FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Rehabilitation Project for an Energy Autonomous House

Ana Margarida Martins de Almeida

DEVELOPED WITHIN THE COURSE OF DISSERTATION
HELD IN
A400 – PROJETISTAS E CONSULTORES DE ENGENHARIA, LDA.

Master's in Chemical Engineering

Supervisor: Dr. Carlos Gabriel Bernardo, PhD

Co-Supervisor: Prof. Vasco Freitas, PhD

Coordinator A400: Eng. Tiago Lima, MSc

July 1, 2019

© Margarida Almeida, 2019

Rehabilitation Project for an Energy Autonomous House

Ana Margarida Martins de Almeida

Master's in Chemical Engineering

July 1, 2019

Resumo

Como consequência do aumento do comsumo energético, algumas questões ambientais estão a tornar-se mais alarmantes. Esta dissertação explora uma casa familiar com o objetivo de otimizar a sua eficiência energética. Os edifícios são responsáveis por 40 % do consumo global de energia e a intervenção em edifícios já existentes é a chave para conseguir uma redução significativa no consumo energético do setor.

A metodologia aplicada é baseada num software chamado IES VE, que permite realizar simulações dinâmicas dedicadas a melhorar o desempenho dos edifícios. A casa foi modelada no software e várias simulações foram realizadas para comparar, selecionar e otimizar soluções passivas e ativas para a reabilitação do edifício. Além disso, o processo de decisão tentou seguir a regulamentação portuguesa para o setor residencial e teve em conta o custo real das tecnologias no atual mercado português.

A casa em estudo é uma casa germinada, localizada na cidade do Porto, com a fachada principal orientada a Sudoeste, tem pouca resistência térmica e elementos construtivos antigos na sua essência.

A reabilitação proposta alcançou o conforto térmico desejado e também uma autonomia energética total. Para tal, foram consideradas diversas medidas como isolamento térmico, ações comportamentais para arrefecimento passivo, implementação de sistema de climatização, instalação de coletores solares, paineis fotovoltaicos e baterias para armazenamento de energia.

O custo de investimento previsto para a reabilitação foi de 50 000 euros com um retorno anual do investimento de 6 % e uma recuperação de investimento esperada de 175 % após 35 anos. A opção de investimento faseado também foi apresentada, tratando-se de uma alternativa que permitiria um impacto suave na economia do agregado familiar e também aproveitar os futuros avanços tecnológicos.

Percebeu-se que uma avaliação completa da casa e seu estudo de reabilitação são aspetos bastante desafiadores. Um edifício e o ambiente em que este está inserido são sistemas complexos, nos quais aspectos económicos, técnicos, tecnológicos, ecológicos, sociais, de conforto e estéticos devem ser tidos em conta. A interdependência destes subsistemas desempenha um papel significativo, no qual todos os eles influenciam o desempenho geral da casa.

Palavras-chave: Reabilitação, casa energeticamente autónoma, conforto térmico, IES VE, eficiência energética.

Abstract

As a consequence of the energy demand upsurge, environmental issues are becoming more apparent. This dissertation explores the rehabilitation of a living house with the goal of optimizing its energy efficiency. Buildings are responsible for 40% of the global energy consumption and the intervention in existing buildings is the key to achieve a significant decrease in this sector energy demand.

The methodology applied is based in a software called IES VE, which allows dynamic simulation dedicated to improve the buildings' performance. The house was modelled in the software and several simulations were performed in order to compare, select and optimize passive and active solutions for building rehabilitation. Furthermore, the decision making process tried to follow the Portuguese regulation for the residential sector and took into account the real cost of the technologies in the current Portuguese market.

The house under study is a semi-detached house, located in Porto, with its main façade towards South-West, with poor thermal resistance and old constructions in its essence.

The final proposed rehabilitation accomplished the desired thermal comfort and also a total energy autonomy. There were several measures considered such as, thermal insulation, behavioral actions for passive cooling, addition of acclimatization, installation of solar collectors, photovoltaics and batteries for energy storage.

The predicted investment cost for the rehabilitation was 50 000 euros with an annual return of investment of 6% and an expected investment recovery of 175% after 35 years. The option of phasing the investment were also presented which would allow a smooth impact in the household's economy and also take advantage of the close future technological advances.

It was realized that a thorough house evaluation is quite challenging. A building and its environment are complex systems, in which economical, technical, technological, ecological, social, comfort, and aesthetic aspects must be taken into account. The interdependence between those sub-systems plays a significant role in which all sub-systems influence the overall house performance.

Keywords: Rehabilitation, energy autonomous house, thermal comfort, IES VE, energy efficiency.

Acknowledgements

Firstly, I must express my gratitude towards my thesis supervisor, Dr. Gabriel Bernardo, for all the autonomy given during this path, for his flexibility and constructive feedback that was, undoubtedly, a huge help. Also towards Prof. Vasco Freitas, for his availability and patience to share his knowledge and valuable experience with me.

A special thanks to my coordinator at A400, Eng. Tiago Lima, who followed all the process closely and shared the difficulties, uncertainties, and achievements. Thank you for the time spent, constant motivation and enthusiastic problem-solver attitude.

To Prof. Adélio Mendes my sincere gratitude, for being the first believer in his students' capacities and for provoking them to learn and become key players of society. Fortunately, I was one of them and could not be more inspired with this passion to spread and share knowledge.

I also owe my gratitude to Prof. António Torres Marques, the owner of the house under study, António Almeida from MC Frio, Eng. Carlos Garrido from EFACEC, Eng. Leonel Nunes from AFS, Eng. Pedro Pacheco from VisBlue, Eng. Telmo Lopes from Sunaitec and Eng. Jorrit Bleeker. Thank you for sharing your experience in this field and helping me turn this dissertation one step closer to reality.

I must thank the Board of European Students of Technology, an organization that gave me several opportunities to broaden my horizons, overcome my fears, cultivate my ambitions and dare to grow. Particularly for my Local Group, BEST Porto, for the good memories, family spirit and for turning my clumsiness and lunatic ideas into a weapon that I proudly carry with me.

For Rui Pacheco, in honor of the symbiosis status that he conquered in my life, for being the most enthusiastic reader of this thesis and for believing in me more than myself.

These five years were full of knowledge, inspiration, experiences, challenges, and growth, but the best I take with me are the people who crossed my path and left in me a good mark of themselves. Thank you.

Para os meus pais, Rosa Almeida e José Almeida, por me educarem pelo exemplo, obrigado pelos valores de altruismo, despreendimento, sentido de utilidade e de propósito. Obrigado pelo amor, pelo suporte infinito e por serem a maior alavanca de tudo o que alcancei e quero atingir.

Para a minha irmã, Eduarda Almeida, um obrigado especial, porque também ela está a terminar uma etapa e não há outra pessoa com quem eu gostasse mais de partilhar este sentimento de conquista. Obrigado pela resiliencia com que me inspiras, pela garra e segurança com que enfrentas o mundo e obrigado pelos meus dois sobrinhos, Diogo e Rodrigo , que têm os abraços mais doces de sempre e já são duas razões que provam que vale a pena deixar o mundo um pouco melhor do que o encontrei.

"Instead of looking for hope, look for action."

Greta Thunberg.

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.

Signature: ____
Margarida Almeida. July 1, 2019.

Contents

List of Figures

List of Tables

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAPV	Building applied photovoltaics
BIPV	Building integrated photovoltaics
COP	Coefficient of Performance
CSP	Concentrated Solar Power
DHW	Domestic Hot Water
DSM	Dynamic Simulation Model
EAH	Energetic Autonomous House
ECES	Eletrochemical energy storage
EER	Energy Efficiency Ratio
EPBD	Energy performance of building directive
EPS	Expanded polystyrene
ETICS	External Thermal Insulation Composite Systems
EU	European Union
G20	Group of Twenty
GW	Glass wool
HVAC	Heating, ventilation, and air conditioning
ICB	Insulation cork board
IES VE	Integrated Environmental Solutions Virtual Environment
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LHV	Lower Heating Value
LNEG	Laboratório Nacional de Energia e Geologia
nZEB	nearly Zero Energy Building
O&M	Operations and Maintenance Costs
PF	Phenolic Foam
PU	Polyurethane
PV	Photovoltaics
PVC	Polyvinyl chloride
REH	Regulamento de Edifícios de Habitação
REH	Regulamento Edificios de habitação
ROI	Return of Investment
SC	Self-Consumption
SCE.ER	Sistema de Certificação de Edificios. Energias Renováveis
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
SW	Stone wool
TBP	Torrefied biomass pellets
UR	Utilization Ratio

USD	United States Dollar
VRV	Variable Refrigerant Volume
XPS	Extruded polystyrene

Chapter 1

Introduction

1.1 Framing and presentation of the work

Despite the addition of 1 billion new households by 2050, overall building energy consumption would only be $4/5$ of today's level. This was predicted by IRENA, in its road map to 2050 that aims an inevitable global energy transformation [1].

In addition, the majority of electricity consumed in buildings (58%) should come from renewable sources. Together with solar thermal, modern biomass, and district heating, overall renewables could ramp up to 81%, from 36% today's contribution for the sector. Nonetheless, to materialize this predictions, a global investment of around USD 32 trillion (28 trillion euros) is expected between now and 2050 [1].

In the European Union, the nearly zero-energy building-standard (nZEB) will be obligatory for all new buildings by 2021 [2]. Although the increase in energy demand will be reduced with this measure, it does not really affect the energy consumption at present. It is imperative to design energy efficiency retrofit and renovation financing schemes. For many years to come, only measures taken in existing buildings will have a significant effect on the total energy demand in the building stock.

This dissertation aims to develop a rehabilitation project for a '50s House under study, in order to turn it into an energy autonomous building, without compromising the thermal comfort of the household. The designation "energy autonomous" refers to a house operating without fossil fuels and without purchase of electricity from the grid. All the energy consumed has to be generated on-site or nearby, through renewable energy sources [3].

The existing house was modeled in IES VE software in order to perform several dynamic simulations. This was a cost and time effective way of analyzing thermal comfort and energy requirements of the building. The first step was the implementation of passive solutions to decrease the required heating and cooling energy loads and guarantee the thermal comfort of the inhabitants. Secondly, there was a continuous search and application of systems to supply the thermal and electrical energy needs with renewable sources.

Furthermore, an economical and technical assessment was done for all considered interventions and technologies. Instead of basing its conclusions on optimistic predictions about future solutions, this project looked at the present status of Portuguese regulation and its market, and linked them with the current renewables availability. This type of approach came from the need, as mentioned before, to foster the investment in these sort of interventions straightaway.

1.2 Presentation of the company

A400 was founded in 1995 by António Monteiro, Francisco Bernardo, and Marco Batista. It is nowadays positioned as a company specialized in structural projects and with a strong emphasis in project management and coordination.

The company is structured in six different departments, namely: structural, hydraulics, mechanical, electrical and telecommunications, research and development and coordination departments. Together they provide the main company's services, which are structural steel, timber and concrete design, building and infrastructures hydraulics projects, building thermal end energy designs, HVAC and mechanical projects, electrical and communications projects and construction supervision.

A400 is already spread in Portugal, Morocco, Algeria, Angola, and Mozambique, with over 100 employees worldwide. The main focus of the company is service buildings. This project on the residential sector is a challenge that aims to look into the possibility of broadening the company's target group or even apply the energy autonomous concept in service buildings.

1.3 Contributions of the Work

Among the several studies performed on building retrofit or nearly zero energy houses, this dissertation stands out for its double ambition of turning a more than 60 year old house into an energy autonomous building, with full self-sufficiency in thermal and electrical energy, as well as, providing thermal comfort for the occupants, nonexistent at present in the house. The work developed in terms of comparison of different solutions, systems' simulations and market assessment, intends to be an open door for understanding the main barriers and potentials in terms of building rehabilitation, and boost the implementation of related projects.

1.4 Organization of the thesis

This thesis is divided into 7 chapters. This introductory chapter presents the objective of the thesis and showcases the urgency to intervene in existing buildings as a measure for energy sustainability. Chapter 2 familiarizes the reader to the technical and economic aspects of the technologies under study and covers some of the theoretical knowledge needed to fully understand the presented results. Chapter 3 introduces the methodology followed, with a special focus in the software used for dynamic simulation. In Chapter 4, the house under study is presented and all the considerations and assumptions used to characterize the house are presented and justified. Chapter 5 contains the results obtained in terms of energy autonomy, thermal comfort and project viability, along with the discussion of the decisions taken along the project. Chapter 6 shows the conclusions reached throughout the work. Finally, Chapter 7 puts all the work done in retrospect, presenting the level of achievement of the objectives and also some suggestions for future developments.

Chapter 2

Context and State-of-The-Art

The global economic growth had a direct effect on the energy demand, which rose by 2.2% in 2018 [4]. The increase in energy consumption has translated into a demand boost for all energy sources, including coal, oil, gas, and renewables. Consequently, CO_2 emissions in G20 countries have increased in 2018 (+1.8% at 27 $GtCO_2$), contributing to the climate crises that we are currently facing. [4]. This global energy consumption rise needs to be addressed with a sustainable path.

Nevertheless, the energy independence of buildings based on renewable sources can bring advantages, not only from an environmental perspective but also in terms of household's savings. Portugal is currently one of the countries with the highest price on electricity for households, as shown in Figure 2.1. More than 50% of the price is due to taxes and levies, the second highest share in European countries. [5]

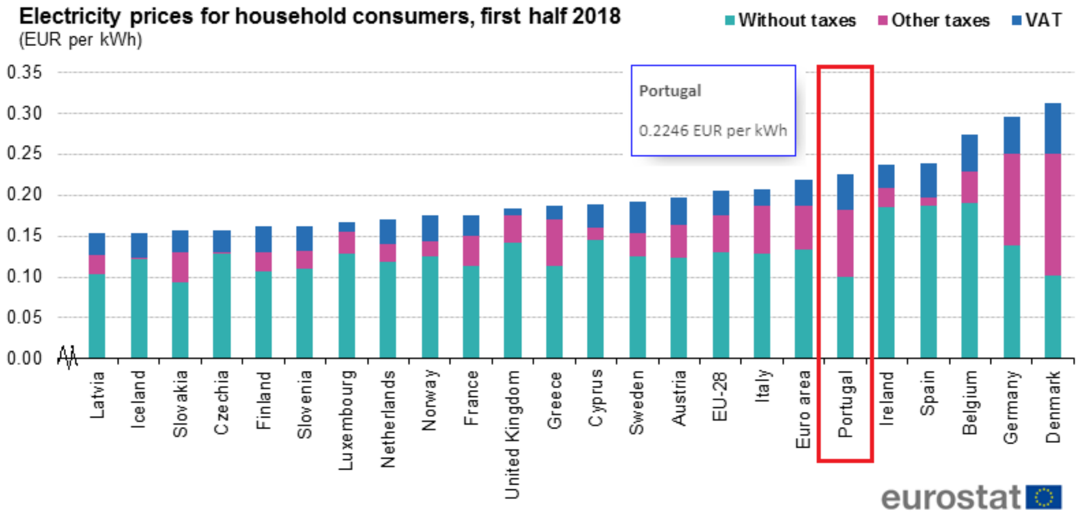


Figure 2.1: Electricity prices for household consumers, adapted from [5]

The thermal comfort of households must be taken into consideration. The Portuguese Regulation indicates, as reference comfort conditions, an air temperature of 20 °C for the heating season and a maximum air temperature of 25 °C for the cooling season. The mean indoor temperatures, in Portugal, identified by a study of adaptive thermal comfort in the residential sector, vary between 12 °C and 21 °C in winter and between 23°C and 34 °C in summer [6]. It should be noted that, for the mentioned temperature ranges, there was a low contribution of air conditioning systems (when existing), contrary to the European tendency to increase the consumption of air conditioning in the residential sector. Portugal is a country that faces energy poverty in terms of thermal comfort, which means that households consume less energy than the energy needed to achieve indoor comfortable temperatures, due to cultural or financial reasons [6].

2.1 Building envelope retrofit

The main objective of the energy performance of building directive (EPBD 2002/91/EC) and its recast (EPBD 2010/31/EU) is to promote the cost-effective improvement of the overall energy performance of buildings [2]. One of the best opportunities to do so would be during building retrofit.

In general practice, it is a strategic approach to insulate a building from main componentsmain components where heat tranfer takes place (e.g. walls, doors and windows). This is also called the thermal envelope.. Thermal insulation helps in preserving energy efficiency, which depends on the air temperature gradient (the difference between inside and outside of building), geographical location, climatic condition and heating space type [7]

In accordance with the Portuguese Decree-Law no. 118/2013, the value of the heat transfer coefficient, U, of an element characterizes the heat transfer occurring between it and the surrounding environment. U is calculated in accordance with European standards in force:

$$U = \frac{1}{R_{si} + \sum_j R_j + R_{se}}, \quad [W \cdot m^{-2} \cdot {}^{\circ}C^{-1}] \tag{2.1}$$

Where:

- R_j - The thermal resistance of layer j, $[m^2 \cdot {}^{\circ}C \cdot W^{-1}]$
- R_{si} - The outdoor thermal resistance, $[m^2 \cdot {}^{\circ}C \cdot W^{-1}]$
- R_{se} - The indoor thermal resistance, $[m^2 \cdot {}^{\circ}C \cdot W^{-1}]$

2.1.1 Intervention in the External Walls

Walls occupy the largest area of a building, and the employment of thermal insulation directly affects the overall building heat gain/loss. In order to achieve best performance, the insulating material should be installed close to the location of the heat inflow or outflow. [7] There are three main trends for façade insulation systems on the market:

External Thermal Insulation Composite Systems (ETICS) are a constructive system for façades composed of multiple layers: the wall, the insulation material, the fixing on the substrate, the reinforcing intermediate coating, reinforcement mesh and a decorative finish coating. (Figure 2.2) The objective of ETICS is to minimize the losses and to remain reliable and durable to protect the building against environmental and climatic factors. Furthermore, the installation of the insulation material outside the main wall eliminates thermal bridges. Thermal bridges are localized areas of the building envelope where the heat flow is different compared to the adjacent areas [8]. The system must have high resistance to mechanical stress, impermeability to water and permeability to CO_2 and water vapor [9].

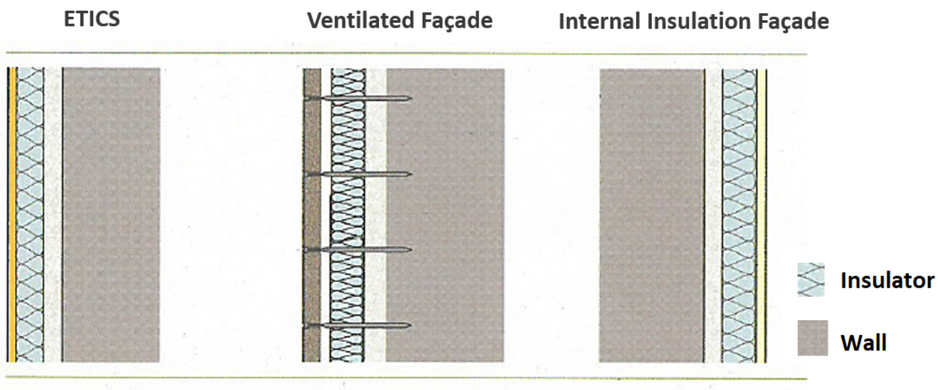


Figure 2.2: Constructive details of the façade systems, adapted from [8]

The ventilated façade is a system consisting of a multi-layered building envelope with an outer layer that is mechanically connected by a galvanized steel, stainless steel or aluminum frame to the inner layer. This inner layer is insulated from the outside with board or foam insulation and is attached with adhesive mortar and/or dish-shaped dowels, depending on the thickness and type of insulation.(Figure 2.2) The ventilated façade allows free air circulation through the intermediate cavity, removing moisture and improving the energy performance of these façade systems under the effect of the solar radiation relative to conventional façades. [9]

The internal insulation façade is a construction solution of an enclosure composed of an outer main wall, insulation and inner cladding. The insulation layer is fixed with metallic profiles that are mechanically connected to the floor and ceiling. (Figure 2.2) This system is the most common for the rehabilitation of existing buildings since there is no intervention in the outer wall and the aspect of the façade stays original. Internal insulation is one of the cheaper options but must take into account the interruption of insulation in the ceilings and walls, which can produce thermal bridges [8].

2.1.2 Intervention in the Roof Space

Roofs can represent up to 32% of the horizontal surface of built-up areas and have a huge contribution in terms of heat gain in buildings. Heat transmission through the roof could be reduced simply by providing insulation as a radiant and conduction barrier [10]. A conventional house in Portugal has a tiled roof with a ceiling. The insulation can be applied in the roof space, under the roof or above the ceiling (Figure 2.3)

For retrofitting of old houses, the foil covered insulation blanket could be laid simply over the ceiling board (Figure 2.3, on the left). Insulating above (or above and between) the roof timbers is an effective way to cause minimal intrusion into a valuable living space (Figure 2.3, on the right). It also ensures that the structure is kept at or near the internal environmental conditions, reducing thermal stress and condensation risk. [11]

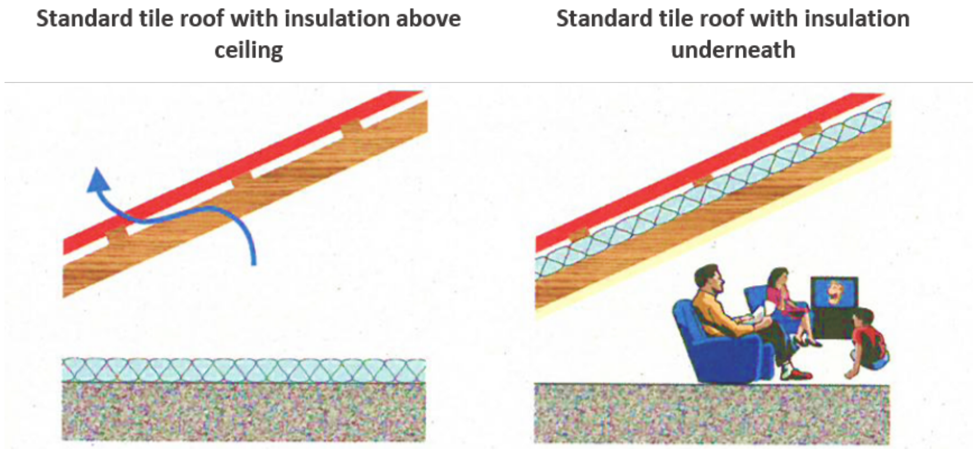


Figure 2.3: Constructive details of tiled roof insulation systems, adapted from [8]

2.1.3 Intervention in glazed areas

In addition to energy saving, window replacement improves the indoor climate of the building, its interior and architectural appearance as well. However, the replacement of original windows with new ones is not as effective in terms of heat energy saving as are the insulation of a roof, walls and other improvements because the investments are large and take a long time to be repaid [12]. The sequence of building operations determines when the replacement of windows should be done, and the retrofit in glazed areas shall be applied differently (Figure 2.4), depending on the desirable balance between thermal transmittance and solar gains.

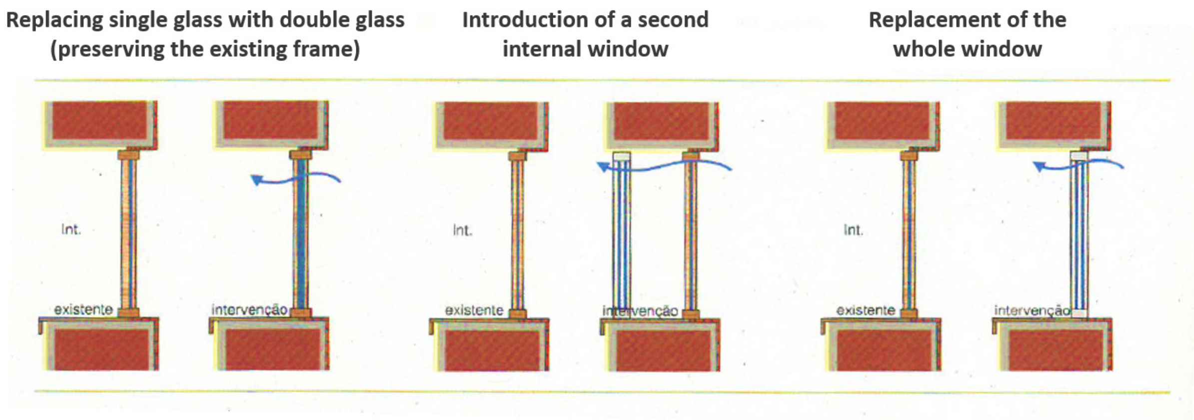


Figure 2.4: Energy conservation solutions for glazed areas, adapted from [8]

From the energy point of view, replacing the whole window is more efficient than keeping the old frame. [8] But even among the double glazing options, there are several combinations of frame materials and air thickness between glazed layers [12].

2.1.4 Insulation Materials

The principle of thermal insulation consists of the proper installation of insulating materials that reduce the heat loss or heat gain of the thermal envelope, leading to a reduction of energy consumption [13].

The European market of insulation materials is still dominated by two groups of products. Inorganic fibrous materials account for 60% of the market, mostly consisting of stone wool (SW) and glass wool (GW). Organic foamy materials account for approximately 30% of the market, the most common of which is expanded polystyrene (EPS), followed by extruded polystyrene (XPS) and the less widespread polyurethane (PU) and phenolic foam (PF). All the other materials accounted for less than 10% together, including insulation cork board (ICB), wood wool, and Aerogel [9].

Table 2.1: Review on materials for building insulation, adapted from [7]

Insulation materials	**EPS**	**XPS**	**GW**	**SW**	**ICB**
Thermal conductivity, λ, $(W \cdot m^{-1} \cdot {}^{\circ}C^{-1})$	0.029-0.041	0.025-0.035	0.040-0.050	0.035-0.071	0.045-0.055
Bulk Density, $(kg \cdot m^{-3})$	18-50	20-80	10-100	5-300	90-140
Thermal attributes	Average	Average	Average	Average	Average
Resistance at biological dangers	Good	Good	Good	Good	Average
Fire resistance	-	-	Good	Very Good	-

2.2 Solar technologies for buildings

Typical energy key Figures for houses with renewables are the thermal solar fraction, $f_{sol,th}$, and electrical solar fraction,$f_{sol,el}$ [3], (Eq.2.2 and Eq. 2.3, respectively).

$$f_{sol,th} = \frac{solar\,gains}{total\,heat\,input} \tag{2.2}$$

$$f_{sol,el} = 1 - \frac{electricity\,purchase\,from\,grid}{total\,house\,consumption\,input} \tag{2.3}$$

A house concept with focus on thermal energy is the solar house (also known as solar active house) where a combination of large solar thermal collectors with a big thermal storage is used for getting high solar fraction rates (> 0.5). Normally the remaining leak of thermal energy is supplied by a fireplace. [14]

House concepts like “Plus energy house” and “efficiency house plus”, have their focus on electric energy, based on a maximum output of electrical energy by photovoltaic. As a consequence, the total yearly primary energy balance is negative (more output than input) [11]. This concept is controversial due to the annual balancing of primary energy with a big stress for the power grid during summer (high amount of electricity-input from PV) and winter (high amount of electricity purchase caused by heating devices) [14].

The effectiveness of the installed solar technique, can be controlled by measuring the self-consumption of electricity ($SC_{sol,el}$, Eq. 2.4) which compares the solar electricity used by the house and the solar electricity yield. The solar utilization ratio, in terms of thermal and electrical energy, reflects how much of the available solar irradiation the systems are using to produce electricity. ($UR_{sol,th/el}$, Eq.2.5), [3].

$$SC_{sol,el} = \frac{(solar\,electricity\,yield) - (electricity\,export\,to\,grid)}{solar\,electricity\,yield} \tag{2.4}$$

$$UR_{sol,th/el} = \frac{total\,yield\,by\,energy\,system}{total\,solar\,irradiation\,perpendicular\,on\,collector} \tag{2.5}$$

2.2.1 Photovoltaics for electrical supply

The photovoltaic effect is a physical and chemical phenomenon that consists in the creation of free charge carriers (holes and electrons), upon absorption of light, which due to a potential difference are then directed to opposite electrodes, creating an overall flow of charges - resulting in electricity [15].

Several combinations of different modules are already in the market. The main factors affecting the PV power output are: the PV type/materials, the amount of incident solar irradiance and the operating temperature. [16]

Based on the method of installation and construction in the building, the PV systems can be classified as building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV):

- In BAPV, the PV modules are directly attached to the buildings using additional mounting structure and/or moving rails. Here, the PV modules do not have any direct effect on the building structures and the way they function. The PV modules are installed at certain tilt angles either on roof or façade, based on local weather conditions. BAPV can also be installed on the horizontal roof and vertical wall. [17]
- In BIPV, the PV modules are integrated within the building structures mainly into roof or façade. Here the PV modules replace the traditional building materials used for the construction of roof or walls by the BIPV products. This includes the PV modules in the form of transparent or semitransparent glass [17]

Conventionally, solar PV modules are installed to maximize the yearly electricity generation and rooftops are usually the preferable host. However, as urban agglomerates develop vertically, the available area for PV deployment on rooftops becomes scarcer. Thus, vertical façades of buildings should not be disregarded, despite their non-optimal inclination. In fact, in the early morning and late afternoon, the position of the sun in the sky is closer to the horizon, which means that sunlight will reach vertical surfaces more perpendicularly, increasing the harvesting of solar radiation and corresponding electricity production from a PV façade. On the other hand, a tilted rooftop PV system will generate more electricity around noon, when the sun is located near the zenith, as illustrated in Figure 2.5

The same illustration 2.5 is valid when relating summer and winter time PV generation: due to the variable solar declination, the solar path in the sky is closer to the horizon during winter, with higher solar elevations in the summer. In winter, the contribution from PV systems installed in façades is expected to match, or even surpass, the rooftop's [3].

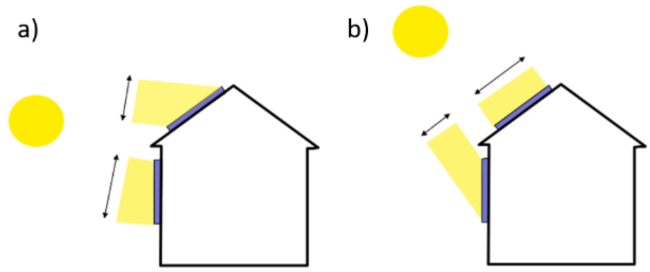


Figure 2.5: Incidence of direct sunlight in vertical façades and tilted rooftops in: a) morning/afternoon; and b) around noon, from [18]

2.2.2 Thermal collectors' systems

In terms of solar collectors currently available in the market, it is possible to distinguish two different types of systems, usually applied in the residential sector: Thermosyphon and forced circulation systems.

In thermosyphon systems all components of the solar thermal system are outside. The system and the reservoir is placed at an upper level of the solar collector. The thermal fluid is heated up in the collector and moves to the highest point (the reservoir) due to its lower density , where it transfers the energy to the water from the mains. This movement is continuous and only ceases when the radiation is low or zero, for example at night. The reservoir receives water from the public supply and has an outlet for end-use heated water [19].

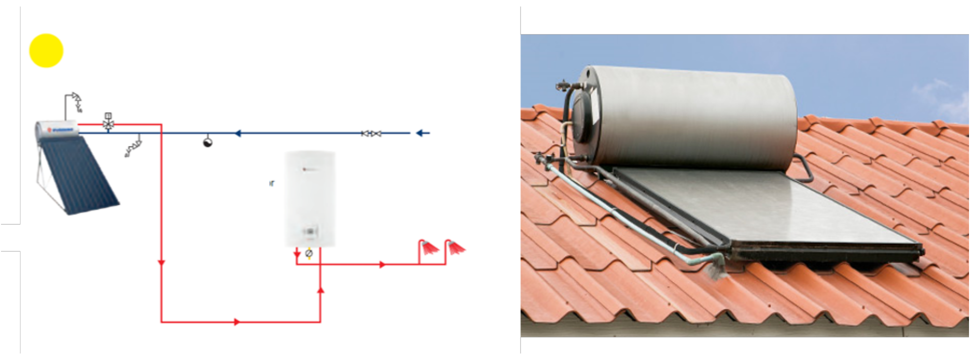


Figure 2.6: thermosyphon system [19]

The forced circulation system requires a circulation pump to move the thermal fluid from the collector to the reservoir, which in this case, is placed in a weather protected area. The circulation pump is controlled by a control system that integrates temperature sensors. It only runs when the temperature of the fluid in the collector is higher than the water in the reservoir [19].

In a general point of view, the thermosyphon is simpler, cheaper but less energy efficient and prone to breakdown due to air leakage into the reservoir. The forced circulation system consumes a small amount of electrical energy and it is more complex, but it is also more energy efficient and more versatile [20].

There are basically two types of solar collectors: non-concentrating (or stationary) and concentrating. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. [21]

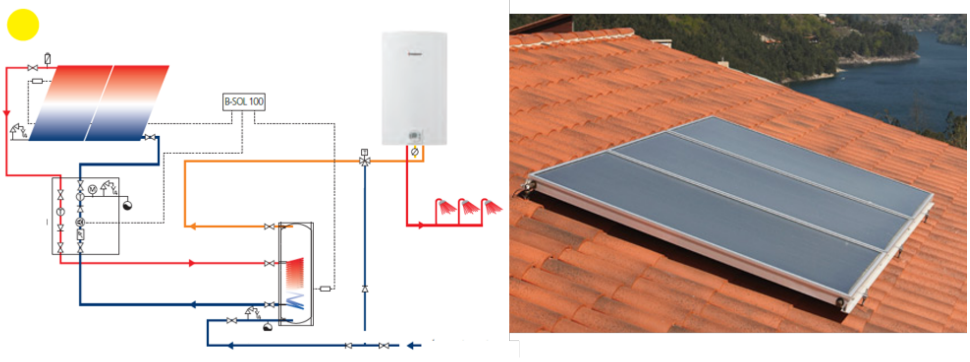


Figure 2.7: forced circulation system [19]

An emerging concentrated solar power (CSP) technology, which has been patented nationally and internationally, is being commercialized by a Portuguese company called Sunaitec.

The equipment consists of technical columns and a variable number of solar thermal receivers, aligned with the sun by active guidance sensors. This feature ensures greater energy efficiency compared to traditional fixed equipment, since the smart solar orientation mechanism keeps the receiver constantly aligned with the Sun [22].

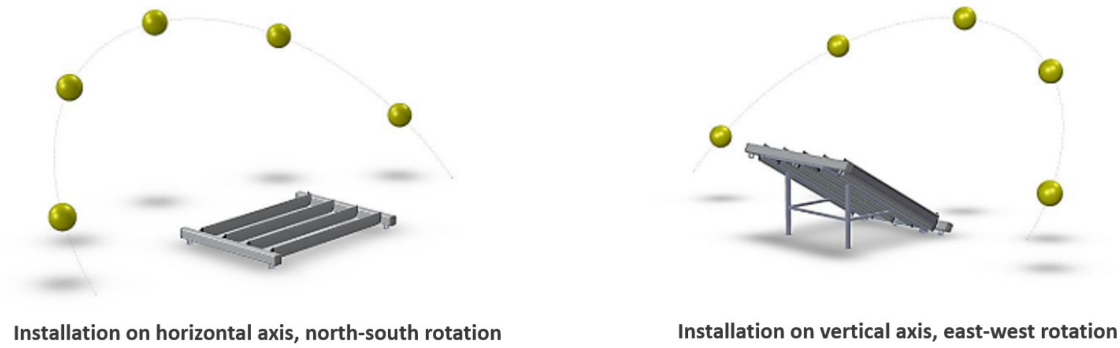


Figure 2.8: Versatility and smart solar orientation of sunaitec receivers, adapted from [22]

The new high performance thermal receiver, (solar concentration 19x), allows, even in the winter months, on sunny days, water heating without any kind of support. Furthermore, the use of mainly polymer based materials and the total absence of weldings gives the equipment a superior longevity. [23] Unlike conventional systems, the Sunaitec equipment allows an architectural integration and a diversity of solutions. [18]

2.3 Eletrochemical energy storage

The continuous supply of electricity from renewable sources, such as photovoltaics, requires a low cost and reliable electricity storage solution to overcome the unstable production of renewables. [24]

In the case of PV panels, the power output usually peaks at the solar noon and is null during the night. Energy storage systems are the key to stabilize PV power output output and avoid a big stress for

Figure 2.9: Examples of architectural integration and diversity of Sunaitec technology [22]

the power grid during summer (high amount of electricity-input from PV) and winter (high amount of electricity purchase caused by heating devices) [14].

Table 2.2: Key figures for main battery technologies in use today, adapted from [25]

ECES technology	Gravimetric Energy Density / $Wh \cdot kg^{-1}$	Round-trip efficiency	Cycle life / cycles	Energy cost (2016) / €$\cdot kWh^{-1}$	Energy cost (2030 prediction) / €$\cdot kWh^{-1}$
Lead acid	25 – 50	75 – 85 %	3000	147	74
Lithium ion	100 – 200	95 %	4000 – 8000	352	147
NaS	120 – 150*	85 – 90 %	4300 – 6000	368	162
Vanadium RFB	10 – 50	80 %	>>13 000	347	119

Lithium ion and lead acid batteries are the most common electrochemical energy storage solutions in the market today. However they have some disadvantages to overcome, such as, not being able to withstand deep charge-discharge cycles, due to electrode corrosion. [25]

Analyzing the Table 2.2, it is possible to conclude the optimized balance between round trip efficiency, cycle life and energy cost will be vanadium redox flow batteries. Vanadium redox flow battery has over 40 years of electrolyte lifetime, is non-explosive, has no self-discharge and 100% deep discharge capability, low maintenance and is repairable [26].

2.4 Biomass as thermal energy supply

Biomass heating systems from an energy perspective can provide a very attractive and feasible option for 100% renewable domestic hot water and space heating demands in the residential sector. [27]

The disadvantages of biomass as a sustainable alternative fuel to coal and other fossil fuels are mainly attributed to its low energy density, high moisture content, and heterogeneity. The introduction of pellet fuels boosted biomass heating technologies. It was the changing point to achieve enough maturity and successfully compete in terms of ease of use, utilization of energy and pollutant emissions. [27]

The comparison of different types of biomass treatments for better thermal efficiency is presented in Table 2.3

Table 2.3: Fuel properties of wood chips, wood pellets, torrefied biomass, torrefied biomass pellets (TBPs), and bituminous coal, adapted from [28]

	Wood chips	**Wood pellets**	**Torrefied biomass**	**TBPs**	**Bituminous coal**
Moisture content /% wt	30–60	7–10	3	1–5	5–10
Mass density $/Kg \cdot m^{-3}$	250–400	600–650	230	750–850	800–1000
LHV (MJ/kg)	6–13	16.2	19.9	19–22	425
Calorific value $/MJ \cdot Kg^{-1}$	1.7–3.6	4.5	5.5	5.2–6.2	7
Energy density $/MWh \cdot m^{-3}$	0.7–0.9	3	1.3	4.2–5	5.6–7
Hygroscopic nature	Hygroscopic	Hygroscopic	Hydrophobic	Hydrophobic	Hydrophobic
Biological degradation	yes	yes	no	no	no

Wood pellets have a higher energy density, higher calorific value, and lower moisture content than wood chips or untreated biomass.(see Table 2.3) Despite their lower moisture content, wood pellets retain the hygroscopic nature of wood and remain vulnerable to water. The possibility of biological degradation can cause storage problems and implies that special precautions need to be taken in the logistics chain in general [28].

New developments of biomass converting processes suggests that torrefaction is a promising technique to improve the performance of biomass for energy utilization. Biomass is completely dried during torrefaction and its hygroscopic nature changes to hydrophobic. Uptake of moisture after torrefaction is very limited. This implies that biological degradation does not occur anymore [28]. (see Table 2.3)

The combination of both torrefaction and pelletizing stages results in the torrefied biomass pellets (TBP's), an energy dense biomass solid fuel with many similar properties to coal, such as high bulk and energy density, high calorific value, and hydrophobic nature [29].

Figure 2.10: Wood chips (a1), wood pellets (a2) and torrified chips (d1) and TBP at 270 °C, [29]

Despite their many good fuel properties, TBP's are still a new fuel, and, unlike the case of wood chips and wood pellets, there is not yet much experience on their large-scale handling and use, however, new investments in this area are being done by a company based in Portugal, called Advanced Fuel Solutions [30].

Chapter 3

Proposed Methodology

This project aims to establish energy performance as a key component for retrofit design towards the upcoming generation of energy efficient and sustainable buildings. The dynamic simulation model (DSM) is a cost and time effective way of analyzing thermal comfort and energy requirements within a building. Therefore, the methodology applied is based in a software called IES VE, which allows dynamic simulation dedicated to improve the performance of any building.

3.1 IES VE Software

IES VE 2018 stands for Integrated Environmental Solutions Virtual Environment 2018, it is a software traditionally focused on creating analysis tools for building design. The main explored applications were ModelIT, SunCast, ApacheSIM, MacroFlo and VistaPro. The work-flow carried-out for simulation execution can be summarized in the following steps in performing analyses:

1. Recreate the building geometry
2. Set location and weather data
3. Create and assign constructions
4. Create room templates
5. Create and assign the Systems
6. Define renewable systems
7. Perform simulation runs
8. Analyze the results

Regarding the building geometry, and since the building does not have any digital document with its architecture, the modeling of the house was conducted in Model IT by following the dimensions indicated in the physical house plan, see Appendix B. Model IT allows the user to create the 3D models required by other components within the Virtual Environment (VE).

The location and weather file were extracted from LNEG $Climas - SCE$ software, which integrates the portuguese Building Certification System, Decree-law 118/2013 of 20 August. SunCast was used to calculate the position of the sun in the sky (3.1, track solar penetration throughout the building interior and calculate shadows. It can be used at any stage of the design process to perform shading and solar insulation studies and generate images or animations quickly and easily from the model created.

A building element is a component of the building such as a wall, ceiling, floor or window. In the software, a construction consists of a layer-by-layer description of the element's thermophysical properties, together with other data such as surface solar absorptivity and emissivity. Two kinds of data need to be set

Table 3.1: Table of solar altitudes during the year, given by SunCast simulation

Month	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Jan	-	-	-	-	-	-	-	-	8.78	16.83	22.99	26.65	27.37	25.04	19.98	12.74	3.9	-	-	-	-	-	-	-
Feb	-	-	-	-	-	-	-	4.05	14.09	22.92	29.9	34.28	35.4	33.06	27.67	19.94	10.62	0.26	-	-	-	-	-	-
Mar	-	-	-	-	-	-	1.07	12.17	22.73	32.24	39.94	44.78	45.79	42.69	36.21	27.46	17.33	6.43	-	-	-	-	-	-
Apr	-	-	-	-	-	-	10.88	22.14	33.13	43.35	51.89	57.24	57.69	53.04	44.9	34.89	23.98	12.74	1.54	-	-	-	-	-
May	-	-	-	-	-	6.69	17.59	28.81	40.04	50.83	60.32	66.59	66.7	60.59	51.16	40.4	29.18	17.95	7.03	-	-	-	-	-
Jun	-	-	-	-	-	8.98	19.65	30.75	42.01	53.08	63.25	70.63	71.32	64.75	54.86	43.87	32.61	21.46	10.7	0.61	-	-	-	-
Jul	-	-	-	-	-	6.86	17.56	28.69	39.96	50.99	61.08	68.51	69.84	64.09	54.63	43.81	32.57	21.37	10.48	0.21	-	-	-	-
Aug	-	-	-	-	-	1.95	12.97	24.23	35.38	45.96	55.13	61.27	62.15	57.35	48.86	38.58	27.54	16.27	5.15	-	-	-	-	-
Sep	-	-	-	-	-	-	7.28	18.42	29.04	38.57	46.12	50.43	50.35	45.93	38.29	28.71	18.07	6.92	-	-	-	-	-	-
Oct	-	-	-	-	-	-	1.12	11.78	21.54	29.86	35.94	38.95	38.32	34.17	27.23	18.34	8.22	-	-	-	-	-	-	-
Nov	-	-	-	-	-	-	-	4.82	13.91	21.45	26.82	29.43	28.9	25.31	19.14	11.02	1.53	-	-	-	-	-	-	-
Dec	-	-	-	-	-	-	-	0.03	9.03	16.55	22.06	25.02	25.06	22.19	16.75	9.28	0.31	-	-	-	-	-	-	-

for building elements in the Apache view: construction data describing the element's thermal properties, and adjacency data describing its thermal boundary conditions that is set automatically as a function of building geometry.

After assigning all the constructions assumed, the creation of room templates allows to manage data about room regulations, room conditions, systems, internal gains and air exchanges, and modify it easily when required. For each internal gain or system, it is possible to assign the respective schedule for gains or operation profiles.

The system specifications entered in Apache View are used for sizing central plant and calculating fuel consumption. The function *ASHRAE Loads Calculation* generates accurate building, room, and system loads for building design engineering and HVAC equipment sizing, based on the ASHRAE Heat Balance Method.

3.1.1 ASHRAE Heat Balance Method

The Heat Balance Method calculates the time delay effects explicitly, with some basic assumptions like uniform surface temperatures. Conductive, convective, and radiative heat balance is calculated directly for each surface within a room. There are no arbitrarily set parameters.

Within the framework of the assumptions, the heat balance can be viewed as four distinct processes [31]:

1. Outdoor-face heat balance:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{k0} = 0 \tag{3.1}$$

Where:

- $q''_{\alpha sol}$ = absorbed direct and diffuse solar radiation flux (q/A), $W \cdot m^{-2}$
- q''_{LWR} = net long-wave radiation flux exchange with air and surroundings,$W \cdot m^{-2}$
- q''_{conv}= convective exchange flux with outdoor air, $W \cdot m^{-2}$
- q''_{k0} = conductive flux (q/A) into wall, $W \cdot m^{-2}$

All terms are positive for net flux to the face except q''_{k0}, which is traditionally taken to be positive from outdoors to inside the wall.

2. Wall conduction process

Cause heat balances on both sides of the element induce both the temperature and heat flux, the solution must deal with this simultaneous condition.

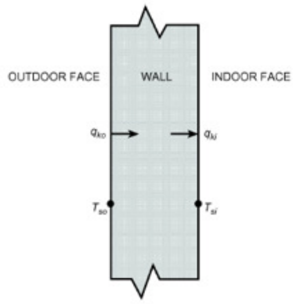


Figure 3.1: Schematic of wall conduction process [31]

3. Indoor-face heat balance

$$q''_{LWX} + q''_{SW} + q''_{LWS} - q''_{ki} + q''_{sol} + q''_{conv} = 0 \tag{3.2}$$

Where:

- q''_{LWX} = net long-wave radiant flux exchange between zone surfaces, $W \cdot m^{-2}$
- q''_{SW} = net short-wave radiation flux to surface from lights, $W \cdot m^{-2}$
- q''_{LWS}= long-wave radiation flux from equipment in zone, $W \cdot m^{-2}$
- q''_{ki}= conductive flux through wall, $W \cdot m^{-2}$
- q''_{sol} = transmitted solar radiative flux absorbed at surface, $W \cdot m^{-2}$
- q''_{conv}= convective heat flux to zone air, $W \cdot m^{-2}$

4. Air heat balance

$$q_{conv} + q_{CE} + q_{IV} - q_{sys} = 0 \tag{3.3}$$

Where:

- q_{conv} = convective heat transfer from surfaces, W
- q_{CE} = convective parts of internal loads, W
- q_{IV}= sensible load caused by infiltration and ventilation air, W
- q_{sys}= cheat transfer to/from HVAC system, W

3.1.2 Integration of HVAC, DHW and Renewable systems

ApacheSim provides a robust and uncomplicated system model that has been harmonized with the aim of providing a point of reference and common ground between alternative compliance methods. It allows to describe the characteristics of systems supplying the heating, ventilating and air conditioning requirements of rooms.

Solar shading, thermal mass, and self-shading of the building are taken into account to more accurately determine cooling loads for 'right-sizing' HVAC equipment. The main parameters for energy efficiency of HVAC systems are the coefficient of performance (COP) and energy efficiency ratio (EER), the higher the number, the more efficient the system is.

$$COP = \frac{\sum Q_i}{W_{net}} \ , \quad [W/W] \tag{3.4}$$

$$EER = \frac{\sum Q_i}{W_{net}} \ , \quad [BTU/Wh] \tag{3.5}$$

Where Q_i represents the power output, compared with W_{net}, that is the net energy supplied from external sources. The COP is dimensionless because the input power and output power are measured in Watt. The energy efficiency ration, EER, stands for a more common measurement for space cooling performance. The EER is usually specified under certain conditions of dry and wet bulb temperature, relative humidity and dew point. It is the ratio of output cooling energy (in BTU) to electrical input energy (in Watt-hour)

$$EER = COP \times 3.41 \tag{3.6}$$

Alternatively, the SEER and SCOP are a representative measurement of how the system behaves over a season where the outdoor temperature varies. They provide a comparison between systems more adjustable among different technologies under different climates. It is known that as the delta temperature goes down, the efficiency goes up, so the SEER is greater than the EER (typically by about 15% to 35%). These are the main variables to introduce in Apache systems to classify HVAC systems energy efficiency.

$$SCOP = \frac{Output\ heating\ energy\ over\ a\ season}{input\ electrical\ energy\ over\ the\ same\ season} \ , \quad [Wh/Wh] \tag{3.7}$$

$$SEER = \frac{Output\ cooling\ energy\ over\ a\ season}{input\ electrical\ energy\ over\ the\ same\ season} \ , \quad [BTU/Wh] \tag{3.8}$$

The effect of some common renewable technologies can be included in ApacheSim analysis. The available renewable systems in the software are Photovoltaic (PV) systems, wind generators, combined heat and power (CHP) and solar water heating systems. Taking into consideration the nature of the project and its limitations and objectives, the only renewable systems explored were photovoltaics and solar water heating.

A solar heating system is assumed by ApacheSim to consist of solar panels using propylene glycol as the heat transfer medium, linked to a heat exchanger that transfers the collected solar heat to a storage cylinder. The mains cold water supply is preheated in this cylinder before being fed into the DHW storage tank.

Data on solar panels expresses the performance of the device in terms of a conversion efficiency at ambient temperature, η_0, and two heat loss coefficients, a_1 and a_2. Values for η_0, a_1 and a_2 are available from solar panel manufacturers. The heat output of the device is written in terms of these coefficients by Equation 3.9.

$$Q_{thermal} = \eta_0 \cdot I - a_1(T - T_a) - a_2(T - T_a)^2 \tag{3.9}$$

Where:

- $Q_{thermal}$ is the heat output per unit panel area, $W \cdot m^{-2}$
- I is the incident solar irradiance (after allowing for shading and degradation), $W \cdot m^{-2}$.
- T is the panel temperature, K
- T_a is the outside air temperature, K

Regarding photovoltaics, ApachSim allows the characterization of a photovoltaic system supplying electrical power to the building. The main performance parameters includes the PV module nominal efficiency, η_0, which is the fraction of solar radiant power that is converted to useful electrical power at a standard temperature and solar irradiance. The Nominal cell temperature (NOCT) is calculated under standard test conditions – ambient air temperature 20°C and irradiance either 800 or 1000 $W \cdot m^{-2}$. The temperature coefficient for module efficiency, β, describes the rate at which the panel's conversion efficiency falls off with increasing cell temperature.

The conversion efficiency,η, at cell temperature T_c and outside temperature T_a can be given by Equation 3.10

$$\eta_{elect} = \eta_0 \cdot [1 - \beta (T_c - T_a)] \tag{3.10}$$

3.1.3 Thermal Comfort Evaluation

A principal purpose of Heating, Ventilation, and Air Conditioning (HVAC) is to provide conditions for human thermal comfort, defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation", see Figure 3.2 [31].

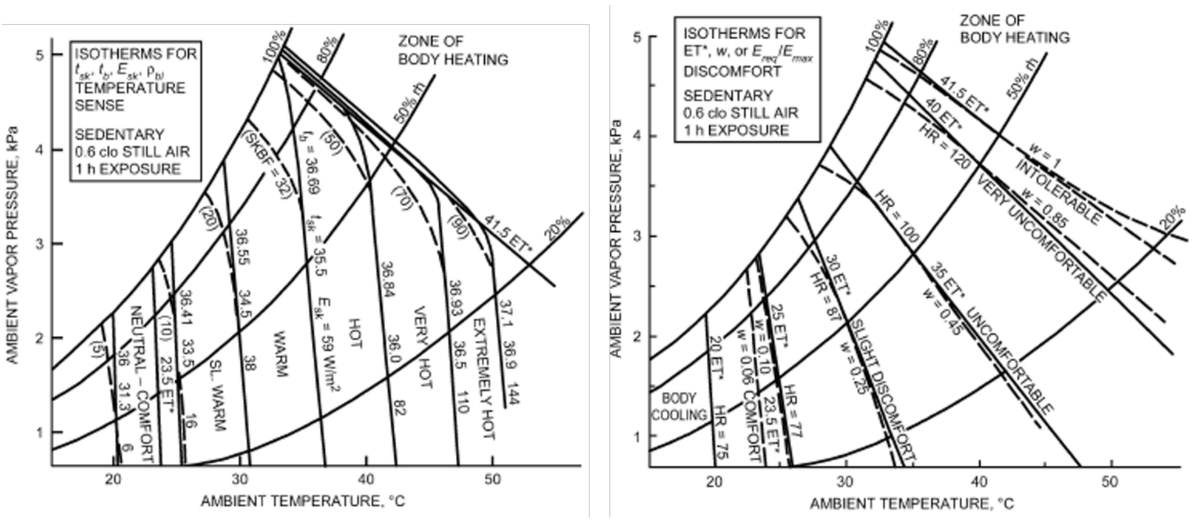


Figure 3.2: Effect of environmental conditions on physiological variables (left) and effect of thermal environment on discomfort (right) [31]

In order to evaluate the thermal comfort of the occupants, an index predicting comfort within the space, based on the following scale can be consulted in VistaPro application, Figure 3.2.

Table 3.2: Comfort Index

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Very Cold, Danger	Cold, Shivering	Cool, Unpleasant	Cool, Acceptable	slightly cool, Acceptable	Pleasant/cool, Comfortable	Pleasant, Comfortable	Pleasant/warm, Comfortable
9	**10**	**11**	**12**	**13**	**14**	**15**	
Slightly warm, Acceptable	Warm, acceptable	Warm, Unpleasant	Hot, Very uncomfortable	Very hot, Danger	Unoccupied	non-sedentary	

3.2 Auxiliary Resources

Besides IES VE software, other platforms were used to compensate IES VE limitations or expedite procedures and decision making processes.

3.2.1 SCE.ER Software

SCE.ER Software is a program of performance analysis of solar systems, through numerical simulation of energy balances over a reference year, and specially designed for the climatic and technical conditions of Portugal. It was developed by LNEG, the General-Direction of Energy and Geology, in the context of the Building Certification System Decree-law 118/2013 of 20 August. SCE.ER Software is prepared to be used in accounting for the contribution of renewable energy systems to the energy balance of buildings.

The simulations performed were mainly to compare solar heating systems and collect data about their solar fraction, productivity, collectors' yield, thermal losses and parasitic consumption.

3.2.2 Battery simulation

IES VE does not provide simulations with a PV system connected with an energy storage system. The battery simulation was performed separately, by treating the data given by IES dynamic simulations about the house electricity consumption and electricity production during a whole year, with a hourly time step. Manufactures usually give information about batteries round trip efficiency, energy density and cycle life. Notice that users are not penalized for partial cycles, for example two partial 50% cycles are equivalent to one full cycle.

The round trip efficiency can never be 100% because during the whole storage process there will be always inevitable energy losses. The first assumption made for this battery simulation was that the losses during charging would be the same as during discharging, meaning equivalent deficiencies during charging and discharging ($\eta_{charge} = \eta_{discharge}$).

$$Round\ trip\ efficiency = \frac{Energy\ recovered}{Energy\ input} \times 100 = \eta_{charge} \times \eta_{discharge}\ ,\ \ [\%] \tag{3.11}$$

To express the state of charge of the battery determined for each hour of the year, a pseudo-code is presented below, where ΔE means the energy balance in each time step, (the difference between the energy consumed and the energy produced), the variable $Storage$ indicates the capacity of the battery in use, $Min.capacity$ and $Max.capacity$ the minimum and maximum capacity of the battery. For convenience purpose, so it is easier to distinguish energy consumption and production, the energy consumption was considered positive and the generation negative.

---

if $\Delta E > 0$ **then**
  Storage= MIN(Min.capacity; Storage + $\frac{\Delta E}{\eta_{discharge}}$)
else if $\Delta E < 0$ **then**
  Storage= MAX(Max.capacity; Storage + $\Delta E \times \eta_{charge}$)
else
  Storage = Storage
end if

The energy purchased and exported to the grid is a function of energy deficit or energy overflow inside the battery. The variables E_{bought} and E_{sold} were created to collect the amount of energy exchanged with the grid, in each time step.

if Storage= Max.Capacity **then**
  $E_{sold} = \Delta E + Storage_{previously} - Max.Capacity$
else if Storage= Min.Capacity **then**
  $E_{bought} = \Delta E + Storage_{previously} - Min.Capacity$
else
  return
end if

Considering that the house is energy autonomous whenever it does not need to purchase electricity from the grid, its annual autonomy can be measured as

$$Autonomy = \frac{hours\ without\ energy\ deficit\ during\ a\ year}{total\ hours\ during\ a\ year} \times 100\ , \quad [\%] \tag{3.12}$$

3.3 Economical Parameters

Regarding economical evaluation parameters, it was used the levelized cost of energy (LCOE) to compare the costs of the generated energy, usually given in €$\cdot kW^{-1}$, the return of investment (ROI) to evaluate the efficiency of the initial investment and payback time, which refers to the amount of time it takes to recover the cost of an investment, calculated by comparison of the previous scenario expenses with the new one over time.

$$LCOE_{(n=lifetime)} = \frac{\sum_{y=1}^{n}(Investment\ Cost_y + O\&M\ Costs_y + Fuel\ expenditures_y)}{\sum_{y=1}^{n} Energy\ generated_y} \tag{3.13}$$

$$ROI = \frac{Annual\ savings}{Total\ investment} \times 100\ , \quad [\%] \tag{3.14}$$

$$Payback\ time = \frac{Total\ investment + O\&M}{Annual\ Savings}\ , \quad [years] \tag{3.15}$$

The heat losses by the external envelope during the heating season can be measured following Equation 3.16 [8]:

$$Q = 0,024 \times U \times A \times DD\ , \quad [kWh] \tag{3.16}$$

Where:

- U - Heat transfer coefficient / $W \cdot m^{-2} \cdot ^{\circ}C^{-1}$
- A - Area of the external envelope / m^2
- DD - Heating degree days [1], $^{\circ}C \cdot days$

[1] Heating degree days are a measure of how much (in degrees), and for how long (in days), the outside air temperature was below a certain level.

Using equation 3.16, an effective benefit of insulation, for the year n, can be calculated with Equation 3.17, that gives a hypothetical value of energy expenses saved if all the heat losses were compensated by a heating system.

$$Effective\ Benefit_{year\ n} = \sum_{n=0}^{n-1} \left(\frac{Q_{in} - Q_f}{\eta} \times \frac{C_{el} \times (1+\beta)^n}{(1+\alpha)^n} \right) - C_i \tag{3.17}$$

Where:

- Q_i - heat losses before retrofit, / $W \cdot m^{-2} \cdot ^\circ C^{-1}$
- Q_f - heat losses after retrofit, / $W \cdot m^{-2} \cdot ^\circ C^{-1}$
- η - Nominal efficiency of the heating system, considered 1 in this case.
- C_{el} - Cost of electricity for the year n=0.
- β - Annual rate of energy price growth, considered 4%.
- α - The interest rate, necessary to remit the capital to year zero, considered 3%.
- C_i- Investment cost.

For realistic pricing, it was used CYPE Prices Generator for rehabilitation [2], which includes a parametric system designed to include all typological, geographic and economic options that affect the final cost of the work, while integrating products from leading manufacturers, with all the options for each of them. For example, location, area of intervention, real estate market situation, degree of intervention, and difficulty of execution are conditions taken into account that can offer an approximation to the real price, including auxiliary materials and labor cost.

There are other conditions that can never be predicted a priory because they depend on particular relationships between the manufacturer and the client, such as discounts, forms of payment, loyalty, discounts for purchase volume, etc. Although the prices of the products of commercial houses are supplied by the manufacturer himself, this does not assume either a commitment to maintain its prices or a general distribution policy. It was carried out a personal contact with a manufacturer in order to estimate the total investment cost for the HVAC systems, PV installation and Solar collectors.

[2]Available at: http://www.geradordeprecos.info/reabilitacao/

Chapter 4

Case Study

This dissertation explores the rehabilitation of a living house with the goal of optimizing its energy efficiency. The building under study is a semi-detached house (2 inhabitants, currently), situated in the city of Porto, in the north region of Portugal, latitude of 41.10ºN and longitude of 8.36ºW and 118m of altitude (Figure 4.1).

Figure 4.1: Building under study and its orientation

The number of degree-days, heating season duration, the average temperatures and the corresponding climate zones have been extracted from LNEG Climas SCSE software, which integrates the Building Certification System, Decree-law 118/2013 of 20 August. and the outcomes are presented in Table 4.1 .

The house has approximately 170m^2 of gross area and its main facade is towards south-west. The building has a basement and 2 upper floors, the 3 storeys are connected by staircases. The net floor area of each floor is approximately 47 m^2 and its average height is 2.95 m. The glazing area represents 10.8% of the above-grade wall area (m^2).

The first challenge of this dissertation was to model the house and the adjacent building, taking the physical house plan as a starting point (Appendix B). The modeling was done using Model IT from IES VE software, see Figure 4.2.

Table 4.1: Weather conditions for the building location

	Residence Coronel Almeida Valente Street
Climate zones (NUTS III)	I1 & V2
Degree-days	1288.4 °C· days
Average winter external temperature	9.7 °C
Average summer external temperature	20.9 °C
Heating season duration	6.2 months

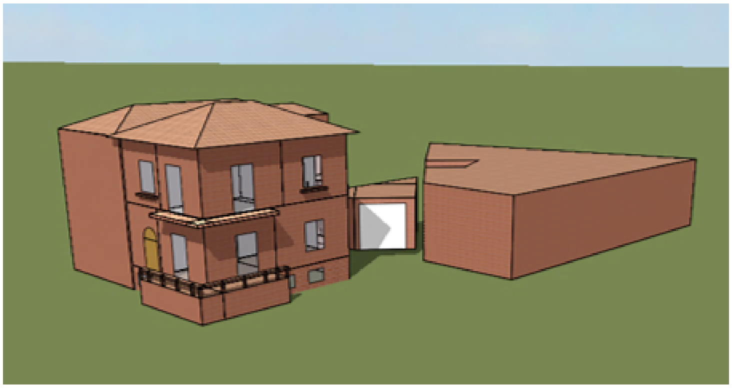


Figure 4.2: Model of the house in Model IT

4.1 Thermal Envelope

There was the need of characterizing the constructions of the thermal envelope to characterize the heat exchanges between the building and its surroundings. The thermal envelope was defined as the set of external walls, adjacent walls, roof, windows, doors and ground floor.

The house was built in a period between 1950 and 1952, having some old construction methods in its essence and no reported information available about the construction's materials. All the constructions were assumed based on personal visits to the house and the ITE 50 information.

The house has standard single glazed windows (U = 5.4 $W \cdot m^{-2} \cdot^{\circ} C^{-1}$) with metal frames in the basement, but the rest of the windows in the second and third storeys were already replaced by double glazed windows (U = 2.3 $W \cdot m^{-2} \cdot^{\circ} C^{-1}$) with PVC frame. The tilted roof has a light slab of normal concrete blocks, without insulation (3.00 $W \cdot m^{-2} \cdot^{\circ} C^{-1}$). [1] The value for the basement floor in contact with the ground was assumed accordingly to recommendation in REH (0.80 $W \cdot m^{-2} \cdot^{\circ} C^{-1}$).(The external walls are built in granite with no thermal insulation (U = 3.16 $W \cdot m^{-2} \cdot^{\circ} C^{-1}$). The assumed constructions can be found in Appendix C.

As it is possible to notice in Table 4.2, the values are far from the desirable values of U, which means that the thermal envelope has a low resistance to the energy flux between indoor and outdoor, promoting low indoor temperatures during winter and high temperatures during the summer.

[1] Values from ITE 50

Table 4.2: Heat transfer coefficient for the building thermal envelope and the reference heat transfer coefficient from Portuguese regulations.

Construction	Heat transfer coefficient (U) / $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$	Reference heat transfer coefficient (U_{ref}) / $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$
External Wall	3.16	0.50
Wall in contact with the adjacent building	2.46	0.80
Roof	3.00	0.40
Floor in contact with the ground	0.80	0.5
Double glazed windows with PVC frame	2.23	2.80
Single glazed windows with metal frame	5.40	2.80
Main Door	5.40	2.80

The ventilation rate for habitations should be between the target range of 0.4 and 0.6 air changes per hour. The air renewal rate of the house was determined following thermal parameters presented in the Order nº 15793-K/2013, and taking into account the building framing, air intake openings in the envelope and the energy balance. In natural Ventilation the airflow is due to wind and dynamism through cracks in the building envelope or purposely installed openings [31]. The figured value for natural ventilation of this building was 0.48 air changes per hour, calculated using the average temperature of the coldest month and the annual mean wind speed. That air renewal rate was assigned to each room of the building in the software.

4.2 Energy Consumption

The current energy consumption of the house is a result of the energy consumed by the installed equipment, lighting and domestic hot water (DHW) demand. There are no heating or cooling systems in the existing house, only a small wood burning stove, not in use due to its small efficiency.

According to Portuguese Regulation for residential buildings, the daily consumption of DHW in the residential sector is, in average, 40 litres per person per day and the consume profile assumed was the one recommended by the general administration of energy and geology, Figure 4.3

Considering two inhabitants, and an electric water heater as the system to heat up the water from 15ºC (average water supply temperature) to 50ºC (the desired temperature for consumption), it is expected a daily energy demand of 3.26 $kWh \cdot day^{-1}$, 11.72 $MJ \cdot day^{-1}$.

In order to simulate the equipment's and lights' consume, there was a personal visit to the house. For lighting, it was assumed a maximum of 60 W of power per room and 20 W in the halls. For equipment, an average value of 9 $W \cdot m^{-2}$ was assumed for the greater part of the rooms. Only in the kitchen, where the majority of the equipment is placed, and in the room which is currently used as a music studio, were considered 30 $W \cdot m^{-2}$. All the equipment and lights are powered by electricity from the grid. These maximum values of power associated with the rooms are combined with usage patterns that were decided accordingly to inhabitants' information. Those profiles for lighting, equipment and occupation can be consulted in Appendix D.

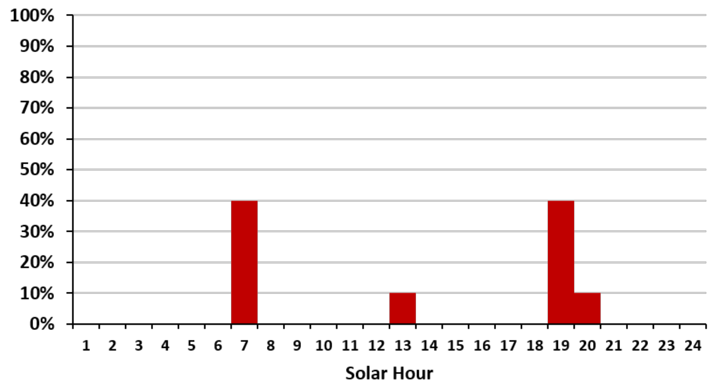


Figure 4.3: Daily DHW Consume profile

Internal heat gain is the sensible and latent heat emitted within an internal space from any source and results in an increase in the temperature and humidity within the space [31]. Along with the internal gains related with lights and equipment, the occupancy gain considered was a maximum sensible gain of 75 W and 55 W per person, respectively.

To align the real electricity consumption of the house and the consumption assumed in the software, the electricity bills from 23 of October 2019 until 8 of March 2019 were collected Table 4.3

Table 4.3: The electricity consumed by the house, during the period 23/10/18 until 8/03/19.

From	Until	Nº of days	Real Consume / kWh
23/10/18	**07/12/18**	46	405
08/12/18	**7/01/19**	31	269
08/01/19	**07/02/19**	31	227
08/02/19	**8/03/19**	28	212
Total		136	1113

The total amount of energy spent during that period (136 days) was 1.113 MWh. Using that information, it can be predicted an average daily electricity consumption of 8.18 $kWh \cdot day^{-1}$ and consequently an annual amount of 2.987 $MWh \cdot year^{-1}$. Since the time frame chosen was the winter season, it is expected to be an overestimated value, and sufficient for all the inhabitants' needs during the whole year.

All the considerations related to the house behavior were applied in IES VE software. The resulting energy consumption matched the values expected from the electricity consumption data, differing only by 1.5%. The annual consumption outcome from the software was 3.032 $MWh \cdot year^{-1}$, with the distribution represented in Figure 4.4

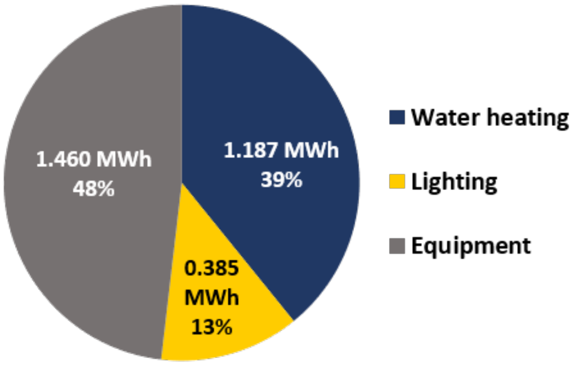


Figure 4.4: Annual distribution of energy consumption by type of end use, for the house under study.

4.3 Heating and cooling needs

One of the objectives of this project is to provide thermal comfort inside the house. The reference comfort conditions, mentioned in Chapter 2, are a minimum air temperature of 20 °C for the heating season and a maximum air temperature of 25 °C for the cooling season.

Taking, as an example, the bedroom on the upper floor, and the living room on the ground floor, it is possible to evidence the influence of poor thermal insulation in the room temperature.

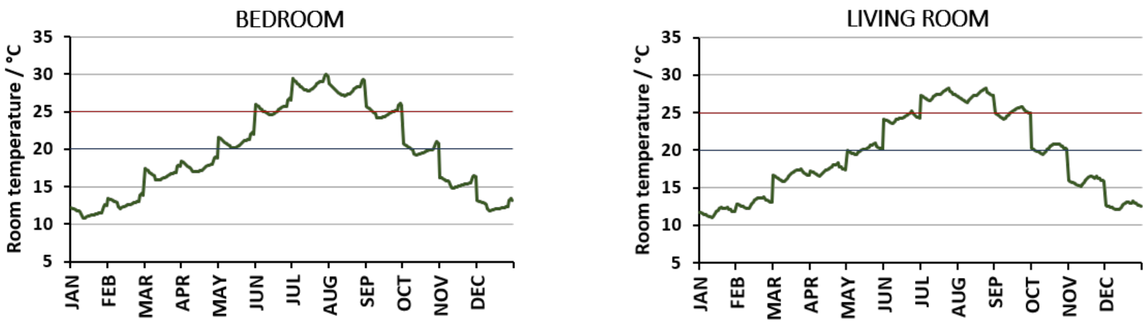


Figure 4.5: Average temperature during a day for each month in the bedroom and living room

In fact, the thermal zones spend, on average, 24% of the hours under occupation above 25 °C and 55% under 20 °C degrees. To counter this situation, a system for cooling and heating shall be installed in some parts of the house with current use, Table 4.4

In order to compare the thermal envelope performance before and after the retrofit, the hypothetical loads of boilers and chillers, used as acclimatization systems to keep the rooms temperatures between 20 °C an 25 °C are presented in Figure 4.6

Figure 4.6 evidences one of the first problems that applying an HVAC system implies in terms of energy consumption. The boilers' loads are way higher than the chillers' ones, which means that larger energy demand is required during the winter season. This fact is an obstacle for the use of the sun as an energy resource because its potential is higher during the summer.

Table 4.4: Thermal zones and their heating and cooling needs.

Storey	House space ID	Net Area (m^2)	Heating	Cooling
1	001 -1-Classroom	31	x	x
1	002 -1-Hall	10.5	-	-
1	003 -1-Storage Room	5.3	-	-
2	004 0-Kitchen	5.7	x	x
2	005 0-Dinner Room	15.0	x	x
2	006 0-Hall	14.4	-	-
2	007 0-Living Room	12.3	x	x
2	008 0-WC	1.0	-	-
3	009 1-Bathroom	6.9	x	-
3	010 1-Bedroom	11.4	x	x
3	011 1-Hall	7.7	-	-
3	012 1-Dressing room	12.6	x	x
3	013 1-Music studio	8.1	x	x

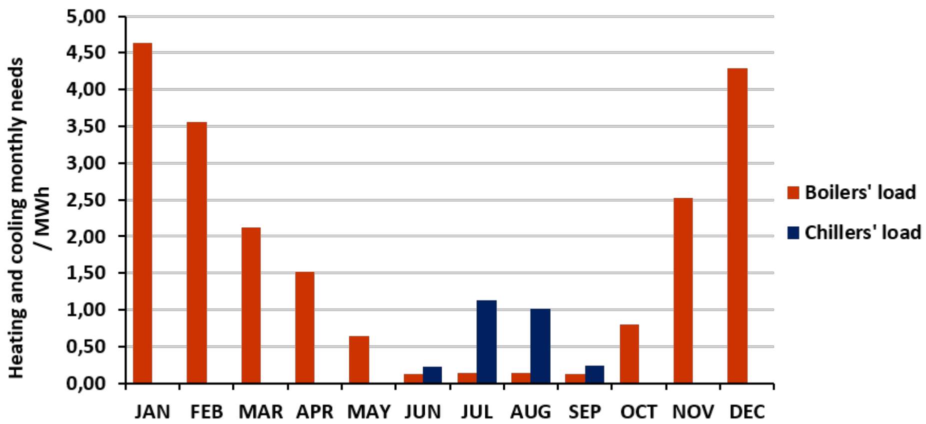


Figure 4.6: Monthly boilers' and chillers' loads for heating and cooling the thermal zones to the desired reference comfort conditions.

From the ASHRAE report of the case study, the heating loads are 174 $W \cdot m^{-2}$, the total room plant load is 13.2 kW and the total central plant load is 17.9 KW. The cooling loads are 57 $W \cdot m^{-2}$ with a total room plant load of 6.3 KW and total central plant load of 5.8 KW. Therefore a retrofit of the thermal envelope is essential in order to promote lower losses of heat to the surroundings and consequently decrease the heating loads of the building, that are at present extremely high.

Chapter 5

Results and Discussion

Since this rehabilitation project aims a long lifetime for the building, the suggested solutions will take into account a possible increase in the number of inhabitants. The average household size in Portugal was 2.5 inhabitants in 2018 [32], therefore, the general house occupation and DHW demand will count with 3 inhabitants. Moreover, the so-called dressing room will be treated as a second bedroom in terms of internal gains and energy consumption.

5.1 Passive solutions

5.1.1 Building retrofit

The first intervention in the building discussed was the improvement of the thermal resistance of the envelope and consequently bettering the retention of the heat inside the building, which implies a decrease in its heating loads.

To understand the impact of different interventions in the thermal behavior of the house, diverse simulations were done, where various parts of the thermal envelope were replaced by others with U_{ref} values, Table 5.1.

Table 5.1: Impact in the heating and cooling needs of diverse types of intervention in the thermal envelope

Inervention	U	U_{ref}	**Impact in boilers' loads / %**	**Impact in chillers' loads / %**
Insulation of the external wall	3.16	0.50	-51.82	-17.46
Insulation of the wall in contact with the adjacent building	2.46	0.80	-0.96	+0.44
Insulation of the roof space	3.00	0.40	-11.33	-22.09
Insulation of the floor in contact to the ground	0.80	0.50	-2.21	-2.23
Replacement of doors and single glazed windows for double glazed ones	5.4	2.8	-0.04	-2.75

By analyzing Table 5.1, it was decided to insulate only the external wall and the roof, the rest of the interventions were considered not impactful enough for the investment they may require.

There are three decisions to be taken, concerning the insulation of the external wall and roof space:

- The insulator material;

- The insulator thickness;
- The technique for the insulation application.

Two of the tree main trends for façade insulation systems, referred in Figure 2.2, were compared - ETICS and internal insulation. Ventilated façade system is a complex and old fashion technique to apply in an existing building, which would lead to a non competitive investment cost due to its complicated application, therefore, it was not studied.

For each system, different insulation materials were compared by using a construction price generator, available for the portuguese buildings' features [1]. As a starting point for comparison, the thickness of each insulator was chosen so that the heat transfer coefficient, (U), of the external wall would be the same or lower than $U_{ref} = 0.50\ W \cdot m^{-2} \cdot ^{\circ}C^{-1}$.

Table 5.2: Comparison in terms of cost of effectiveness for different materials and types of applications.

System	Material	Thermal conductivity, λ $W \cdot m^{-1} \cdot ^{\circ}C^{-1}$	thickness / m	U for the insulated external wall $W \cdot m^{-2} \cdot ^{\circ}C^{-1}$	Cost / € $\cdot m^{-2}$
ETICS	ICB	0.040	0.070	0.400	112.08
	PF	0.021	0.040	0.446	93.52
	SW	0.036	0.060	0.499	77.37
	GW	0.034	0.060	0.475	68.67
	XPS	0.034	0.060	0.475	65.39
	EPS	0.037	0.070	0.448	55.92
	EPS with graphite	0.032	0.060	0.452	55.56
Internal Insulation	GW	0.034	0.060	0.475	59.29
	SW	0.032	0.060	0.452	39.87
	SW	0.036	0.065	0.466	34.73

The most competitive materials for each technique, (EPS with graphite for ETICS and SW for internal insulation) were then set side by side to study their effective benefit [2], according to Equation 3.17. The main objective was to find out the optimal thickness of each material, that would promote the best effective benefit at long term (5, 10, and 15 years).

Figures 5.1 and 5.2 represents the analyses of thickness's influence in the investment cost and the annual savings in energy expenses. The optimal thickness for each year, in terms of effective benefit, is highlighted.

For ETICs the most favorable thickness was considered to be 8 *cm* of EPS with graphite and 8.5 *cm* of SW for internal insulation. Although internal insulation indicates a lower cost per square meter in Table 5.2, the necessary area to insulate is bigger than in ETICs due to the need of avoiding thermal bridges, as illustrated in Figure 5.3. Therefore, the investment cost ends up similar for both techniques. Since the material thermal conductivity is lower in EPS with graphite than SW, the years' savings are

[1] The price generator also includes the price of labor and other necessary materials for the intervention

[2] It was only taken into account the heating season because the cooling season represents only 11% of the global annual energy needs.

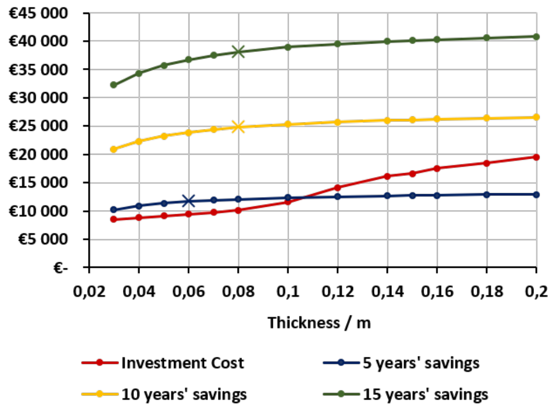


Figure 5.1: ETICs, EPS, λ = 0.032

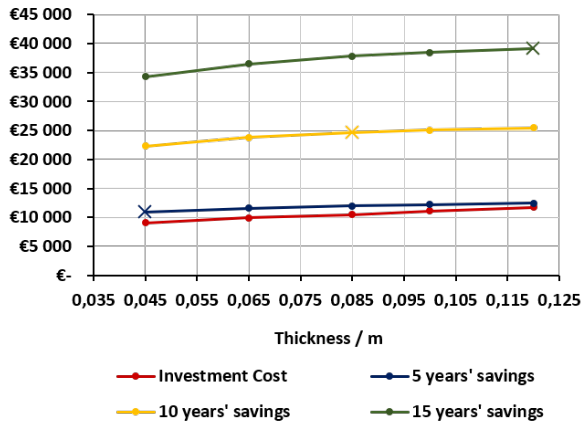


Figure 5.2: Internal insulation, SW, λ = 0.036

higher. As a consequence, ETICs presents better values of effective benefit than Internal insulation technique, as presented in Figure 5.3.

(a) ETICs system

(b) Internal insulation system

Figure 5.3: Differences between ETICs, (a), and internal insulation (b) in terms of insulation area needed (in red color), in the third storey.

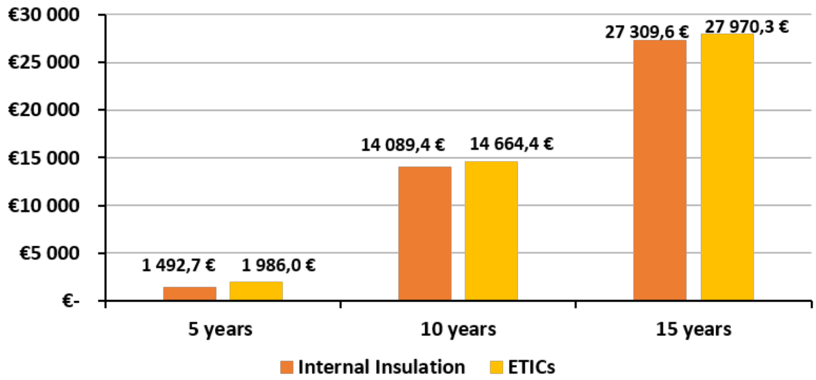


Figure 5.4: The effective benefit of materials' optimal thickness for each technique.

The final decision for external wall insulation was then to use ETICs technique, with EPS with graphite as insulator material and 8 *cm* of insulator thickness.

The roof space of the existing house is a non-living space, so that, among the two techniques presented in Figure 2.3, the insulation above the ceiling is more appropriated, a simpler intervention and cheaper. Therefore, a comparative study in terms of cost per square meter of different materials was done using the same price generator used before, presented in Table 5.3.

Table 5.3: Comparison in terms of cost of effectiveness for different materials applied above the ceiling

Material	**Thermal conductivity, λ** $W \cdot m^{-1} \cdot ^{\circ}C^{-1}$	**thickness** / m	**U for the insulated external wall** $W \cdot m^{-2} \cdot ^{\circ}C^{-1}$	**Cost** / € $\cdot m^{-2}$
EPS	0.033	0.070	0.400	17.48
SW	0.040	0.100	0.354	7.95
GW	0.042	0.100	0.370	7.60

Despite the fact EPS is expressively more expensive, its durability is much higher than SW or GW. The inorganic materials tend to degrade by cause of high humidity sensed in the roof space. Even requiring a higher investment, EPS tend to perform better insulation along time and consequently, it will be the chosen material. To decide the optimal thickness of EPS that should be applied, a study of effective benefit was performed, Figure 5.5. The optimal thickness chosen was 10 cm because its effective benefit, shown in Figure 5.6, was the maximum value obtained for 10 years and also its effective benefit was very close to the maximum value for 15 years (thickness of 14 cm) making an higher investment in larger thickness not worth it.

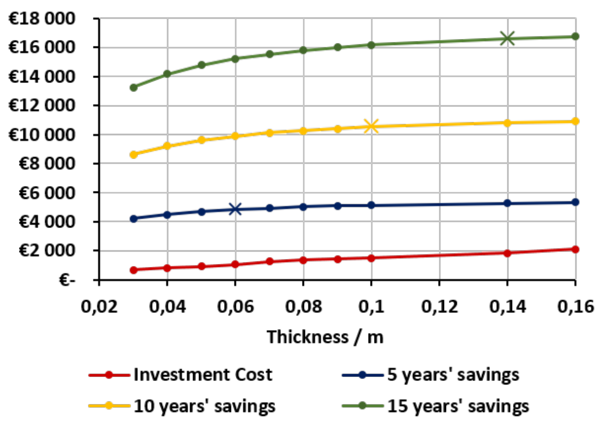


Figure 5.5: Investment cost and years' savings for different thicknesses of roof insulation with EPS, λ=0.33

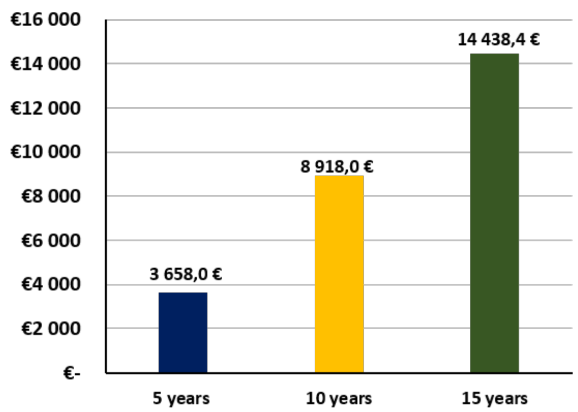


Figure 5.6: The effective benefit of 10 cm of EPS above the ceiling.

To sum up, the building retrofit suggested is:

- The addition of an insulation layer of EPS with graphite in the external wall from the exterior (ETICs), with 8 cm of thickness
- The application of 10 cm of EPS above the ceiling in the roof space.

The following Table 5.4 presents the posterior values of the heat transfer coefficient of the thermal envelope

Table 5.4: Heat transfer coefficient for the building thermal envelope, after retrofit.

Construction	**Heat transfer coefficient** (U) / $W \cdot m^{-1} \cdot ^{\circ}C^{-1}$.
External Wall	0.352
Roof	0.298
Floor in contact with the ground	0.80
Double glazed windows with PVC frame	2.23
Single glazed windows with metal frame	5.40
Main Door	5.70

The impact of these interventions was simulated in IES VE, and the reductions of heating and cooling needs are shown in Figure 5.7.

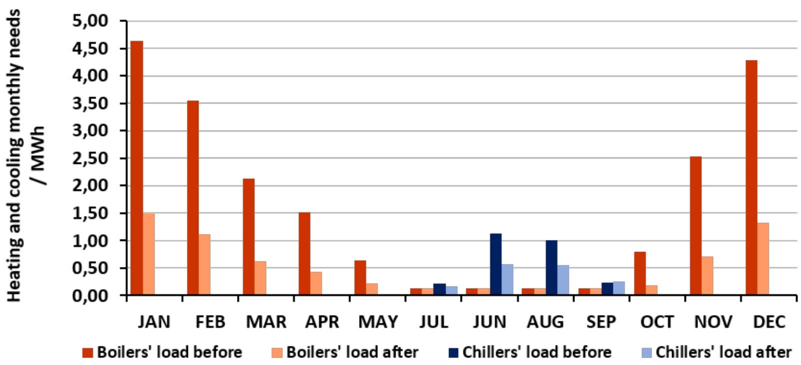


Figure 5.7: Heating and cooling needs before and after the proposed retrofit

The proposed insulation of the thermal envelope enables a reduction of 65% of the total energy needs for heating and cooling the thermal zones. The boilers' load decreases from 20.60 $MWh \cdot year^{-1}$ to 6.62 $MWh \cdot year^{-1}$ and the chillers' load from 2.61 $MWh \cdot year^{-1}$ to 1.53 $MWh \cdot year^{-1}$.

5.1.2 Passive Cooling

As a consequence of insulation, indoor temperatures' fluctuation tends to decrease with the improvement of the thermal resistance of the building. It is also expected an overall increase of rooms' temperatures, as a result of higher heat retention of the internal gains, Figure 5.8.

Passive cooling is a measure applied that tends to improve the indoor thermal comfort by controlling heat gains or by dissipating heat with low or no energy consumption. The indoor temperature of the house, when insulated, sometimes reached values above the outdoor temperature. Due to the high inertia of the

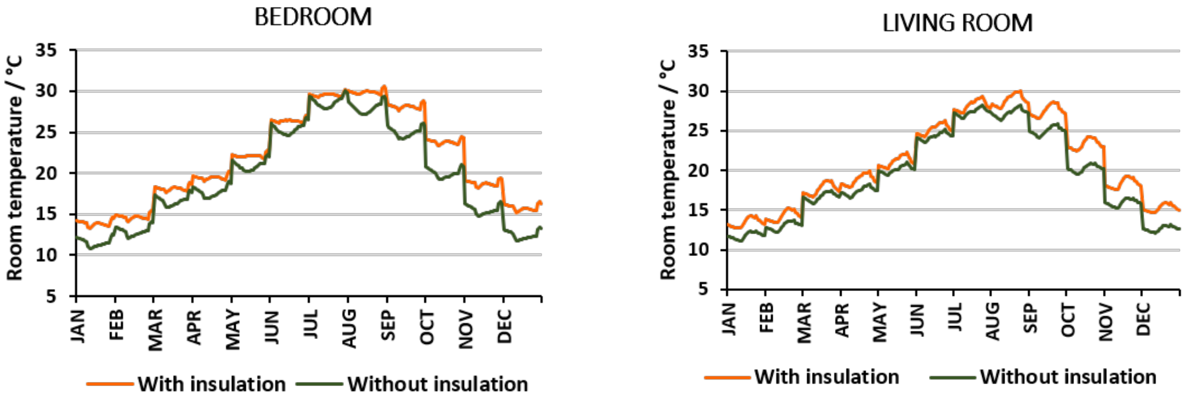


Figure 5.8: Average temperature during a day for each month, in the bedroom and living room, before and after the building retrofit

thermal envelope, it takes a lot of time to dissipate that heat. To counter that fact, the behavioral action of opening the windows was taken into account.

In every open-able window, it was assigned a function that opens 20% of the glazed area in a certain house space if its room temperature is above $25°C$ and the outdoor temperature is bellow $23°C$. Thus, the air flux from outdoor operates as an efficient cooler, as shown in Figure 5.9.

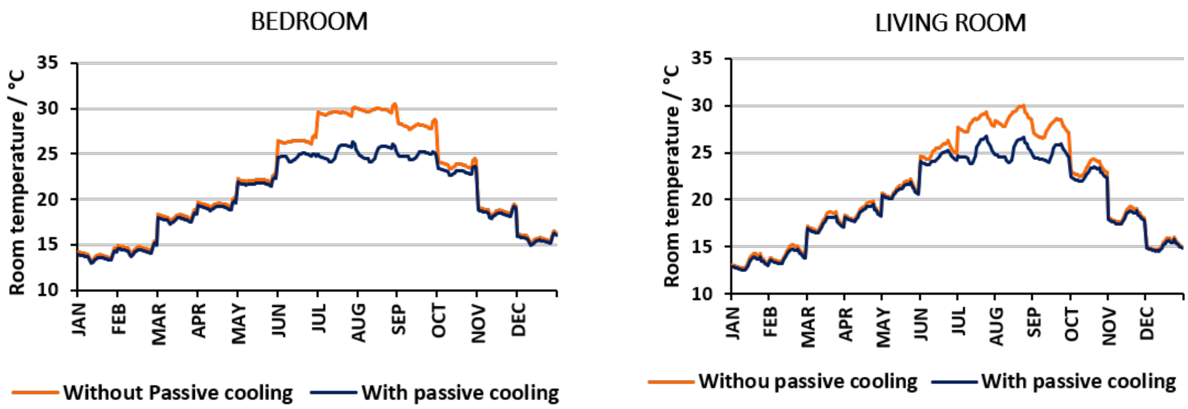


Figure 5.9: Average temperature during a day for each month in the bedroom and living room, with and without passive cooling applied.

This assumption has a direct impact on the thermal comfort of the inhabitants, reducing more than 20% of the time above the maximum comfort temperature ($25°C$) in all the thermal zones, as represented in Figure 5.10.

From the ASHRAE report for the passive solutions applied, the new heating loads are 52 $W \cdot m^{-2}$, the total room plant load is 4.6 kW and the total central plant load is 5.1 kW. The new cooling loads are 39 $W \cdot m^{-2}$ with a total room plant load of 4.2 kW and total central plant load of 3.9 kW. These values are the base to determine the capacity needed for the air conditioning active solutions.

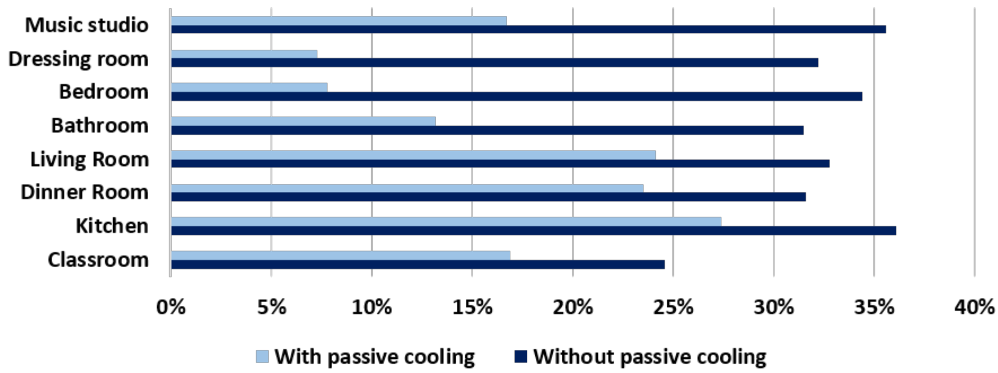


Figure 5.10: Percentage of hours under occupation with room temperatures above 25°C, with and without passive cooling applied

5.2 Active solutions

5.2.1 Solar thermal Collectors

As mentioned in the beginning of Chapter 5, the DHW demand for this project will count with 3 inhabitants in the house, which implies an increase in the expected DHW daily supply. For 3 inhabitants consuming 40 litres per person per day, the daily volume of 120 litres of hot water delivered requires an energy consumption of 4.88 kWh per day, 1.783 MWh per year. The consumption profile assumed is the same as the one presented in Figure 4.3.

An analysis into the market of thermal collectors was conducted in order to correlate different types of systems. For each type, the systems under study that presented better features (see Table 5.5) were chosen to perform a simulation in SCE.ER Software. It was taken into account the location and the orientation of the building.There was also a simulation with a standard model given by REH, which is the basis for comparison. The performance of each system is revealed in Table 5.6.

Table 5.5: Main characteristics of several types of solar collectors

System	Number of collectors	Effective area / m^2	Assigned water storage capacity / l	Optical yield / %	1^{st} order heat losses coefficient /$W \cdot m^{-2} \cdot ^{\circ} K^{-1}$	2^{nd} order heat losses coefficient /$W \cdot m^{-2} \cdot ^{\circ} K^{-2}$	Expected cost /€
Standard Model, REH	3	1.95	120	73.0	4.12	0.014	
Thermosyphon, flat collector	2	4.2	300	83.6	3.793	0.020	2034.17
Compact Thermosyphon, evacuated tube collectror	1	2.61	200	56.0	0.729	0.012	2224.27
Forced Circulation, flat collector	2	4.7	250	81.4	2.645	0.033	3161.27
Forced Circulation, evacuated tube collector	2	4.16	200	93.0	1.623	0.002	3387.04
Concentrated Solar Power, receiver RTS Plus 02	2	2.26	200	60.9%	1.84	0.000	3324.08

After analyzing the simulations, several aspects were considered to decide which system to apply. The thermosyphon system is the cheapest option to adopt, however the maintenance costs are expected to be higher, as mentioned in the Chapter 2, since the water storage is placed outside and the air leakage in

Table 5.6: Simulation results of several types of solar collectors

System	**Tilt**	**Azimuth**	**Solar fraction**	**Productivity**	$UR_{sol,th}$
	(° from horizontal)	(° clockwise from south)	/ %	$/ kWh \cdot m^{-2} \cdot year^{-1}$	/ %
Standard Model, REH	35°	0°	60	545	39
Thermosyphon, flat collector	35°	30°	85	360	34
Compact Thermosyphon, evacuated tube collector	35°	30°	62	420	34
Forced Circulation, flat collector	35°	30°	88	332	31
Forced Circulation, evacuated tube collector	35°	30°	85	366	33
Concentrated Solar Power, receiver RTS Plus 02	smart solar orientation	30°	71	434	49

the reservoir could lead to an accelerated decrease of productivity over time. Forced circulation was the system that performed the higher solar fraction, but the collectors' yield was inversely affected. If on the one hand, its large production of thermal energy allows higher solar exploitation, on the other hand, it is expected some overheating during summer times that implies the use of heat sinks to avoid collectors damage, and consequently, higher maintenance costs.

Besides the large investment cost, concentrated solar power system presents a good balance in terms of solar fraction and collectors' yield, overcoming the REH performance in both aspects. Furthermore, due to its architectonic integration versatility, it can be placed as a flowerbed pergola on the main façade entrance, as represented in Figure 5.11. This way, the roof surface does not need to be occupied by the collectors, and it counts as available area for PV installation.

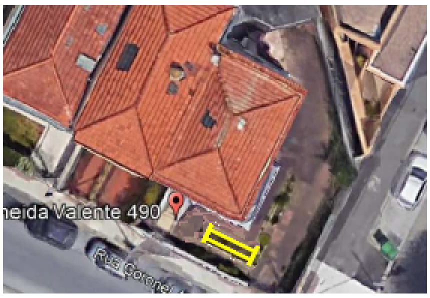
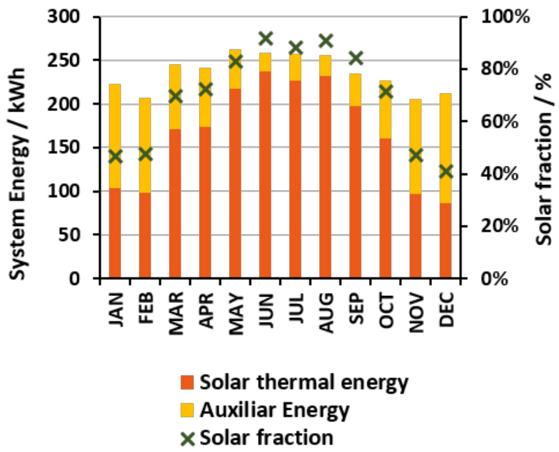


Figure 5.11: Suggested architectural integration of RTS Plus receivers

Regarding summertime, in this equipment there is no excess of temperature in the receivers. They automatically misalign themselves if they exceed the temperature for which they are configured. This is one of the great advantages, in addition to the integration, because the maintenance costs are practically non-existent.

For all the reasons mentioned, the CSP system is the one suggested for implementation. An energy report was asked to the company Sunaitec, and the annual energy balance predicted for the system is shown in Figures 5.12. In order to cover all the energy consumption related to DHW, the auxiliary annual energy load is 826 kWh per year. This energy demand can be covered by electricity, by adding a resistance inside the reservoir, or by integrating the space heating system capacity, by adding a heating coil inside the reservoir.



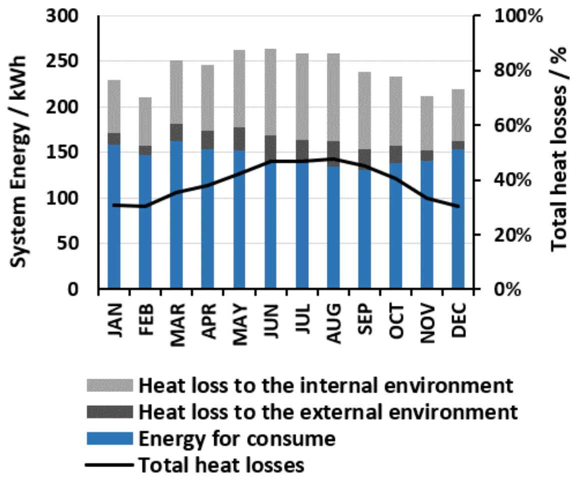


Figure 5.12: Energy balance of solar DHW system

5.2.2 Acclimatization

The objective of providing thermal comfort to the household implies the adoption of a system to adjust the temperature when it is outside the comfort zone, such systems are commonly referred to HVAC systems. The Portuguese legislation for the residential sector (REH) is increasingly more strict in terms of energy efficiency and the present requirements for different types of equipment are summarized in Appendix A.1.

After insulation of the house, the thermal loads for heating and cooling are expressively lower, see figure 5.7. Because of that, the dimensioning process of HVAC systems can be focused on equipment with relative low nominal heating and cooling capacity, only with the target of covering the 5.1 kW and 4.2kW as heating and cooling plant loads, respectively.

Several systems were taken into consideration, and the summary of the most competitive ones, in terms of energy efficiency[3], are presented in table 5.7.

As it is noticeable, the cost of VRV is higher than multi-split because it is a technology that allows avoiding second distributors. However, for this case, in which the length of the pipes between internal and external units is not representative, the higher investment cost seems to be not worth it (VRV is more commonly used in service buildings). The equipment heat pump mono-block seems to be more expensive than using several multi-splits to serve the heating and cooling needs. However, the fact that it also covers the auxiliary energy demand of DHW, brings higher energy savings over time. It would be also possible to combine multi-split units and a mono-block only for DHW, but then, the investment cost becomes higher than the heat pump monoblock, and the major efficiency difference would be felt during the summer, while the winter time is actually the bottleneck for the autonomous purpose.

The systems chosen for comparison in the software were:

[3]Clarification of the terms SCOP and SEER in Chapter 3.

Table 5.7: Main characteristics of several acclimatization systems

	Nominal heating capacity / kW	**Nominal cooling capacity** /kW	**SCOP**	**SEER**	**DHW Supply**	**Cost** /€
Heat Pump Mono-block	6.9	5.15	4.14	3.85	yes	4 220
VRV	8.4	12.1	4.6	8.1	-	3 765
Multi-split (x4 units)	8.6	6.8	4.19	8.03	-	1 975
Multi-split (x3 units)	5.2	6.8	4.60	8.58	-	1 675
Mono-block only for DHW	300L	-	4.30	-	yes	2 340
	Nominal heating capacity / kW	**Conversion efficiency** /%	**Thermal power to air** / kW	**Thermal power to water** /kW	**DHW Supply**	**Cost** /€
Pellets Boiler	4.7 to 12.2	92	2.6	9.5	yes	3997.5

1. A pellets' boiler, with a hot water reservoir and radiators inside the rooms for heating. For cooling, a multi-split with internal wall air conditioning units (which can also be used for heating, in case of lack of pellets or preference of the inhabitants)
2. A heat pump mono-block, with fan coils as internal units, and a radiator in the bathroom.

Both scenarios also support the remaining energy demand for DHW that solar collectors do not cover during winter time.

As mentioned before, there was the concern of guaranteeing that the heating and cooling capacity would always be enough to cover the values given by the ASHRAE report, when all rooms referenced in Table 4.4 are acclimatized on continuous. Nonetheless, a more realistic scenario was simulated in IES VE, based on the occupation profiles. The assumed profiles for HVAC system assign to the thermal zones can be consulted in Appendix D. With this measure, we try to avoid waste of energy when inhabitants are not using the rooms, without compromising their thermal comfort. When both systems were simulated in IES VE, the energy and electricity consumption were collected and presented in Figure 5.13.

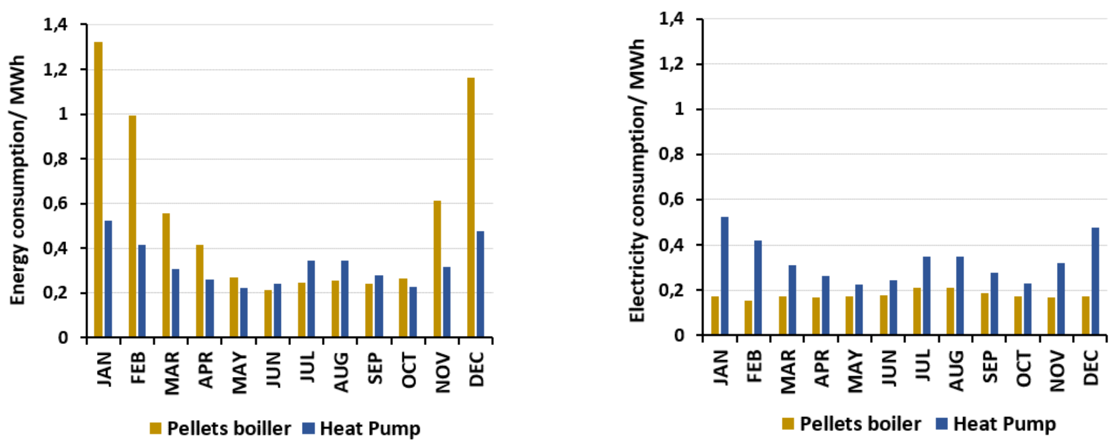


Figure 5.13: Annual energy (left) and electricity (right) consumption for both scenarios

Heat pump presents the lower value in terms of energy, however, the pellets boiler is the one that allows the lowest amount of electricity consumption. In terms of energy source, the boiler's scenario consumes 4.42 MWh per year of biomass and 2.13 MWh per year of electricity, while in the case of heat pump's scenario, all the energy is electrical dependent, totaling 3.97 MWh per year. It is possible to analyze the implications of that values in terms of energy related expenses, using the LCOE (considered 0.2246 €$\cdot kW^{-1}$ for electricity from the grid and 0.04 €$\cdot kW^{-1}$ for biomass). The expected annual expenses in electricity are lower for the scenario with the pellets' boiler (aprox. 655 € per year) than with the heat pump (aprox. 892 € per year).

Furthermore, despite the fact that biomass presents a higher energy demand, the chances of covering its low electricity consumption with solar energy from photovoltaics are higher. Both facts, the lower electricity dependence and the lower levelized cost of energy for pellets, point to the decision of proposing scenario 1 as acclimatization system for the envisioned autonomous house rehabilitation. The distribution of energy per type of end use for this scenario can be analyzed in Figure 5.14.

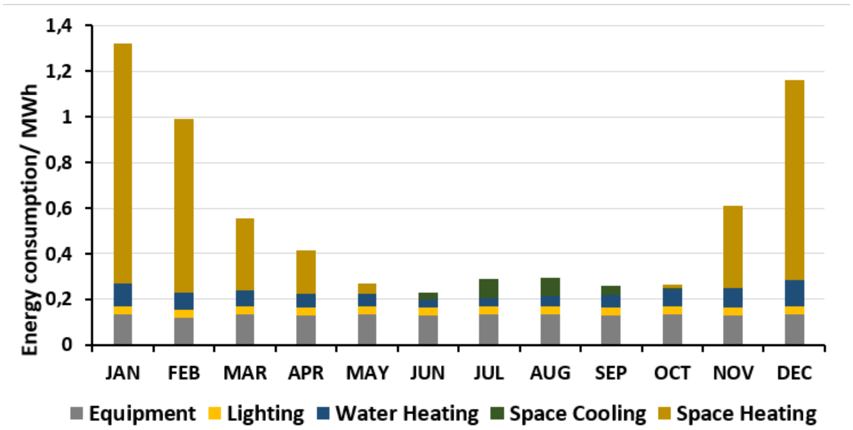


Figure 5.14: Monthly distribution of energy consumption by type of end use, with acclimatization applied.

5.2.3 Photovoltaics with storage system

Recalling the definition of energy autonomous house presented in Chapter 2, the designation "energy autonomous" refers to a house operating without resorting to non-renewable energy sources and without purchase of electricity from the grid. Having this in mind, the integration of photovoltaic panels is the most reliable solution for energy production on-site.

IES software allows an insulation analyses of the environment to identify the areas with better solar incidence, see Figure 5.15.

The higher potential of the two sides of the roof towards the south is outstanding. It is also visible the shading effect of the balconies in the walls under them. Since the case study is a house with 3 storeys, the roof area per gross area of the house is very limited. The application of solar panels vertically in the façades, would imply around 35% less solar incidence per square meter per year. Also, the installation and maintenance costs would be higher, since it is a more atypical integration and the areas with higher shading factor would have to be covered with dummy panels, only keeps the aesthetics of the façade uniform. As a consequence, there is a large restriction in terms of available area for PV installation. The high efficiency

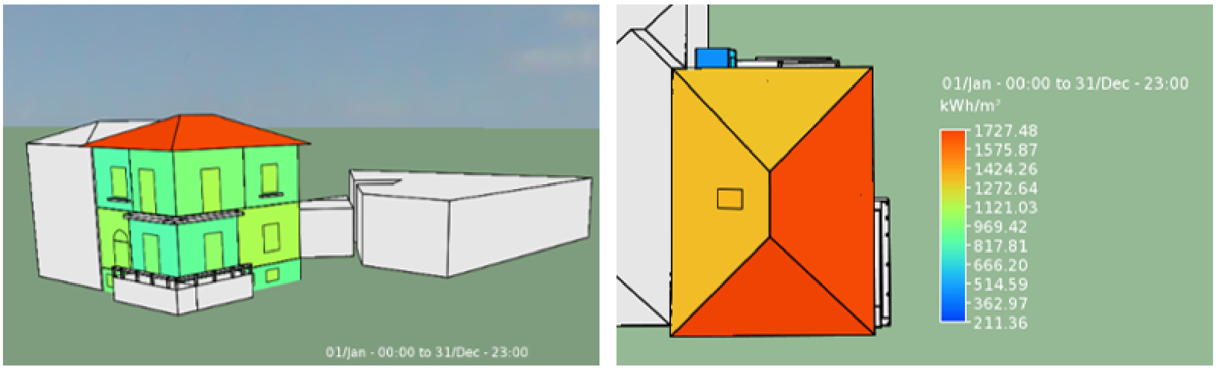


Figure 5.15: Annual solar incidence per square meter of the building surfaces.

of the photovoltaic modules must play an important role regarding the energy autonomy goal, therefore, all the PV modules considered have an efficiency superior to 16%, as presented in Table 5.8

Table 5.8: Different type of photovoltaic modules and their characteristics.

	Type of cells	**Module Efficiency /%**	**Dimension /mm**	**Wp**	**Expected Cost / € per module**
1	Monocrystalline silicon	21.1	1558 x 1046 x 46	335	619.33
2	Monocrystalline silicon	18.52	1640 x 992 x 35	300	150.12
3	Polycrystalline silicon	16.67	1640 x 992 x 35	270	146.00

The vision of this project is to convert a normal house into an energy autonomous one, and therefore the integration of a storage system is an important step to achieve total independence. Without a storage system, only the electricity generated hand in hand with the electricity consumption can be self consumed. By adding a battery, the excess of electricity produced in each moment can be stored, and used later in those periods when there is no PV generation (for example, during the night).

In order to evaluate the performance of a PV installation with a storage system, an analysis into the market was conducted and it was chosen the battery with higher capacity found (13.5 kWh), from Table 5.9, to simulate different scenarios.

Table 5.9: Features of different batteries present in the market for the residential sector

	Type of Battery	**Round-trip efficiency / %**	**Power /kW**	**Useful Capacity / kWh**	**Expected Cost / € per kWh**
1	lithium-ion	92.5	3.3	6.4	469
2	lithium-ion	90.0	5.0	13.5	437

There was a long path until finding the scenario that would provide 100% of autonomy. The several trials are summarized below:

1. Cover the south-east side of the roof with PV modules type 2.

2. Add PV modules type 2 also on the south-west roof side.
3. Substitute the PV modules for type 1, with higher efficiency, to see if it would be enough to achieve total independence.
4. Cover the 3 parts of the roof (SW, SE and W) with PV modules type 2.
5. Since the 100% autonomy was achieved in the previous scenario, this simulation replaced the modules type 2 for the type 3 (with lower efficiency, but also cheaper) to see if the total autonomy would be kept.

It is possible to visualize in Figure 5.16 the PV installations mentioned above. The first figure shows the installation for the first simulation. The figure in the middle shows the installation mentioned in simulation 2 and 3. Simulations 4 and 5 counted with the total PV area installed of 29 m^2, as displayed in the figure on the right. The results of the 5 different simulations performed are summarized in Table 5.10.

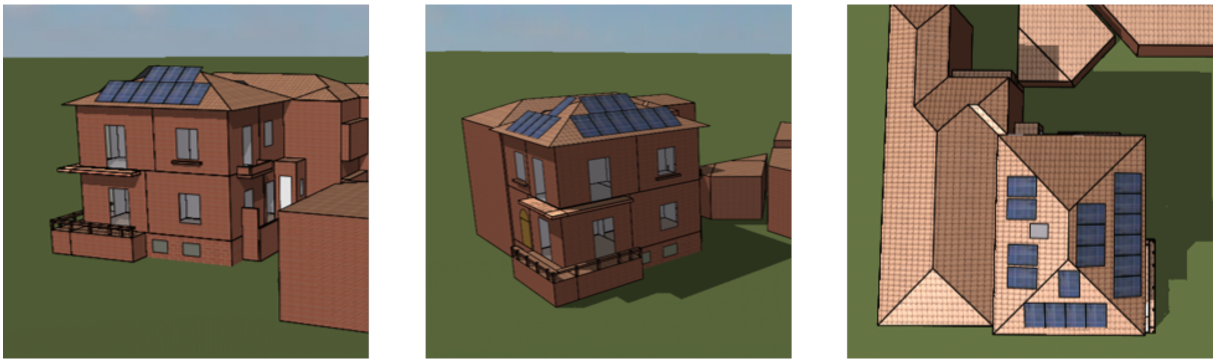


Figure 5.16: PV installation and arrangement in the 3 roof sides.

Table 5.10: Simulation results for different PV instalation

Simulation results	**1**	**2**	**3**	**4**	**5**
Total Electricity Consumption / kWh			2 138		
Electricity yield / kWh	4 026	4 565	6 253	**7 624**	6 862
Electricity export to grid / kWh	-1 854	-2 356	-4 006	**-5 374**	-4 614
Electricity purchase from grid / kWh	90.4	53.5	6.2	**0.00**	2.5
Self-Consumption, ele.	54%	48%	36%	**30%**	33%
Solar fraction, ele.	96%	98%	100%	**100%**	99%
Autonomy (h/h)	95%	97%	99%	**100%**	99%
Autonomy (d/d)	87%	92%	98%	**100%**	99%
Autonomy without storage (h/h)	37%	37%	427%	447%	44%

Simulation 4 was the scenario where 100% autonomy was achieved and the average state of charge of the battery can be consulted in A.4. As a consequence of high autonomy rate, the self-consumption of solar energy decreased significantly (30 %). As it was predictable, by increasing the PV power installed, the energy production turns out to be sufficient for the winter times, but oversized during the rest of the year. However, in terms of total energy balance, the excess of energy produced annually is almost the same produced by biomass during the winter, which implies an almost neutral energy balance of the house, see Figure 5.17 where negative values refer to production and the positives to consumption. Overall, each year the house would produce 1.06 MWh more of solar energy than its total consumption.

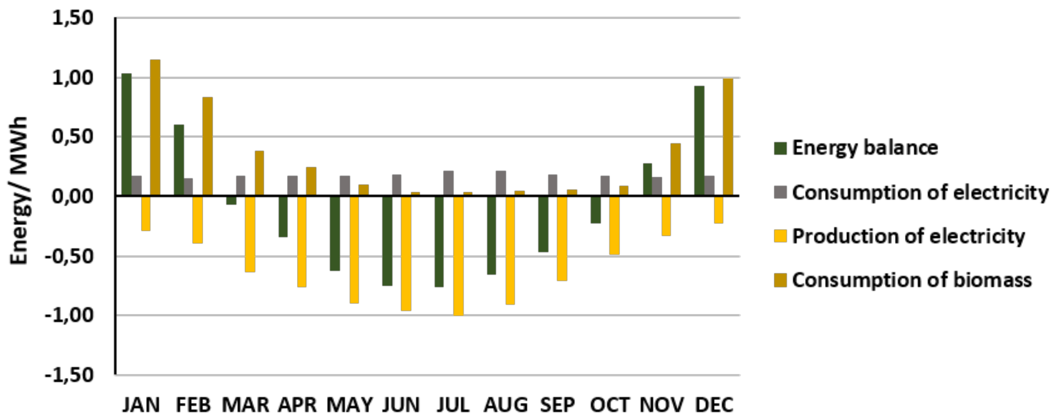


Figure 5.17: Annual production and consumption of energy

5.3 Energy rentability assessment

The total investment cost needed for the implementation of the passive and active solutions suggested, are presented in Table 5.11. There was the concern of trying to predict all the expenses related with these interventions, in terms of equipment and its installation, related materials, and labor costs. The investment in insulation retrofit was based in the prices generator mentioned before. The estimated budget for solar collectors, acclimatization, and photovoltaics installation were given by real companies that work in the field.

A total investment of almost 55 000 € expected is a considerable value for the purchasing power of the Portuguese society. However, there were two aspects that the solution proposed covered: firstly, the thermal comfort of the household, secondly the energy independence.

Starting with the evaluation of thermal comfort, the comfort index measured by IES VE software was applied for the 3 different stages of the project: the house without intervention (case study), the house with insulation applied and the house with active and passive solutions applied. The range between 6 to 8 in the comfort index means a comfortable temperature inside the room for the inhabitants, as can be consulted in Chapter 3. The percentage of hours under occupation with thermal comfort increased from an average of 12% to almost 100%, as demonstrated in Figure 5.18. This increase in thermal comfort is hard to quantify, but it brings an huge impact in terms of life quality for the occupants and an increment in the house value.

Table 5.11: The total investment cost for the rehabilitation project

			Total Investment	Taxes applied (+ 23 %)
Insulation	**External wall**	10 094 €	11 574 €	14 236 €
	Roof Space	1 480 €		
Solar Collectors System			4074 €	5 011 €
Acclimatization	**Heating**	6 523 €	10 598 €	13 035 €
	Cooling	4 075 €		
PV instalation			7 575 €	9 317 €
Battery			7 997 €	9 836 €
Total			**40 220 €**	**49 470 €**

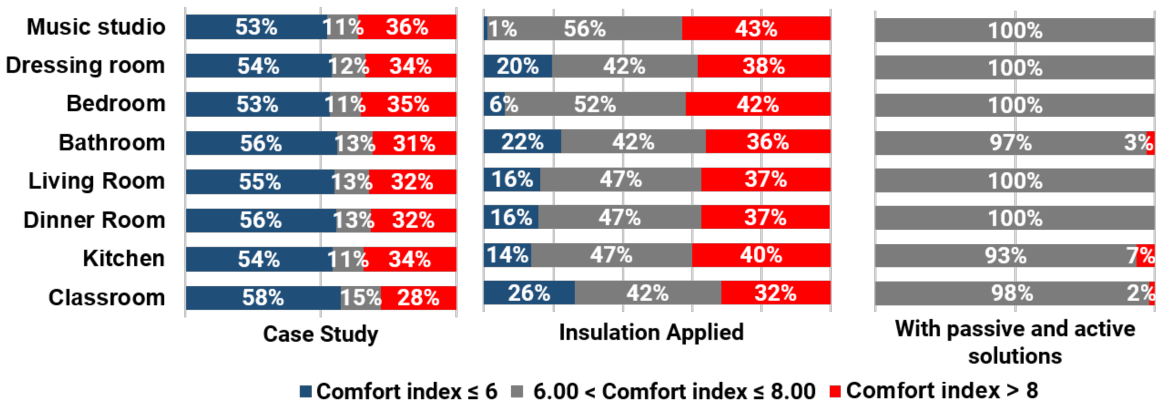


Figure 5.18: Percentage of hours under occupation in each range of comfort index, for all the thermal zones of the house, before and after interventions.

The other objective achieved was the energy independence. The rehabilitation proposed would allow a total self consumption of energy, having as resource biomass and the sun, both considered renewable. Furthermore, the energy not self-consumed could be exported to the grid generating annual revenues.

The payback time for the investment expected was calculated by comparing the performance of the house after and before rehabilitation, when the same levels of thermal comfort are provided.The house does not have any type of equipment for acclimatization. To make this comparison feasible, it was assumed that the heating and cooling loads, mentioned in Figure 4.6, necessary to keep indoor temperature between 20 and 25 degrees would be covered, respectively, by a natural gas boiler for heating, and for cooling by electricity from the grid. Also, the DHW demand would be covered by the existent electric water heater in the house.

In order to sum up the expected differences in terms of annual demand and annual expenses, related with energy supply, Figure 5.19 shows the annual energy demand for both cases and the expected cost for each source. The levelized cost of energy (LCOE) used for natural gas was 0.06€$\cdot$ kWh^{-1}, the average cost of electricity from the grid, mentioned in Chapter 2, was 0.2246 €$\cdot$ kWh^{-1}, and the exported one 0.05 €$\cdot$ kWh^{-1}. For the cost of biomass, in this case pellets, its minimum recommended heating value is 16.5MJ$\cdot kg^{-1}$, 4.58 kWh $\cdot kg^{-1}$. Its commercial price is about 135€ per ton during the cooling season, and 175 € per ton during the heating season. Also, for small quantities, around 15kg of pellets can be bought in every commercial areas for the average price of 3.5 €. That is, pellets cost can vary between 0.02 to 0.05 €$\cdot$ kWh^{-1}, and the LCOE considered was then 0.04 €$\cdot$ kWh^{-1}.

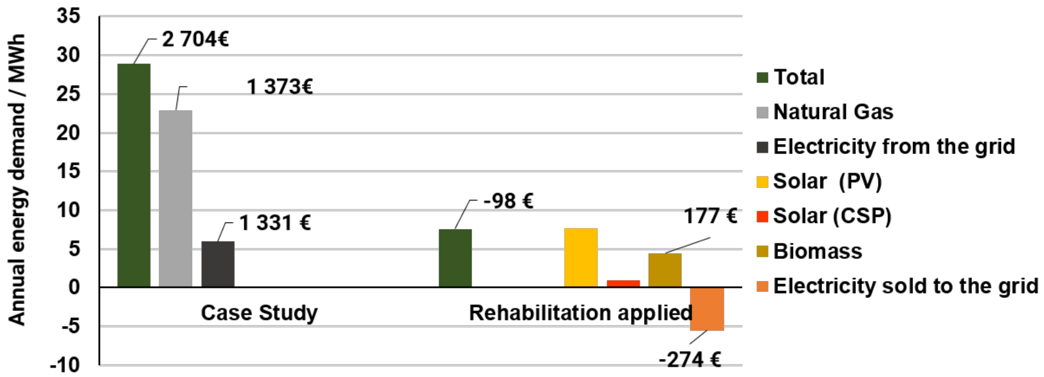


Figure 5.19: Comparative annual energy demand by type of source and respective annual cost.

All the equipment installed have an expected lifetime over 25 years, and warranty per at least 10 years, therefore, the operation and maintenance cost considered during the first 10 years were residual, around 0.001% of the investment cost. After the first ten years, that value was increased to 0.5% of the investment cost. When the life-time of some equipment were achieved (25 years) it was considered a new investment of 5% of the investment cost dedicated to repairs or purchase of new equipment, and similarly, 30 years after rehabilitation, it was considered a new investment of equivalent to 10% of the initial one.

Figure 5.20 shows the analysis over time of all the investments made in energy for both scenarios, without taking into consideration the inflation or the annual increment in the energy price imported and exported from the grid. Those values are difficult to predict in the long term, thus, the assumption here was that those factors would counterbalance the residual efficiency loss of the equipment.

For the case study scenario, the annual expenses expected were accumulated year by year. For the solution proposed, the initial investment was the starting value, the operation and maintenance expenditures were added year by year, and also the expenses with biomass and the revenues from the exported electricity. The concept of payback time considered was the one expressed in Equation 3.15.

The payback time expected with this simulation is 19 years, with an annual return of investment of 6%. At the end of 35 years it is expected to have an investment recovery of 175%. Nevertheless, it is still an investment with a lot of variables out of control, regarding the energy market, making this project risky and difficult to predict. Having in mind that the initial investment presented can be an obstacle for many Portuguese households, there is also the option of intervening in the house partially, with later complementary actions.

The solution presented previously was maximized for thermal comfort and total energy independence. However, there is the possibility of treating the project with lower ambition in terms of autonomy and

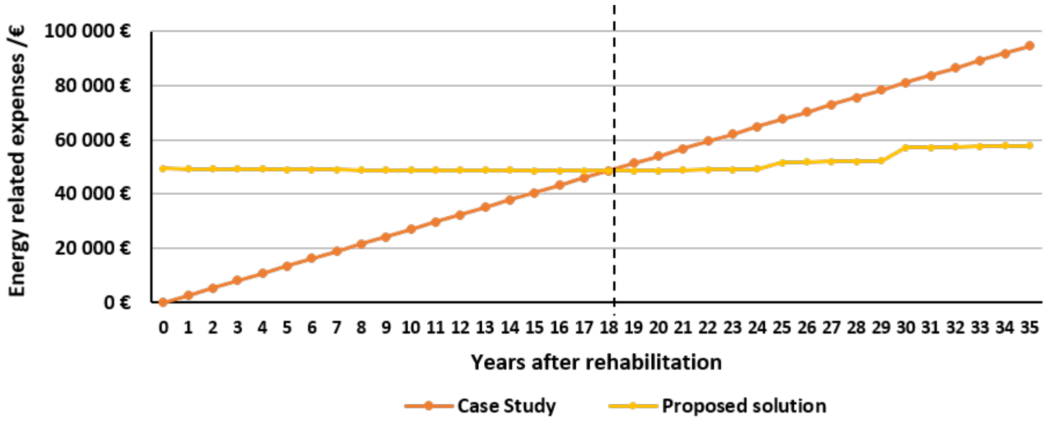


Figure 5.20: Determination of the payback time of the total investment cost.

comfort to achieve lower initial investment. Nevertheless, the following solution is not an alternative scenario but a primary stage of the results presented before.

The suggestion is to postpone the installation of an HVAC system for cooling, since the cooling needs after insulation are 1/5 of the heating ones, see Figure 5.7. The PV area and the battery capacity may also be partially installed, and all these options can be upgraded later.

Regarding photovoltaics, it is suggested to start installing them in the wider available roof surfaces. It is also recommended to line up the modules in rows when possible, because it decreases the installation complexity, which leads to lower installation costs. The optimized simulation performed is represented in Figure 5.21. It has 16 m^2 and a maximum power output registered of 2.91 kW.

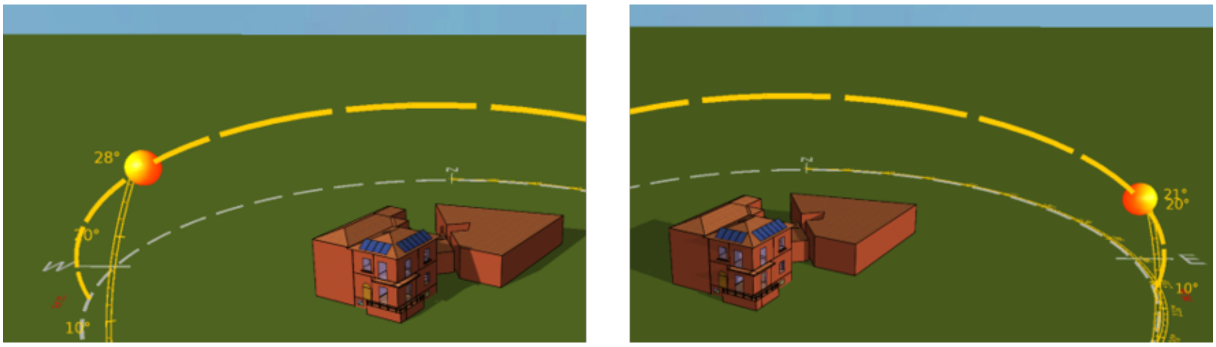


Figure 5.21: Suggested initial area of PV Panels and its solar incidence during the early morning (right) and late afternoon (left).

The panels are distributed on both roof sides that face south. This fact increases the daily time of solar incidence in the panels. During the morning, the South-East modules are the ones with higher productivity, while South-West modules are privileged during the afternoon. This PV distribution allows a direct supply of electricity from the panels during a longer period of daily time, which means that the storage need is lower than only covering one of the surfaces. The battery capacity for this case chosen was 7 kWh, and its main features are also presented in Table 2.2.

With this scenario, the electricity produced by photovoltaics is 4.50 MWh per year, of which 2.47 MWh are sold to the grid. This means that the self-consumption of the electricity generated is 45.12%

with a storage system and 19% without it. With battery integrated, the solar fraction also ramps up to 95.78%, from 43% without energy storage, which means that only 85.85 kWh per year is purchased from the grid. In terms of autonomy, this scenario indicates that 94.51% of the hours during a year can be self-sufficient, see. The daily autonomy of the house during the whole year is indicated in Table A.5. The partial investment suggested is summarized in Table 5.12

Table 5.12: The partial investment suggested

	Initial Investment	**Cost with taxes (+ 23 %)**
Insulation	11 574 €	14 236 €
Solar Collectors System	4 074 €	5 011 €
Heating System	6 523 €	8 003 €
PV installation	4 186 €	5 148 €
Battery	4 830 €	5 940 €
Total	**31 186 €**	**38 359 €**

This scenario saves 22% of the previous investment costs and its annual energy expenses are presented in Figure 5.22. The case study scenario for comparison also suffered some changes, the cooling loads were also removed to provide a fair comparison.

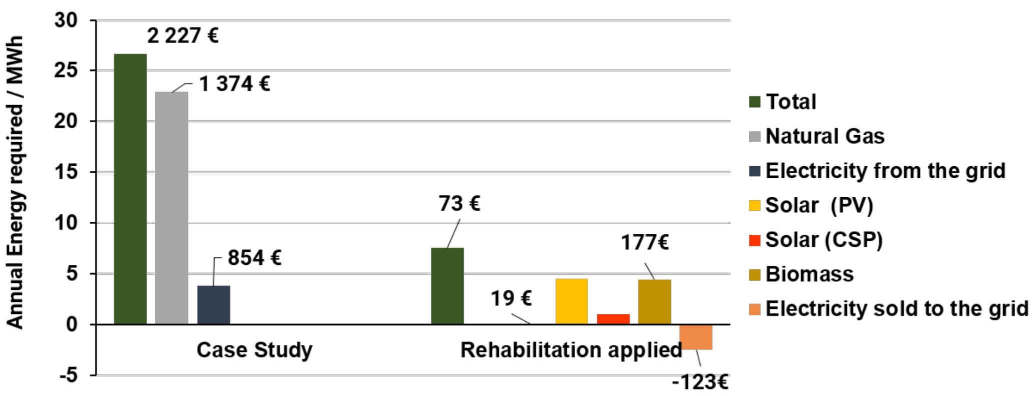


Figure 5.22: Energy demand by source and respective annual costs, for partial rehabilitation.

As it is noticeable, by comparing the case study and partial rehabilitation expenses, both providing the same conditions, it is predicted 2154.52 € of annual savings, which means that after the 6^{th} year, the recovery of the investment is enough to upgrade the house equipment and turn it 100% autonomous, with total thermal comfort. Consequently, between 6 and 10 years after the first interventions proposed, it is suggested to complement that investment, taking into account the purchasing power of the household and the evolution and maturity of the technology at that moment.

Chapter 6

Conclusion

A Portuguese house built in the ’50s has been submitted to a study which aimed a rehabilitation project for an autonomous energy house, which would also garantee a comfortable indoor environment for the occupants. Several dynamic simulations were performed in IES VE to achieve the thesis goal.

The suggested rehabilitation firstly tried to increase the house energy efficiency by adding insulation to the external wall and roof space. Those were the only impactful areas of the thermal envelope to intervene. For the external wall, ETICS technique showed higher effective benefit at long term than internal insulation. EPS with graphite is a good cost-effective insulator combined material, due to its low thermal conductivity. Since the roof space is an unoccupied area, the insulation was applied above the ceiling, with EPS material because of its higher durability when compared to SW or GW. The optimal insulation thickness for the conditions under study were 8 cm in the external wall and 10 cm in the roof space. These insulation options resulted in a thermal conductivity even lower than the reference values from REH.

Since the house insulation also retained the internal heat gains during the summer time, it was taken into consideration the behavioral action of opening partially the windows when the indoor temperature is higher than the comfort limit and the outdoor temperature is not. This simple aspect decreased the discomfort time during summer by almost 25%.

Regarding active solutions, the thermal energy demand was covered by a pellets boiler and concentrated solar power (CSP) installation, and the electricity needs were supplied by the integration of PV panels and a battery for energy storage. The system chosen for cooling space was a multi-split installed in the main rooms, with high energy efficiency and low investment cost compared with other equipment.

The preference for CSP collectors with smart solar orientation was highlighted among thermosyphon and forced circulation systems. Despite the higher initial investment, they offer good performance indicators, lower maintenance costs and a flexible architectural integration, important feature to free up the roof area for PV installation. The use of pellets fuel to cover the remaining heat demand for DHW and space heating enabled a stable and low house’s electrical dependence during the whole year. This was a critical aspect to make the photovoltaic power output be enough for electrical supply during the winter season.

The total autonomy was only achieved with 28.8 m^2 of PV panels with 18.52% module efficiency, covering three of the four sides of the tilted roof. The battery integration system was responsible for doubling the autonomy and the solar fraction of electricity. Although a system for energy storage requires a significant investment, it is crucial when the energy autonomy is desired.

The total investment cost for the presented rehabilitation project totaled almost 50 000€, with 6% of annual return of investment and 19 years of payback time. The higher initial investment and long return period can become an obstacle for turning this project a reality. Therefore, a phased investment was also suggested. The PV area, and battery capacity were decreased and there was no investment in a system for cooling space. Those measures decreased the first investment by 22%. This new scenario provided 95% of energy autonomy and 45% of electricity self-consumption. After 6 years it is expected that the savings in energy related expenses will be enough to cover the rest of the investment needed for achieving 100% of autonomy. At that point, the household has the freedom to choose what is the best timing for the second investment and probably will take some advantage of the technological advances in this field.

To conclude, when studying an existing building, there are some imposed limitations, such as the architecture, the building location, orientation, and current activity. The challenge of improving its energy efficiency is higher and will probably lead to higher investment costs. However, allied with an ambitious rehabilitation project comes a remarkable effect on the house's energy performance. In this case, the impact would be reflected in thermal comfort for the household, nonexistent before, and much lower dependence on the energy market.

Chapter 7

Assessment of the work done

7.1 Objectives Achieved

The use of a dynamic simulator to predict the thermal comfort and energy performance of the studied house, under different scenarios, were an effective way to achieve the desired thermal comfort and energy independence.

The results show that with an investment around 50 000€ it is possible to rehabilitate the house and achieve 100% of energy autonomy, where all the energy consumed is generated on site, through renewable sources: the sun and biomass. The suggested rehabilitation provides an increase of hours under occupation with thermal comfort from an average of 12% to almost 100%.

The high investment cost seems to be the drawback of the results presented. As an alternative, it is possible to opt for a partial initial investment, with a posterior upgrade for the total energy independence scenario.

7.2 Limitations and Future Work

Although a deeper study about the whole process of energy certification in residential buildings was not part of the objectives of this thesis, it would be a good complement in order to look for financial support, given by the government or other institutions, for example IFRU, FNRE or *Casa Eficiente* 2020. Those type of incentives for rehabilitation could easily increase the reliability of this project.

IES VE proved to be a proficient software for this kind of projects, but it does not simulate energy storage systems. Therefore, it would be beneficial to include a simulation of the battery performance with higher precision.

Nevertheless, after this macro analysis of the house and available technologies for possible implementation, it is important to keep a personal contact with the household and discuss the best solution that fits their interests and needs.

7.3 Final Assessment

The fact of having a real house under study allied with the guidance of a project consulting company, made this thesis more realistic and closer to a technological approach, instead of a scientific study. It was easier to identify and face several barriers and constraints that are limiting the implementation of technologies in the field of autonomous houses.

The contact with the IES VE and other resources was an opportunity to acquire several skills that can be useful for future projects, such as, modeling and dynamic simulation performance. The theme of this thesis has an indirect relation with the traditional chemical engineer background. That fact was sometimes a barrier to understand concepts related to other fields of studies, but, undoubtedly, this challenge broadened the knowledge acquired to areas with significant impact in the energy performance of buildings.

References

[1] IRENA. *Global Energy Transformation: A Roadmap to 2050*. 2019.

[2] EPBD 2002/91/EC. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings, 2010.

[3] Thomas Storch, Timo Leukefeld, Tobias Fieback, and Ulrich Gross. Living Houses with an Energy-autonomy - Results of Monitoring. *Energy Procedia*, 91(0):876–886, 2016.

[4] Séverine Morel. 2018 :Historically High Energy Consumption & CO2 Emissions. *Enerdata*, pages 1–2, 2019.

[5] Eurostat. Electricity prices for household consumers, first half 2018, 2018.

[6] Luís Matias and Carlos Santos. Conforto térmico adaptativo no setor residencial em portugal. *Congresso Internacional da Habitação no Espaço Lusófono*, (November):1–12, 2013.

[7] L. Aditya, T. M.I. Mahlia, B. Rismanchi, H. M. Ng, M. H. Hasan, H. S.C. Metselaar, Oki Muraza, and H. B. Aditiya. A review on insulation materials for energy conservation in buildings. *Renewable and Sustainable Energy Reviews*, 73(January):1352–1365, 2017.

[8] Vasco Peixoto ; Ana Guimarães; Claudia Ferreira; Sandro Freitas Alves. *Edifícios existentes, medidas de melhoria de desempenho energético e da qualidade do ar interior*. Porto, 2011.

[9] Jesús Boschmonart-rives, Xavier Gabarrell, and Jorge Sierra-p. Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions. 113(2016):102–113, 2015.

[10] K. S. Ong. Temperature reduction in attic and ceiling via insulation of several passive roof designs. *Energy Conversion and Management*, 52(6):2405–2411, 2011.

[11] Ehsan Asadi, Manuel Gameiro, Carlos Henggeler, and Luís Dias. Multi-objective optimization for building retrofit strategies : A model and an application. *Energy & Buildings*, 44:81–87, 2012.

[12] Arturas Kaklauskas, Edmundas Kazimieras Zavadskas, Saulius Raslanas, Romualdas Ginevicius, Arunas Komka, and Pranas Malinauskas. Selection of low-e windows in retrofit of public buildings by applying multiple criteria method COPRAS: A Lithuanian case. *Energy and Buildings*, 38(5):454–462, 2006.

[13] Isidore C. Eczema. Insulation materials. In Vivian W.Y. Tam and Khoa N. Le, editors, *Sustainable Construction Technologies*, chapter 9, pages 237–262. Penrith, NSW, Australia, 2019.

[14] Angeliki Kylili and Paris A. Fokaides. European smart cities: The role of zero energy buildings. *Sustainable Cities and Society*, 15(2015):86–95, 2015.

[15] Jusué Lima Morais. *Sistemas Fotovoltaicos da Teoria à Prática*. Weidmuller, 2009.

[16] Ion Visa, Bogdan Burduhos, Mircea Neagoe, Macedon Moldovan, and Anca Duta. Comparative analysis of the infield response of five types of photovoltaic modules. *Renewable Energy*, 95:178–190, 2016.

[17] Nallapaneni Manoj Kumar, K. Sudhakar, and M. Samykano. Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions. *Case Studies in Thermal Engineering*, 13(December 2018):100374, 2019.

[18] Sara Regina Teixeira Freitas. *Photovoltaic Potential in Building Façades*. PhD thesis, Universidade de Lisboa, 2018.

[19] IFRRU2020. Catálogo de Soluções técnicas - eficiência energética na habitação. Technical report, Républica Portuguesa, 2016.

[20] K. Balaji, S. Iniyan, and Ranko Goic. Thermal performance of solar water heater using velocity enhancer. *Renewable Energy*, 115:887–895, 2018.

[21] Soteris A. Kalogirou. *Solar thermal collectors and applications*, volume 30. 2004.

[22] Sunaitec. Energia Solar Inteligente | Sunaitec. 2018. URL: http://www.sunaitec.pt/.

[23] Sunaitec. Projecto Hotel. Lisboa, 2018.

[24] Jim Eyer and Garth Corey. Energy Storage for the Electricity Grid : Benefits and Market Potential Assessment Guide. *Sandia Report*, (February):232, 2010.

[25] Pedro Teixeira Pacheco. Development and optimization of a passive internal mixing strategy for the electrolyte tanks in a commercial redox flow battery system. Master's thesis, Faculdade de engenharia da Universidade do Porto, 2018.

[26] Selina Weber, Jens F. Peters, Manuel Baumann, and Marcel Weil. Life Cycle Assessment of a Vanadium Redox Flow Battery. *Environmental Science and Technology*, 52(18):10864–10873, 2018.

[27] V. K. Verma, S. Bram, and J. De Ruyck. Small scale biomass heating systems: Standards, quality labelling and market driving factors - An EU outlook. *Biomass and Bioenergy*, 33(10):1393–1402, 2009.

[28] L. J.R. Nunes, J. C.O. Matias, and J. P.S. Catalão. A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. *Renewable and Sustainable Energy Reviews*, 40:153–160, 2014.

[29] Maryam Manouchehrinejad, Ian van Giesen, and Sudhagar Mani. Grindability of torrefied wood chips and wood pellets. *Fuel Processing Technology*, 182(August):45–55, 2018.

[30] Leonel J R Nunes. Torrefied Biomass Pellets for Thermal Energy. Porto, 2018.

[31] ASHRAE. *Handbook - Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., si edition edition, 2017.

[32] INE. Dimensão média dos agregados domésticos privados, 2018. URL: https://www.pordata.pt/Portugal/Dimens{~{a}}o+m{é}dia+dos+agregados+dom{é}sticos+privados+-511.

Appendix A

Additional Information

A.1 Energy efficiency Requirements

Table A.1: REH Minimum efficiency requirements for thermal production units

Equipment	Energy efficiency Required
Heat pumps, Split, multi-split, compact, VRF, Rooftop units.	class B (see tables below)
Gas or liquid fuel Boiler	class A ($\eta \geq 89\%$)
Solid fuel boiler	$\geq 75\%$ // $\geq 85\%$
Heat recovery unit and fireplaces	≥ 75 %

Table A.2: Performance rating of split, multi-split, VRF and compact units with air-to-air exchange

Class	Units with external air exchange			
	Cooling		Heating	
	Split, multissplit and VRF	**Compact units**	**Split, multissplit and VRF**	**Compact units**
A	EER > 3,20	EER > 3,00	COP > 3,60	COP > 3,40
B	3,20 ≥ EER > 3,00	3,00 ≥ EER > 2,80	3,60 ≥ COP > 3,40	3,40 ≥ COP > 3,20
C	3,00 ≥ EER > 2,80	2,80 ≥ EER > 2,60	3,40 ≥ COP > 3,20	3,20 ≥ COP > 3,00
D	2,80 ≥ EER > 2,60	2,60 ≥ EER > 2,40	3,20 ≥ COP > 2,80	3,00 ≥ COP > 2,60
E	2,60 ≥ EER > 2,40	2,40 ≥ EER > 2,20	2,80 ≥ COP > 2,60	2,60 ≥ COP > 2,40
F	2,40 ≥ EER > 2,20	2,20 ≥ EER > 2,00	2,60 ≥ COP > 2,40	2,40 ≥ COP > 2,20
G	EER ≥ 2,20	EER ≥ 2,00	COP ≥ 2,40	COP ≥ 2,20

A.2 Battery Performance

Table A.3: Performance rating of chiller type compressor heat pump units

Class	Units with external air exchange		Units with external water exchange	
	Cooling	**Heating**	**Cooling**	**Heating**
A	EER $\geq$ 3,1	COP $\geq$ 3,2	EER $\geq$ 5,05	COP $\geq$ 4,45
B	3,1 > EER $\geq$ 2,9	3,2 > COP $\geq$ 3,0	5,05 > EER $\geq$ 4,65	4,45 > COP $\geq$ 4,15
C	2,9 > EER $\geq$ 2,7	3,0 > COP $\geq$ 2,8	4,65 > EER $\geq$ 4,25	4,15 > COP $\geq$ 3,85
D	2,7 > EER $\geq$ 2,5	2,8 > COP $\geq$ 2,6	4,25 > EER $\geq$ 3,85	3,85 > COP $\geq$ 3,55
E	2,5 > EER $\geq$ 2,3	2,6 > COP $\geq$ 2,4	3,85 > EER $\geq$ 3,45	3,55 > COP $\geq$ 3,25
F	2,3 > EER $\geq$ 2,1	2,4 > COP $\geq$ 2,2	3,45 > EER $\geq$ 3,05	3,25 > COP $\geq$ 2,95
G	EER < 2,1	COP < 2,2	EER < 3,05	COP < 2,95

Table A.4: Average battery state of charge, for each day of the year, for the scenario of total autonomy.

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	86.5%	87.6%	89.5%	91.4%	92.1%	93.3%	92.5%	92.5%	89.6%	89.0%	88.7%	71.1%
2	85.2%	87.9%	89.6%	91.5%	93.3%	93.2%	91.8%	92.6%	88.7%	88.1%	87.7%	50.5%
3	76.3%	85.9%	90.2%	89.5%	93.1%	93.2%	91.1%	91.9%	89.1%	89.2%	82.2%	37.4%
4	77.1%	86.7%	90.3%	91.5%	92.2%	93.3%	92.7%	91.9%	90.0%	89.5%	82.3%	28.2%
5	86.5%	86.3%	88.4%	92.5%	92.6%	93.8%	92.9%	91.7%	91.7%	88.9%	86.1%	30.0%
6	86.5%	85.2%	88.7%	91.2%	92.9%	94.7%	91.7%	91.5%	91.4%	86.3%	87.8%	29.3%
7	76.4%	87.8%	89.4%	91.0%	93.3%	94.3%	92.0%	92.3%	90.3%	88.1%	85.9%	21.8%
8	70.1%	87.3%	89.1%	90.9%	93.4%	93.1%	91.8%	93.4%	89.5%	89.2%	86.1%	49.7%
9	73.6%	86.7%	87.3%	91.7%	94.0%	92.9%	91.4%	91.4%	89.9%	89.2%	85.0%	85.9%
10	67.9%	81.8%	89.2%	92.3%	94.0%	92.9%	92.3%	90.6%	89.0%	89.0%	85.6%	86.6%
11	50.7%	83.8%	90.1%	93.4%	93.3%	91.6%	93.4%	91.8%	89.5%	89.0%	85.3%	85.3%
12	54.4%	88.0%	89.9%	93.1%	93.3%	93.1%	93.7%	91.9%	91.0%	88.6%	86.1%	76.9%
13	78.3%	88.3%	89.7%	92.1%	93.3%	94.3%	92.5%	91.9%	90.5%	88.9%	74.8%	75.7%
14	85.5%	89.3%	90.1%	92.1%	93.3%	94.1%	92.5%	91.8%	88.4%	88.7%	54.0%	70.7%
15	67.1%	89.4%	90.9%	92.1%	92.6%	92.9%	92.7%	92.3%	78.2%	89.2%	64.2%	47.4%
16	57.1%	86.4%	90.8%	92.2%	94.0%	92.5%	92.2%	91.8%	75.4%	89.2%	87.8%	37.3%
17	76.5%	87.5%	90.8%	92.2%	93.7%	92.8%	92.3%	90.7%	86.2%	90.0%	86.8%	61.3%
18	87.3%	79.0%	90.8%	92.3%	93.1%	92.7%	92.8%	90.7%	90.2%	89.3%	85.3%	74.2%
19	82.7%	81.2%	89.8%	91.7%	93.2%	93.1%	91.9%	89.9%	92.0%	88.3%	87.1%	76.6%
20	79.8%	78.9%	89.7%	91.1%	93.4%	94.3%	91.1%	89.4%	91.8%	87.7%	86.1%	78.1%
21	84.1%	81.8%	91.5%	91.7%	93.1%	93.2%	90.8%	89.7%	90.8%	87.5%	86.9%	73.2%
22	86.1%	87.6%	91.8%	91.9%	92.5%	92.8%	90.8%	90.3%	90.5%	88.8%	87.4%	68.4%
23	85.2%	87.9%	89.0%	92.0%	93.8%	93.1%	91.0%	89.5%	90.5%	83.8%	86.0%	66.6%
24	77.3%	88.6%	89.7%	92.1%	93.9%	92.6%	89.4%	87.5%	90.4%	85.6%	86.8%	72.7%
25	77.1%	88.9%	90.9%	91.8%	91.4%	92.2%	91.6%	87.7%	90.6%	87.7%	87.4%	58.5%
26	84.3%	88.6%	87.8%	87.7%	92.5%	92.8%	92.3%	86.6%	88.6%	86.2%	87.4%	49.8%
27	86.1%	88.6%	90.2%	89.3%	91.6%	93.9%	91.7%	89.7%	89.7%	86.7%	86.0%	69.8%
28	87.4%	89.7%	89.8%	92.0%	91.3%	93.2%	91.0%	90.8%	90.3%	73.0%	87.2%	86.0%
29	87.7%		90.7%	91.6%	93.3%	92.8%	90.0%	91.5%	90.3%	76.7%	86.3%	85.0%
30	87.6%		90.9%	91.5%	94.7%	92.9%	90.0%	91.4%	89.8%	88.8%	85.8%	85.2%
31	86.0%		91.1%		94.4%		91.1%	90.3%		89.5%		86.5%

Table A.5: Percentage of hours, during each day of the year, with self-supply of electricity. Autonomy (h/h) in the scenario of partial investment.

Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	88%
2	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	42%
3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	33%
4	67%	100%	100%	100%	100%	100%	100%	100%	100%	100%	88%	50%
5	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	71%	58%
6	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	96%	42%
7	96%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	46%
8	54%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%
9	54%	100%	100%	100%	100%	100%	100%	100%	100%	100%	88%	100%
10	33%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%	100%
11	29%	83%	100%	100%	100%	100%	100%	100%	100%	100%	83%	100%
12	63%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%	100%
13	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	71%
14	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	21%	33%
15	75%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%	25%
16	63%	100%	100%	100%	100%	100%	100%	100%	75%	100%	100%	54%
17	96%	100%	100%	100%	100%	100%	100%	100%	67%	100%	100%	63%
18	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	96%
19	100%	71%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%
20	79%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
21	63%	83%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%
22	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	29%
23	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%
24	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	67%
25	71%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	25%
26	71%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	58%
27	63%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	63%
28	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	100%	100%
29	100%		100%	100%	100%	100%	100%	100%	100%	67%	100%	100%
30	100%		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
31	100%		100%		100%		100%	100%		100%		100%

Appendix B

House Plan

Figure B.1: House Façades

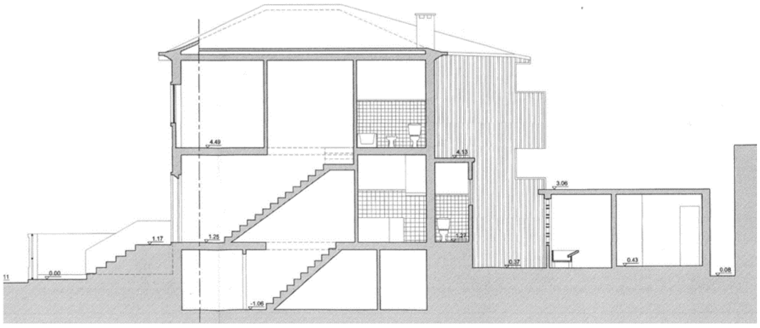


Figure B.2: Section Cut

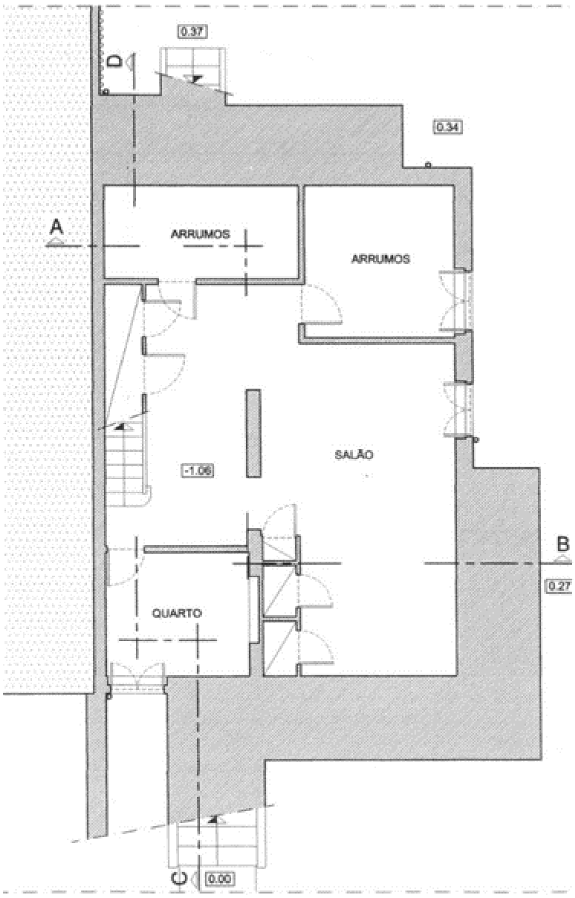


Figure B.3: Basement

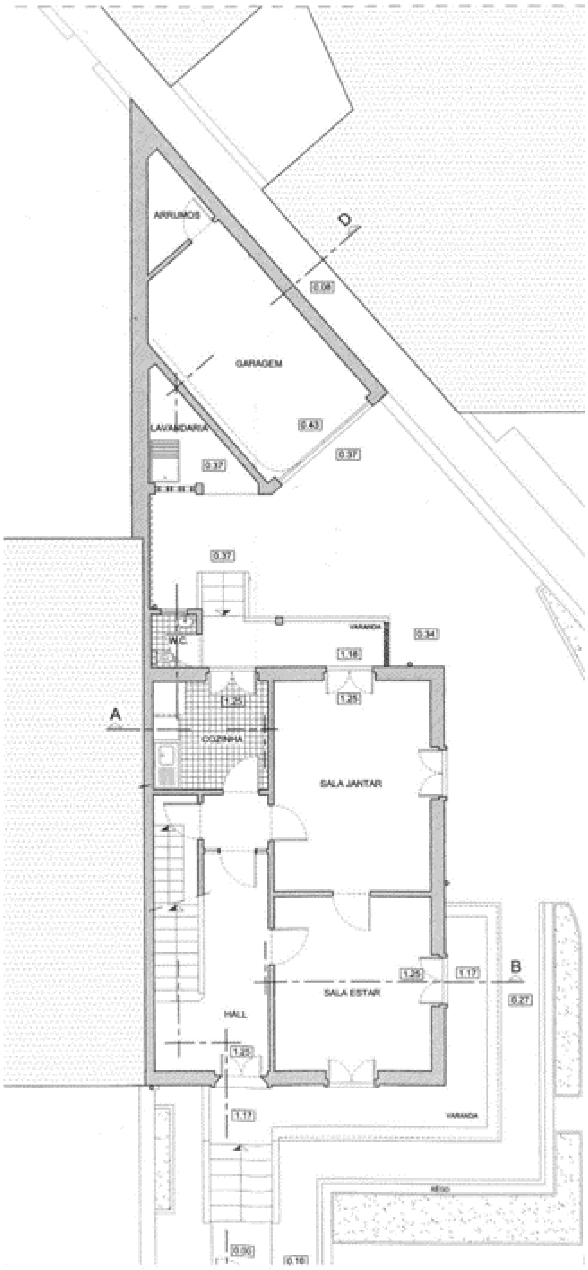


Figure B.4: Ground Floor

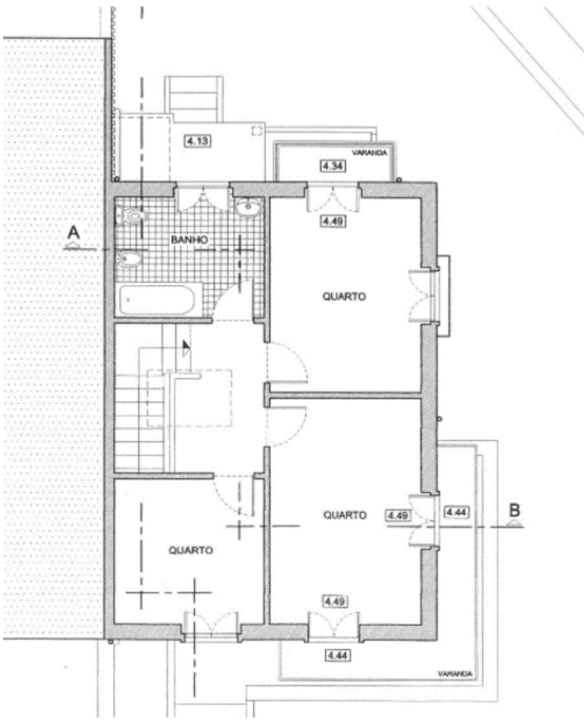


Figure B.5: Second Floor

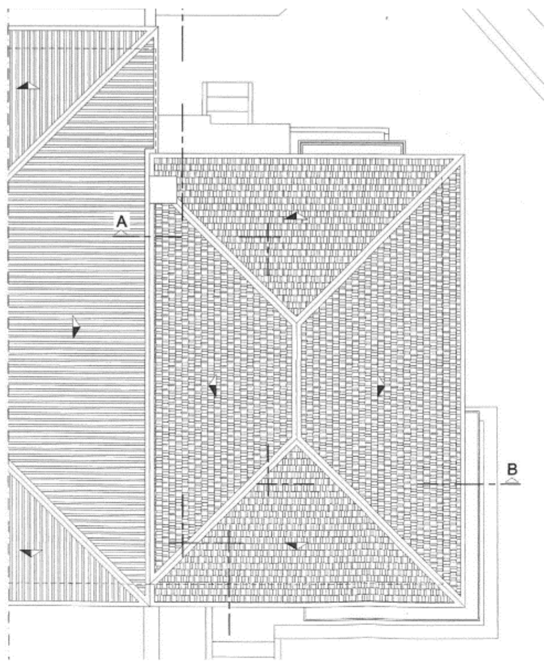


Figure B.6: Roof

Appendix C

Assumed Constructions

Table C.1: External wall construction

	Thickness (e) /m	Thermal conductivity of the material (λ) $/W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$	Thermal Resistance (R) $/m^2 \cdot {}^{\circ}C \cdot W^{-1}$
Outdoor thermal resistance (Rse)			0.040
Plaster	0.03	1.30	0.023
Granite	0.28	2.80	0.100
Plaster	0.03	1.30	0.023
Indoor thermal resistance (Rsi)			0.130
Total	0.34		0.316

Thermal Transmission Coefficient (U)	3.163	$W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$

Table C.2: Internal ceiling (roof) construction

	Thickness (e) /m	Thermal conductivity of the material (λ) $/W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$	Thermal Resistance (R) $/m^2 \cdot {}^{\circ}C \cdot W^{-1}$
Outdoor thermal resistance (Rse)			0.100
Concrete	0.15	2.00	0.075
Plaster	0.03	1.30	0.023
Indoor thermal resistance (Rsi)			0.100
Total	0.18		0.298

Thermal Transmission Coefficient (U)	3.355	$W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$

Table C.3: Internal partition construction

	Thickness (e) /m	Thermal conductivity of the material (λ) $/W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$	Thermal Resistance (R) $/m^2 \cdot {}^{\circ}C \cdot W^{-1}$
Outdoor thermal resistance (Rse)			0.13
Plaster	0.02	1.30	0.023
Ceramic Brick	0.07	0.37	0.190
Plaster	0.02	1.30	0.023
Indoor thermal resistance (Rsi)			0.130
Total	0.11		0.481

Thermal Transmission Coefficient (U)	2.08	$W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$

Table C.4: Internal Partition in contact with the adjacent building construction

	Thickness (e) /m	Thermal conductivity of the material (λ) $/W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$	Thermal Resistance (R) $/m^2 \cdot {}^{\circ}C \cdot W^{-1}$
Adjacent thermal resistance (Rsi)			0.13
Plaster	0.03	1.30	0.023
Granite	0.28	2.80	0.100
Plaster	0.03	1.30	0.023
Indoor thermal resistance (Rsi)			0.130
Total	0.34		0.406

Thermal Transmission Coefficient (U)	2.46	$W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$

Table C.5: Internal floor construction

	Thickness (e) /m	Thermal conductivity of the material (λ) $/W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$	Thermal Resistance (R) $/m^2 \cdot {}^{\circ}C \cdot W^{-1}$
Indoor thermal resistance (Rsi)			0.100
Wooden flooring	0.04	1.30	0.174
Concrete	0.15	2.00	0.075
Plaster	0.03	1.30	0.023
Indoor thermal resistance (Rsi)			0.100
Total	0.22		0.472

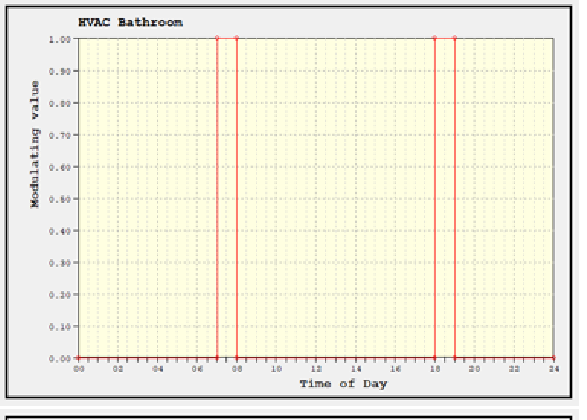
Thermal Transmission Coefficient (U)	2.12	$W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$

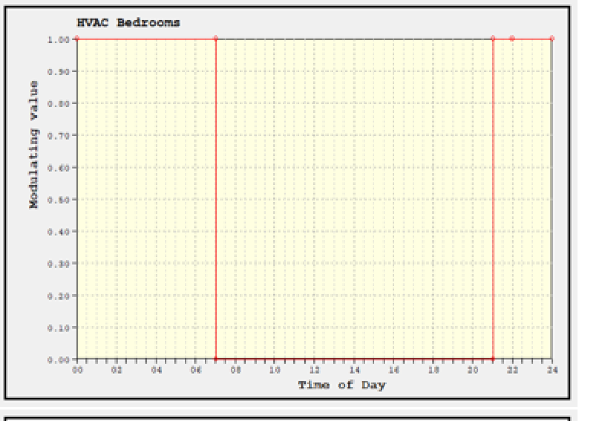
Appendix D

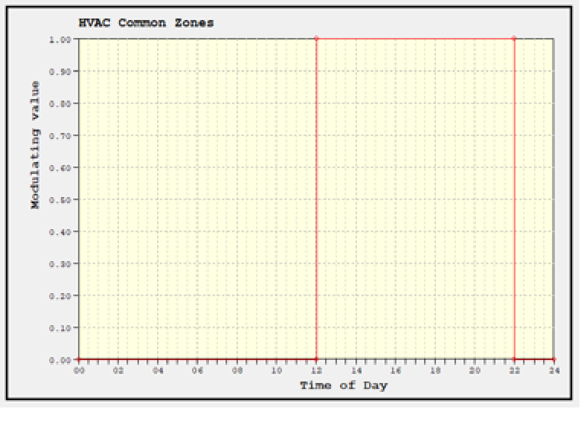
Assumed Profiles

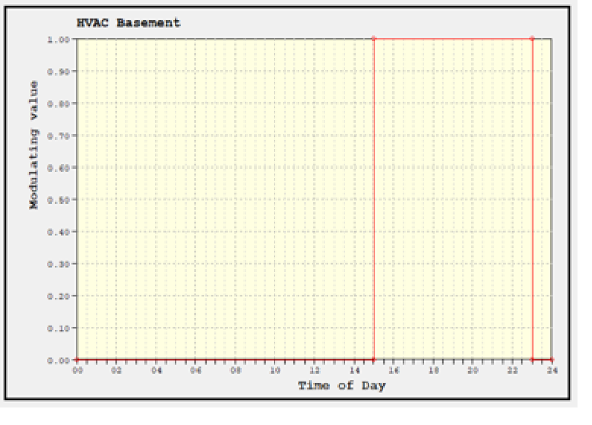
D.1 Acclimatization

[1]



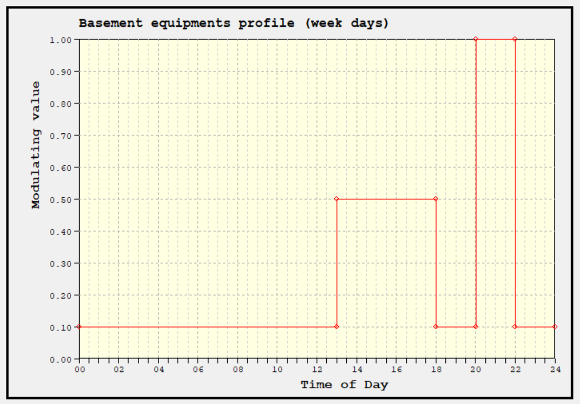


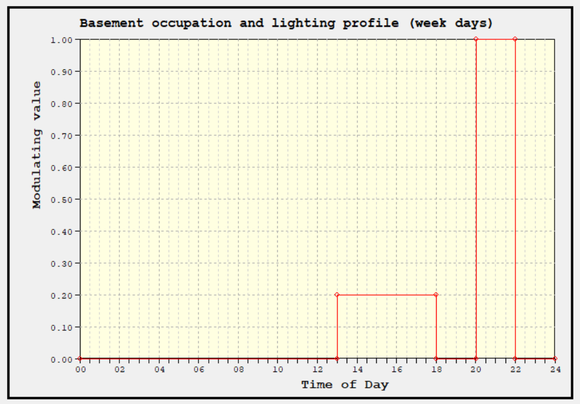


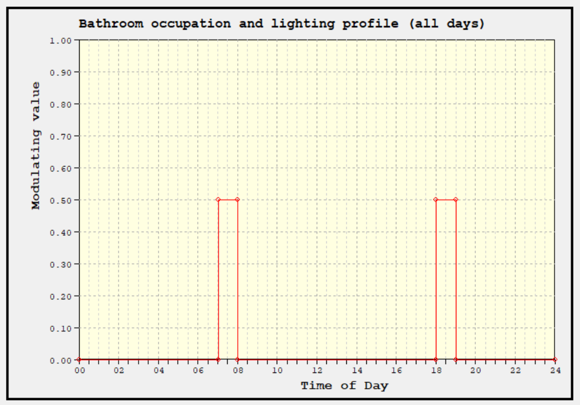


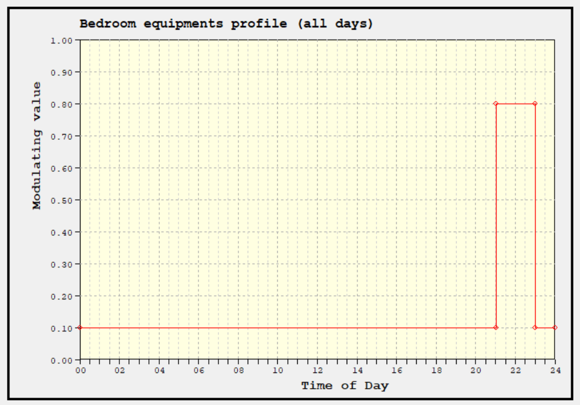
D.2 Internal Gains

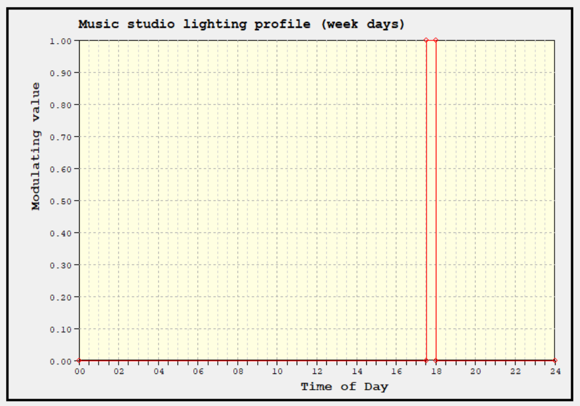
[1]Common zones were a designation for the spaces that are usually frequented during the daily occupation

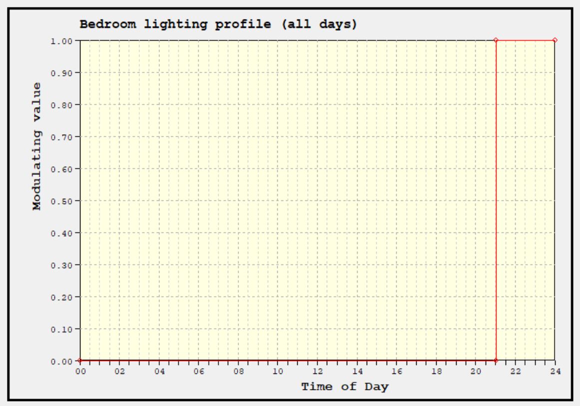

Basement equipments profile (week days)
Modulating value
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00 02 04 06 08 10 12 14 16 18 20 22 24
Time of Day

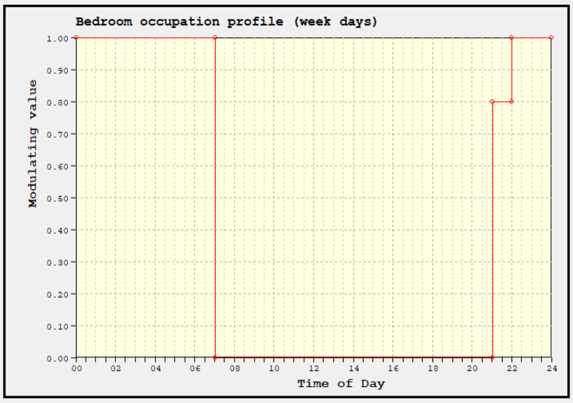

Basement occupation and lighting profile (week days)
Modulating value
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00 02 04 06 08 10 12 14 16 18 20 22 24
Time of Day

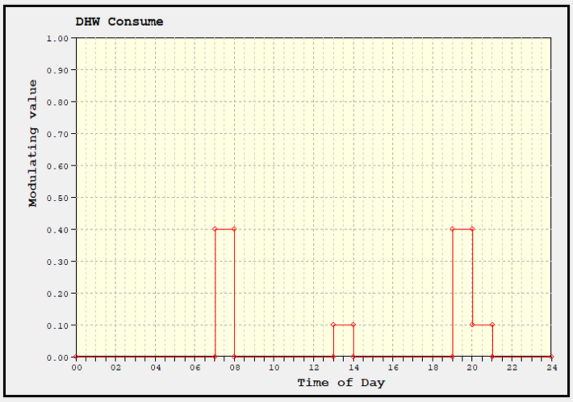

Bathroom occupation and lighting profile (all days)
Modulating value
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00 02 04 06 08 10 12 14 16 18 20 22 24
Time of Day

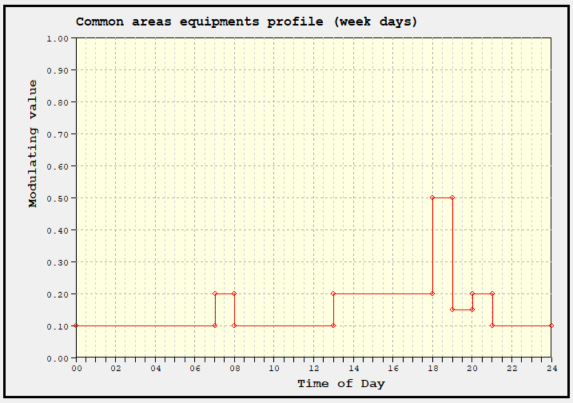

Bedroom equipments profile (all days)
Modulating value
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00 02 04 06 08 10 12 14 16 18 20 22 24
Time of Day

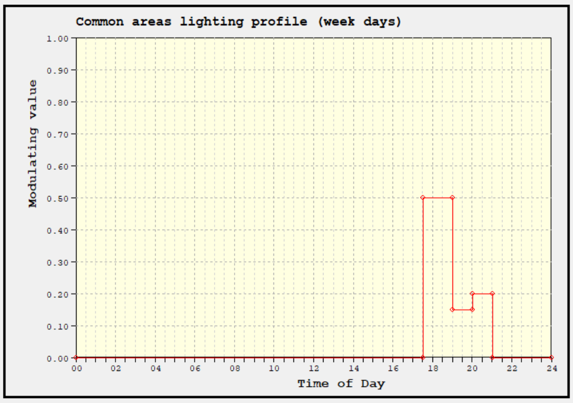

Music studio lighting profile (week days)
Modulating value
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00 02 04 06 08 10 12 14 16 18 20 22 24
Time of Day

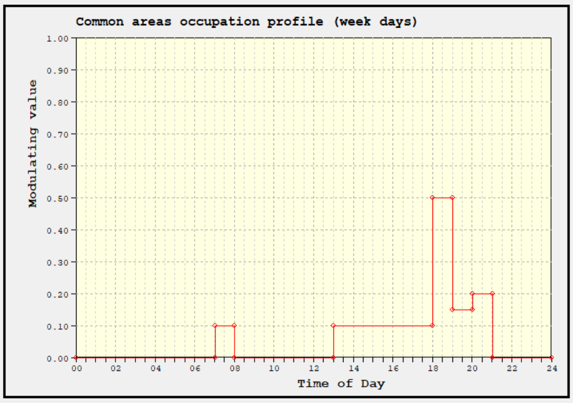

Bedroom lighting profile (all days)
Modulating value
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00 02 04 06 08 10 12 14 16 18 20 22 24
Time of Day

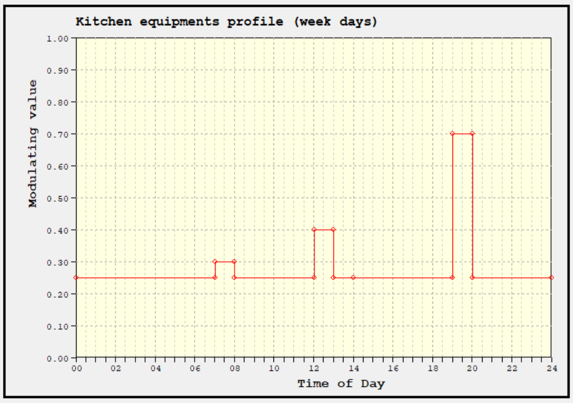

Bedroom occupation profile (week days)
Modulating value
Time of Day

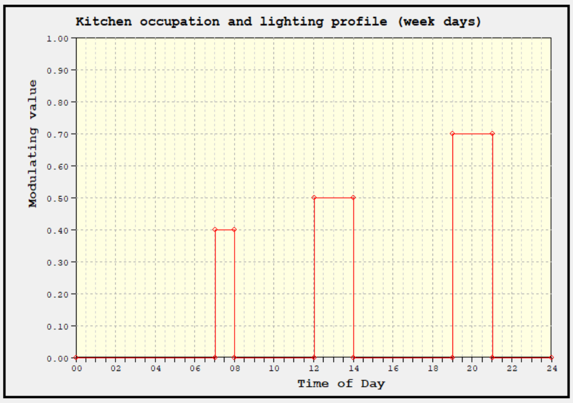

DHW Consume
Modulating value
Time of Day

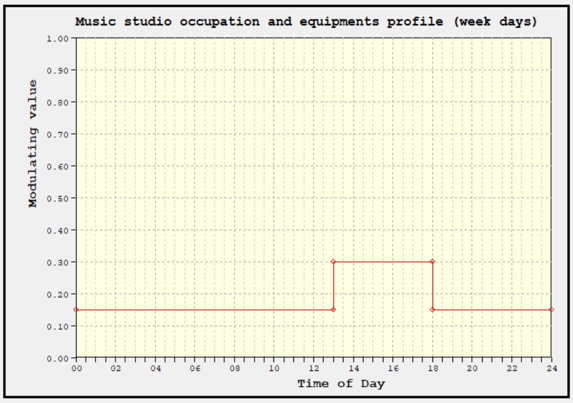

Common areas equipments profile (week days)
Modulating value
Time of Day

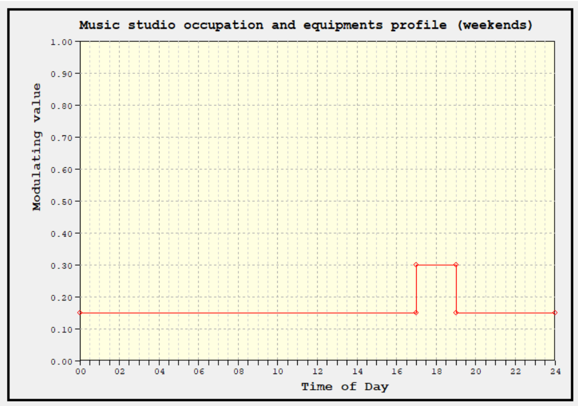

Common areas lighting profile (week days)
Modulating value
Time of Day

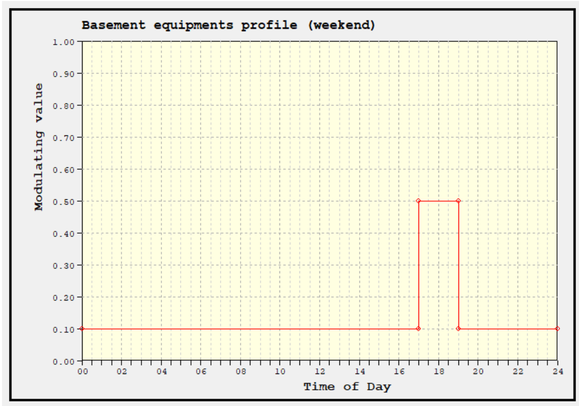

Common areas occupation profile (week days)
Modulating value
Time of Day

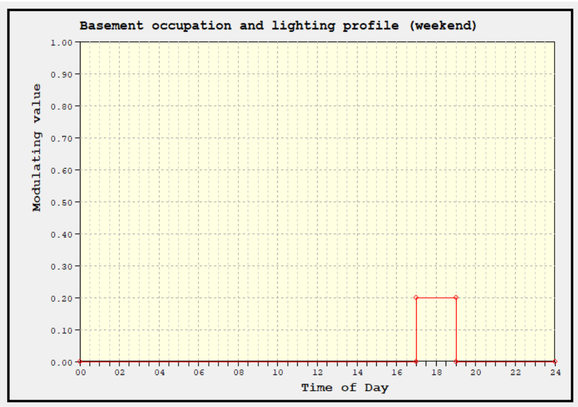

Kitchen equipments profile (week days)
Modulating value
Time of Day

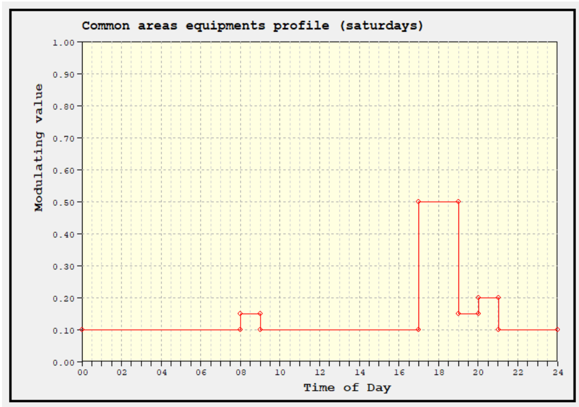

Kitchen occupation and lighting profile (week days)
Modulating value
Time of Day

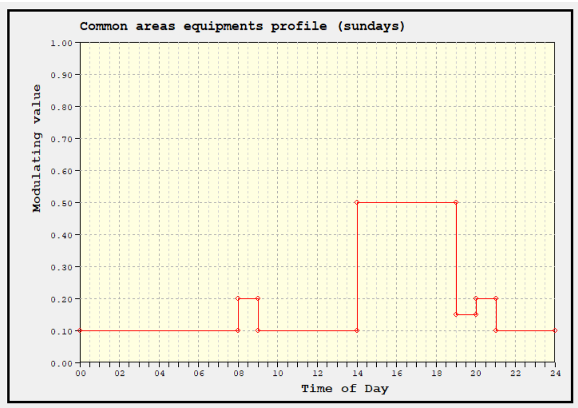

Music studio occupation and equipments profile (week days)
Modulating value
Time of Day

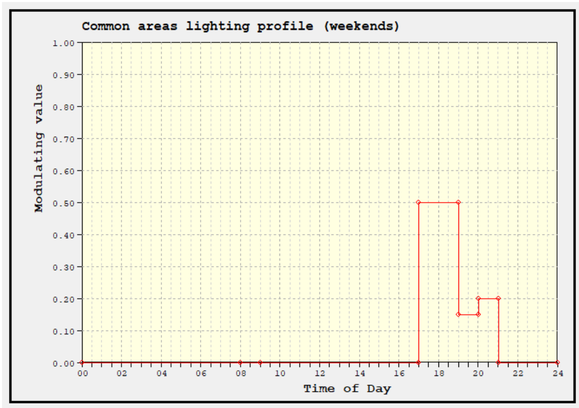

Music studio occupation and equipments profile (weekends)
Modulating value
Time of Day


Basement equipments profile (weekend)
Modulating value
Time of Day


Basement occupation and lighting profile (weekend)
Modulating value
Time of Day


Common areas equipments profile (saturdays)
Modulating value
Time of Day


Common areas equipments profile (sundays)
Modulating value
Time of Day


Common areas lighting profile (weekends)
Modulating value
Time of Day