Master in Chemical Engineering

Assessment of a nearly zero energy house

A Master's dissertation

of

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"You cannot get through a single day without having an impact on the world around you. What you do makes a difference, and you have to decide what kind of difference you want to make."

(Jane Goodall)

Abstract

The present work aims at studying the energy consumption in a household in Porto region and its contribution in the integration of photovoltaic and storage systems. Two goals were established: the search for the more economical scenario and the one that leads to a total independence from the public electric grid. For this study was used an energy simulation software tool named EnergyPlus.

In the first scenario, the influence of the PV panels area on energy production and the contribution of the battery were assessed. Then an economic analysis was performed to search the PV area that leads to the best annual savings being also taking in account the investment and O&M costs. For the second scenario all the available area of the building was covered with PV panels for reach the total independence from the grid. The integration of a wind turbine and biomass was also studied.

EnergyPlus is a software that showed be able to perform the proposed studies and give realistic results for the correct evaluation of the project. As result of the studies for the first scenario can be conclude that the implementation of a storage system increases for double in some cases the autonomy of the building in relation to the grid. With larger PV areas, better autonomy but larger investment and O&M costs. This way, the viable projects that leads to the best savings, are not the ones with larger PV area. For the second scenario can be conclude that is possible have a house with total independence from the grid, with all electricity produced in site, and being an economically viable project.

Keywords: EnergyPlus; PV system; storage system; total independence, economic analysis.

Declaration

I hereby declare, on my word of honour, that this work is original and that all non-original contributions were properly referenced with source identification.

Porto, 2 July 2018

(Fábia Catarina Silva Leal)

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Notation and Glossary

R	Remuneration of the electricity to the grid	€
E	Energy	kWh
C	Taxes	€
P	Power	kW
K_t	Price coefficient	
T	Temperature	$^\circ$C
$\dot{Q}$	Heat flow	W
h_c	Convective heat transfer coefficient	W m^{-2} $^\circ C^{-1}$
A	Area	m^2
C_P	Thermal capacity	J kg^{-1} $^\circ C^{-1}$
$\dot{m}$	Mass flow	kg s^{-1}
η	Efficiency	
q	Battery capacity	Ah
I	Current	A
k	Constant	h^{-1}
c	Parameter indicating the ratio of available charge capacity	
Δt	Elapsed time	h
E	Open circuit potential	V
V	Battery terminal potential	V
R	Battery internal resistance	Ω

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i	Counter

List of Acronyms

RTBCB	Regulation of the thermal behaviour characteristics of buildings
R&D	Research and development
PCU	Power conditioning unit
DC	Direct current
AC	Alternating current
PV	Photovoltaic
LCOE	Levelized cost of electricity
CSP	Concentrating solar power
PUSC	Production units for self-consumption
SERPU	PUSC electronic registration system
GDEG	General direction of energy and geology
LRM	Last resort marketer
PUEN	Public utility electricity network
OIEM	Operator of the Iberian energy market
GEIC	General economic interest costs
HVAC	Heating, ventilation and air conditioning
COP	Coefficient of performance
LCOE	Levelized cost of energy
DHW	Domestic hot water
O&M	Operation and maintenance

1 Introduction

1.1 Framing and presentation of the work

Currently all aspects related to energy have been studied and discussed becoming more of the public interest all over the world. In the past years there has been a growing concern about the high energy consumption and an increasing investment in renewable energy sources and technologies to produce energy.

Buildings are one of the fields where measures can be adopted to reduce the energy consumption and integrate renewable energy technologies with high impact. Much has been done over the last few years with studies for the best shape and solar orientation of the buildings to reduce the heating and cooling loads as well as the best materials with the suitable characteristics to increase the quality of the thermal envelope.

The integration of renewable technologies into buildings gained recently a new dimension owed to the fact that it can effectively reduce the overall cost of energy. Also in this field, several studies and efforts to improve the efficiency of the equipment, life cycle and cost reduction have been made. These studies target to teach the best combination of technologies to reduce the energy bill and to make buildings more sustainable and in compliance with the relevant national laws.

But in the last years, the fact that technologies that harness the sun's energy only be able to take advantage of its power during the day, many times being superior to the demand, and buy all the electricity need for the night to the grid arise the study of the integration of a storage system. This system aims at to store energy during the daytime releasing it during the night as needed, making the buildings more autonomous and contributing for reducing the energy costs.

Building energy modelling has gained significance in the last years becoming indispensable for engineers and architects. Energy simulation tools allow the building characteristics improvement envisaging the reduction of the overall energy consumption and make buildings more sustainable.

Following this path, this dissertation has the objective of simulating a household, with all the parameters to comply with the Portuguese Regulation and integration of thermal solar collectors, PV panels and an electrochemical storage system for two scenarios. The first one aims at minimizing the cost of energy while the second scenario optimizes the combination of different technologies to obtain the complete energy independence at the lowest cost. For both it was made an economical and technical assessment considering PV panels, thermal solar collectors, electrochemical storage and biomass technologies to obtain the partial or total energy supply from renewable sources.

1.2 Contributions of the Work

The development of this work contributes for better understanding the impact of the integration of different renewable energy related technologies in a common household. Especially the contribution that an integration of storage system may have in the reduction of the electricity purchased to the grid or in the electrical house independence from the grid. Also contributes for the knowledge of investment and maintenance costs that may occur and the cost of production electricity versus purchase to the grid.

1.3 Organization of the thesis

This dissertation was organized in seven chapters. In the first chapter, *Introduction*, is made a brief presentation of the project, describing the problematic behind the chosen topic and its objectives.

The second chapter, *Context and State of the art*, a literature survey is conducted on relevant related information related, namely thermal envelope of the buildings, PV, solar thermal and storage systems.

Chapter three, *Simulator*, describes the software, EnergyPlus, as well as the governing equations by which the software rules.

In chapter four, *Studied cases*, are described all the parameters that were defined to design the building and its electrical energy consumption, as well as the specifications of PV and storage systems.

In chapter five, *Results and discussion*, the obtained results by EnergyPlus such as energy consumption, photovoltaic production and energy storage are presented and discussed.

Chapter 6, *Conclusions*, presents the final remarks where the main conclusions are discussed.

In chapter 7, *Assessment of the work*, is made an evaluation of the work regarding the accomplishment of the proposed objectives and some suggestions for future work are presented.

2 Context and state of the art

A sustainable building refers to a structure and to the application of processes envisaging an efficient use of energy, water and other resources, the reduction of residues and environmental degradation and the protection of occupant health [1].

There are several good reasons to explain why the construction of sustainable buildings and reduction of energy consumption is a very important practice. Firstly, the climate change; earth temperature is increasing over time due to the emission of greenhouse gases, namely CO^2. In Portugal, for example, the 2015 average emission of CO^2 from buildings represented 6 % of the total CO^2 emissions, which is a non-negligible contribution [2]. On the other hand, the consumption of energy is still based on fossil fuels. Its combustion causes environmental damages and adverse health impacts. The reduction of energy consumption in buildings and the use of sun and wind energy contributes to reduce the consumption of fossil fuels and make buildings more energy independent. However, renewable energy sources are intermittent. The solution to solve this problem is the integration of a storage system. Such system will store electricity when there is a surplus production and deliver electricity when necessary.

Therefore, to improve building performance several practices and technologies must be employed [3]:

- Climate, building shape and sunlight orientation;
- Construction materials with low thermal transmittance;
- Efficient domestic appliances;
- Integration of renewable energy related technologies;
- Integration of storage systems connected to renewable energy related technologies.

2.1 Climate

Climate, outdoor temperature, humidity, atmospheric pressure, wind speed, precipitation and the amount of solar radiation are relevant aspects in a building development and construction. These factors determine the heat exchanges between the building and its surrounding. During winter the energy flows from the indoor to the outdoor of the building (thermal losses), while in the summer the flow happens in the opposite direction (thermal gains). Solar radiation is one of most important factor in thermal comfort of buildings, heating the indoor space during winter, while during summer is a heat source to avoid.

2.2 Building shape and orientation

Building shape and orientation are aspects that affect the heating and cooling loads, daylighting, ventilation and on the dimensioning of integrated solar energy systems, namely PV and thermal collectors. The building shape is related to its dimensions (height, width, length among others) and the orientation refers to the direction that the longest horizontal dimension is oriented (north, south among others) [4].

In Portugal, for example, the facades oriented to south receive more solar radiation than facades oriented in other directions. In winter is the most effective strategy for capturing solar radiation for heating the building. In summer, the roof is the zone that receive more solar radiation, leading to less solar gains in windows, which is important for the cooling of the building [5].

2.3 Thermal envelope

The term thermal envelope refers to the frontiers of the building that act like a barrier against heat losses from indoor to outdoor, that can be done by conduction, convection and radiation or to the penetration of unwelcome heat into the building [4].

Air can flow into or from the building through leaks that may exist, as represented in Figure 1. This process is called air infiltration and is undesired because the airflow is uncontrolled. Its effect affects the use of energy, thermal comfort and can cause damage to the building structure due to the humidity it carries [6].

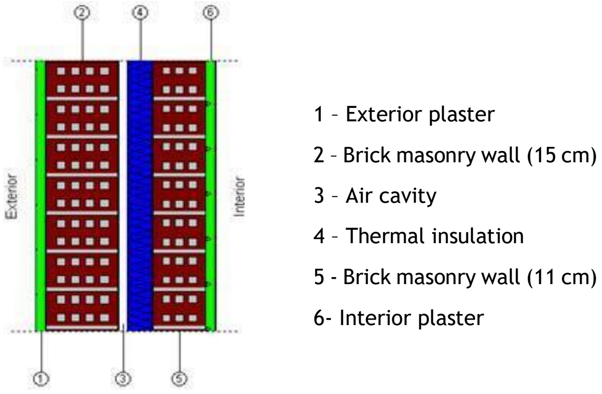
Figure 1 - Air leakage in a common house. Extracted from [33].

These barriers are defined as floor, roof, walls, windows and doors. Are also very important in terms of humidity air infiltration, noise and climate conditions, wind and rain.

2.3.1 Thermal insulation in external walls and roofs

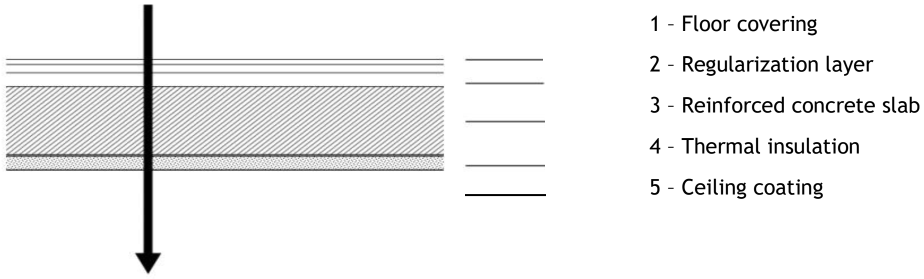
In the last years, the most used material for thermal insulation is expanded or extruded polystyrene in the form of a layer with specific thicknesses.

The Portuguese regulation for thermal behaviour in buildings (RTBCB) established the maximum permissible values of thermal transmission coefficients for walls between 1.5 and 1.8 W m^2 ºC^{-1} and for roofs and floors between 0.90 and 1.25 W m^2 ºC^{-1} depending on the region of construction [7]. Figure 2,Figure 3 and Figure 4 are schematic representations of the construction of exterior walls, floor and ceiling respectively, that are common in Portugal.



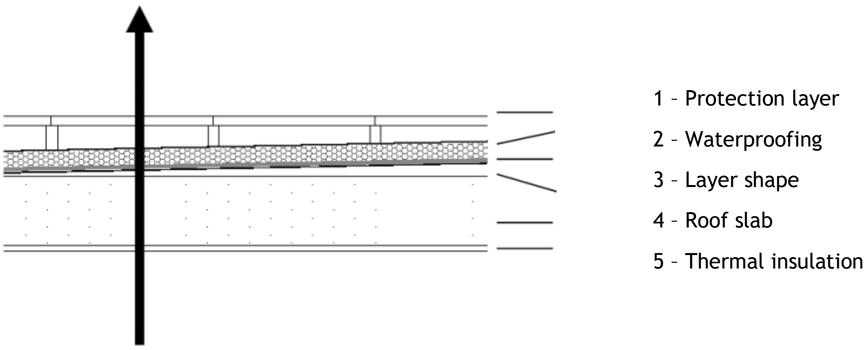
1 – Exterior plaster
2 – Brick masonry wall (15 cm)
3 – Air cavity
4 – Thermal insulation
5 - Brick masonry wall (11 cm)
6- Interior plaster

Figure 2 - Double facade walls. Extracted from [34].



1 – Floor covering
2 – Regularization layer
3 – Reinforced concrete slab
4 – Thermal insulation
5 – Ceiling coating

Figure 3 - Flooring on the outside and ground floor. Extracted from [35].



1 – Protection layer
2 – Waterproofing
3 – Layer shape
4 – Roof slab
5 – Thermal insulation

Figure 4 – Roofing for flat roofs. Extracted from [35].

2.3.2 Thermal insulation in windows

Heat can flow through windows by transmission of solar radiation, emission of infrared radiation, conduction of heat through glass, convection between the panes of glass and infiltration of air [4]. With so many ways to lose heat are necessary options to minimize these heat losses, increasing thermal resistance of windows. The most used option is applying extra layers of glass because the motionless layer of air between glass increases the thermal resistance of the window, as schematized in Figure 5.

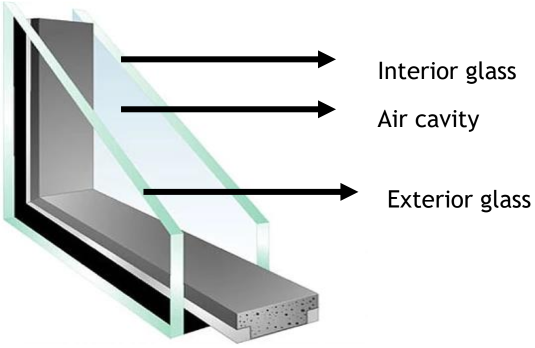


Figure 5 – Double glass window. Extracted from [36].

2.4 Building integrated renewable energy technologies

Renewable energy derives from natural processes, like sunlight and wind, that are refuelled faster that it is consumed. Solar, wind, geothermal, hydro and some forms of biomass are sources of renewable energy [8]. Those that are more common used in renewable energy technologies for buildings are solar and wind power. Despite these types of technology have not been easily accepted, because they are environmentally friendly in relation to technologies that use fossil fuels has made their use more frequent.

2.4.1 Photovoltaic systems

Photovoltaic solar energy is the energy obtained directly from solar radiation conversion. In the past years, because has become cheaper and considered the most flexible of renewable energy sources, it has been increasingly used in the most varied applications, including in buildings. During the period between 2006 and 2016 was installed 94 % of the total installed capacity. It is observed in Figure 6 that in the past years Asia have been increasing the photovoltaic industry with strong growth rates, surpassing Europe in 2016. The market for photovoltaic systems will continue to grow in the future as strongly as so far, due the thrust of subsidies, tax breaks and other financial incentives. Support of R&D and technology evolution are very important aspects in accelerating the implementation of photovoltaic systems [9].

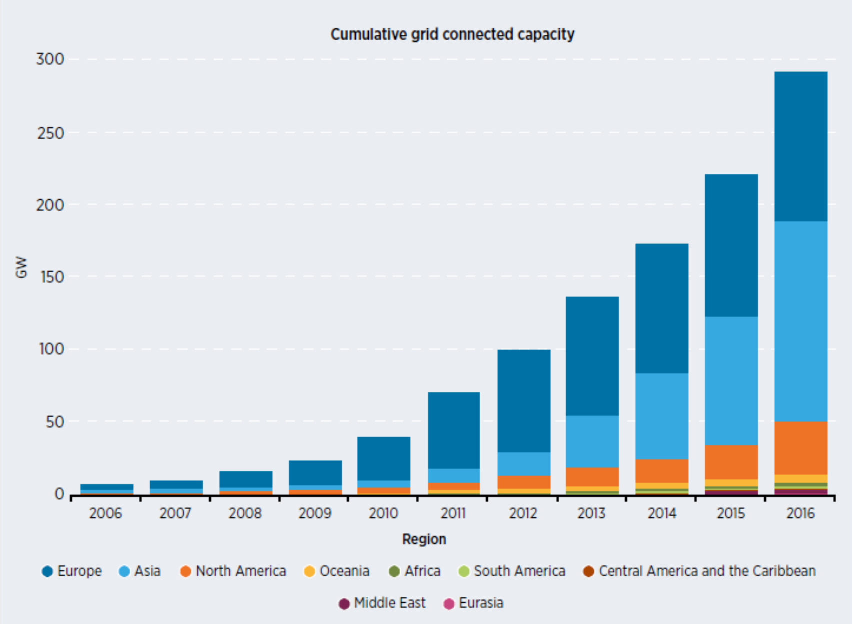


Figure 6 - Yearly cumulative global PV capacity, 2006-2016. Extracted from [9].

A PV panel consists of a number of PV cells wired together in series, usually with a metal frame and a glass cover for protection and rigidity. A PV cell can be made from a single crystal of silicon, from multiple crystals, from amorphous silicon, or from other materials. Crystalline and polycrystalline cells, thin-film cells and nanocrystalline/amorphous silicon cells and dye sensitized solar cells are the main categories of PV cells. The first ones are the most used and they have the highest efficiency, around 20 %, but require high manufacturing costs with the use of very pure materials and with perfect crystal structure. Thin-film cells are less used because despite they have lower construction costs their efficiency is low, 6 %. The last ones are used to create windows that are transparent to visible solar radiation while they convert infrared solar radiation into electricity [4] [10]. The photovoltaic technology based on crystalline silicon accounted for about 94 % of the total production in 2016, with more expression to the polycrystalline silicon cells, as Figure 7 shows.

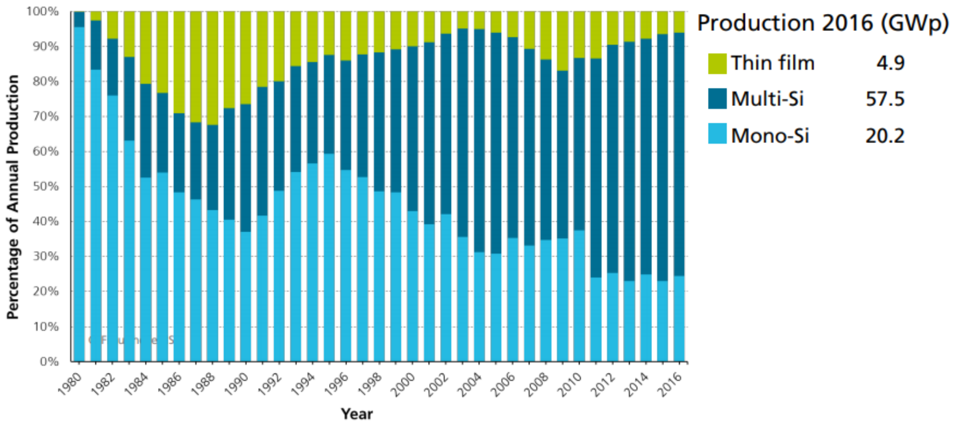


Figure 7 - PV Production by Technology. Extracted from [10].

There are two types of photovoltaic systems for buildings. Those that feed the generated energy directly to the grid and those that are disconnected from the grid and are connected to batteries [11].

The first type of PV system, grid-connected, shown in Figure 8, send DC power to a conditioning unit (PCU) that transform DC to AC and sends power to the building. When the PV systems produce less energy than the immediate demand, the PCU will release the remaining power from the grid. If the PV system produces more than the demand, the excess is sent to the grid.

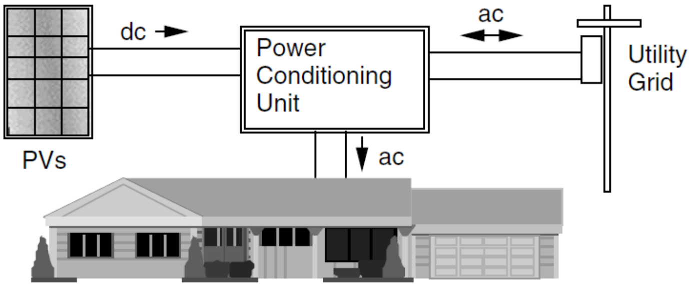


Figure 8 - Grid-connected PV system. Extracted from [11].

The second case is an off-grid, stand-alone system with battery storage and a generator for back-up power, as shown in Figure 9. In this case an inverter is used to convert the battery DC voltage into AC for conventional household electricity. When the PV system produce more energy than the demand, the battery charge with the excess energy, when the PV system produce less, the battery discharge.

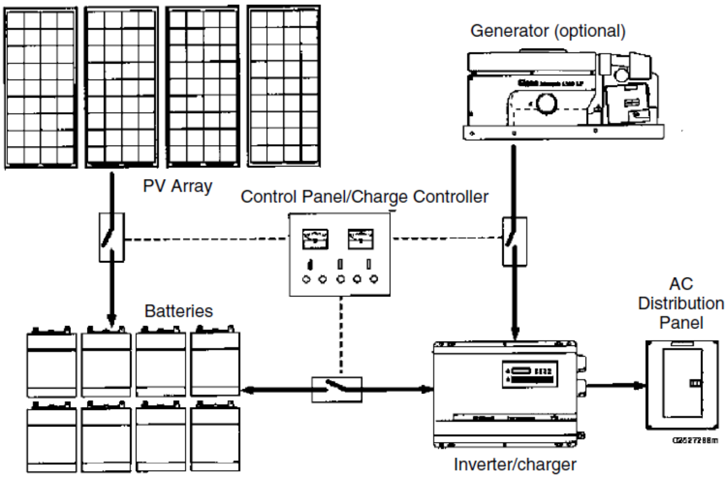


Figure 9 - Stand-alone PV system with optional generator for back-up. Extracted from [11].

In buildings the PV panels can be placed in many places to make the best use of solar radiation and building area. Can be integrated into a sloped roof, a flat roof, on facades as in Figure 10, as skylights, as shading surfaces and in windows as in Figure 11.

Figure 10 - Master Integrated Building Systems Eth Zurich Facade with Solar Panels. Extracted from [43].

Figure 11 - Window-integrated PV. Extracted from [42].

Due to the evolution of photovoltaic technology, the installation and LCOE price decreased in the last years. Using Spain as an example, Figure 12 shows that the total installation cost reduced *ca.*48 % between 2013 and 2017. In Figure 13, can be seen that the LCOE price for photovoltaic solar energy reduced dramatically, below 0.1 € kWh^{-1} in 2017. The O&M costs associated are defined as being 1 % of the investment costs per year [12].

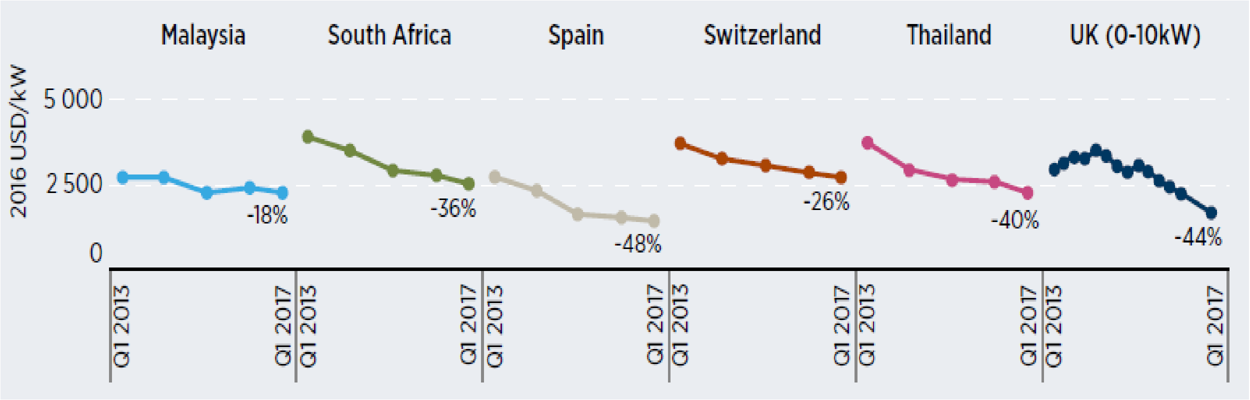


Figure 12 - Average total installed costs of residential solar PV systems by country. Extracted from [9].

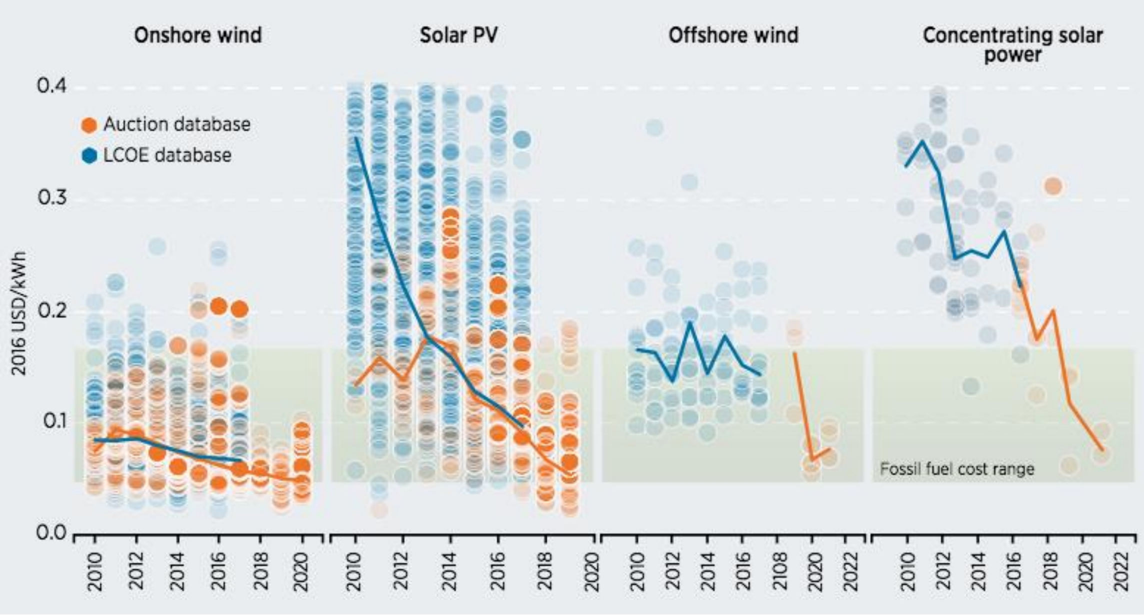


Figure 13 - The levelized cost of electricity for projects and global weighted average values for CSP, solar PV, onshore and offshore wind, 2010-2022. Extracted from [9].

2.4.2 Solar thermal energy

Solar thermal energy can be collected, stored in hot water tanks and used for domestic hot water or to provide indoor heating. Thermal solar collectors can be divided in flat-plate, shown in the Figure 14, evacuated-tube, shown in Figure 15, and parabolic solar collectors that currently is not used in buildings. The first ones can produce hot water at a temperature of 60 – 95 ºC and are less expensive than evacuated-tube collectors. Thermal solar collectors achieve efficiency of 30 % to 60 %, and the evacuated-tube collectors have the best efficiency. The energy is collected by thermal solar collectors that can be mounted on the roof or, if they are flat collectors, in other parts of the buildings [4].

Figure 14 - Flat plate solar collectors mounted in a flat roof. Extracted from [37].

Figure 15 - Evacuated-tube solar collector mounted into a sloping roof. Extracted from [38].

2.4.3 Electrochemical energy storage

The produced energy by a PV system depends on the intensity of available solar radiation that changes throughout day and seasons of the year and the same happens for wind systems. For this reason, it is advantageous to use storage systems. The electrochemical storage is the most used type for this purpose, especially lithium-ion batteries, as is represented in Figure 16. In buildings, the excess of generated energy by the PVs during the day can be stored and used during the night when there is no solar radiation.

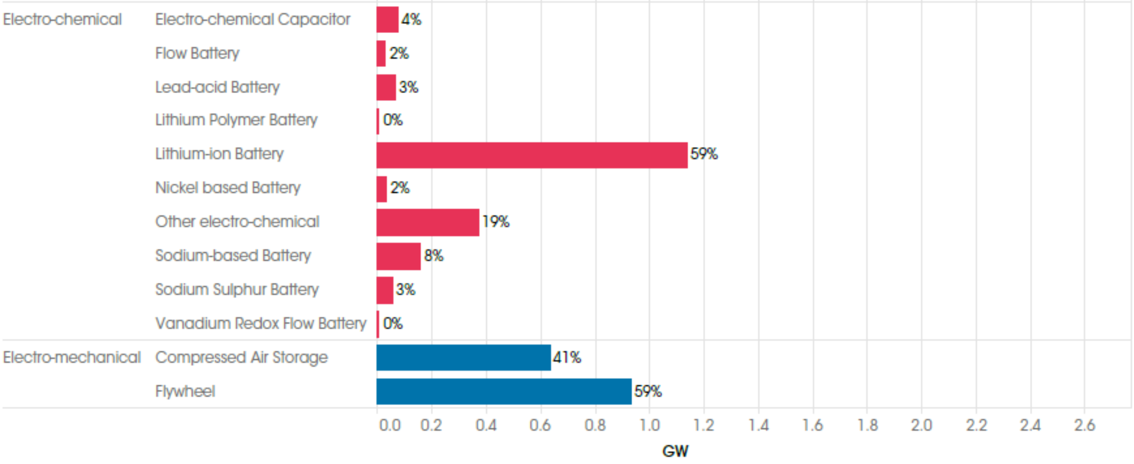


Figure 16 - Electrochemical energy storage power capacity by technology, mid-2017. Extracted from [29].

Battery storage systems can be integrated with an alternating AC/DC inverter directly connected to the AC bus bar, a DC connected battery system, or DC/DC converter in parallel to the PV generator, an AC connected battery system as shown in Figure 17, respectively

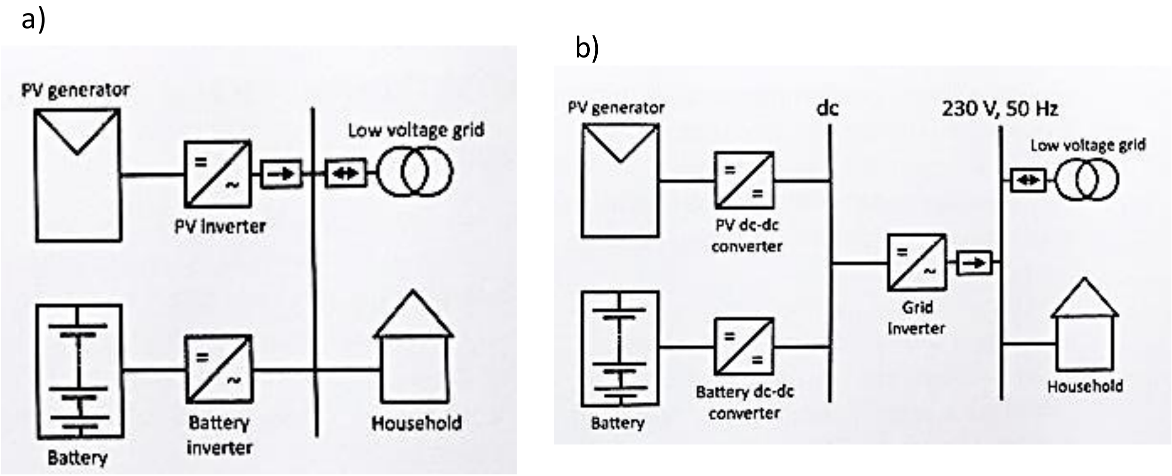


Figure 17 – a) DC connected battery system. b) AC connected battery system Extracted from [13].

The battery dimension depends on the energy consumption. Thus, the storage capacity of the battery must correspond to 50 % of the daily energy consumption, considering that the annual photovoltaic production is equal to the energy consumption of the house [13].

Currently, the total installed costs for batteries can be a barrier despite the evolution of technology. Nonetheless, Figure 18 foresees a significant decrease in costs for all types of batteries until 2030. The redox flow batteries are the ones where the largest decrease is expected, around 66 %. Moreover, redox flow batteries display independent capacity and power values [14], which is of particular interest for households that aim the complete energy autonomy.

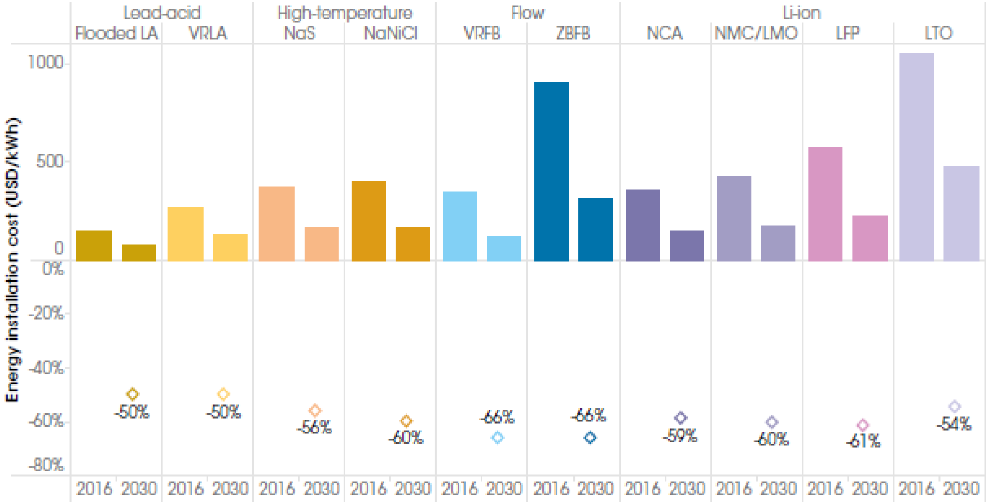


Figure 18 - Energy installation costs estimate for battery technologies, 2016 and 2030.Extracted from [29].

2.4.4 Legislation

The juridical regime applicable to the production of electricity, destined to self-consumption, with or without connection to the public electric grid, based on renewable or non renewable-technologies, for the designated production units for self-consumption (PUSC), is described in the Law Decree no 153/2014 of October 20.

When the installed power is superior to 250 kW, which is the case of this project, is necessary a licensing process that begin with an application for registration in the PUSC electronic registration system and ends with its acceptance, whose sequence is represented in Figure 19.

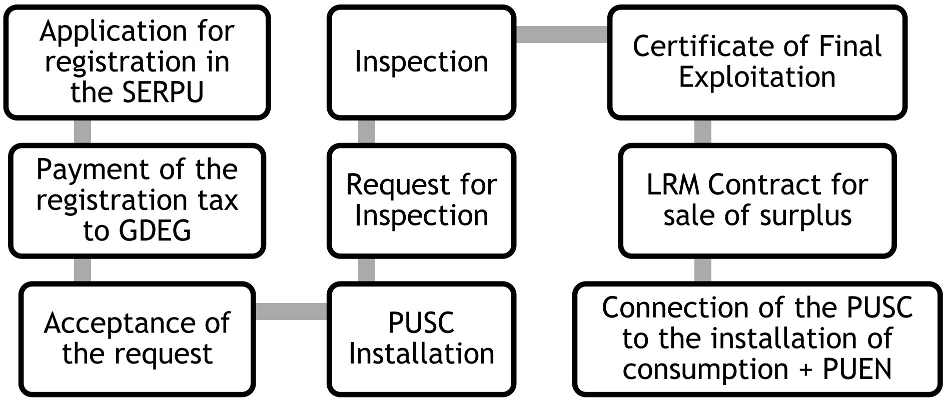


Figure 19 – Sequence of the licensing process.

Because of the dimension of the project are necessary several requisites for the PUSC if it is connected to the grid which are resumed in Table 1. But it is an off-grid project there are no requirements.

Table 1 – Requirements for PUSC. Adapted from [15].

	1.5 kW – 1 MW	Off-grid
Register	Prior check/ Certificate of exploitation	-
Registration tax	✓	-
Counting equipment	✓	-
Excess remuneration	✓	-
Compensation	✓	-
Civil liability insurance	✓	-

The owner of the PUSC must support the cost associated with the counting equipment that measure the total electricity produced by the PUSC, as well as the amount of electricity injected to the public electric grid.

The surplus electricity produced by the PUSC and not consumed can be sold to the grid and the remuneration is calculated according to the Equation 1 [16]:

$$R_{PUSC,m} = E_{provided,m} \cdot P_{OIEM,m} \cdot 0.9 \tag{1}$$

where $R_{UPAC,m}$ is the remuneration of the electricity provided to the grid in the month *m*, $E_{provided,m}$ is the energy provided in month *m* and $P_{OIEM,m}$ is the value resulting from the simple arithmetic mean of the closing operator of the Iberian energy market for Portugal (market daily), for month *m*.

On the other hand, is necessary pay a compensation that allows the recovery of part of the costs arising from energy policy, sustainability or general economic interest costs (GEIC). This compensation is calculated by Equation 2 [16]:

$$C_{PUSC,m} = P_{\mathrm{PUSC}} \cdot V_{\mathrm{GEIC,t}} \cdot K_t \tag{2}$$

where $C_{PUSC,m}$ is the compensation paid in month *m* by kW of installed power, P_{UPAC} is the value of the installed power of the PUSC, $V_{GEIC,t}$ is the value that allows to recover the GEIC of the PUSC, for year t, K_t is the ponderation coefficient, between 0 % and 50 %, to apply to the $V_{GEIC,t}$ and t is the emission year of the operating certificate of the respective PUSC.

The owner still must execute the civil liability insurance to repair corporal or material damages caused to other people as result of the exercise of electricity production for self-consumption.

2.5 Energy simulation tools

Building energy modelling and control has gained significance since last decade and many research facilities have been working on developing control strategies with the objective to reduce energy use in buildings and thus, fighting for sustainability [17]. Energy simulation tools are an important base used by architects, engineers and designers to help project buildings to spend the minimum amount of energy possible. These tools, with some inputs can determine with accuracy some variables that can help the professionals to take decisions about the building.

In addition to the total energy consumption in the building, simulation tools can also calculate the next variables [18]:

- Indoor temperatures;
- Needs for heating and cooling;
- Consumption needs of HVAC systems;
- Natural lighting;
- Indoor comfort of the habitants;
- Levels of ventilation.

Firstly, is necessary to design the building. This can be done by introducing coordinates into the software or can be done in a more intuitive way in a design software, like AutoCAD or Google SketchUp, and later upload the file into the simulation program. Then is necessary to introduce all the variables needed to run the simulation as follow [18]:

- Type of building (office, housing, etc);
- Human activities carried out;
- Existing equipment (lighting, refrigeration, air conditioning systems, furnaces, etc);
- Daily schedules.

Some energy software tools are available and can be used for the purpose. Below is a description of some of the most commonly used tools. In Table 12 in the Appendix 1, is a comparison between the described softwares.

2.5.1 EnergyPlus

EnergyPlus has its origins in both BLAST and DOE–2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE–2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools. Their intended audience is a design engineer or architect that wishes to size appropriate HVAC equipment, develop retrofit studies for life cycling cost analyses, optimize energy performance, etc. EnergyPlus is a simulation program for energy analysis and thermal load and can calculate heating and cooling loads to maintain thermal control set points, loads for the HVAC system and determine the energy consumption of primary plant equipment [19].

2.5.2 ESP-r (Energy Simulation Software tool)

This software tool was developed to support the construction project on energy and environmental performance in a realistic and accurate way. ESP-r is based on a finite volume conservation approach in which a problem (specified in terms of geometry, construction, operation, leakage distribution, etc.) is transformed into a set of conservation equations (for energy, mass, momentum, etc.) which are then integrated at successive time-steps in response to climate, occupant and control system influences. [20]

2.5.3 TRNSYS

TRNSYS is a transient system simulation software tool that has been specially designed to develop complex systems related to energy. TRNSYS is made up of two parts. The first is an engine (called the kernel) that reads and processes the input file, iteratively solves the system, determines convergence, and plots system variables. The kernel also provides utilities that, among other things, determine thermophysical properties, invert matrices, perform linear regressions, and interpolate external data files. The second part of TRNSYS is an extensive library of components, each of which models the performance of one part of the system. The standard library includes approximately 150 models ranging from pumps to multizone buildings, wind turbines to electrolysers, weather data processors to economics routines, and basic HVAC equipment to cutting edge emerging technologies [21].

3 Simulator

For the accomplishment of this work the energy software tool chosen was the EnergyPlus because, considering the comparison table (Table 12, Appendix 1), is one of the most complete for the purpose and is free. First, was used the 3D modelling software, SketchUp, for building design. Then, OpenStudio was used for the whole building energy modelling. Finally, through EnergyPlus software was integrated the energy storage system and the calculations were performed, as shown in Figure 20.

Figure 20 - Sequence of the methodology used.

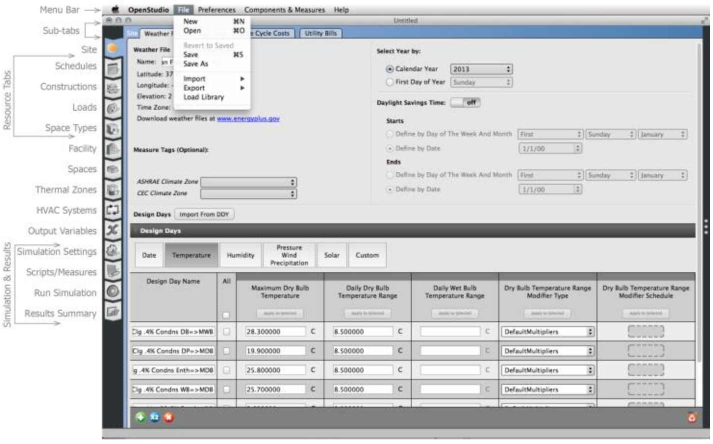
3.1 SketchUp

SketchUp is a software that belongs to Google and allows to perform the geometry of the building, defining:

- Types of surface, as walls, roofs, floors, windows and doors;
- Types of contact, if it is with the outside environment or not;
- Exposure to the environment, sun and wind;
- Definition of thermal zones.

3.2 OpenStudio

OpenStudio is a software with a set of tools that are used to model the energy demand in buildings using EnergyPlus. With this software is possible introduce information about almost all aspects related to energy in a building and in Figure 21 is shown the interface of the software.



Weather File
Name: an F
Latitude: 37
Longitude: -
Elevation: 2
Time Zone:
Download weather files at www.energyplus.gov

Measure Tags (Optional):
ASHRAE Climate Zone
CEC Climate Zone

Select Year by:
● Calendar Year 2013
○ First Day of Year Sunday

Daylight Savings Time: off

Starts
○ Define by Day of The Week And Month First Sunday January
● Define by Date 1/1/00

Ends
○ Define by Day of The Week And Month First Sunday January
● Define by Date 1/1/00

Design Day Name	All	Maximum Dry Bulb Temperature	Daily Dry Bulb Temperature Range	Daily Wet Bulb Temperature Range	Dry Bulb Temperature Range Modifier Type	Dry Bulb Temperature Range Modifier Schedule
Clg .4% Condns DB=>MWB	☐	28.300000 C	8.500000 C	C	DefaultMultipliers	
Clg .4% Condns DP=>MDB	☐	19.900000 C	8.500000 C	C	DefaultMultipliers	
g .4% Condns Enth=>MDB	☐	25.800000 C	8.500000 C	C	DefaultMultipliers	
Clg .4% Condns WB=>MDB	☐	25.700000 C	8.500000 C	C	DefaultMultipliers	

Figure 21 – Interface of OpenStudio. Extracted from [39].

3.3 EnergyPlus

The EnergyPlus integrated solution manager, whose scheme is shown in Figure 22, manages the surface and air heat balance modules and works between the heat balance and the building systems simulation manager as an interface. The surface heat balance module does the interconnections between heat balances in inside and outside surfaces and boundary conditions, conduction, convection, radiation, and mass transfer effects. The air heat balance module works with several mass flows like exhaust air, ventilation air, and infiltration. All these program modules work together to calculate the required energy for heating and cooling a building. The building system simulation manager makes the communication between the heat balance engine, air loops, the HVAC and water [19].

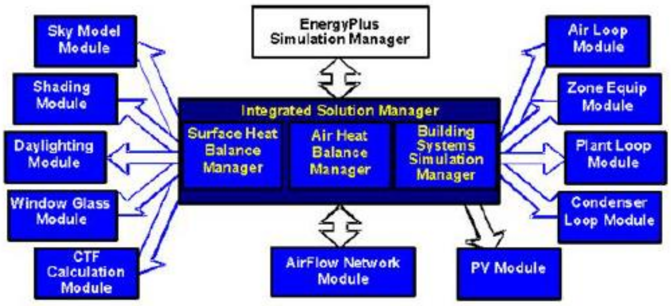


Figure 22 - EnergyPlus Program Schematic. Extracted from [19].

3.3.1 Weather file

For make possible all the calculations and give results EnergyPlus needs a file, a weather file, that contains information about geographic coordinates, soil temperature, dew and bubble point temperature, solar radiation and daylighting, direction and wind speed and information about sky and clouds between other information's for all days of the year [22].

3.3.2 Zone and air system integration

The heat balance on the zone air can be done by Equation 3 [19]:

$$C_z\frac{dT_z}{dt}=\sum_{i=1}^{N_{sl}}\dot{Q}_i+\sum_{i=1}^{N_{surfaces}}h_iA_i(T_{si}-T_z)+\sum_{i=1}^{N_{zones}}\dot{m}_iC_p(T_{zi}-T_z)+\dot{m}_{inf}C_p(T_\infty-T_z)+\dot{Q}_{sys} \qquad (3)$$

where $\sum_{i=1}^{N_{sl}}\dot{Q}_i$ is the sum of convective internal loads, $\sum_{i=1}^{N_{surfaces}}h_iA_i(T_{si}-T_z)$ is the convective heat transfer from the zone surfaces, $\sum_{i=1}^{N_{zones}}\dot{m}_iC_p(T_{zi}-T_z)$ is the heat transfer due to interzone air mixing, $\dot{m}_{inf}C_p(T_\infty-T_z)$ is the heat transfer due to infiltration of outside air, $C_z\frac{dT_z}{dt}$ is the energy stored in zone air and $\dot{Q}_{sys}$ is the air systems output.

Air systems has the function of meet heating and cooling loads of the zones by providing heat or cold air. Therefore, the energy provided to the zone, $\dot{Q}_{sys}$, can be calculated by Equation 4, and it is the difference between the supply air enthalpy and the enthalpy of the air leaving the zone [19]:

$$\dot{Q}_{sys}=\dot{m}_{sys}\cdot C_P\cdot(T_{sup}-T_z) \qquad (4)$$

3.3.3 Zone air mass flow conservation

The zone air mass flow conservation count with supply air flow rates, return air flow rates, zone exhaust fan flow rates, zone mixing flow rates and infiltration flow rates as is represented in Figure 23, for a case with two thermal zones.

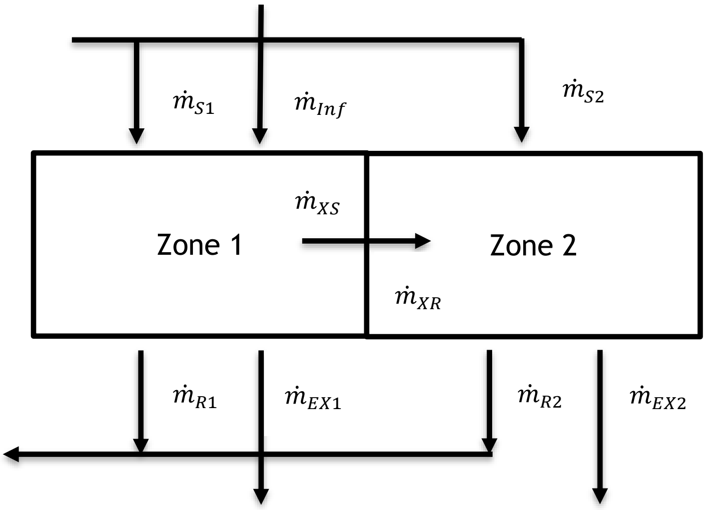


Figure 23 - Zone air mass flow balance components. Adapted from [19]

The return total air flow from the zone is the sum of the zone inlets less the sum of the zone exhausts and is calculated by Equation 5 [19]:

$$\dot{m}_R = \mathrm{MAX}\{0.0,\ \dot{m}_S - [\dot{m}_{EX,tot} - \dot{m}_{EXF,bal}] + [\dot{m}_{XR} - \dot{m}_{XS}]\} \tag{5}$$

where $\dot{m}_S$ is the total zone supply air mass flow rate, $\dot{m}_{EX,tot}$ is the total zone exhaust air mass flow rate from all zone exhaust air node, $\dot{m}_{EXF,bal}$ is the balanced zone exhaust fan air mass flow rate, $\dot{m}_{XR}$ is the zone mixing mass flow rate as a receiving zone and $\dot{m}_{XS}$ is the zone mixing mass flow rate as a source zone.

The infiltration air mass flow rate required to balance a zone is given by Equation 6:

$$\dot{m}_{Inf-required} = MAX[0.0, \dot{m}_{XS} + \dot{m}_{EX} + \dot{m}_R - \dot{m}_S] \tag{6}$$

3.3.4 Photovoltaic panels

The Simple Model was the chosen one and is the simplest model for predicting photovoltaic energy production. In this model, the user specifies the efficiency with which the PV panels convert incident solar radiation into electricity. Is used a full geometric model for solar radiation, including sky models, shading and reflections, to determine the incident solar resource. The photovoltaic energy production, *P*, is calculated with Equation 7:

$$P = A_{surf} \cdot f_{activ} \cdot G_T \cdot \eta_{cell} \cdot \eta_{invert} \tag{7}$$

where *P* is the electrical power produced by photovoltaics, A_{surf} is the area of surface, f_{activ} is the fraction of surface area with active solar cells, G_T is the total solar radiation incident in the PV array, η_{cell} is the module conversion efficiency and η_{invert} is the DC to AC conversion efficiency.

3.3.5 Electrical storage – Kinetic battery model

The model is called kinetic because it is based on a chemical kinetics process to simulate the battery charging and discharging behaviour. This model assumes that the battery charge is distributed over two tanks: an available-charge tank and a bound-charge tank. The tank for available charges can supply electrons directly to the load, whereas the tank for chemically bound charges can only supply electrons to the available-charge tank. At any time, the total charge, q, in the battery is the sum of the available (q_1) and bound charge (q_2) as in Equation 8:

$$q = q_1 + q_2 \tag{8}$$

The battery capacity can be related to a constant charge/discharge current (*I*) calculated by Equation 9:

$$q_{max}(I) = \frac{q_{max} \cdot k \cdot c \cdot t}{1 - e^{-kt} + c(k \cdot t - 1 - e^{-kt})} \tag{9}$$

where $q_{max}(I)$ is the maximum capacity at charge or discharge current I, q_{max} is the maximum capacity at an infinitesimal current, t is the charge or discharge time, defined by $t = \frac{q_{max}(I)}{I}$, k is the constant coefficient and c is the parameter indicating the ratio of available charge capacity to total capacity.

If a constant current is used in any time step for charging and discharging, the available charge (q_1) and bound charge (q_2) at any time step are given by Equations 10 and 11:

$$q_1 = q_{1,0}e^{-k\Delta t} + \frac{(q_0kc - I)(1 - e^{-k\Delta t})}{k} - \frac{Ic(k\Delta t - 1 + e^{-k\Delta t})}{k} \tag{10}$$

$$q_2 = q_{2,0}e^{-k\Delta t} + q_0(1 - c)\left(1 - e^{-k\Delta t}\right) - \frac{I(1 - c)(k\Delta t - 1 + e^{-k\Delta t})}{k} \tag{11}$$

where $q_{1,0}$ is the available charge at the beginning of time step, $q_{2,0}$ is the bound charge at the beginning of time step, q_0 is the total charge at the beginning of time step, with $q_0 = q_{1,0} + q_{2,0}$ and Δt is the time step.

The battery's open circuit voltage is modelled in the same form for charging and discharging, but with different coefficients. The open circuit voltage in charging (E_c) and discharging (E_d) can be respectively expressed by Equations 12 and 13:

$$E_c = E_{0,d} + A_c \cdot X_c + \frac{C_c \cdot X_c}{D_c - X_c} \tag{12}$$

$$E_d = E_{0,c} + A_d \cdot X_d + \frac{C_d \cdot X_d}{D_d - X_d} \tag{13}$$

where $E_{0,c}$ is the open circuit voltage for a fully charged battery, $E_{0,d}$ is the open circuit voltage for fully discharged battery, A_c, C_c, D_c are constant parameters for charging, A_d, C_d, D_d are constant parameters for discharging and X_c, X_d are normalized maximum capacity at a given charging or discharging current, calculated as in Equation 14:

$$X = \begin{cases} \dfrac{q_0}{q_{max}(I)}, & \text{(charging)} \\ \dfrac{q_{max} - q_0}{q_{max}(I)}, & \text{(discharging)} \end{cases} \tag{14}$$

where "A" represents the initial linear variation of internal battery voltage with state of charge and is usually a negative number in discharging mode and positive number in charging mode, "C" represents the battery voltage's increase or decrease when battery is progressively discharged or charged and is always negative in discharging mode, and positive in charging mode and “*D*” represents the battery voltage's increase or decrease when the battery is progressively discharged or charged and is always positive and is normally a number close to the maximum capacity value.

With open circuit voltage, the battery terminal voltage (*V*) can be calculated as in Equation 15:

$$V = E - I \cdot R \tag{15}$$

where *R* is the battery internal resistance, the current is positive for discharging and negative for charging.

Given desired power in/out of the battery, the desired charge or discharge current can be calculated from the basic power equation: $P = V \cdot I$. In this calculation, iteration is needed to ensure the electric current has converged and the battery operation satisfies all specified technical constraints such as maximum discharge current and charge rate limit.

4 Studied cases

4.1 Building design

The building is a house located in Porto, latitude of 41.23° and longitude of 8.68°, with 357 m^2 and the longest facade oriented to south. The building is constituted by 3 bedrooms, 3 dressing rooms, 4 bathrooms, 2 halls, a kitchen, a living room, a storeroom, a technical room, a laundry and a garage. The house was divided in four thermal zones, as Figure 24 shows, which means that are four zones in the building with different acclimatization conditions. The separation into different thermal zones is related with heating and cooling needs and ventilation for the different divisions of the house. In Table 2 are represented the different thermal zones and the needs for each division of the building.

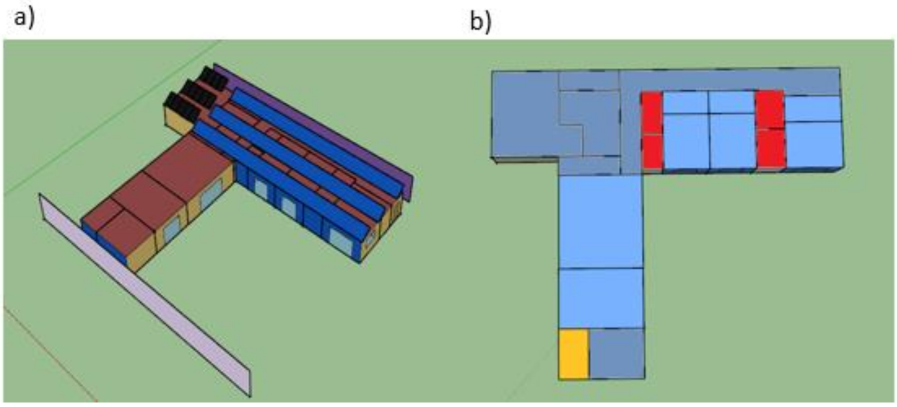


Figure 24 – a) House design. b) Thermal zones of the house.

Table 2 – Needs for heating, cooling and ventilation for each house division.

House division	Thermal zone	Area (m^2)	Heating	Cooling	Ventilation
Garage	4	47.1	-	-	-
Storage room	4	8.6	-	-	-
Technical room	4	23.1	-	-	-
Hall 2	4	48.0	-	-	-
Bathroom 2	2	6.5	✓	-	✓
Bathroom 1	2	5.4	✓	-	✓
Dressing room 1	1	7.8	✓	✓	-
Bedroom 1	1	17.8	✓	✓	-
Dressing room 2	1	7.8	✓	✓	-
Bedroom 2	1	18.0	✓	✓	-

Bathroom 4	2	7.7	✓	-	✓
Bathroom 3	2	7.7	✓	-	✓
Dressing room 3	1	10.5	✓	✓	-
Bedroom 3	1	18.4	✓	✓	-
Hall 1	4	8.1	-	-	-
Living room	1	53.3	✓	✓	-
Kitchen	1	33.4	✓	✓	-
Laundry room	3	9.8	-	-	✓
Storeroom	4	17.9	-	-	-

4.2 Building operation schedules, heat gains and ventilation

Were defined fractional schedules for occupation, use of lights and electric equipment, use of water in sinks and showers that are presented in Appendix 2. The house is surrounded by trees in the north and south facades. This way, it was necessary to create a transmittance schedule to represent the transmittance of trees throughout the year. A fractional schedule was created with a value of 0.75 for winter, between October 1 and 31 March, and 0.25 for summer, between April 1 and August 31.

The house is occupied by four people and was defined an irradiance of 5 W m^{-2} and an equipment irradiance of 5 W m^{-2} [23]. For the activity of the occupants in the house was considered a heat gain of 120 W m^{-2}, defined by EnergyPlus for households.

Regarding air flows, it was defined an indoor infiltration design flow rate of 1 air changes per hour and 0.4 for the ventilation flow rate for the thermal zones when need according to the RTBCB [7] (Table 2).

4.3 Thermal envelope

In Table 13 to Table 17 (Appendix 3) are described the constructions for the exterior and interior walls, roof and floors as well as the characteristics of construction materials. Two types of pavement were defined, one called wet floor applied in the kitchen, bathrooms, laundry, storeroom, technical room and garage. The other one, dry floor, was applied in the bedrooms, dressing rooms and in the halls. The interior doors are made of wood and the exterior doors of metal. All windows and glass doors are double-glazed, each 6 mm thick, with a 6 mm air cavity between them.

In Table 3 are presented the heat transfer coefficients for all types of constructions present in the house. All values comply with the limits imposed by the Portuguese regulation.

Table 3 - Heat transfer coefficient of constructions.

Construction	Heat transfer coefficient $W\ m^{-2}\ K^{-1}$
Exterior Wall	0.26
Roof	0.38
Wet floor	0.38
Dry floor	0.37
Window	3.09
Exterior door	1.00

In all windows of the building was applied a pull-down shade for reducing the amount of solar radiation. During winter the shading device may be open to maximize solar heat gains and to reduce heating loads. During summer, these devices may work in the reverse way to reduce the cooling loads. For this control was defined a set point for irradiance, 27 W m^{-2}, optimized in EnergyPlus.

4.4 HVAC system

As already mentioned the house has four thermal zones, with two schedules of temperature for heating and cooling associated for thermal zone 1, one schedule for heating in thermal zone 2 and none for thermal zones 3 and 4. The cooling set point was set to 25 ºC and the heating set point to 20 ºC.

The chosen HVAC system of possible choices offered by the software was the Packaged Rooftop VAV with Reheat, which is represented in Figure 25. The cooling and heating coils are water. In the supply side of the loop are the cooling and heating coils and the fan. In the demand side is the thermal zone that is intended to heat or cool.

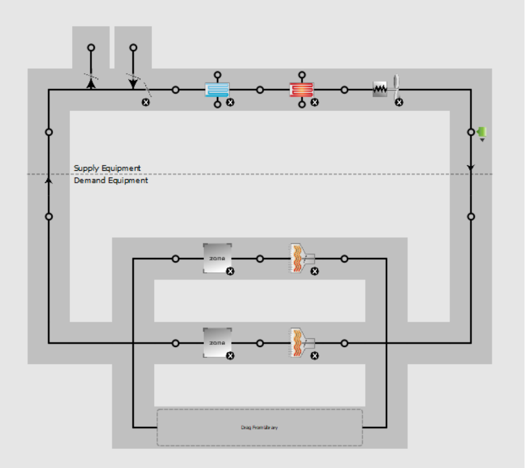


Figure 25 – Loop Packaged Rooftop VAV with Reheat.

For cooling, two different loops are needed: the condenser water loop and the chilled water loop represented Figure 45 and Figure 46, respectively (Appendix 4). In the first loop, there is a cooling tower in the supply side to feed the chiller in the demand side. Following the chiller, a heat exchanger was installed in the demand side to take advantage of the heat released from the chiller to heat the water in a storage tank and the hot water loop Figure 47, Appendix 4. In the other one, the chiller with a COP of 6 is in the supply side to feed the cooling coil [24]. This last loop has a set point schedule wherein the control variable is temperature, to cool the water to 6.70 ºC, defined by the software. In the supply side, the hot water loop (Figure 48,Appendix 4) comprises a water pump with a COP of 3.7 and 270 L [25], a storage tank with heat recovered from the heat exchanger with 450 L and a 500 L storage tank with water heated by 4.8 m^2 of thermal solar collectors with an tilt angle of 32º (Figure 49, Appendix A). On the demand side is the heating coil, water, and the set point manager for setting the temperature of water at 60 ºC. The collector area and tilt angle were optimized in the software through several iterations.

4.5 Domestic hot water

For the supply of hot water to sinks, showers, washing machines and other household appliances, the domestic hot water loop has an area of thermal solar collector of 3.2 m^2 with a tilt angle of 32º, to heat the water in the 800 L storage tank which is in the demand side. To complete the desired temperature of water to supply the water connections, a heat pump with a COP of 3.7 and 270 L should be installed. Once again, a set point manager for controlling the water temperature at constant 60°C is installed. These two loops are represented in Figure 50 and Figure 51 (Appendix 5).

4.6 Scenarios

With the objective of integrating a photovoltaic system in the building together with electrochemical storage system two scenarios were studied: One when was searched the most economically viable scenario and another leading to a total independence from the electric grid, considering the energy consumption of the building. The house was projected to consume only electricity so that studies are made for the most extreme situation in terms of electric energy consumption.

For the first one, the PV area and battery capacity was changed to obtain the best savings in relation to the grid. On the other hand, to obtain the total independence from the grid, all the available roof area of the building was covered with photovoltaic panels, as shown in Figure 26. All PVs in the roof are installed with a tilt angle of 32°, which is the one that leads to a greater production of electricity.

In both cases, the facade oriented to south was also covered with photovoltaic panels to take advantage of solar radiation during the winter season.

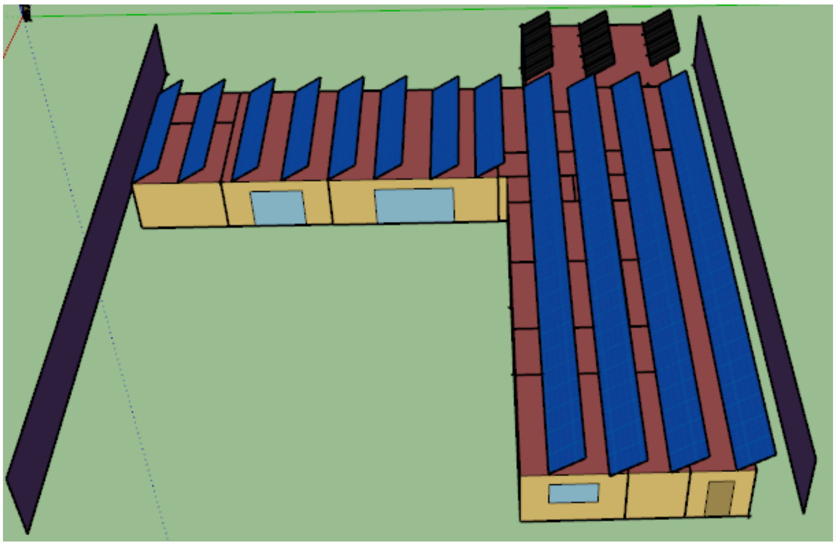


Figure 26 – PV panels in the building for total independence scenario.

4.7 Indicative prices and assumptions

To perform the economic analyses is necessary to be aware of the prices that are currently practiced. Are necessary the investment costs, the operation and maintenance costs and the levelized cost of energy (LCOE) for each technology.

The investment costs for thermal solar collectors in Portugal are estimated. In 2016, the investment cost in Brazil was 240 € m^{-2} and in Germany was 680 € m^{-2} [26] and considering that irradiance in Portugal is lower than in Brazil but higher than in Germany, 460 € m^{-2} for Portugal is the average of the two prices. The estimated investment costs for the PV systems, biomass installation of a fireplace with heat recovery (biomass) and for storage systems are 96 € m^{-2} [27], 3500 € [28] and 304 € kW^{-1} [29], respectively.

The O&M costs were defined as being 1 % of the investment costs for solar technologies [12] and 2 % for the storage system [29].

The LCOE for thermal solar collectors was defined based on the same assumption for the investment costs. This way, in Brazil the LCOE is 0.02 € kWh^{-1} and in Germany 0.11 € kWh^{-1}, therefore the value for Portugal resulted in 0.065 € kWh^{-1} [26]. For photovoltaic energy, the LCOE for residential application, in 2017, in Spain and in Italy was 0.055 € kWh^{-1} [30]. Considering that in Portugal the irradiance is similar to Italy and Spain, a value of 0.06 € kWh^{-1} was defined. For biomass, considering the calorific power of pellets of 17 MJ kg^{-1} and that a 15 kg pellet sack costs 3.5 €, the LCOE price is 0.05 € kWh^{-1} [28]. For storage, with the number of life cycles of 13 000, the cost of the battery and its capacity the calculated price per kWh was 0.023 €.

The electricity purchased to the grid costs 0.223 € kWh^{-1} [31] and the feed-in tariff for the surplus electricity is paid a 0.05 € kWh^{-1} [32].

5 Results and discussion

5.1 Most economically viable scenario

The total annual consumption of the house is 25 345 kWh. There are loads in a building that represent more energy consumption than others and it is important to know this information to understand where to act aiming the minimization of electricity consumption. As Figure 27 shows, it is the interior equipment that consumes more electricity in the building, followed by water systems that include domestic hot water and indoor heating.

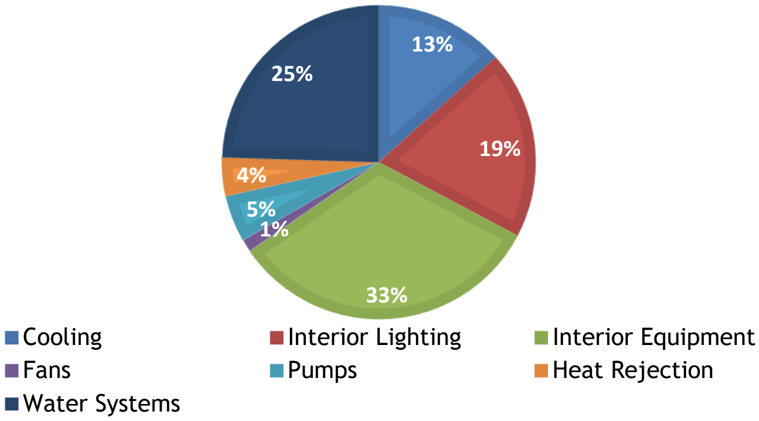


Figure 27 - Distribution of the electric consumption in the house.

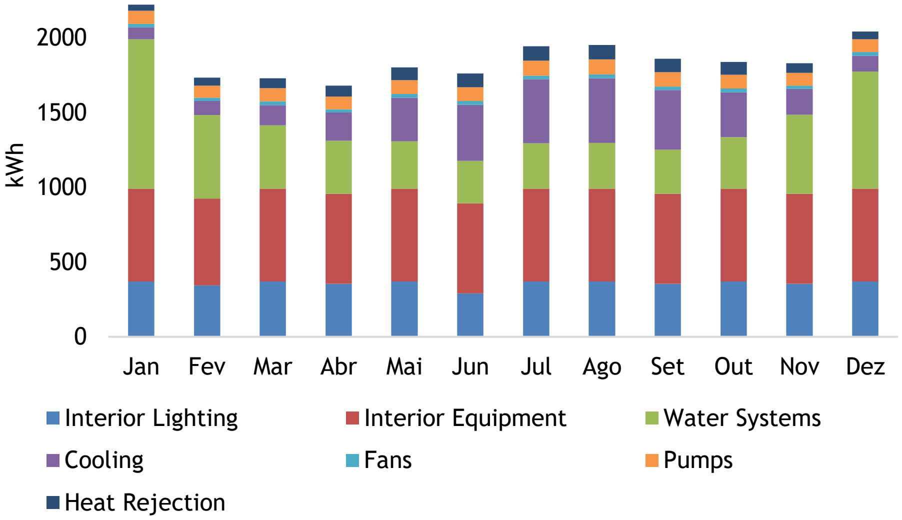


Figure 28 - Distribution of the electric consumption in the house by month.

As Figure 28 shows, the electric consumption is higher in January and December, winter months, and July and August, summer months. This happens because in winter there is an increase of consumption due to the heating needs and in summer due to the cooling needs. In the graph the heating needs are represented in water systems category, once that the heating coil is water. It can also be observed that the parcel that represents heat rejection is larger in summer months because it is when the chiller works more and by consequence rejects more heat. Ventilation, represented by fans has in a general way the same consumption all over the year, representing the smaller parcel of the total consumption.

Considering Table 2, thermal zone 1 has a heating and cooling set point, and the zone temperature meet the established set points, as Figure 29 shows. Thermal zone 2 has only a heating set point that is satisfied. Thermal zones 3 and 4 do not have defined set points. This way, as expected, the temperature is thermal zones 2, 3 and 4 is higher than in thermal zone 1 since there is no cooling set point. Despite thermal zones 3 and 4 do not have a heating set point, the temperature is rarely lower than 20 °C, making the temperature difference between rooms low, which is good for thermal comfort.

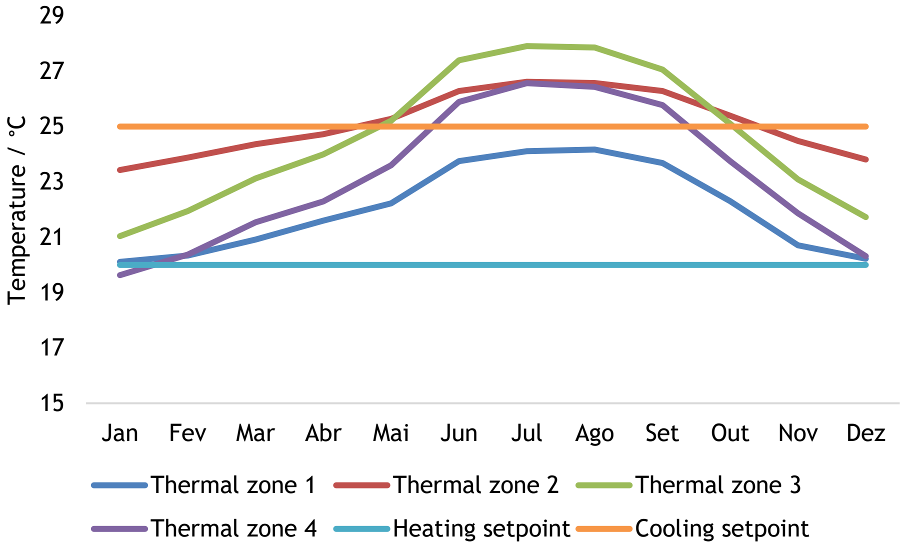


Figure 29- Thermal zones temperatures.

The first measure that was adopted to minimize electricity consumption was the integration of thermal solar collectors for domestic hot water and indoor heating. The collector area and tilt angle were optimized in the software being 8 m^2 and 32°. This measure allowed to reduce the electricity consumption in 3217 kWh per year.

In the search for the most economically viable scenario, the one that leads to greater savings, several simulations were performed with different PV area. The efficiency of all PV panels was defined to be 20 %.

The storage system used is a vanadium redox flow battery, that as is shown in the state of the art in Figure 18, is the one whose price is expected to decrease more in the coming years. Several battery capacities were simulated for a PV area of 193 m^2 to see the autonomy that each battery can proportionate to the house. The results are presented in Table 4 and as can be seen, the increase of battery capacity does not represent a big increase in the autonomy but raises the needed monetary investment. This way the battery selected has a capacity of 9.6 kWh and its characteristics are specified in

Table 5.

Table 4 – Relation between battery capacity and autonomy from the grid.

Battery capacity (kWh)	Autonomy (%)
4.8	-
9.6	91.05
14.4	91.94
19.2	92.80
24.0	93.64

Table 5 – Characteristics of the used battery.

Number of battery models in parallel	3
Number of battery models in series	37
Maximum module capacity (Ah)	100
Maximum storage state of charge fraction	1
Minimum storage state of charge fraction	0
Fully charged module open circuit voltage (V)	38
Fully discharged module open circuit voltage (V)	48

Five simulations were realized, for the same characteristics and loads of the house, with thermal solar collectors integrated and the same storage system but with different PV area. The results of the simulations are presented in Table 6.

Table 6 – Simulations results with PV and storage systems.

Simulation	PV area (m^2)	PV production (kWh)	Corresponding electricity (%)	Autonomy without storage(%)	Autonomy with storage(%)
1	193	46 391	183	40.82	91.05
2	156	34 121	135	38.29	84.39
3	105	16 764	66	31.19	49.64
4	83	9443	37	24.57	30.73
5	66	6405	25	20.12	22.74

As expected, the larger the PV area the larger the electricity production by the PV panels. Comparing the autonomy achieved with or without a storage system, it can be concluded that the battery integration doubles the autonomy in the first simulations. This is crucial to harness the excess energy produced by the PV system for when there is no production, increasing the energetic autonomy of the house. For simulation 1 and 2 the electricity produced by the PV system correspond to more than 100 % of the electricity consumed in the house. Despite that and even with the help of a storage system, the autonomy in relation to the grid does not reach 100 %. This happen in the winter, when the heating needs are higher and there are many days in a row which the solar radiation is less intense, leading to a lower PV production. In Figure 30, the information corresponds to simulation 1, and can be seen that for all months the energy produced by the PV system is higher than the demand, even in the winter months when solar radiation is less intense. However, is not enough for the house to be autonomous, even with the storage system.

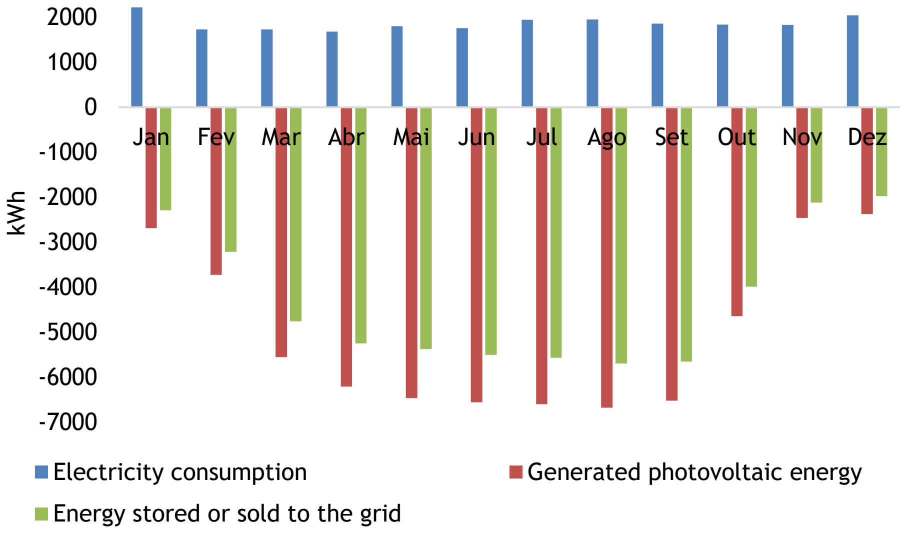


Figure 30 – Relation between energy consumed, generated, stored or sold.

It is also noted that the decrease of autonomy from simulation 3 to 5 is more accentuated than the others because the predominant area of PV panels is vertical, on the south facade. Although in winter more energy can be produced with this orientation, as can be observed in Figure 31, in the rest of the year these PV panels produce less energy than those are in the rooftop.

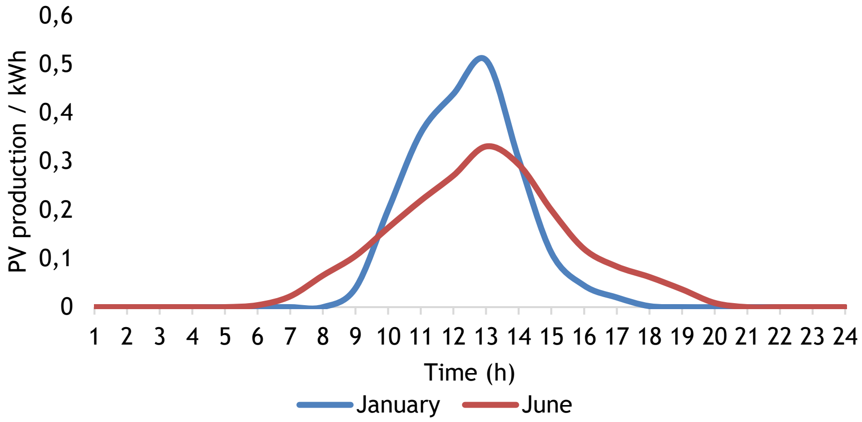


Figure 31 – Energy production for vertical PV panels in winter and summer.

It was defined that the supply energy was sold to the grid ending the energy waste and making the project as viable as possible. In order to do the economic analyses, it is needed to consider the costs of investment of the devices, the operation and maintenance costs and the LCOE for each technology, which are presented in section *Indicative prices and assumptions*, chapter 4.

Table 7 shows the results for the economic analyses made for all the scenarios in order to find the most economically viable scenario.

Table 7 – Economic analyses results.

Simulation	Annual savings (€)	Annual O&M (€)	Investment (€)	Payback period (years)
1	2722	278	24 922	10
2	3039	243	21 490	7
3	4194	193	16 548	4
4	4564	173	14 486	3
5	4914	156	12 782	3

It was predictable that the larger the PV area the larger the investment that is needed as well as the O&M costs. As the results show, the annual savings in relation to buy all the electricity to the grid is not proportional to the PV area once that the larger the PV area the larger the PV production and storage and O&M costs. Considering a life cycle of PV panels, thermal solar collectors and battery of 20 years, all projects are economically viable.

On the other hand, it can be also concluded that the most viable projects are the ones that have the smaller autonomy from the grid. The projects that lead to the best autonomy are the ones that have higher investment, leading to a longer payback period. This way, for achieving the most economically viable projects it is necessary to sacrifice the house independence to the grid.

It was already known and proved that the integration of thermal solar collectors and PV systems into buildings are economically viable projects and contribute significantly to decrease the amount of electricity purchased to the grid. However, with these results, it is also proved that the integration of storage systems in residential buildings, which has been slowly recognized, is a viable project, contributing not only to reduce even more the purchased electricity but also to increase the house electric autonomy.

To search the PV area that leads to maximum savings was made a graph that describes the annual savings in relation to the PV area. The graph presented in Figure 32 and obey to a polynomial function.

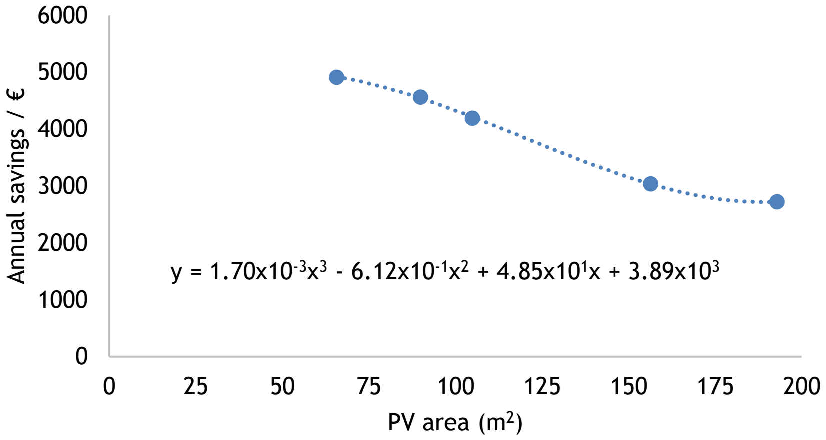


Figure 32 – Annual savings in relation to the PV area.

The maximum of the polyonomy function corresponds to a PV area of 51 m^2 that leads to annual savings of 4997 € and a payback period of 3 years. For PV areas inferior to 51 m^2, the annual savings decrease and despite the investment is smaller the payback period increase.

5.2 Total independence scenario

In the search for total independence it was maximized the PV area in order to increase the production of electricity to achieve this goal. Thus, the total rooftop area of the house was covered with photovoltaic panels, an area corresponding to 278 m^2.

Some simulations were performed, whose results are presented in Table 8, for the same needs of the house, thermal solar collectors and PV area but increasing the battery capacity in the attempt of achieving an autonomy of 100 %.

Table 8 – Autonomy in relation to battery capacity.

Battery capacity (kWh)	Autonomy (%)
4.8	-
9.6	98.88
14.4	99.58
24.0	99.96

As can be observed by the results from the table above, increasing the battery capacity corresponds to a very small increase in the autonomy. This way and because the increase in the battery capacity also leads to a raise in the investment and O&M costs the battery chosen has a 9.6 kWh capacity.

Therefore, the PV system for the available area of the building with the help of a storage system is not enough to achieve 100 % of autonomy. So it was integrated a wind turbine to help and see if it is possible to achieve the goal. The characteristics of the wind turbine chosen are presented in Table 9.

Table 9 – Characteristics of the wind turbine.

Rotor type	Vertical axis turbine
Rotor diameter (m)	5.2
Overall height (m)	11
Number of blades	3
Rated power (kW)	10
Cut in wind speed (m s^{-1})	3
Cut out wind speed (m s^{-1})	25

With the wind turbine integrated and for a battery of 9.6 kWh the autonomy goes up only to 99.55 %. This result shows that for this region is not viable have a wind turbine once that energy production is small, because as represented in Figure 33, the wind speed in the region is low, with the average annual wind speed of 2.95 m s^{-1}. Especially in relation to the energy production by the PV panels, as Figure 36 shows, the electricity produced by the wind turbine is five times less than the photovoltaic production.

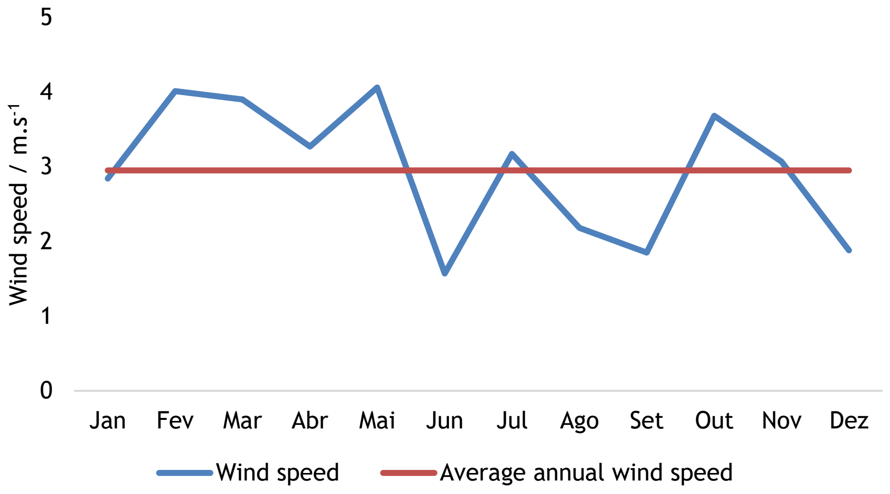


Figure 33 – Monthly and annual average wind speed.

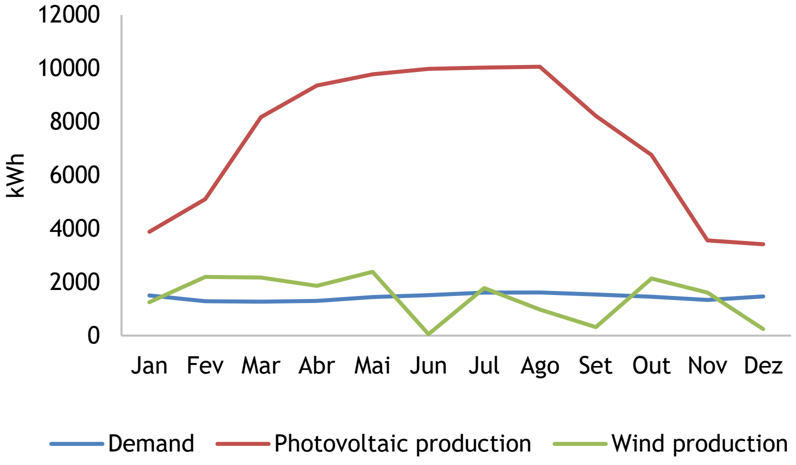


Figure 34 – Photovoltaic and wind energy production throughout the year.

As can be seen in the graph, the energy produced by the wind turbine in relation the PV production and demand practically does not help, particularly in January and December when is more necessary, justifying the result for the small increase in autonomy.

Another attempt for achieving the goal of total independence it was integrated biomass for substitute the energy intended to heat the indoor space and domestic hot water, keeping the photovoltaic production and the battery but excluding the wind turbine. As can be observed in Figure 35 the demand with biomass integrated decrease significantly, making possible to reach the goal. This way, excluding the 5367 kWh per year intended to water systems the autonomy reaches 100 %, complying the proposed objective.

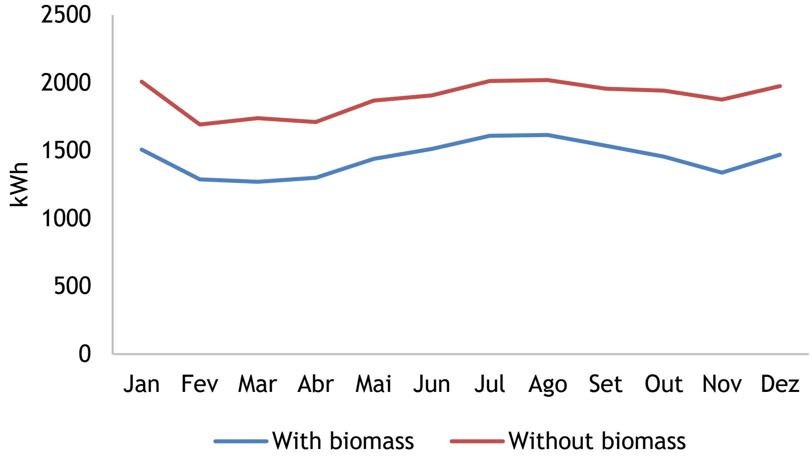


Figure 35 – Demand difference with and without biomass integrated.

Analysing the demand during the year, it can be noted a slight increase in the winter months due the heating loads and in the summer months due the cooling loads, but in general there is no big changes because the temperature of the house is controlled all year. This tendency for cooling and heating loads can also be observed in Figure 36 and it can be seen that the cooling loads are much higher than the heating loads.

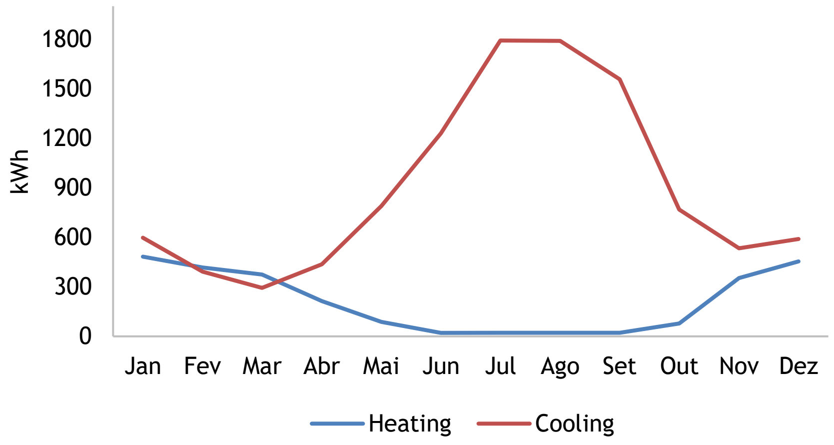


Figure 36 – Heating and cooling loads all over the year.

The difference between the energy spent for heating and for cooling can be justified by the region climate and with the heat recovered by the heat exchanger. Although the heat recovered is much higher in summer because it is when is necessary more cooling, in winter months heat is also recovered as can be seen in Figure 37.

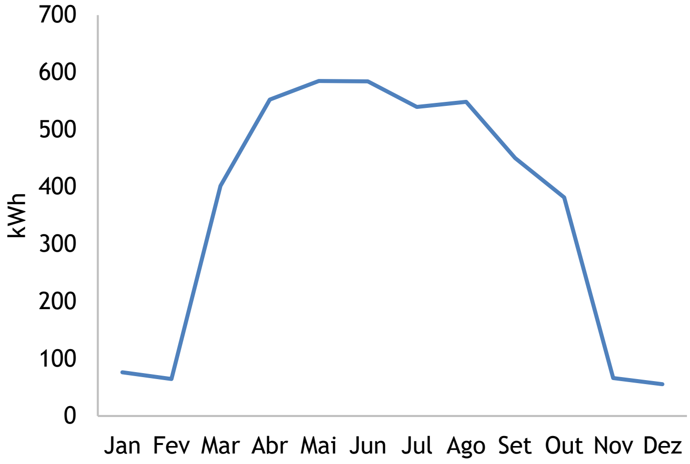


Figure 37 – Heat recovery by the heat exchanger from the heat rejected by the chiller.

As Figure 34 shows, the photovoltaic production is higher in the summer months and smaller in the winter months. The same is expected for the state of charge of the battery, as Figure 38 represents, once that when the energy production is smaller the battery charges less and discharges more.

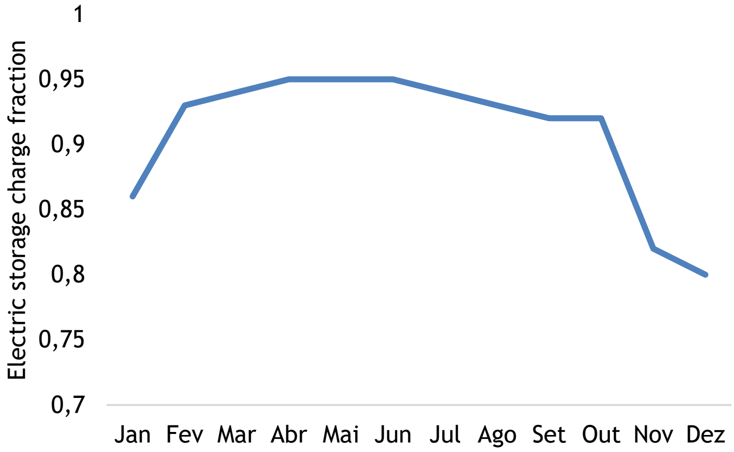


Figure 38 – Battery state of charge during the year.

Once that with the integration of biomass the autonomy from the electric grid reaches 100 %, it was searched the minimum PV area that still can maintain the same result, in order to save money in the investment costs. The new PV area is 258 m^2. In Table 10 are presented the results of the economic analyses. Once again, the surplus energy is sold to the grid in the attempt of making the project viable, because it is much higher than the demand, as Figure 39 shows.

Table 10 – Economic analyses for total independence scenario.

Annual savings (€)	Annual O&M (€)	Investment (€)	Payback period (years)
2319	335	34 376	15

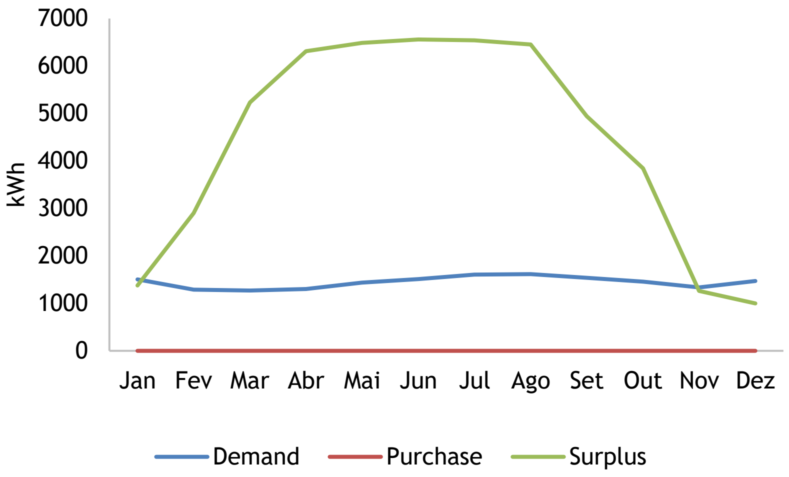


Figure 39 – Relation between the demand and surplus energy.

As the results show, with this configuration the house has a total independence and it is a project economically viable once that the payback period is inferior to the life cycle of the equipment. After 20 years the profit of this project is 18 708 €.

The obtained results show that having a house total independent from the grid, producing all electricity in site is a possible scenario. Annually, it is less expensive to produce electricity this way than purchase all the electricity to the grid, once that there are annual savings, even with the O&M costs amortized. The electricity purchased to the grid costs 0.223 € kWh^{-1} and the produced at home costs 0.198 € kWh^{-1}, that is 0.025 € kWh^{-1} cheaper.

So, it can be concluded that, currently, it is possible having a house total independent from the grid, with annual savings, a production price smaller than the grid price and a payback period smaller than the life cycle of the equipment.

5.2.1 Selling surplus electricity at a fair price

According to the Decree Law no 153/2014 of October 20, the government imposes to the citizens a particularly low selling price for the surplus electricity. Currently, an increase of only

0.01 € in the feed-in tariff was enough to reduce the payback period in 3 years. However, a responsible citizen may decide to sell this electricity to the neighbouring at a more reasonable price, for example for charging battery *car*†. The chosen price was 0.12 € kWh^{-1}, which *ca.* half of the present price, which is 0.223 € kWh^{-1} [32]. According to this more favourable and fair scenario, the obtained results are showed in Table 11.

Table 11 – Economic analysis for selling surplus electricity.

Annual savings (€)	Annual O&M (€)	Investment (€)	Payback period (years)	Profit in 20 years (€)
5878	335	34 376	6	89 890

With this scenario, the investment of the project can be amortized in a few years with a big profit at the end of 20 years. It can be said that the investment made is a way to make money better than putting it in the bank, since the bank interest rate for the investment made is much lower comparing to the profit of the project.

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† The author wrote battery car since electrical car is an erroneous designation. According to the accepted nomenclature a car is designated according to the stored fuel as diesel car, gasoline car or hydrogen car. In a battery car energy is stored in electrochemical fuels. Despite the round trip energy efficiency of a battery being high, *ca.* 80 % to 90 %, electricity is just used to charge the battery and electricity is *generated* during the discharging stage; the stored fuel is an electrochemical one and cars running on batteries should then be named electrochemical of battery cars.

6 Conclusion

This work aims at assessing a nearly zero energy household using an energy and thermal comfort simulator. The building considered follows the present legislation concerning thermal comfort, which minimizes the energy consumption. On the other hand, it was assessed the contribution of different technologies for obtaining the thermal comfort and remaining energy needs.

The energy simulation software tool used in this project was the EnergyPlus. This software can size the HVAC system, calculate heating and cooling loads respecting the control set points and determine the energy consumption of primary plant equipment. For a more complete analysis also gave results about the photovoltaic production and energy stored.

According to the results provided by EnergyPlus, indoor appliances and water systems are the most consuming energy items. The suitable battery for this project should have 9.6 kWh capacity. From the analysis of the house with and without a storage system was possible to conclude that the integration of a storage system should double its autonomy. The economic analysis allowed to realize that the PV area that leads to the best savings is not the one that leads to the best autonomy. With the increase of PV area, the investment and O&M costs increase, and the annual savings took the other way. The most economically viable project corresponds to a PV area of 51 m^2, annual savings of 4997 € and a payback period of 3 years.

For the second scenario the PV area used for achieving the goal of total independence was 278 m^2 a battery with capacity of 9.6 kWh. But with this proposal was not possible to achieve the objective, so a wind turbine of 10 kW was implemented. Once again, the total independence was not reached suggesting that is not viable to have a wind turbine in this region with these meteorological conditions. Biomass to comply with the needs for heating and domestic hot water and achieve the 100 % of autonomy were necessary. Therefore, is possible to have a house completely independent from the grid during all year. This scenario led to an investment of 34 376 €, 2319 € of annual savings and a payback period of 15 years, making this project economically viable. The project profit corresponded to 18 708 €. The produced energy on site costed 0.198 € kWh^{-1}, which is 0.025 € kWh^{-1} cheaper than the electricity purchased to the grid. If the surplus electricity was sold to the vicinity at a more reasonable price, 12 € kWh^{-1}, the annual savings would increase to 5878 €, the payback period would reduce to 6 years and the project profit would increase to 89 890 €.

7 Assessment of the work done

7.1 Objectives Achieved

The proposed goals in this work were successfully achieved. The use of an energy simulation software tool, EnergyPlus, was successfully accomplished since it was able to obtain results that allowed to reach the remaining objectives.

For the first scenario was studied the contribution of a storage system and the economic analysis was made allowing reach the PV area, with integration of a storage system, that leads to the best annual savings.

Finally, was proved that it is possible have a house that is 100 % independent from the grid with the integration a PV system, biomass and storage system. Currently is already an economically viable project and the electricity produced this way is cheaper than purchase to the grid.

7.2 Limitations and Future Work

The unique limitation of this work was the chosen software for simulation, EnergyPlus, that sometimes was not flexible to perform some situations which were intended in the modelling of the building, like combined loops or inertial tanks.

As future work is recommended that other energy simulation tools are used to understand what is the best and more flexible to perform the proposed work. The same work must be tried for different types of buildings, location, sun exposure and construction materials.

7.3 Final Assessment

The achievement of this project was a big challenge because before working exclusively to get knowledge about the theme and results I had to learn how to work on the chosen software, which represented a large part of the work time. It took a great persistence to learn in time and enough to get the work done.

This work allowed me to develop new software skills and to gain insights on construction materials and other concepts and their influence on energy consumption of a given building.

At the end, it is gratifying to look back the path taken up to point and being able to achieve the proposed objectives.

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Appendix 1 – Energy software tools comparison

Table 12 – Comparison between different energy software tools. Extracted from [18].

	EnergyPlus	ESP-r	TRNSYS
Simulation of loads, systems and solutions	X	X	X
Iterative solution of nonlinear systems	X	X	X
Variable time intervals per zone for interaction of the HVAC system	X	X	-
Simultaneous selection of buildings systems and user	X	X	X
Dynamic variables based in transient solutions	X	X	-
Walls, roofs, and floors	X	X	X
Windows, skylights, doors and external coatings	X	X	X
Polygons with many faces	X	X	X
Imports of building from CAD programs	X	X	X
Export geometry of buildings for CAD software	X	X	-
Import/Export of simulation model programs	X	X	-
Calculation of thermal balance	X	X	X
Absorption/release of humidity from the building materials	X	-	X
Internal thermal mass	X	X	X
Human thermal comfort	X	X	X
Solar analysis	X	-	X
Analysis of isolation	X	X	X
Advanced fenestration	X	X	X
Calculations of the building in general	X	X	X
Surface temperatures of zones	X	X	X
Airflow through the windows	X	X	X
Driving surfaces	X	X	X
Heat transfer from the soil	X	X	X
Thermophysical variable	-	-	-
Daylighting and lighting controls	X	X	-
Infiltration of a zone	X	X	X
Automatic calculation of coefficients of wind pressure	-	-	-
Natural Ventilation	X	X	X
Natural and mechanical ventilation	-	-	X
Control open of windows for natural ventilation	X	X	X
Air leaks in multiple zones	X	X	X

Solar energy	X	X	X
Trombe Wall	X	X	X
Photovoltaic panels	X	X	X
Hydrogen systems	-	X	X
Wind energy	-	X	X
Electrical Systems and Equipment	-	-	-
Energy production through R.E	X	X	X
Distribution and management of electric power loads	X	X	X
Electricity generators	X	-	X
Network connection	X	X	X
HVAC idealized	X	X	X
Possible configuration of HVAC systems	X	X	X
Repetitions cycle air	X	X	X
Distribution systems	X	X	X
Modelling CO^2	-	-	X
Each distribution of air per area	X	X	X
Forced air unit per zone	X	X	X
Equipment unit	X	X	X

Appendix 2 – Building operation schedules

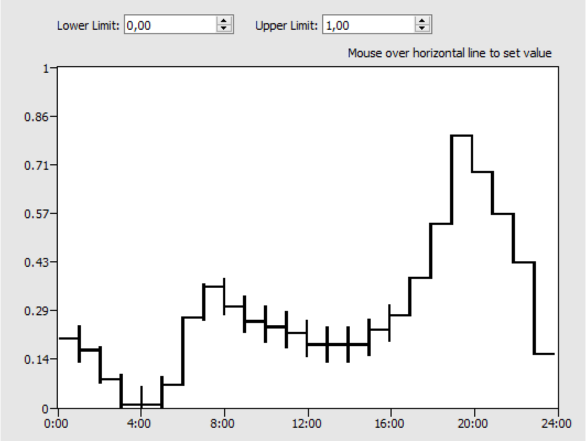
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Figure 40 – Lights house schedule.

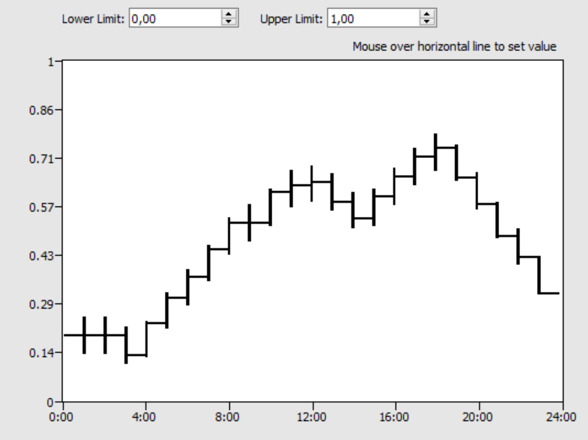
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Figure 41 - Equipment house schedule.

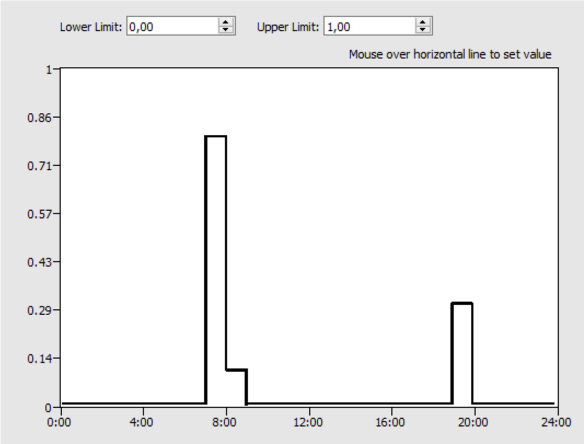
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Figure 42 - Occupation house schedule.

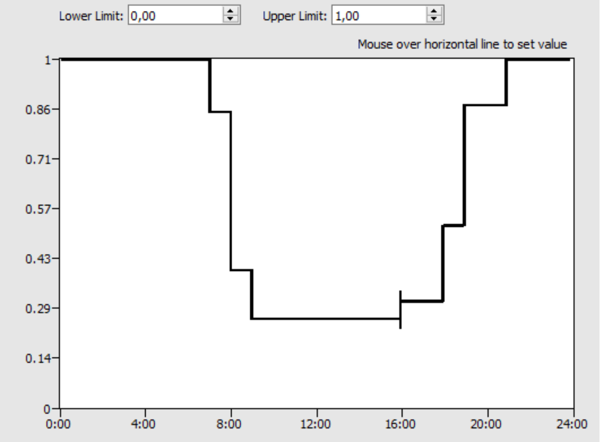
Lower Limit: 0,00 Upper Limit: 1,00

Figure 43 – Showers use schedule.

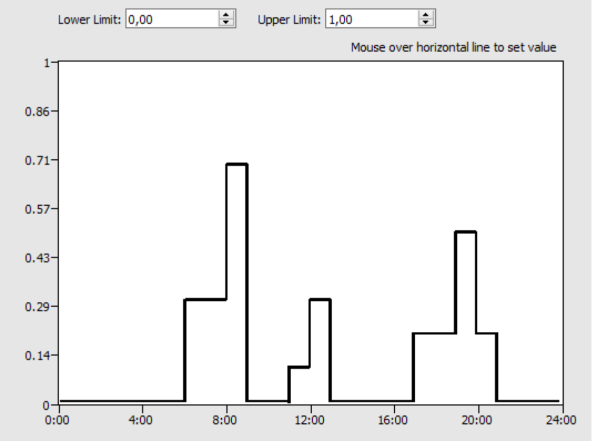
Lower Limit: 0,00 Upper Limit: 1,00

Figure 44 – Sinks use Schedule.

Appendix 3 – Constructions

Table 13 - Exterior wall construction.

Material	Thickness (m)	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Thermal resistance (m^2 K W^{-1})
Plaster	0.015	1.30	2000	900	-
Bored brick	0.150	-	-	-	0.39
Air cavity	0.030	-	-	-	0.18
Extruded polystyrene	0.070	0.04	30	1210	-
Bored brick	0.110	-	-	-	1.27
Plaster	0.015	1.30	2000	900	-

Table 14 - Interior wall construction.

Material	Thickness (m)	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Thermal resistance (m^2 K W^{-1})
Plaster	0.015	1.30	2000	900	-
Bored brick	0.110	-	-	-	1.27
Air cavity	0.030	-	-	-	0.18
Extruded polystyrene	0.070	0.04	30	1210	-
Bored brick	0.110	-	-	-	1.27
Plaster	0.015	1.30	2000	900	-

Table 15 - Roof construction.

Material	Thickness (m)	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Thermal resistance (m^2 K W^{-1})
Gravel	0.050	2.00	1950	900	-
Extruded polystyrene	0.070	0.04	30	1210	-
Waterproofing	0.005	-	-	-	0.02
Expanded clay	0.050	0.70	1300	790	-

Concrete	0.200	2.00	2400	960	-
Plaster	0.020	1.30	2000	900	-

Table 16 - Wet floor construction.

Material	Thickness (m)	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Thermal resistance (m^2 K W^{-1})
Extruded polystyrene	0.070	0.04	30	1210	-
Concrete	0.200	2.00	2400	960	-
Regularization layer	0.040	1.30	2400	900	-
Cement	0.065	1.30	1900	900	-
Tile	0.020	1.00	60	795	-

Table 17 - Dry floor construction.

Material	Thickness (m)	Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Thermal resistance (m^2 K W^{-1})
Extruded polystyrene	0.080	0.04	30	1210	-
Concrete	0.200	2.00	2400	960	-
Regularization layer	0.040	1.30	2400	900	-
Polystyrene foam	0.050	-	-	-	0.44
Floating floor	0.060	0.30	20	1297	-

Appendix 4 – HVAC loops

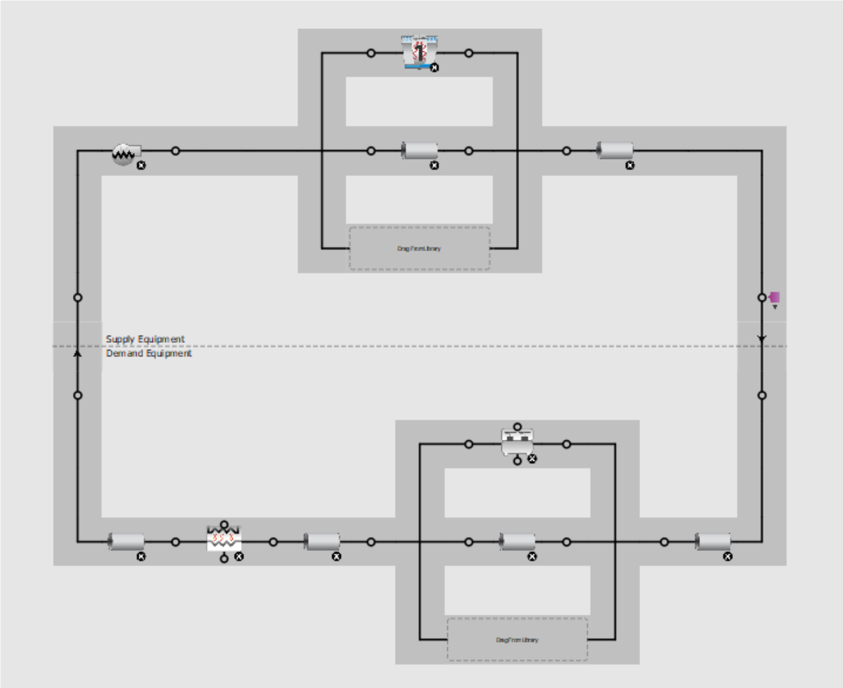

Figure 45 - Condenser water loop.

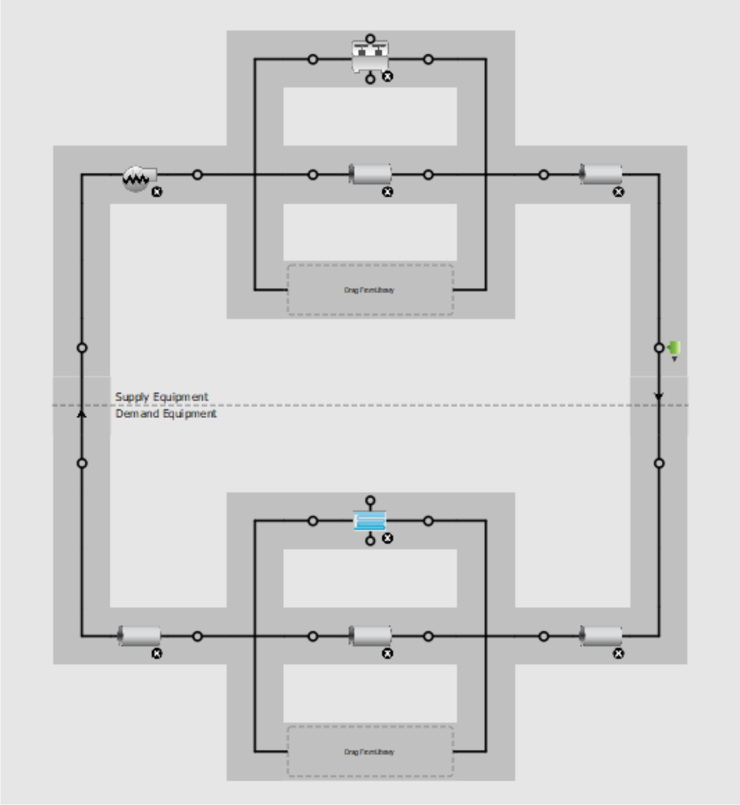

Figure 46 – Chilled water loop.

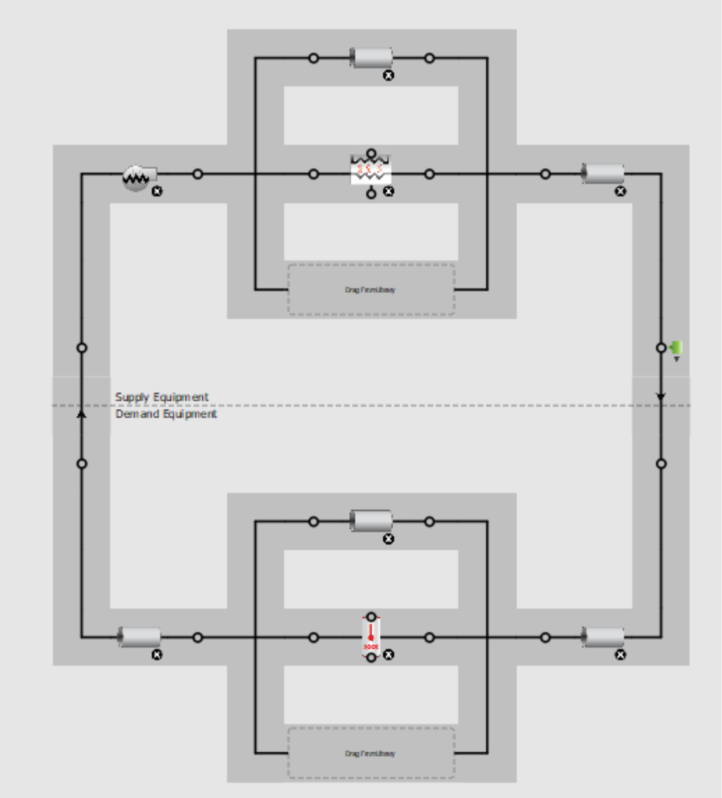

Figure 47 – Heat recovery loop.

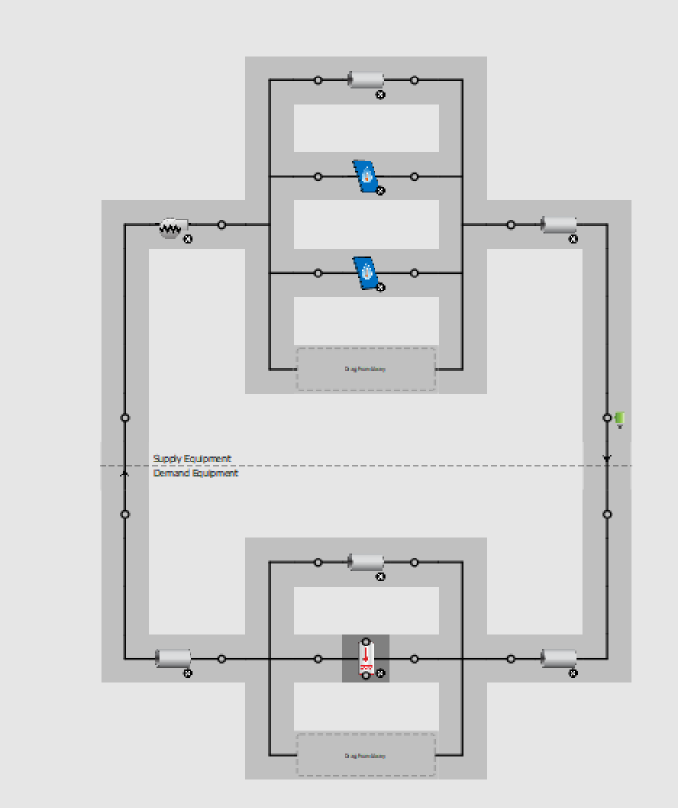

Figure 48 – Supply loop to storage tank for indoor heating.

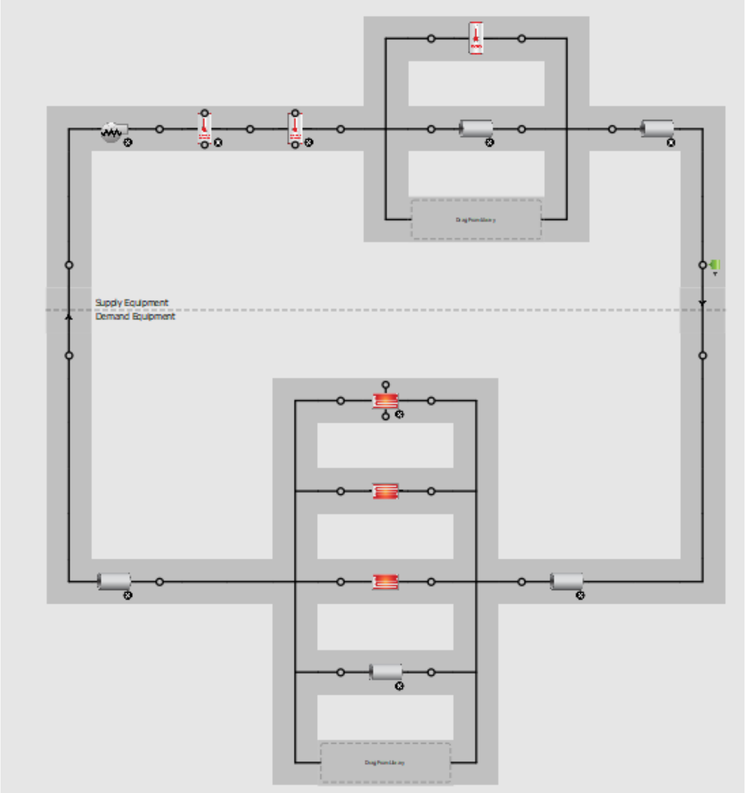

Figure 49 – Hot water loop.

Appendix 5 - Domestic hot water loops

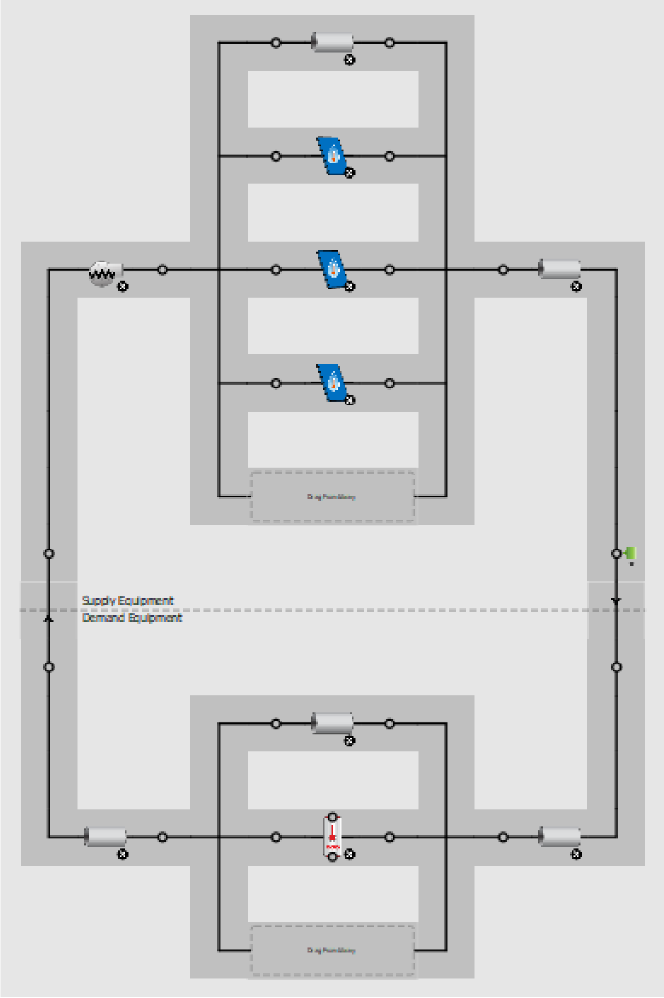

Figure 50 – Supply loop to the storage tank for DHW.

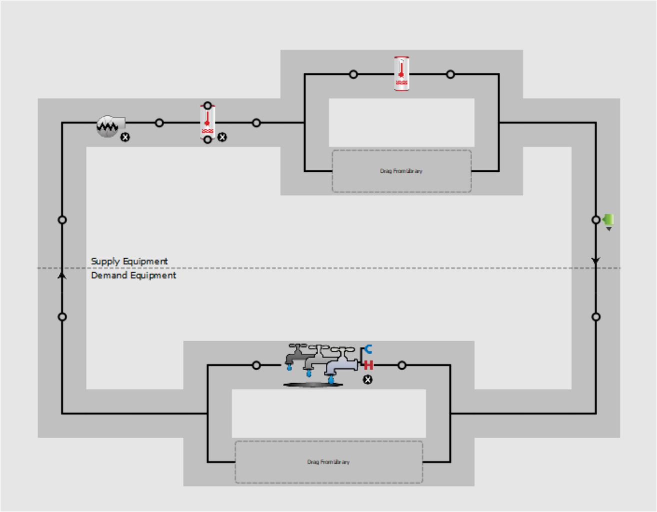

Figure 51 – Supply loop to the water connections.