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Investigating the potential of energy flexibility in an office building with façade BIPV and a PV parking system

Dissertação para obtenção do Grau de Mestre em

Engenharia Electrotécnica e de Computadores

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UNIVERSIDADE NOVA DE LISBOA

Janeiro, 2017

Dedicated to my parents who have always supported me.

Acknowledgements

During this thesis, I had the chance of getting the help of a lot of people, in different ways. In first place, I would like to give my greatest thank to my coordinators Dr.Laura Aelenei and Professor João Murta Pina. I also have to thank Professor Daniel Aelenei and Rui Lopes who helped me, in technical terms, to take the right path towards the aim of the thesis. Naturally, I thank Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa for these years of new experiences and consolidated knowledge. I thank to eng. Luís Alves Pereira from IAPMEI for providing me some exceptional data essential to the thesis. In Solar XXI, I had the help of eng. Ana Rute Ferreira, eng. Carlos Rodrigues and Ruben Alves who I thank for the patience and all the given support.

My personal acknowledgements are no less important, because no one can graduate without the support of family and friends. I start by thanking to my parents, who always believed in my capabilities and supported me along the graduation, my beloved sister Ana and Gonçalo, my grandparents, my aunt Mila, and my other aunt Celeste, that besides everything will always be present and ready to help me no matter what. A special thank to my grandmother, Maria, who is no longer with us but always said that study is the path to success in life. Particularly on this work I am grateful to have a great friend as João Branco, who directly helped in this thesis, as I am grateful to have my girlfriend Franziska Glas that always showed her love supporting me during the thesis period. I also thank Gabriel Anacleto for all these years of brotherhood and trust; to Flávio Jacinto for all the advice, support and all the exaggerations, which are also important occasionally and Ricardo Ferreira, for his honesty and constant presence in good and bad moments. In my academical life anTUNiA was really important for all the things that made me learn and the life lessons that made me grow as a person. In anTUNiA, I found friends for life, where I highlight Eduardo Pontes who always stood up for me in every kind of moments. I also thank my friends of anTUNiA, João Sénica, Miguel Santos, homonymous, Bernardo Melo, Luis Gonçalves, Paulo Fernandes, Fábio Pereira and António Silva who also shared a lot with me, being companions of music and party. 'Friends for life' are those kind of friends who we never forget and who become part of us, and so my big gratitude to Josefa Fula, André Vieira, Guilherme Pimentel, Vasco Pires and Fábio Leitão, people who were important so far in this journey, and will certainly carry on being there.

Abstract

Building Integrated Photovoltaic (BIPV), is becoming an attractive solution in the context of high penetration of photovoltaic systems in buildings caused by the strive to achieve net or nearly zero energy status. Besides retrieving solar radiation to produce electrical energy, BIPV also offers aesthetical advantages because of its architectural feature. However, when integrated into vertical façades, the angle of the Photovoltaic (PV) modules may considerably affect the efficiency of BIPV when compared with horizontally oriented modules in the same location and latitude.

This work reports on the electric energy performance of an office building, Solar XXI, located in Lisbon, Portugal, based on the opportunity of having two PV technologies in the same building. The system installed on the south façade is a BIPV (12 kWp) and the second is a parking lot PV installed in a nearby car park facility (12 kWp). This situation enables the comparison of Load Match Factors, but mainly Load Match Index, between the two systems. The use of small scale loads in energy flexibility operational measures to study the potential for flexible demand on an Net-Zero Energy Building (NZEB) office building is also possible. Two different scenarios were taken into development, from monitoring data obtained during March 2016 (winter period) and July 2016 (summer period). *PVGIS* is a tool used to verify the possibility of a PV optimization in the parking lot PV and *EnergyPlus* is used to create an energy consumption model of the building aiming to be validated by the real values.

Keywords: BIPV, Load Match Factors, Energy Flexibility, Load Shifting, Energy Efficiency in Buildings

Resumo

Building Integrated Photovoltaic (BIPV) começa a ser uma solução atractiva no contexto de sistemas fotovoltaicos em edifícios, tendo por objectivo atingir o estatuto de edifício zero ou quase zero em termos energéticos. Além do uso da radiação solar para produção de energia elétrica, o BIPV tambem oferece vantagens estéticas, tendo em conta a sua arquitectura. Quando integrado em fachadas verticais, o ângulo dos módulos PV pode afetar consideravelmente a eficiência do BIPV face a módulos orientados verticalmente na mesma localização e latitude.

Este trabalho descreve a performance energética de um edifício de serviços, o Solar XXI, localizado em Lisboa, Portugal, baseado na oportunidade de ter duas tecnologias PV no mesmo edifício. O sistema instalado na fachada virada a sul é um BIPV (12 kWp) e o segundo um PV instalado no parque de estacionamento do edifício (12 kWp). Esta situação permite a comparação entre os dois sistemas em termos de *Load Match Factors*, mas essencialmente de *Load Match Index*. É também possível utilizar pequenas cargas em medidas operacionais de flexibilidade energética com o objectivo de estudar o potencial desta flexibilidade. Dois cenários diferentes são apresentados, sendo que foram desenvolvidos a partir da recolha de dados obtidos em Março 2016 (Período de Inverno) e Julho 2016 (Período de Verão). A ferramenta *PVGIS* é utilizada para verificar uma possível optimização a fazer no PV do parque de estacionamento e o *EnergyPlus* é usado para criar um modelo de consumo energético do edifício com o objectivo de ser validado pelos valores reais.

Palavras-chave: *BIPV*, *Load Match Factors*, Flexibilidade Energética, *Load Shifting*, Eficiência Energética em edifícios.

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Acronyms

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers.

BAU Business as Usual.

BIPV Building Integrated Photovoltaic.

BIPV-T Building Integrated Photovoltaic - Thermal.

CD Cooling Dominated challenge.

CHP Combined Heat and Power.

DER Distributed Energy Resources.

DR Demand Response.

DSM Demand Side Management.

EES Energy Efficient Systems.

EPBD Energy Performance of Buildings Directive.

GHP Ground Source Heat Pumps.

GI Grid Interaction.

HCD Heating and Cooling Dominated challenge.

HD Heating Dominated challenge.

HVAC Heating, Ventilation and Air Conditioning.

LED Light-Emitting Diode.

LM Load Matching.

LMI Load Match Index.

LNEG Laboratório Nacional de Energia e Geologia.

LOLE Loss of Load Expectation.

LOLP Loss of Load Probability.

MPC Model Predictive Control.

nZEB Nearly Zero Energy Building.

NZEB Net-Zero Energy Building.

OCP Optimal Control Problems.

PA Passive Approach.

PV Photovoltaic.

RES Renewable Energy Systems.

SWH Solar Water Heating System.

TES Thermal Energy Storage.

var-RE Variable Renewable Energy.

ZEB Zero Energy Building.

Chapter 1

Introduction

1.1 Motivation

Nowadays Energy Efficiency in buildings is a more and more important subject, mainly because of the significant share that buildings have on the energy consumption scale. Finding solutions to this problem is a major objective from the scientific community, particularly on both renewable energies and building construction fields, hence a good interaction between this two becomes a crucial, at some extent necessary, matter. The enhancement of this same interaction follows the growth of an important concept, the concept of NZEB.

The work developed within this master thesis aims to reinforce the improvement of Energy Efficiency in Buildings, with the focus given to a particular study case - Solar XXI - the most well-known NZEB example in Portugal. Recognizing the lack of information about energy flexibility in NZEB was the real motivation for this work. During the data collection, the possibility of comparing parking lot PV with façade BIPV emerged, which was not found in the literature review, so this comparison became the main focus of this work always with energy flexibility study behind as the primary purpose.

1.2 Objectives

In this thesis, the main questions put into discussion are the potential for flexible demand in an office building with two different PV technologies, façade BIPV and a parking Lot PV, and their interaction in a matter of Load Match Index (LMI), for winter and summer periods. The State of the Art in the following chapter has the task of introducing all the meaningful concepts for the work, being Solar XXI, described in chapter 3, the study case for it.

Chapter 4 is a comprehensive outline of the methodology used to understand all the process, where an energy analysis is performed in detail with a time resolution of 15 minutes, to better interpret the load behaviour at the building. By taking the chance of having real data from two different PV technologies, it becomes possible to perform all the calculations useful to study LM.

EnergyPlus and *PVGIS* are tools implemented to simulate, respectively, real consumption and generation values of the building. *PVGIS* also has the function of investigating the optimization of the PV generated values.

Load Match Factors are essential to verify the different behaviour between two PV technologies to the same consumption values. To ascertain the building interaction with the distribution grid, LMI's have to be calculated to describe the degree of use of on-site energy generation related to the local energy demand. LM also checks if the optimization of the energy consumption by its user, is possible to achieve through energy consumption reduction measures.

The scope of Load Shifting is to validate the potential of the building energy flexibility as an operational measure of Demand Side Management (DSM), and to show how much flexibility is available at a given instant or interval of time during a day. PV generated energy is not 100% reliable because it is dependent on natural factors, meaning that energy flexibility can also help on avoiding periods of overproduction.

The aggregated LM and Energy Flexibility studies give a robust analysis on how good can the use of this NZEB be, as discussed in chapter 5.

The general scope of goals of this thesis, having in mind the work projected at Solar XXI, is given below.

Experiment at Solar XXI

- Perform detailed energy analysis using energy analysers with 15 minutes time resolution
- Use of *EnergyPlus* software and a survey to model the annual energy consumption
- Calculate Load Matching Factors using the detailed energy analysis data
- Through Load Matching Factors and Load Shifting analysis, verify Energy Flexibility potential

Chapter 2

State of the Art

The State of the Art comprehends the objective of displaying all the relevant concepts linked to the work, found out through an exhaustive literature review, containing a slight description of the main concepts to be accounted in the work. This is followed by an overview of the NZEB concept, with an extent set of known cases, finishing with central information regarding energy flexibility.

2.1 Net Zero Energy Building - NZEB

A real NZEB can be defined, as a building that is able to produce the same amount of energy as its consumption. The periodicity is an essential point regarding the benchmarking of this relation.

Such buildings need to have a particular care in a matter of energy efficiency during the design period, and this particular requirement gives the possibility to reach the general NZEB definition. With low energy consumption and good energy generation through renewable energies, it is possible to achieve the zero balance expected value.

As highlighted before the time resolution is critical when it comes to energy variations in a NZEB. The relationship between energy generation and consumption can be, for example, daily, or yearly, which is the typically employed time fraction, and in addition covering all the operation settings concerning the meteorological conditions is essential. Even if the building can produce a high amount of energy by renewable technologies, in order to be considered a NZEB, the consumption levels also need to be low, always depending on its users.

These buildings will have a significant role in the near future of our planet. For instance, if one analyses the values, the level of energy consumption from commercial and residential buildings match 40% of the primary energy and 70% of electrical energy in United States of America [1]. Other data shows that the energy used by the construction sector continues to increase, electrical energy consumption in the commercial building sector doubled between 1980 and 2000 and is expected to increase another 50% by 2025 [1].

Europe has been giving more importance and credibility to NZEBs. The proof is that Energy Performance of Buildings Directive (EPBD) recast established that all state members of European Union have to guarantee from 2021 on that all new buildings need to be Nearly Zero Energy Building (nZEB). From 2019 on all the new public buildings need to be as well nZEB [2]. Figure 2.1 shows an exceptional example of a public building considered a NZEB presented in Subtask C of Solar Heating and Cooling Programme of the International Energy Agency [3].

Figure 2.1: NZEB example of a primary school in Italy [4]

2.1.1 Conventional definitions

A variety of authors defined Zero Energy Building (ZEB) differently depending on the objectives to achieve and its characteristics.

According to Torcellini [5] the definition of a ZEB is a residential or commercial building with greatly reduced energy needs, through efficiency gains and construction techniques using renewable resources instead of fossil fuels. Iqbal [6] defines *Zero energy home* or a *Residential Zero Energy Building* in a similar way but considering only residential buildings.

Globally, four ZEB definitions can be coined [5] [7], *Net Zero Site Energy*, *Net Zero Source Energy*, *Net Zero Energy Cost* and *Net Zero Energy Emissions*.

Net Zero Site Energy is a ZEB that produces at least as much energy as it uses in a year when accounted for at the site [5].

Net Zero Source Energy is a ZEB that produces at least as much energy as it uses in a year when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a total source energy of the building, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers or energy carriers [5].

Net Zero Energy Costs is a ZEB where the amount of money, that the owner receives, for the energy that the building exports to the grid, is at least equal to what this owner pays for the energy used over the year [5].

Net Zero Energy Emissions is a building that produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources [5]. If the building is over a year carbon neutral, it is considered *Zero Carbon Building*. These buildings can use electrical energy produced by CO_2 free sources, such as large windmills, nuclear power, and PV solar systems which are not integrated into the buildings or at the construction site [8].

Nevertheless, other authors defined different kinds of ZEB. Kilkis [9] explained a concept called *Net Zero Exergy Building* where quantity and quality (exergy) are considered. A *Net Zero Exergy Building* has a zero annual balance of exergy transfer, during all electric transfer, in a certain period of time, across the "*building-district boundary in a district energy system*".

The European Union Commission and Parliament have, in their recast of the Directive on the Energy Performance of Buildings [2], defined ZEB as "*a building that has a very high energy performance, determined in accordance with Annex I*". In Europe each country is giving its own nZEB definition regarding its position, necessity and objective having in mind the previous mentioned recast [10]. A nZEB should be covered by energy from renewable sources, including renewable energy produced on-site or nearby [2].

Laustsen [8] defined buildings depending on the kind of grid connection, where they can be 'self-sufficient', 'autonomous' or 'standalone'. A good definition for *Zero Stand Alone Buildings* could be "*a building that does not require connection to the grid or only as a backup*". This building has the supply capacity of all the energy that it needs and also to storage for night-time or winter time use.

The on-grid ZEB, also known as *Net Zero Energy*, *Grid Connected* or *Grid Integrated*, is always connected to one or more energy infrastructures, as electrical energy grid, district heating, and cooling system, gas pipe network, biomass, and biofuels distribution networks [7]. Therefore, it has the possibility of both purchasing energy from the grid and injecting energy to the grid.

Salom [11] also referred a concept related to ZEB called "prosumers" where these buildings are not only consumers but at the same time producers of heat and electrical energy.

It can be concluded, built on the literature review that, for now, there is still no standard and official definition for ZEB, due to the fact that a ZEB definition is always depending on the aim of its construction in terms of energy efficiency.

2.1.2 NZEB: Design

As discussed in the previous section 2.1.1, renewable sources in NZEB are fundamental to achieve most of the conventional definitions. The renewable sources can either be available on the site (e.g. sun, wind) or need to be transported to the site (e.g. biomass) [7]. The integration of these renewable sources is directly connected with the levels of comfort, efficiency and some of the NZEB characteristics. This integration also brings further issues concerning the interaction with the grid which will be reviewed in subsection 2.1.4.

Even if the investment in renewable energy generation in buildings is growing this proves not to be enough to reach a generic definition of NZEB. For that, on the design and construction stage, the building has to consider a big amount of characteristics to make possible the energy consumption reduction to maximum levels.

The building features should include, form and sun exposure; isolation of the walls, floor, and roof; window type and ventilation system.

The building's need to warm up in the winter and cool down in the summer is directly connected to all these design features. Its sun orientation in winter allows the interior comfort levels to rise, reducing the energy consumption in warm systems. The opposite situation also happens in the summer. The isolation of the walls and windows and the type of floor and roof are as well important to the energy balance, as these characteristics allow to maintain high temperatures inside the building in the winter and the high temperatures outside in the summer.

No less important are the kind of warm up and cool down systems. The most used and known are central heating and Heating, Ventilation and Air Conditioning (HVAC), but there are other solutions such as Building Integrated Photovoltaic - Thermal (BIPV-T) systems or earth-tubes. These will be explained in chapter 3.

Lighting represents just 10% of the total energy consumption of a building but concerning NZEB all kind of energy use reduction counts. The use of Light-Emitting Diode (LED) lamps is an extra cost but, in a long term, it can be a helpful way of reducing energy consumption.

If the building includes some of the mentioned characteristics, then it might reach one of the cited NZEB definitions present in 2.1.1.

NZEB: Characteristics

The following items are used as main NZEB characteristics and enabled the cross-case analysis presented in section 2.1.5.

- Building use, a building can be Office, Educational, Industrial, Commercial or Residential building.
- Net Floor Area, is the considered area of the building.
- Annual primary energy demand, is the value that shows the amount of primary energy which each building needs along one year.
- Annual primary energy generation, represents the capability of energy generation along one year.
- Annual primary energy balance, is the difference between Annual primary energy demand and generation.
- Climate Challenge, regards to if the building is Heating Dominated challenge (HD)[1], Heating and Cooling Dominated challenge (HCD)[2] or Cooling Dominated challenge (CD)[3].
- U-Value, indicates the heat transmission through a building part and if its low, indicates a better isolation of the building.
- g–value, is the solar heat gain or incident solar radiation of a building part.
- Heating and/or cooling system, includes Solar Water Heating System (SWH), BIPV, earth-tubes, Ground Source Heat Pumps (GHP) or Combined Heat and Power (CHP).

As mentioned below in *Energy Efficiency* and *Energy Comfort*, the first principle in the NZEB design focuses on decreasing the amount of energy demand through Passive Approach (PA). The second principle aims at implementing Energy Efficient Systems (EES), given the inherent needs of artificial lighting and possible heating and/or cooling. The Renewable Energy Systems (RES) are essential to offset the energy demand required for lighting, heating, and cooling [12].

This procedure enables the identification of the set of relevant NZEB design issues by combining the three previously mentioned issues as displayed on figure 2.2.

[1] For cold temperature countries.
[2] For temperate climate countries.
[3] For warm countries.

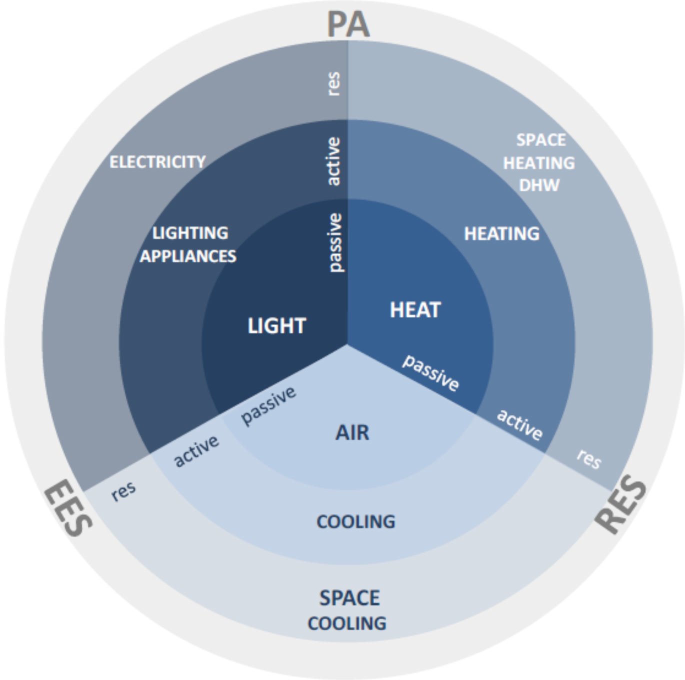


Figure 2.2: Overview of the three main design issues [12]

Energy Efficiency

Agency for Energy of Portugal (ADENE) [13] presents a brief definition of *Energy Efficiency*: *"The energy efficiency is the optimization of the energy consumption by its user"*, all this through energy consumption reduction measures without loss of comfort and unnecessary waste of energy. A real ZEB definition should first encourage energy efficiency, and then use renewable energy sources available on-site. Efficiency measures such as daylighting or combined heat and power devices cannot be considered on-site generation in the ZEB context. However, efficiency measures must have good persistence and should be "checked" to make sure they continue to be energy savers [5]. The main efficiency measure will be presented in figure 2.4.

There are two ways of expressing recommendations on energy efficiency: *prescriptive requirements*, applied to, for example, U-values of walls and windows or HVAC systems; *performance requirements*, used to energy needs, such as, heating, cooling, lighting or total weighted primary energy demand [14].

Passive sustainable design strategies play the main role concerning NZEB design as they directly affect the heating, cooling, ventilation and lighting loads put on the buildings mechanical and electrical systems, and indirectly, the strive for renewable energy generation [12].

Appliance of passive sustainable design strategies is achieved throughout the execution of [12]:

- Building energy demand reduction;
- Generation of electrical energy by means of RES aiming an effective energy balance.

The annual measurability of energy consumption is an excellent aspect of the net zero energy principle. By including the electrical energy consumption, the need to reduce the electrical demands is evident. Figure 2.3 covers a wide range of energy saving measures [15].

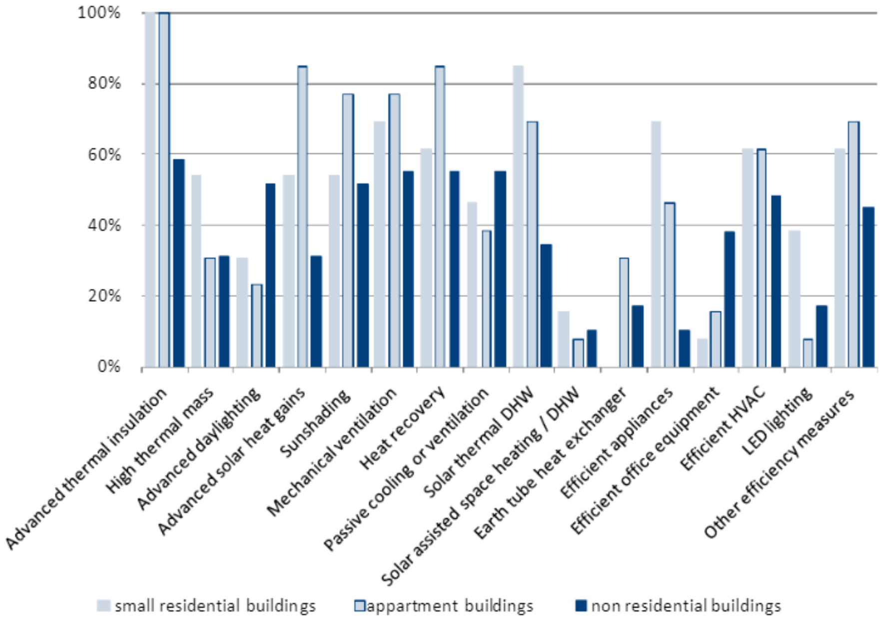


Figure 2.3: Selected Energy saving measures applied in Net ZEBs [15]

Energy Comfort

Energy Comfort is not the main focus on this work, being that the reason for presenting just a slight overview with the purpose of enhancing its importance in terms of energy efficiency in buildings.

Energy Comfort is a fundamental and increasingly relevant concept for the well-being of a human, leading also to a growth in terms of energy consumption. To reach a balance between comfort and consumption, a self-responsible behaviour from an individual is needed, which is possible even without neglecting the comfort part. Nowadays the high initial investment, needed to access ZEBs is still a barrier regarding most of the population.

Using passive strategies in a building is the best way to reduce discomfort indexes and at the same time, reduce the energy needs especially in heating and cooling matters [16].

Aelenei [17] says that the main principles applied in passive sustainable design are well known. The fundamental issue is to find if the same applies in ZEB design as well. The three main steps required to achieve the ZEB performance, are related to specific challenges in terms of lighting, heating and/or cooling and power generation. This procedure has the advantage of facilitating the identification of the set of relevant ZEB design issues, through a combination of PA, EES and RES which are more likely to succeed in reaching the desired energy performance. The three main design issues are well described in *NZEB: Characteristics*.

The Baruch Givoni psychrometric-bioclimatic chart 2.4 can be considered the easiest and most practical tool, based on the comfort zones defined in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, to know and understand the best way to use this passive measures [16].

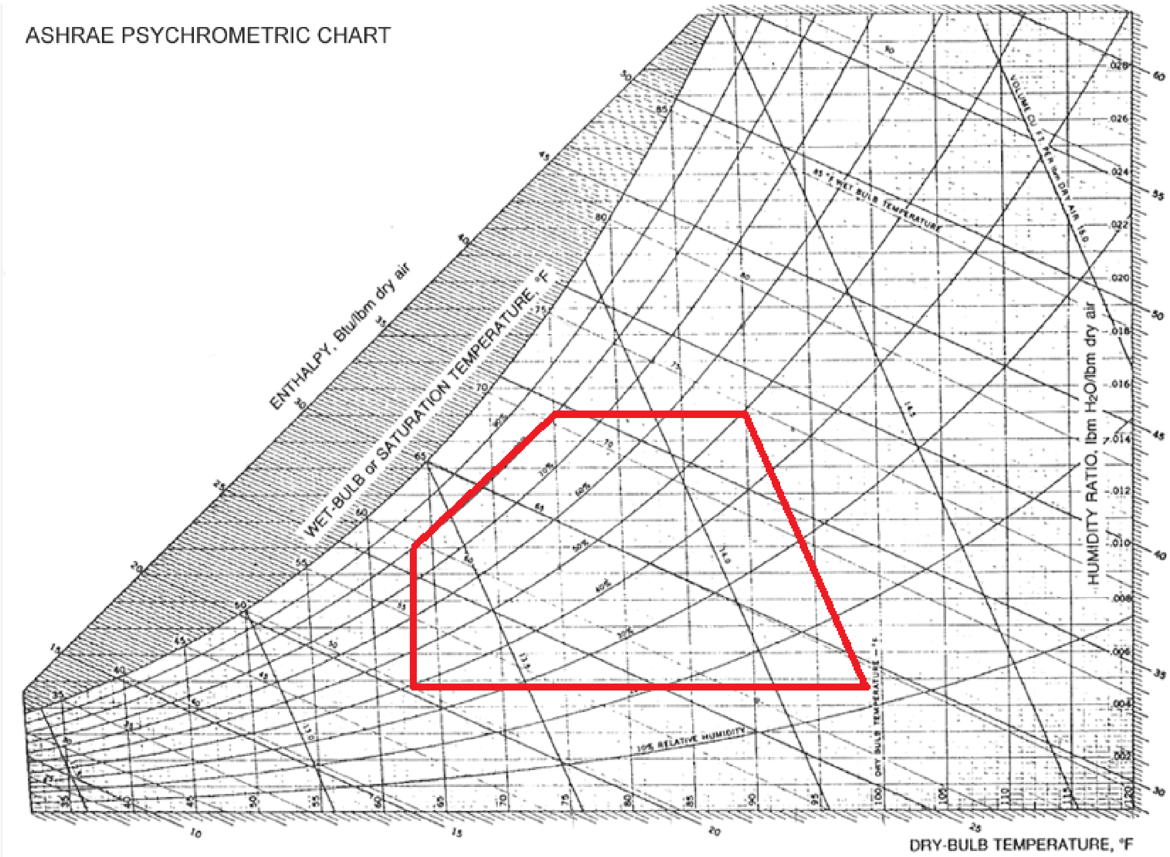


Figure 2.4: Baruch Givoni Psychrometric Chart [18]

This chart crosses 4 different scales including, Wet bulb or Saturation temperature, Enthalpy, Humidity ratio and Dry-bulb temperature. Each region in the planet can be displayed by an area on this chart, as an example, Solar XXI area stands out in red. Depending on the region, different bioclimatic strategies can be taken into account in terms of passive measures and other constructive characteristics towards better comfort indexes and energy building performance [19].

2.1.3 NZEB Boundaries

The definition of the goal will influence designers of buildings in conceiving high-performance infrastructures. The way a ZEB goal is defined is crucial to understand the combination of appropriate efficiency measures and renewable energy supply options.

The boundary of each case can be way larger than the building footprint, which is why there is a high importance of pre-defining boundary conditions as the first step of net balance calculations. A building or a cluster of buildings, depending on where the *system boundary* is placed, is characterized by the load and the types of load, and also by the energy generation capacity [20].

Renewable energy sources available on-site are used passively like solar gains through windows and actively like atmospheric or ground source heat pump to partially satisfy the load of the building. These on-site renewables are also used as energy generators that cover the load and are feed back into the grid, depending on the temporal matching between generation and load and the available storage possibilities [20].

These supply systems, to which a building may be connected, are named with the generalized term of energy grids, or simply grids.

Delivered energy is supplied by the grid to the building and *Feed-in energy* is the one produced but not used in the building and consequently flows to the grid.

The two primary boundary conditions are *System Boundaries* and *Weighting/Crediting System*.

Boundary Conditions

Sartori [14] defined *Building system boundary* as "*necessary to identify what energy flows cross the boundary*". *System Boundary* can be split as *Functionality and effectiveness*, that indicates which kind of building is it (Office, Educational, Residential). This type of boundary is important to check the energy needs of the building based on the population of the building. It can also be split in *Climate and Comfort*, which is also relevant because of the user behaviour and comfort needs that may change radically with the climate challenge considered [14]. The physical boundary is useful to identify if the generation system is within or without the boundary being respectively addressed as on-site or off-site.

Weighting/Crediting System

For the *Weighting System* Sartori [14] considers the four types of metrics mentioned in *ZEB definitions* [5]. This system *"converts the physical units of different energy carriers into a uniform metrics, hence allowing the evaluation of the entire energy chain"*.

Marszal [20] uses the same four type of metrics and includes exergy, environmental credits or even politically factors as deciding factors, but the term used is *Crediting System*.

2.1.4 Grid Interaction, Net Zero Balance and Load Matching in ZEB

The *Net Zero Balance* has to consider on-site generation and building loads (often called LM), and the resulting import/export interaction with the surrounding energy grid, commonly named Grid Interaction (GI).

Grid Interaction

In most of ZEB definitions, the building connection type to the grid is not considered. The only author who does this reference is Kilkis [9]. Marszal cites Kilkis indicating that *"due to different energy qualities between exported and imported energy, the utility grid is often in a worst position than the building"*, therefore proposes a Net Zero Exergy Building definition that better accounts for different energy qualities. It is stated that energy feedback into the grid has to have the same usability as the energy taken from the grid [7]. Figure 2.5 shows an overview of possible renewable supply options.

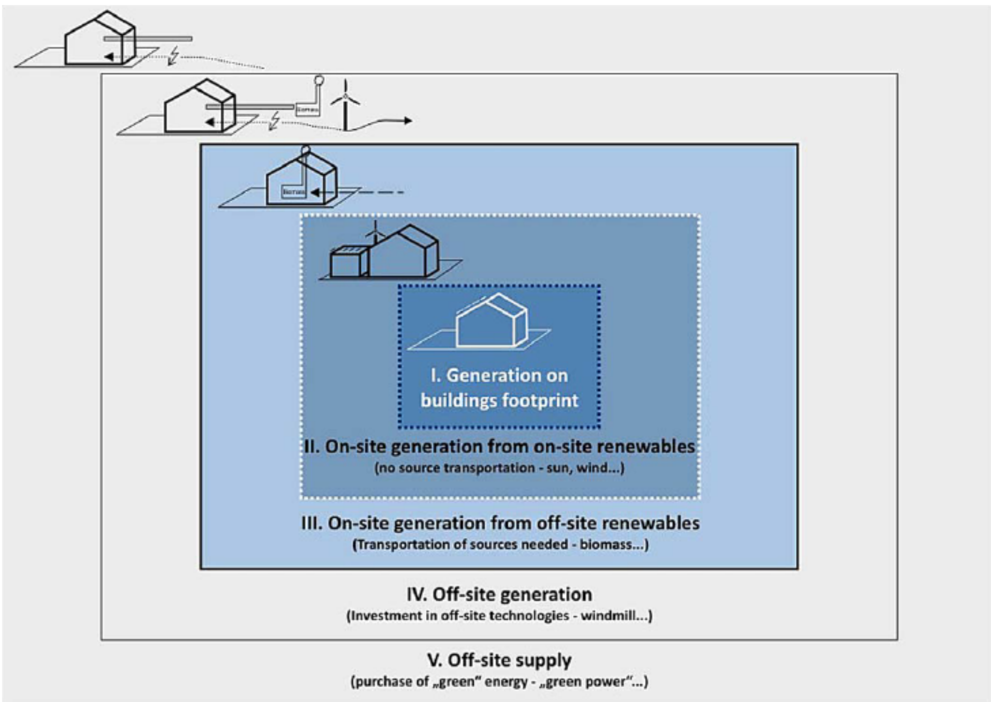


Figure 2.5: Overview of possible renewable supply options [7]

NZEBs are also part of a general concept of Distributed Energy Resources (DER), also known as *distributed generation*, and development in that DER units has to ensure the possibility of high power injections to the grid [11].

When the on-site generation is bigger than loads of the building, excess electrical energy is exported to the utility grid. By using the grid to account for the energy balance, excess generation can offset later energy consumption. Achieving a ZEB without the grid would be tough, as the current generation of storage technologies is limited [5]. Off-grid buildings may be grid independent, but for that, they rely on storage systems. These cannot feed their excess energy generation back onto the grid, so this energy is wasted if the storage capacity limit is reached.

Torcellini [5] developed a ranking of renewable energy sources in the ZEB context. Table 2.1 shows this ranking in order of preferred application.

Table 2.1: ZEB Renewable Energy Supply Option Hierarchy [5]

Option Number	ZEB Supply-Side Options	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.
On-Site Supply Options		
1	Use renewable energy sources available within the building's footprint	PV, solar hot water, and wind located on the building
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building.
Off-Site Supply Options		
3	Use renewable energy sources available off-site to generate energy on-site	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off-site, or waste streams from on-site processes that can be used on-site to generate electrical energy and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emissions credits, or other "green" purchasing options. Hydroelectric is sometimes considered.

Sartori defines that the GI index represents "*the variability (standard deviation) of the energy flow (net export) within a year, normalized on the highest absolute value*". The difference between exported and delivered energy, within a period of time, is the net export from the building, representing the grid interaction [14].

Grid Interaction Flexibility

An important characteristic from the viewpoint of the grids is the GI flexibility of a NZEB. This is understood as the grids ability to respond to signals, like price fluctuations, "*and consequently adjust load DSM, generation and storage control strategies*" aiming at serving more efficiently the grid and building needs together [21].

The GI flexibility has to be evaluated with a time resolution of an hour or preferably even less. The higher the flexibility, the better the buildings ability to adapt to signals from the grid, being this one important design strategy to improve the GI flexibility.

Flexibility is provided by the storage capacity in the building, or its ability to vary its load or curtail its generation system. *Curtailment* of exported energy during a limited amount of time (1–5%) during the year has a significant impact on the energy exported from the building to the grid.

To evaluate the flexibility potential from the owner/user perspective, two important factors, cost and user acceptance, must be considered [11].

Net Zero Balance

The *balance boundary* defines which energy uses are considered for the *Net Zero Balance*. This balance is another condition and has two important aspects, *Items of the balance* and *Balancing period*. The balance or weighting can be weighted *symmetrically*, using the same weighting factors for both delivered and exported quantities, or *asymmetrically*, using different elements [14].

In a matter of *Items of the balance*, they are essential to quantify the energy that flows in or out the grid considered in the balance. To make this balance possible, all energy delivered to the building from the utility grid and all energy feed-in to the grid by the building needs to be accounted as delivered energy/load and exported energy/generation [20] [21] [22].

For a NZEB, the balance between import and export over a period must be zero, or even positive. Building exchange energy with the electrical grid in the form of energy carriers is converted from or on to primary sources using credits, and the final balance then is calculated by the following equation [20]:

$$NZEB = |export| - |import| \geq 0 \tag{2.1}$$

where

$$import = \sum_i delivered\_energy(i) \times credits(i) \tag{2.2}$$

$$export = \sum_i feed-in\_energy(i) \times credits(i) \tag{2.3}$$

$$i = energy \;\; carriers \tag{2.4}$$

Figure 2.6 represents the overall *Net Zero Balance* concept.

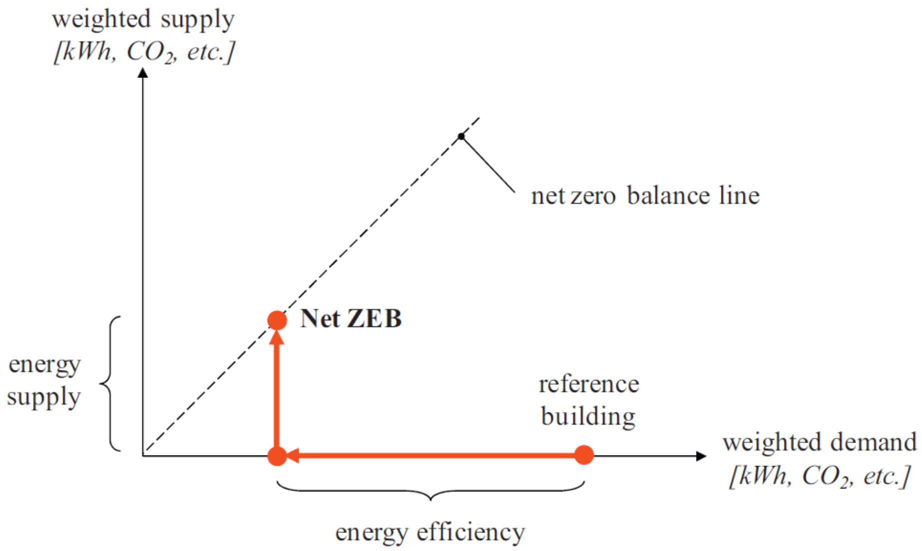


Figure 2.6: Graph representing the *Net Zero Balance* concept [14]

For the *Balancing period* a proper time span for calculating the balance is assumed, often implicitly, to be a year. A yearly balance is suitable to cover all the operation settings concerning the meteorological conditions. Although a seasonal or monthly balance could also be considered, this would have significant consequences on the optimal balance between energy efficiency measures and energy supply options [14].

Load Matching

A higher degree of LM decreases the effective load on a distribution grid, which lowers distributed volumes, counteracts voltage drops and reduces losses. With large amounts of distributed generation, the degree of LM has impacts on the design and operation of distribution grids.

Figure 2.7 shows LM behaviour with 10 minutes, monthly and annually time resolutions considering an annual balance line.

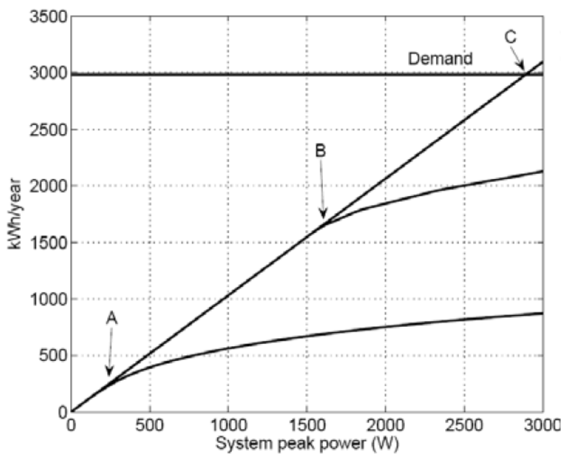


Figure 2.7: LM behaviour with 10 minutes time resolution considering an annual balance line [23]

On the figure above the lower curve (A) represents the LM based on 10 min net metering (max. 28%); the middle one (B) the monthly balance (max. 68%). The straight line (C) considers the annual balance and shows the match with the demand (103%).

DSM and Energy Storage have a direct impact on the improvement of the LM. Storage is, in general, the most effective option, but DSM appears to be a realistic alternative to storage at moderate overproduction levels. For a system with an annual, theoretical perfect, daily match between the generation and the demand, the solar fraction increases from 35% to 65%. This situation can only be reached by storage, but with Load Shifting this solar fraction can reach 41% to 48%. There is theoretical potential for increasing LM, but for that there are still some practical obstacles in order to achieve it [24].

In subsection 4.3.2, *Load Matching Factors* will be depicted, including the formulas used for their respective calculation.

Figure 2.8 highlights the three types of balance, import/export balance between weighted exported and delivered energy; weighted generation and load, and monthly net balance between weighted monthly net values of generation and load.

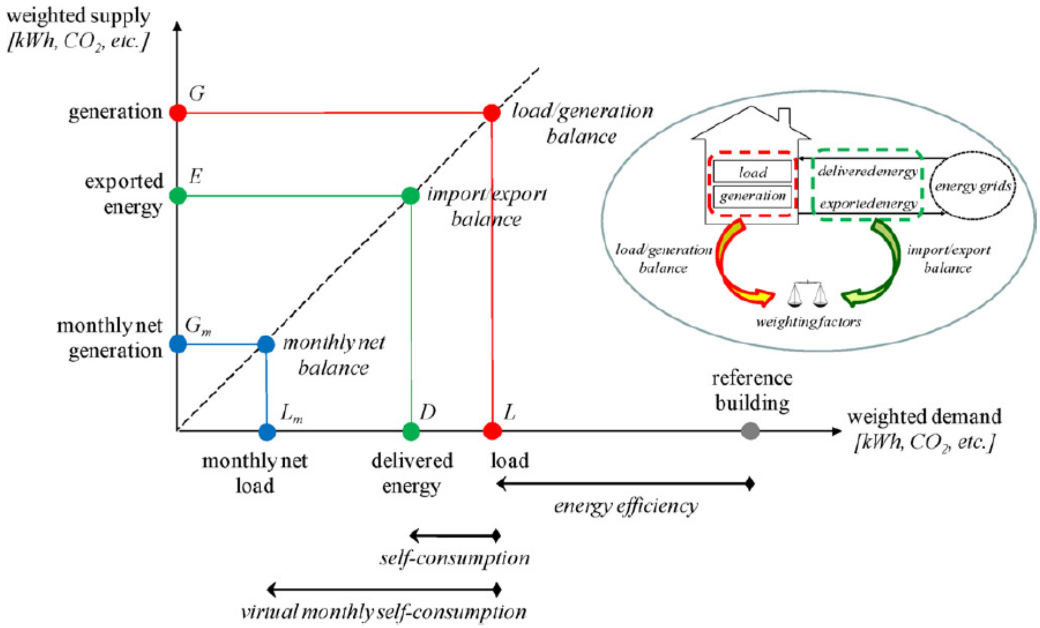


Figure 2.8: Graphical representation highlighting the three previously mentioned types of balance [14]

As it can be seen the virtual monthly self-consumption is the difference between the monthly net load (L_m) and a reference load value (L); the self-consumption value is the difference between the delivered energy (D) and L and the energy efficiency is the difference between L and a building reference value. The figure also shows that the mentioned differences are based upon the weighted demand that can be defined as kWh or CO_2.

2.1.5 ZEB known cases

To present a variety of ZEB examples, the Task40 report [4] was taken as the main source. Some of the examples are represented in 2.9. Task40 was a work from the Solar Heating and Cooling Programme of the International Energy Agency focused on Net Zero Energy Solar Buildings that aimed to discover a clear and international agreement on the ZEB definition and the measures of building performance [25].

Figure 2.9: Map of ZEB examples across the world [25]

The choice was to include the areas where it was possible to find more examples of ZEB, which is the reason for the exclusion of some examples.

Some years later EPBD made a report where only European examples were included. This report encloses some restrictions to building construction in the near future of Europe, including all the knowledge adjacent to it [2].

Some of the examples from Task40 and EPBD are described in [25]. The description is composed by characteristics such as *Building Use, Net Floor Area, Annual primary energy demand, Annual primary energy generation, Annual primary energy balance, Climate Challenge, U-Value, g–value and Heating and/or cooling system*. Those characteristics were already explained in subsection 2.1.2.

[4]First report of greater importance which includes a collection of worldwide known ZEB examples

With the intention of analysing a few NZEB examples from all over the world three tables were created containing the constructive characteristics previously mentioned in this section. Tables 2.2, 2.3 and 2.4 examples can be found in [26] and [3].

Table 2.2: ZEB worlwide examples I

Building/Country	**Building Use**	**Net Floor Area** (m^2)
Solar XXI-*Portugal*	Non-Residential - Office	1500
BCA Academy-*Singapore*	Non-Residential - Office	2180.5
Meridian Building-*New Zealand*	Non-Residential - Office	4795
Green Office-*France*	Non-Residential - Office	21500
Marché Kempthal-*Switzerland*	Non-Residential - Office	1550
Primary School of Laion-*Italy*	Non-Residential - Educational	62511
Die Sprösslinge-*Germany*	Non-Residential - Educational	969116.61
Hauptschule Schrobenhausen-*Germany*	Non-Residential - Educational	7080
Leaf House-*Italy*	Residential - Individual	477151.24
Urban Semi-Detached House-*Ireland*	Residential - Individual	16047.10
“Le Charpak”-*France*	Residential - Dwelling	64729
Ecoterra-*Canada*	Residential - Individual	23450.80
Plus Energy-*Austria*	Residential - Dwelling	7890
Sems Have-*Denmark*	Residential - Dwelling	3388

Table 2.3: ZEB worlwide examples II

Building	**Energy Demand** ($kWh/m^2.year$)	**Energy Generation** ($kWh/m^2.year$)	**Energy Balance** ($kWh/m^2.year$)
Solar XXI	60.00	63.00	3.00
BCA Academy	80.00	87.00	7.00
Meridian Building	154.00	154.00	0.00
Green Office	97.00	51.00	-46.00
Marché Kempthal	97.00	80.93	-16.07
Primary School of Laion	11.00	27.00	16.00
Die Sprösslinge	116.61	113.62	2.99
Hauptschule Schrobenhausen	104.50	0	-104.5
Leaf House	151.24	128.00	-23.24
Urban Semi-Detached House	47.10	0	-47.1
“Le Charpak”	29.00	5.00	-24.00
Ecoterra	50.80	16.35	-34.45
Plus Energy	70.65	113.95	43.3
Sems Have	23.10	6.93	-16.17

Table 2.4: ZEB worlwide examples III

Building	Climate Challenge	New/Renovated	U-Value Wall (W/m^2.K)	g-Value (%)	Heating/Cooling System
Solar XXI	HCD	New	0.45	75	Earth-tubes;SWH;BIPV-T
BCA Academy	CD	New	4.05	33	SWH;CHP
Meridian Building	HCD	New	0.38	44	SWH;CHP;GHP
Green Office	HCD	New	14	-	SWH;CHP;GHP
Marché Kempthal	HD	New	0.12	49	SWH;CHP;GHP
Primary School of Laion	HCD	New	0.22	34	Earth-tubes;SWH;CHP;GHP
"Die Sprösslinge"	HD	New	0.14	51	SWH;CHP;GHP
Hauptschule Schrobenhausen	HD	Renovated	17	-	-
Leaf House	HCD	New	0.15	61	Earth-tube;SWH;CHP;GHP
Urban Semi-Detached House	HCD	Renovated	19	-	-
“Le Charpak”	HCD	New	0.26	53	SWH;CHP
Ecoterra	HD	New	0.16	53	SWH;CHP;BIPV-T;GHP
Plus Energy	HD	New	0.09	55	SWH;CHP;GHP
Sems Have	HD	Renovated	0.2	-	-

Cross-case Analysis

After this ZEB cases review, a choice of some buildings was taken, not only based on climate challenge, but also on the type of building, to perform a cross-case analysis represented in the chart 2.10.

For different values of *Annual primary energy balance*, for each kind of building type and climate challenge, the *Heating and/or cooling system* have an important role. Even with a negative balance, it is impressive, how small are the values of primary energy demand for large area buildings. HD buildings have the lowest *U-Value* wall mainly because of their higher isolation levels need.

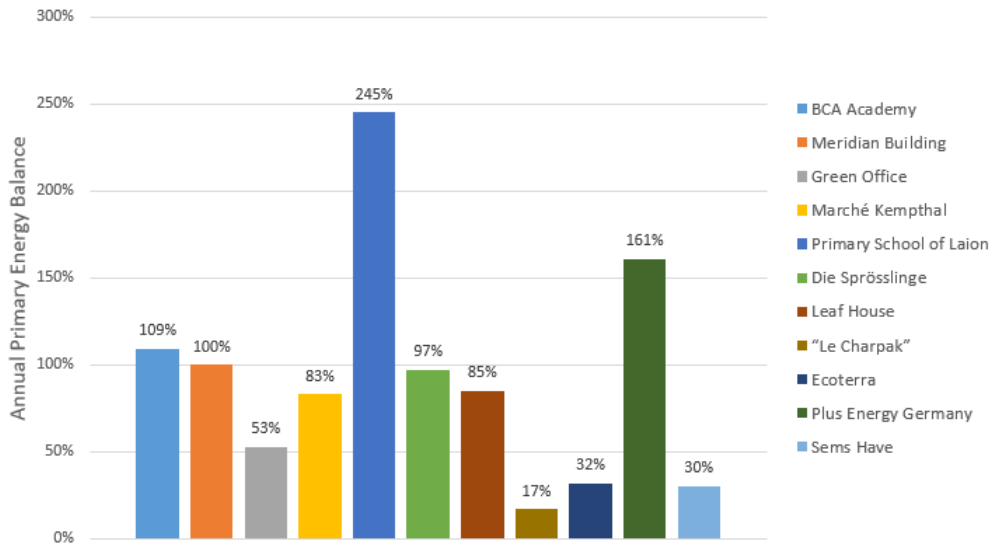


Figure 2.10: Cross-Case Analysis of Annual Primary Energy Balance

This kind of buildings with lower *U-Value*s are HD and were all designed according to Passive House concept. With higher *U-Value*s are HCD, and even higher CD buildings.

Concerning the *g-values*, they are around 50%, but BCA Academy and Laion have smaller values because they are not HD buildings. These U-values and g-values have to be balanced depending on the climate challenge. One can draw the conclusion that low *U-values* along with high *g-values* are appropriate for a cold climate.

In educational and office buildings energy demands are mostly driven by the internal loads of the building as can be seen in the Meridian Building and Die Sprösslinge Kindergarten [17].

Every example presented had a substantial energy demand reduction. In Hauptschule Schrobenhausen and Urban Semi-Detached House, there were no generation systems included and that is the reason for the energy balance of 0% and to not be represented on the graphic above. Nevertheless, the energy demand reduction was substantial. Other buildings could reach more than 100% which is perfect and means that they produce even more than they need.

2.2 Energy Flexibility

With the growing investment on the introduction of renewable energies in society, investments and studies on energy flexibility of buildings are getting more important. The improvement of building energy flexibility allows to take advantage of renewable energy and adapt it to the design of buildings towards a sustainable energy development.

With the integration of renewable energy, grows the amount of intermittent energy that flows to the grid, causing ocasional periods of overproduction, otherwise the generated energy would not be 100% reliable since it is of natural factors dependent [27].

To suppliers, the gap between generation and consumption is always a problem. This issue can be solved if there is an introduction of flexibility in the energy supply throughout carbon intensive generators. However, this goes against the sustainable development and should be solved throughout cleaner solutions [28].

Considering energy flexibility, the electric system of a building should not be simply a problem of the supplier. For the supplier, this flexibility can be enhanced throughout clean Demand Response (DR) measures [28]. This measures, represent the ability of customers to modify their usual consumption profile due to different electrical energy prices in different periods of time. DR measures aim to improve the performance of power systems and, consequently, to reduce CO_2 emissions [27].

Although not referring to flexibility implicitly, two main approaches are frequently used to deviate the electrical energy consumption of a particular building from the typical plan.

- Thermal Energy Storage (TES) is usually used to anticipate the energy consumption of an individual electrical device (air conditioner, electrical water tank or heat pump), typically by taking in mind the thermal properties of the device itself or of the respective building. Consequently reducing the consumption of electrical energy during off-peak times, one has into consideration the thermal comfort needs of the users in the building [28].
- Operation shifting is one of the main approaches typically used to deviate the electrical energy consumption of a specific building from the common plan through Load Shifting [28]. It is based on an approach that shifts the electrical energy demand, from on-peak to off-peak periods, through the control of some electrical devices (washing machines, clothes dryers, and dishwashers), to periods of lower electrical energy prices or bigger renewable energy generation [29].

2.2.1 The importance of Flexibility

Similarly to NZEB, there is no generic definition of energy flexibility, as this typically depends on the system under study. R. Amaral [28] in his literature review concludes that "*flexibility can be split into two main approaches*". They are deviation of electrical energy consumption by TES or *Load Shifting*, where electrical energy demand shifts, to periods of lower electrical energy prices or greater renewable energy generation, through the control of some electrical devices. De Coninck [30] gives his definition as "*the possibility to deviate the electrical energy consumption from the Business as Usual (BAU) consumption at a certain point in time and during a certain time span*". De Jonghe [31] defines flexibility as the elasticity of the demand as a function of the electrical energy price. It is important to say that this Load Shifting cannot contribute to a comfort reduction [32].

There are two different kinds of renewable energy technologies. Technologies such as hydropower, biomass and geothermal are reliable for the generation of electrical energy on demand. Technologies such as wind, wave power, and solar photovoltaics are considered variable types that depend on intermittent resources that fluctuate on timescales of seconds to days.

Taking into account the regular repeating patterns of social behaviour, electrical energy demand may be relatively easy to predict, but unexpected peaks can still occur. For Lannoye this situation "*may lead to a system lacking the ability to respond to variability, due to load or variable generation*" [33], being clear that the best way to operate a power system to cope with the increased variability is by energy flexibility [34].

The introduction of these *variable types* or *distributed renewable energy technologies*, enhances the role of energy flexibility. This flexibility ensures that not only is there sufficient generation capacity available to meet future demand but that those resources can be operated in a sufficiently flexible manner making also possible to account for expected system ramps and reserve requirements [35]. With this share of intermittent renewable energy growing, also increases the renewable electrical energy generation injected in a decentralized manner, the electrical load caused by the change from fossil fuelled systems toward high efficient electrical equipment and the stagnating number of traditional controllable power plants [36].

Reduction of *peak power, consumption, emissions, and costs* are the main reasons to invest in energy flexibility in De Coninck perspective [30]. Ottesen [37] shows a more consumer-orientated view, as he states that energy flexibility, based on demand side activities, is integrated with smart grid technologies leading to a significant cost reduction for energy consumers, to the ability of intermittent renewable energy generation and electric vehicles integration improvement, enabling a bigger reliability over the energy system, and to less costly network reinforcements.

2.2.2 Flexibility Potentials and Time Scales

The flexibility potential is stated as "*the power consumption increase and decrease that can be realized at a particular time of day, combined with how long this power increase or decrease can be sustained*" [36]. This flexibility potential can be used as an instrument to determine the impact or economic viability of any demand response program.

Flexible capacity can be used to respond to unexpected peaks or "*last-minute imbalances*" [38] [39]. Flexibility Time Scales can be categorized into the following way:

- Very short duration (From milliseconds to 5 minutes), which is a too sharp deviation that can damage equipment, lead to tripping of power generating units, or even to a system collapse over 80% of the power line disturbances last for less than a second.
- Short duration (From 5 minutes to 1 hour), a time scale where *spinning reserve* refers to online power generation capacity synchronized to the grid having a short response time for ramping up but allowing several hours of use. *Non-spinning reserve* is similar to *spinning reserve*, but without immediate response requirement.
- Intermediate duration (From 1 hour to 3 days), a time scale where *load following*, which is a continuous grid service, used to obtain a better match between power supply and demand. Energy storage can be used for this purpose, by storing power during a period of low demand and injecting it back into the grid during a period of low supply.

2.2.3 Operational measures to increase flexibility

Intermittent resources cannot be trustworthy because of their *"meteorological forecasting"* dependency. This situation increases the doubts regarding the power systems ability to manage the balance between supply and demand with a bigger integration of Variable Renewable Energy (var-RE), maintaining a *"secure and stable operation"* [38].

In smaller systems, which are less able to absorb large fluctuations, the combination of some technologies and storage, is useful in such a way that the aggregated output at the point of connection to the grid is relatively smooth. If the combined outputs of many variable resource power plants, which are based on different resources and located over a wide area, are to be considered jointly, their net variability becomes smoother than individual plants.

Different measures to optimize flexibility are given below.

Demand side management

DSM can provide flexibility through a balance between electrical energy generation and load, which is necessary for var-RE generation, and response in various time scales. Figure 2.11 illustrates the measure possibilities on the demand side which offer substantial opportunities to reduce system costs, due to demand peaks. The level of demand peaks can be reduced by introducing incentives to consumers to reduce their consumption at such times.

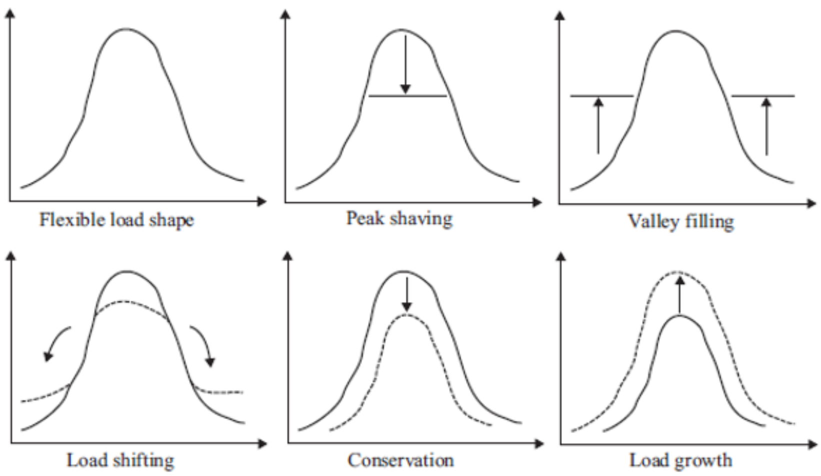


Figure 2.11: Illustration of different approaches to Demand Side Management [39]

DSM occurs when the individual energy prosumers have a prominent role in the energy market due to their inherent contribution [40]. However, there is a big amount of home appliances which are not suitable for DSM and *"consumers will not accept a restricted use of that devices"* [41].

Electric heating in combination with a hot water storage tank, dishwashers, and electric vehicles have a very high potential for DSM and all household appliances have a potential of about 20% to 30% of their load without restriction of consumer needs. Different descriptions for DSM were given by some others.

- Lund perspective: *"Demand Side Management comprises a broad set of means to affect the patterns and magnitude of end-use electrical energy consumption"*. Through operational measures DSM can be categorized to reduce (peak shaving, conservation), increase (valley filling, load growth) or reschedule (load shifting), energy demand [39].
- Lannoye perspective: *"Demand Side Management could be available either to curtail demand, where a consumer will reduce demand when the price rises above a certain level, shift demand where moving a load from a time of higher prices to a time of lower prices or assisting the integration of Variable Generation"*. Periods of high Variable Generation should correspond to low prices [34].

Important to regard is also Puchegger's [42] work, as he shows how is the behaviour of loads with and without DSM, comparing this two approaches.

Demand Side Response

One other important concept is the concept of *Demand Side Response*. Following a definition of Lannoye [34], *"the development of the smart grid should become a more widespread resource, as customers participate actively in the market"*. Currently *Demand Side Response* is considered the least utilized form of a flexible resource as it is not stimulated by the markets.

Gottwalt [43] states that to assess the value of flexible residential devices for a Demand Response aggregator, first the reduction in microgrid generation costs is estimated. Therefore, the uncontrolled scenario is compared with the integrated optimization where devices can be scheduled. In terms of flexibility, it is indeed a relevant matter.

Load Shifting

One of the primary DSM approaches used to deviate the electrical energy consumption of a concrete building from the regular plan is *Load Shifting*. It is based on an approach which shifts the electrical energy demand to later times through the control of some electrical devices (washing machines, clothes dryers, and dishwashers), to periods of lower electrical energy prices or bigger renewable energy generation.

Loads are categorized into *non-shiftable, shiftable and controllable*. For *shiftable load units*, *"the total load must always be met, but it may be moved within a given time interval"* [37].

There are four types of load units described below [37]:

- *Curtailable load units*, that may be reduced without being replaced, at a possible loss of comfort for the user.
- *Reducible load units*, where the load can be reduced down to a certain level without switching off.
- *Disconnectable load units*, where the unit is either on or completely off.
- *Inflexible load* unit class, that covers all load units where load must be met under any circumstance.

Figure 2.12 below displays different load flexible classes.

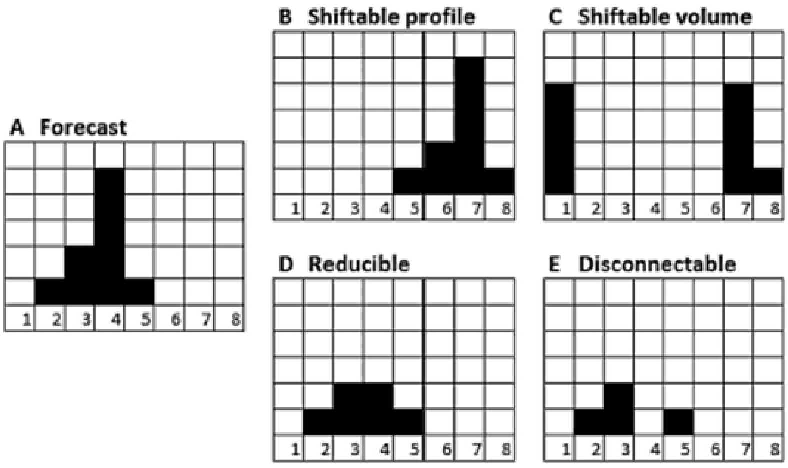


Figure 2.12: Illustration of the different load flexible classes [37]

The methodology proposed by Six [44] and improved by Nuytten [45] considers the flexibility of an accurate system as the ability to shift the consumption of a certain amount of electrical power in time. These studies quantify the flexibility of a particular system as the number of hours the electrical energy consumption can be delayed or anticipated. This methodology was tested to quantify the flexibility of residential heat pumps combined with thermal energy storage and to quantify the flexibility of a CHP system with TES.

2.2.4 Methodologies to quantify Energy Flexibility

The quantification of energy flexibility, in light of what has been mentioned throughout this chapter, proves to be a significant measure to accomplish.

From De Coninck [30] [46] point of view, the first step in the quantification process is to create a simple but appropriate and accurate system model in order to be able of predicting the behaviour of the system. *"At least three Optimal Control Problems (OCP) need to be solved to determine the flexibility at a particular point in time and during a certain time span"*.

Cost functions represent the amount of flexibility and associated costs. Aggregation of multiple cost curves can also be done. It is clear that an aggregated system can provide more flexibility than a single system. Also, by aggregating costs functions, it is often possible that a certain amount of flexibility can be offered at a lower price than any of the subsystems could provide. This opens the possibility to decide whether to invest on this flexibility in a specific building with specific characteristics [30].

Chapter 3

Case Study: Solar XXI

Solar XXI is a NZEB living lab, which was designed and constructed as result of a research project coordinated by Laboratório Nacional de Energia e Geologia (LNEG).

The building has a high energy performance integrating RES, including active and passive, composed by façade BIPV, a SWH system on the roof and a parking lot PV available at the site. All energy generated by the BIPV system is immediatly consumed by the building needs, however, knowing that the parking lot PV energy generation is rather high, when not consumed, instead of being feed-back into the grid, is used by the other buildings which compose the campus of Solar XXI. Pointing out the integrated technologies, several construction methods were implemented for a higher thermal comfort level. It comprehended methods such as thermal and solar radiation, as well as isolation, and south oriented windows that allow the building to have solar gain in winter time and shade in the summer time.

Regarding cooling systems, the building has no HVAC but a system composed of buried tubes, generally called earth-tubes, which allow natural ventilation.

The innovative aspect of this building is related to the integration of photovoltaic modules on the façades which combines energy generation and heat recovery.

Since the opening of Solar XXI in 2006, it was monitored several times, becoming a case study of several investigation projects. In one of the monitoring periods it was concluded that the building has around 80% of the energy consumption produced by renewable sources and this is the reason why it is considered a nZEB.

Next figure 3.1 shows Solar XXI shortly after its construction.

Figure 3.1: Representation of the Case Study: Solar XXI [47]

Following will be presented the diverse systems which compose Solar XXI split into two kinds of systems based on the type of energy. *Heat Systems* described in section 3.1 are systems related to heat transfer, *Sunlight Systems* present in section 3.2 are systems directly connected with solar energy.

3.1 Heat Systems

3.1.1 Heating Strategies

In the interior, the permanently occupied offices are south oriented to allow the direct insulation and solar gains in the winter time. North oriented rooms are casually occupied, so they do not need the same comfort levels as the permanently occupied offices.

Thermal building characterization

In this matter, just the most important thermal aspects will be referred so, in table 3.1 some of these characteristics are presented.

Table 3.1: Constructive characteristics of Solar XXI [47]

U-Value Wall	0.45 ($W/m^2.K$)
U-Value Roof	0.26 ($W/m^2.K$)
U-Value Ground Floor	0.55 ($W/m^2.K$)
U-Value Windows	4.5 ($W/m^2.K$)

Solar XXI as different levels of thermal isolation thickness reducing the heat losses of the building during the winter. The isolation was installed from the outside part of the building increasing the thermal efficiency.

Heat Recovery

The south façade was projected with the combination of the photovoltaic modules and the windows allowing to produce some of the building used energy. This system, known as BIPV-T and represented in figure 3.2, is also used to recover the heat generated by the photovoltaic modules and using it as natural heat in the winter throughout a cavity by natural convection system that can be opened or closed by the user.

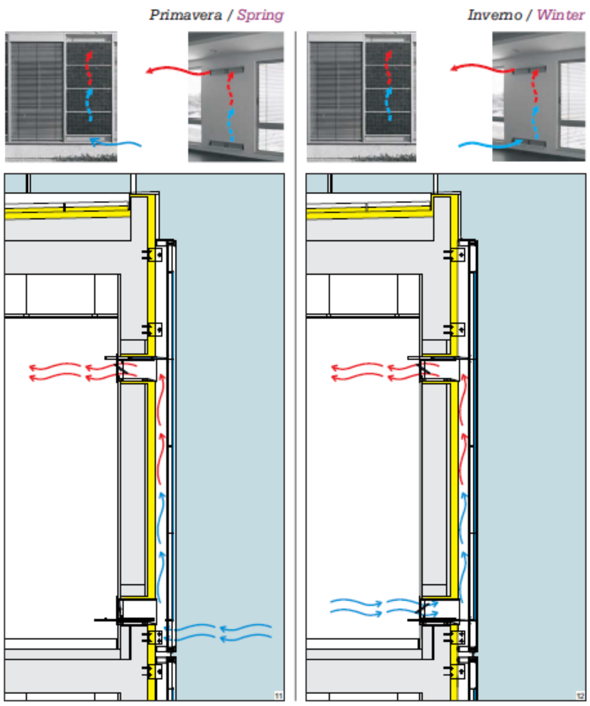


Figure 3.2: BIPV-T system used as a heat recovery system [47]

The SWH system is connected to a natural gas boiler in the basement of the building which allows it to have always central heating especially in the north areas in the winter time. The solar direct gain through windows located on the south façade and the building orientation with the main façade south oriented especially for capturing high level of radiation is also a heating strategy.

3.1.2 Cooling Strategies

The wide windows on the façade are essential for heating in the winter, while, in the summer the amount of solar radiation is higher, so the exterior adjustable blinds are necessary for the user comfort in the summer allowing the reduction of the sunlight through the windows.

Passive cooling through the ground

The cooling comes from an exterior air entrance that is connected to the building by 32 tubes. Knowing that the underground temperature is lower than the surface temperature, the objective of the tubes is to enable the contact of the air that goes naturally to the building to be pre-cooled. In each office, the user can control the exit of the air by just opening or closing a door. This system is represented in figure 3.3.

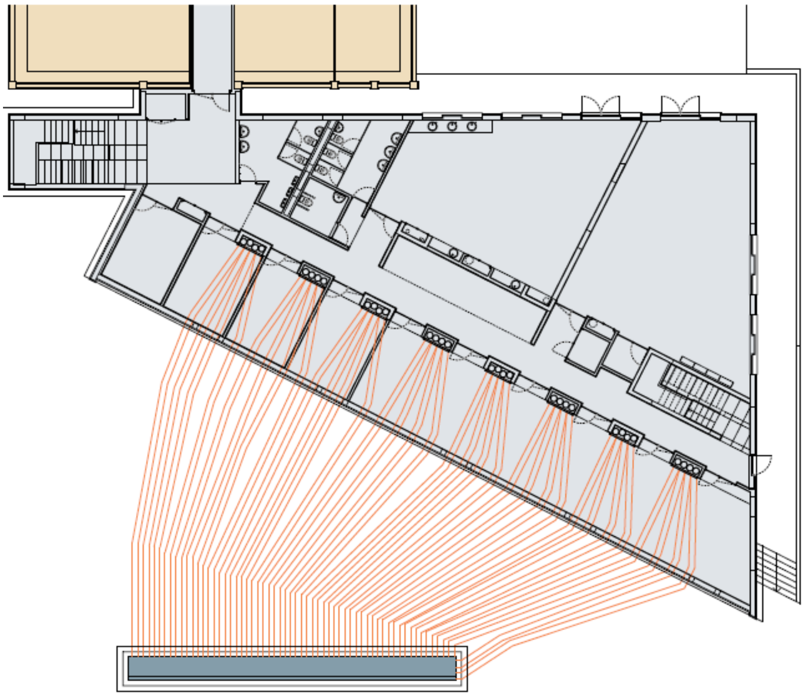


Figure 3.3: Earth-Tubes system used as a main cooling strategy [47]

Natural Ventilation

Particularly in the summer, Solar XXI has natural ventilation because of its characteristics that allow transversal ventilation. For example, every office door has frames that lead to the natural ventilation of the offices. Some of all ventilation strategies determine the thermal loads level in the interior of the building, essential to cool down the temperature levels during the night in the summer, coming from the outside source.

The cavity between the photovoltaic modules, while being ventilated, can contribute to its efficiency, giving way to their convective refreshment by their upper part.

3.2 Sunlight Systems

Natural Light

The windows are a major source of light and their size in the south façade is essential for that. The central open space that connects all floors is also an important source of light that makes unnecessary, the use of electrical light in that area. The north oriented offices have also light communication with the central open space through the door frames. Both main ways of natural light are showed in the next figure 3.4.

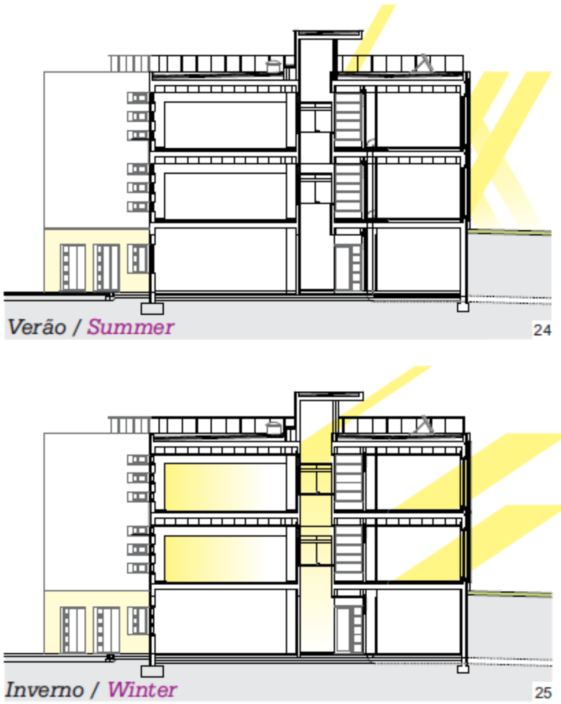


Figure 3.4: Representation of natural light for winter and summer periods [47]

3.2.1 Renewable Energy Systems

Photovoltaic Systems

The photovoltaic system integrated into the south façade includes about 100 m^2 of photovoltaic modules of multi crystalline silicon, producing an average of 12 kWp directly used by the building.

In the parking lot of the building, another PV CIS [1] system was installed with around 12 kWp. This system was integrated into the project but is completely separated from the building electrical system.

[1] CIS stands for the elements copper (C), indium (I) and selenium (S).

Solar Water Heating System

The building is also composed by a SWH system installed on the roof which includes 7 modules and which purpose was previously described on 3.1.1.

3.3 Building Design and Energy features

Main features representation

According to the features described in subsection 2.1.2 one can relate them as in the following scheme (figure 3.5).

Figure 3.5: Scheme composing Solar XXI main characteristics [26]

Energy Balance analysis and Index

Energy balance analysis is crucial in a building such as Solar XXI due to its importance as an NZEB and energy efficiency unit of LNEG. The analysis of 2009 is represented on table 3.2.

Table 3.2: Daily average values of energy produced and consumed in Solar XXI until 2009 [47]

Energy Produced (kWh)			**Consumption** (kWh)	**Energy Produced** (%)
Parking lot	PV Façade	PV Total	Solar XXI	PV/Consumption
23	31	54	78	78

In order to explicitly assess the impact of constructive solutions, an evaluation study has been made by means of heat and energy simulations of the building. The simulations considered only the actual distributions of occupation, lighting power and equipment by thermal zone based on data from the building usage [47].

After simulations, one concluded that the building has an excellent performance in thermal, light and electrical energy generation matters. At the end of one year, in a case of primary energy, the consumption is around 16 kgep/(m .year), so Solar XXI is an A+ energetic class building.

3.4 Electrical panel boards description

Solar XXI is composed of 10 electrical panel boards that will be described from the highest to the lowest floor. The cover of the roof has its own electrical panel board (Q.COB.) linked to the main board (Q.G.), such as the first floor (Q.P1) and the underground floor (Q.P-1). The scholarship holders office has one electrical panel board (Q.S.B.) as well as the conference office (Q.S.P.), both also directly wired to the main board. An auditorium on the first floor has its own panel board connected to the Q.P1 also as (Q.D.C.) present in a room currently without a specific function. The underground electrical panel board is connected to two other boards, one for Biomass Lab (Q.L.B) and another for a lab called the wind tunnel lab (Q.T.V). The PV monitoring is also made through the main board. No loads such as a HVAC or other big loads compose Solar XXI, therefore, that kind of description was not performed. The electrical panel boards diagram of the building can be found below in figure 3.6.

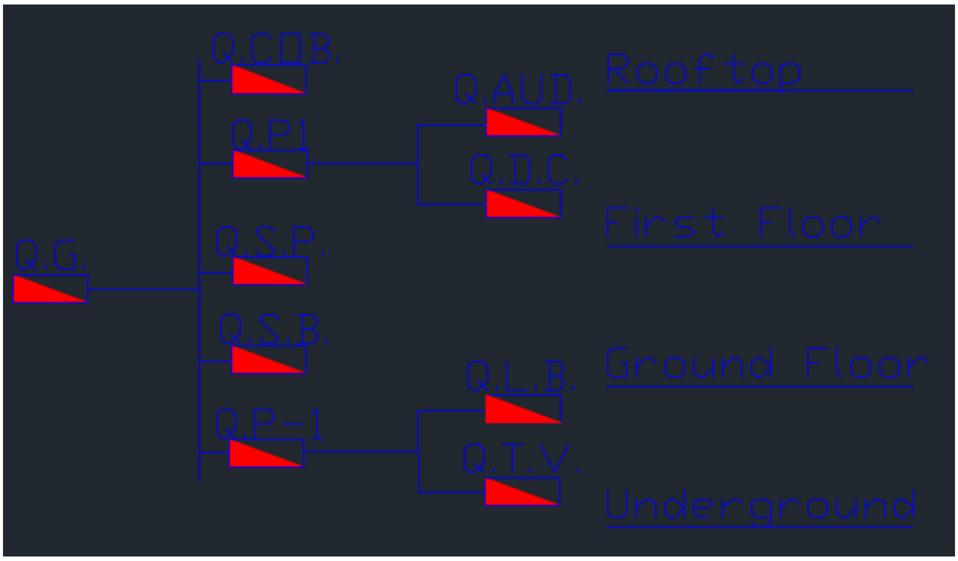


Figure 3.6: Display of the electrical panel boards diagram of the building

Chapter 4

Methodology

This chapter contemplates all the data retrieval description, including energy in the form of electricity and compares real and simulated data from *EnergyPlus* and *PVGIS*. It also considers Net Zero Balance and Load Matching Indicators applied in the case study, leading to the acquisition of useful information to verify the Energy Flexibility potential of the building.

All the steps concerning the methodology, including simulations, are performed in a realistic way using all the building characteristics and data retrieved.

4.1 Experimental Analysis

4.1.1 Consumption and Generation data collection corresponding to winter and summer periods

In Solar XXI, every load and generation values are monitored with 10 minutes precision but only corresponding to the total amount of the entire building energy consumption and generation. In this sense, a decision was taken to collect the data with the discretization of the load and PV generation. The purpose was to allow an easier analysis of the loads. Several energy analysers were used and installed in different electrical panels of the building, enabling the achievement of the exact consumption per electrical panel and the PV generation associated with the respective panel. The energy analysers employed were *Chauvin Arnoux* models *8334*, *8334B* [48] and *8331* [49]. The analysis started at 05:30 PM and ended at the same hour, one week after.

Initially, this data collection was made in an entire week, in particular the first week of March, with 1-minute precision, representative of the winter period. Still, due to a time mismatch between some energy analysers, an algorithm had to be created to transform this data with an accuracy of 15 minutes.

In July the process was repeated, which represented the summer period. The only difference was that this new data collection was obtained from the beginning, with a 15 minutes precision, to avoid a possible mismatch from the energy analysers.

Following a monthly comparison between consumption and generations is presented as well as the experimental periods with a weekly time resolution symbolized by seasonal load diagrams.

4.1.2 Annual consumption-generation contrast

To have a better understanding of the building's load behaviour along one year some data was provided by LNEG. Figure 4.1 represents the comparison between energy consumption and generation per month, on an annual basis.

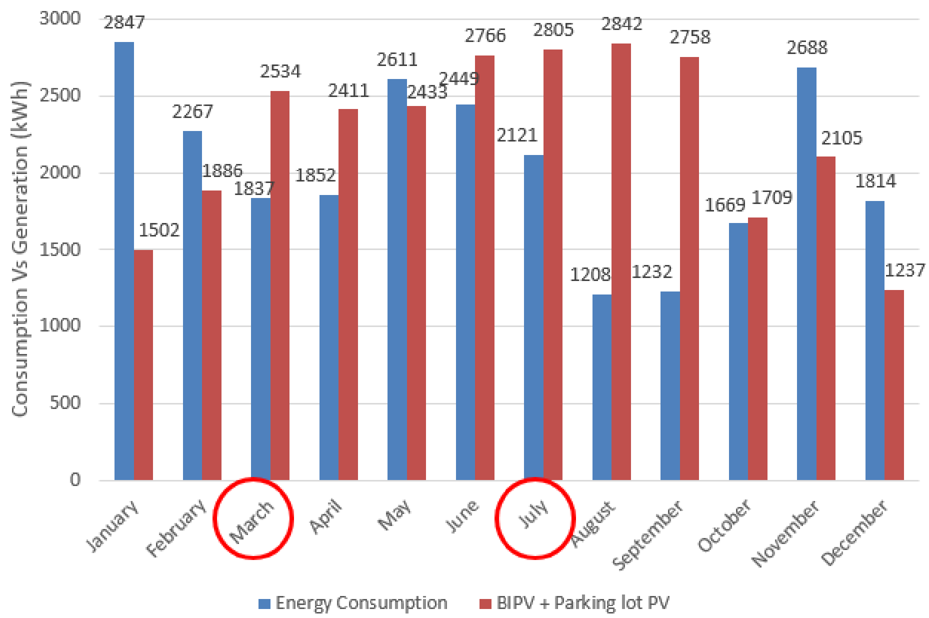


Figure 4.1: Solar XXI comparison between energy consumption and generation

An observation regarding figure 4.1 is present on section 4.3.1 on the basis of the annual energy balance. Bearing in mind the annual comparison, of the mentioned figure 4.1, the same comparison is displayed, but on a weekly basis, in section 4.1.3. To highlight this situation, during which the study took place, both months are signalled on the respective figure.

4.1.3 Seasonal load diagrams

For the further analysis, both data sets from March and July were considered. Figure 4.2 is an example of one of the Load Diagrams created for each electrical panel of Solar XXI, indicated in chapter 3, to allow a better understanding of the load behaviour collected in a discretised manner.

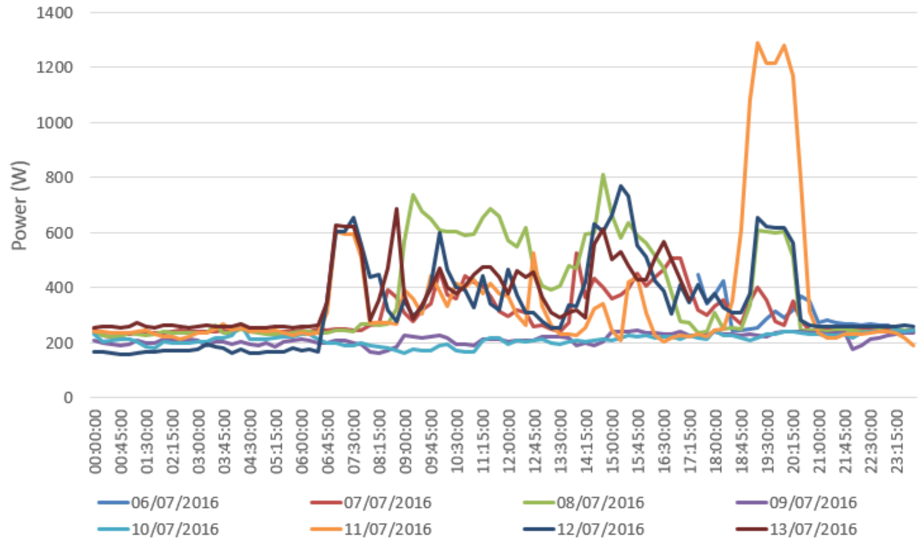


Figure 4.2: Load diagram of the electrical panel of 1st floor (Q.P1) for summer period

Figure 4.3 represents the total energy used in that week, which had to be calculated adding the PV generation values to the Energy Balance values.

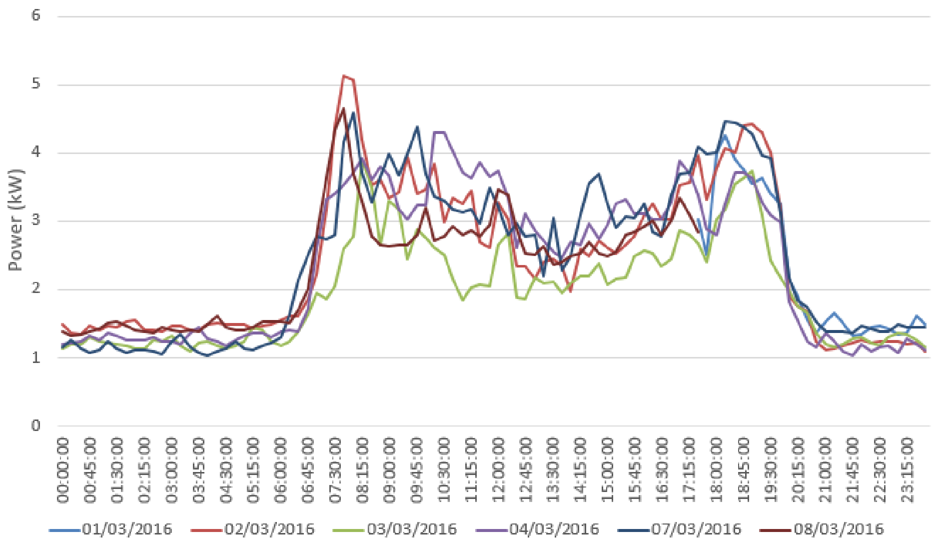


Figure 4.3: Load diagram of Power Consumption of the building for winter period

In March no roof loads were taken, but due to ventilation connected to the fume cupboards of the laboratory in the building during July, these loads needed to be accounted for. Figure 4.4 shows these loads.

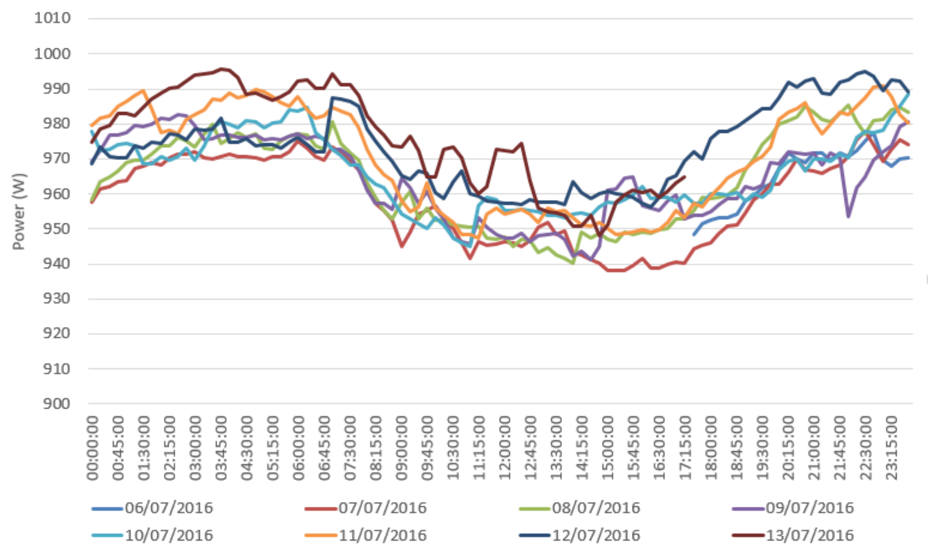


Figure 4.4: Load diagram of roof's electrical panel (Q.COB.) for summer period

Significant is also the fact that the lab is not used every day, but at least two times a week, and those times encompass nightly laboratory tests. On those days the fume cupboards are permanently turned on. These tests regularly include long heating and cooling periods and support the reason why, the loads of the Q.COB. electrical panel appear in July.

4.1.4 Consumption vs. generation diagrams

Figures 4.5 and 4.6 represent one example of the comparison between consumption and generation of one day, for both periods.

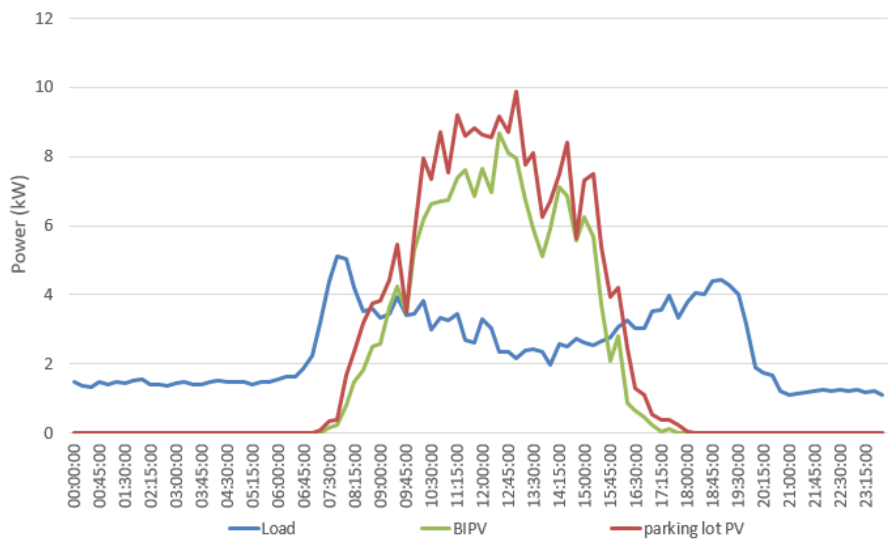


Figure 4.5: Load Diagram of consumption and generation on the 2nd of March representing a winter day

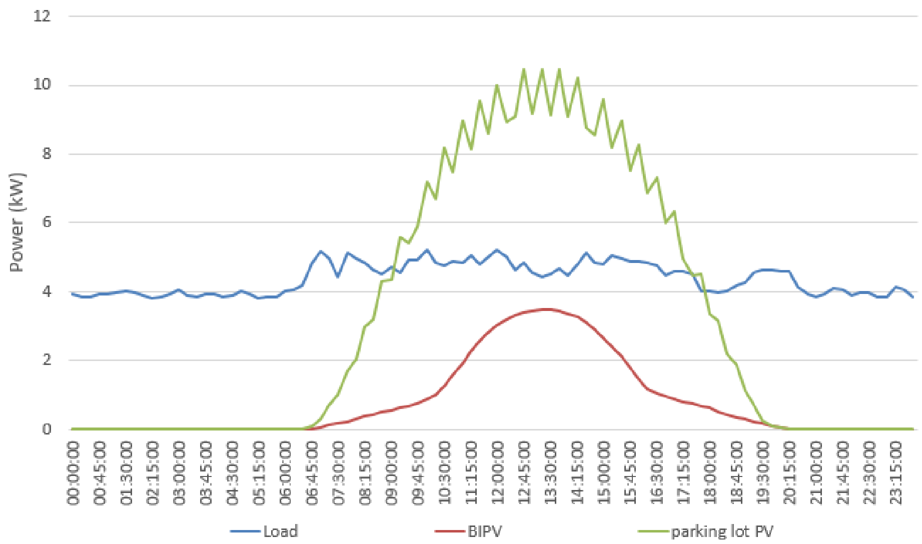


Figure 4.6: Load Diagram of consumption and generation on the 12th of July representing a summer day

On figure 4.6 the parking lot PV curve has an unexpected appearance, especially on the bigger energy generation period. The conversion of the readings of accumulated energy to power having a time-scale of 15 minutes, and not a smaller time-scale, was probably the reason for the unexpected appearance, otherwise, the behaviour of the curve would be much less regular as it is.

An average of the daily consumption and generation, for both PV technologies, was carried out. Hence, it was possible to create a Cumulative Weekly Data chart and another chart considering Grid Export Energy, Grid Import Energy and the energy generated directly used by the building. The comparison between the consumption and generation for both periods was also possible.

4.1.5 Energy consumption: characterization of user's behaviour

Having in mind the encouragement of energy efficiency as a primary step and the understanding of Solar XXI energy consumption behaviour of the users, a survey was carried out. The survey includes all the possible hours of building occupation for a working week and all the building characteristics that could make a difference in terms of energy use being presented in appendices A.2. It is rather relevant to refer that the survey included a small sample composed by only 10 persons which represents the current population of the building. To a better understanding of this characteristics figure 4.7, retrieved from the building plans, shows an example of an office room in Solar XXI highlighting some of the survey features, such as the location of the door, window and respective shutters, central heating and the Earth-tubes exit.

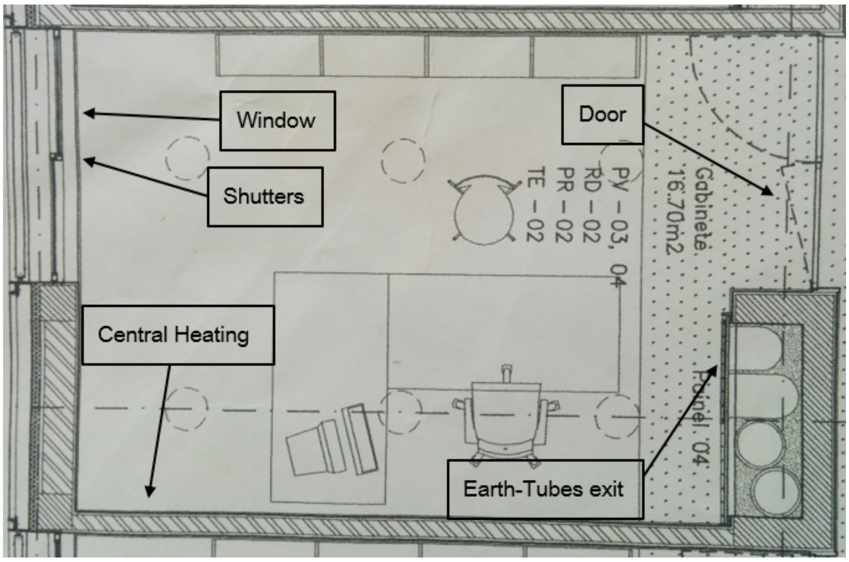


Figure 4.7: Office example display highlighting some energy use features

Even with the previous figure BIPV-T and the Door Frames were not possible to highlight so a decision, to seize the opportunity of having a *SketchUp* draw of the building, was taken and a second representation of the office can be seen in figure 4.8.

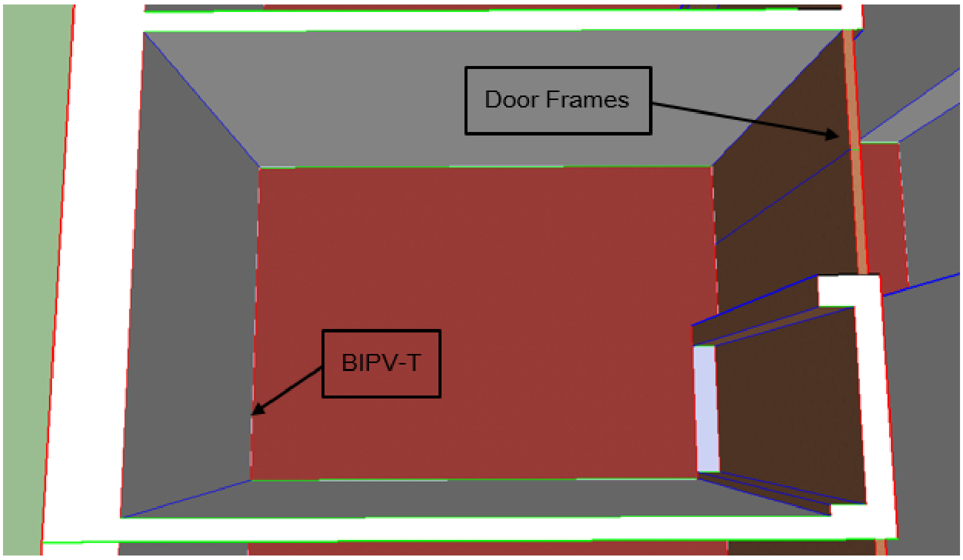


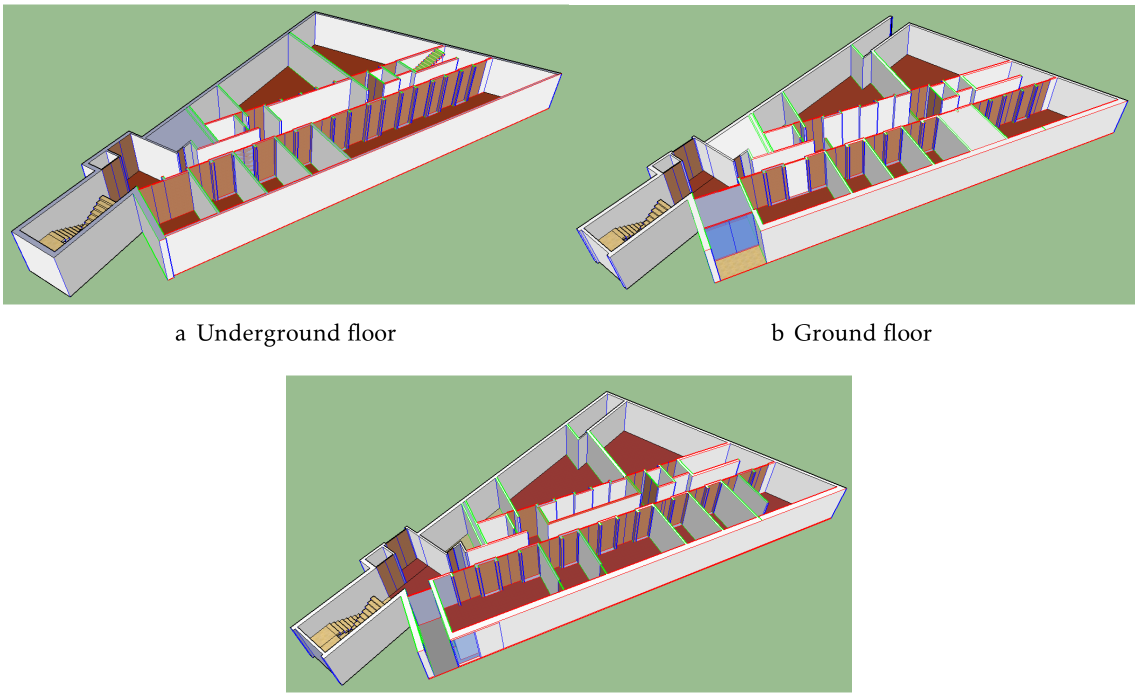
Figure 4.8: Office example displayed in 3D

The survey know-how served to find out new significant users behaviour issues to complete the *EnergyPlus* model, described as follows.

4.2 Numerical Analysis

4.2.1 *EnergyPlus* model description, evaluation and calibration

After the literature review, it became particularly important to understand all the technical detailed features of the case study, Solar XXI. In chapter 3, these same features are clarified, nevertheless, it was imperative to study and understand the building, so the first step was to create a *SketchUp* model of Solar XXI. To create this model, it was important to study how to interpret building plans, and from them and some *AutoCAD* files design three *SketchUp* draws, one per floor of the building. Figure 4.9 represents these models.



a Underground floor

b Ground floor

c First floor

Figure 4.9: Representation of Solar XXI *SketchUp* model composed by three figures, one for each floor

The decision to create a model resulted also from the need to understand the building more accurately. Knowing how to work with *SketchUp* was also necessary, being the reason for a lack of details in the model represented by figure 4.9. Figure 4.10 shows the final *SketchUp* model of Solar XXI.

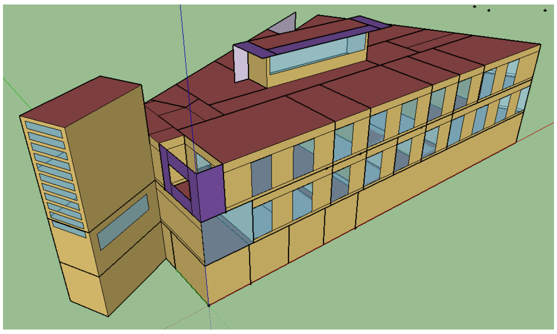


Figure 4.10: Original *SketchUp* Model of Solar XXI

To have a working *SketchUp* file, an *EnergyPlus* .idf file was imported to *OpenStudio* (a cross-platform collection of software tools) to support the whole building energy modelling.

EnergyPlus is a whole building energy simulation software, developed by U.S. Department of Energy Building Technologies Office, used to model both energy consumption — for heating, cooling, ventilation, lighting, plug and process loads — and water use in buildings [50].

EnergyPlus has frequent upgrades and using a transition version enabled the update of a first .idf file to an earlier version. The weather data file that allows the simulation to run on the study location was required and downloaded [51].

The *EnergyPlus* model of Solar XXI is composed of information on the building constructive materials, electrical equipment and lights, and users schedules.

EnergyPlus IDF Editor enabled the edition of the model filling specific classes from the *Class List* such as *Schedules*, *Surface Construction Elements* and *Internal Gains* displayed on the following figures 4.11 and 4.12.

On figure 4.11 it is possible to understand that only some of the fields of each class were filled and fields such as *SteamEquipment* were not, because Solar XXI is not composed by those.

```
Schedules
--------------------------
[0007]  ScheduleTypeLimits
[------]  Schedule:Day:Hourly
[------]  Schedule:Day:Interval
[------]  Schedule:Day:List
[------]  Schedule:Week:Daily
[------]  Schedule:Week:Compact
[------]  Schedule:Year
[0010]  Schedule:Compact
```

a Schedules

```
Surface Construction Elements
--------------------------
[0028]  Material
[0001]  Material:NoMass
[------]  Material:InfraredTransparent
[0001]  Material:AirGap
[------]  Material:RoofVegetation
[------]  WindowMaterial:SimpleGlazingSystem
[0001]  WindowMaterial:Glazing
[------]  WindowMaterial:GlazingGroup:Thermochromic
```

b Surface Construction Elements

```
Internal Gains
--------------------------
[0009]  People
[------]  ComfortViewFactorAngles
[0029]  Lights
[0018]  ElectricEquipment
[------]  GasEquipment
[------]  HotWaterEquipment
[------]  SteamEquipment
[------]  OtherEquipment
```

c Internal Gains

Figure 4.11: Display of Solar XXI *EnergyPlus* model classes edition

On figure 4.12 the edition of the fields is represented, and lights and equipment are well divided. Also the amount of people per office is displayed on the mentioned figure. A simulation using that model was performed, where it was concluded that, one needed a deeper analysis, where the survey described on 4.1.5 was essential. This survey outcome lead to the fulfilling of the *Schedules* class.

Field	Units	Obj1	Obj2	Obj3
Name		Gab_1.02	Gab_1.04	Gab_1.05
Zone or ZoneList Name		Gabinete 0.1 Therm	Gabinete 0.3 Therm	Gabinete 0.4 Therm
Number of People Schedule Name		Office Occupancy S	Office Occupancy S	Office Occupancy S
Number of People Calculation Method		People	People	People
Number of People		1	1	1
People per Zone Floor Area	person/m2			
Zone Floor Area per Person	m2/person			
Fraction Radiant		0,6	0,6	0,6
Sensible Heat Fraction				
Activity Level Schedule Name		Office Activity Sche	Office Activity Sche	Office Activity Sche

a People

Field	Units	Obj1	Obj2	Obj3
Name		E_Cir_0	E_Circ_1	E_Gab_0.1
Zone or ZoneList Name		Circulação 0 Therm.	Circulacao 1 Therm.	Gabinete 0.1 Therm
Schedule Name		Office Equipment Sc	Office Equipment Sc	Office Equipment Sc
Design Level Calculation Method		EquipmentLevel	EquipmentLevel	EquipmentLevel
Design Level	W	200	200	350
Watts per Zone Floor Area	W/m2			
Watts per Person	W/person			
Fraction Latent		0,3	0,3	0,3
Fraction Radiant		0,2	0,2	0,2
Fraction Lost		0,5	0,5	0,5

b Equipment

Field	Units	Obj13	Obj14	Obj15	Obj16
Name		I_Gab_1.2	I_Gab_1.3	I_I.S._-1	I_I.S._0
Zone or ZoneList Name		Gabinete 1.2 Therm	Gabinete 1.3 Therm	I.S. -1 Thermal Zone	I.S. 0 Thermal Zone
Schedule Name		Office Lights Sched	Office Lights Sched	Office Lights Sched	Office Lights Sched
Design Level Calculation Method		LightingLevel	LightingLevel	LightingLevel	LightingLevel
Lighting Level	W	0	474	290	325
Watts per Zone Floor Area	W/m2				
Watts per Person	W/person				
Return Air Fraction		0	0	0	0
Fraction Radiant		0,42	0,42	0,42	0,42
Fraction Visible		0,18	0,18	0,18	0,18

c Lights

Figure 4.12: Display of Solar XXI *EnergyPlus* model fields edition

The *Output* class was also completed on several fields to allow an easier way for interpreting the results. The constructive materials information was acquired in Solar XXI.

The calibration process estimates input parameters in a time interval, in order to reach a convergence of results between the real and simulated values, so that the predicted values can be verified [52]. Calibrations related with, the number of users, equipment, and other loads had to be done, to make the model more realistic, enabling its validation under the objectives of this work.

4.2.2 *PVGIS* simulations

With *PVGIS*, an online solar photovoltaic energy calculator, the PV generation for both PV technologies, BIPV, and parking lot PV simulation, for the same location, was possible. This photovoltaic geographical information system allowed the comparison between those values and the real values for a time resolution of one-year [53]. A representative image of *PVGIS* online calculator is shown on figure 4.13.

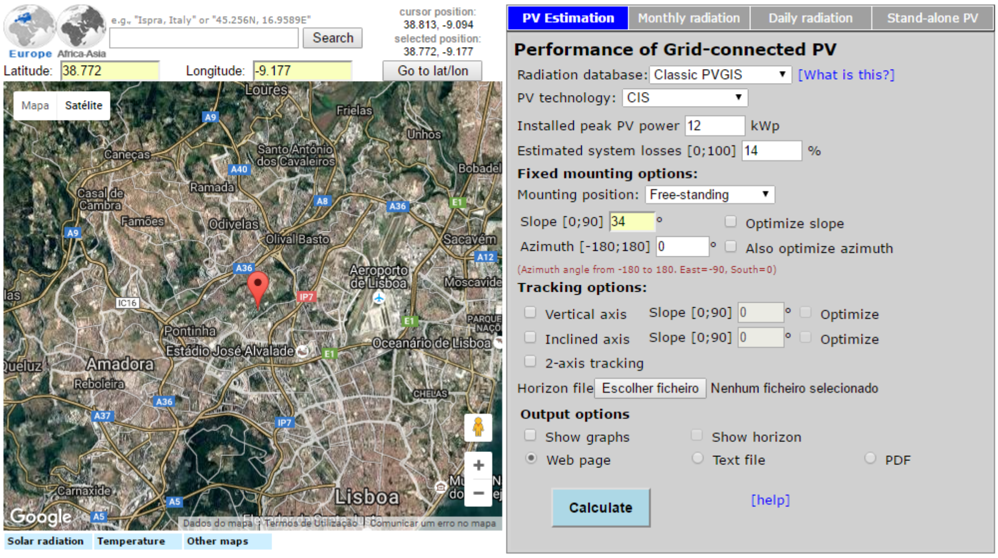


Figure 4.13: *PVGIS* online calculator representation

On the figure above it can be seen the parking lot edition example, one of the two examples used and created in *PVGIS*. On both examples, several characteristics were set. Following, a list of characteristics that were changed from the pre-defined characteristics, representing respectively the façade BIPV and the parking lot PV, can be found.

- Radiation Database, Classic PVGIS was chosen for both cases because the most reliable radiation information comes mainly from geostationary satellites.
- PV Technology, crystalline silicon and CIS.
- Installed peak PV power, 12 and 12 kWp.
- Mounting Position, Building Integrated and Free-Standing.
- Slope, 90º and 34º.
- Latitude, 38.772.
- Longitude, -9.177.

4.3 Net Zero Balance and Load Matching analyses of Solar XXI

To have evidence on the performance of NZEBs, it is essential to compare the annual energy demand and generation on the building site, i.e., its annual balance.

Based on table 2.1 presented in subsection 2.1.4, Solar XXI has two different ZEB Supply-side options, both on-site options described below:

- The façade BIPV is the renewable energy source within the buildings footprint.
- The parking lot PV is the renewable energy source available at the site.

4.3.1 Net Zero Balance

Through Sartori, Solar XXI *Boundary* can be split in:

- *Functionality and effectiveness*, which indicates the building as an Office Building, where the energy needs are based on the population of the building.
- *Climate and Comfort*, showing the behaviour and comfort needs of the users.

The building is a HCD because Portugal is a temperate climate country. The physical boundary is useful to identify if the generation system is within or without the boundary being considered, respectively on-site or off-site. Solar XXI has an on-site strategy as the energy generator systems cover, in part the load and are feed back into the grid [14].

The following two figures represent the energy balance of Solar XXI respectively on a annual and weekly basis. Figure 4.14 represents the energy balance on a annual basis.

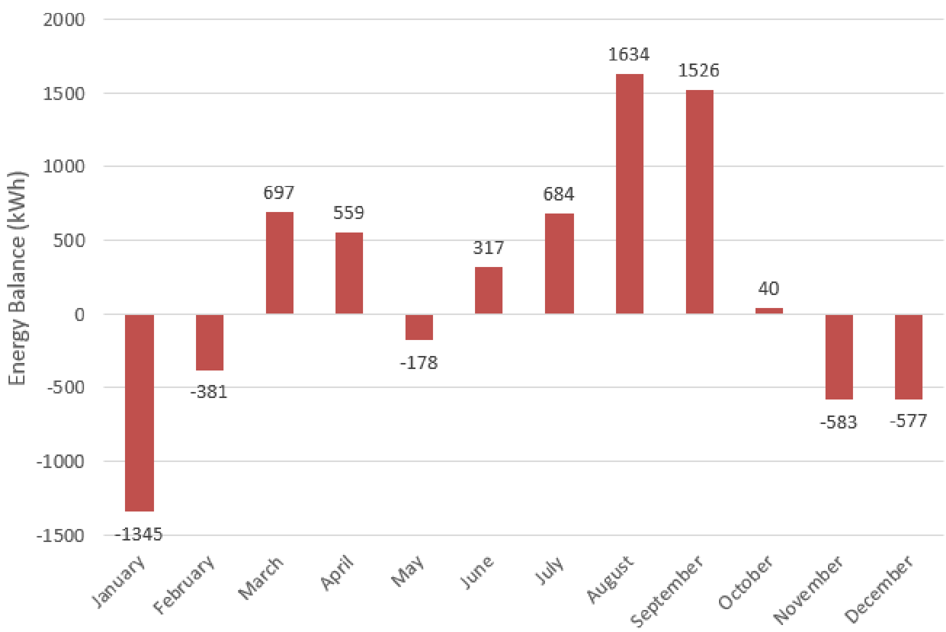


Figure 4.14: Solar XXI monthly energy balance

Since Solar XXI monthly energy balance is an outcome of the consumption-generation chart (figure 4.1), it can be observed that January had a considerable negative balance of -1345 kW, being the consumption almost the double of generation. Also May had an unexpected negative balance also due to the excessive energy consumption. February, November and December had predictable negative balances because of its foreseeable consumption and generation values. March, April, July and August had expected positive balances, based on the regular matching between energy generation and consumption in a temperate climate country such as Portugal. September overcomes all the expectations with high values of generation.

Figure 4.15 represents the main electrical panel (Q.G.) diagram, on a weekly basis, showing the Energy Balance of the building with some negative values due to the fact that all the energy produced on the BIPV is instantaneously consumed.

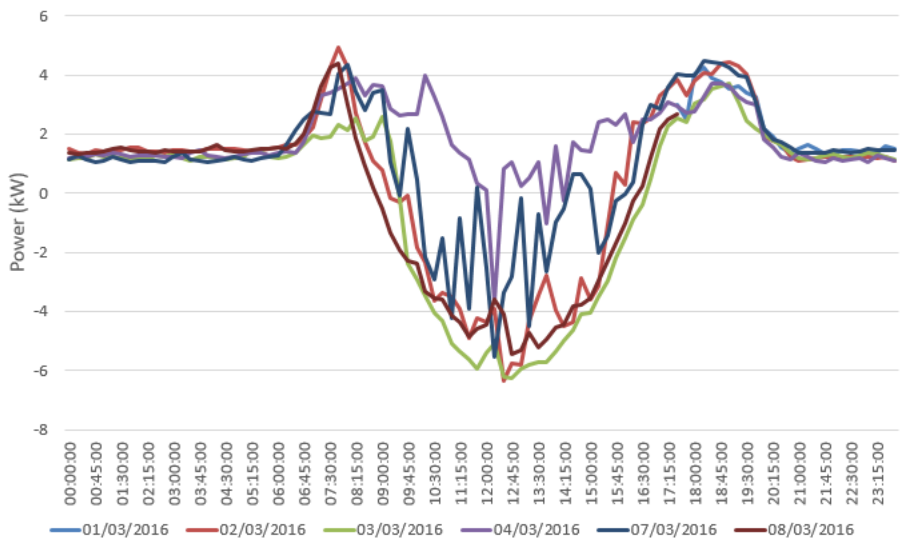


Figure 4.15: Load diagram of Power Balance of the building for winter period

4.3.2 Load Matching and respective indicators

For individual buildings with on-site generation, LM determines how the building interacts with the distribution grid, which may have impacts on the value of the electrical energy generated on-site if bought and sold electricity are valued differently.

As long as overproduction is feed-in to the grid for free or receives a low credit, it is reasonable to adjust the system size, so that does not happen.

If a NZEB draws power during peak times, from the point of view of the grid, there will be little difference between the NZEB and a conventional building. If the LM issue and GI are not adequately addressed, NZEB might not reach their full potential regarding energy conservation, promotion of renewable energy sources and global reduction of carbon emissions [21].

Load Matching Indicators intend to describe the degree of utilization of on-site energy generation related to the local energy demand [11].

Load Match Index

With respect to other on-site power generation options, the indicator is named LMI within the context of NZEB. All generated power exceeding the load is considered part of the grid. The annually based LMI of a NZEB is, by definition, equal to 1 or 100%. As the index strongly reflects the considered time resolution, the time interval must be part of the index name. With increasing time interval, excess generation decreases. Three similar equations can be used to calculate it [23].

First:

$$f_{load,i} = \min\left[1, \frac{on\text{-}site\ generation}{load}\right] \times 100[\%] \tag{4.1}$$

$$i = time\ \ interval(h,d,m) \tag{4.2}$$

or equivalent, but based on net-metering instead of load metering:

$$f_{load,i} = \min\left[1, \frac{on\text{-}site\ generation}{net\ metering + on\text{-}site\ generation}\right] \times 100[\%] \tag{4.3}$$

Net-metering allows consumers to use their generated electrical energy any time, instead of when it is generated.

Second [14]:

$$f_{load,i} = \frac{1}{N} \times \sum_{year} \min\left[1, \frac{g_i(t)}{l_i(t)}\right] \tag{4.4}$$

where g and l stand for generation and load, respectively, and i represents energy carrier. N stands for the number of data samples, i.e. 12, if having the monthly data for one year, and this makes the difference with the first way of calculating it.

Third [21]:

$$f_{load,T} = \min\left(1, \frac{G(i) - S(i) - L_0(i)}{L(i)}\right) \tag{4.5}$$

where T is the period of evaluation, G the PV generation, S the net energy exchange with the storage system and L the building load.

The higher the LMI, the lower the seasonal unbalance of energy exchanged with the grid [14].

The presence of on-site battery storage, which is not the situation in the case study discussed here, implies that the index must be modified by adding the battery energy balance to the on-site generation. This modification is achieved by changing equation 4.1, into the following formula:

$$f_{load,i} = \min\left[1, \frac{\textit{on-site generation} + \textit{batery balance}}{\textit{load}}\right] \times 100[\%] \tag{4.6}$$

Battery storage is visible on the hourly or daily level only, due to the practical limitations of the storage capacity available within system solutions existing nowadays [23].

From the point of view of the study case, it is important to stress that all calculations, regarding *Load Matching Indicators*, were carried out for the two technologies individually and with both together. Equation 4.5 was used to calculate the LMI for different time resolutions. The time resolutions are 15 minutes, daily, weekly, monthly and yearly based on the data that was collected in the specific week and the data that was requested for the remaining months.

The LMI and the following indicator, *Load Cover Factor*, are meant to express the same thing, the share of the load that is covered by the on-site generation for a specific energy carrier. Nevertheless, the two factors are not equivalent, since their mathematical definition, found in Salom literature [54], is different. The definition uses, for both factors, integral notation and the same nomenclature, thereafter, the two are further manipulated in order to write them in a comparable fashion and highlight the difference between them. Due to the previously mentioned reason the numerical difference between the two indicators may be expected to be small but there is nevertheless a difference [54].

Load Cover Factor

Load Cover Factor represents the percentage of electrical demand covered by on-site electrical energy generation. γ_s is the factor that identifies how well the local demand is covered by BIPV system generation, and γ_D is the factor that shows how well the BIPV system covers the demand [11]. The effectiveness of the building PV systems for reducing the electrical energy demand from the main distribution grid is expressed by quantifying the *Load Cover Factor* [55].

Figure 4.16 shows a schematic view that represents all the energy flows and electrical energy behaviour in NZEB.

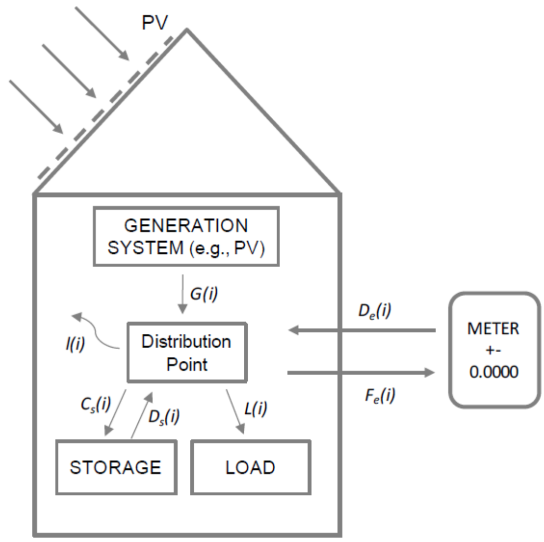


Figure 4.16: Schematic view of the energy flows in an all-eletricity NZEB [11]

When $\gamma_s = 1$, local generation is covered by local demand and no excess flows to the grid, when $\gamma_D = 1$ local generation could meet all demand [56] .

For further calculation of the *Load Cover Factor* of the building for both study weeks, the following equation was taken [21]:

$$\gamma_{load,T} = \frac{\sum_{i}^{N+1} min[G(i) - S(i) - l(i), L(i)]}{\sum_{i}^{N+1} L(i)} \tag{4.7}$$

where l stands for the energy looses.

Self-Consumption Factor

The supply cover factor, also known as *Self-Consumption Factor*, is defined representing the percentage of the on-site generation which is used by the building [11].

This factor is represented by ξ and can be defined as [57]:

$$\xi = \frac{E_{pv,load} + E_{bat,load}}{E_{load}} \tag{4.8}$$

where $E_{pv,load}$ is the produced energy directly consumed by the loads, $E_{bat,load}$ is the demanded energy supplied by the battery and E_{load} is the total amount of required energy [57].

To use the stored electrical energy, a building has to be equipped with a battery inverter. This inverter does not only carry out the energy conversion but allows the control of power flows in the house. The objective of these controllers is to maximize ξ, and their key features [57].

The relationship between energy flows and the capacity is not linear. As expected, the relationship between self-consumption factor and the capacity follows the same evolution. This relationship is an important design criterion, which implies, that oversized storage does not produce relevant energy benefits concerning the local energy optimization. The use of DSM strategies entails relevant advantages as:

- Reduction of energy losses, since that a DSM system has not direct energy losses because there is not physical contact with the energy system. On the other hand, a storage system has different losses depending on the technology.

- Reduction of battery size and therefore the cost, given that a DSM system only needs to control electronics and depending on the devices, the cost is low compared with a large storage system.

- Increase of energy management possibilities, by controlling the demand, it can be implemented new energy strategies.

- Scalability, meaning that an increase of the required energy does not involve an increase in the DSM size because it is a software controller.

The combination of small-scale storage with DSM significantly improves the local use of PV, thus increasing the PV value for the user. This combination will play a significant role in future smart grids [57].

The battery system was a variable neglected, concerning the calculation of the ξ factor, because the case study does not actually have one. Nonetheless, through the literature review, all the Load Matching Indicators presented would have better results if in the case study a battery system was included[21].

Loss of Load Probability

At a given time step identified with the index i [21]:

$$G(i) = L(i) + S(i) + l(i) + E(i) \tag{4.9}$$

where E stands for the net energy exported to the grid and:

$$E(i) = F_e(i) - D_e(i) \tag{4.10}$$

where F_e stands for the energy feed-in to the grid, D_e stands for the delivered energy from the grid and

$$S(i) = C_s(i) - D_s(i) \tag{4.11}$$

where C_s is the charging energy to the storage and D_s is the discharge energy from the storage.

$$LOLP = \frac{time_{L(i)>[G(i)-S(i)-l(i)]}}{T} \tag{4.12}$$

The last parameter defined above Loss of Load Probability (LOLP) measures the probability of demand exceeding the capacity during a given period. This shows the percentage of time in which the local generation does not cover the building demand, and thus the amount of extra generation capacity which needs to be installed or must be supplied by the grid [21]. When applying this particularly to a building simulation, the concept can be simply calculated through the following equation [56]:

$$LOLP = \frac{Time\ load\ exceeds\ generation[h]}{period[h]} \tag{4.13}$$

Values of LOLP for NZEBs are around 0.7 for all the analysed cases. Apparently, an in-depth analysis of the influence of an increasing number of NZEBs in the grid requires knowledge about the grid topology, the stochasticity of the building consumption, and the control systems on both, building and the grid side [11].

When LOLP is given in a number of hours per year, it is also called the Loss of Load Expectation (LOLE). Local generation in a building will often be of a stochastic nature (e.g. Photovoltaic), whereas the demand could be either stochastic or controllable DSM [56]. Equation 4.12 was used to calculate the LOLP [11].

The advantage of these indicators over energy demand and generation profiles is the possibility of taking into account the influence of different types of storage, e.g. batteries or building thermal mass. Moreover, when computing the Load Cover Factor, the impact of various strategies and measures of load modulation, e.g. DSM, can be investigated. It should be noted that without knowing the characteristics of the local energy systems, it cannot be concluded whether high or low cover factors are preferable [11].

Some graphics were carried out with LMI and *Cumulative Weekly Data* related to the already mentioned factors.

Cumulative Weekly Data

To calculate *Cumulative Weekly Data* first of all, a frequency distribution table was constructed, then the frequency of each value, every fifteen minutes, was calculated and finally every individual value was set in accordance with the next formula.

$$C_{WD}(\%) = \left(\frac{C_{WD}}{N}\right) \times 100 \tag{4.14}$$

where C_{WD} is the *Cumulative Weekly Data* and N is the number of all frequencies.

4.4 Solar XXI Energy flexibility

Energy flexibility, already mentioned in chapter 2, can be split into two main approaches, using deviation of electrical energy consumption by TES or applying *Load Shifting*. In the present study applying *Load Shifting* as an operational measure of energy flexibility was possible, because TES is based on thermal properties of the device itself. Devices such as an air conditioner, electrical water tank or heat pump do not exist in the building.

Load Shifting

Based on Energy Flexibility information present in section 2.2, a trial to shift some loads of low generation periods to the highest electrical energy generation period, between 12 AM and 2 PM, was performed. In contrast to a residential home, Solar XXI does not have permanent shiftable loads, like a dishwasher or an electric car. The only shiftable loads were the energy consumption of the cleaning periods of the building and of the charging period of the laptops.

Regarding the *Flexibility Time Scales*, *Intermediate Duration* is the time scale employed in this work because the applied *Load Shifting* is between 1 h and three days and the system belongs to a continuous grid service that is used to obtain a better match between the power supply and demand [39].

An analysis of the Load Diagrams of both weeks in the morning periods was carried out, to find out the cleaning periods, as explained below. In figure 4.17 it is visible that from 6:15 until 8:00 and from 18:00 until 20:00 the loads are higher than the residual load during the night, and in this period there are no users in the building. Figure 4.18 representing the summer period, displays the same morning period but in the end of the day the time-scale changes to 18:45 until 20:45, considering this periods the cleaning periods.

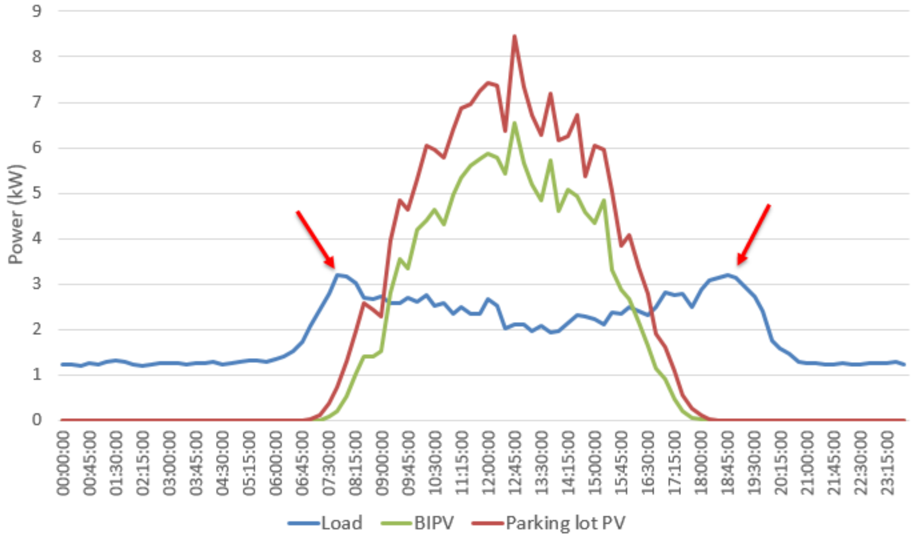


Figure 4.17: Load Match Index with BIPV and parking lot PV for winter period

Both figures above and below have the previously mentioned periods signaled.

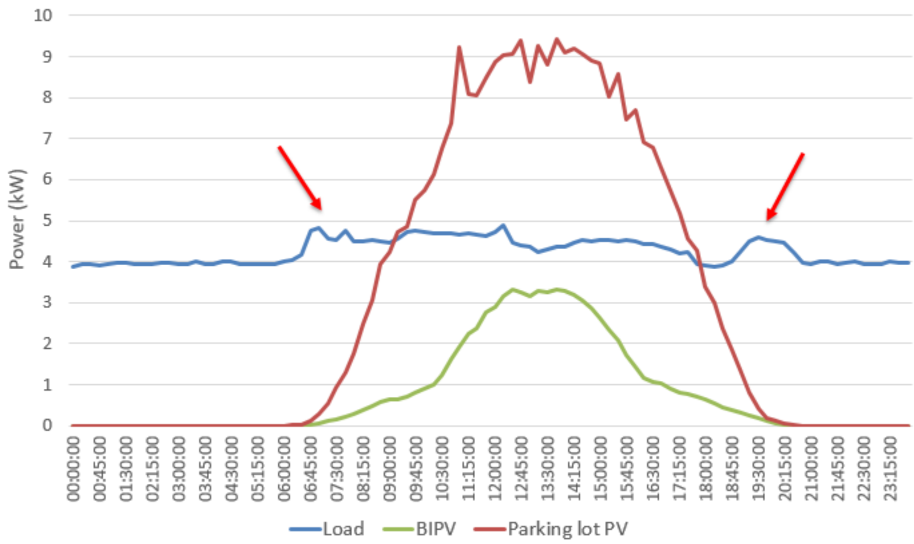


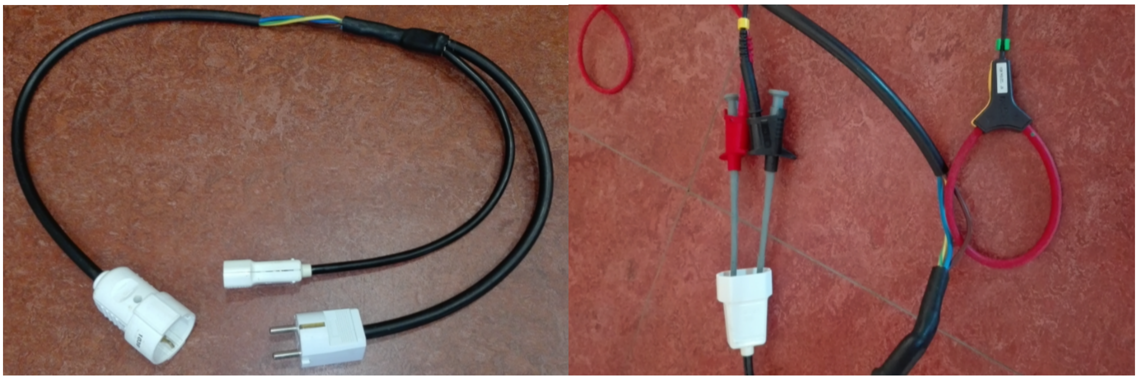
Figure 4.18: Load Match Index with BIPV and parking lot PV for summer period

To calculate the cleaning periods use of energy a deduction had to be done as in the following equation:

$$CPC(i) = (LV(i) - RAV) \tag{4.15}$$

CPC being the *Cleaning Period Consumption* value, *LV* the *Load Value* in that period and *RAV* the *Residual Average Value*. Another average of all *CPC* values was achieved into an *Average Cleaning Period Consumption* (*ACPC*) value. To ease the calculation's explanation the previous value will be split into $ACPC_m$ and $ACPC_a$, corresponding respectively, to morning and afternoon periods.

To estimate the consumption of the laptop, an analysis to one laptop was carried out. In particular the charging period has been conducted. To perform this analysis, the installation was composed by a current clamp and two voltage probes connected to one *Chauvin Arnoux* energy analyser. Instead of the regular connection of the charger to the plug, this charger was connected to a cable from LNEG. The current clamp was measuring the current, and it was placed in the current flow direction. The two voltage probes were connected to the phase and neutral of another plug, measuring the voltage, connected to the wire and just then connected to the main plug. Figure 4.19 shows the cable and the installation respectively.



a Auxiliary cable to measure voltage and current   b Measurement of the laptop charging period

Figure 4.19: Installation of the measurement of the laptop charging period

The laptop charging load value was achieved calculating an average of *LCC* being the *Laptop Charging Consumption* values correspondent to the charging period, resulting into an *Average Load Charging Consumption* (*ALCC*) value.

After obtaining the *ALCC*, this value was multiplied by 6, the number of laptops, giving the total shiftable load value of laptops.

As for the laptop, also the same kind of analysis was carried out on a desktop computer aiming to find out its regular consumption, by measuring it for 2 hours and considering it the *Desktop Consumption* (*DC*) value. The purpose of this procedure was to find out the energy consumption of the 5 desktop computers in the building, to subtract their total consumption value in the beginning of the day, which corresponds to 08:00 until 08:45, and adding it after on lunch time as a laptop, enabling the possibility of converting theoretically those loads into laptop loads raising the energy flexibility potential. A desktop computer does not have energy flexibility potential, however laptops do have it.

By summing the total shiftable load value of laptops ($ALCC * 6$) to the desktops computer loads turned also into laptop loads ($ALCC * 5$), it was possible to shift these values, corresponding to 11 laptops, to the bigger renewable energy generation period, i.e., the lunch break. Also, the two cleaning period loads were added. This process is displayed on the following equation leading to the total potentially shifted value.

$$Total\ value\ to\ shift = (ALCC \times 11) + ACPC_m + ACPC_a \tag{4.16}$$

Regarding DSM, it can offer valuable opportunities to reduce system costs, due to demand peaks but mainly for Residential Buildings and not so much in Office Buildings such as Solar XXI.

No methodologies to quantify energy flexibility based on OCP, cost functions or Model Predictive Control (MPC) were used, since the quantification of flexibility was not the focus of this work (and that would be a complex task due to the characteristics of the building) [36] [58].

This chapter outlines a feasible approach to all types of buildings, of which it can be simply summarized in the three following main sections:

- Data acquisition, which for deeper analyses includes the creation of a building model and only then the investigation of the building in terms of energy.
- Net Zero Balance and LM analyses.
- Energy Flexibility potential research.

Chapter 5

Results and Discussion

In this chapter, regarding the previously defined concepts and applied methods, the results obtained will be analysed and discussed in terms of *Load Matching* and its indicators, *Load Shifting*, electrical energy consumption and generation based on *PVGIS* and *EnergyPlus*, and energy consumption behaviour of Solar XXI users.

5.1 Load Match Diagrams

Figures 5.1 and 5.2 represent the average daily profile of power consumption and generation of the building, for winter and summer weeks, where a distinction between the two PV technologies behaviour can be seen. The two figures resulted from the data collected on consumption and generation and described on subsection 4.1.1 and also on the average of the daily consumption-generation charts exemplified by figure 4.14 present in subsection 4.1.4.

Figure 5.1: Load Matching representation considering BIPV and parking Lot PV for winter period

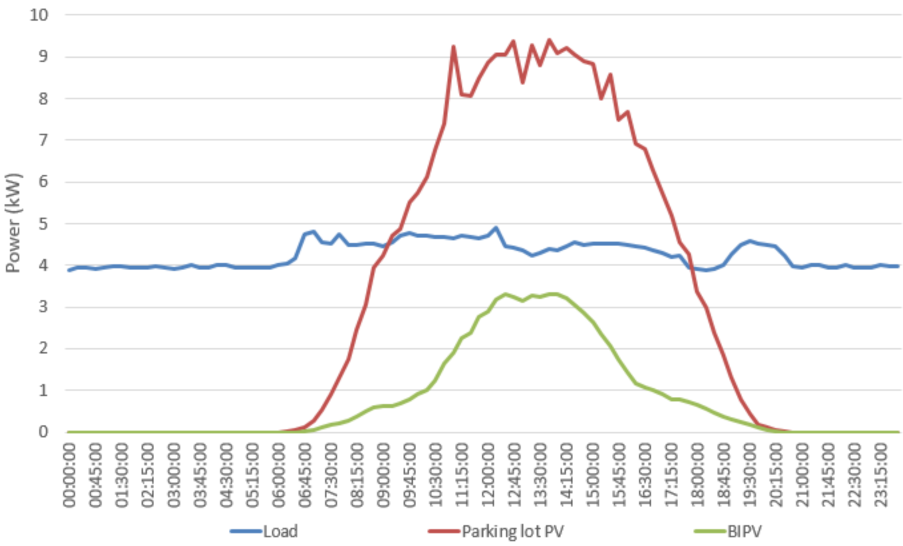


Figure 5.2: Load Matching representation considering BIPV and parking Lot PV for summer period

It is evident that the parking lot PV generation behaviour is similar in both periods but due to the annual behaviour of the vertical BIPV the generation in July is much smaller than in March. It is possible to see an increase of load consumption, either for winter and summer times, this load was previously explained in section 4.4.

5.2 Energy consumption: characterization of user's behaviour outcome

As a conclusion on the behaviour characterization of Solar XXI occupants, in terms of energy, a decision to create one chart concerning each experimental period was taken, since each period has a utterly distinctive behaviour. For March, the ideal situation would be at every moment to have closed doors, closed door frames, closed windows, opened shutters and use of the BIPV-T system to reduce the use of the central heating system. The ideal situation aims for a more efficient use of thermal energy, as an effective use of thermal energy increases the comfort of the users, therefore leading to a reduction of electrical energy consumption.

Figure 5.3 shows the percentage of users that respect the ideal situation for each characteristic.

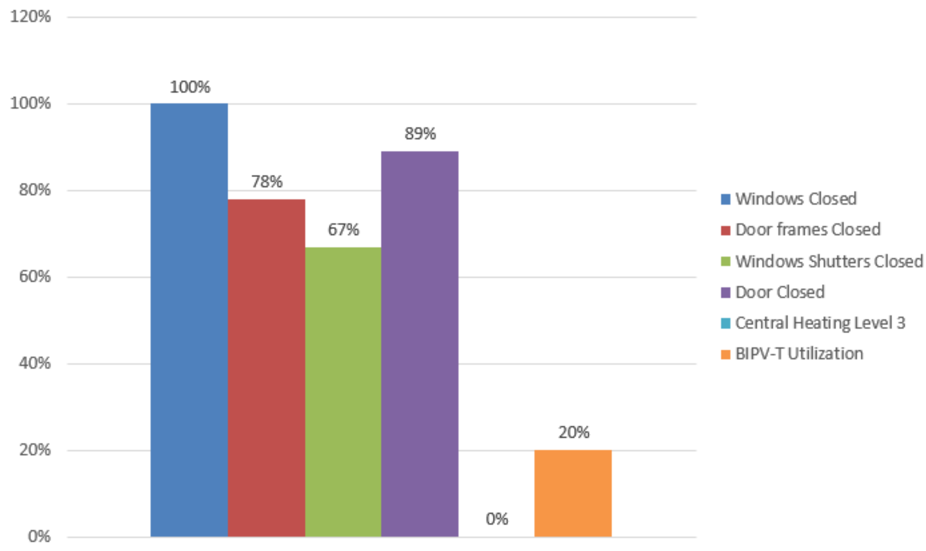


Figure 5.3: Survey results for the winter period

Through the chart, it is estimated that, in March, the selected characteristics are respected in around 59% of the cases.

For July, some of the selected features take opposite behaviours. The ideal situation would be to have, at every moment, open door, open door frames, open windows in the morning, semi-open shutters, earth-tubes utilization with low use of their electric ventilation system and little use of illumination. As in March, the ideal situation aims a more efficient use of thermal energy. Figure 5.4 shows the respective percentage of users that respect the ideal situation.

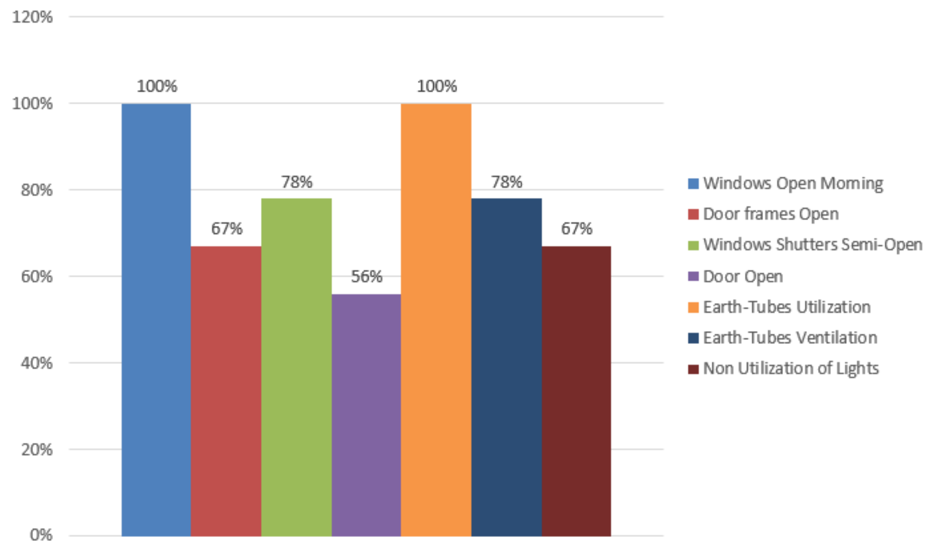


Figure 5.4: Survey results for the summer period

In July the selected characteristics are followed in around 78% of the cases, where these features are way more respected in summer period compared with winter, the latter with low values for a reduced needs building.

In general, the occupants need to have a bigger concern related to the door frames in the winter because they are an air flow passage that reduces the temperature inside the room, and a more significant use of the BIPV-T system, to lessen the applicability of the central heating system. In both periods the sunlight needs to be more exploited, especially in the rooms on the south façade, to reduce the use of electrical light.

5.3 EnergyPlus model validation

As an outcome of the *Numerical Analysis* present of chapter 4, the objective of *EnergyPlus* model validation is to compare the concept model composed by real retrieved values with the simulation representation that implements that conception. This determines if *EnergyPlus* model is an accurate representation of the real system in consideration of the input parameters. Validation is usually achieved through the calibration of the model, mentioned in the previous chapter, as an iterative process of comparing the model to the numerical data using the discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is considered to be acceptable [59] [60].

After repeating the process, *EnergyPlus* model reached an acceptable accuracy that can be observed in figure 5.5.

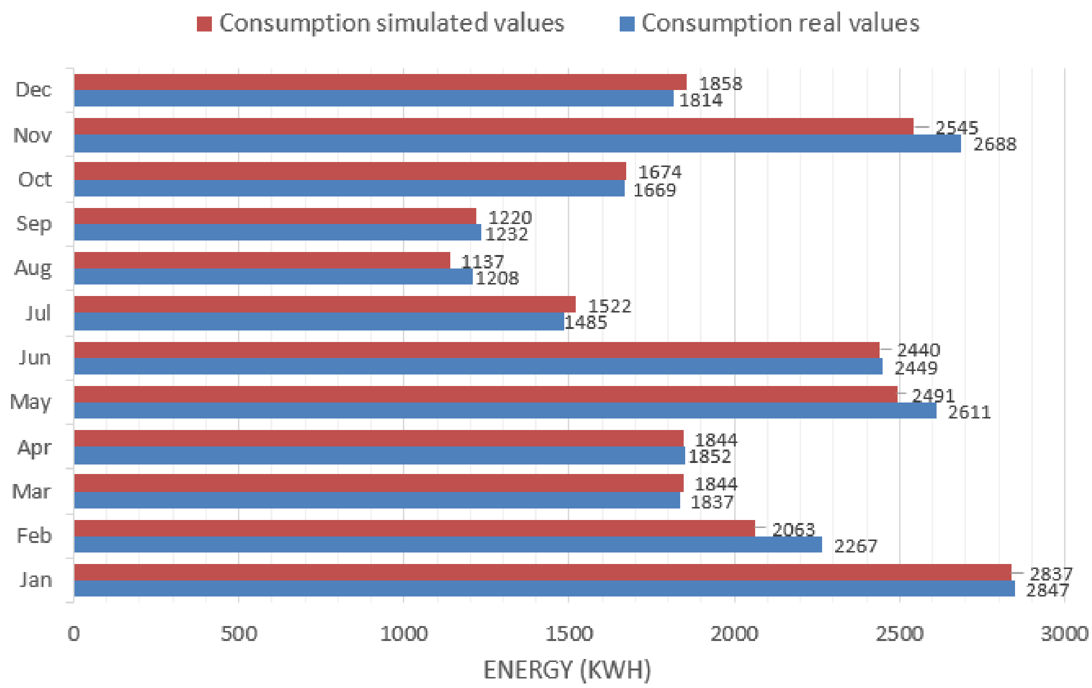


Figure 5.5: Comparison between real and estimated energy consumption values per month of Solar XXI

The graphic above, with a time resolution of one year, shows the difference between the real annual value of consumption, 23959 kWh, and the simulated value, 23475 kWh, which is 484 kWh. This value means that between the real and simulated yearly value exists an error of 2.0%, thus validating the *EnergyPlus* model.

Such errors explain the difference between observed results and predicted values for the model and an analysis of this error was taken and calculated by the equation 5.1 presented below.

$$Error(\%) = \left[1 - \left(\frac{SV}{RV}\right)\right] \times 100 \tag{5.1}$$

where SV is the *Simulated Value* and RV is the *Real Value*.

If the time resolution is monthly, it is legitimate to say that January, March, April, June, July, August, September, October and December have a regular energy consumption. Some of these months have a simulated value a bit higher than the real value. In February, May, and November, it is clear that the energy consumption is higher than expected and the reason for that are likely unanticipated situations that resulted in greater use of energy in those months. This reason is the main *EnergyPlus* model limitation and is highlighted by the mentioned error value.

It is also suitable to split this consumption in Lights and Equipment. The share of light consumption is 63% while the equipment consumption is 37% as figure 5.6 shows. It is relevant to say that this separation is only viable for the simulated case.

In Solar XXI there is no chance for doing this separation with real values because the period of consumption of Lights or Equipment is unknown. Figure 5.7 represents the same comparison but only to the March and July weeks with the estimated amount of energy consumption in each type of load.

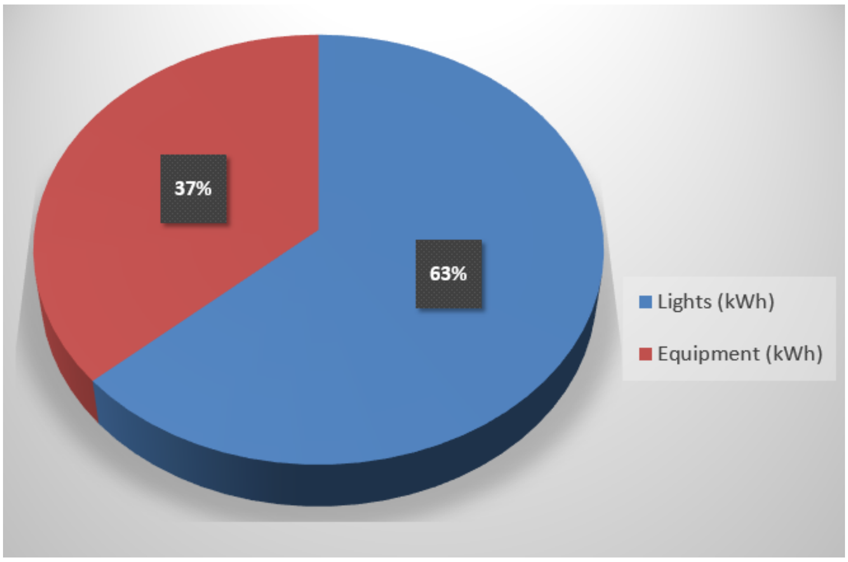


Figure 5.6: Share of Lights and Equipment in Solar XXI on an annual basis

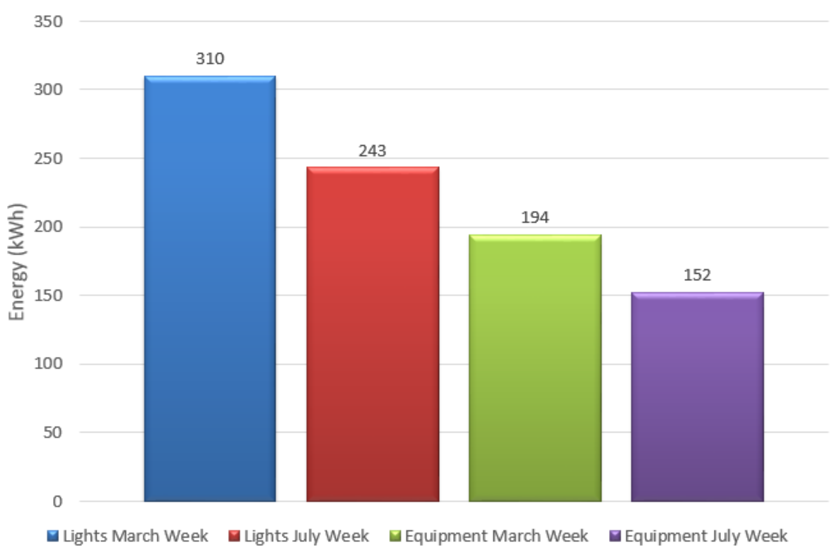


Figure 5.7: Comparison of the share of Lights and Equipment in March and July weeks

The share of Lights takes almost the double of the share of the Equipment mainly since we are talking about an Office Building with low power equipment.

5.4 PV analysis through PVGIS model validation

PVGIS model was simulated and validated with data regarding the PV generation of the entire year. Figures 5.8 and 5.9 show the two types of comparisons.

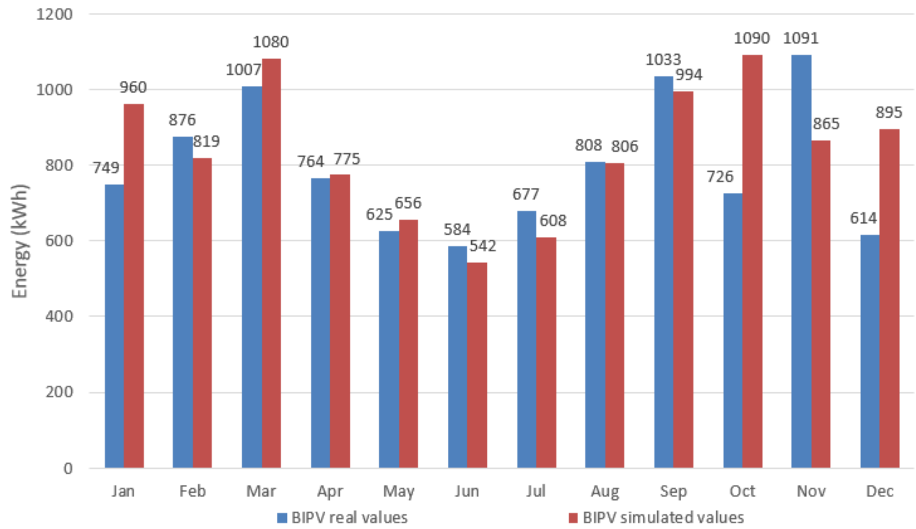


Figure 5.8: BIPV comparison between real and simulated values

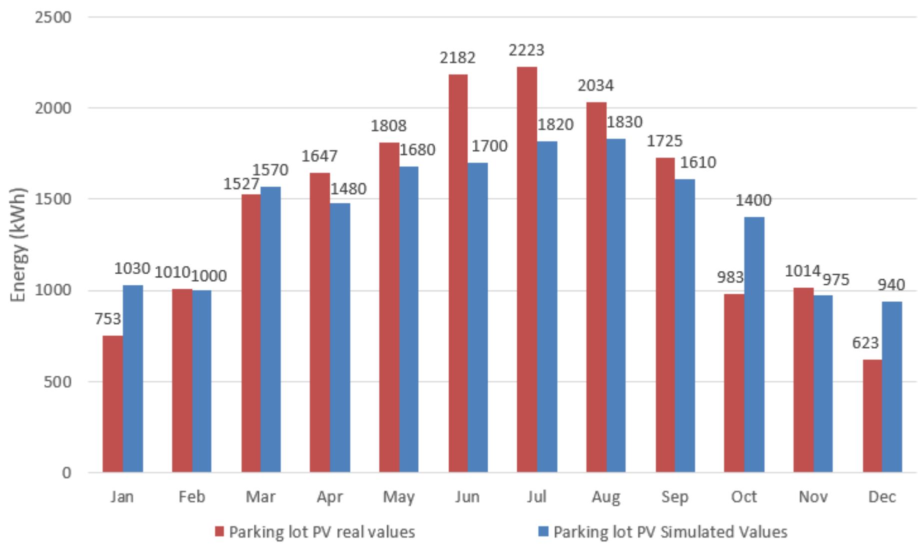


Figure 5.9: Parking Lot PV comparison between real and simulated values

The real values validate the simulation for parking lot PV because it shows an average error of 41 kWh for the real values over the simulated values, and for BIPV, 45 kWh of the real values below the simulated values. For BIPV, half of the real values are below the simulated values, and for parking lot PV only one-third of the real values are below the simulated values.

A study with the purpose of taking the maximum efficiency of the PV panels was possible. It was known that orienting the PV arrays would result in a high power supply, so *PVGIS* enabled to calculate the maximum value of energy that is possible to generate if the parking lot PV varies its angle [55].

Table 5.1: Study over the optimization of the parking Lot PV modules

Month	**Best Angle** (°)	**Maximum Generated value** (kWh)	**Energy Gain** (kWh)
January	70	1140	110
February	61	1040	40
November	70	1040	65
December	70	1050	110

Table 5.1 shows the maximum amount of energy that the parking lot PV could produce in the months with energy consumption higher than energy generation.

Realizing a study including all months would result in a higher amount of energy generation in the end of the year, however, the application although possible would not be realistic, since it would involve the installation of a tracking system in the solar modules that would be an expensive investment. It is therefore proposed to consider only the critical months when the energy balance is negative.

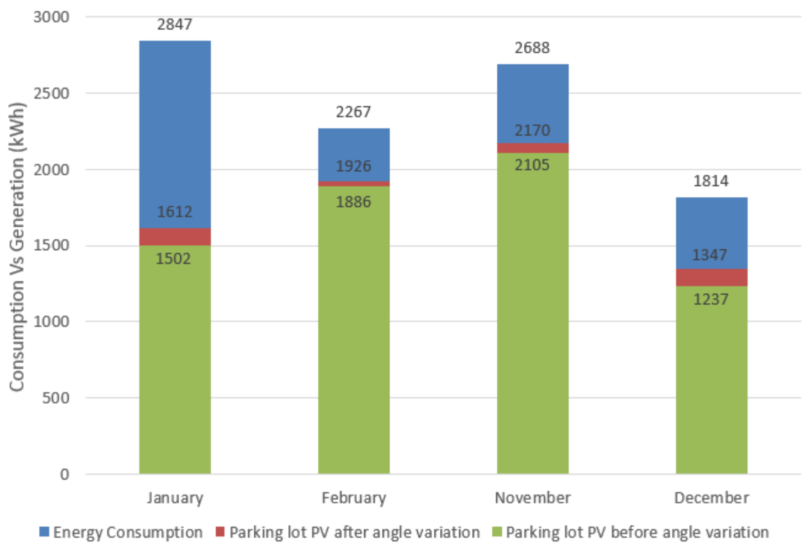


Figure 5.10: Parking lot PV analysis before and after angle variation

As it can be observed in the figure above this angle variation would not be enough to cover the energy consumption in these months, nevertheless this optimization enables a LM analysis displayed on subsection 5.6.2.

5.5 Load Matching and respective indicators results

Regarding LM, it was possible to reach final values for the specifically referred indicators for winter and summer periods, represented respectively in tables 5.2 and 5.3.

Table 5.2: Load Matching Indicators in winter

Factor	**BIPV** (%)	**parking lot PV** (%)	**BIPV + parking lot PV** (%)
Load Cover Factor ($\gamma_{load,T}$)	32	36	38
Self-Consumption Factor (ξ)	32	36	38
Loss of Load Probability ($LOLP$)	74	70	67
Load Match Index ($f_{load,T}$) - 15 min	32	36	38
Load Match Index ($f_{load,T}$) - Daily	82	90	96
Load Match Index ($f_{load,T}$) - Weekly	76	100	100
Load Match Index ($f_{load,T}$) - Monthly	44	69	90
Load Match Index ($f_{load,T}$) - Annually	40	73	100

Table 5.3: Load Matching Indicators in summer

Factor	**BIPV** (%)	**parking lot PV** (%)	**BIPV + parking lot PV** (%)
Load Cover Factor ($\gamma_{load,T}$)	18	44	45
Self-Consumption Factor (ξ)	18	44	45
Loss of Load Probability ($LOLP$)	100	65	63
Load Match Index ($f_{load,T}$) - 15 min	18	44	45
Load Match Index ($f_{load,T}$) - Daily	21	66	100
Load Match Index ($f_{load,T}$) - Weekly	19	72	91
Load Match Index ($f_{load,T}$) - Monthly	44	69	90
Load Match Index ($f_{load,T}$) - Annually	40	73	100

As can be observed in tables 5.2 and 5.3, $\gamma_{load,T}$ takes the same value of $f_{load,T}$ for a time resolution of 15 minutes and the reason is explained in 4.3.2 on the *Load Match Index* description. The reason for similar values of the two previously mentioned factors and *Self-Consumption Factor* is the lack of a battery system in this case study, as mentioned before, making the outcome value of these three factors to be the same.

Analysing BIPV individually, it is clear that *Load Cover Factor* and *Self-Consumption Factor* have a higher percentage in the winter period which leads to a higher rate of LOLP in the summer period. The reason for this is the large amount of energy consumption in the summer period. Analysing parking lot PV, the opposite tendency is observed, because the energy generation is much higher than the energy consumption in some periods.

Also, the LOLP has high values since it includes night values where residual consumption and no energy generation exists. For this reason the $f_{load,T}$ values, with a time resolution of 15 minutes, are really low for both periods, however, the parking lot PV and the two technologies together in the summer period have unlikely higher values than in the winter period because, in contrast to the BIPV value in the same period, covers higher energy generation values than in the winter.

Figures 5.11 and 5.12 represent the LMI, for each time resolution, for both PV technologies together and individually, in terms of percentage.

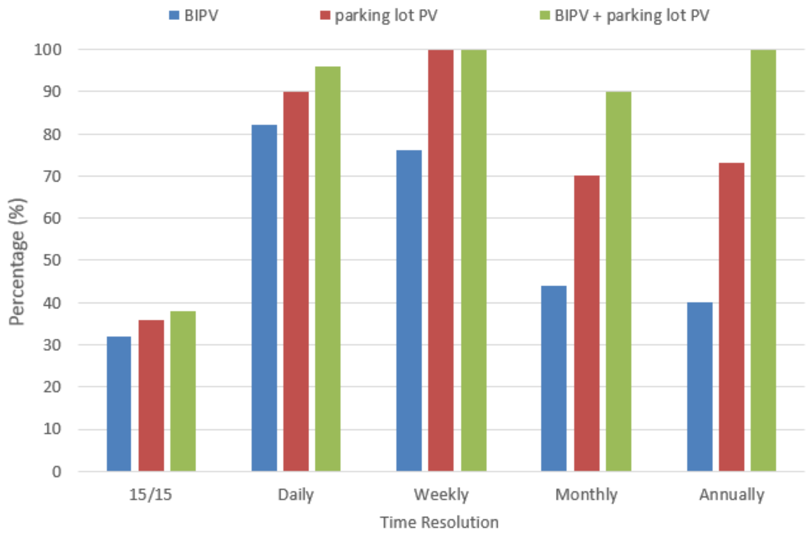


Figure 5.11: Load Match Index for the winter period

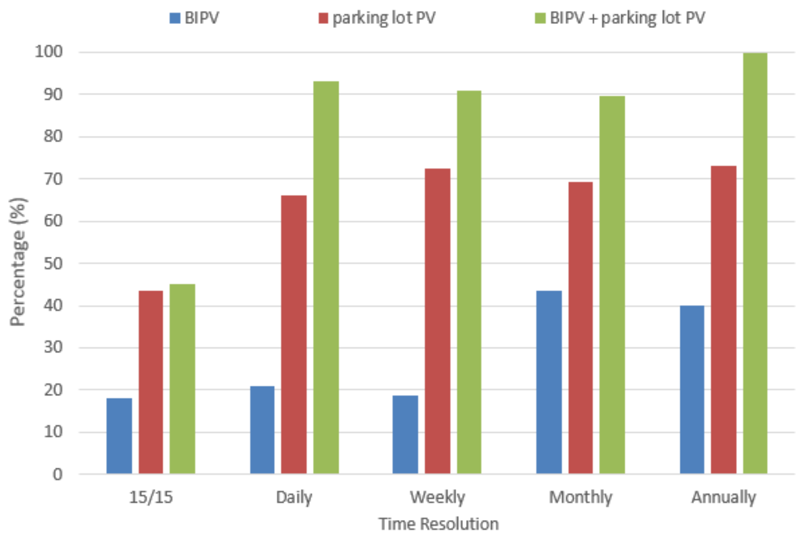


Figure 5.12: Load Match Index for the summer period

There is a striking difference between winter and summer periods. LM in the winter is much higher due to new loads which exist in the summer, as ventilation in the roof and often use of the lab in the basement, which did not take place in the winter. Accounting for an only BIPV system, the monthly and annually analyses result in lower values than expected [23]. Citing the NZEB definition in 2, in a time fraction of one year, the BIPV individually, it is not enough to make the building an NZEB. However, from parking lot PV or with both technologies together, the building *"is able of producing the same amount of energy as it consumes"*, for a weekly time resolution in the winter. This situation happens because for both samples the total generation on that week was bigger than the energy consumption. With a LMI of 100% it is considered a NZEB, in particular, a *Net Zero Site Energy Building* [5].

The $f_{load,T}$ values, with monthly and annually time resolutions, are equal in winter and summer because they cover the same period and share the same values. In July only with an annually time resolution and adding the two PV technologies the system reaches 100%.

Analysing the building in a matter of energy efficiency, for both study weeks, efficiency takes the values of LMI. For a weekly resolution, in the winter, for example, BIPV alone provides an efficiency of 76%, yet in the summer, BIPV alone provides only 19% efficiency, and even adding the parking lot PV it does not reach 100% in that week.

Cumulative Weekly Data

Based on equation 4.14, *Cumulative Weekly Data* is represented with the objective of getting a different perspective on load and generation variation in time in a cumulative way. Figures 5.13 and 5.14 show that in the winter period, parking lot cumulative PV generation exceeds the cumulative load, starting at the biggest PV generation period. As desired, the previous statement proves that the PV generation is bigger than the total energy consumption, in the end of the day.

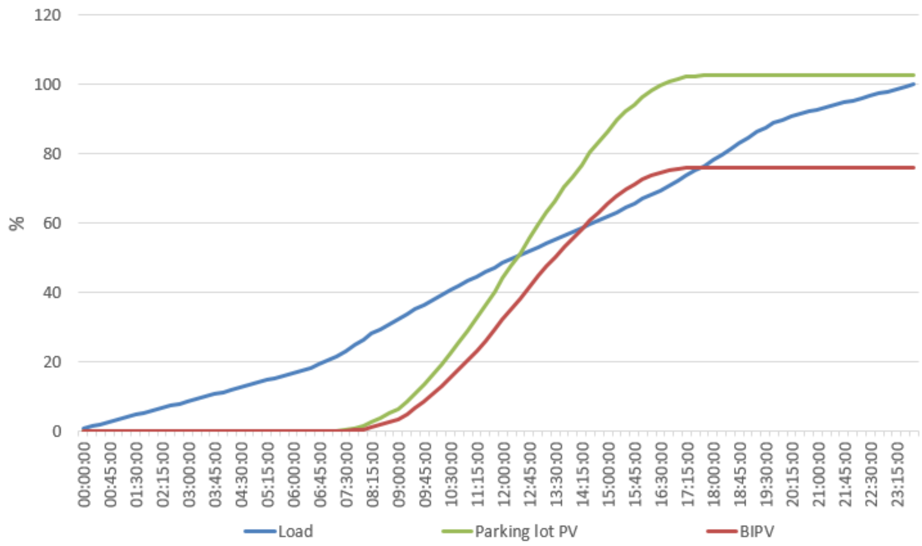


Figure 5.13: Cumulative Weekly Data with BIPV and parking Lot PV for winter period

In the summer the load is much higher for the same reasons, so the parking lot PV has only a small area above the load line, and the BIPV has none being much lower.

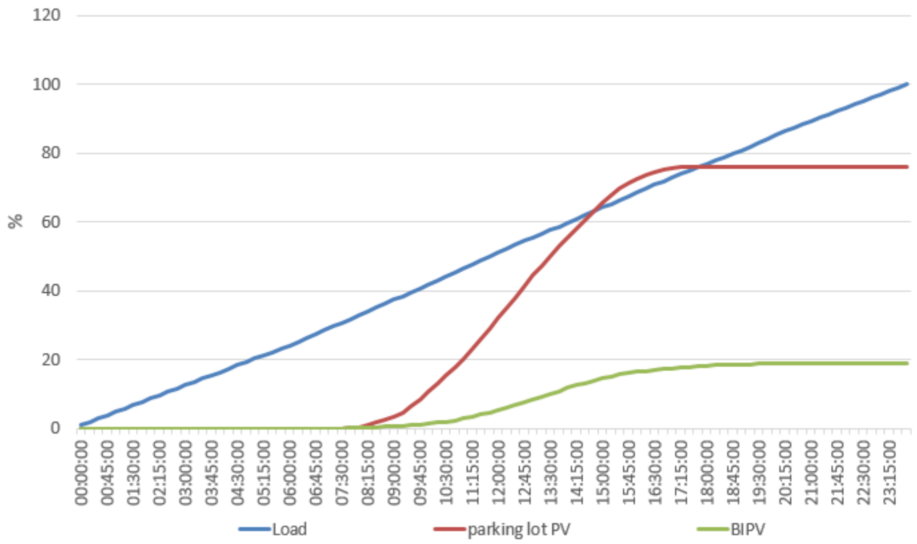


Figure 5.14: Cumulative Weekly Data with BIPV and parking Lot PV for summer period

Average of Energy Load-Generation

Figures 5.15 and 5.16 show the energy which the building imports from the grid, the energy the building uses directly from the PV Generation and the building exports to the grid, representing all the energy that is not used. It is important to mention that the energy imported from the grid has only negative values, which highlights the difference. This analysis represents the daily average values of one week, therefore, daily is the time resolution considered.

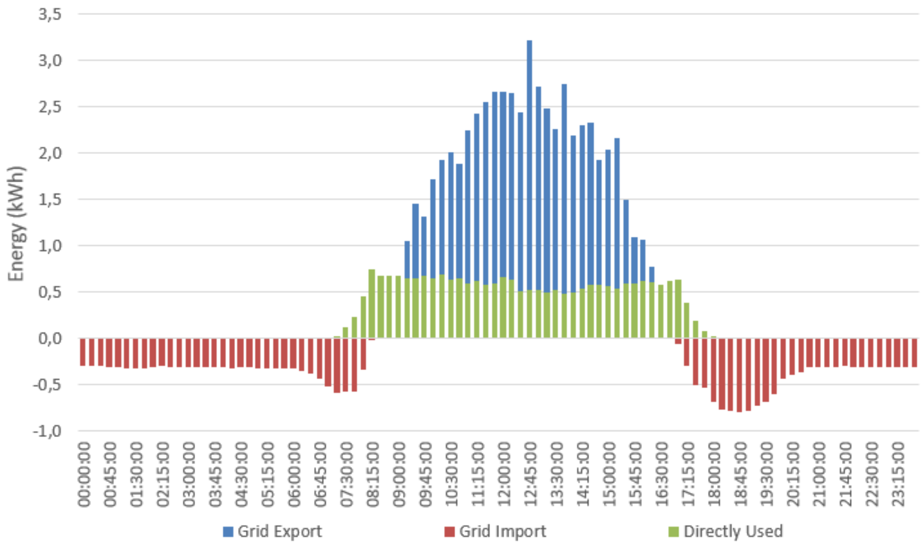


Figure 5.15: Average of Energy Load-Generation for winter period

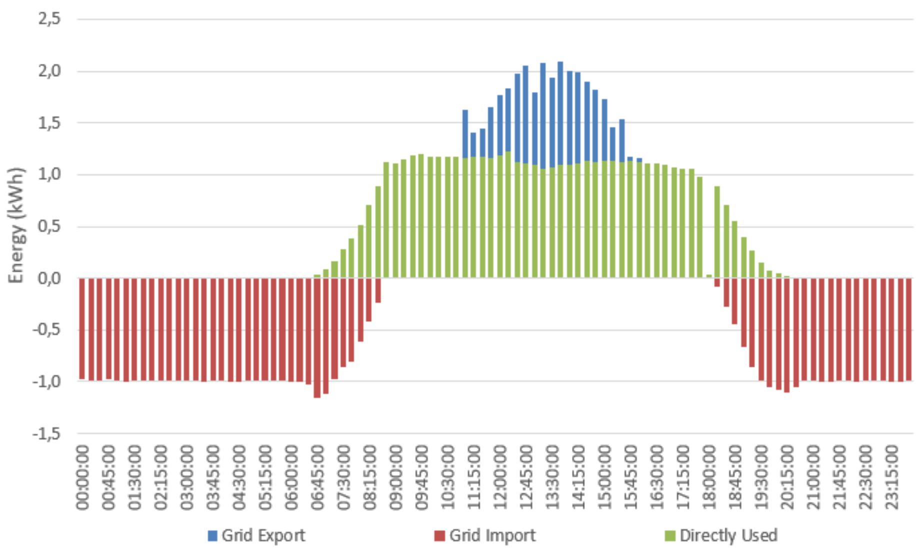


Figure 5.16: Average of Energy Load-Generation for summer period

It is possible to check that, during summer, the amount of energy directly used from the PV generation is much larger than in the winter. This difference does not happen because the grid export energy is higher, but due to the fact that the grid import is double the grid import value in the winter period.

5.6 Load Shifting outcome

Figure 5.17 represents the laptop charging behaviour, in a consumption matter, where the difference between the laptop charging period and the regular consumption period, is evident. This chart derived from the analysis based on the installation mentioned in chapter 4, section 4.4.

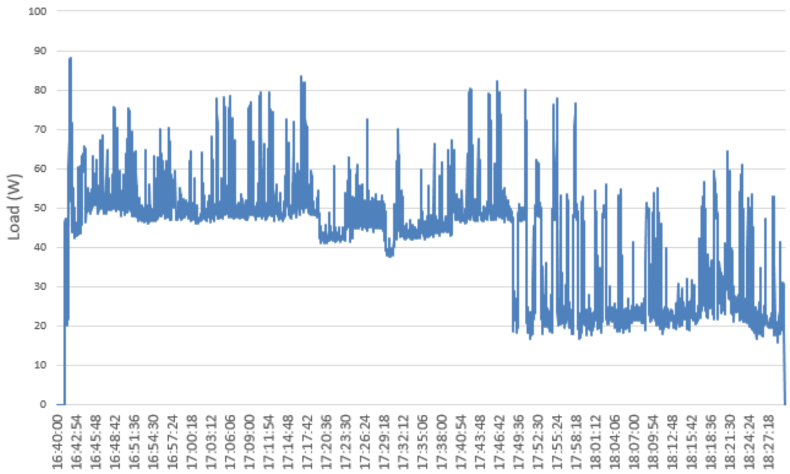


Figure 5.17: Graphic showing the behaviour of a Laptop Charging for around 1 hour

Figure 5.18 represents a desktop computer consumption behaviour.

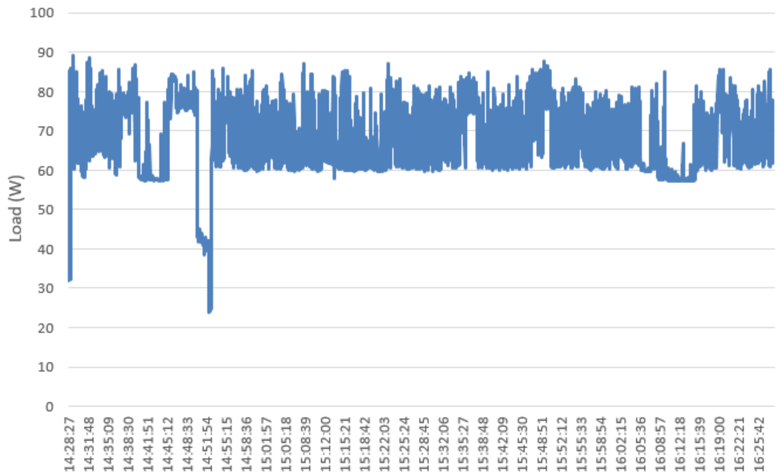


Figure 5.18: Graphic showing the behaviour of a Computer consumption for around 3 hours

Bearing in mind the methodology explained in section 4.4, the obtained *Average Load Charging Consumption* and *Desktop Consumption* values for March and July are represented in the following table 5.4. Number 6 and 5 represent respectively the number of laptops and desktop computers in the building.

Table 5.4: *Average Load Charging Consumption* ($ALCC$) and *Desktop Consumption* (DC) values

$ALCC$	$ALCC \times 6$		DC	$DC \times 5$	
(Wh)	(Wh)	(W)	(Wh)	(Wh)	(W)
50.09	300.54	1202.18	68.24	341.20	1364.78

$ALCC$ was added on the lunch time in March and July and the DC subtracted before as mentioned. Only the cleaning periods ($ACPC_m$, $ACPC_a$) had different values for these winter and summer periods.

In chapter 4 figures 4.14 and 4.15 have signaled the cleaning periods that have been mentioned in that chapter. Figures 5.19 and 5.20 demonstrate the Load Diagrams with all mentioned loads shifted to the lunch break and the two loads corresponding to the PV generation. These two figures also display a distinction between the load before and after the *Load Shifting*.

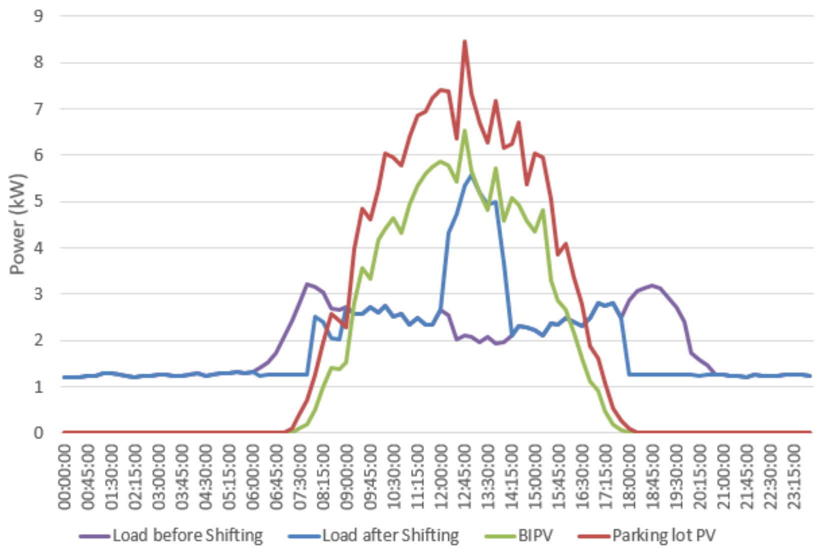


Figure 5.19: Load Diagram showing the Load Shifting operational method applied for winter period

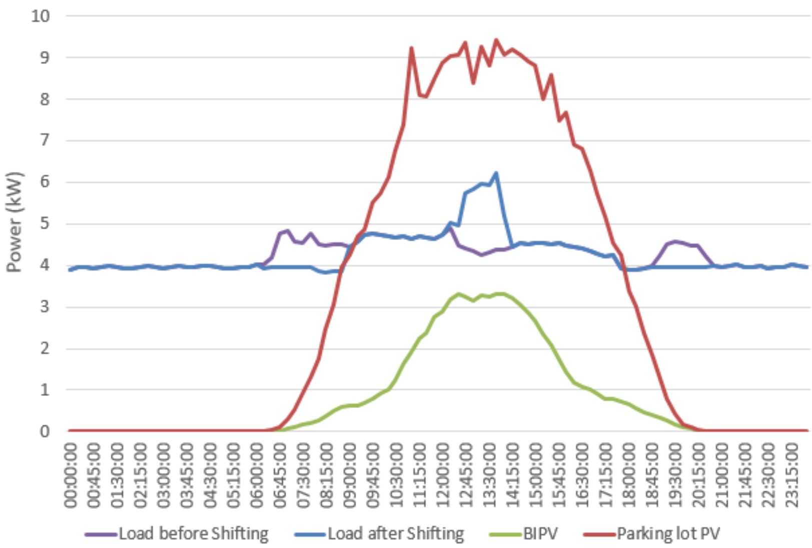


Figure 5.20: Load Diagram showing the Load Shifting operational method applied for summer period

The values corresponding to the $Total\ value\ to\ shift$ in winter and summer periods were respectively 22.06 kW and 9.44 kW. Both values are distributed for 1 hour and 45 minutes, on the bigger energy generation period. In March as desired the load values reach the energy generation, resulting in a good exploitation of this bigger generation period, achieving an ideal LM. In July the *Load Shifting* is also significant but still not enough as desired.

5.6.1 Load Matching after Load Shifting

Regarding the main objective of the current work, *"Investigating the potential of energy flexibility in an office building with façade BIPV and a PV parking system"*, a decision of carry out a new LMI analysis already including the Load Shifting was taken. Table 5.5 presents this new study.

Table 5.5: Load Matching after Load Shifting

Winter	**BIPV** (%)	**parking lot PV** (%)	**BIPV + parking lot PV** (%)
LMI (15 min) before Load Shifting	32	36	38
LMI (15 min) after Load Shifting	35	39	41
Summer	**BIPV** (%)	**parking lot PV** (%)	**BIPV + parking lot PV** (%)
LMI (15 min) before Load Shifting	18	44	45
LMI (15 min) after Load Shifting	18	45	46

Bearing in mind conclusions of the present section the indexes got an increase of 3% in winter time and almost no difference or only 1% in summer time.

5.6.2 Load Matching after PV arrays orientation variation

Taking into account section 5.4, the simulation resulted in the energy generation optimization of the four negative balance months. Table 5.6 displays the LMI values of the parking lot PV and the same added to the BIPV, for the monthly and annually time resolutions, before and after the variation of the PV arrays orientation.

Table 5.6: Load Matching analysis before and after PV arrays orientation variation

	parking lot PV (%)	**BIPV + parking lot PV** (%)
LMI (Monthly) before PV array orientation variation	69	90
LMI (Monthly) after PV array orientation variation	71	91
LMI (Annually) before PV array orientation variation	73	100
LMI (Annually) after PV array orientation variation	77	100

As in the previous LMI analysis, the increase is as expected low, due to the fact that a monthly or annually analysis always includes a big amount of energy, therefore even with a significant energy generation increase this is not enough to change radically the percentage of LMI for these two time resolutions. The monthly LMI had an increase of 1% and the parking lot PV annually analysis had an significantly increase of 4% because it considers four months together.

Chapter 6

Conclusions

6.1 Achievements and improvements

The investigation presented in this thesis, based on the opportunity of having two PV technologies in the same footprint, allowed a comparison of *Load Match Factors*, taking energy use and on-site generation into account. It also allowed the use of small scale loads as energy flexibility operational measures to study the potential for flexible demand on a NZEB office building. A conclusion was that *Load Match Factors* got similar values, as expected from the literature review.

In the summer, the energy spent for cooling is lower than the energy consumed for heating in the winter. In this work, only the electrical part was studied, therefore despite the need of being mentioned, the gas energy for heating in the winter was not included in the calculations. This exclusion is the main reason for this unexpected conclusion of lower values of *Load Match Factors* for the summer.

The *Load Match Factors* used to verify the behaviour between the two PV technologies with the same consumption values, proved that the determination of how the building interacts with the grid has an impact on the value of the electrical energy generated on-site. The factors were also useful to describe the degree of use of on-site energy generation related to the local energy demand.

Taking the *Load Cover Factor* values, it was clear that the influence of different strategies and measures of load modulation, like DSM, is relevant.

From the analysis of the LMI, it was possible to conclude that daily time resolution seems to be suitable for studying a NZEB building, although weekly time resolution also appears to be a real possibility regarding this study. LM helped to optimize the energy consumption by Solar XXI users, through energy consumption reduction measures without loss of comfort and unnecessary waste of energy. In the context of the potential for flexible demand, it is possible to reduce the use of energy in the highest spending period and shift it to the time with bigger renewable energy generation. This situation proves that the building can be even more efficient and that efficiency is directly connected with energy flexibility.

BIPV alone is not the best PV technology to use as energy generation variable in flexibility demand, remaining strongly dependent on the electrical energy grid and never reaching the intended 100 % index. But adding the parking lot PV, is more than enough, in an annual perspective, mainly due to the energy generation difference between these two technologies. The parking lot PV energy generation tends to compensate the lack of generation of the BIPV system during the summer.

A relevant feature was to notice the expected low energy generation, coming from the BIPV in July. Due to its vertical structure, June and July are the months when it generates the least amount of energy. Comparing with March, this is an evident fact.

Load Shifting demonstrated that every building has always a way of being energy flexible however, the energy flexibility potential of Solar XXI is reduced, leading also to a reduced economic impact. Concluding, periods of overproduction were regular during the study, but *Load Shifting* will not increase significantly Solar XXI efficiency. This low potential mainly happens because it is an Office Building, showing that, in general, this kind of buildings do not have much flexibility potential because there are not so many flexibility measures available to apply.

After the application of *Load Shifting*, LMIs took, as expected, low values finding a meaningless difference compared with the scenario before *Load Shifting*.

EnergyPlus model can be used in another experiment in Solar XXI, as it is validated by the real values. *PVGIS* model is also confirmed by the real data because, as mentioned in the previous chapter, it registered similar values to the real ones. Through the PV optimization investigation it could be concluded that the investment in a tracking system for the parking lot PV in the low energy generation months would not make a considerable difference proved by small LMI values after taking optimization in consideration.

It was also possible to compare the Load Macthing values before and after the inclusion of the Load Shifting resulting in expected low values of change.

The LM and *Energy Flexibility* studies aggregated gave a robust and deep analysis of how an energy reduced needs building can always be more efficient based on its users and characteristics.

6.2 Future work

- Energy Flexibility study on a cluster of buildings including Solar XXI

  One of the future works in Solar XXI could be the study of the building aggregation with another building as a cluster, in a matter of energy flexibility, because the potential of energy flexibility in a cluster is theoretically higher. If that other building is residential, the study potential would be enormous because the overproduction in the office building, on the daily regime, can be used in the nightly regime of the residential building.

- Optimization of LM through the inclusion of a battery system study in Solar XXI

  Through all the literature review it was evident that an on-site generation system always works better in a matter of LM, if it is equipped with a battery system, rather than without one. The possibility of Solar XXI to have a battery system would significantly increase not only the flexibility potential but also the efficiency of the building with better LM values.

6.3 Original Contributions

Due to the innovative benchmarking between the two different PV systems, based on the Load Matching and Energy Flexibility studies, emerged a paper to be presented on *bires 2017 - First International Conference on Building Integrated Renewable Energy Systems* to be held between 6 and 9 of March 2017 in Dublin and to be possibly published on Renewable Energy International Journal.

- Title - Investigating the potential for flexible demand in an office building with a vertical BIPV and a PV roof system

- Authors - Daniel Aelenei [1], Miguel Santos [2], Laura Aelenei [3]

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Appendix A

Appendices

A.1 Chauvin Arnoux 8334B model Datasheet

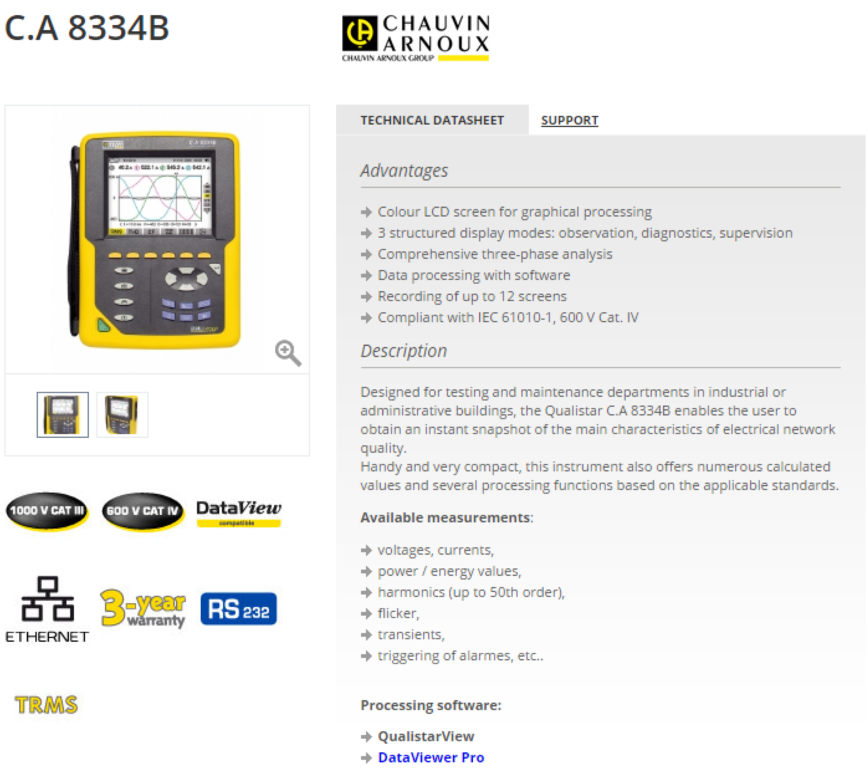
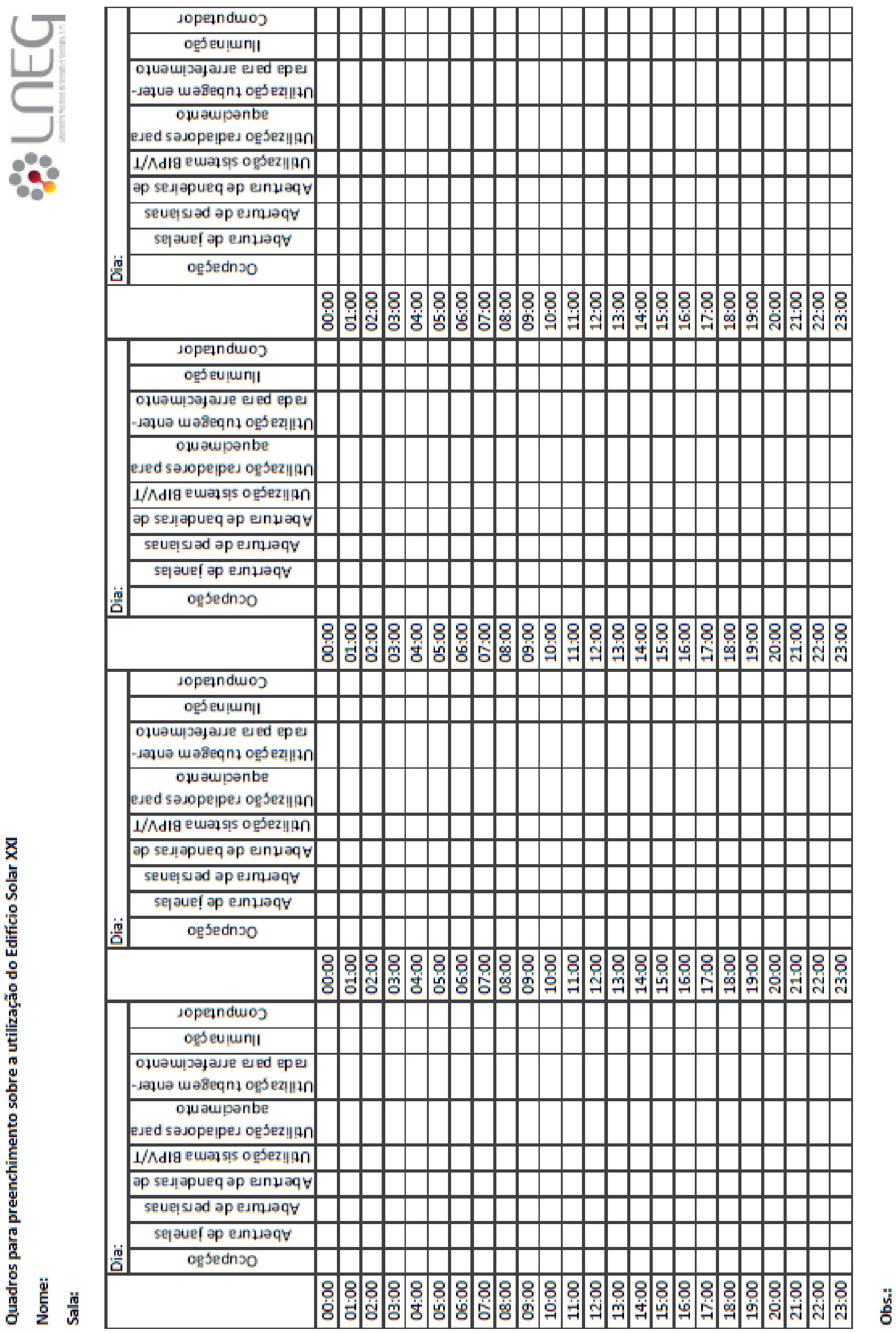


Figure A.1: Chauvin Arnoux 8334B Technical Description [48]

A.2 Solar XXI Energy Use Survey



Quadros para preenchimento sobre a utilização do Edifício Solar XXI

Nome:

Sala:

	Dia:								
	Ocupação	Abertura de janelas	Abertura de persianas	Abertura de bandeiras de	Utilização sistema BIPV/T	Utilização radiadores para aquecimento	Utilização tubagem enterrada para arrefecimento	Iluminação	Computador
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	Dia:								
	Ocupação	Abertura de janelas	Abertura de persianas	Abertura de bandeiras de	Utilização sistema BIPV/T	Utilização radiadores para aquecimento	Utilização tubagem enterrada para arrefecimento	Iluminação	Computador
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23:00									

	Dia:								
	Ocupação	Abertura de janelas	Abertura de persianas	Abertura de bandeiras de	Utilização sistema BIPV/T	Utilização radiadores para aquecimento	Utilização tubagem enterrada para arrefecimento	Iluminação	Computador
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	Dia:								
	Ocupação	Abertura de janelas	Abertura de persianas	Abertura de bandeiras de	Utilização sistema BIPV/T	Utilização radiadores para aquecimento	Utilização tubagem enterrada para arrefecimento	Iluminação	Computador
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Obs.:

Figure A.2: Energy use behaviour survey of Solar XXI

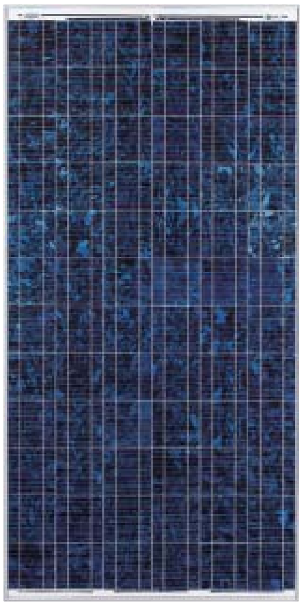
A.3 Solar XXI BIPV modules Datasheet

bp solar

160 Watt Photovoltaic Module

BP 3160

4015E-1 12/03



BP 3160S scale 1:14

The BP 3160 is an advanced 160W module. For better absorption it uses polycrystalline cells with anti-reflective SiN coating. With a new tighter power tolerance of 3% a higher average power output is guaranteed. The BP 3160 has been especially designed for grid connect applications such as large commercial roofs, residential systems and photovoltaic power plants. This 72 cell module offers a superior price – performance relationship due to its tighter power tolerance, white tedlar back sheet and the innovative, high-efficiency cells.

Performance

Rated power	160W
Module efficiency	12.7%
Nominal voltage	24V
Warranty	90% power output over 12 years 80% power output over 25 years Free from defects in materials and workmanship for 5 years

Configuration

BP 3160S	Clear Universal frame with output cables and polarized Multicontact (MC) connectors
BP 3160L	Unframed laminate version of BP 3160S

Qualification Test Parameters

Temperature cycling range	-40ºC to +85ºC for 200 cycles
Damp heat test	85ºC and 85% relative humidity for 1000h
Front & rear static load test (eg: wind)	2400 Pa
Front load test (eg: snow)	5400 Pa
Hailstone impact test	25mm hail at 23m/s from 1m distance

Quality and Safety

- Manufactured in ISO 9001 and ISO 14003 certified factories
- Conforms to European Community Directive 89/33/EEC, 73/23/EEC, 93/68/EEC
- Certified to IEC 61215

Module power measurements calibrated to World Radiometric Reference through ESTI (European Solar Test Installation at Ispra, Italy)

Framed modules certified by TÜV Rheinland as Safety Class II (IEC 60364) equipment for use in systems up to 1000 VDC

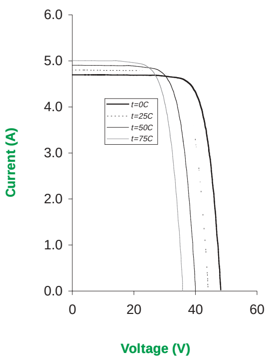
Framed modules listed by Underwriter's Laboratories for electrical and fire safety (Class C fire rating)

Laminates recognised by Underwriter's Laboratories for electrical and fire safety (Class C fire rating)

Efficiency (%)

9-11	11-12	12-13	13-14	14-15

BP 3160 I-V Curves



TÜV

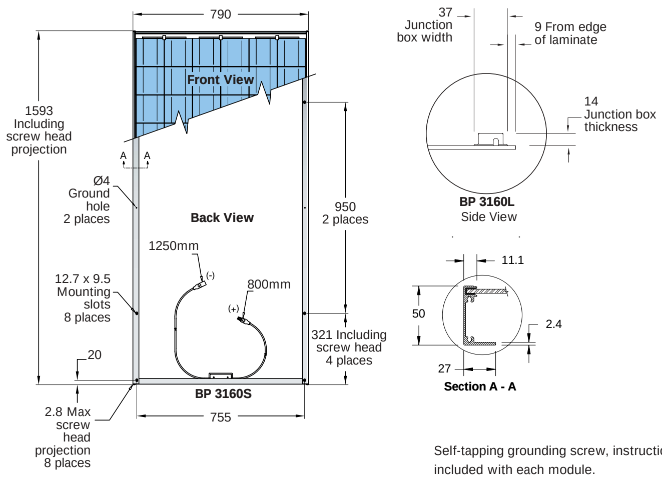
bp solar

160 Watt Photovoltaic Module

BP 3160

4015E-1 12/03

Module Diagram



Self-tapping grounding screw, instruction sheet and warranty document included with each module.

Typical Electrical Characteristics	BP 3160
Maximum Power (P_{max})	160W
Warranted minimum power	155W
Voltage at P_{max} (V_{mp})	35.1V
Current at P_{max} (I_{mp})	4.55A
Short circuit current (I_{sc})	4.8A
Open circuit voltage (V_{oc})	44.2V
Temperature coefficient of I_{sc}	(0.065±0.015)%/K
Temperature coefficient of V_{oc}	-(160±20)mV/K
Temperature coefficient of P_{max}	-(0.5±0.05)%/K
NOCT (Air 20ºC; Sun 0.8kW/m^2; wind speed 1m/s)	47±2ºC
Maximum series fuse rating	15A
Maximum system voltage	1000V (IEC 61215 rating) 1000V (TÜV Rheinland rating)

Standard test conditions - irradiance of 1000W/m^2 at an AM1.5G solar spectrum and a temperature of 25°C.

Mechanical Characteristics	BP 3160S	BP 3160L
Dimensions (mm) (Overall tolerances +/-3mm)	1593 x 790 x 50	1580 x 783 x 19
Weight (kg)	15.0	12.4
Frame (BP 3160S)	Clear anodised aluminium alloy type 6063T6. Silver Universal frame.	
Solar cells	72 cells (125mm x 125mm) configured geometrically for a 6 x 12 matrix connected in series.	
Output cables	RHW AWG# 12 (4mm^2) cable with polarized weatherproof DC rated Multicontact connectors; asymmetrical lengths 1250mm (-) and 800mm (+).	
Diodes	Three 9A, 45V Schottky by-pass diodes included.	
Construction	Front: High transmission 3mm tempered glass. Rear: White tedlar; Encapsulant: EVA.	

Your BP Solar Distributor:

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A.4 Solar XXI Parking lot PV modules Datasheet

Schüco CIS thin-film modules in the TF series

Technical information

Innovative thin-film modules with CIS technology
Schüco CIS modules (CIS = copper, indium, selenium) have excellent power output even at high temperatures and make maximum use of diffuse daylight. Schüco CIS modules deliver stable output values because they show no disproportionate initial degradation. Inverters can be dimensioned during mounting and do not have to be adjusted later. The module efficiency level is up to 10,1 % with an effective performance tolerance of +5/-0 %. The rated output is always achieved or exceeded.

Comprehensive guarantee
Schüco CIS modules have a 5-year product guarentee. The guarantee on rated output under standard test conditions is that after 20 years, the module will still provide at least 80 % of its rated output. Every CIS module is manufactured according to current quality standards.

Optimised labelling
Prior to delivery, every CIS module is subject to a visual and electrical quality test. The performance data measured is marked on the reverse side of the module and packaging. This means that homogeneous module fields can be grouped together effectively.

High level of operational reliability
A connecting box with bypass diode bridge on the reverse of the module prevents the active module surface from overheating. This ensures the reliable operation of the whole system.

Environmental protection
The thin-film technology minimises the use of raw materials in production. Schüco CIS modules do not contain cadmium or lead. The energy payback period is approx. one year only.

Attractive and robust
The black module frame made from torsion-proof, anodised aluminium meets the highest standards in terms of stability and corrosion resistance. The module surface is also black, creating an attractive design. Schüco CIS modules can be installed with components from the Schüco PV Light installation system. Rounding off the overall look, the module clips are also black anodised.

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Schüco CIS thin-film modules

Key electrical data	Module output categories		
Output data (except NOCT) under Standard Test Conditions (STC)*:	SPV 70-TF	SPV 75-TF	SPV 80-TF
Rated output (Pmpp)	70 Wp	75 Wp	80 Wp
Effective output tolerance (Δ Pmpp)	+5 % /-0 %	+5 % /-0 %	+5 % /-0 %
Guaranteed minimum output (Pmpp min.)	70 W	75 W	80 W
Rated voltage (Umpp)	37,6 V	40,5 V	41,0 V
Rated current (Impp)	1,85 A	1,85 A	1,95 A
Open circuit voltage (Uoc)	54 V	55,5 V	56,5 V
Short circuit current (Isc)	2,2 A	2,2 A	2,26 A
Module efficiency	8,8 %	9,5 %	10,1 %
Temperature coefficient α (Pmpp)	-0,39 % / °C	-0,39 % / °C	-0,39 % / °C
Temperature coefficient β (Isc)	+0,04 % / °C	+0,04 % / °C	+0,04 % / °C
Temperature coefficient χ (Uoc)	-0,19 % / °C	-0,19 % / °C	-0,19 % / °C
Temperature coefficient δ (Impp)	+0,004 % / °C	+0,004 % / °C	+0,004 % / °C
Temperature coefficient ε (Umpp)	-0,26 % / °C	-0,26 % / °C	-0,26 % / °C
Normal Operating Cell Temperature (NOCT)**	48 °C (± 2 °C)	48 °C (± 2 °C)	48 °C (± 2 °C)
Max. permissible system voltage	1.000 V	1.000 V	1.000 V
Active module area	1203 x 610 mm	1203 x 610 mm	1203 x 610 mm

* Intensity of solar radiation 1000 W/m², air mass 1.5, cell temperature 25°C

** Intensity of solar radiation 800 W/m², ambient temperature 20 °C, wind speed 1 m/s

Key mechanical data	
Outer dimensions (l x w x h)	1235 x 641 x 35 mm
Design of aluminium frame	Anodised, black
Front glass	Toughened safety glass (TSG)
Weight	12,5 kg
Connection system/cross section of solar cable	Multi-contact type 3 / 2.5 mm²
Lengths: Positive cable / negative cable	100 cm ± 5 cm / 100 cm ± 5 cm

Miscellaneous	
Weight of packing unit	26 kg
Schüco installation system	PV-Light
Schüco Art.-No. End clip	Typ 39-1
Schüco Art.-No. Intermediate clip	Typ 39-2
Schüco Art.-No. SPV 70-TF	256018
Schüco Art.-No. SPV 75-TF	256019
Schüco Art.-No. SPV 80-TF	256020
Packing unit	2 modules

Guarantee	
Electrical classification	Safety class II
Product standard	IEC 61646
Product guarantee	5 years
Output guarantee to 90 % Pmpp min	10 years
Output guarantee to 80 % Pmpp min	20 years

Output				
70 to 80 Wp	▶	Optimised power density	▶	Highest yields
Positive output tolerance	▶	Rated output is achieved or exceeded		
Design and production				
Optimised labelling	▶	Individual rated output data on module and packaging		
Anodised aluminium frame	▶	Meets the highest quality standards		
Bypass diodes	▶	Prevents the active module area from overheating		
Extended product and output guarantee	▶	Investment security and reliable system operation		
Highest Schüco quality				
Manufactured in accordance with current quality standards	▶	Tests to determine performance data; data listed for each module		

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P 3033/GB/06.08/Printed in Germany