [W/m·°C]	R-Value [m^2·°C/W]	U-Value [W/m^2·°C]	Heat Capacity [kJ/kg·°C]	Volumetric Mass [kg/m^3]	Thermal Storage [kJ/m^2·°C]
ZBH Roof	Rse	-	-	0.0400	0.11	-	-	-
	OSB	0.0150	0.130	0.1154		1.70	650.0	16.6
	EPS	0.3500	0.040	8.7500		1.55	15.0	8.1
	Plasterboard	0.0125	0.190	0.0658		1.00	680.0	8.5
	Rsi	-	-	0.1000		-	-	-
		0.3775		**9.0712**				**8.5**

3.2.7 Thermal bridges

Thermal bridges are crucial to assess the thermal performance of a building, particularly in a highly insulated building, where the heat loss through the envelope is low. Thermal bridges, also known as cold bridges, are normally the focus point where heat is transferred with the exterior.

Two types of cold bridges can be taken into account: repeating thermal bridges and linear or non-repeating thermal bridges. Repeating thermal bridges, such as the timber studs which sustain the building, were taken into account in U-Value calculations. The heat loss in non-repeating thermal bridges is known as linear thermal transmittance (Ψ) and it varies with the type of junction between the constructive elements.

An illustrative example of existing cold bridges in one bedroom located the middle floor of the house can be seen in the table and figures below, that where obtained from Knauff Insulation's catalog for thermal bridging [40] and a Portuguese investigation institute called ITeCONS [41].

Table 12 - Linear thermal bridges in the "Zero Bills Home" Bedroom 2

	Junction between:	Linear thermal transmittance Ψ [W/m·°C]	Length B [m]	Ψ ·B [W/°C]
Linear Thermal Bridges (Bedroom 2)	External wall and an intermediate floor within a dwelling – South	0.07	2.208	0.155
	External wall and an intermediate floor within a dwelling – East	0.07	3.410	0.239
	External wall and party wall gable, insulation at a ceiling level – South	0.24	2.208	0.530
	External wall and party wall gable, insulation at a ceiling level - East	0.24	3.410	0.818
	External wall, normal corner	0.09	2.500	0.225
	External wall and window frame	0.28	1.050	0.294

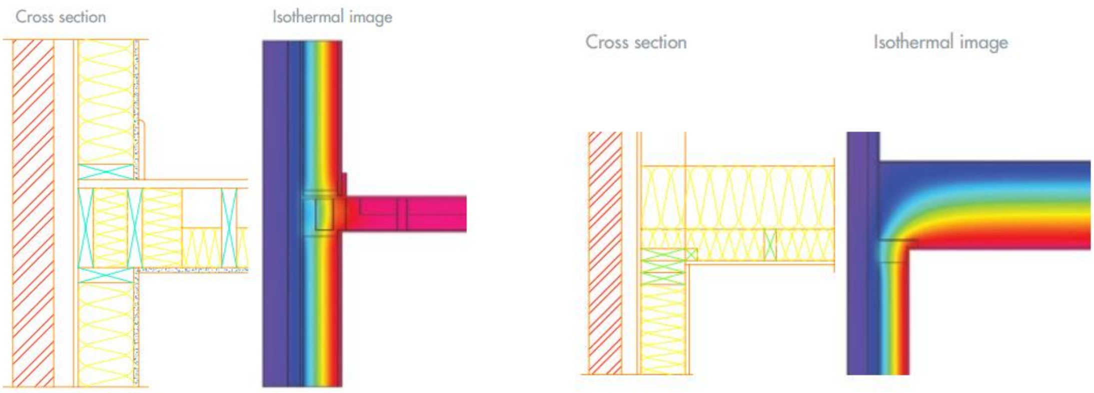

Figure 11 - Junction with an external wall and an intermediate floor within a dwelling (left) and Junction with a party wall gable, insulation at ceiling level (right) [40]

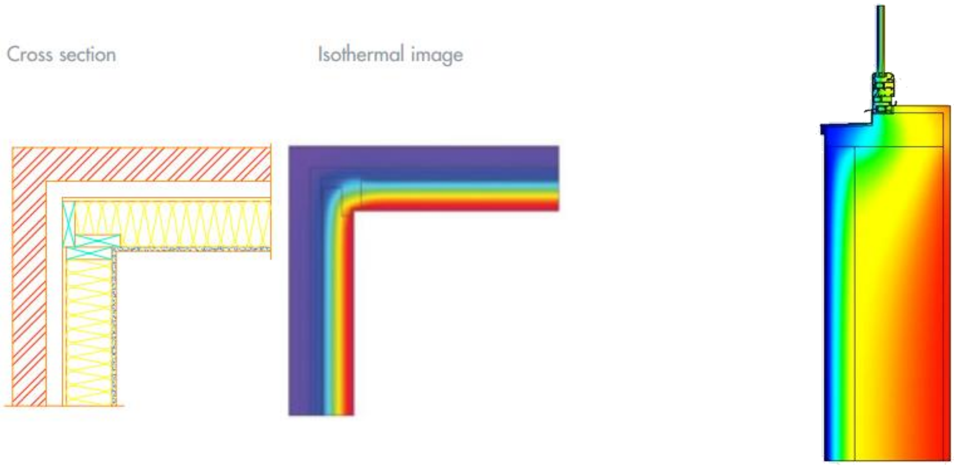

Figure 12 - Junction with an external wall – normal corner (left) and Junction between an external wall and window frame (right) [40], [41]

3.2.8 Fenestration

The fenestrations used in this building are composed by double glazed windows with timber frame. Different glazing types are used within the building, but they are all made by the same manufacturer and have approximately the same solar factor and U-Values. The thermal properties of the following windows and glass doors where obtained from the supplier’s catalogue.

Table 13 - “Zero Bills Home” Window Type 1 details

	Frame	Frame/Window Ratio	Internal Shading Device	G-Value	U-Value [W/m^2·°C]
Window Type 1	Double glazing with timber frame	0.36	No	0.63	1.40

Table 14 - "Zero Bills Home" Window Type 3 details

	Frame	**Frame/Window Ratio**	**Internal Shading Device**	**G-Value**	**U-Value [W/m^2·°C]**
Window Type 3	Double glazing with timber frame	0.64	No	0.63	1.54

Table 15 - "Zero Bills Home" Window Type 4 details

	Frame	**Frame/Window Ratio**	**Internal Shading Device**	**G-Value**	**U-Value [W/m^2·°C]**
Window Type 4	Double glazing with timber frame	0.37	No	0.63	1.42

Table 16 – "Zero Bills Home" Velux Rooflight details

	Frame	**Frame/Window Ratio**	**Internal Shading Device**	**G-Value**	**U-Value [W/m^2·°C]**
Velux Rooflight	Double glazing with timber frame	0.36	No	0.63	1.40

Table 17 - "Zero Bills Home" Double glass doors details

	Frame	**Frame/Window Ratio**	**Internal Shading Device**	**G-Value**	**U-Value [W/m^2·°C]**
Double Glass Doors	Double glazing with timber frame	0.43	No	0.62	1.47

3.3 Climate description

In order to understand the thermal behaviour of the building, it is of a great importance to comprehend the climatic conditions of the site where it is located. Concerning the control of the heat transfer between the building and the exterior, it is fundamental to know the weather changes on the outside of the thermal envelope.

One of the goals of this project was to establish a comparison between the thermal behaviour of the "Zero Bills Home" in London (United Kingdom) and in a location with a different climate, which was chosen to be Porto (Portugal).

The weather analysis of both sites was made resorting to the climatic data obtained from "Climate Consultant" software. Attached to this document, follows a detailed table with the climatic conditions of both these locations, in Annex A.

According to the Köppen-Geiger climate classification [42], London has a temperate oceanic climate (Cfb), whereas Porto features the Mediterranean climate (Csb).

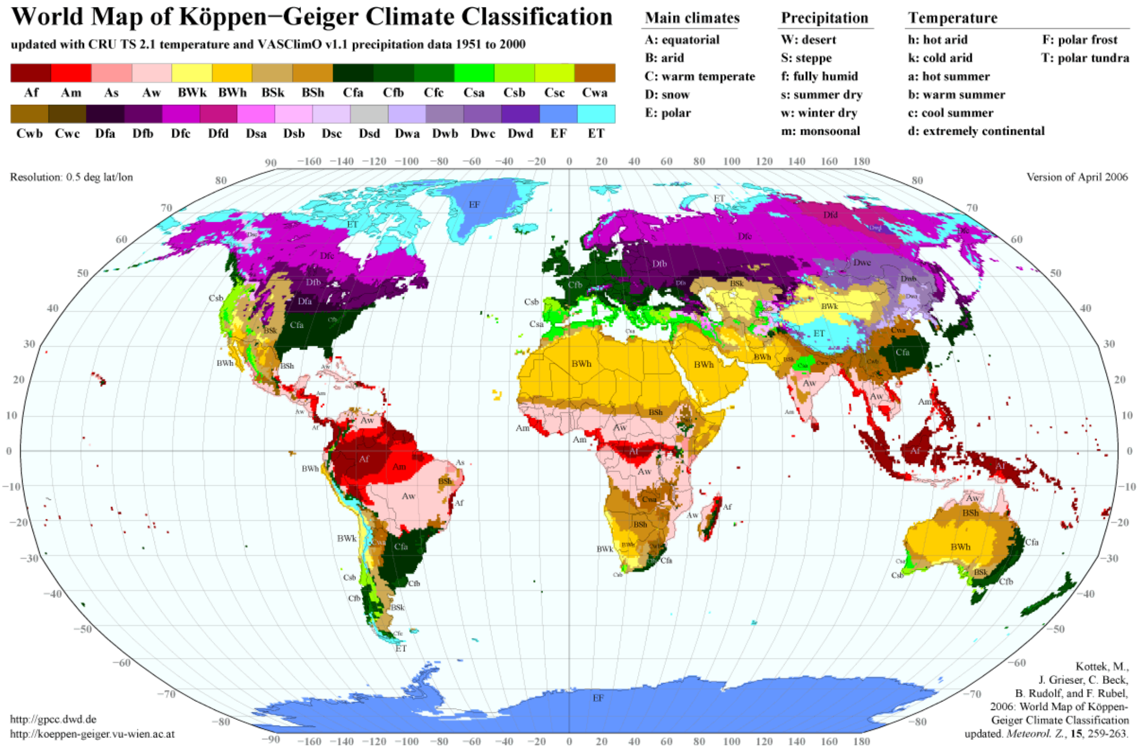

Figure 13- World Map of Köppen- Geiger Climate Classification [42]

The “World Map of Köppen-Geiger Climate Classification” is the most widely used climate classification map in the fields of geography and climatology [42]. It features a distinctive sorting scheme, where each climatic type is described by a code consisting of uppercase and lowercase letters, whose combination denotes the types and subtypes considered. This system divides the climates into five main groups (A, B, C, D, E), each having several types and subtypes.

The first letter is an uppercase that escalates from “A” to “E”, going from the equator to the poles. It refers to the main characteristics of the climate of a region, which can be classified as the equatorial zone (A), the arid zone (B), the warm temperature zone (C), the snow zone (D) and the polar zone (E).

It is followed by a second letter that is used to quantify and classify the distribution of precipitation. Normally it is a lowercase letter, except when the first letter is a “B” or an “E”. In those cases, the second letter is also a capital one, denoting the amount of the total annual rainfall or the annual mean air temperature.

Finally, the third letter characterizes the climate’s seasonal temperatures according to the average monthly air temperature.

The following tables show the criteria used by this classification system [43]:

Table 18 - Key to calculate Köppen-Geiger’s climate formula for the main climates and subsequent precipitation conditions [43]

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18°C$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60mm$
Am	Equatorial monsoon	$P_{ann} \geq 25(100- P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60mm$ in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60mm$ in winter
B	**Arid climates**	$P_{ann} < 10\ P_{th}$
BS	Steppe climate	$P_{ann} > 5\ P_{th}$
BW	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperature climates**	$-3°C < T_{min} < +18°C$
Cs	Warm temperature climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40mm$
Cw	Warm temperature climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperature climate, fully humid	Neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3°C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40mm$
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climate, fully humid	Neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10°C$
ET	Tundra climate	$0°C \leq T_{max} < +10°C$
EF	Frost climate	$T_{max} \leq 0°C$

Where:

$$P_{th} = \begin{cases} 2\ (T_{ann}) & if\ at\ least\ 2/3\ of\ the\ annual\ preciptiation\ occurs\ in\ winter \\ 2\ (T_{ann}) + 28 & if\ at\ least\ 2/3\ of\ the\ annual\ preciptiation\ occurs\ in\ summer \\ 2\ (T_{ann}) + 14 & otherwise \end{cases}$$

Table 19 - Key to calculate Köppen-Geiger’s third letter temperature classification [43]

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18°C$
k	Cold steppe / desert	$T_{ann} < +18°C$
a	Hot summer	$T_{max} \geq +22°C$
b	Warm summer	Not (a) and at least 4 $T_{mon} \geq +10°C$
c	Cool summer and cold winter	Not (b) and $T_{min} > -38°C$
d	Extremely continental	Like (c) but $T_{min} \leq -38°C$

3.3.1 London

London is located in the southeast of the United Kingdom, which in turn is in the northwest of Europe. Its geographic coordinates are: 51°30′26″N; 00°07′39″W.

Figure 14- Location of London, United Kingdom [44]

London's climate is known for being temperate with no dry season and warm summers, therefore being classified according to Köppen-Geiger as Cfb. It can also be described as a temperate oceanic climate.

According to the weather data obtained from the "Climate Consultant" software, the average annual temperature is about 10.4 degrees Celsius, being that the average high occurs in July and it is approximately 23°C, whereas the average low is around 1°C taking place in the month of February as shown in the Figure 15. In this figure, the white gap represents the mean temperature, the yellow band is referent to the average temperatures and the green band corresponds to the design peaks.

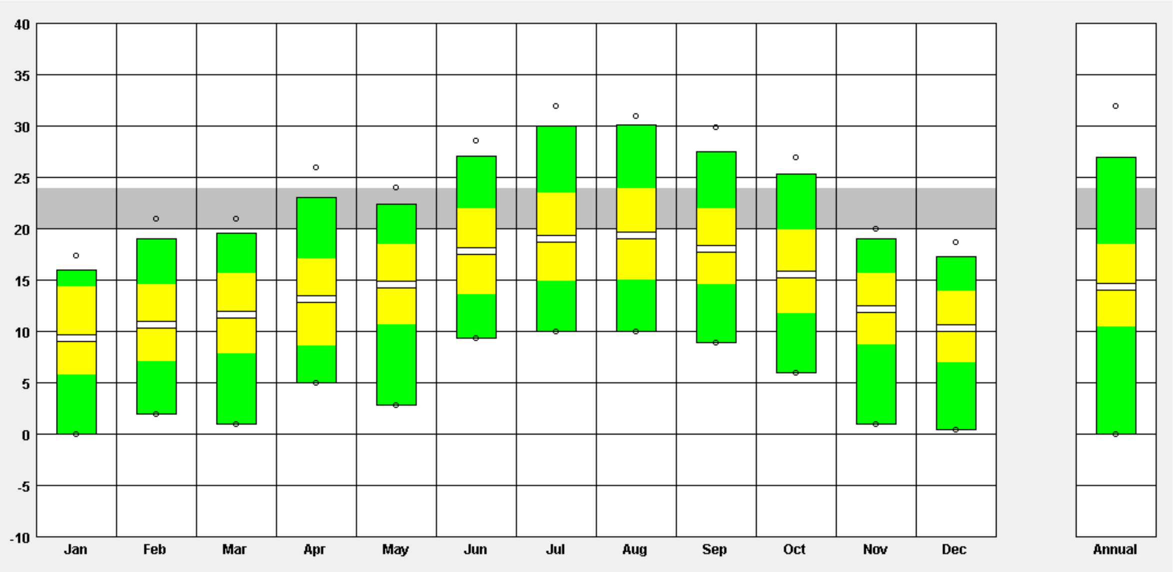

Figure 15 - Annual dry bulb temperature range in London (according to Climate Consultant Software)

The relative humidity of this site is high, usually fluctuating between 60 and 90% in summer and over 80% in winter. Studies show that the total annual precipitation averages 594mm, without significant variation over the year, meaning that the existence of a dry season cannot be considered [45].

The mean annual sum of all global horizontal radiation in London is around 1000 kW·h/m^2, as can be verified in Figure 16, according to a geographical information system called "SolarGIS". This means that the daily average is 2.75 kW·h/m^2, as reported on the "Radiation Range" data obtained from Climate Consultant software, which can be found attached to this document in Annex A.

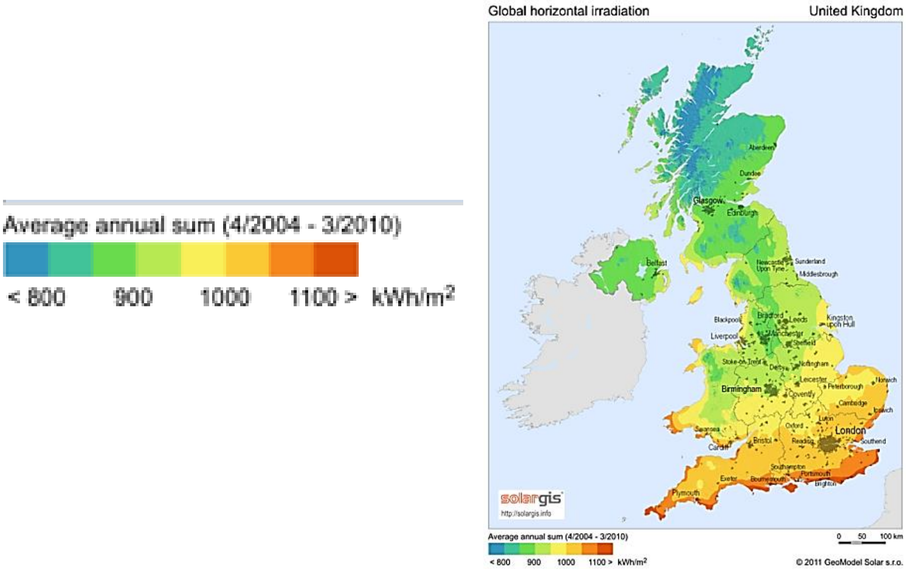

Figure 16 - Annual global horizontal radiation in the United Kingdom [46]

3.3.2 Porto

Porto is a city in the northwest of Portugal, which is located in the southwest of Europe. Its geographic coordinates are: 41°9′43.71″N; 8°37′19.03″W

Figure 17 - Location of Porto, Portugal [44]

According to Köppen-Geiger’s classification system, Porto’s climate is categorized as Csb, since it has a temperate Mediterranean climate. It is known for having moderate temperatures, alongside with dry and warm summers.

The mean monthly temperatures usually float between 9°C and 19°C, thus resulting in an annual average temperature of 14°C. The average high is about 24°C and it usually occurs between the months of July and September. On the other hand, normally in January, it can drop as low as 5°C, as shown on the following Figure 18 obtained from “Climate Consultant”:

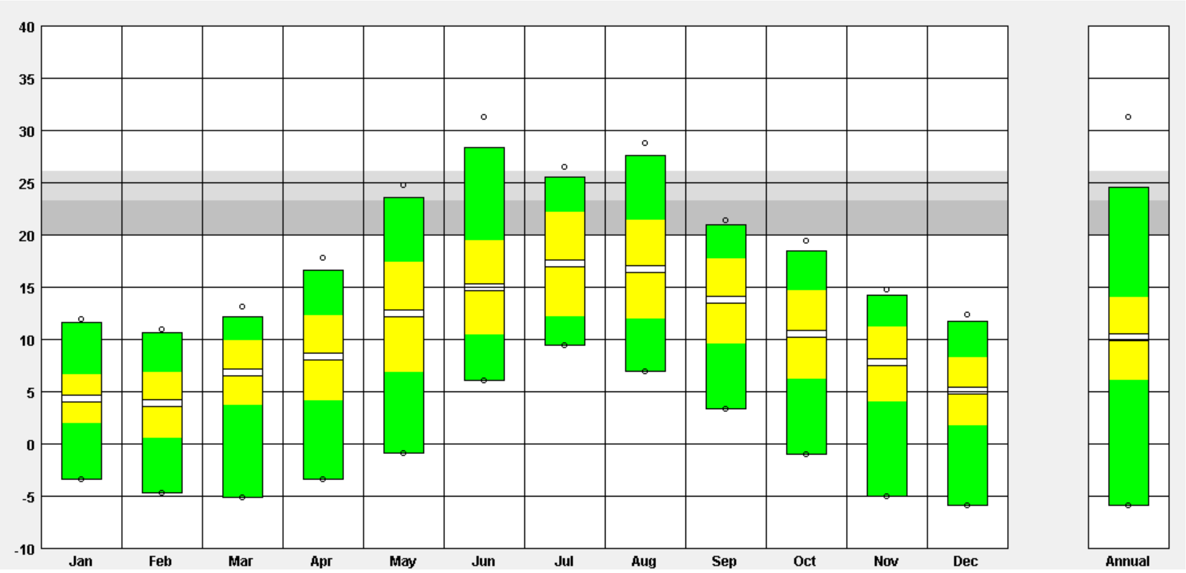

Figure 18 - Annual dry bulb temperature range in Porto (according to Climate Consultant Software)

As for the relative humidity, it usually fluctuates between 60 and 90% during the whole year, while the monthly mean is around 78%. The total annual precipitation averages 1267mm, even though Porto’s climate is characterized by having dry summers. During the remaining months, precipitation is much more frequent and intense [47].

The daily average global horizontal radiation is approximately 4.3 kW·h/m^2, thus totalling 1600 kW·h/m^2 during one year, as illustrated on Figure 19 and in Annex A, obtained from “Climate Consultant” software.

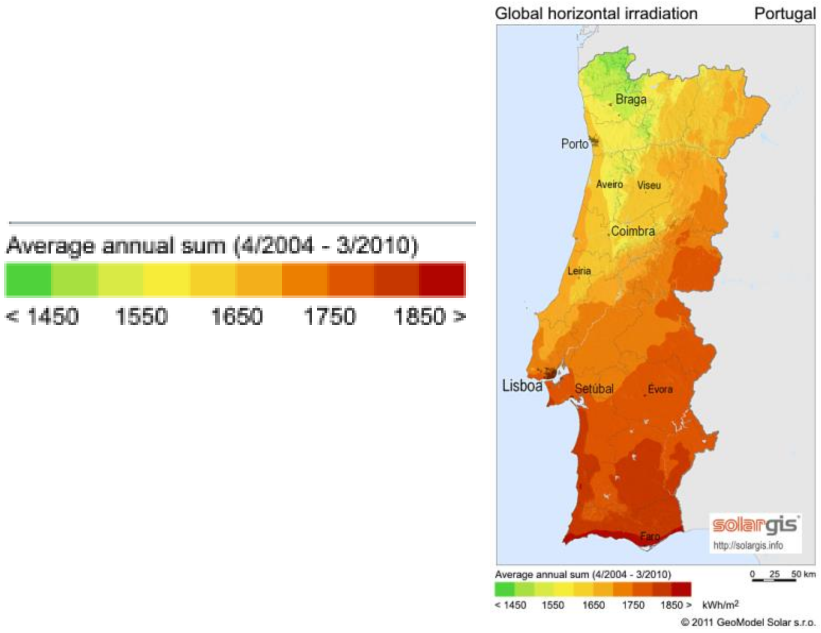

Figure 19 - Annual global horizontal radiation in Portugal [46]

3.3.3 Comparative analysis

As shown above, these two cities have different climatic conditions both in summer as in winter. While London is known by its continuous precipitation throughout the year, Porto usually has dry summers. The average monthly temperature in Porto is also higher than in London, meaning that if the exact same building would be located in both these sites, in Porto it would have lower heating demands together with increased cooling demands.

By analysing the average global horizontal radiation for both locations, it is quite obvious that Porto can harness more solar radiation per square metre than London, thus increasing its solar potential and making it, in theory, a better place to produce energy that uses the sun as a power source, such as photovoltaic systems.

It is always essential to adapt every building to the climate where it will be constructed in order to improve its thermal behaviour, reduce its energy demands, and increase the electric energy generation, if specific systems are used. For each climate and building typology, by achieving a perfect ratio between insulation, thermal mass and air tightness, buildings will become more efficient and less energy will be spent.

3.3.4 Design conditions

The outdoor design temperature defined for London for both winter and summer were based on weather data records, where the cumulative probability of occurrence is 95%, meaning that the considered temperature is only exceeded 5% of the time. [48]

Table 20- Seasonal Outdoor Design Temperatures for London (95%)

	Outdoor Design Temperature [°C]	
London	Winter	Summer
	-1	25.6

For the summer period the wet bulb temperature was also obtained from the previous weather data records and it is stated as 18°C. On the other hand, for winter, a relative humidity of 80% was adopted, taking into account the results from the climatic analysis made using Climate Consultant software.

3.4 Simulation development

3.4.1 TRNSYS Simulation Studio

For this project, in order to obtain more realistic and comparable data, three case scenarios were analysed, reflecting different occupant behaviours and sustainable awareness. Their main differences lay on the user-defined thermostat set points which will influence space heating demands, on the hot water demands and in the general electric energy consumption, as can be seen in the subsequent table:

Table 21 - Analysed case scenarios

	Case 1 **Standard User**	**Case 2** **Intermediate User**	**Case 3** **Excessive User**
Thermostat Set Points	18°C - 25°C	21°C - 25°C	21°C - 25°C
Hot Water Demands	40 litres/person/day	40 litres/person/day	50 litres/person/day
General Electric Energy Consumption	23 kWh/m^2/year	23 kWh/m^2/year	28 kWh/m^2/year

In addition to the difference in the thermostat set points, which was chosen to show that different occupants have different comfort requirements, when comparing the third case with the previous ones, an increase of 25% in both the hot water demands and the general electric energy consumption was considered, thus describing excessive and sustainably unacquainted users.

The hot water demands were estimated having as basis governmental statistical documents produced by the BRE [49] and the Energy Saving Trust enterprise [50]. As for the general electric energy consumption, also known as unregulated electric loads or plug loads, which include all household electric applications, including the HVAC system were assumed to be equivalent to the ones monitored on BedZED, thus totalling 23 kWh/m^2/year for the first and second case scenarios [51].

The following figure shows a graphical overview of the main simulation made for this project, which combines two central parts: The building model and the photovoltaic model, which will be explained in detail in the subsequent sub-chapters.

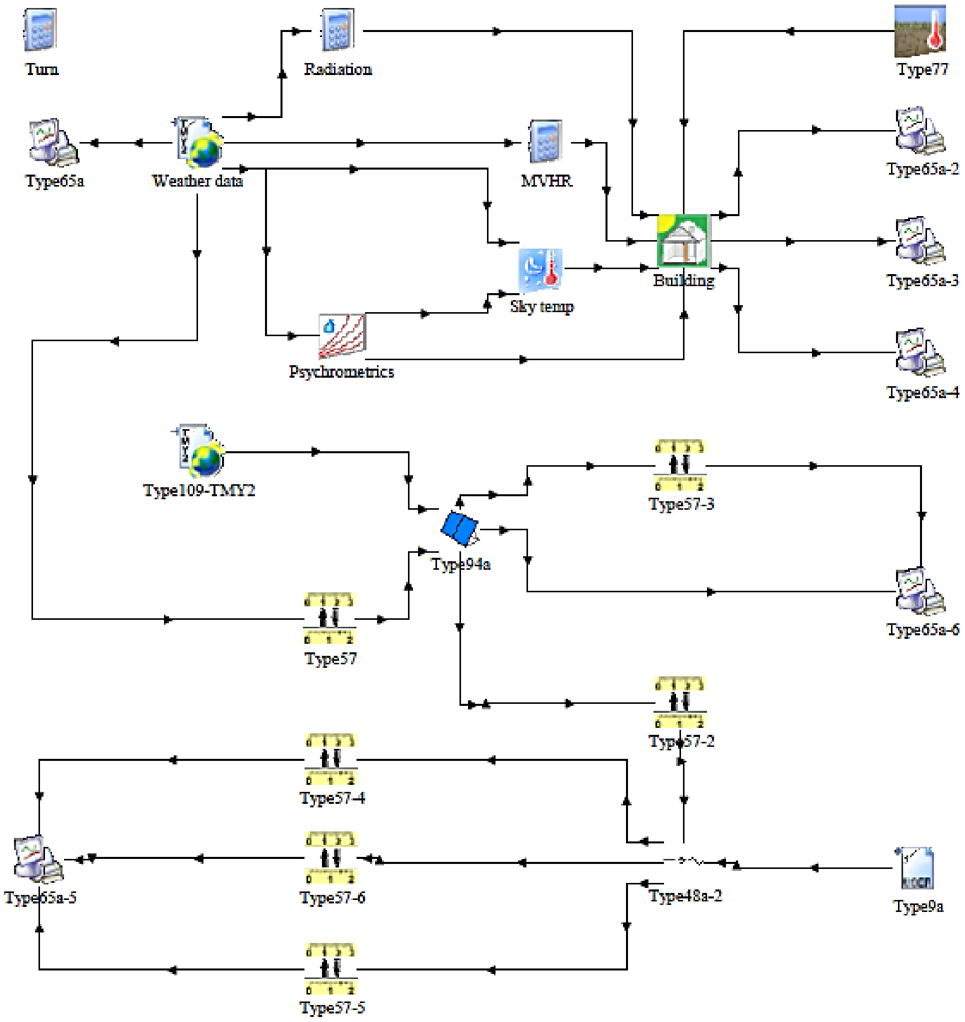

Figure 20- Graphical overview of the complete model in TRNSYS

3.4.2 Photovoltaic model

The key component used for electricity generation in the “Zero Bills Home” is the ZEDroof, which is a building-integrated photovoltaic system connected to the grid, composed of large interlocking solar panels made of monocrystalline solar cells. Because the system is connected to the national grid, there are no energy storage units, such as batteries. So the ZEDroof is connected to an inverter that converts the variable direct current (DC) from the photovoltaic panel into an alternating current (AC) that is provided to the grid. In the “Zero Bills Home”, an inverter with 97% efficiency is used, and its details can be checked in Annex B.

In most grid-connected applications, the photovoltaic panel is connected to the grid through an inverter/max power point tracking device that allows it to optimize its performance to the best possible load. If the panel is connected to this device, then it continually adjusts its operating voltage to keep operating at its maximum power point. Maximum Power Point Tracking (MPPT), is an electronic system that operates the photovoltaic modules in a way that allows them to produce all the power that they are capable of. This is not a mechanical tracking system that “physically moves” the modules, in order to allow them to point more directly at the sun. It is a fully electronic system that varies the electrical operating point of the modules so that they are able to deliver the maximum available power. This technology can be used in conjunction with a mechanical tracking system, but they are two independent and different systems [52]. A model of this system was developed in TRNSYS, as can be seen on the following figure:

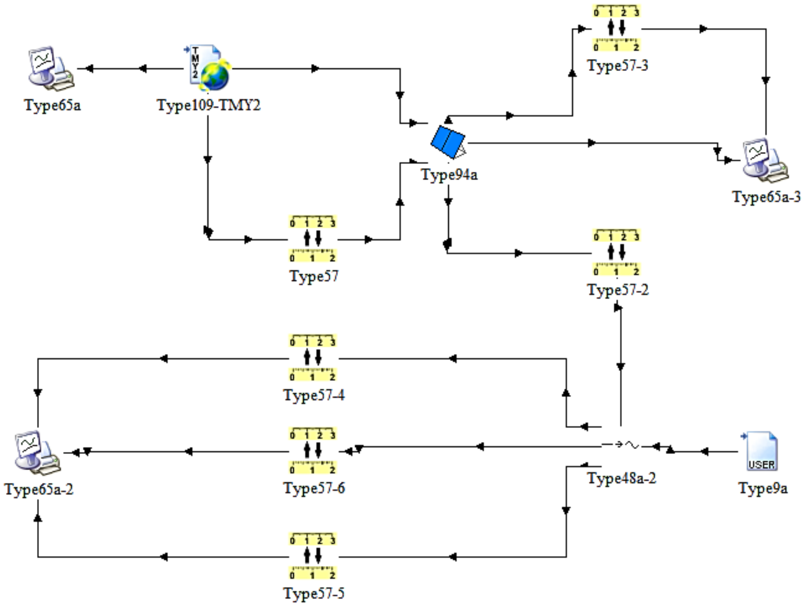

Figure 21 - Graphical overview of the photovoltaic model in TRNSYS

The main component is TRNSYS' Type 94, which models the electrical performance of a photovoltaic array and Type 48a, which model an inverter used in systems without battery storage, as such. Several unit conversion routines were also used in this model. Type 94 may be used in simulations involving electrical storage batteries, direct load coupling, and utility grid connections. It employs equations for an empirical equivalent circuit model to predict the current-voltage characteristics of a single module. This circuit consists of a DC current source, diode, and either one or two resistors. The strength of the current source is dependent on solar radiation and the IV characteristics of the diode are temperature-dependent. The results for a single module equivalent circuit are extrapolated to predict the performance of a multi-module array. Type 94 also includes an optional incidence angle modifier correlation to calculate how the reflectance of the PV module surface varies with the angle of incidence of solar radiation [53].

The inputs used in Type 94 mainly depend on the technical characteristics of the photovoltaic modules considered and they are given in Table 22.

Table 22 - Characteristics of the photovoltaic modules used as inputs in TRNSYS Type 94

Module short-circuit current (I_{sc}) at reference conditions	8.68	**A**
Module open-circuit voltage (V_{oc}) at reference conditions	37.6	V
Reference temperature	298	K
Reference insolation	1000	W/m2
Module Voltage at max power point and reference conditions	31	V
Module current at max power point and reference conditions	8.06	A
Temperature coefficient of I_{sc} at reference conditions	0.036	-
Temperature coefficient of V_{oc} at reference conditions	-0.346	-
Number of cells wired in series	60	-
Number of modules in series	30	-
Number of modules in parallel	1	-
Module temperature at NOCT	339	K
Ambient temperature at NOCT	293	K
Insolation at NOCT	800	W/m2
Module Area	1.63	m2
Tau-alpha product for normal incidence	0.95	-
Semiconductor bandgap	1.12	-
Slope of IV curve at ISc	0	-
Module series resistance	-1	-

Besides solar irradiance, there are other fundamental variables which directly affect the electrical output of the photovoltaic system and its efficiency, such as the operating cell temperature, wind speed, and even dust and dirt that might accumulate on the panels. It is important to consider these constraints when modelling PV systems, in order to obtain a more realistic approach. The results obtained for this model can be seen further ahead in Chapter 4.1.3.2.

3.4.3 Building model

The dynamic simulation of the building is the centrepiece of this project, as without it would be impossible to understand how it behaves and to determine its yearly energy demands. The core of the building model done in TRNSYS lays on Type 56, the multizone building model. Because of its complexity, Type 56 is linked with a TRNSYS application known as TRNBuild, which will thoroughly be explained in Annex C.

Several other TRNSYS components are used in this model and are therefore linked with the multizone building model. Amongst them, there is the "Data Reader and Radiation Processer" Type 109 whose main purpose is to convert the weather data into a desired system of units and processing the solar radiation data to obtain tilted surface radiation and angle of incidence for different surfaces. This previous component is also linked with Type 33 "Psychrometrics: Dry Bulb and Relative Humidity Known" which uses the dry bulb temperature and relative humidity of moist air as input and by calling the TRNSYS Psychrometrics routine, returns the psychrometric properties of the air. Using outputs from both Type 109 and Type 33 as inputs is Type 69 "Effective sky temperature for long-wave radiation exchange" whose goal is to calculate the cloudiness factor of the sky and to determine the effective sky temperature, which is used to calculate the long-wave radiation exchange between external surfaces and the atmosphere. The multizone building also uses inputs from Type 77 "Soil Temperature Profile ", which models the vertical temperature distribution of the ground [53]. In addition to these components, the calculator tool is used in the building simulation with different purposes. It is used to correctly rotate the building according to its orientation, to link different radiation types with multiple surfaces and to account for the mechanical ventilation system with heat recovery. A graphical overview of this model can be seen in the following figure:

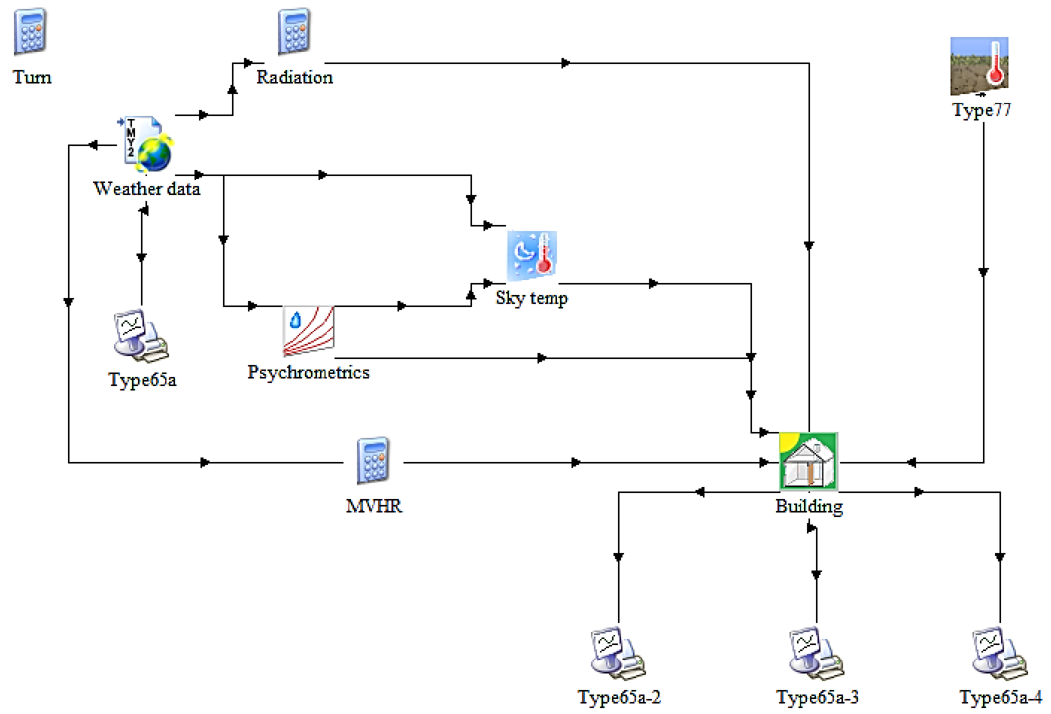

Figure 22 - Graphical overview of the building model in TRNSYS

3.4.3.1 Building Layout

The geometry of the model and the definition of the building envelope are central pillars in the field of building simulation. In order to start a model in TRNBuild, it is essential to define the number of thermal zones. With this in mind, every room of the house was considered a thermal zone of the model, thus making 15, as shown previously on Figure 9:

- Living Room
- Hall 0
- WC
- Kitchen / Dining Room
- Bedroom 1
- Bathroom
- Hall 1
- Power Room
- Bedroom 2
- Bedroom 3
- Storage
- Master Bedroom
- En-Suite Bathroom
- Hall 2
- Solar Loft

3.4.3.2 Internal gains

The internal gains of a building are usually divided into three major groups: Occupancy, Illumination and Equipment. All of these internal gains can be scaled by using a constant value, an input or a schedule. For each one of these types, different schedules where built according to the characteristics of the zone and whether it would be a weekday or a weekend, in order to provide more realistic and accurate results.

There are two options to define the heat gain from the occupants: according to the international norm ISO 7730 or according to VDI 2078. In this simulation, ISO 7730 was used and the stated degree of activity was adjusted accordingly to the behaviour of the occupants in each division.

The artificial lighting is characterized by the total heat gain per square metre alongside with the respective convective part. The “Zero Bills Home” uses energy-saving fluorescent lamps, thus having a convective part of 40% together with a total heat gain of 5W/m^2.

In order to define the gain from equipment, it is necessary to input the radiative power, the convective power and the absolute humidity of every different piece of equipment used in the simulation. For this model there were considered 3 different inputs, whose power and radiative and convective fraction were obtained from the ASHRAE Journal [59].

Table 23 - Convective and radiative power of the internal gains modelled in TRNBuild [59]

Gain	Total Power [W]	Radiative Part [%]	Convective Part [%]
TV	100	40	60
Laptop	50	10	90
Cooking	250	50	50

As for all the schedules, they can be found attached to this document in Annex D.

Internal gains have a big influence on the heating and cooling demands of a building, due to the fact that occupants, lights and electric equipment release both sensible and latent heat that will increase the temperature within the interior of each zone. The impact that each of these internal gains has on the energy demands of this building will be analysed further ahead.

3.4.3.3 Infiltration and ventilation

The infiltration and the ventilation type are both characterized by the number of air changes per hour that occur inside each zone. Infiltrations account for the natural uncontrolled and usually undesired air that enters the zone, whereas the ventilation rates are defined by the controlled amount of air that would be forced to enter the zone.

In TRNBuild, the Infiltration Type Manager, allows the user to easily define the amount of outside air at ambient conditions that flows inside each zone. Much similar to the internal gains, infiltrations can also be scaled as a constant value, an input or according to a schedule. In this model, for almost every zone of the building, it was used the value of 1.5 air changes per hour at 50 Pa, used in accordance with previous airtightness test results on similar constructions developed by ZEDfactory. A pressure of 50 Pascal is, as stated before, the typical value used in building airtightness tests, such as the blower door test. For domestic buildings, it is possible to estimate the average infiltration rate at normal conditions from these airtightness tests, since it has been shown that under average weather conditions, the air infiltration can be approximated using a simple “rule of thumb”, which involves dividing the number of air changes per hour at a test pressure of 50 Pa by 20. Therefore, 1.5ACH at 50 Pascal would equal 1.5/20 = 0.075 air changes per hour, which was considered as the air leakage of this dwelling.

This value was assumed for every zone of the building with the exception of the Solar Loft, which is considered to be an exterior ventilated zone, since it has a gap through which air flows. In this room, the main concern was that it could overheat during the summer, due to its solar exposure, so, in order to avoid this problem, the maximum temperature that it could reach had to be limited. This temperature depends on how much exterior air is entering this zone through the gap. In furtherance of restricting the maximum inside temperature of the Solar Loft to 35°C, it was verified through an iterative modelling process using TRNSYS that it is necessary to have a natural ventilation rate of, at least, 25 air changes per hour in this zone.

It was necessary to dimension the height of the Solar Loft gap through which air flows, as it is supposed to extend all along the length of the façade. This was made in accordance with Bernoulli’s equation that explains the physics behind air leakage,

$$\frac{\rho \cdot v^2}{2} + P + \rho \cdot g \cdot z = Const.$$

where the first term is referent to the effect of the wind and the third to the stack effect. Because air infiltration is a complex process, it is necessary to distinguish the pressure loss that derives from these two causes. The calculations which led to a gap height of 23.4mm can be found attached to this document, in Annex E.

As for forced ventilation, at first it was not considered since it was necessary to determine the thermal demands of the building without aggravating it with ventilation gains. Subsequently to this phase, a ventilation system was implemented, in order to guarantee that the indoor air quality requirements for the occupants were met. This was done in accordance with the Building Regulations Part F, tables 5.1a and 5.1b [61].

Table 24 - Minimum extract ventilation rates according to the Building Regulations Part F [61]

Room	Minimum rate: continuous extract
Kitchen	13 l/s
Bathroom	8 l/s

Table 25 - Whole dwelling ventilation rates according to the Building Regulations Part F [61]

Number of bedrooms in dwelling	1	2	3	4	5
Whole dwelling ventilation rate (l/s)	13	17	21	25	29

In this project, fresh air will be supplied to the living areas, such as all the bedrooms and the living room, whereas the air will be exhausted from the kitchen and bathrooms. For the living areas it was considered an occupancy of 5 persons in the living room, 2 in the master bedroom and 1 in each one of the remaining bedrooms. In order to maintain an even balance between the air coming in and out of the dwellings, the same airflow is necessary for both situations. The airflow defined for each zone also takes into account the usage of a fan with 92% efficiency, provided by the heating recovery unit. Acknowledging all the previews considerations, the ventilation rates for both supplying and exhausting air where defined and can be seen in Annex F.

As for the Ventilation Type Manager in TRNSYS' Type 56, the air change rate in each zone was considered as follows:

Table 26 - Ventilation rates considered for each thermal zone

Supply Air	Air Change Rate [ACH]	Exhaust Air	Air Change Rate [ACH]
Living Room	1.9	WC	4.6
Bedroom 1	0.5	Kitchen / Dining Room	0.9
Bedroom 2	0.5	Bathroom	2.8
Bedroom 3	0.5	En-suite Bathroom	3.4
Master Bedroom	0.9		

In addition to the air changes per hour in each zone, it is possible to determine the air flow rate of the dwelling by dividing the total supplied/exhausted air flow by the volume of the building. In this project, this accounts for a whole dwelling ventilation rate, as can be seen in the previously mentioned attachment.

Because the airtightness of this building is one of the key factors for its performance, as soon as a mechanical ventilation system is used, the total heat loss will increase due to the exchange of air with the outside. In order to minimize this problem, a MVHR unit with 90% efficiency on heat recovery was used, to assure that when the fresh air is coming inside the building it can be exchange heat with the air that is being exhausted, and therefore increasing its temperature and reducing heat loss. A heat recovery a unit is a strategy that is widely implemented in most of the energetic efficient buildings, such as the PassivHaus. This unit, as well as the remaining ventilation system will be discussed in detail further ahead in chapter 4.1.4.

3.4.3.4 Heating and cooling

Both the Heating and Cooling Type Manager allow the user of TRNBuild to define a room temperature control that can be a constant set temperature or one that follows a certain input or schedule, as if it is controlled by a thermostat. This account for many possibilities, however the most typical and simplistic combination would be a set temperature of 20°C in winter and 25°C in summer. A study case study has been made regarding the total energy demands for heating considering the building equipped with this standard thermostat and with one programmed setback thermostat. The results obtained are shown further ahead in this thesis. Also, several cases of occupants with different behaviours and sustainability awareness were made, which include occupants with particular thermostat set points.

The setback thermostat, works as a programmable thermostat that changes according to the period of the day. As an example of one of the cases used, instead of having the thermostat always at 18°C in the winter and 25°C in the summer, a thermostat with different behaviours during a weekday and during the weekend both for winter and summer was defined, as shown in the following table:

Table 27 - Setback thermostat definitions used in Case 1

	Winter		Summer	
	Week	Weekend	Week	Weekend
Occupied	18	18	25	25
Unoccupied	16	-	29	-
Night (sleeping period)	18	18	27	27

The possibility of letting the temperature slightly decrease during winter or increase during summer while the building is unoccupied will not affect the thermal comfort of the habitants. While allowing energy savings throughout a year, this strategy would increase the heating loads when the system is re-starting. Subsequently, an optimized solution for this project was chosen, taking into account all the different studied scenarios previously described in chapter 3.4.1. This will be explained in detail in chapter 4.1.1.

There is also the option to limit or not the heating and cooling power of each zone. Since the goal of this simulation was to determine the total loads in order to maintain the temperature inside the room according to the thermostat restrictions, “unlimited power” was selected.

In the Heating Type Manager, by turning on the Humidification option, it is possible to define the desired relative humidity in each zone.

4. Data analysis and developed work

4.1 London

In Northern Europe, space heating is the main concern that has to be dealt with, in order to guarantee users thermal comfort. In the United Kingdom it is not uncommon that people have their household heating systems turned on from seven to eight months throughout the year, mainly turning it off between June and September. For the purpose of this study space cooling was not intended to be analysed, as passive strategies, such as cross ventilation, night flush and free-cooling are planned to be used in order to counterbalance the existing cooling demands. With these solutions, by not allowing the building to overheat it is possible to eliminate the need for mechanical cooling systems, thus reducing energy demands.

Due to all the constructive properties of this house, when compared with a normal building, it is easy to understand that space heating demands will be considerably lower. Hot water demands will then represent a larger share in the energy demands of the “Zero Bills Home”, as well the remaining general electric energy consumption. Bringing together the energy demands of this building, they will be then compared with the total electric energy produced by the ZEDroof, in order to position this house in the NZEB concept line. The results obtained for the different scenarios will be analysed in the following subchapters.

4.1.1 Heating demands

The first and main goal of the building simulation developed in TRNSYS was to determine the space heating demands for this house type. Obviously, they will be highly influenced by the thermostat set points chosen by the occupants, which will reflect on their thermal comfort. In order to cover different types of occupant needs, the three different case scenarios were developed with two thermostatic variants: while in the first case the minimum comfort temperature was defined as 18°C, for the second and third cases it was set as 21°C. Continuous thermostat settings were chosen over programmable setback thermostats, as will be explained in the succeeding subchapter.

Therefore, assuming that the minimum temperature inside each zone remains unchanged throughout the year, the following results were obtained when comparing the heating demands for the three case scenarios.

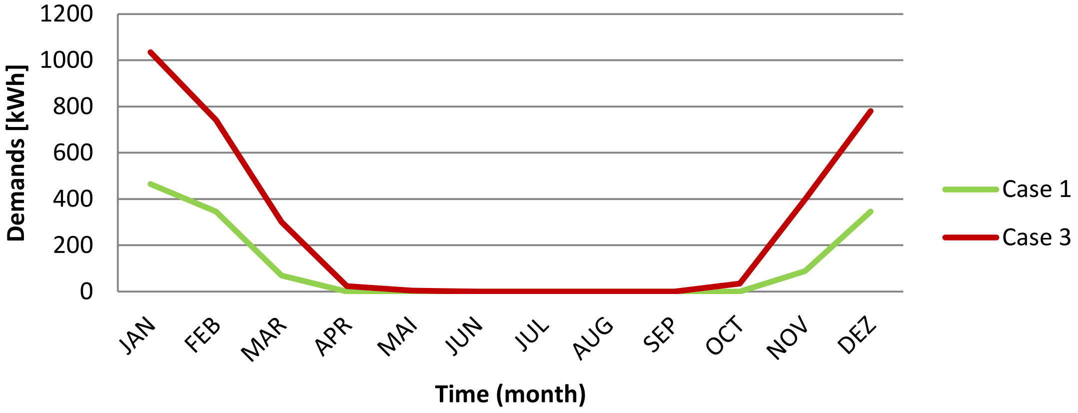

Figure 23 - Comparison between the monthly heating demands for cases 1 and 3

Table 28 - Annual space heating demands for cases 1 and 3

	Annual space heating demands [kWh]
Case 1	1314
Case 3	3318

By increasing the minimum comfort temperature in 3°C, from 18°C to 21°C, the annual heating demands will, as expected, greatly rise, thus reproducing how much users can influence the energetic consumption of their house. This temperature interval, although it may seem narrow, will cover most of the different user comfort conditions.

The next figure demonstrates the share that each zone represents in the total space heating demands. This statistics will not be very different between the three scenarios; therefore the results obtained from the first case were used as an illustrative example.

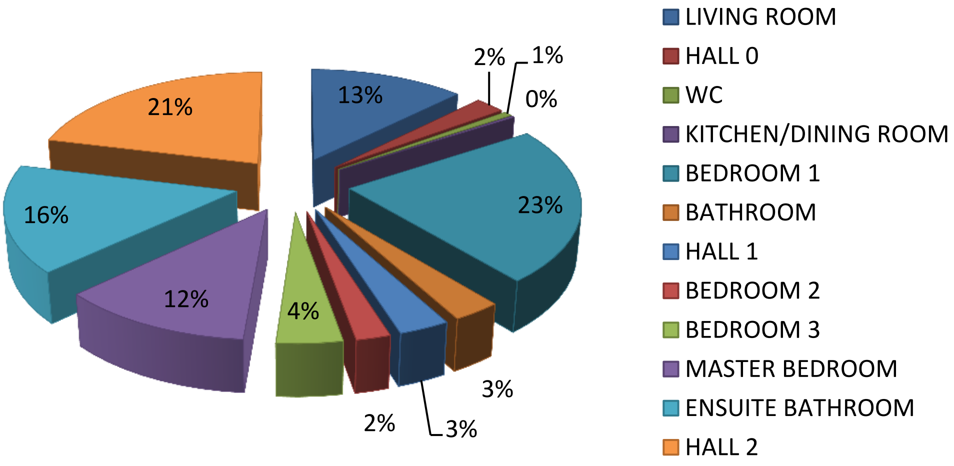

Figure 24 - Zone contribution for the total space heating demands for Case 1

Rooms in the top floor, such as the Master Bedroom, the En-suite Bathroom and Hall 2, contribute together to half of the building's heating demands which are mainly due to their proximity to the open Solar Loft and to heat loss through the roof. In addition to these zones, both the Living Room and Bedroom 1 also play an important role, since they have wide glazing areas facing north.

4.1.1.1 Thermostats

As previously stated, the continuous thermostat was preferred over the programmable one. Whereas in the first situation a constant minimum temperature was considered across the year, in the second, the temperature would slightly float during the time that the building would be unoccupied or during the night while the occupants would be sleeping, without causing thermal discomfort. The results obtained with both these solutions are shown below using the first case as an example, since the remaining would follow the same principle.

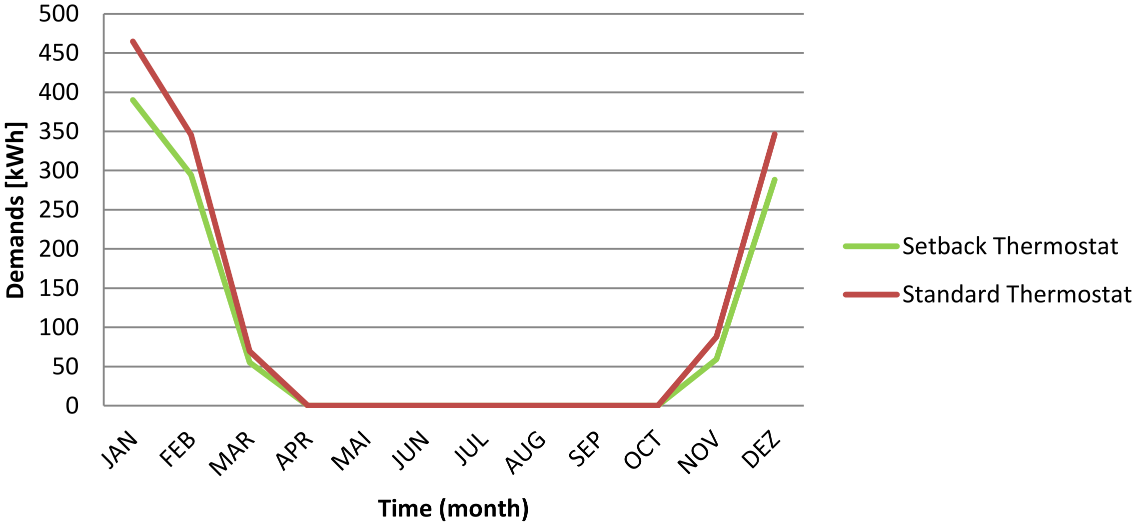

Figure 25 - Comparison between the monthly heating demands using different thermostats for case1

Table 29- Annual space heating demands using different thermostats for case 1

	Annual space heating demands [kWh]
Standard Thermostat	1314
Setback Thermostat	1087

As expected, a programmable thermostat in every thermal zone would allow a reduction of 17% in the annual space heating demands, if properly used. Nonetheless, by implementing this solution, the complexity of the system would increase, as well as the heating loads, which need to be counterbalanced. This reduction on the annual heating demands, although it is significant, will become less noticeable once it is converted to electric demands. On the other hand, by using a setback thermostat, because the heating loads would increase, more sophisticated and, therefore, expensive equipment would need to be installed.

4.1.1.2 Space heating loads

By comparing the heating loads obtained when using either one these solutions, it becomes possible to decide which strategy would be more feasible for the project in hands. Once more, this analysis will be done using the data obtained in the first case as reference.

Implementing setback thermostats, brings as benefit an annual reduction in the total heating demands, but because there is a higher temperature difference between when the building is occupied to when it is not, the heating loads will increase considerably, as can be seen in Figure 32:

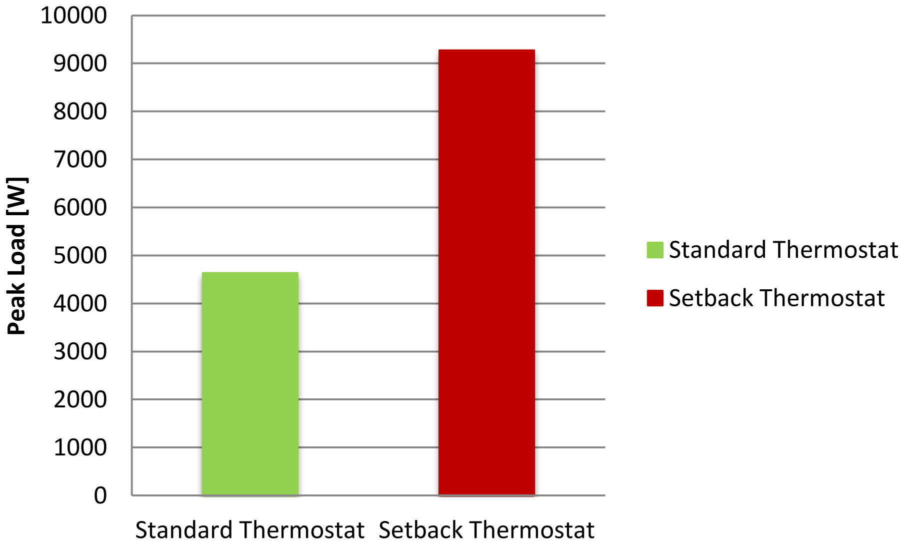

Figure 26- Comparison between the heating loads using different thermostats for Case 1

With the installation of programmable thermostats, one would be reducing the annual heating demands in 17%, while drastically increasing the heating loads due to space heating for this house from 4.6kW to 9.3kW. The consequences of this sudden increase in the temperature difference inside each zone reflect on the size of the equipment that is needed to overcome these loads. Equipment this size would be impracticable to use in this project, and since the increase in the total space heating demands is not as significant as the one in the loads, a standard thermostat was the solution chosen to be implemented in every thermal zone.

After establishing this comparison and selecting the continuous thermostat as the technology to be used, it is then possible to determine the heating loads in the Winter Design

Day. The Winter Design Day is when the maximum heating load is verified, without taking into account the influence of solar or internal gains, therefore being majorly influenced by the building envelope. In this simulation, that day would be the 14th of January.

In order to satisfy all the different case scenarios, the installed system has to be dimensioned for critical case, which corresponds to the third case, where the minimum comfort temperature is set to 21°C. The obtained loads can be seen in the following figure:

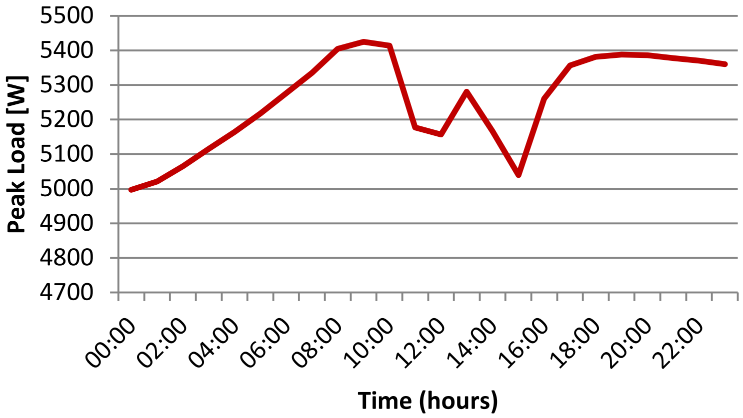

Figure 27 - Winter Design Day space heating loads for Case 3

In this case, the space heating load is 5.4kW and occurs at 9:00h. Because the heating loads are mostly due to heat loss through the building envelope, they increase during the night period, when the outside temperature is cooler and decrease during the day, when it gets warmer. Because of its high insulation, the building is shielded from the outdoor temperature variations and therefore the amplitude in the daily peak loads is not very accentuated.

In comparison with the heating loads obtained for the first case scenario, in the second and third case, as expected, they are significantly higher, as the requirements are more restrictive. While the space heating loads totalize 5.4kW in the last two cases, this value drops to 4.6kW in the first.

The space heating loads have been determined for every thermal zone, as they will be needed to dimension the underfloor heating system. Together with the hot water peak loads, they will set the standard for the size of the HVAC system, which will be subsequently approached in this thesis.

4.1.1.3 Internal gain influence

When it comes to highly insulated buildings like the “Zero Bills Home”, internal gains play a crucial role in the heating demands of a building. Since the heat loss to the exterior is minimized, every internal source of heat will remain inside the building, thus increasing the temperature of each thermal zone. Once more, the first case will be used as an explanatory example of the influence that each internal gain has in this. On the following figure, it is possible to see the relative share that each internal gain has on its total.

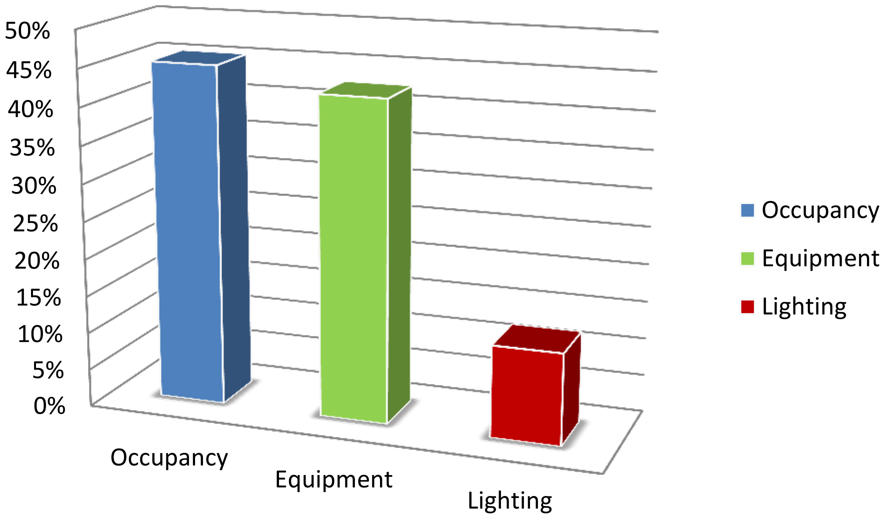

Figure 28 - Internal gains share for Case 1

The internal gains that are generally considered in the thermal analysis of a building are given by the people who occupy the house, by the equipment and lighting used. They play an important role in the heating demands of a building and when compared to an unoccupied house, they have a relative heating contribution of 45% for the occupancy, 43% for the equipment and 12% for the illumination. This simulation shows that if the house was unoccupied, the minimum indoor temperature would be around 4°C, but by combining all the internal gains in a normal occupancy profile, it would increase to 11°C. Simply by adding the lighting it could go up by 1°C, with the equipment up by 3° and with the occupants it could increase as much as 4°C, if the building would remain enclosed.

4.1.1.4 Ventilation influence

In traditional residential houses in the United Kingdom, ventilation systems are frequently not considered due to the added complexity and financial costs. In order to maintain indoor air quality, occupants would often open the windows, thus allowing “fresh” outside air to enter the building. Even though this is a very common and widely used solution, it should not be considered in airtight buildings. In this type of buildings the goal is to minimize heat loss to the outside, and reducing as much as possible the amount of air exchanged seems to be the logical step. Therefore, an airtight building should remain enclosed and windows should not be opened, thus avoiding uncontrolled heat exchanges with the outside.

In order to guarantee indoor air quality in airtight buildings the implementation of a ventilation system is fundamental. The ventilation system will allow outdoor treated air to enter the building replacing the contaminated inside air. Obviously, with this this kind of solution, heat will be exchanged with the outside, but it is possible to minimize it with the use of heat recovery technologies. Most new airtight constructions, such as the PassivHaus, have highly efficient heat recovery units installed, which allow the warm exhausted air to exchange heat with the cool outside air. With this solution, the temperature of the air that is being supplied to the thermal zones will then be closer to the comfort temperature needed, thus reducing the thermal demands added by the implementation of the ventilation system.

In this project, the ventilation system was designed to ensure occupant indoor air quality, by supplying the minimum air required in accordance to the Building Regulations Part F, as previously shown in Tables 26 and 27. A comparative study, for the first case scenario, was made to understand the influence that the ventilation system and the heat recovery unit would have in the annual heating demands of the modelled building, as can be seen in the following figure:

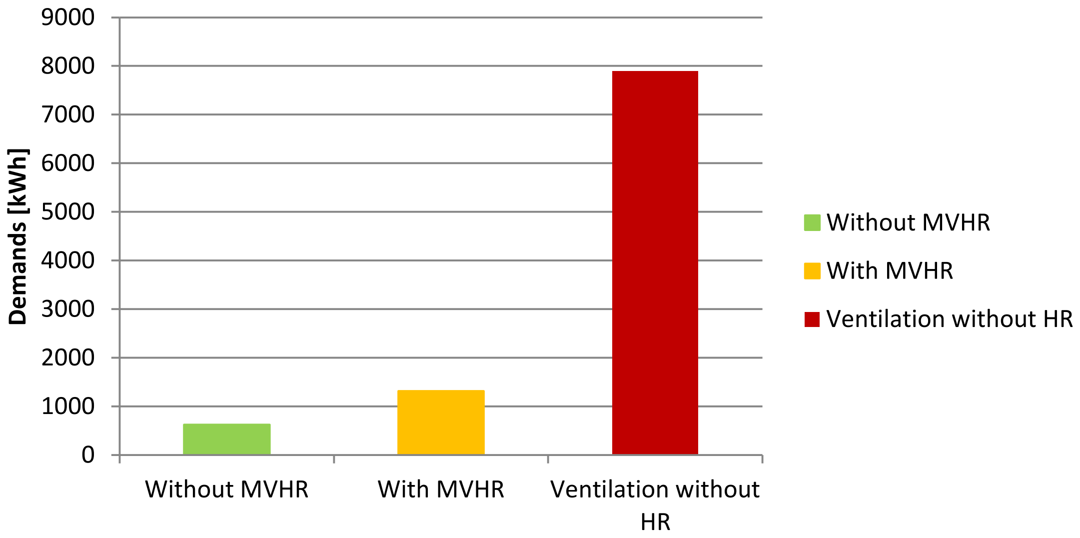

Figure 29 - Ventilation influence for Case 1

When comparing the model with and without the MVHR system, if the building would remain enclosed, the implementation of this system would double the annual space heating demands, which would increase from 624 kWh to 1314 kWh, since air would be exchanged with the outside. Obviously, in order to ensure indoor air quality, fresh air needs to be supplied to the building; therefore it would not be feasible to overlook the ventilation system. However there is a tremendous difference in the thermal demands of a building when using a heat recovery unit. An efficient heat recovery unit would reduce the total heating demands in over 6.5 MWh during the year, thus being a key technology used in low-energy buildings.

The ventilation system, including the heat recovery unit, will be explained in detail in chapter 4.1.4.

4.1.2 Hot water demands

In a highly insulated house such as the “Zero Bills Home”, where space heating demands are minimized, hot water demands play a leading role in the total heating demands of the building. As such, it is fundamental that new buildings are equipped with hot water saving strategies. In the “Zero Bills Home”, different technologies are used for this purpose, such as aerated shower heads, low flow taps and shower heat recovery units, as explained previously in chapter 1.3.

In order to determine the hot water usage in a residential building, some assumptions had to be made, which were based in statistical documents produced by the BRE [49] as can be seen in the subsequent table:

Table 30 - Hot water usage assumptions

	Total Water Usage per cycle (L)	Hot/Total Water Ratio	Hot Water Usage per cycle (L)
Bath	100	0.65	65
Shower	48	0.65	31
Hand and Face Washing	-	-	5
Dishwasher	-	-	Cold Feed
Washing Machine	-	-	Cold Feed

While traditional shower heads deliver a flow rate of 10 litres per minute, an aerated shower can reduce this value up to 50%. For the scope of this work, a flow rate of 6 litres per minute was considered. Since the average shower in the U.K. takes about 8 minutes, it was considered, that using this solution, occupants would be spending 48 litres of water per shower. This corresponds to 31 litres of hot water, assuming that in showers a mixture of 65% hot water with 35% cold water is used. Merging both showers and baths into a single category, allows an easy determination of the water usage for bathing. Assuming that during one year, 95% of bathing is done in showers while 5% is in baths, the total water used for this purpose corresponds to 33 litres per person per day. Modern washing machines as well as dishwashers come with a built-in heater, and therefore use cold water as an input, which is subsequently heated.

Combining all these different consumptions and considering the usage of hot water saving technologies, for the first and second cases, the total hot water usage was considered to be 40 litres per person per day. As for the third case scenario, it was considered that the hot water usage would be 25% superior, thus totalling in 50 litres per person per day.

Subsequent to determining the daily water usage per person, it was then possible to calculate the annual hot water demands, for both scenarios. Using the first case as an illustrative example:

$$Q = \rho \cdot cp \cdot \dot{V} \cdot n \cdot \Delta T$$

where:

the water volumetric mass, ρ =1000 kg/m^3

the specific heat coefficient of water, c = 4.1855 kJ/kg.K

the daily water consumption per person, $\dot{V}$ = 40 l/person/day

the number of days in a year, n = 365.25

and the temperature difference between the inlet water temperature and the temperature in the tank, ΔT = 36.7°C. According to a governmental document produced by the Energy Saving Trust [50], the average inlet temperature in the United Kingdom is 16.2°C and the tank temperature is 52.9°C.

Therefore, for the first case, the annual hot water demand per person (Q) would be 623 kWh and assuming a safety coefficient of 20% due to heat loss, this value would increase to 748 kWh. Considering five occupants in this building, the total annual hot water demands would be 3740kWh. As for the third case scenario, since the main difference lays on the added 25% on the daily water consumption, the hot water demands would be 4675kWh, as can be seen in the following figure:

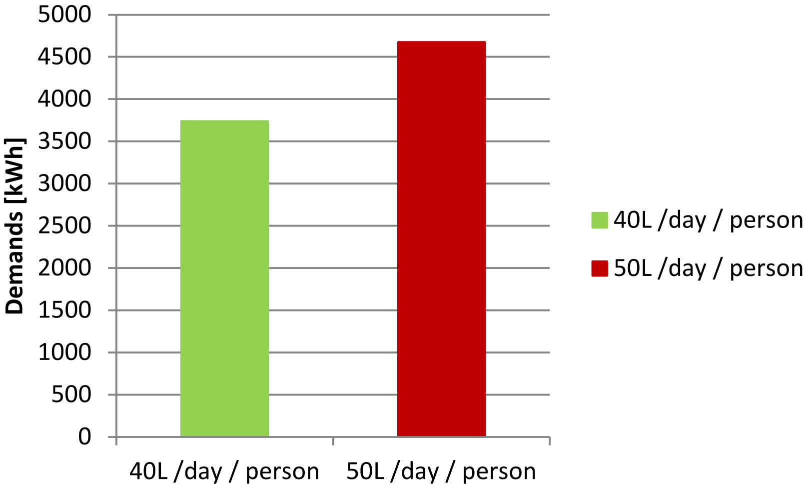

Figure 30 - Annual hot water demand comparison between cases 1 and 3

Both the hot water and the space heating demands will set the standard for the equipment needed to overcome the total heating requirements. In order to dimension the HVAC system, one must firstly determine the total heating loads.

4.1.2.1 Hot water heating loads

In a building, such as the "Zero Bills Home", where hot water demands overcome the total space heating demands, it is crucial to determine the heating loads for this first case. These loads are given by the total power needed to heat the water tank during a certain period of time, thus guaranteeing enough hot water to satisfy occupants' needs.

This house type will have installed a 300 litre water cylinder, which is fully heated during the night period in order to assure enough hot water to the occupants during daytime. For the purpose of this work, a six hour heating period, starting at midnight, was considered. This will account for a reduced load, while still supplying the necessary daily hot water requirements.

Knowing the total volume of the tank and the time that is needed to heat it, it is then possible to determine the volumetric flow rate, and subsequently the mass flow rate, which will be necessary to calculate the hot water heating loads. This is given by:

$$\dot{V} = \frac{V}{t} = \frac{300\ [l]}{6\ [h]} = 1.39 \cdot 10^{-5}\ [m^3/s]$$

$$\dot{m} = \dot{V} \cdot \rho = 1.39 \cdot 10^{-5}\ [m^3/s]\ \cdot 1000\ [kg/m^3] = 0.0139\ [kg/s]$$

As previously referred, the temperature difference between the water leaving and entering the tank is 36.7°C. Therefore, the total hot water heating loads will be given by the power needed to heat a 300 litre water tank in 36.7°C in six hours, thus totalling in:

$$\dot{Q} = \dot{m} \cdot cp \cdot \Delta T = 0.0139\ [kg/s]\ \cdot 4.1855\ [kJ/kg \cdot K] \cdot 36.7\ [°C] = 2.1\ kW$$

The hot water heating loads will remain the same for the three different case scenarios, as in all of them, the same tank was considered as it has enough capacity to cover the occupants' hot water needs. Together with the space heating loads previously obtained, it is now possible to dimension the equipment needed for the HVAC system used in this model of the "Zero Bills Home", as can be seen in the following table:

Table 31 – Heating loads for the different case scenarios

	Case 1	**Case 3**
Space heating loads [kW]	4.6	5.4
Hot water heating loads [kW]	2.1	2.1
Total heating loads [kW]	**6.7**	**7.5**

As expected, the total heating loads in the third case are higher than in the first one, as the desired conditions are more restrictive. In order to guarantee that the building is prepared to overcome the behaviour of different users, the chosen equipment has to be dimensioned for the worst case scenario. The detailed HVAC system used will be explained in detail in chapter 4.1.4.

4.1.3 Energy analysis

4.1.3.1 Energy demands

In grid connected systems, the power used to operate domestic appliances and to provide energy for lighting and heating processes is provided by the electric power industry. In order to achieve a balance between the consumed and produced electricity, it is necessary that the same energy source is being considered. In the scope of this work, annual electric demands will be compared with the photovoltaic electrical production for the different case scenarios. The energy demands for this building can be divided into two main categories: thermal demands and general electrical demands.

Thermal demands account for the energy required to overcome both hot water and space heating demands, thus ensuring occupants' thermal comfort. As previously shown in chapter 4.1.2, the hot water demands were determined considering a daily usage of 40 litres per occupant for the first and second case, and 50 litres in Case 3, resulting in a total annual thermal demand of 3740kWh and 4675 kWh, respectively. In this regard, a constant monthly average was considered throughout the year. As for space heating demands, they were determined in TRNSYS, assuming a continuous thermostat, for the first case scenario with a minimum comfort temperature of 18°C and 21°C for the remaining cases. The results obtained can be found in chapter 4.1.1.

Combining both hot water and space heating demands, it is then possible to determine the total heating demands for each case, as can be seen in the following figure:

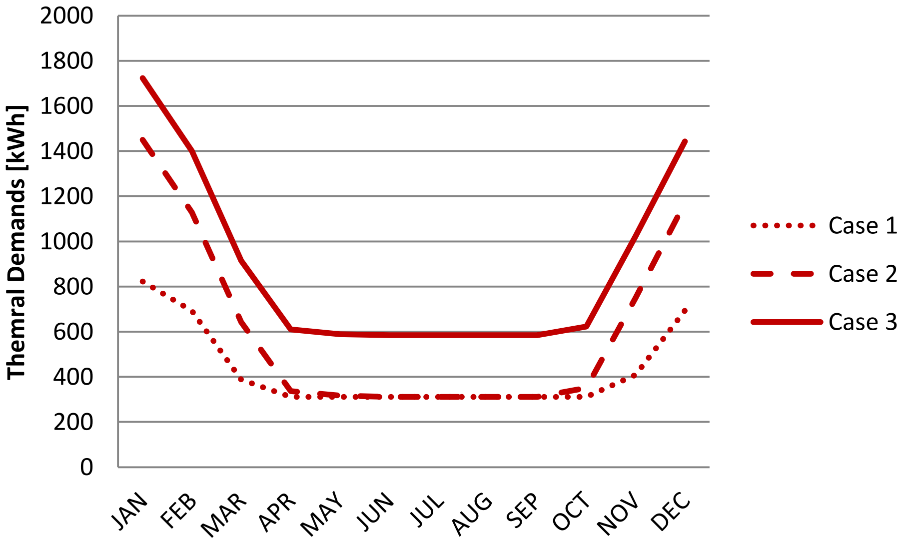

Figure 31 - Heating demands for the different case scenarios

As expected, the third case scenario shows increased heating demands every month, when compared with the other scenarios. From April to October, in all the three cases, the heating demands tend to remain constant, which shows that during this period there is almost no need to provide space heating . Since for the first and second case, a hot water usage of 40 litres per person per day was considered, during these months, the total demands are approximately the same.

As previously stated in chapter 3.4.1, the general electric energy consumption was assumed, for the first and second case, to be equivalent to the BedZED monitored demands, thus totalling an annual value of 23 kWh/m^2 [51]. As for the third case scenario, a 25% increase in the general electric energy consumption was considered in order to characterize an excessive occupant behaviour, resulting in 28 kWh/m^2/year. The “Zero Bills Home” AX4 model has an internal gross floor area of 120 m^2, as previously shown in Table 3. This means that in the first two cases, the general electric energy consumption would correspond to 2760 kWh, while in Case 3 it would amount to 3360 kWh.

In order to determine the total energy demand of the building, it is necessary to transform the thermal energy into electrical demands. Because a heat pump will be used to overcome the total heating loads, it is crucial to know the coefficient of performance (COP) of that unit for the heating season. In this project, an air source heat pump with a COP of 4.1 was used (more details about this unit can be found in chapter 4.1.4.3). Therefore, by dividing the thermal demands by the heat pump's COP and adding the general electric demands, it is then possible to determine the total energy consumption of this building for the three different case scenarios, as can be seen in the next figure:

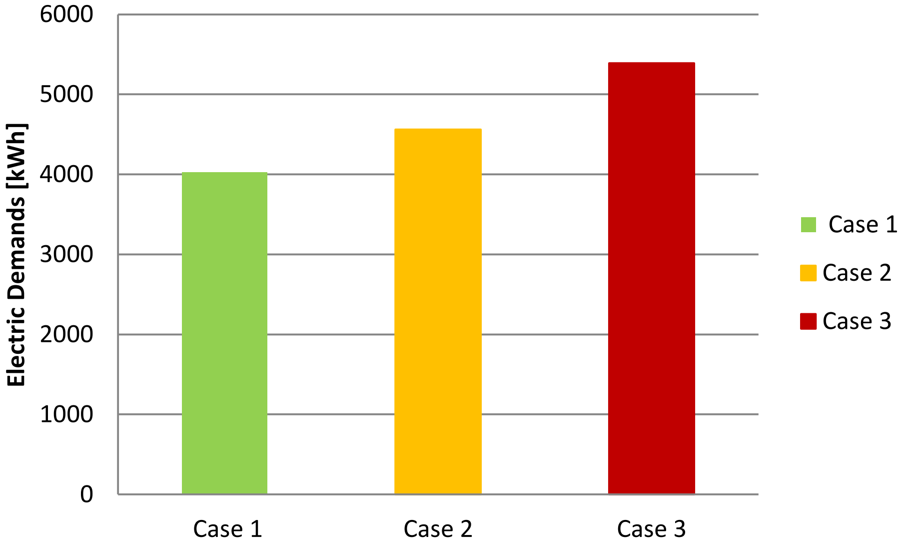

Figure 32 - Annual electric demands for the different case scenarios

The annual electrical consumption per sector, for the different scenarios, is shown in the following table and Figure 39 represents a graphical overview of the share that each one of them embodies.

Table 32- Annual electric consumption per sector for the different case scenarios

	Case 1	**Case 2**	**Case 3**
General electric energy demands [kWh]	2760	2760	3360
Hot water demands [kWh]	912	912	1140
Space heating demands [kWh]	353	890	890
Total electric consumption [kWh]	**4025**	**4562**	**5390**

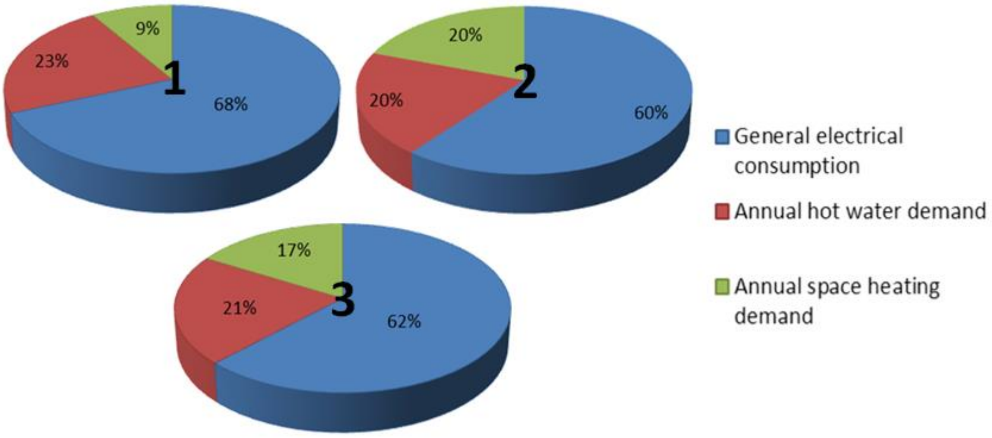

Figure 33- Share in annual electric demands for the different case scenarios

It is clear that plug loads contribute greatly to the total electric demands of this building, representing a share of over 60%. The sovereignty of the general electric demands is also due to the fact that a more efficient heat pump unit is used to overcome the heating demands, thus reducing the total electrical energy needed and minimizing its share in the annual electric demands. Typical heating COP values for domestic heat pumps range between 2 and 3. As anticipated, in a highly insulated building where the annual space heating demands are reduced, hot water demands will represent a greater share in the global energy consumption.

4.1.3.2 PV production

In the “Zero Bills Home”, the ZEDroof is responsible for the electric energy generation of the building and the purpose of this 7.5kWp photovoltaic system is to overcome the annual electrical consumption. It consists of a 30 panel array, where each unit has a peak power output of 250W. A dynamic simulation of this system was developed in TRNSYS in order to determine the energy produced throughout the year and to verify if it would be possible to produce more electricity than the amount consumed, thus guaranteeing an annual energy surplus. Because this system is always connected to the grid, it imports external electricity when it needs, uses its own produced electric energy when it can, and when available, exports the electrical surplus to the grid.

The model developed in TRNSYS, as explained previously in chapter 3.4.2, takes into consideration all the characteristics and parameters of the photovoltaic system, as well as the inverter used to convert the variable direct current (DC) into the alternating current (AC) which delivers the electric power to the building with an efficiency of 97%. By combining these two central units together with the specific weather data, it is possible to determine the total electric energy produced throughout the year for each location. In order to guarantee a more realistic approach of this model, it is fundamental to understand how the solar energy production can be influenced beyond TRNSYS' inputs. Besides inverter losses, which in this case account for 3%, one should similarly include cables and wiring losses, as well as account for a decline in production caused by accumulating dust on the photovoltaic panel surface. For the scope of this work, these additional losses to the developed photovoltaic system were considered to be 14%, in accordance to the reference value used in the Photovoltaic Geographical Information System (PVGIS) tool.

PVGIS is an online solar photovoltaic energy calculating tool developed by the Joint Research Centre's Institute for Energy and Transport (IET) from the European Comission's in-house science services. It is a part of the SOLAREC action which contributes to the implementation of renewable energy in the European Union as a sustainable and long-term energy supply. The modelling accuracy of the PVGIS values in the database was evaluated against the input meteorological data used in the computation. Comparing the yearly averages of the daily global horizontal irradiation, the mean bias error was 0.3% and the root mean square error obtained was 3.7%, thus making this a very reliable tool [62].

The following figure shows the monthly energy produced as modelled in TRNSYS, which accounts for inverter losses and subsequently the electric energy produced including a total 14% loss. In this model, the annual electric energy production would be approximately 7.6 MW per year, whereas by including the remaining losses, a total of 6.8 MW per year can be produced, thus providing a more realistic approach to the developed dynamic model.

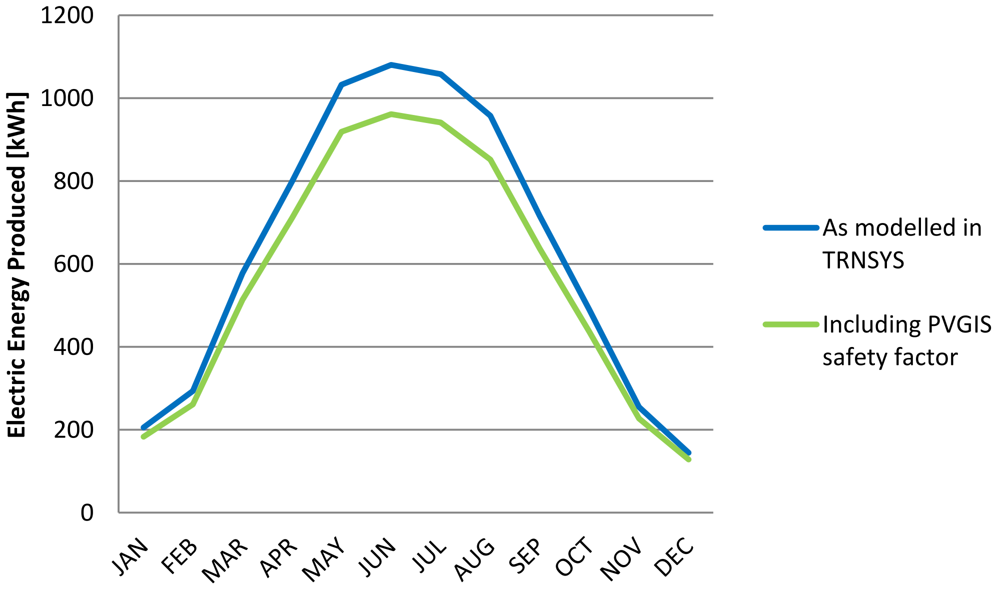

Figure 34 - Photovoltaic electrical production scenarios

In order to certify the "Zero Bills Home" concept, it is vital to determine if during the course of one year, the photovoltaic energy production can overcome the total electrical consumption. By ensuring this for the worst case scenario (Case 3), the remaining cases will be inevitably guaranteed as well. A comparative analysis between the energy demands for this case, which are referenced in the previous subchapter, and the annual production can be seen in the following figure and in Table 35.

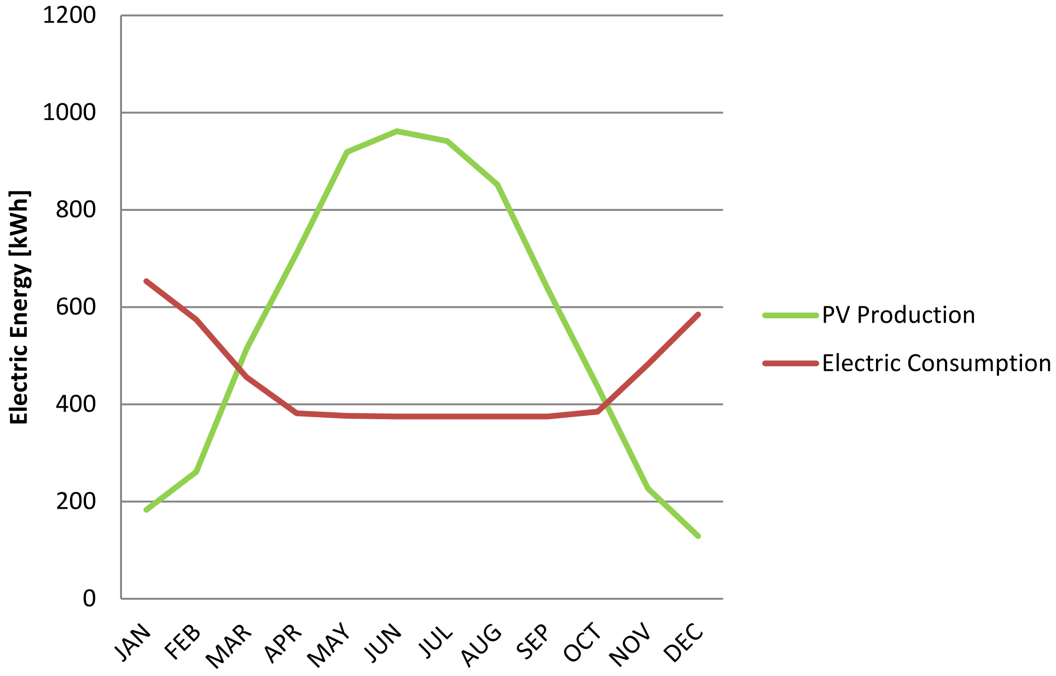

Figure 35 - Monthly electric energy production vs. consumption for Case 3

Table 33- Monthly electric energy balance for Case 3

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Production [kWh]	183	261	514	711	919	961	941	852	637	436	227	128	6769
Consumption [kWh]	653	574	456	381	376	375	375	375	375	384	482	584	5390
Surplus [kWh]	**-470**	**-313**	**58**	**330**	**543**	**586**	**566**	**477**	**262**	**51**	**-255**	**-456**	**1379**

By analysing the figure above, it is clear that this building is not always able to overcome its energy needs, mainly during the winter season. This is due to the fact that in these months, additional space heating demands are required in order to maintain occupants' thermal comfort which cannot be counterbalanced by the small amount of solar energy produced. On the contrary, between the months of March and October, the increasing monthly electric energy produced combined with the decreasing energy consumption, allows the building to have an energy surplus, which can be sold to the national grid. Only during the winter period, from November to January, the “Zero Bills Home” is not able to overcome its needs. But this does not account for a problem, as the system is directly connected to the grid, it can import the remaining energy to cover its needs. In total, there is a four month negative and an eight month positive balance, which sums up to an annual electric surplus of approximately 1.4 MWh. This shows that even for the worst case scenario, the “Zero Bills Home” delivers a residential building which during the course of the year produces more energy than it consumes, thus raising up to the challenge.

4.1.4 HVAC system

After determining the energy requirements of the studied building, it is necessary to develop a solution for the HVAC system and dimension its components, in order to guarantee the thermal comfort of the occupants.

In the scope of this project, the chosen system combines an MVHR unit and an air-source heat pump with a hot-water cylinder, which enables the system to deliver large quantities of domestic hot water at the same time as efficiently performing whole house heat recovery and ventilation. In addition, for the purpose of space heating, hot water is provided for towel rails and underfloor heating, which are responsible for overcoming the thermal loads of this building during the winter period. In order to maintain indoor air quality, a centralized ventilation system is implemented to supply the minimum fresh air requirements to the selected thermal zone and subsequently extract the contaminated air. As previously stated, during the summer, passive strategies will be used, as it was not intended to develop any mechanical solution for this period. In order to do so, passive cooling strategies, such as cross-ventilation, night flush and free-cooling by setting the MVHR unit in bypass mode, thus diverting incoming air away from the heat exchanger to prevent warm outside air being further heated, will be used.

In the following subchapters, the selected equipment will be explained in detail, as well as the calculations behind the dimensioning of these units. All the considerations and data used were based on the results obtained from the analysis of Case 3. As this is the worst case scenario, if the selected equipment guarantees a proper functioning for this case, it will perform in every other situation.

4.1.4.1 Underfloor heating

In the “Zero Bills Home”, in order to meet the space heating requirements, underfloor heating was the solution chosen. It consists of a piping system enclosed in a screed cement layer spread throughout the different thermal zones. These pipes circulate hot water, at a relatively low temperature when compared with other heating systems, which is produced by the air source heat pump. Unlike typical radiators where the mean temperature of the circulated water is about 80°C, in underfloor heating systems it is common that the water leaves the tank at a temperature range between 35° and 45°C. According to the European norm EN 1264-3, the maximum temperature for the water leaving the tank is 45°C and the maximum difference between the inlet and return temperature in the circuit is 5°C. In addition, the mean pavement temperature should not be higher than 29°C, with the exception of bathrooms where it can increase slightly. Because underfloor heating systems heat the whole floor area, and since warmer air tends to rise due to its lower volumetric mass, these systems allow for a uniform temperature distribution in each thermal zone, thus increasing occupants’ thermal comfort. These systems are also very practical since they allow a total freedom in room design and if correctly installed, practically no maintenance is needed, as there are no moving parts.

As in most underfloor heating systems, the pipes where water is circulated are made of cross-linked polyethylene (PEX) and they are spaced between centres with a 10cm distance. By having a smaller distance between the pipes, it is possible to obtain a higher output and this spacing could be slightly smaller next to the walls, where the heat loss occurs, and slightly bigger in the centre of each room. A constant 10cm distance was considered, together with a 2mm thickness, an external diameter of 16mm, and a pipe wall conductivity of 0.51 W/m·K.

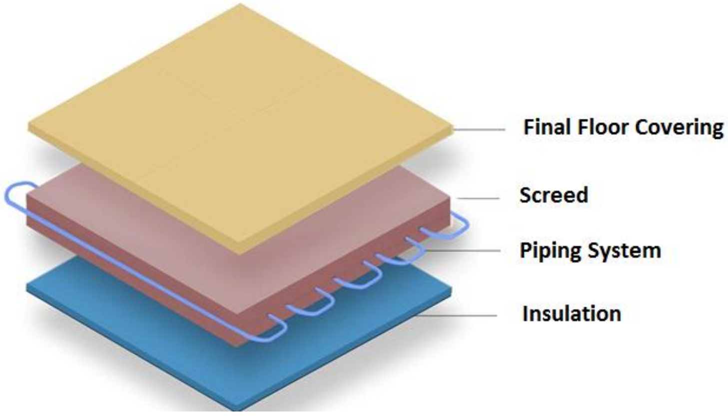

Figure 36 - Underfloor heating layer layout [63]

The purpose of the underfloor heating is to provide enough heat to each thermal zone in order guarantee that the inside temperature never drops below a selected temperature, thus ensuring occupants' thermal comfort. In the third case scenario, a minimum temperature of 21°C was considered and the heating loads for the winter design day were determined in TRNSYS and can be seen in Table 34. To properly design an underfloor heating system, it is necessary to determine the maximum heat output per area, which will define the water temperature leaving the tank. To do so, in rooms where there is permanent furniture, such as bathtubs, stairs, etc., one must subtract these areas to the total floor area, as the piping system should not be installed beneath them. Taking this factor into account it is then possible to calculate the output needed in each heated thermal zone. These values can be found in the next table:

Table 34 - Heat output needed per zone for Case 3

Zone	Heating Load [W]	Gross Area [m^2]	Output needed [W/m^2]
Living room	795	16.1	49
Hall 0	262	4.15	63
WC	115	2.71	42
Kitchen/Dining room	680	16.28	42
Bedroom 1	935	17.51	53
Bathroom	174	3.4	51
Hall 1	252	4.51	56
Bedroom 2	399	7.53	53
Bedroom 3	563	8.5	66
Master bedroom	595	11.44	52
Ensuite bathroom	264	2.54	104

In addition to the underfloor heating system, heated towel rails can provide a different heating source for the bathrooms. Therefore, the maximum heat output needed from the underfloor heating system is 66 W/m^2 and it occurs in Bedroom 3. This is a very standard maximum output which can easily be obtained with typical installations. It is important to understand that different materials used as floor finishes provide different outputs. In this building, all the ground floor and the bathrooms are covered in tile whereas the remaining divisions have a wood floor. Since ceramic tiles have a higher thermal conductivity then wood, for the same inlet water temperature, increased outputs can be obtained by using the first material as a floor covering. However, wood is used as the floor finish in Bedroom 3, and 66 W/m^2 is the output that the system as to be designed to overcome.

In accordance with the European norm 1264, it is possible to determine the heat output of an underfloor heating system by knowing the logarithmic temperature difference, ΔTh, which can be calculated with the following equation:

$$\Delta Th = \frac{T_i - T_r}{\ln\left(\frac{T_i - T_{amb}}{T_r - T_{amb}}\right)}$$

Where:

T_i is the temperature of the water leaving the tank

T_r is the temperature of the water returning to the tank

T_{amb} is the interior room temperature

By firstly determining the logarithmic temperature difference with the heat output, it is then possible to calculate the temperature at which water needs to leave the tank. This can be done resorting to the following graphic, which was developed by underfloor heating manufacturers [64], using the previously mentioned norm as reference. This simplified graphic shows the correspondence between the heat output and the logarithmic temperature difference for different pipe spacing for a wooden floor.

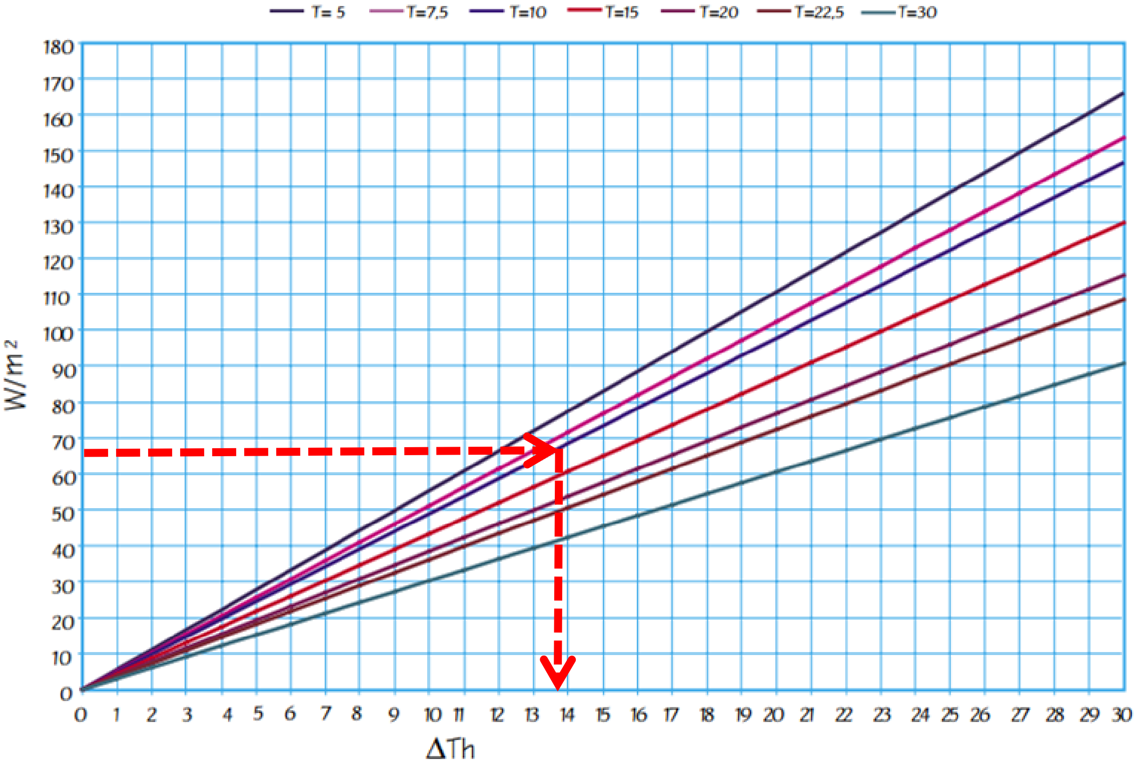

Figure 37 - Underfloor heating heat output vs. logarithmic temperature difference for wooden floor [64]

As shown above, using a piping system in which the pipes are spaced by 10cm, in order to obtain an output of 66 W/m^2 the logarithmic temperature difference should be approximately 13.8°C. Considering a temperature difference between the water leaving the tank and the return temperature of 5°C, in accordance with EN 1264, it is then possible to determine the inlet temperature for the third case scenario, where the indoor temperature is 21°C.

$$13.8 = \frac{5}{\ln\left(\frac{T_i - 21}{T_i - 5 - 21}\right)} \therefore T_i = 37.5°C$$

In order to ensure a 66 W/m^2 for a wooden floor, hot water would have to leave the tank at 37.5°C and return at 32.5°C.With these conditions, the remaining thermal zones are also safeguarded and can be individually controlled with the use of flow regulating and thermostatic blending valves. A sketch of the piping distribution of the underfloor heating system can be found in the attached CAD drawings in Annex G.

4.1.4.2 Mechanical ventilation heat recovery unit

An efficient centralized MVHR unit is the core of any low-energy building’s heat recovery ventilation system, because it allows for energy conservation in buildings by recovering heat from the extracted air and transferring it to the incoming fresh air. This system is used to ensure indoor air quality, whilst maintaining a balance between air supply and extraction and minimising indoor heat loss. These are the main reasons why this system is widely implemented in low-energy buildings. However, their use is only justified in terms of energy conservation in airtight buildings, where the amount of uncontrolled air exchanged with the outside is minimized.

The performance of a low-energy building is widely dependent of the heat recovery efficiency of the MVHR unit installed. The PassivHaus standard states that only units with a minimum efficiency of 75% can be specified [20], but at the moment the heat recovery efficiency of MVHR units available in the market for this type of buildings can go up to 95%.

For the scope of this work, a mechanical ventilation heat recovery unit with 90% efficiency was considered, using as basis a BRE certified and SAP Appendix Q eligible unit, which specifications can be found attached to this document in Annex H. SAP is the British Government's Standard Assessment Procedure for Energy Rating of Dwellings and is used as part of the methodology for calculation of the energy performance of buildings in the UK.

The HRU ECO 4 is a high efficiency heat recovery unit, which has a sophisticated counter-flow heat exchanger. In this heat exchanger, the incoming and outgoing air is moving via triangular canals, where each of them is surrounded by canals in which air flows in the opposite direction. This creates an enormous surface area to exchange heat and it is one of the reasons why it is possible to obtain a thermal efficiency of over 90%, as can be checked in the technical description attached to this document in Annex H. Besides the normal operation mode, this unit also allows different solutions for the summer and winter seasons, such as summer bypass mode and the frost protection mode, as can be seen in the following figure:

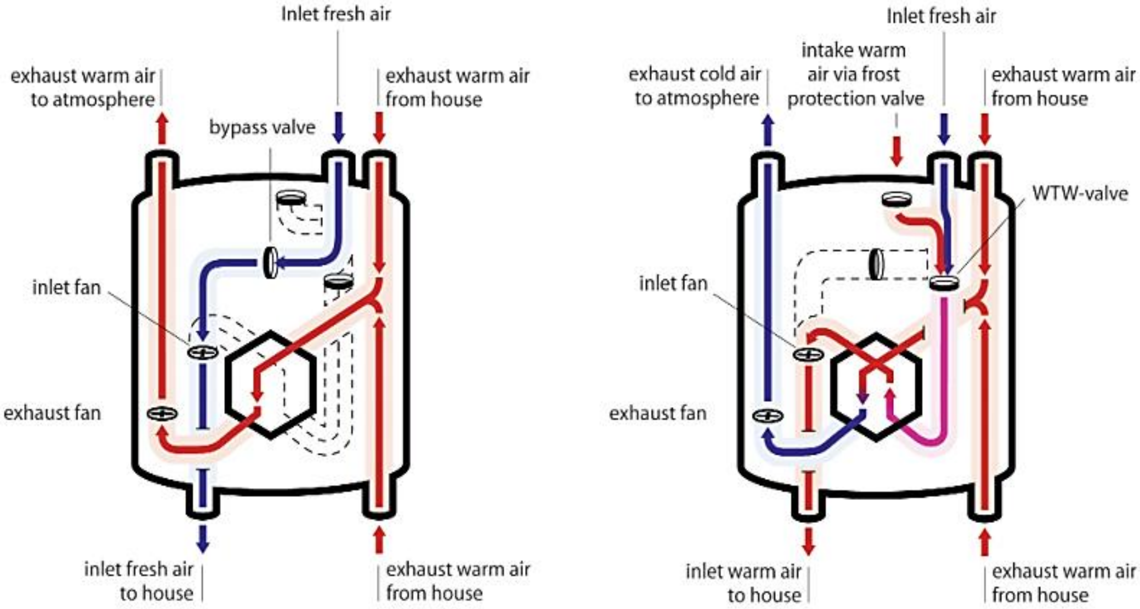

Figure 38 - HRU ECO 4 additional operative modes: Summer bypass mode (left) and Frost protection mode (right)

For the summer bypass mode, this unit has an integrated bypass valve which diverts the air supply around the heat exchanger, therefore not allowing the extracted air to heat the incoming fresh air. There is also a fully automatic temperature controller that makes sure the valve is opened in the desired situation, especially when the inside temperature is higher than both the maximum comfort temperature and the outside temperature, and also during summer nights, in order to cool the building.

On the other hand, the frost protection mode prevents the heat exchanger from freezing, by resorting to an integrated valve in the upper part of the system. When this valve opens, it extracts warm air from the area where it is installed and mixes it with the inlet fresh air, which will allows warmer outside air to enter the heat exchanger.

In order to model the effect of the MVHR system in TRNSYS, as shown in chapter 3.4.3, it was necessary to implement an equation which accounts for the efficiency of this system in heating the outside air entering the building. The efficiency of the heat exchanger is given by the following equation:

$$\varepsilon = \frac{T_s - T_o}{T_e - T_o}$$

Where

ε – heat exchanger efficiency

T_s – supply air temperature after heat recovery

T_o – outside air temperature

T_e – exhaust air temperature before heat recovery unit

An illustrative example for the third case scenario was made to show how important this unit is in regards of energy conservation and minimizing heat loss. In this case, the exhaust air temperature would be 21°C, as this is the minimum comfort temperature considered. For a cold winter day where the outside temperature would be 0°C, with an efficiency of 90%, the supplied air temperature after heat recovery would be 18.9°C. With this remarkable increase it is possible to ensure the minimum fresh air requirements of the occupants, without seriously compromising energy demands.

4.1.4.3 Air source heat pump

In the "Zero Bills Home", the purpose of the air source heat pump is to cover all the domestic heating demands, from space heating to domestic hot water. The ASHP absorbs heat from the outside air and releases it inside the building, in order to overcome the heating demands.

As shown in Table 33, when combining the total space heating and domestic hot water heating loads, for the worst case scenario a total of 7.5 kW is obtained. Because in this project it is not intended to resort to any auxiliary systems, such as induction heaters, the nominal capacity of the air source heat pump needs to be higher than this value. It was then decided to install an 8 kW heat pump. In addition to the nominal capacity, the coefficient of performance of the heat pump is an important parameter, as it will determine the ratio between the output and input energy. According to the manufacturer's catalogue, as shown in Annex I, the selected heat pump has a COP of 4.1 for the heating season and an Energy

Efficiency Ratio, EER, of 3 for the cooling season. For the purpose of this work this last parameter is not important, as the cooling loads were not intended to be analysed.

The Monobloc system combines all the main hydraulic components in a single outdoor unit, which provides a practical solution for buildings where there are space constraints, without significantly increasing the outside unit. The dimensions of the air source heat pump used in this model of the "Zero Bills Home" are shown in the following figure and details on this unit can be found in Annex I.

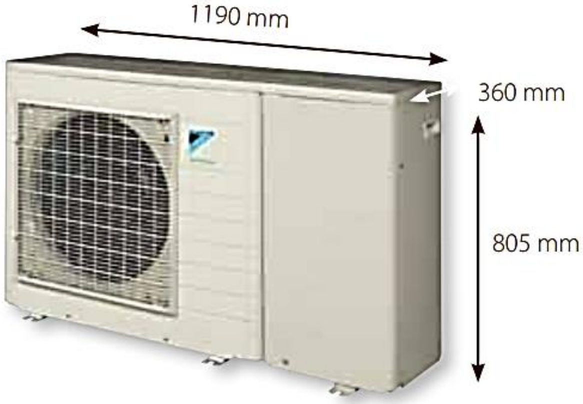

Figure 39 - 8kW Daikin Altherma Low Temperature Monobloc unit [65]

4.1.4.4 Air supply diffusers

In a centralized ventilation system, the final units used to supply air to the desired thermal zones establish the interface between the HVAC system and the architecture of the interior spaces. The units used for this purpose are typically either grilles or diffusers. It is important to carefully analyse the various options so as to achieve thermal visual comfort of the occupants. In the "Zero Bills Home", it is intended that the air supply to the interior spaces is done by displacement ventilation.

Thermal displacement ventilation is based on cool air supply at low level and stratification of room air temperature and contaminants as a result of the natural buoyancy forces created by the heat sources [66]. The supplied cool air spreads throughout the occupied zone with low velocity, typically between 0.1 m/s and 0.3 m/s. Meanwhile, due to heat exchange with interior heat sources, such as occupants and equipment and in this building, underfloor heating, that air is heated which creates upward convective currents, known as thermal plumes. Because the air is supplied at floor level, the exhaust should be done above the occupied zone, such as at ceiling level. With this strategy, the rising thermal plumes will carry away contaminants towards the exhaust which improves indoor air quality in the occupied zone. Because it is a more efficient system than mixing ventilation, displacement ventilation provides additional energy savings

In this project, it was intended that in order to satisfy the minimum fresh air requirements, air would be supplied to all the bedrooms and living room and extracted from the bathrooms and kitchen, maintaining a balance. In accordance with the Building Regulations the minimum air flow rates were determined and can be seen attached to this document in Annex F. For the supplied zones, the air flow necessary to ensure indoor air quality is as follows:

Table 35- Supplied air flow per zone

Zone	Air flow [m^3/h]
Living Room	78
Bedroom 1	21
Bedroom 2	9
Bedroom 3	10
Master Bedroom	27
TOTAL	**145**

In order to supply this amount of air to each zone, the displacement diffusers had to be selected and sized accordingly. Trox QLF Displacement Flow Diffusers where chosen between the wide variety of displacement ventilation units as they are notable for their flat, space-saving and elegant construction, which has a big impact in residential buildings. The specifications on this unit can be found attached in Annex J.

Figure 40 - Trox QLF Displacement Flow Diffusers [67]

Regarding the speed limits for the supplied, these units were sized considering a recommended air speed of 0.15 m/s, thus ensuring a correct ventilation distribution. These units also guarantee a pressure drop below 3 Pa and a sound power level below 20 dB, which is a crucial parameter in terms of comfort.

Table 36 - Diffusers used in each zone and supplied air speed

Zone	Number of diffusers	Dimensions [m x m]	Air speed [m/s]
Living Room	2	0.4 x 0.2	0.14
Bedroom 1	1	0.3 x 0.15	0.13
Bedroom 2	1	0.2 x 0.1	0.13
Bedroom 3	1	0.2 x 0.1	0.14
Master Bedroom	1	0.3 x 0.2	0.13

In order to ensure thermal comfort, in accordance with ASHRAE, it is necessary to determine the Air Diffusion Performance Index (ADPI) which gives the percentage of points within the occupied zone that are not in thermal comfort. This can be analysed both for the ankle and the neck region, however, since in this building the air is supplied at floor level with a displacement ventilation strategy, it is only necessary to guarantee thermal comfort in the ankle region. To do so, one must first calculate the effective temperature which is given by the following equation:

$$\theta = (T_x - T_e) - 8.0 \cdot (V_x - 0.15)$$

Where:

Θ is the effective temperature,

T_x is the supplied air temperature

T_e is the room temperature

V_x is the supplied air velocity

For the third case scenario developed in this project, the room temperature is 21°C and as previously explained in chapter 4.1.4.2, due to the efficiency of the MVHR unit the supplied air temperature is 18.9°C. Considering a recommended air speed of 0.15 m/s, the effective temperature obtained is:

$$\theta = (18.9 - 21) - 8.0 \cdot (0.15 - 0.15) = -2.1℃$$

By using this parameter as input, together with the supplied air velocity, it is possible to determine the ADPI resorting to the following chart provided by ASHRAE:

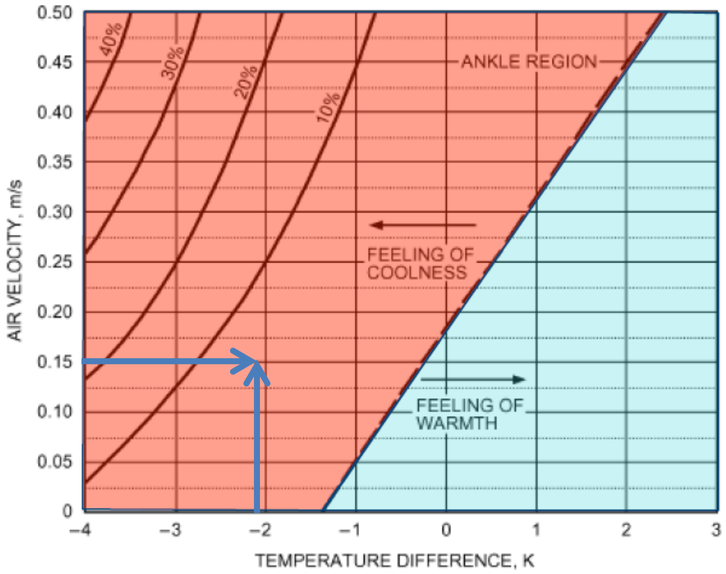

Figure 41- ADPI chart [68]

As shown above, with this system, there is a total of approximately 8% discomfort inside the thermal zone, which is a perfectly reasonable value, as the maximum percentage allowed is 15%.

4.1.4.5 Air exhaust valves

The exhaust valves used in this project were dimensioned according to the minimum air flow that was necessary to extract from the different zones in order to ensure indoor air quality. In the "Zero Bills Home" air is extracted from the kitchen and the remaining wet rooms, and the required air flow is shown in the subsequent table, which can be found with more detail in Annex F:

Table 37 - Extracted air supply per zone

Zone	Qext [m^3/h]
Kitchen / Dining Room	52
WC	31
Bathroom	31
Ensuite Bathroom	31
TOTAL	**145**

For this purpose, Trox LVS adjustable disc valves were chosen to be used in this project since, in addition to their design and adjustability, they represent a cost-effective solution for small rooms where small quantities of air are circulated, and its specifications are shown in Annex K.

Figure 42- Trox LVS disc valves [67]

In order to dimension these valves, it was necessary to guarantee that they could supply enough air to overcome the minimum requirements, considering a maximum air speed of 4 m/s. This was not a problem, since the 125mm unit is able to supply an air flow up to 180 m^3/h, as shown in the following table:

Table 38 - Exhaust valves used in each zone

Zone	Number of valves	Diameter [m]	Air flow up to [m^3/h]
Kitchen / Dining Room	2	0.125	180
WC	1	0.125	180
Bathroom	1	0.125	180
Ensuite Bathroom	1	0.125	180

Additionally, the pressure drop and sound power level of these valves are very low, therefore not compromising occupants' comfort and ventilation efficiency, as can be seen in the following performance chart:

:

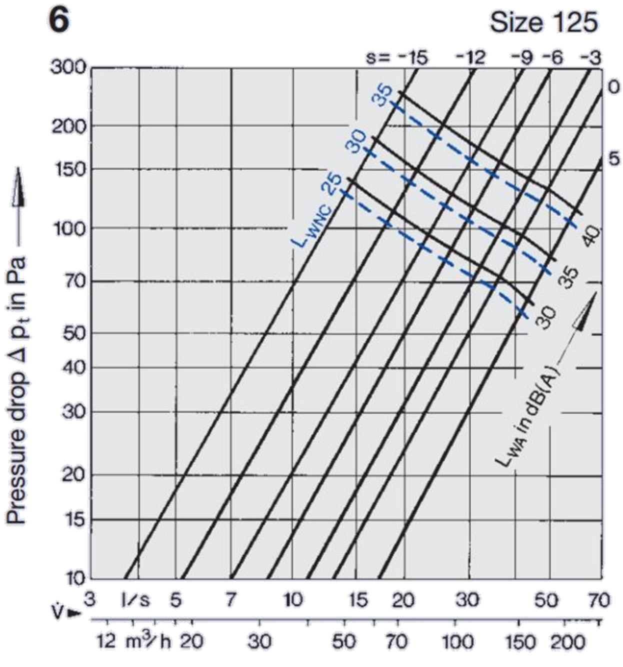

Figure 43 - Trox LVS valves pressure drop and sound power level [69]

4.1.4.6 Ducts

In the “Zero Bills Home” there are two main duct lines which are used to supply and extract air from the building. It is essential to dimension these ducts and each one of the subsequent branches regarding the architecture of the building, but most importantly, the circulated air flow, and the air speed. It is crucial that this air speed is regulated according to the ducts’ proximity to the occupied zones, in order to avoid excessive noise and pressure drop. In the scope of this project, because all the ducts are enclosed in the interior of the building, a maximum air speed of 2.5 m/s was considered. Circular ducts were chosen to be implemented in this house, since when compared with rectangular ducts, they account for lower pressure drop and installation costs. Subsequently, a CAD sketch of the air distribution system was made, which can be seen attached to this document in Annex G.

Once the distribution inside the building was finished, the ducts used for both supply and exhaust had to be dimensioned while ensuring circulated air speeds lower than 2.5 m/s. The duct sizes for both situations can be found in the Annex L and Annex M. The following step was to calculate the pressure drop for the critical branch of both the exhaust and supply duct lines.

The total pressure drop in a duct system combines the pressure drop that occurs from friction loss and fitting loss. The pressure drop caused by friction loss is easily calculated, as it can be obtained from the friction chart in ASHRAE’s “2005 ASHRAE Handbook – Fundamentals” [70]. Using as input the air flow in each duct and the respective air speed, one can obtain the pressure drop per metre, which when multiplied by the length of the duct results in the pressure drop due to friction loss. The calculations behind the pressure drop due to fitting loss in each duct are relatively more complex. It was also necessary to resort to the previously mentioned document, where after identifying fitting type it was possible to determine the respective pressure drop coefficient. By multiplying this coefficient by the air’s volumetric mass and its squared speed, one can obtain the pressure drop caused by fitting loss for each duct. The total pressure drop in the critical branches for both supply and exhaust branches is obtained by adding these two types of pressure drop and can be found in Annex L and Annex M.

The fan units used in the HVAC system have to be powerful enough to overcome this pressure drop. The necessary fan power can be determined by multiplying the total pressure drop by the air flow that circulates in the critical branch. There are two fan units used to exchange air inside the building: one for the air extraction and another one for the supply. The respective fan power of these units can be found in the following table:

Table 39 - Fan power necessary for air supply and extraction

	∑ΔP [Pa]	**Diffuser ΔP [Pa]**	**Total pressure drop [Pa]**	**Fan power [W]**	**Specific fan power [W/l/s]**
Supply	14.77	3	17.77	0.7	0.02
Exhaust	12.27	25	37.27	0.8	0.04

Combining together all these previously mentioned technologies and HVAC strategies, it is possible to minimize thermal demands and energy consumption, thus reinforcing the “Zero Bills Home” concept of a low-energy and low-carbon building.

4.1.5 Embodied carbon analysis

Although carbon dioxide exists in the atmosphere as part of a natural cycle, human activities, mainly the burning of fossil fuels, have been increasing the emissions of this greenhouse gas since the industrial revolution. Over the last decade, the reduction of carbon dioxide emissions has become increasingly important in the struggle against global warming and to do so, sustainably-focused governmental legislations have been implemented in most developed countries. In the building industry, requirements that target to minimize the carbon dioxide emission rate of new dwellings, for example by installing low carbon technologies, are becoming mandatory in countries such as the United Kingdom, where they are enforced by the Building Regulations Part L. It is of a great importance that societies become aware of new cutting-edge strategies to diminish CO_2 emissions and essentially that fossil fuel consumption is reduced.

Therefore, it is crucial that in order to label new constructions as low-carbon buildings, a careful analysis on the CO_2 emissions during a designated period of time is made. For this purpose, different methodologies associated with different stages of a building’s lifespan can be used. The most widely known environmental impact assessment technique is the Life-Cycle-Assessment (LCA), which is commonly associated with all the stages of the product’s life from cradle-to-grave. This definition covers the all the lifespan of the building, such as construction, use, maintenance and disposal.

In the scope of this project, an interesting additional self-suggested challenge was to determine if this building was “Carbon Neutral” and how long it would take for this model of the “Zero Bills Home” to pay back its embodied carbon footprint. According to the UK

Department of Energy and Climate Change, "*Carbon neutral means that through a transparent process of calculating emissions, reducing those emissions and offsetting residual emissions – net carbon emissions equal zero*" [71].By using the on-site renewable energy, this building is able to generate an annual energy surplus, which gives it the ability to offset its carbon footprint, unlike conventional buildings which never manage to do so.

A comparative analysis between the annual electric carbon payback and the total embodied carbon in the building construction was made in order to determine the number of years necessary until this building could be labelled as "Carbon Neutral". In order to determine the embodied carbon in the construction of the building, a Cradle-to-Gate boundary was selected as the ideal scope of this study, which includes all the emissions from extraction, manufacturing and transportation until the products leave the factory gate. In normal constructions, the final boundary condition would include the remaining transport until the products reach the site, known as Cradle-to-Site. In the "Zero Bills Home", with the existence of the previously mentioned local assembly unit, the factory gate and the construction site are located in the same place; therefore the difference between Cradle-to-Gate and Cradle-to-Site is negligible in this project.

The embodied carbon is the amount of CO_2 emissions, given in kilograms of carbon dioxide, necessary to produce and deliver a single material. Therefore, in order to calculate the amount of carbon dioxide emitted up to the construction of this building, it was necessary to determine the total volume and embodied carbon factor of each material that is used to assemble it. This was done in accordance with the Inventory of Carbon and Energy (ICE), developed by the University of Bath. ICE is an embodied energy and carbon footprint database for building materials, mainly directed towards UK constructions. This database contains data of more than 200 materials, divided into over 30 main categories. Its data was, and continues to be, collected from secondary resources in the public domain, such as Life-Cycle-Assessments, scientific articles, books, conference papers, and even data from UK material producers and suppliers, thus making it a very reliable and open-access database to be used in the construction industry [72].

In order to estimate the embodied energy and embodied carbon of each material incorporated in this database, five criteria were applied:

1. Compliance with the approved methodologies/standards: in the development of this database, preference was given to data sources that complied with accepted

methodologies, such as the international standard of environmental life cycle assessment ISO 14040/44.

2. System boundaries: where a Cradle-to-Gate analysis was selected as being the most commonly specified boundary condition.

3. Origin of data: preference was given to the embodied carbon data obtained from UK sources, due to national differences in fuel mixes and electricity generation.

4. Age of data sources: where for the obvious reasons, modern sources of data were preferred

5. Embodied Carbon: when existing, data was obtained from detailed studies which consider life cycle carbon emissions, such as LCAs, but there is often an absence of such data for different materials. In some cases, values had to be estimated using the typical fuel split for the specific UK industrial sector. [72]

The obtained embodied energy and carbon factors for the different materials were then comprised in the form of an open-access database, which was used in the scope of this project.

Subsequently, the total volume of every material used for the construction of this “Zero Bills Home” model was determined by thoroughly analysing all the constructive elements of this building, including the integrated photovoltaic panel.

By multiplying the total volume of each material used in this building by its volumetric mass, one determines its total weight. Then when multiplying it by the referenced embodied carbon factor (kg CO_2 / kg), obtained from the ICE database, it is possible to obtain the total embodied carbon (kg CO_2). This methodology was followed for all the different materials used in this construction, with the exception of the monocrystalline photovoltaic cells and the glazing units. In this case the embodied carbon factor was given per area (kg CO_2/m^2) and therefore, the total area of these surfaces was measured so as to determine the associated embodied carbon. For these cases, the embodied carbon factor of the photovoltaic cells was obtained from the manufacturer’s data and from a British construction article for the double-glazed windows [73]. Additionally, the embodied carbon factor for the timber used in this building was also obtained from the manufacturer which accounts for the carbon sequestration properties of wood. All these considerations and calculations can be found attached to this document in Annex N.

The total embodied carbon of this building's construction was obtained by adding this parameter from all the different materials. In order to determine the number of years until the "Zero Bills Home" would offset its carbon footprint the annual electric carbon payback had to be calculated. This was done for the intermediate case (Case 2), since it would establish an average number of years for the different occupants of the "Zero Bills Home". To do so, the results obtained from the second case scenario were considered and can be found in the following table:

Table 40 - Annual electrical balance of the "Zero Bills Home" for the second case scenario

Annual Electrical Generation	6769 kWh
Annual Electrical Demand	4562 kWh
Annual Electrical Surplus	**2207 kWh**

In this scenario there would be an annual electrical surplus of approximately 2.2 MWh, which during the lifespan of this building will counterbalance its embodied carbon. According to the UK Department for Governmental Food and Rural Affairs, the electrical energy CO_2 emission factor is 0.527, which means that the national grid releases 0.527 kilograms of CO_2 per kWh of electricity produced [74]. When multiplying this factor by the total surplus energy which is sold to the national grid, it is possible to calculate the annual electric carbon payback. In this case, it corresponds to 1163 kg CO_2, meaning that this amount of carbon dioxide can be discounted annually from the total embodied carbon of the building. Lastly, one can determine the number of years needed to achieve a carbon neutral building by dividing its embodied carbon by the annual payback. These values can be found in the subsequent table:

Table 41 - "Zero Bills Home" carbon neutral balance

Annual Generation [kg CO_2]	(-) 3567
Annual Demand [kg CO_2]	(+) 2404
Annual Carbon Payback [kg CO_2]	(-) 1163
Embodied Carbon in Building Construction [kg CO_2]	(+) 17906
Number of years until Carbon Neutral	**15**

As a final note, the "Zero Bills Home", more than an energetically efficient housing system, can also be labelled as a carbon neutral building as it is capable of overcoming its embodied carbon footprint in 15 years.

4.2 Porto

In the scope of this work, one of the proposed goals was to analyse how the same building model of the “Zero Bills Home”, with the exact same construction elements would behave if it would be built in a country with different climatic conditions. For this purpose, it was intended to develop a corresponding thermal simulation for the Portuguese city of Porto where the thermal demands of the building and the annual photovoltaic electrical production were to be determined.

As expected, in a location such as Porto where, in comparison to London, it is warmer throughout the year, the same highly insulated building would have its cooling demands increased together with a reduced amount of heating demands. In fact, heating demands will almost be nullified giving rise to thermal cooling demands, as shown in Figure 44. This means that during the summer period, it is very likely that if the building remained unchanged, it would overheat. To avoid this situation, different passive design strategies should be implemented together with carefully planned alterations in the constructive elements of the building envelope. These strategies will be referred still in this chapter.

When thermal demands seem to constitute a problem to the construction of a “Zero Bills Home” in Portugal, the photovoltaic energy production reinvigorates this intention. Because of its beneficial location and high solar potential, Porto can harness far more solar radiation per square metre than London, which greatly increases the annual electric energy produced by having the same building integrated photovoltaic system installed.

Porto’s higher solar potential which will boost the electric energy production may still offset the increased annual thermal demands, especially if new constructive design strategies are implemented. Based on the results subsequently outlined, the “Zero Bills Home” main concept might still be able to stand in countries with different climatic conditions.

An annual thermal demand analysis made for the first case scenario shows that the by using the standard “Zero Bills Home” construction with an highly insulated and airtight building envelope, the annual space heating demands can be nullified in Porto, totalizing in 16 kWh per year. However the cooling demands would increase, as can be seen in the following graphic obtained from TRNSYS, which shows the annual thermal demands of each room enclosed in the ground floor of this house.

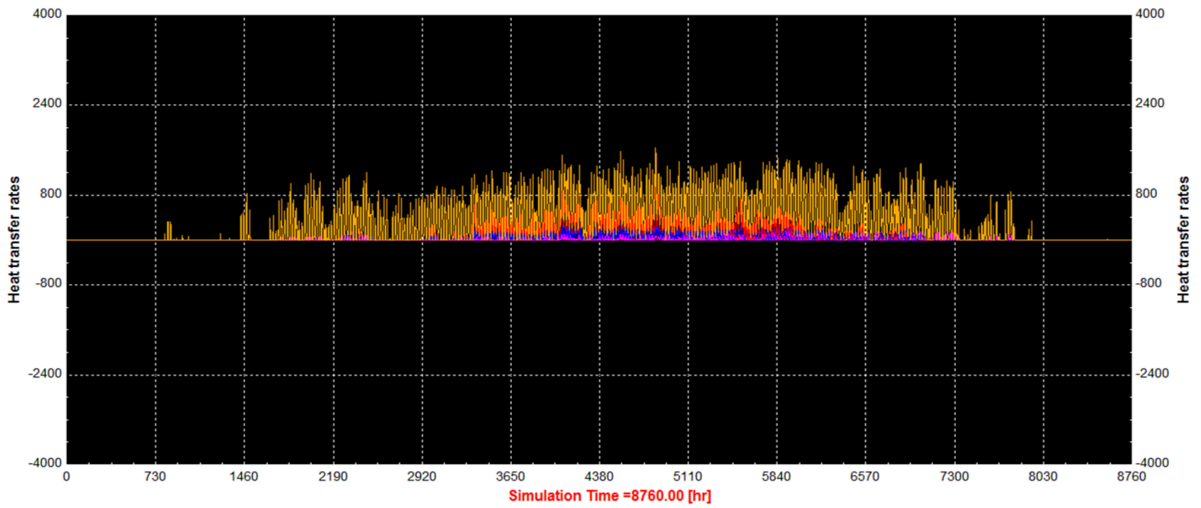

Figure 44 - Ground floor thermal demands of "Zero Bills Home" in Porto

For the whole dwelling, the thermal demands due to space cooling would be approximately 10 MWh, which then had to be converted into electrical demands in order to allow an appropriate comparison with the annual electrical production. Most of these cooling demands could be removed using the same passive cooling strategies as in London, such as cross ventilation, night flush and free-cooling. By doing so in the first day where the maximum thermal comfort temperature was overcome, the total annual cooling demands would never reach the amount obtained in the simulation, as the inside temperatures would never be as high.

Nevertheless, it is necessary to understand if the increase on the thermal demands is enough to overthrow the "Zero Bills Home" concept, when compared to the increase in the energy produced by the ZEDroof. The exact same photovoltaic system composed of 30 panels, each with a peak output of 250 W, was modelled in TRNSYS. The subsequent graphic shows the monthly electric energy produced for both these locations which together with Table 44, establishes a comparison between both, where the relative increase in production is shown.

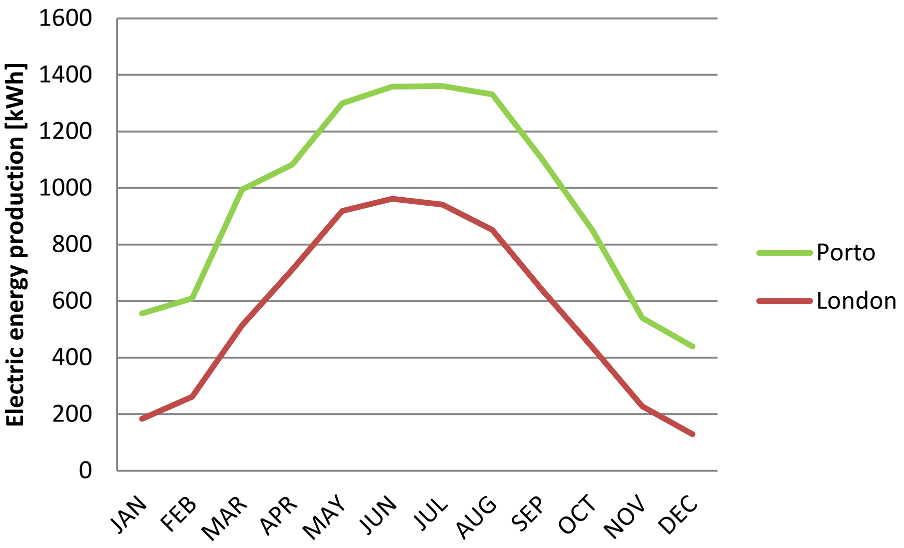

Figure 45 - Monthly electric energy production in London and Porto

Table 42 - Comparison between the monthly electric energy production in London and Porto

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
London [kWh]	183	261	514	711	919	961	941	852	637	436	227	128	**6769**
Porto [kWh]	555	609	994	1082	1299	1358	1360	1331	1099	850	540	440	**11518**
Relative Increase	204%	133%	94%	52%	41%	41%	45%	56%	73%	95%	138%	242%	**70%**

As shown above, there is a relative increase of 70% in the total energy produced by the photovoltaic system when installing it in Porto, rather than in London. Such an increase is likely to counterbalance the annual energy consumption of this building. In order to determine this balance, the considerations used for the first case scenario in London were applied, as it is intended for this housing system to have hot water and electricity saving strategies installed, despite its location. Therefore, assuming an annual general electric energy consumption of 23 kWh/m^2 and hot water consumption of 40 litres per person per day, together with the obtained space cooling demands it is possible to determine the total annual electric consumption of this building. To do so it is necessary to convert the thermal demands into electric energy. Despite the peak loads, which were not intended to be determined for the purpose of this work, using a Daikin Altherma air source heat pump, the typical COP for heating is 4.1 whereas for cooling, the EER is 3. This means that 1 kW of electric energy can produce 4.1 kW to heat the hot water cylinder or 3 kW to cool the building. Combining all this information, it is then possible to compare the annual electric consumption with the total energy generated by the ZEDroof, as can be seen in the following table:

Table 43 - “Zero Bills Home” annual electric energy balance in Porto

General electric energy consumption [kWh]	2760
Hot water demands [kWh]	912
Space cooling demands [kWh]	3790
Annual electric consumption [kWh]	7462
Annual electric production [kWh]	11518
Annual electric surplus [kWh]	**4056**

Therefore it is clear that the “Zero Bills Home” concept still stands in a different country with different climatic conditions, such as Portugal. The increase in the energy produced by the photovoltaic system greatly contributed to this fact, as it remains possible to generate an annual electric surplus, thus counterbalancing the increased thermal demands. Nonetheless, it is of a great importance that if this housing system was to be built in a different site, it should be adapted to the local climatic conditions, in order to improve its performance and reduce its energy consumption.

The main problem if this model of the “Zero Bills Home” was to be constructed in Porto is overheating. In order to avoid this problem, cross ventilation, night flush ventilation and free-cooling strategies should be used to cool down the building when the temperature starts to raise above thermal comfort conditions. An efficient ventilation system with heat recovery is also an essential component for this location, as it can be used both in winter as in summer, in this last case with a bypass valve. It is indispensible that overhangs are designed such as to allow passive solar gain during the winter, while fully shading the windows during the summer. Using more efficient glazing units with a lower thermal emissivity is beneficial, but it is important that they located are in the south façade. Also, by using bright colours that reflect infra-red light in the external façades, it becomes easier to avoid overheating during the summer period. High thermal mass interior surfaces should be used in order to store passive heat during the winter and summer night coolness. One of the key design guidelines in a low-energy building which can keep the inside temperature uniform, is to keep it highly insulated. This allows it to store the heat from internal gains during the winter, which greatly reduces heating demands. Nevertheless, it would still be beneficial to reduce the insulation of its constructive elements, in order to allow a reduction in the annual cooling demands, whilst keeping it well insulated if it was to be built in this climate.

Summing up, because Porto has one of the most confortable climates, it is essential properly design the building in order to optimize its thermal performance, whilst keeping it comfortable for the occupants. By implementing these strategies it is possible to achieve an even more energetically efficient building solution.

5. Conclusions and future work

5.1 Conclusions

The central purpose of the developed work was to validate the “Zero Bills Home” concept by means of a detailed analysis of its energy performance. In accordance with the previously presented results, this can be achieved by implementing efficient strategies in a carefully designed building. Combining good insulation, thermal mass and airtightness, with efficient heat recovery ventilation and heating strategies in a well orientated building makes it possible to reduce thermal demands. In addition, using hot water saving strategies, such as aerated showers, low-flow taps and shower heat recovery units, together with energy efficient electric appliances and lighting one can easily cut down on the annual electric energy consumption. When incorporating on-site renewable energy sources, such as photovoltaic panels, the energy demands of a building can be offset, therefore generating annual revenues instead of bills.

In this case study, even in the worst case scenario, Case 3, which accounts for a minimum thermostat set point of 21°C, together with a hot water consumption of 50 litres per person per day and a general electric consumption of 28 kWh/m^2, the on-site electric energy generation, which equals 6769 kWh per year, is able to overcome the annual electric energy consumption of 5390 kWh.

The foundation of this concept as an energy efficient building can be similarly verified in countries with different climatic conditions, as long as detailed construction plans are followed and specific solutions are implemented for each location. When compared with the United Kingdom, Mediterranean countries have a higher solar potential which makes them more suitable for the integration of solar energy generation solutions, given that financial incentives are provided. In Porto, the same 7.5 kWp photovoltaic system is able to generate 11518 kWh during the course of a year, which corresponds to a relative increase of 70% over its production in London. However, if the same housing system was to be built in Porto, the annual electric consumption would similarly increase, reaching 7642 kWh. Nevertheless, the “Zero Bills Home” concept can be verified due to the existence of an annual electric energy surplus of 4056 kWh.

As building standards progressively become more stringing, new buildings have to be meticulously designed, in order to achieve specified requirements. This means that these constructions cannot be solely developed based on architectural knowledge; they require thermodynamic engineering assessments. Dynamic thermal simulation software, such as TRNSYS, is a powerful tool which if integrated in the design process of a building can optimize its thermal performance and reduce its energy demands. This improvement allows buildings to meet the required standards with greater ease and helps reducing both financial and material costs. Nevertheless, accurate simulation results can only be obtained from accurate inputs introduced by the users. This is the main reason why differences between the simulated results and real-life occur. More experienced users with background knowledge are able to identify and understand what lies behind the figures obtained, which minimizes disparities between the final results. Simply because one can perform a thermal simulation in the most accurate software available does not mean that good results will always be obtained.

Upon the completion of the dynamic simulation, an HVAC system has to be correctly designed in accordance with the necessities of each dwelling. These systems are fundamental in buildings with low energy consumption, mainly due to the heat recovery unit. These units provide the inside of the building with fresh air without letting the heat out and this way, one can greatly reduce thermal demands, whilst guaranteeing indoor air quality for the occupants. Because of their importance in NZEB and low-energy buildings, it is recommended that units with heat recovery efficiencies of 90% or more are installed. In addition, other highly efficient and energy saving units, such as Air-Source Heat Pumps, should be used in order to further increase the performance of the building. The HVAC system implemented in this building was designed for the critical case and it includes an 8kW Air-Source Heat Pump, combined with a 90% efficient heat recovery unit and ventilation system, where the air supply is done by displacement ventilation. A 300 litre hot water cylinder is installed in order to overcome the hot water demands, and space heating demands are counterbalanced by an underfloor heating system.

One main focus on Europe’s 2020 targets is to reduce greenhouse gas emissions. Buildings such as the “Zero Bills Home” positively contribute to this, as by generating annual surpluses via on-site renewable energy sources, they can progressively offset their embodied carbon emissions over their lifetime. Once this happens, these buildings are labelled as “Carbon Neutral”. In order to achieve this status and to reduce CO_2 emissions, it is fundamental that in addition to a positive electric energy generation vs. consumption ratio, natural materials are used in the constructive elements of every building. Timber structures and cork insulation boards are the most ecological solutions, as they counterbalance these emissions with their net carbon storing properties. This change in the construction industry will reduce the embodied carbon footprint of newly assembled buildings, which will represent an important step in the achievement of the proposed targets. In London, for the intermediate case scenario analysed (Case 2), this building generates an annual electric energy surplus of

2207 kWh. The United Kingdom’s national grid releases 0.527 kilograms of CO_2 per kWh of electricity produced, which means that this building would have an annual carbon payback of 1163 kilograms of CO_2. In its construction, the embodied carbon sums up to 17906 kg of CO_2, meaning that in approximately 15 years, the “Zero Bills Home” would be able to offset its carbon footprint, thus verifying the concept of a “Zero Carbon” building.

So how can the building industry contribute to a continuous sustainable development? The answer is simple: Increasing the energy performance of every building and reducing demands. It is a matter of uniting efficiency with sufficiency.

5.2 Future Work

Regardless of the completion of all the proposed objectives set out for this project, there are still several lines of research which can be pursued in order to improve the developed work.

Because the main focus of this work was to determine the heating demands of the case study building, the cooling demands were overlooked, mainly due to its location. It would be important to develop a thorough analysis in this last parameter and to study the influence of passive cooling strategies using TRNSYS software. As a result, it would be possible to optimize the design of the building together with its thermal performance.

Additionally, natural materials should be implemented in the constructive elements of this building. For instance, cork could be used to replace synthetic insulation such as expanded polystyrene or mineral wool, so as to reduce the embodied carbon of the building while ensuring similar thermal properties.

One of the proposed goals in the scope of this work was to determine if it would be possible to validate the “Zero Bills Home” concept in a different country. In order to do so, an energy analysis was developed, which consisted of a balance between the annual energy demands and the on-site renewable electric energy generation. If it was intended to build this housing system in another country, a more detailed analysis would have to be made. This would include re-designing this building according to the country’s legislation and climatic conditions, determining the heating and cooling loads so as to design an adequate HVAC system and developing an optimized model where different strategies would be tested.

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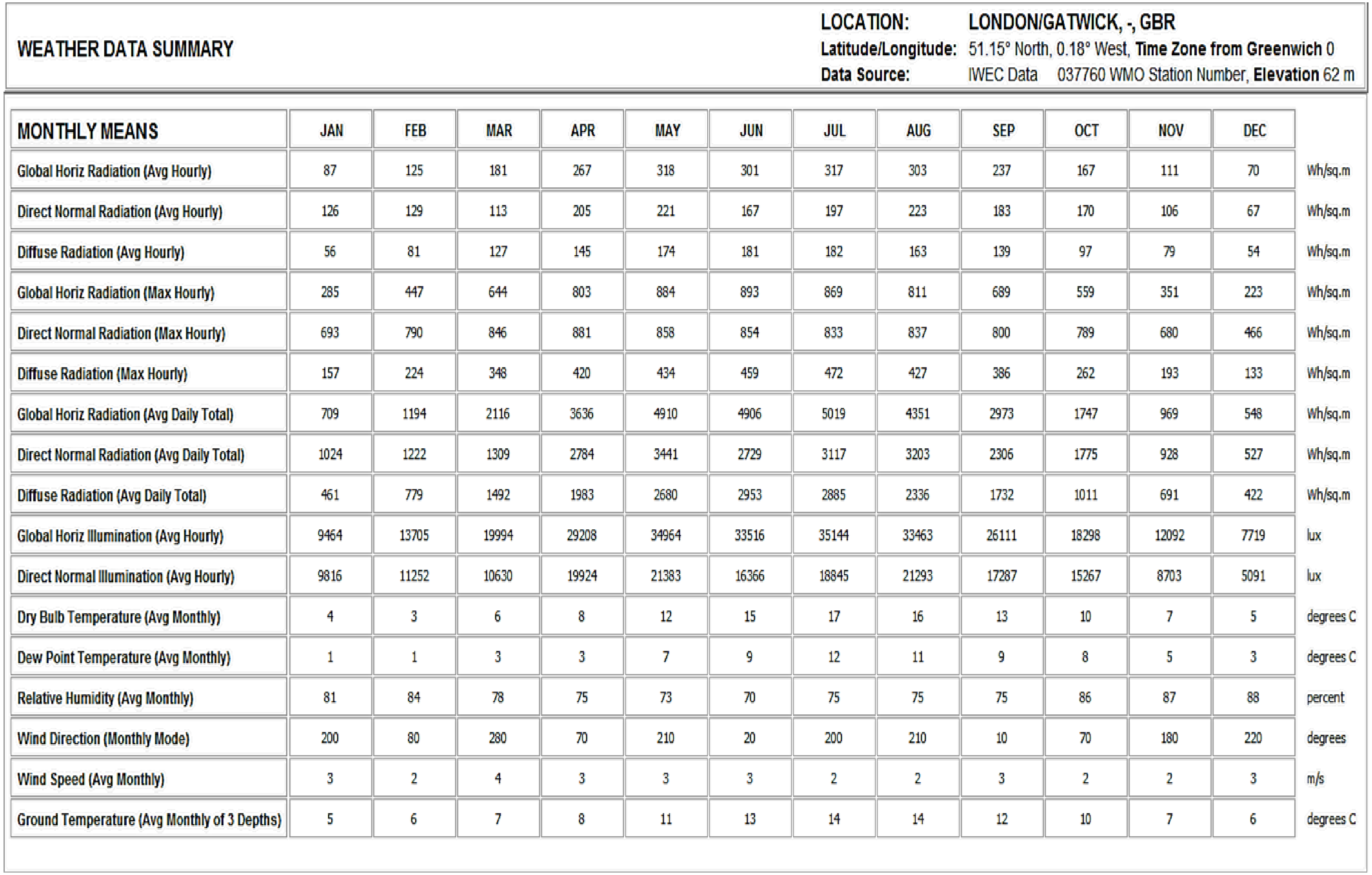
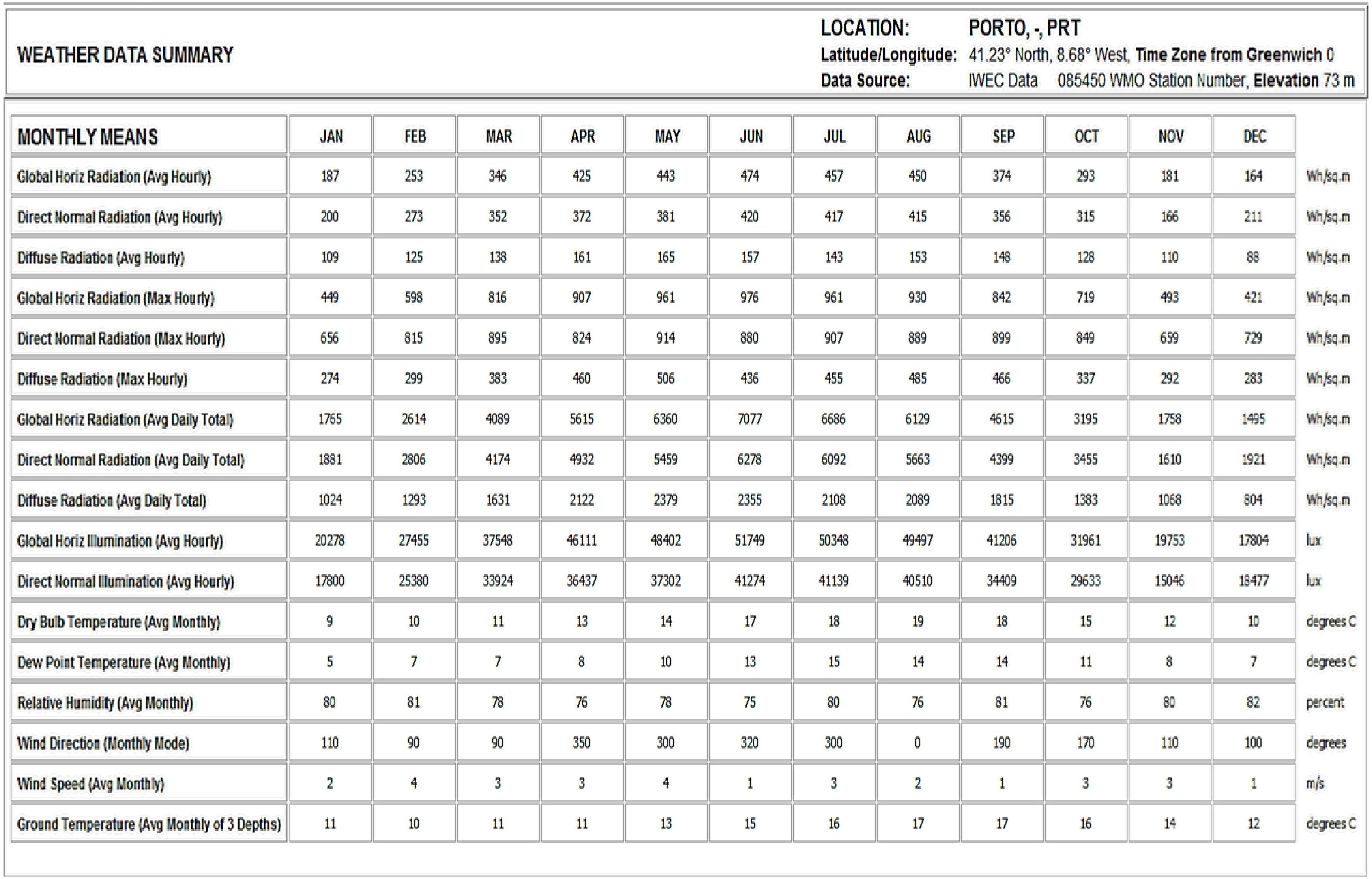
ANNEX A – Climatic Conditions



WEATHER DATA SUMMARY

LOCATION: **LONDON/GATWICK, -, GBR**
Latitude/Longitude: 51.15° North, 0.18° West, **Time Zone from Greenwich** 0
Data Source: IWEC Data 037760 WMO Station Number, **Elevation** 62 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	87	125	181	267	318	301	317	303	237	167	111	70	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	126	129	113	205	221	167	197	223	183	170	106	67	Wh/sq.m
Diffuse Radiation (Avg Hourly)	56	81	127	145	174	181	182	163	139	97	79	54	Wh/sq.m
Global Horiz Radiation (Max Hourly)	285	447	644	803	884	893	869	811	689	559	351	223	Wh/sq.m
Direct Normal Radiation (Max Hourly)	693	790	846	881	858	854	833	837	800	789	680	466	Wh/sq.m
Diffuse Radiation (Max Hourly)	157	224	348	420	434	459	472	427	386	262	193	133	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	709	1194	2116	3636	4910	4906	5019	4351	2973	1747	969	548	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	1024	1222	1309	2784	3441	2729	3117	3203	2306	1775	928	527	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	461	779	1492	1983	2680	2953	2885	2336	1732	1011	691	422	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	9464	13705	19994	29208	34964	33516	35144	33463	26111	18298	12092	7719	lux
Direct Normal Illumination (Avg Hourly)	9816	11252	10630	19924	21383	16366	18845	21293	17287	15267	8703	5091	lux
Dry Bulb Temperature (Avg Monthly)	4	3	6	8	12	15	17	16	13	10	7	5	degrees C
Dew Point Temperature (Avg Monthly)	1	1	3	3	7	9	12	11	9	8	5	3	degrees C
Relative Humidity (Avg Monthly)	81	84	78	75	73	70	75	75	75	86	87	88	percent
Wind Direction (Monthly Mode)	200	80	280	70	210	20	200	210	10	70	180	220	degrees
Wind Speed (Avg Monthly)	3	2	4	3	3	3	2	2	3	2	2	3	m/s
Ground Temperature (Avg Monthly of 3 Depths)	5	6	7	8	11	13	14	14	12	10	7	6	degrees C

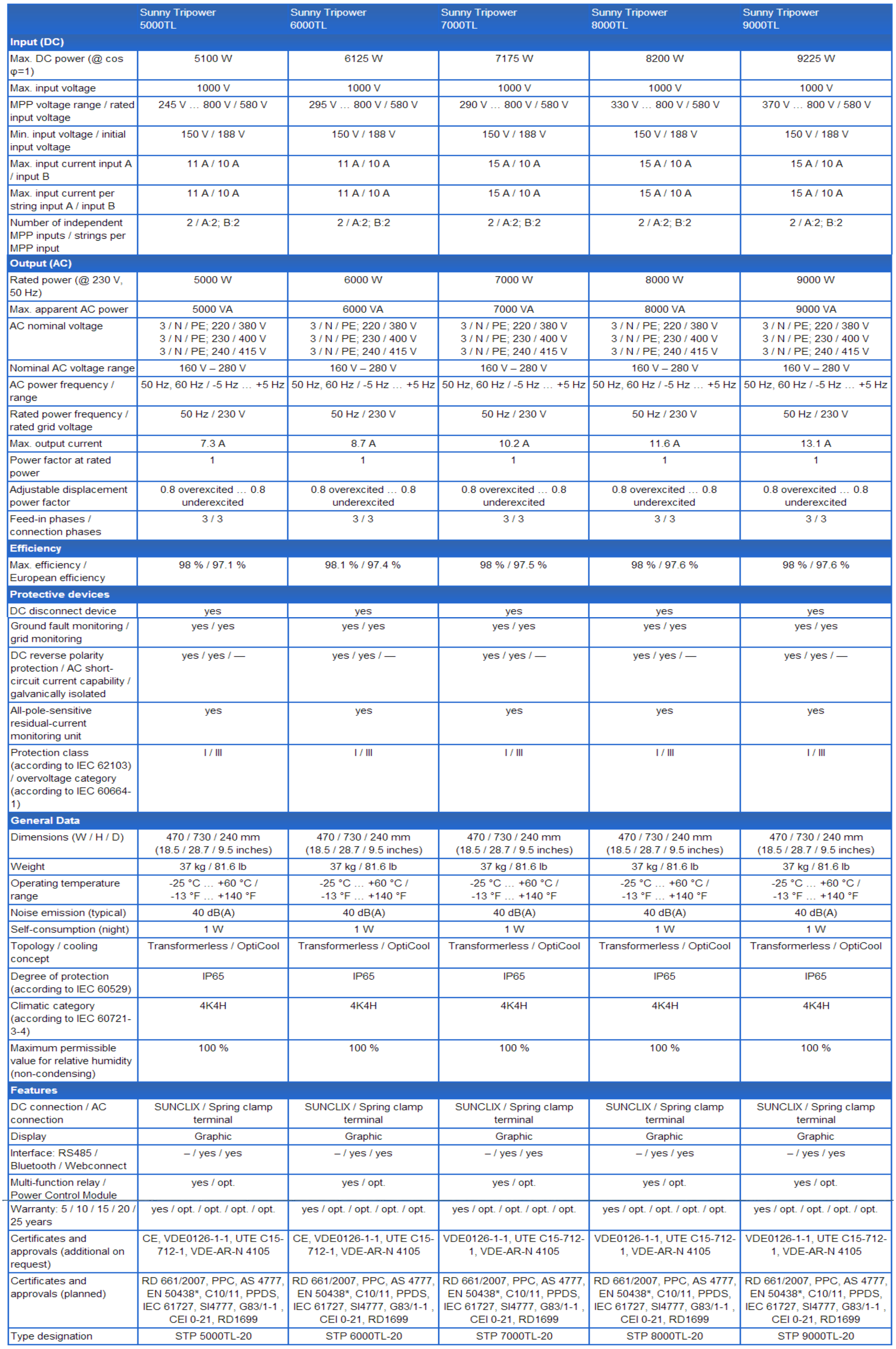


WEATHER DATA SUMMARY

LOCATION: **PORTO, -, PRT**
Latitude/Longitude: 41.23° North, 8.68° West, **Time Zone from Greenwich** 0
Data Source: IWEC Data 085450 WMO Station Number, **Elevation** 73 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	187	253	346	425	443	474	457	450	374	293	181	164	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	200	273	352	372	381	420	417	415	356	315	166	211	Wh/sq.m
Diffuse Radiation (Avg Hourly)	109	125	138	161	165	157	143	153	148	128	110	88	Wh/sq.m
Global Horiz Radiation (Max Hourly)	449	598	816	907	961	976	961	930	842	719	493	421	Wh/sq.m
Direct Normal Radiation (Max Hourly)	656	815	895	824	914	880	907	889	899	849	659	729	Wh/sq.m
Diffuse Radiation (Max Hourly)	274	299	383	460	506	436	455	485	466	337	292	283	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	1765	2614	4089	5615	6360	7077	6686	6129	4615	3195	1758	1495	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	1881	2806	4174	4932	5459	6278	6092	5663	4399	3455	1610	1921	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1024	1293	1631	2122	2379	2355	2108	2089	1815	1383	1068	804	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	20278	27455	37548	46111	48402	51749	50348	49497	41206	31961	19753	17804	lux
Direct Normal Illumination (Avg Hourly)	17800	25380	33924	36437	37302	41274	41139	40510	34409	29633	15046	18477	lux
Dry Bulb Temperature (Avg Monthly)	9	10	11	13	14	17	18	19	18	15	12	10	degrees C
Dew Point Temperature (Avg Monthly)	5	7	7	8	10	13	15	14	14	11	8	7	degrees C
Relative Humidity (Avg Monthly)	80	81	78	76	78	75	80	76	81	76	80	82	percent
Wind Direction (Monthly Mode)	110	90	90	350	300	320	300	0	190	170	110	100	degrees
Wind Speed (Avg Monthly)	2	4	3	3	4	1	3	2	1	3	3	1	m/s
Ground Temperature (Avg Monthly of 3 Depths)	11	10	11	11	13	15	16	17	17	16	14	12	degrees C

ANNEX B – Inverter

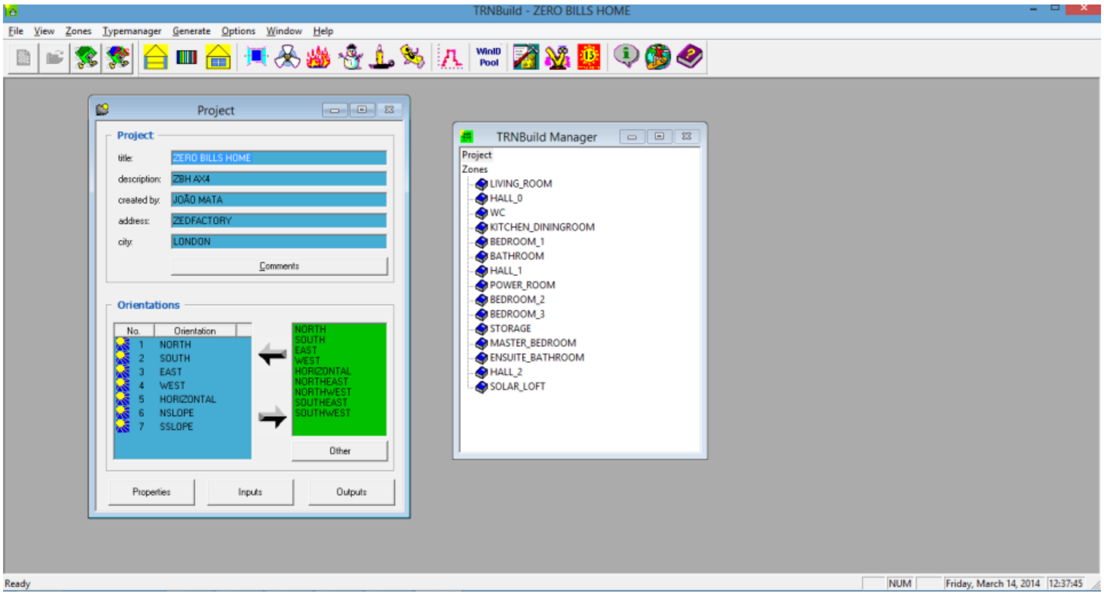


	Sunny Tripower 5000TL	Sunny Tripower 6000TL	Sunny Tripower 7000TL	Sunny Tripower 8000TL	Sunny Tripower 9000TL
Input (DC)					
Max. DC power (@ cos φ=1)	5100 W	6125 W	7175 W	8200 W	9225 W
Max. input voltage	1000 V	1000 V	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	245 V … 800 V / 580 V	295 V … 800 V / 580 V	290 V … 800 V / 580 V	330 V … 800 V / 580 V	370 V … 800 V / 580 V
Min. input voltage / initial input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	11 A / 10 A	11 A / 10 A	15 A / 10 A	15 A / 10 A	15 A / 10 A
Max. input current per string input A / input B	11 A / 10 A	11 A / 10 A	15 A / 10 A	15 A / 10 A	15 A / 10 A
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2	2 / A:2; B:2	2 / A:2; B:2	2 / A:2; B:2	2 / A:2; B:2
Output (AC)					
Rated power (@ 230 V, 50 Hz)	5000 W	6000 W	7000 W	8000 W	9000 W
Max. apparent AC power	5000 VA	6000 VA	7000 VA	8000 VA	9000 VA
AC nominal voltage	3 / N / PE; 220 / 380 V 3 / N / PE; 230 / 400 V 3 / N / PE; 240 / 415 V	3 / N / PE; 220 / 380 V 3 / N / PE; 230 / 400 V 3 / N / PE; 240 / 415 V	3 / N / PE; 220 / 380 V 3 / N / PE; 230 / 400 V 3 / N / PE; 240 / 415 V	3 / N / PE; 220 / 380 V 3 / N / PE; 230 / 400 V 3 / N / PE; 240 / 415 V	3 / N / PE; 220 / 380 V 3 / N / PE; 230 / 400 V 3 / N / PE; 240 / 415 V
Nominal AC voltage range	160 V – 280 V	160 V – 280 V	160 V – 280 V	160 V – 280 V	160 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	50 Hz, 60 Hz / -5 Hz … +5 Hz	50 Hz, 60 Hz / -5 Hz … +5 Hz
Rated power frequency / rated grid voltage	50 Hz / 230 V	50 Hz / 230 V	50 Hz / 230 V	50 Hz / 230 V	50 Hz / 230 V
Max. output current	7.3 A	8.7 A	10.2 A	11.6 A	13.1 A
Power factor at rated power	1	1	1	1	1
Adjustable displacement power factor	0.8 overexcited … 0.8 underexcited	0.8 overexcited … 0.8 underexcited	0.8 overexcited … 0.8 underexcited	0.8 overexcited … 0.8 underexcited	0.8 overexcited … 0.8 underexcited
Feed-in phases / connection phases	3 / 3	3 / 3	3 / 3	3 / 3	3 / 3
Efficiency					
Max. efficiency / European efficiency	98 % / 97.1 %	98.1 % / 97.4 %	98 % / 97.5 %	98 % / 97.6 %	98 % / 97.6 %
Protective devices					
DC disconnect device	yes	yes	yes	yes	yes
Ground fault monitoring / grid monitoring	yes / yes	yes / yes	yes / yes	yes / yes	yes / yes
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	yes / yes / —	yes / yes / —	yes / yes / —	yes / yes / —	yes / yes / —
All-pole-sensitive residual-current monitoring unit	yes	yes	yes	yes	yes
Protection class (according to IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III	I / III	I / III	I / III	I / III
General Data					
Dimensions (W / H / D)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inches)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inches)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inches)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inches)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inches)
Weight	37 kg / 81.6 lb	37 kg / 81.6 lb	37 kg / 81.6 lb	37 kg / 81.6 lb	37 kg / 81.6 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	-25 °C … +60 °C / -13 °F … +140 °F	-25 °C … +60 °C / -13 °F … +140 °F
Noise emission (typical)	40 dB(A)	40 dB(A)	40 dB(A)	40 dB(A)	40 dB(A)
Self-consumption (night)	1 W	1 W	1 W	1 W	1 W
Topology / cooling concept	Transformerless / OptiCool	Transformerless / OptiCool	Transformerless / OptiCool	Transformerless / OptiCool	Transformerless / OptiCool
Degree of protection (according to IEC 60529)	IP65	IP65	IP65	IP65	IP65
Climatic category (according to IEC 60721-3-4)	4K4H	4K4H	4K4H	4K4H	4K4H
Maximum permissible value for relative humidity (non-condensing)	100 %	100 %	100 %	100 %	100 %
Features					
DC connection / AC connection	SUNCLIX / Spring clamp terminal	SUNCLIX / Spring clamp terminal	SUNCLIX / Spring clamp terminal	SUNCLIX / Spring clamp terminal	SUNCLIX / Spring clamp terminal
Display	Graphic	Graphic	Graphic	Graphic	Graphic
Interface: RS485 / Bluetooth / Webconnect	– / yes / yes	– / yes / yes	– / yes / yes	– / yes / yes	– / yes / yes
Multi-function relay / Power Control Module	yes / opt.	yes / opt.	yes / opt.	yes / opt.	yes / opt.
Warranty: 5 / 10 / 15 / 20 / 25 years	yes / opt. / opt. / opt. / opt.	yes / opt. / opt. / opt. / opt.	yes / opt. / opt. / opt. / opt.	yes / opt. / opt. / opt. / opt.	yes / opt. / opt. / opt. / opt.
Certificates and approvals (additional on request)	CE, VDE0126-1-1, UTE C15-712-1, VDE-AR-N 4105	CE, VDE0126-1-1, UTE C15-712-1, VDE-AR-N 4105	VDE0126-1-1, UTE C15-712-1, VDE-AR-N 4105	VDE0126-1-1, UTE C15-712-1, VDE-AR-N 4105	VDE0126-1-1, UTE C15-712-1, VDE-AR-N 4105
Certificates and approvals (planned)	RD 661/2007, PPC, AS 4777, EN 50438*, C10/11, PPDS, IEC 61727, SI4777, G83/1-1 , CEI 0-21, RD1699	RD 661/2007, PPC, AS 4777, EN 50438*, C10/11, PPDS, IEC 61727, SI4777, G83/1-1 , CEI 0-21, RD1699	RD 661/2007, PPC, AS 4777, EN 50438*, C10/11, PPDS, IEC 61727, SI4777, G83/1-1 , CEI 0-21, RD1699	RD 661/2007, PPC, AS 4777, EN 50438*, C10/11, PPDS, IEC 61727, SI4777, G83/1-1 , CEI 0-21, RD1699	RD 661/2007, PPC, AS 4777, EN 50438*, C10/11, PPDS, IEC 61727, SI4777, G83/1-1 , CEI 0-21, RD1699
Type designation	STP 5000TL-20	STP 6000TL-20	STP 7000TL-20	STP 8000TL-20	STP 9000TL-20

ANNEX C – TRNBuild

TRNBuild is a user interface software for modelling the thermal behaviour of a building divided into different thermal zones, which in this case are the rooms of the house. Each thermal zone is modelled as a single air node, thus having its properties uniformly distributed throughout the zone. This means that each thermal zone may be set with different inputs, such as geometric properties, infiltration, ventilation, heating, cooling, internal gains, comfort, and humidity settings, amongst others.

Due to the complexity of a multizone building the parameters of TYPE 56 are not defined directly in the TRNSYS input file. Instead, two files are assigned containing the required information, the building description (*.BLD) and the ASHRAE transfer function for walls (*.TRN). The data entered in TRNBuild is saved in a so-called building file (*.BUI), a readable ASCII text file [54].



Project

title: ZERO BILLS HOME
description: ZBH AX4
created by: JOÃO MATA
address: ZEDFACTORY
city: LONDON

Orientations

No.	Orientation
1	NORTH
2	SOUTH
3	EAST
4	WEST
5	HORIZONTAL
6	NSLOPE
7	SSLOPE

NORTH
SOUTH
EAST
WEST
HORIZONTAL
NORTHEAST
NORTHWEST
SOUTHEAST
SOUTHWEST

Project
Zones
- LIVING_ROOM
- HALL_0
- WC
- KITCHEN_DININGROOM
- BEDROOM_1
- BATHROOM
- HALL_1
- POWER_ROOM
- BEDROOM_2
- BEDROOM_3
- STORAGE
- MASTER_BEDROOM
- ENSUITE_BATHROOM
- HALL_2
- SOLAR_LOFT

Figure 46 - TRNBuild Interface

Because TRNSYS16 was used instead of the newer version TRNSYS17, which allows importing a 3D model of the building, the geometry had to be defined from scratch. For each zone, every wall and window had to be numerically defined according to its area, category and surroundings. Besides defining the building envelope geometric characteristics, in order to complete the model it is necessary to add the internal gains, heating, cooling, infiltration and ventilation settings as inputs.

The Type 56 building model allows TRNSYS users to obtain the desired outputs as soon as this model is integrated with other units, such as TYPE 15 Weather data and TYPE 33

Psychometrics. These outputs can be user-defined in TRNBuild, where the default ones are the air temperature and the sensible energy demand for each zone.

Type 56’s mathematical model is described in this section and it is based and partially extracted from the manual “Multizone building modelling with Type 56 and TRNBuild” published by the University of Wisconsin-Madison, from where the subsequent equations were drawn [54].

This building model is, as stated previously, a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and other capacities that can be closely connected to the air node, such as furniture. Therefore, the node capacity is a separate input from the zone volume.

By default, TRNBuild considers that the thermal zones are entirely empty and full of air, thus accounting for a thermal capacitance of 1.2 times the zone volume. But this is rarely the case because rooms are usually filled with objects. Hence, this value is difficult to determine, by virtue of the amount of furniture that exists in each division, along with the type materials of which they are made of.

After approaching this topic in conversation with an expert from TESS, which is the leading group of researchers on TRNSYS building simulations, a value of 5 times the volume of the room was recommended as a standard rule when defining the thermal capacitance of any zone.

The model used by Type 56 is based on the Heat Balance Method (HBM), which consists of heat balances on the interior and exterior surfaces of opaque constructive elements as well as glazing and the air inside the zone. Each of the heat fluxes vary throughout the day as the sun changes position in the sky and as the outdoor ambient and radiation temperature changes. Some assumptions are made by this model, such as considering a uniform interior temperature within a zone, diffuse radiative surfaces and unidimensional conduction throughout the surfaces. This method can be broken down into an energy balance to the exterior surfaces, an energy balance to the inner surfaces and an energy balance in the air. The process of energy balance accounts for a daily analysis of the inner and outer surfaces of the zone temperatures, including the effect of thermal inertia. As for the internal loads within the zone, it is necessary to distinguish sensible and latent gain according to each internal gain type [55].

In order to comprehend the mathematical model used in Type 56 it is important to understand the energy balance that exists for each point of this nodal structure. Considering a control volume that encompasses the thermal zone and the air that surrounds it, it is easy to understand that there are three major methods of heat transfer within the zone: convection, radiation and conduction. In any building, these three mechanisms occur at the same time and the scenario modelled in Type 56 is an aggregate of them all.

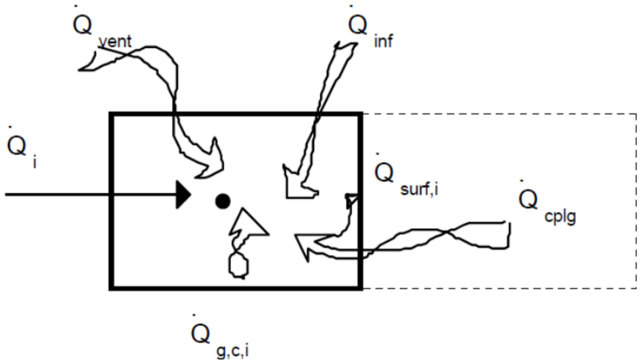


Figure 47 - Convective heat balance on the zone air node [54]

Convective heat transfer occurs when there is an airflow that is circulating between two adjacent zones with an adjacent surface, thus heating or cooling the respective divisions. This boundary surface should be perfectly insulated so as not to account for conductive transfers, while allowing the air to flow. In this model it accounts for the convective heat gain from the inner surface of a zone, $\dot{Q}_{surf,i}$, alongside with the convective gains by infiltration $\dot{Q}_{inf}$, ventilation $\dot{Q}_{vent}$, internal gains $\dot{Q}_{g,c,i}$ (by people, equipment, illumination, etc.) and the convective gains due to air flow from the boundary condition $\dot{Q}_{cplg}$. Thereby, the convective heat balance $\dot{Q}_i$ is determined by the following equation:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf} + \dot{Q}_{vent} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg}$$

Radiation is a physical phenomenon of energy transfer that occurs in the form of electromagnetic radiation as a result of absorption, emission and scattering processes. In Type 56 it is calculated by:

$$\dot{Q}_r = \dot{Q}_{g,r,i} + \dot{Q}_{sol} + \dot{Q}_{long} + \dot{Q}_{wall-gain}$$

Where:

$\dot{Q}_r$ represents the radiative gain for the wall surface temperature node,

$\dot{Q}_{g,r,i}$ is the radiative internal gains received by the wall,

$\dot{Q}_{sol}$ is the solar gains through the windows, received by the walls,

$\dot{Q}_{long}$ is the long-wave radiation exchange between this and all other walls and windows, with $\varepsilon_i = 1$,

And finally, $\dot{Q}_{wall-gain}$ is the user-specified heat flow to the wall or window surface.

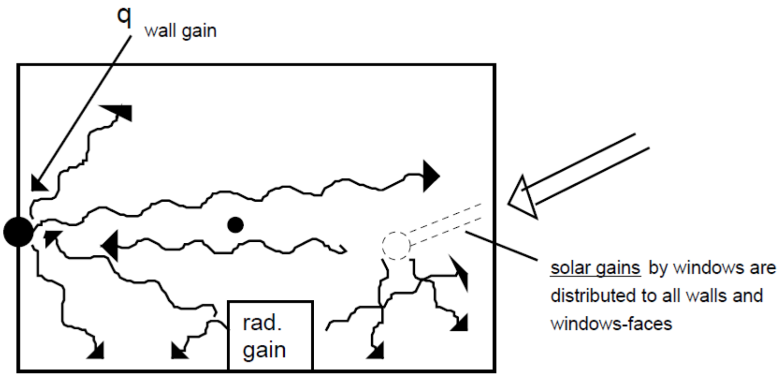


Figure 48 - Radiative energy flows considering one wall with its surface temperature node [54]

Heat transfer between two zones can also occur through conduction, when those zones are adjacent to one another and the heat is only transferred through walls, windows, etc. In order to ensure that there is no air mass circulating from one zone to the other, there should be no physical openings that allow natural air circulation.

The following figure shows the black box model of a wall, which characterizes its thermal behaviour by conduction:

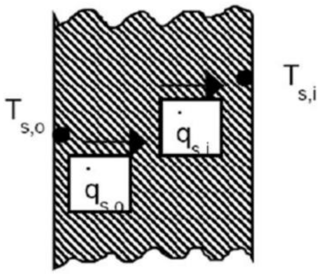


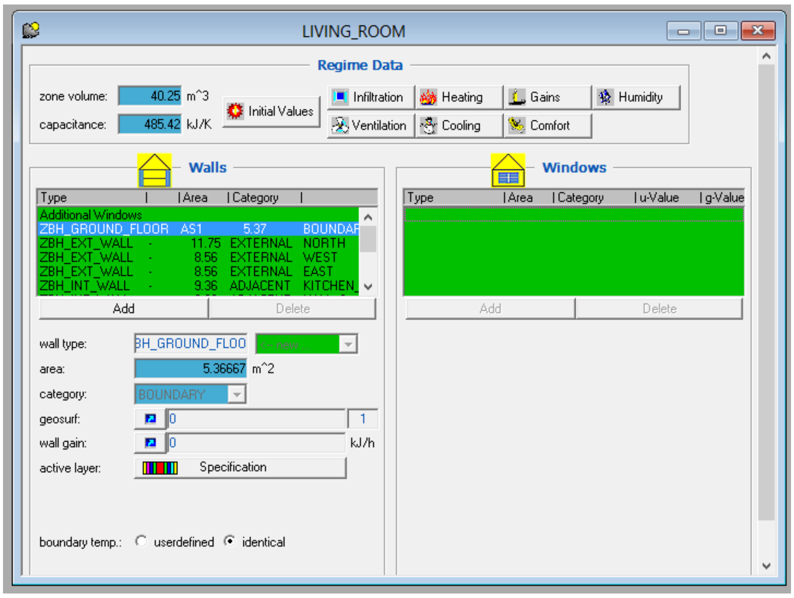
Figure 49 - Black box model of a wall [54]

In this software, the walls are modelled according to the transfer function relationships of Mitalas and Arseneault [56,57,58] defined from surface to surface. For every wall, the heat conduction at the surfaces is given by:

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k$$

$$\dot{q}_{s,0} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,0}^k$$

Where $\dot{q}_{s,i}$ represents the conductive heat flux from the wall at the inside surface and $\dot{q}_{s,0}$stands for the conductive heat flux into the wall at the outside surface. These time series equations in terms of surface temperatures and heat fluxes are evaluated at equal time intervals. The subscript *k* refers to the term in the time series and the coefficients *a*, *b*, *c* and *d* are determined within the Type 56 model by using z-transfer functions present in literature. [57]



zone volume: 40.25 m^3
capacitance: 485.42 kJ/K

Type		Area	Category	
Additional Windows				
ZBH_GROUND_FLOOR	AS1	5.37	BOUNDAR	
ZBH_EXT_WALL	-	11.75	EXTERNAL	NORTH
ZBH_EXT_WALL	-	8.56	EXTERNAL	WEST
ZBH_EXT_WALL	-	8.56	EXTERNAL	EAST
ZBH_INT_WALL	-	9.36	ADJACENT	KITCHEN_

Type	Area	Category	u-Value	g-Value

wall type: BH_GROUND_FLOO
area: 5.36667 m^2
category: BOUNDARY
geosurf: 0 1
wall gain: 0 kJ/h
boundary temp.: ○ userdefined ● identical

Figure 50 - Zone modelling in TRNBUILD

For every zone several inputs had to be considered, starting with the zone volume and thermal capacitance. The relation between these two parameters was defined in the previous subchapter.

Then it is necessary to add the geometry of each zone by defining every wall and window that it integrates. When adding a new wall to the zone, some parameters need to be added, and they can differ depending on the category of each wall, but it is always essential to define the wall type, its area, category, the value of “geosurf” and respective wall gain.

Every wall is composed by several layers that in TRNBuild are specified in the Layer Type Manager window. There are four types of layers that can be used: massive, massless, active and chilled ceiling. In this particular project, the first three types of layers are used.

In order to define a massive layer one needs to enter the material's thermal conductivity, alongside with its specific heating capacity and volumetric mass, whereas for the massless layer, only the thermal resistance needs to be specified. An active layer is used when there is a piping system with a fluid circulating in it, such as in underfloor heating systems. In this case, the user needs to identify the fluid's specific heat coefficient together with piping details such as the spacing from centre to centre, the outside diameter and wall thickness and also the thermal conductivity of the pipe wall. Subsequently, when selecting a wall/floor with an active system, the user needs to define the inlet temperature and the number of fluid loops, as well as the minimum desired and the minimum allowed inlet flow rate. Depending on the definition of these parameters, it might be necessary to define several segments. The first segment of a heating system will have the highest surface temperature, resulting in a higher heat flow to the room, while the next segments will be somewhat smaller and so on. There is an automatic specification tool, called "Autosegmentation" that is provided in order to ease the use of the active layer and to support a physically correct use [54].

In the Wall Type Manager window, the previously defined layer can be inserted from the inner to the outer part of the window, and by adding a thickness to each layer, a final reference U-Value is given. It is also important to add the convective heat transfer coefficient of the front and back part of each wall.

The wall category can be selected between external, internal, adjacent and boundary. Each one of these types will trigger a different combination of inputs that need to be added in order to fully define each wall. When adding an external wall the geographical orientation is one of the necessary parameters together with the “view factor to the sky”, which is a fraction of the sky to the total hemisphere seen by the wall (i.e. 1 for a horizontal surface, 0.5 for a vertical one). By selecting an internal wall, no extra inputs are needed, whereas if an adjacent wall is used, one has to enter the name of the zone that it is adjacent to and if it is the front or the back of this wall that belongs to this zone. Finally, by choosing a boundary wall, it is essential to define the boundary temperature, which can be identical to this wall or used-defined.

The value of “geosurf” represents the fraction of the total entering direct solar radiation that strikes the surface. The sum of all values of GEOSURF is not allowed to exceed 1within a zone and its default value. If the sum of values within a zone is zero, the direct radiation is distributed the same way as the diffuse radiation, by absorptance weighted area ratios [54].

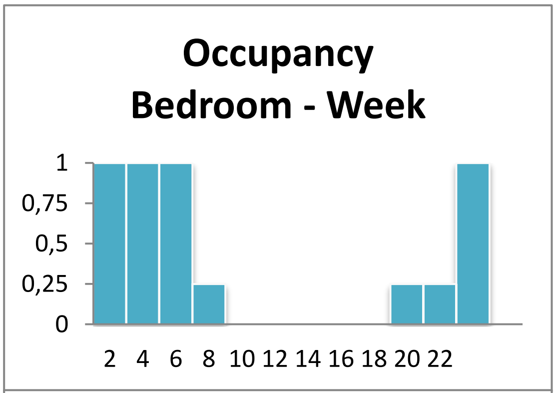
The user can also enter a wall gain which corresponds to an energy flux to the inside wall surface.

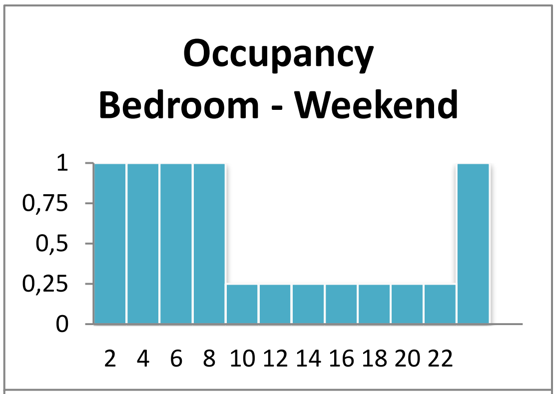
A window can also be added to a wall, where it would be needed to input the window type, its area, “geosurf” value, window gain, orientation, “view factor to the sky” and also if there is any internal or/and external shading factor.

By opening the Window Type Manager box, it is possible to define new window constructions by characterizing its glazing, frame, shading devices and the convective heat transfer coefficient of the entire window. The most important parameters needed to describe a window are its U-value, the area fraction between the frame and the window, and the glazing’s respective U-Value and g-value.

After having all these parameters entered, the model of building envelope is then finished, and the next step is to define the gains for each thermal zone.

ANNEX D – Schedules


Occupancy
Bedroom - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22


Occupancy
Bedroom - Weekend
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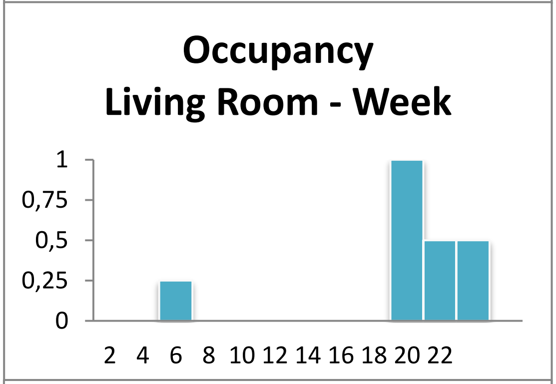
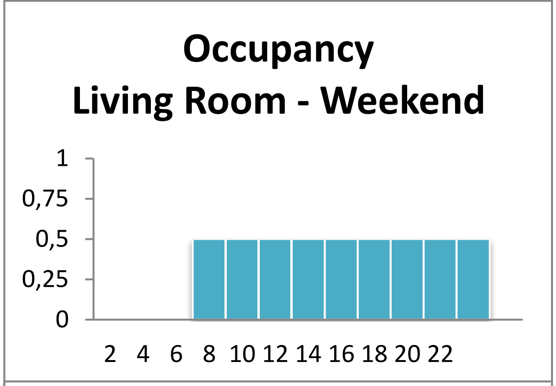
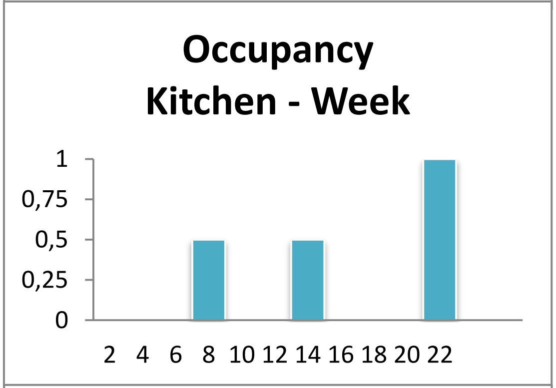
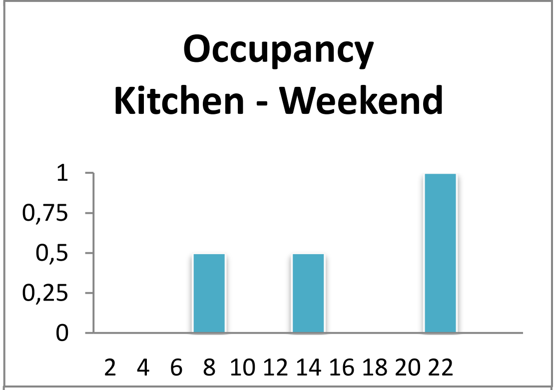
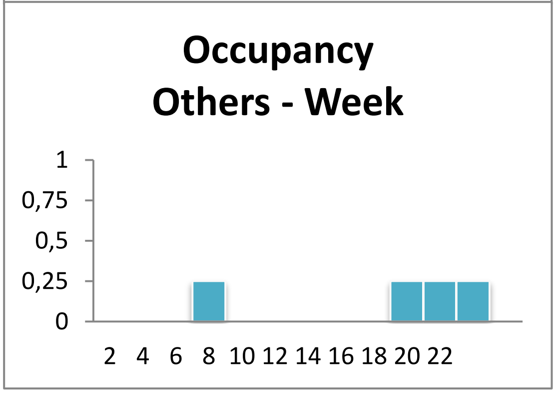
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

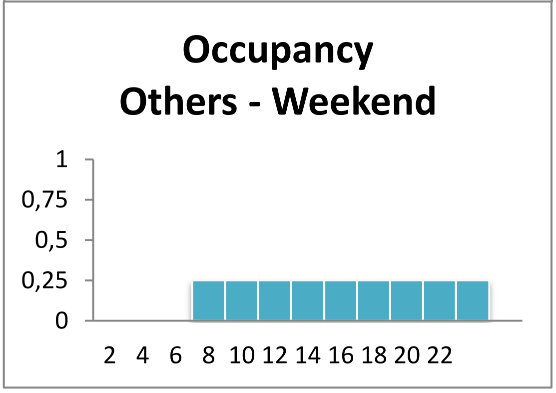

Occupancy
Living Room - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

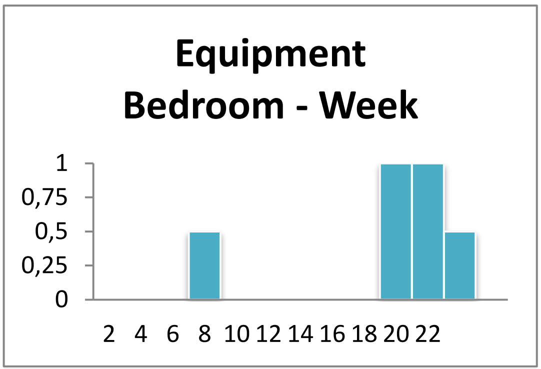

Occupancy
Living Room - Weekend
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

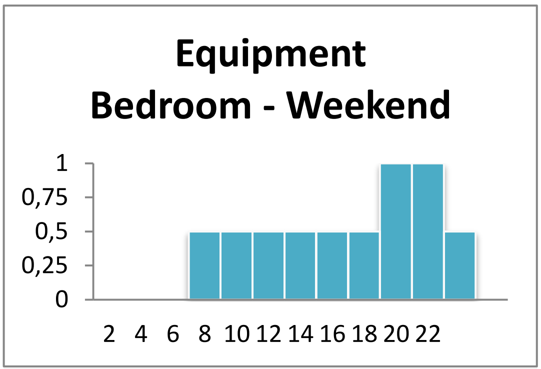

Occupancy
Kitchen - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

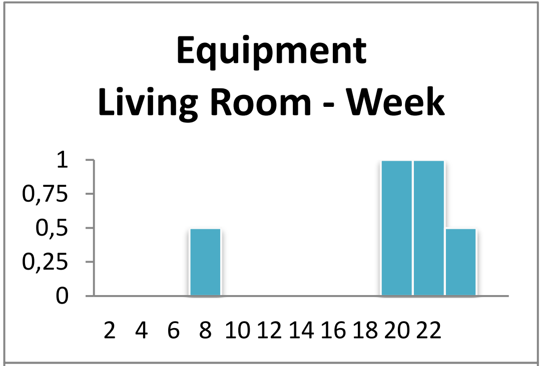

Occupancy
Kitchen - Weekend
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

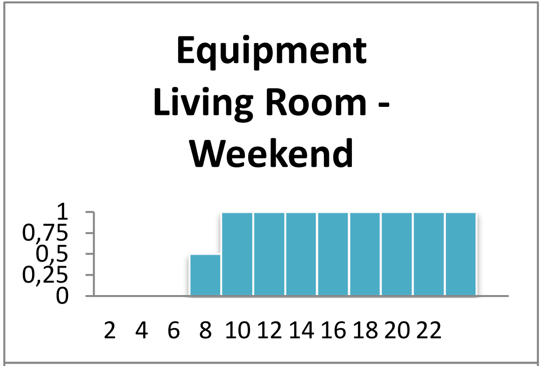

Occupancy
Others - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

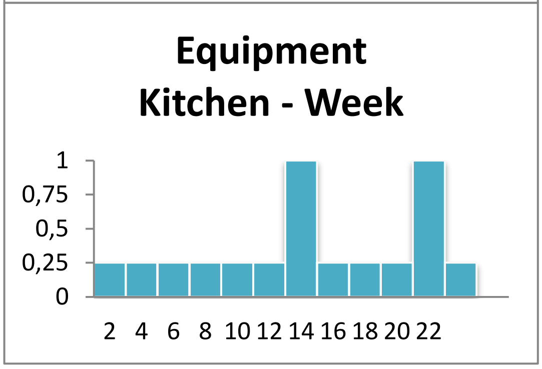

Occupancy
Others - Weekend
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

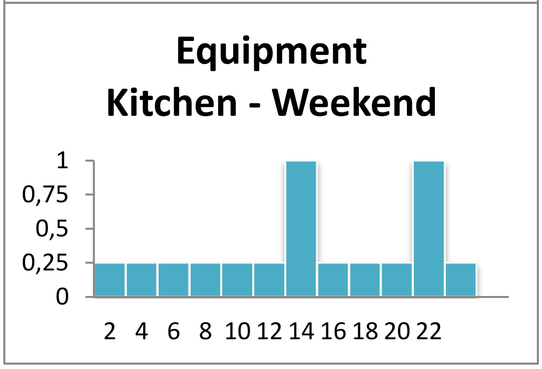

Equipment
Bedroom - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

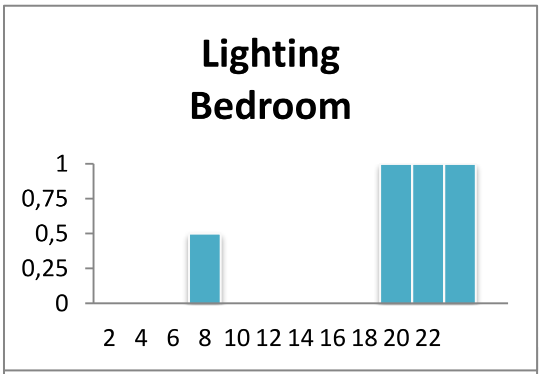

Equipment
Bedroom - Weekend
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

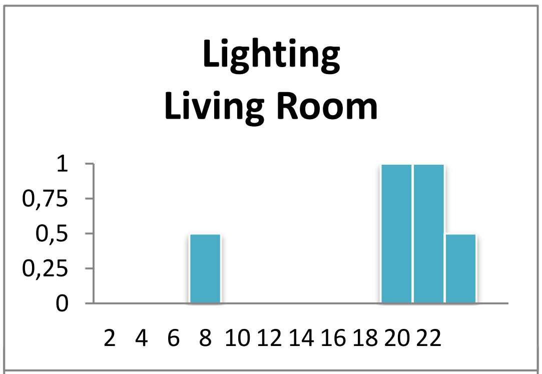

Equipment
Living Room - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

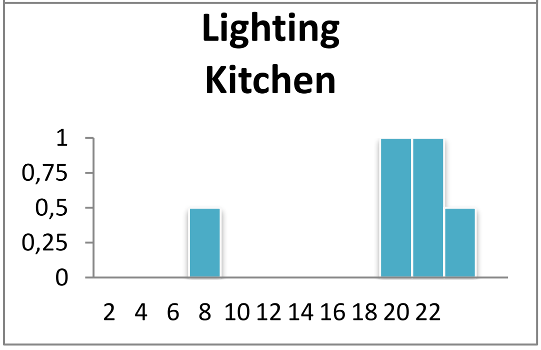

Equipment
Living Room - Weekend
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

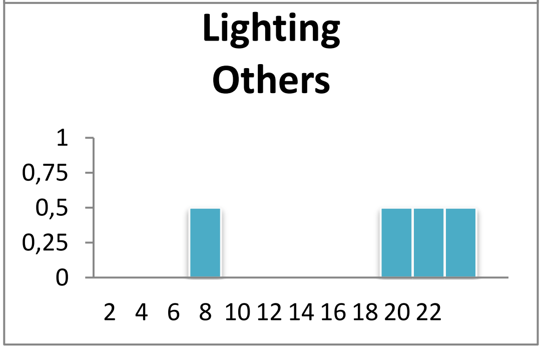

Equipment
Kitchen - Week
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22


Equipment
Kitchen - Weekend
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22


Lighting
Bedroom
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22


Lighting
Living Room
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22


Lighting
Kitchen
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22


Lighting
Others
1
0,75
0,5
0,25
0
2 4 6 8 10 12 14 16 18 20 22

ANNEX E – Solar Loft Gap

In the absence of wind, the first term of Bernoulli's equation can be neglected. The pressure loss resulting from the stack effect (ΔP_s) is a consequence of the density difference between two air masses with distinct temperatures and is given by the following equation:

$$\Delta P_s = \Delta\rho \cdot g \cdot \Delta h = (\rho_a - \rho_i) \cdot g \cdot \Delta h$$

Where:

ρ_a (T=27°C; P=101.325kPa)=1.176 kg/m^3

ρ_i (T=35°C; P=101.325kPa)=1.146 kg/m^3

g = 9.8 m/s^2

Δh = 2.4 m

Therefore:

$$\Delta P_s = (1.176 - 1.146) \cdot 9.8 \cdot 2.4 = 0.7056\, Pa$$

As for the wind, considering that it flows horizontally, Bernoulli's equation can be simplified, by neglecting the third term, to:

$$\frac{\rho \cdot v^2}{2} + P = Const.$$

The resultant pressure loss caused by this phenomenon (ΔP_w) can be obtained from the following equation:

$$\Delta P_w = cp \cdot \frac{\rho_a \cdot v^2}{2}$$

Where the first term (c_p) is a pressure coefficient that is used for each façade of the building and that depends on the wind direction. For buildings with three stories or less in height, the pressure coefficient for each wall is given by the following function:

$$cp(\phi) = \frac{1}{2} \cdot \begin{aligned} &\{[c_p(1) + c_p(2)] \cdot (\cos^2\phi)^{\frac{1}{4}} + [c_p(1) - c_p(2)] \cdot (\cos\phi)^{\frac{3}{4}} \\ &+ [c_p(3) - c_p(4)] \cdot (\sin^2\phi)^2 + [c_p(3) - c_p(4)] \cdot (\sin\phi)\} \end{aligned}$$

Where:

cp(1) is the pressure coefficient when wind is at 0°,

cp(2) is the pressure coefficient when wind is at 180°,

cp(3) is the pressure coefficient when wind is at 90°, cp(4) is the pressure coefficient when wind is at 270°,

and Φ is the wind angle measured clockwise from the normal to the wall.

The following table shows typical values for the pressure coefficients obtained from the measured data used to develop the harmonic function from Akins et al. (1979) and Wiren (1985) [60].

Table 44 - Typical pressure coefficients

cp (1)	0.6
cp (2)	0.3
cp (3)	-0.65
cp (4)	-0.65

When the wind angle (Φ) is normal to the wall, Φ=0:

$$cp(0) = 0.6$$

In addition to the pressure coefficient, in order to determine the pressure loss given by the effect of the wind, it is necessary to identify the wind speed (v) of this infiltration. Resorting to Climate Consultant software it is possible to study the average wind speed between the months of May and September, when it is more likely for the Solar Loft to overheat, as can be seen in the following figures:

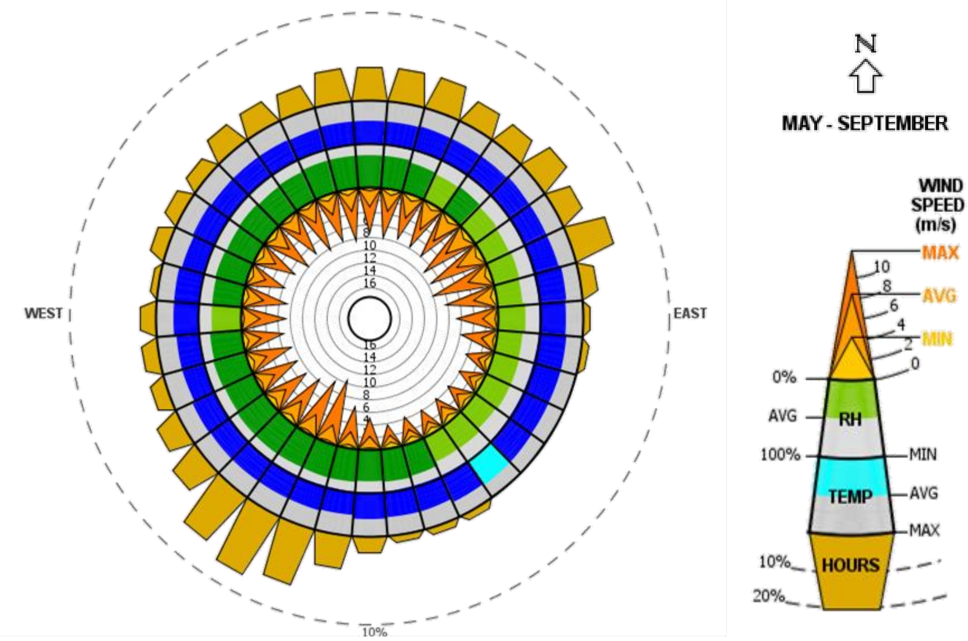


Figure 51 - Wind wheel in London from May to September (according to Climate Consultant software)

Table 45 - Average wind speed in London from May to September (according to Climate Consultant software)

Monthly average wind speed (m/s)	May	June	July	August	September	Average
	4	1	3	2	1	2.2

Considering an average wind speed of 2,2m/s for this period, the pressure loss caused by the effect of the wind will be:

$$\Delta P_w = 0.6 \cdot \frac{1.176 \cdot 2.2^2}{2} = 1.7076$$

thus, totalling the global pressure loss in:

$$\Delta P_g = \Delta P_s + \Delta P_w = 0.7056 + 1.7076$$

$$\Delta P_g = 2.4132\ Pa$$

Once the global pressure loss is calculated, it is possible to determine the velocity at which air is flowing inside the Solar loft, and it is given by the following equation:

$$V = \sqrt{\frac{2 \cdot \Delta P_g}{\rho}} = \sqrt{\frac{2 \cdot 2.4132}{1.176}} = 2.0259$$

As stated previously, in order to guarantee that the inside temperature on the Solar Loft does not exceed 35°C, it is necessary have 25 air changes per hour in that zone. The volumetric air flow that enters this zone can then be calculated by multiplying the air change rate and its volume:

$$\dot{V} = 25ACH\ \cdot 32.15m^3 = 0.2233\ m^3/s$$

Subsequently, the area through which the air is infiltrating the building can be easily found using the following equation:

$$A = \frac{\dot{V}}{V} = \frac{0.2233}{2.0259} = 0.1102\ m^2$$

The south façade, where the gap is located, has a length (l) of 4.7m and in order to dimension the gap, its height has to be determined:

$$h = \frac{A}{l} = \frac{0.1102}{4.7} = 0.0234\ m = 23.4mm$$

Therefore, by restricting a minimum rate of 25 air changes per hour, the gap in the Solar Loft needs to be at least 23.4mm high, along the whole façade.

ANNEX F – Ventilation

According to Building Regulations Part F -Ventilation

Zone	**Volume [m^3]**	**Min Extract Rate [L/s]**	**Min Airflow [m^3/h]**	**92% Eff Min Airflow/0,92 [m^3/h]**	**Min Extract ACH**
WC	6.775	8	28.8	31	4.6
KITCHEN/ DINING ROOM	55.94	13	46.8	52	0.9
BATHROOM	11.12	8	28.8	31	2.8
ENSUITE BATHROOM	9.25	8	28.8	31	3.4
ZBH	**263**	**37**	**133.2**	**145**	**0.6**

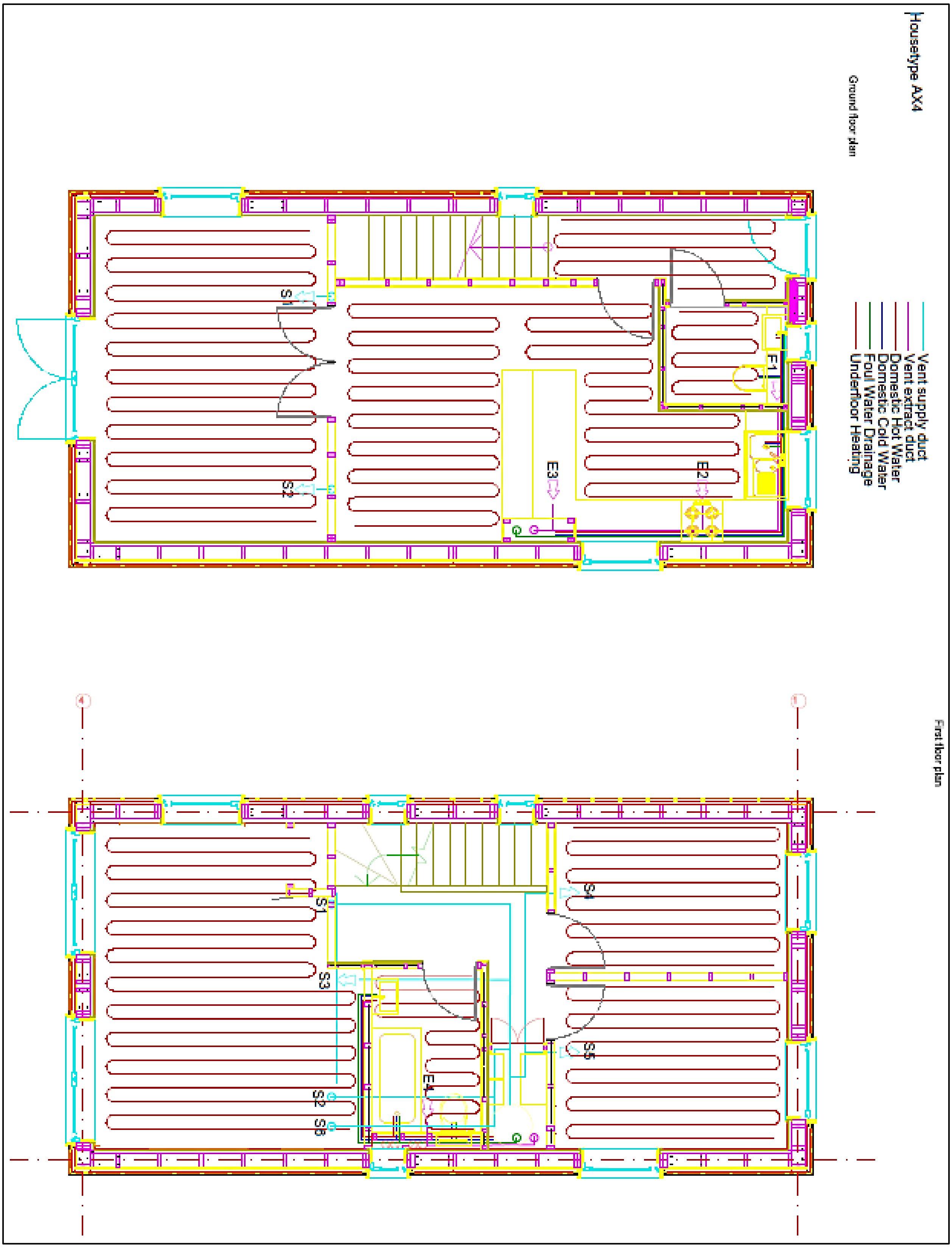
4 Bedrooms in dwelling	
Min Whole Dwelling Ventilation Rate [L/s]	25

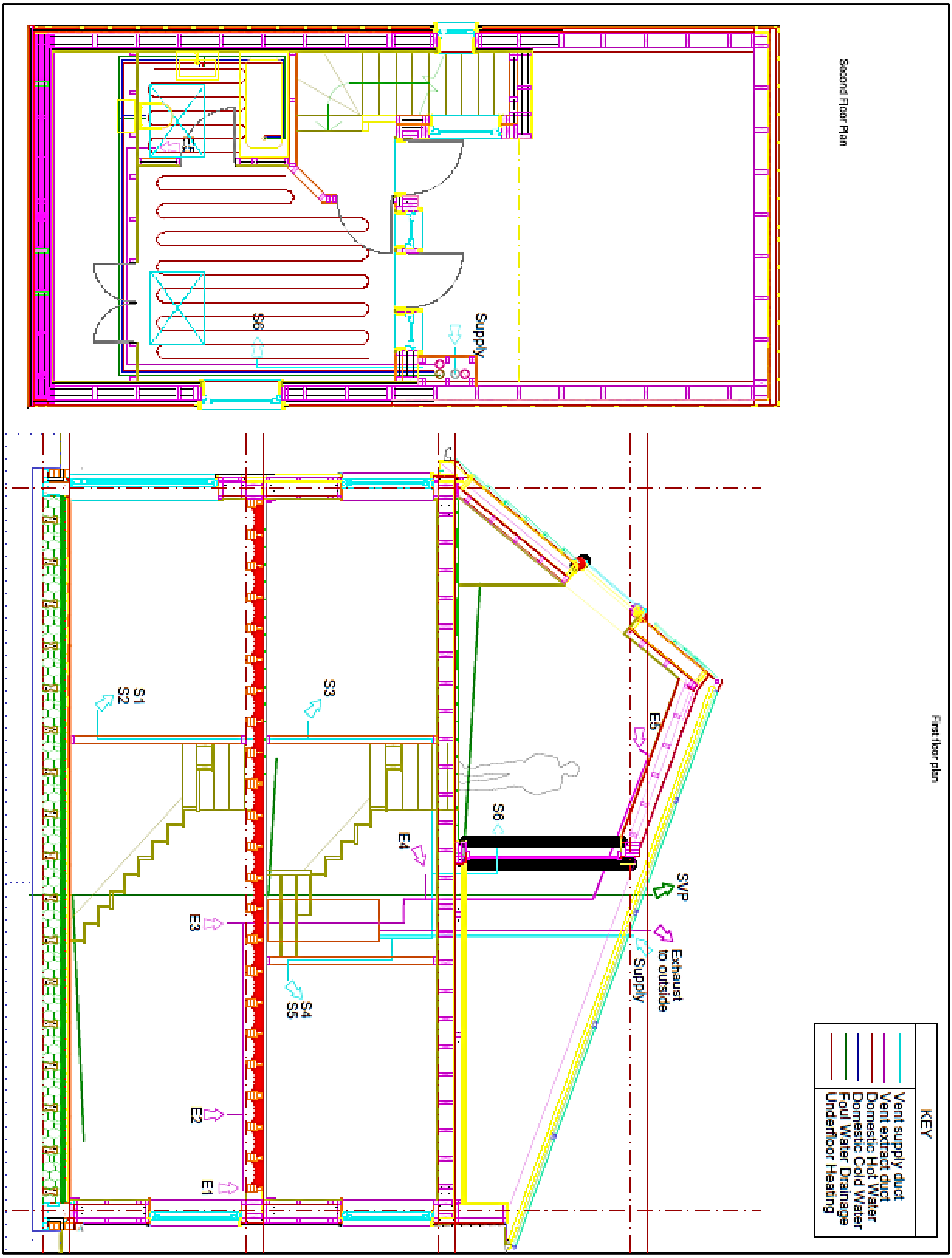
Zone	**V [m^3]**	**A [m^2]**	**Min Supply Rate per Room [L/s]***	**Min Supply Rate [L/s]****	**Min Airflow [m^3/h]**	**92% Eff Min Airflow [m^3/h]**	**Min Supply ACH**
LIVING ROOM	40.25	16.1	4.83	20	72	78	1.9
BEDROOM 1	43.78	17.5	5.25	5.25	18.9	21	0.5
BEDROOM 2	18.83	7.5	2.25	2.25	8.1	9	0.5
BEDROOM 3	21.25	8.5	2.55	2.55	9.18	10	0.5
MASTER BEDROOM	29.52	11.4	3.42	7	25.2	27	0.9
ZBH	**263**	**-**	**-**	**37**	**133.38**	**145**	**0.6**

*min supply rate = 0,3L/s per m2

**add 4L/s per occupant

ANNEX G – CAD Drawings


Housetype AX4
Ground floor plan
First floor plan
Vent supply duct
Vent extract duct
Domestic Hot Water
Domestic Cold Water
Foul Water Drainage
Underfloor Heating
S1
S2
E2
E3
F1
S1
S3
S4
S5
E4
S2
S8


Second Floor Plan
First floor plan
Supply
S6
E1
S1
S2
S3
E5
S6
E4
SVP
Exhaust to outside
Supply
E3
S4
S5
E2
E1
KEY
Vent supply duct
Vent extract duct
Domestic Hot Water
Domestic Cold Water
Foul Water Drainage
Underfloor Heating

ANNEX H – Mechanical Ventilation Heat Recovery

HRU ECO 4

Suitable for new builds and high and low rise buildings, the Itho HRU ECO 4 is one of the most energy efficient whole house ventilation and heat recovery systems on the market, with a Specific Fan Power (SFP) as low as 0.46 W/l/s and a heat recovery efficiency of 91%.

SAP Appendix Q eligible, the HRU ECO 4 is fitted with a sophisticated synthetic heat exchanger offering maximum surface area for heat to be transferred, along with a quiet energy saving DC motor for maximum efficiency.

Technical Information

- The HRU ECO 4 has a specific fan power (SFP) of 0.46 W/l/s.
- The heat exchange efficiency of the HRU ECO 4 is 91%.
- Ducting within the dwelling should be 204mm x 60mm modular plastic or 125mm diameter rigid plastic ducting. NOTE: Connections to the unit are 150mm diameter.
- The HRU ECO 4 comes with two G3 filters.
- Dimensions: height 848mm, width 730mm, depth 477mm.
- Condensate discharge diameter: 40mm external.
- The HRU ECO 4 comes in two versions- Apartment and House. The Apartment version has all four duct connections at the top of the unit: The House version has both the "fresh air supply to" and "stale air extract from" the dwelling connections at the bottom of the unit.

HRU ECO 4 variations available (supplied with silencer).

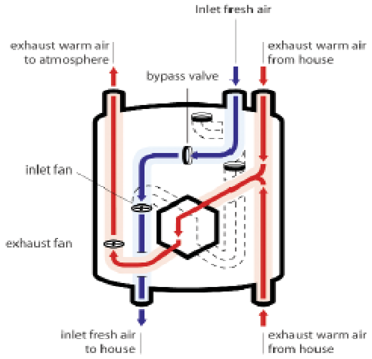
UK CODE	PRODUCT	m3/hr	Voltage
105-0058	HRU ECO 4 (House) 5 core cable	325	230
105-0060	HRU ECO 4 (House) RF supplied with one Controller	325	230
105-0059	HRU ECO 4 (Apartment) 5 core cable	325	230
105-0061	HRU ECO 4 (Apartment) RF supplied with one Controller	325	230

Ventilation for all seasons...

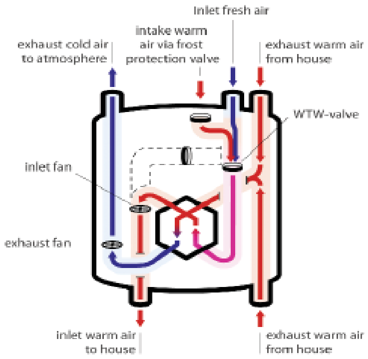
100% summer bypass valve diverts incoming air away from the heat exchanger to prevent warm outside air being further heated.

An integral frost protection device prevents the unit from freezing during the colder months.

Example based on House Version



Example based on House Version



Technical Information

	Capacity [m³/h]	Pressure [Pa]	Power [W]*	Current [A]*	Voltage [V]*	Cos phi *	Thermal efficiency [%]
Mode 1 Minimum mode	50	10	8	0.05	230	0.07	98
Mode 1 Low mode	75	20	12	0.1	230	0.55	98
Mode 2 Medium mode	150	40	29	0.24	230	0.53	96.2
Mode 2 Medium mode	150	80	38	0.31	230	0.53	96.2
Mode 3 High mode	225	100	74	0.59	230	0.59	94
Mode 3 High mode	225	150	88	0.69	230	0.56	94
Mode 3 High mode	275	100	106	0.83	230	0.56	93
Mode 3 High mode	275	150	126	0.99	230	0.56	93
Mode 3 Maximum mode	325	100	156	1.22	230	0.56	92
Mode 3 Maximum mode	325	150	176	1.36	230	0.56	92

The right to make changes is reserved 9.04

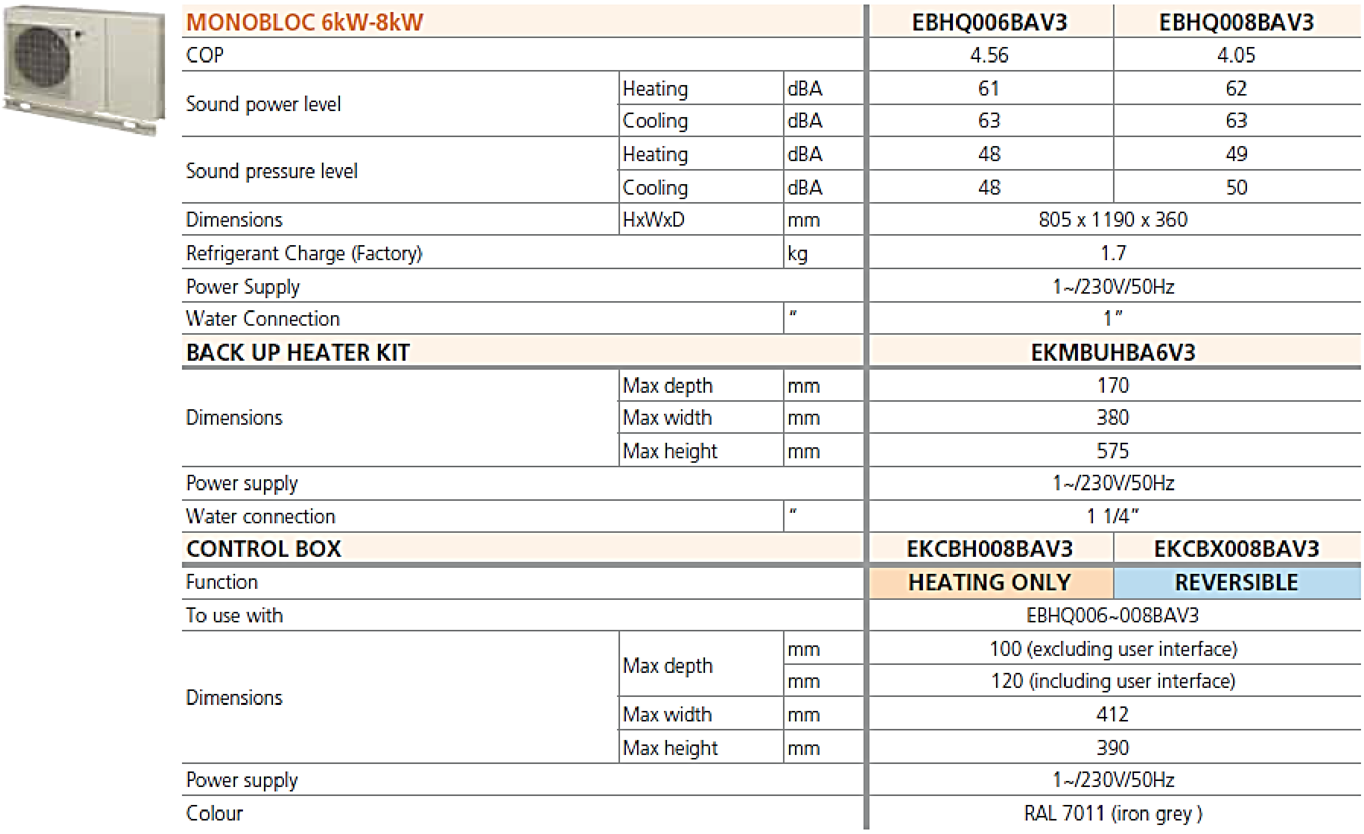
3.3

* Values to be used in the EPC calculation at 230V, according to NEN5128.

Other technical specifications

Power supply:	230V	Condensate discharge diameter:	40mm external
Frequency	50Hz	Filterclass:	G3
Dimensions:	height 848mm width 730mm depth 477mm		

ANNEX I – Air Source Heat Pump



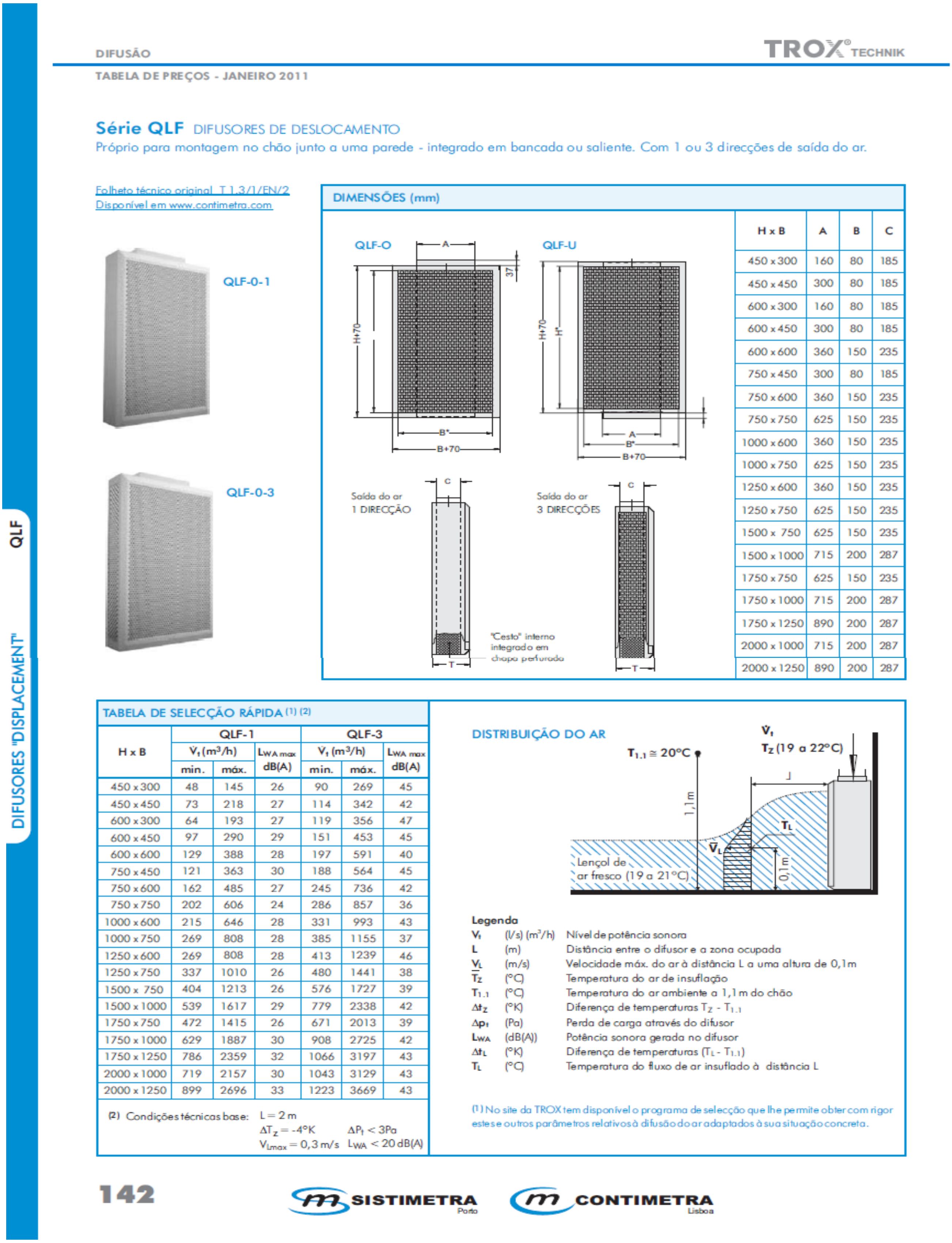
MONOBLOC 6kW-8kW			EBHQ006BAV3	EBHQ008BAV3
COP			4.56	4.05
Sound power level	Heating	dBA	61	62
	Cooling	dBA	63	63
Sound pressure level	Heating	dBA	48	49
	Cooling	dBA	48	50
Dimensions	HxWxD	mm	805 x 1190 x 360	
Refrigerant Charge (Factory)		kg	1.7	
Power Supply			1~/230V/50Hz	
Water Connection		"	1"	
BACK UP HEATER KIT			**EKMBUHBA6V3**	
Dimensions	Max depth	mm	170	
	Max width	mm	380	
	Max height	mm	575	
Power supply			1~/230V/50Hz	
Water connection		"	1 1/4"	
CONTROL BOX			**EKCBH008BAV3**	**EKCBX008BAV3**
Function			**HEATING ONLY**	**REVERSIBLE**
To use with			EBHQ006~008BAV3	
Dimensions	Max depth	mm	100 (excluding user interface)	
		mm	120 (including user interface)	
	Max width	mm	412	
	Max height	mm	390	
Power supply			1~/230V/50Hz	
Colour			RAL 7011 (iron grey)	

Measuring conditions:

Heating Ta DB/WB 7°C/6°C - LWC 35°C (DT=5°C)

Cooling Ta 35°C - LWE7°C (DT=5°C) *E(D/B)L* models can reach -20°C

ANNEX J – Air supply diffusers



DIFUSORES "DISPLACEMENT" QLF

DIFUSÃO

TROX TECHNIK

TABELA DE PREÇOS - JANEIRO 2011

Série QLF DIFUSORES DE DESLOCAMENTO

Próprio para montagem no chão junto a uma parede - integrado em bancada ou saliente. Com 1 ou 3 direcções de saída do ar.

Folheto técnico original T 1.3/1/EN/2
Disponível em www.contimetra.com

DIMENSÕES (mm)

H x B	A	B	C
450 x 300	160	80	185
450 x 450	300	80	185
600 x 300	160	80	185
600 x 450	300	80	185
600 x 600	360	150	235
750 x 450	300	80	185
750 x 600	360	150	235
750 x 750	625	150	235
1000 x 600	360	150	235
1000 x 750	625	150	235
1250 x 600	360	150	235
1250 x 750	625	150	235
1500 x 750	625	150	235
1500 x 1000	715	200	287
1750 x 750	625	150	235
1750 x 1000	715	200	287
1750 x 1250	890	200	287
2000 x 1000	715	200	287
2000 x 1250	890	200	287

TABELA DE SELECÇÃO RÁPIDA (1) (2)

H x B	QLF-1			QLF-3		
	$\dot{V}_t$ (m³/h)		$L_{WA\,max}$ dB(A)	$\dot{V}_t$ (m³/h)		$L_{WA\,max}$ dB(A)
	min.	máx.		min.	máx.	
450 x 300	48	145	26	90	269	45
450 x 450	73	218	27	114	342	42
600 x 300	64	193	27	119	356	47
600 x 450	97	290	29	151	453	45
600 x 600	129	388	28	197	591	40
750 x 450	121	363	30	188	564	45
750 x 600	162	485	27	245	736	42
750 x 750	202	606	24	286	857	36
1000 x 600	215	646	28	331	993	43
1000 x 750	269	808	28	385	1155	37
1250 x 600	269	808	28	413	1239	46
1250 x 750	337	1010	26	480	1441	38
1500 x 750	404	1213	26	576	1727	39
1500 x 1000	539	1617	29	779	2338	42
1750 x 750	472	1415	26	671	2013	39
1750 x 1000	629	1887	30	908	2725	42
1750 x 1250	786	2359	32	1066	3197	43
2000 x 1000	719	2157	30	1043	3129	43
2000 x 1250	899	2696	33	1223	3669	43

(2) Condições técnicas base: L = 2 m
ΔT_Z = -4°K ΔP_t < 3Pa
V_{Lmax} = 0,3 m/s L_{WA} < 20 dB(A)

DISTRIBUIÇÃO DO AR

Legenda

V_t	(l/s) (m³/h)	Nível de potência sonora
L	(m)	Distância entre o difusor e a zona ocupada
$\underline{V}_L$	(m/s)	Velocidade máx. do ar à distância L a uma altura de 0,1m
$\overline{T}_Z$	(°C)	Temperatura do ar de insuflação
$T_{1.1}$	(°C)	Temperatura do ar ambiente a 1,1 m do chão
Δt_Z	(°K)	Diferença de temperaturas T_Z - $T_{1.1}$
Δp_t	(Pa)	Perda de carga através do difusor
L_{WA}	(dB(A))	Potência sonora gerada no difusor
Δt_L	(°K)	Diferença de temperaturas (T_L - $T_{1.1}$)
T_L	(°C)	Temperatura do fluxo de ar insuflado à distância L

(1) No site da TROX tem disponível o programa de selecção que lhe permite obter com rigor estes e outros parâmetros relativos à difusão do ar adaptados à sua situação concreta.

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SISTIMETRA Porto
CONTIMETRA Lisboa

ANNEX K – Air exhaust valves

Dimensions · Installation Details · Quick Selection Table

Dimensions

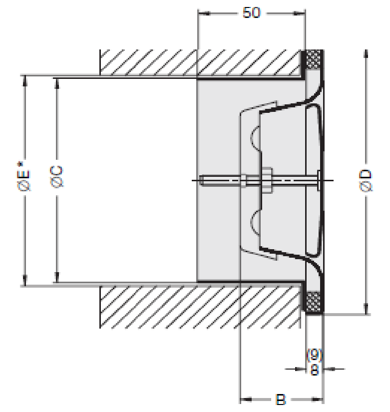
Type	Size	B	ØC	ØD	$ØD_1$	ØE*	Weight in kg
LVS	100	40	99	132	125	104	0.200
	125	46	124	162	150	129	0.290
	160	54	159	205	185	164	0.440
	200	61	199	245	225	204	0.590
Z-LVS	100	40	99	132	125	104	0.230
	125	46	124	162	150	129	0.320
	160	54	159	205	185	164	0.500
	200	61	199	245	225	204	0.670

* Dimension E must be adjusted according to the line used!

Quick selection table (for nomenclature see page 4)

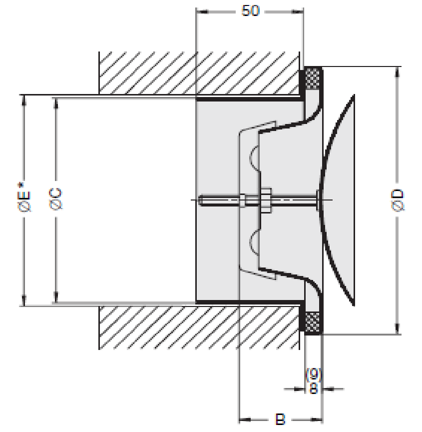
Type	Size	$\dot{V}$ in m³/h	$\dot{V}$ in l/s	Δpt in Pa	L_{WA} in dB(A)	L in m
LVS s = 0 mm	100	115	32	130	40	–
	125	180	50	135	40	–
	160	260	72	125	40	–
	200	350	97	110	40	–
Z-LVS s = 12 mm	100	100	28	37	40	1.7
	125	155	43	77	40	2.5
	160	235	65	90	40	4.0
	200	290	81	90	40	4.6

LVS



( ) – NW 160/200

Z-LVS

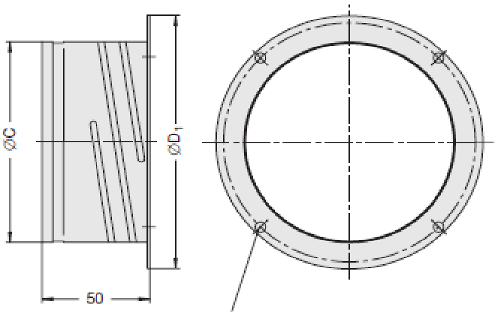


( ) – NW 160/200

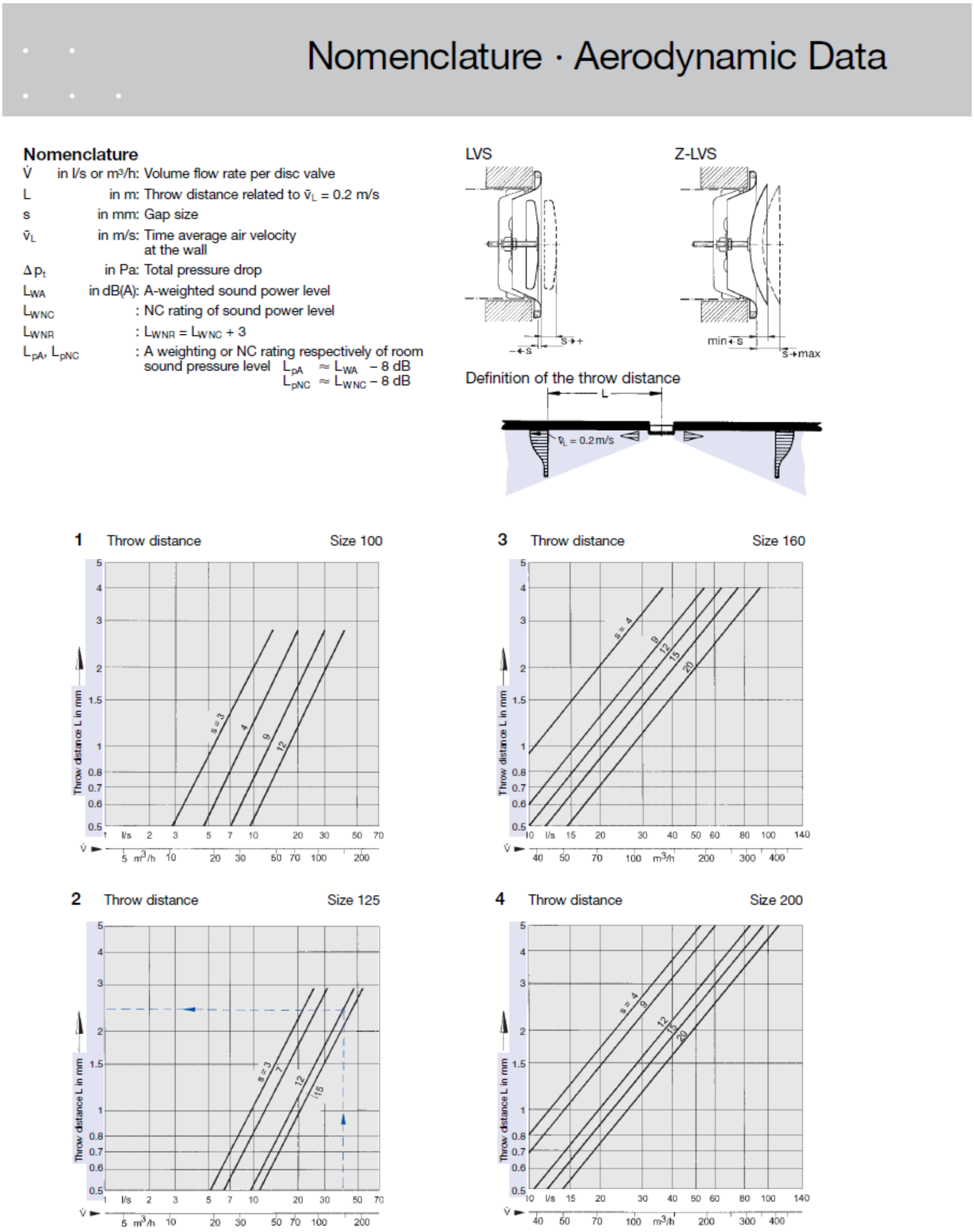
Installation Details

The LVS and Z-LVS units are supplied with subframe.
A bayonet fixing is used to locate the unit in the subframe.

Installation subframe for LVS and Z-LVS



Mounting the installation subframe with screws through the holes provided in the flange.



Nomenclature · Aerodynamic Data

Nomenclature

$\dot{V}$ in l/s or m³/h: Volume flow rate per disc valve

L in m: Throw distance related to $\bar{v}_L = 0.2$ m/s

s in mm: Gap size

$\bar{v}_L$ in m/s: Time average air velocity at the wall

Δp_t in Pa: Total pressure drop

L_{WA} in dB(A): A-weighted sound power level

L_{WNC} : NC rating of sound power level

L_{WNR} : $L_{WNR} = L_{WNC} + 3$

L_{pA}, L_{pNC} : A weighting or NC rating respectively of room sound pressure level $L_{pA} \approx L_{WA} - 8$ dB, $L_{pNC} \approx L_{WNC} - 8$ dB

Definition of the throw distance

1 Throw distance Size 100

2 Throw distance Size 125

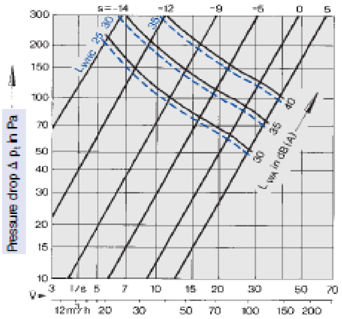
3 Throw distance Size 160

4 Throw distance Size 200

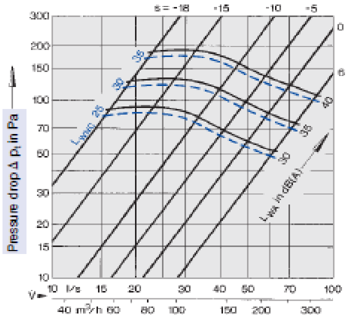
Acoustic Data – Extract Air · Supply Air

Extract air – Sound power level and Pressure drop – **Type LVS**

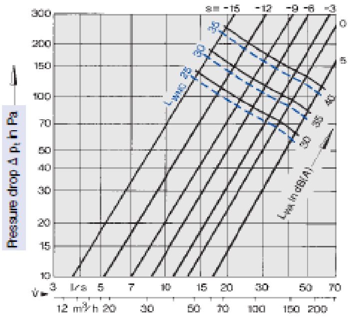
5 Size 100



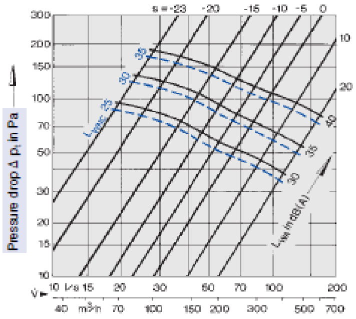
7 Size 160



6 Size 125

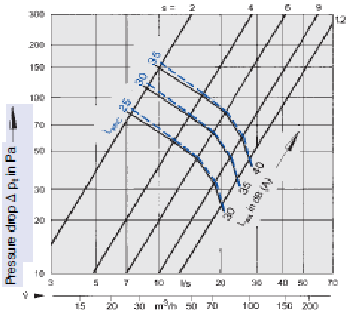


8 Size 200

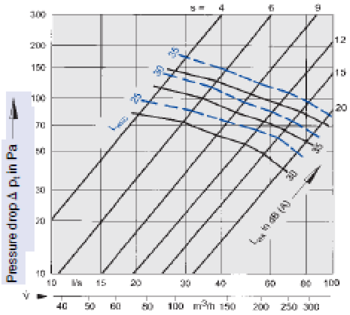


Supply air – Sound power level and Pressure drop – **Type Z-LVS**

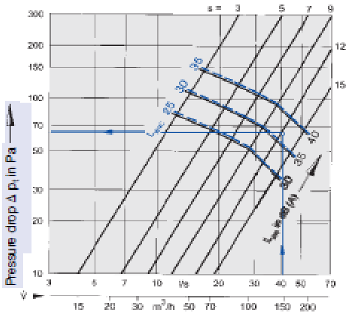
9 Size 100



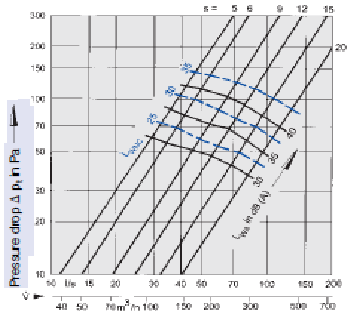
11 Size 160



10 Size 125



12 Size 200



Example

Data given:
Z-LVS / Size 125
Volume flow
per disc valve $\dot{V}$ = 40 l/s
Gap size s = 12 mm

Diagram 10:
Sound power level and Pressure drop
L_{WA} = 37 dB(A) (L_{WNC} = 32 NC)
Δ p_t = 65 Pa

Diagram 2: Throw distance
L = 2.4 m

At a distance of L = 2.4 m, the time average air velocity $\bar{v}_L$ = 0.2 m/s.

ANNEX L – Supply air ducts

n	Qsupply [m3/h]	Qsupply [l/s]	Vmax [m/s]	Area needed [m2]	Duct diameter [m]	Area [m2]	V [m/s]
OUTSIDE	145	40	2.5	0.0161	0.160	0.0201	2.00
S1+S2+S3+S4+S5+S6	145	40	2.5	0.0161	0.160	0.0201	2.00
S1+S2+S3+S6	126	35	2.5	0.0140	0.160	0.0201	1.74
S1+S3	60	17	2.5	0.0067	0.125	0.0123	1.36
S1	39	11	2.5	0.0043	0.080	0.0050	2.16
S3	21	6	2.5	0.0023	0.080	0.0050	1.16
S2+S6	66	18	2.5	0.0073	0.125	0.0123	1.49
S2	39	11	2.5	0.0043	0.080	0.0050	2.16
S6	27	8	2.5	0.0030	0.080	0.0050	1.49
S4+S5	19	5	2.5	0.0021	0.125	0.0123	0.43
S4	9	3	2.5	0.0010	0.080	0.0050	0.50
S5	10	3	2.5	0.0011	0.080	0.0050	0.55

Critical Branch : S1+S2+S3+S4+S5+S6 - S1+S2+S3+S6 - S1+S3 - S1

n	ΔP/L	L	ΔP friction loss	Co	ρ	ΔP local loss	ΔP
S1+S2+S3+S4+S5+S6	0.27	0.4	0.11	2.54	1.2	6.12	6.22
S1+S2+S3+S6	0.30	0.4	0.12	1.17	1.2	2.13	2.25
S1+S3	0.33	1	0.33	2.08	1.2	2.30	2.63
S1	0.27	8.62	2.33	0.48	1.2	1.34	3.67

ANNEX M – Exhaust air ducts

n	Qexhaust [m3/h]	Qexhaust [l/s]	Vmax [m/s]	Area needed [m2]	Duct diameter [m]	Area [m2]	v [m/s]
OUTSIDE	145	40	2.5	0.0161	0.160	0.0201	2.00
E1	31	9	2.5	0.0034	0.080	0.0050	1.71
E2	25.5	7	2.5	0.0028	0.080	0.0050	1.41
E1+E2	56.5	16	2.5	0.0063	0.125	0.0123	1.28
E3	25.5	7	2.5	0.0028	0.080	0.0050	1.41
E1+E2+E3	82	23	2.5	0.0091	0.125	0.0123	1.86
E4	31	9	2.5	0.0034	0.080	0.0050	1.71
E5	31	9	2.5	0.0034	0.080	0.0050	1.71
E4+E5	62	17	2.5	0.0069	0.125	0.0123	1.40

Critical Branch : E1 - E1+E2 - E1+E2+E3

n	ΔP/L	L	ΔP friction loss	Co	ρ	ΔP local loss	ΔP
E1	0.39	2.91	1.13	0.21	1.2	0.37	1.50
E1+E2	0.25	2.15	0.54	3.65	1.2	3.58	4.12
E1+E2+E3	0.52	2.32	1.21	2.63	1.2	5.44	6.64

ANNEX N – Embodied Carbon

Embodied Carbon

Material	Total Volume [m3]	Volumetric Mass [kg/m3]	Weight [kg]	EC Factor [kg CO_2/kg]	Total EC [kg CO_2]
Timber					
Softwood Timber	7.81	500	3907	-0.58	-2266
MDF	19.09	800	15273	-0.58	-8858
OSB	0.93	650	606	-0.58	-352
Plywood	0.85	545	461	-0.58	-267
Hardwood	1.30	500	651	-0.58	-377
Insulation					
Mineral Wool	64.51	33	2129	1.20	2555
EPS	30.63	15	459	2.55	1171
Plaster					
Plasterboard	16.51	680	11227	0.38	4266
Ceramics					
Terra Cotta Brick	6.35	1430	9073	0.74	6714
Terra Cotta Tile	0.85	2000	1692	0.74	1252
Cement					
Screed	7.75	2100	16284	0.17	2785
Aggregate					
Gravel	7.05	2400	16920	0.01	88
Plastics					
PEX	0.08	950	77	2.02	156
Glazing					
Windows and Doors	see table below				1508
PV Pannels					
Monocrystalline Cells	see table below				9620
Alluminium	0.08	2700	206	11.46	2364
Rubber	0.02	1100	18	2.66	47
TOTAL					**17906**
TOTAL per m2					**149**

Windows and Doors	Area [m2]	[kg CO2/m2]	Total EC [kg CO2]
Double Glazing	17.74	85	1508

PV Cells	Area [m2]	[kg CO2/m2]	Total EC [kg CO2]
Monocrystalline Cells	48.16	199.75	9620

Carbon Neutral

Annual Electrical Generation	6769	kWh
Annual Electrical Demand	4562	kWh
Annual Electrical Surplus	2207	kWh

kg CO_2 produced per kWh by the UK National Grid	0.527	$kgCO_2/kWh$
Annual Electric Carbon Payback (grid equivalent)	1163	kg CO_2
Embodied Carbon in Building Construction	17906	kg CO_2

Number of years until Carbon Neutral	15	years