Development of an energy management model for a heating and cooling microgrid in a public building

Lidia García García

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Supervisor: Prof. Carlos Augusto Santos Silva

Examination Committee

Chairperson: Prof. Duarte de Mesquita e Sousa
Supervisor: Prof. Carlos Augusto Santos Silva
Member of the Committee: Dr. Rui Pedro da Costa Neto

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Abstract

In order to seriously address the fossil energy use and climate change crises, buildings clearly offer vast potential for reducing the demand for energy and the corresponding greenhouse gas emissions. This implies large scale strategies as the implementation of low-energy buildings (so called nearly Zero- Energy Buildings or nZEBs).

Enhancing the energy performance of buildings through deep renovation is strongly requested. As one of the European Regional Development programs, the IMPROVEMENT project seeks for the integration of combined cooling, heating and power microgrids in zero-energy public buildings under high power quality and continuity requirements. This work aims to develop and integrate a complete thermal energy management system and help in the development of innovative solutions, to reduce the energy consumption in existing public buildings by converting them into nZEB. Simultaneously, this assessment might help to stablish regional implementation plans under the common climatology conditions.

The empirical part of the research utilizes MATLAB/Simulink, which allows both dynamic building thermal simulation and multi-objective optimization in a single environment, to carry out simulations and validate whether the proposed Energy Managed System was appropriated for the building's features.

The results show strong dependency on the climatic conditions as well as on the configuration of the thermal energy management system. It is hoped that the findings of the present study can help to establish procedures to optimize energy demand and thermal comfort in nZEB buildings in warm regions.

Key-words: Buildings energy performance; Energy Management Systems, retrofit; nearly Zero-Energy Building (nZEB); modelling; climate zones.

Resumo

A fim de enfrentar seriamente as crises da utilização de energia fóssil e das alterações climáticas, os edifícios oferecem claramente um vasto potencial para reduzir a procura de energia e as correspondentes emissões de gases com efeito de estufa. Isto implica estratégias em larga escala como a implementação de edifícios de baixa energia (os chamados edifícios de energia quase zero ou nZEBs).

A melhoria do desempenho energético dos edifícios através de uma renovação profunda é fortemente solicitada. Como um dos programas Europeus de Desenvolvimento Regional, o projecto MELHORIA procura a integração de micro-redes combinadas de refrigeração, aquecimento e energia em edifícios públicos de energia zero sob alta qualidade de energia e requisitos de continuidade. Este trabalho visa desenvolver e integrar um sistema completo de gestão de energia térmica e ajudar no desenvolvimento de soluções inovadoras, para reduzir o consumo de energia em edifícios públicos existentes, convertendo-os em nZEB. Simultaneamente, esta avaliação poderá ajudar a estabelecer planos regionais de implementação nas condições climatológicas comuns.

A parte empírica da investigação utiliza o MATLAB/Simulink, que permite tanto a simulação térmica dinâmica do edifício como a optimização multi-objectivo num único ambiente, para realizar simulações e validar se o Sistema de Gestão de Energia proposto foi apropriado para as características do edifício.

Os resultados mostram uma forte dependência das condições climáticas, bem como da configuração do sistema de gestão de energia térmica. Espera-se que os resultados do presente estudo possam ajudar a estabelecer procedimentos para optimizar a procura de energia e o conforto térmico em edifícios nZEB em regiões quentes.

Palavras-chave: Desempenho energético dos edifícios; Sistemas de Gestão de Energia; retrofit;Edificiod de balanço quase nulo; modelização; zonas climáticas.

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BEMS	Building Energy Management System
DER	Distributed Energy Resources
DHW	Domestic Hot Water
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
FCU	Fan Coil Unit
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiance
HE	Heat Exchanger
HPs	Heat Pumps
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IoE	Internet of Energy
LTV	Linear Time-Varying
MS	Members States
nZEB	nearly Zero-Energy Buildings
PE	Primary Energy
PV-T	Photovoltaic thermal hybrid solar collector
REHVA	Representatives of European Heating and Ventilation Associations
RES	Renewable Energy Sources
SB	System Boundaries
TES	Thermal Energy Storage
Toe	Tonne of oil equivalent

1 INTRODUCTION

1.1 Scope

Over the last years, the European Commission has been following ambitious plans towards the transition to a low carbon economy by 2050. The targets are mainly based on the reduction of greenhouse gas emission (≤40%) and in improve both the energy efficiency (≥30%) and the renewable energy share (≥27%) for the 2020-2030 period, compared to 1990 levels. Worldwide, there have been many attempts to reduce the carbon footprint by integrating Renewable Energy Sources (RES) within the energy generation units, but unfortunately, they will not be sufficient to reach the 2050 objective and there is a need of ensuring the right policies to reach our long-term target.

The European Commission stablishes that the transition towards a low carbon society is feasible and affordable, but it requires innovation and investment. To support this transition, the EU would need to keep investing over the next four decades an average about 1.5% of its GDP per year. As a result, we will experience an upgrade of innovation that will bring significant co-benefits as the development of new growth sectors, the reduction of resource depletion, less dependency on energy imports, and health benefits. Developing successful climate policies requires close stakeholder involvement at all stages, but governments play a crucial role driving efficient measures and increasing the capacity to influence the reduction of high consumption and enhance power quality and reliability of supply. They need to implement more strategic measures. For this purpose, there is a need of innovative approaches able to gradually integrate the Distributed Energy Resources (DER) and improve the energy efficiency. The residential and public buildings are good examples where there are great opportunities to share the investment of new technologies and explore more alternative energy supply systems that might be available locally.

Now a days, new concepts as the Smart or Zero Energy Buildings have emerged within the sustainable construction practices, attracting the interest of the scientific community. These ideas refer to buildings that have advanced control systems, very high energy performance and significant energy use from renewable sources, which makes its carbon footprint equal or nearly equal to zero. Following this approach, different industries and organizations worldwide are investing in the research and development of these concepts and how to implement then in our path towards sustainability.

The complete introduction of the renewable technologies in the grid it is being arduous to achieve due to its natural intermittency. The introduction of Energy Management Systems has been relevant to control the gap between energy supply and demand as well as optimizing the energy costs or increase comfort of living. Consequently, these systems lead to significant reductions in operating costs and greenhouse gas emissions. Thus, there has been a focus on the research of a new generation of Energy Management Systems (EMS) to operate buildings according to the local conditions and therefore harness the onsite renewable sources such as solar, wind, geothermal or biomass. This thesis is also an attempt to reduce the carbon footprint within the building sector.

Portugal, as a country within the Southern Europe region, has a great solar potential to meet a large portion of the energy demand and many companies are strongly investing in the fields of PV and thermal. However, in late 2015, the Solar Thermal (ST) accumulated area in Portugal was around 50% of 2020 target, remaining below the NREAP (National Renewable Energy Action Plan) trajectory [1] while in 2019, the country had a 3% share with 1085 MW, of the total expected 25.4 GW. In conclusion, despite the large potential, it is necessary to develop further research in order to demonstrate how the available renewable resources can be integrated at the building level in order to promote zero energy buildings.

1.2 Objectives

The application of the nZEB concept to Southern Europe countries is regarded as being of great importance to reduce both primary energy demand and final energy consumption associated to buildings. The European methodology provides common methods and tools for the energy performance evaluation of buildings and its management. Nevertheless, there is a clear lack of precise information and homogenization about the nZEB perception and its respective characteristics both at international and national level, as well as within its respective territories that belong to different meteorological characteristics, which impedes the effective implementation of the European nZEB thought.

The main objective of this thesis is to develop a model for the energy management of a heating and cooling microgrid for nZEB buildings. The present research intends to actively contribute to the implementation of the nZEB in Southern Europe, by means of a study for a pilot office case in Lisbon as well as for two other different cities within the south of Europe, Madrid and Marseille, that share a common climate classification. The results of this thesis are expected to be useful for the building sector and to be applicable in parts of the world where weather conditions and solar irradiation profiles match that of Southern Europe regions. As a consequence, the document aims to provide a thorough framework about the nomenclature, definitions and examples according to EN-ISO building related standards and its different implementations, in accordance with national regulations, in the three countries involved in the project (Portugal, France, Spain).

1.3 Thesis structure

The present chapter introduces the context and motivation of the thesis. In the second chapter, an exhaustive review has been carried out to highlight several issues and challenges of the current application and performance of the nZEB conception, as well as to find suited Energy Management System which can add reliability and sustainability. The review is divided in six subsections which cover details about energy consumption, the building environment and the potential, features and limitations of the nZEB approach, the different climate zones within Europe and different developments done in the integration of modern Energy Management Systems. Moreover, a special emphasis the Southern Europe have been done with the intention of stablish regional implementation plans under the common climatology conditions.

Chapter 3 presents in detail the case study, features the established Energy Management System introduced in the retrofit for the nZEB conversion of an office building in Lisbon. The model description and the criteria followed for the selection of the simulation tool have also be discussed and explained in chapter 4.

In Chapter 5, the results obtained through simulations in MATLAB/Simulink environment are presented and discussed. The conclusion and future recommendations are found in chapter 6 as a recap of what has been done and learnt in thisthesis.

2 LITERATUREREVIEW

Various studies have been carried out to find out the best way to develop efficient Energy Management System in buildings. This chapter attempts to closely cover them, by providing some context regarding overall energy consumption, buildings energy consumption and finally by looking into nearly Zero Energy Buildings (nZEB), Energy Management Systems (EMS) and finally addressing different European climatic zones (Portugal, Spain and France).

2.1 Overall Energy consumption

Over the last years, the built environment has been responsible for approximately one third of the final energy consumption and contributes to over 30% of the global CO_2 emissions. Furthermore, these values are expected to continue increasing in the next twenty years [2]. Many international reports confirm and feature that buildings are one of the major energy consumers and contributors of greenhouse gas emissions [3], mainly as a result of both poor building envelope characteristics and inefficient heating systems.

The same trend is also evident in Europe, where buildings are responsible for about 40% of the final energy consumption, 60% of electricity consumption and 36% of the CO2 emissions, making this sector the largest end-use energy consumer in Europe. As shown in Figure 1, during 2018, the EU-27 had a primary energy consumption of about 4.9% above the efficiency target for 2020 and 22.0% away from the 2030 target. Regarding the final energy, the EU consumed about 1124 million toe, 3.2% above the efficiency target for 2020 and 17.0% away from the 2030 target. Portugal, due to its specific climate, has lower figures with a final energy consumption of 16.91 Mtoe, in which the building sector accounted for about 17% [4][5].

In view of the significant impact that the residential sector has on energy consumption, it is of remarkable importance to implement policies aimed to improve energy efficiency in buildings.

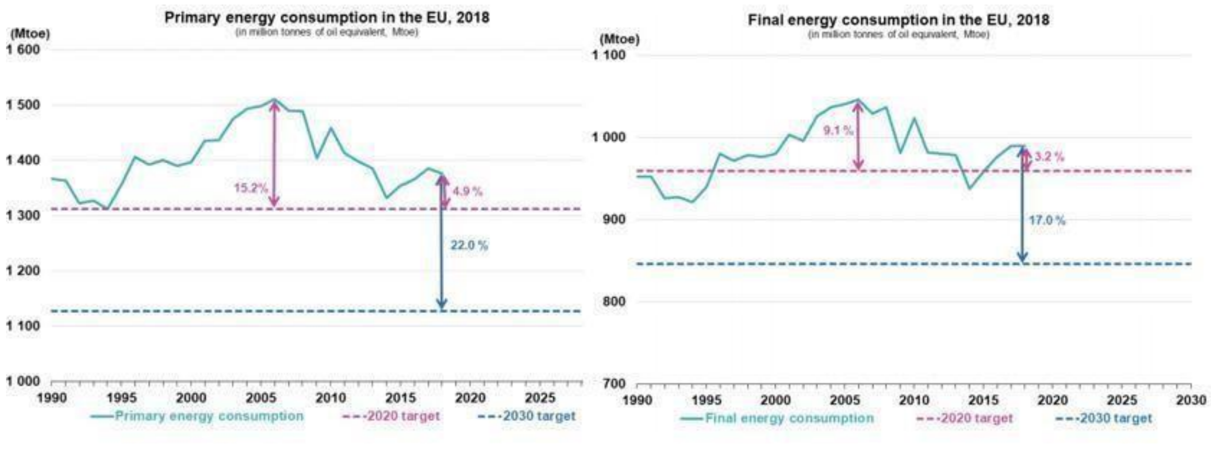

Figure 1 EU-27 Distance to Europe 2020 and 2030 targets for primary energy consumption (left) and final energy consumption (right); Eurostat [5]

To boost the energy performance of buildings, the EU has established a common legislative framework that includes the consolidated version of the Energy Performance of Buildings Directive (EPBD) [6]. This reinforced regulation states, among other measures, that all new buildings have to be nearly zero-energy by the end of 2020 and that all new public buildings already need to be nZEB by 2018. It emphasizes that as well that all EU Member States (MS) are responsible of establish strong long-term renovation strategies and must report detailed applications of the nZEB requirements that in practice, reflect national, regional or local conditions. Encouraging best practices for cost-effective transformation towards sustainability, nZEB has become a legal requirement under the EU directive with the goal of decarbonizing the construction sector by 2050.

All economic sectors must contribute to reduce greenhouse gas emissions accordingly with their own potential. Having a look at global energy mix, the power sector might have the biggest and fastest reduction of emissions through the implementation of low carbon technologies and energy efficient measures and its decarbonization should be practically complete by 2050 (Figure 2). The residential sector can accomplish significant contributions within the emission reduction. This can be achieved by adopting different measures as improving the insulation or increasing the use of low carbon electricity and heat generation and the use of more energy efficient appliances.

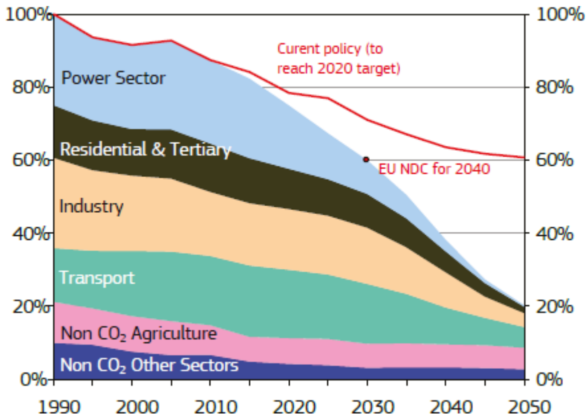

Figure 2 EU's roadmap by 2050; European Commission [7]

Moving forward within its Roadmap to a competitive low-carbon economy in 2050, the European Commission has looked ahead short-term objectives and set out different routes to achieve much deeper emission cuts by the middle of the century.

The aggrupation of energy security, environment, and economy - known as 'Energy trilemma' - has become a concerning element of the modern world. The continuously increasing demand for electricity leads to network congestion problems and even power quality degradation. Moreover, the dominant use of fossil fuel has a serious environmental impact. Therefore, innovative alternatives as energy storage solutions, the smart grid concept or the development of different renewable energy technologies have been proposed over the last years. The efficient use of the produced electricity is an essential consideration in the development of theeconomy.

2.2 Building energy consumption

The building sector is leading the energy consumption sector thus, efficient energy management in buildings has become an international ambition for contemporary technology. Currently, about 35% of the EU's buildings are over 50 years old, and almost 75% of the building stock is energy inefficient. Moreover, only about 1% of Europe's existing buildings are renovated every year [8]. This trend is also linked to climate change and there is a need to share knowledge, build capacity and capitalize on all possible solutions that may arise from the mutual collaboration of key financial actors, decision-makers and social stakeholders.

In particular, there are key gaps that act as main barriers to develop new cutting-edge solutions for the deep energy renovation of existing buildings, such as lack of a standardized set of technical solutions or integrated solutions to comply to new and different building standards requirements, long pay-back times of retrofitting interventions and insufficient incentives. This trend is also linked to climate change and increases intemperature.

The European Commission states that the refurbishment of existing buildings can lead to important energy savings, as it could reduce the Members State total energy consumption by 5-6 % and lower CO2 emissions by about 5%. However, coupling existing building energy systems with modern control and monitoring equipment can arise as a limitation for the refurbishment of the existing building stock.

In Europe, non-residential buildings account for 25% of the total stock. Offices are the second biggest category, after the wholesale and retail buildings, with one quarter of the total non-residential energy use. Moreover, around 50% of the energy consumption in the office buildings are due to HVAC systems [9]. Compared with the residential sector, it constitutes a more complex and heterogeneous sector as its end-uses such as lighting, ventilation, heating, cooling, refrigeration, appliances and IT equipment vary extensively within the different building categories of the sector.

In the residential sector, heating and hot water alone account for 79% of total final energy use (Figure 3 **Final energy consumption in the residential sector by use, EU-28, 2017**. Today still, between 50 and 125 million Europeans suffer from cold in winter [10]. Cooling has a fairly smaller share of total final energy use across Europe, but demand rises substantively during the summer months very significantly especially in southern European countries.

As reported by the 2018 figures from Eurostat, 75% of heating and cooling is still generated from fossil fuels while only 19% is generated from renewable sources. Therefore, energy consumption and its effect on climate change are the most challenging issues in the building sector. To accomplish the EU's ambitious climate and energy targets, the heating and cooling sector must strongly reduce its energy consumption and cut its use of fossilfuels.

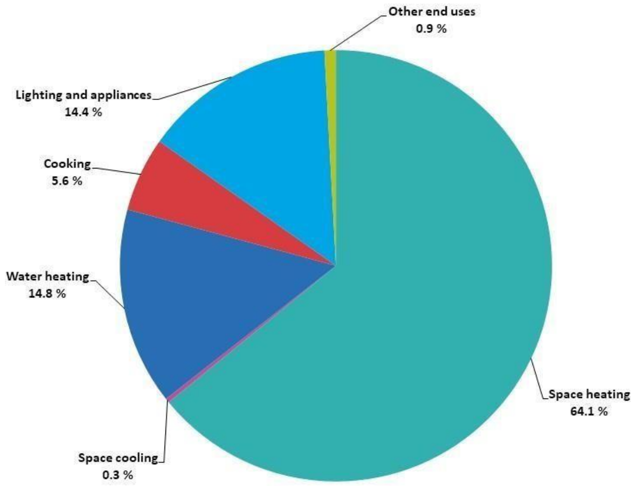

Figure 3 Final energy consumption in the residential sector by use, EU-28, 2017; Eurostat

In order to be able to develop and implement successful energy strategies, it is necessary to know the building energy demand accurately. The occupancy pattern, the external weather conditions, the structure characteristics and used materials play a significant role in the energy consumption of buildings. Likewise, a large part of this consumption is related to HVAC systems, which keep comfortable thermal conditions and indoor air quality. This energy consumption depends significantly on the criteria used for the indoor environment, which also affect the health, productivity and thermal comfort of the occupants. In essence, the thermal behaviour of the building will condition the final selection of technologies, materials or refurbishment techniques to be used to guarantee its energy efficiency.

Reducing the energy demand in buildings and industry can be achieved by using advanced and innovative techniques and materials when constructing or renovating buildings. Smart solutions to manage energy consumption in heating and cooling, such as smart controllers and thermostats, would help to save energy. The use of renewable sources and energy management solutions for heating and cooling technologies, such as solar heating systems combined with heat storage, contribute to reducing the impact of the building sector and achieve the European sustainable goals.

Even though the Member States have recently achieved some progress regarding energy efficiency, this needs to be consolidated over the upcoming years to be able to meet the desired target of a 20% increase in energy efficiency, that corresponds to 1.483 Mtoe of primary energy consumption. Else ways, innovative energy storage solutions will play an important role in ensuring the integration of renewable energy sources into the grid at the lowest cost.

In conclusions, policy makers are implementing measures to improve building energy efficiency and foster sustainable energy usages, like the energy Efficiency Directive (12/27/EU) that stablishes that EU countries are requested to carry out and notify to the Commission an all-inclusive assessment on efficient heating and cooling by the end of this year and if requested, progressively assessments every five years.

2.3 Nearly Zero-Energy Building (nZEB)

The EPBD introduced a clear definition of nZEB as "a building with very high energy performance where the nearly zero or very low amount of energy consumption over a typical year, should be extensively covered by renewable sources produced on-site or nearby". This concept can therefore save primary energy and diffuse the use of sustainable technologies to be used in both residential and commercial constructions. It therefore represents one of the greatest opportunities to enhance energy savings in Europe.

In order to successfully address the required reduction in primary energy demand, is of crucial importance to understand better the key components that affect the energy performance associated to the different steps of nZEB implementation. Figure 4 depicts the role of passive approaches together with energy efficient systems. The value of point A represents the minimum energy performance of a building as indicated by its national/regional legislation, whereas the distance to B represents the energy demand as a result of adopting passive strategies. Further adoption of energy efficient measures reduces the energy demand to point C, where by including Renewable Energy Sources (point D), it is possible to achieve a net zero energy balance (point E).

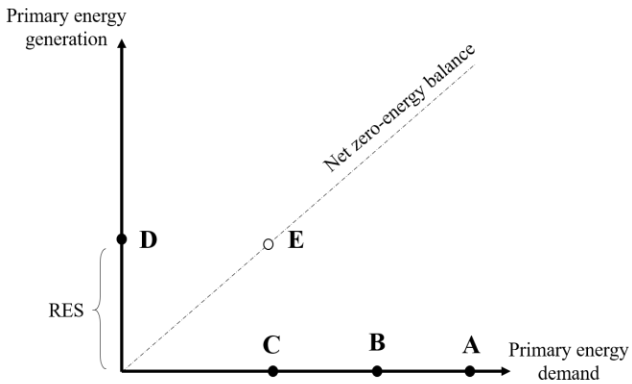

Figure 4 Schematic representation of the nZEB approach [11]

Therefore, the steps to approach the nZEB concept consist in diminish the energy demand by implementing energy efficient measures, together with meeting this demand from renewable energy supply, usually integrated in the building footprint. Regarding energy efficient measures, the priority should initially rely on the adoption of the passive approaches and secondary in the integration and use of high energy performance active systems. J. Oh et al (2017) [12] conducted a state-of-the-art review of nZEB implementation strategies where they define these strategies as:

(i) The passive strategies to reduce the building energy demand should consider both geographical and meteorological factors in the architectural design (building geometry, natural lighting and ventilation) and improve the energy saving techniques (building envelope, heat storage system and lighting designs).

(ii) The active strategies represent different ways to cover the remaining building energy consumption, or at least a significant fraction, through renewable energy sources (RES) and its back-up system. These solutions mainly include mechanic ventilation, heating and cooling systems or DHW production.

The analysis carried out in the mentioned study shows that separately, these strategies are still not enough to achieve the nZEB target, thus a combination of them is needed. Withal, setting the thermal comfort parameters is a big challenge to ensure compliance with comfort requirements, thus there are factors as the Indoor Environmental Quality (IEQ), Internal Air Quality (IAQ) and the CO_2 concentration, that should be also considered as a part of the total building performance.

However, energy retrofit measures may imbalance thermal and visual performances and may lead to consequent opposite effects. Ballarini, I. et al (2019) [13] identified that energy refurbishment actions on the building envelope that would achieve significant improvements in the thermal performance, can also reduce the indoor daylight ensuing higher electricity demand for lighting (36%). In this study, thermal and visual performance assessments were carried out through dynamic simulation using advanced software as Energy Plus and DIVA, respectively. The results of this research highlights that retrofitting design strategies could be much more significant if implemented to enhance a satisfactory daylight provision and visual comfort, while ensuring the same thermal comfort level.

Nowadays, building occupants have a better understanding of the impact that air quality has on their mental health and we are starting to better appreciate the quality and productivity implications in our residences and workspaces. Even so, the ambition to implement these highly energy efficient buildings, represent one of the greatest opportunities to increase global energy savings and improve our lifestyles.

To successfully achieve the required levels of energy performance urge, among other priorities, a cost-effective reduction within the energy consumption of the building sector to a "nearly zero" level. This low-carbon transformation will require a wide range of policies and the innovation and the development of Energy Management Systems is a promising way to reduce these emissions.

2.3.1 Technical features of nZEB

Since the Commission does not give minimum or maximum harmonized requirements it will be up to the Member States to define what for them exactly constitutes a "very high energy performance" and "to a very significant extent by energy from renewable sources". In each of them, this definition shall reflect their national, regional or local conditions and include a numerical indicator of use of primary energy expressed in kWh/m^2 per year.

With the intention to help the experts in the Member States to define the nearly zero energy buildings in a uniform way. In [14], REHVA and the European standardization organization CEN revise the nZEB technical definition and introduce an available methodology suitable to implementable national building codes for the primary energy indicator calculation.

This methodology proposes a set of system boundaries and equations to stablish and compute the primary energy needs, the energy use, the exported and delivered energy and renewable energy ratio calculation. Following this framework, both the primary energy indicator and the renewable energy ratio can be calculated as required by the directive with specifications for nearby renewable energy and for the contribution of renewable energy use.

According to EPBD recast, the energy use in the buildings includes energy used for heating, cooling, ventilation, hot water, lighting and appliances. Additionally, the basic energy balance of the produced, delivered and exported energy can be assessed through three System Boundaries (SB) that allow the primary and renewable energy calculations. These are the on-site, nearby and distant horizons (Figure 5). The energy flow has to be clarified in order to ensure a common calculation methodology of primary energy, as well as renewable energy ratio (RER).

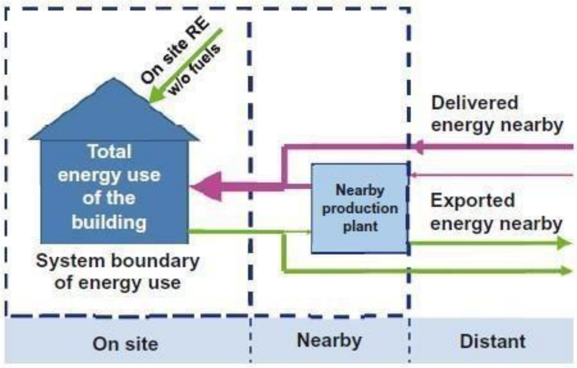

Figure 5 System boundaries for delivered and exported energy calculation [14]

System boundaries for on site assessment connect the building with on-site renewable energy sources to energy networks. To calculate delivered and exported energy nearby, the energy flows of nearby production plant need to be either added or subtracted to the delivered and exported energy flows on site. The availability of national legislation allowing the allocation of the new capacity to the building with a long-term contract is a prerequisite to apply the nearby assessment. It should ensure as well that the investment of the new capacity will lead to a real addition to the grid, district heating, or cooling mix.

As mentioned before, after the assessment of the system boundaries, it is possible to compute both the primary energy indicator and the renewable energy ratio. The concept of primary energy indicator sums up all delivered and exported energy (electricity, district heat/cooling and fuels) into a single indicator. The primary energy (1) and the primary energy indicator (2) are calculated from delivered and exported energy with national primary energy factors as:

$$E_{P,nren} = \sum_i (E_{del,i} f_{del,nren,i}) - \sum_i (E_{exp,i} f_{exp,nren,i}) \quad (1)$$

$$EP_P = \frac{E_{P,nren}}{A_{net}} \quad (\frac{\text{kWh}}{m^2 year}) \quad (2)$$

Where:

EP_P is the primary energy indicator (kWh/m^2/year);

$E_{P,nren}$ is the non-renewable primary energy (kWh/year);

$E_{del,i}$ is the delivered energy on site or nearby (kWh/year) for energy carrier i;

$E_{exp,i}$ is the exported energy on site or nearby (kWh/year) for energy carrier i;

$f_{del,nren,i}$ is the non-renewable primary energy factor (-) for the delivered energy carrier i;

$f_{exp,nren,i}$ is the non-renewable primary energy factor (-) of the delivered energy compensated by the exported energy for energy carrier i, which is by default equal to the factor of the delivered energy, if not nationally defined in other way;

A_{net} Useful floor area (m^2) calculated according to national definition.

As fixed in EPBD recast, the influence of renewable energy produced on site is accounted so that it reduces the amount of delivered energy needed. On site production is not considered as part of delivered energy and may be exported if it cannot used in the building. Figure 6 shows the three system boundaries that need to be taken into account to compute the energy flows (energy need, energy use and energy delivered and exported) within the on-site assessment (nearby production not linked to the building). System boundary of energy use applies also for renewable Energy Ratio (RER) calculation, which includes solar, wind and hydro as RE generators.

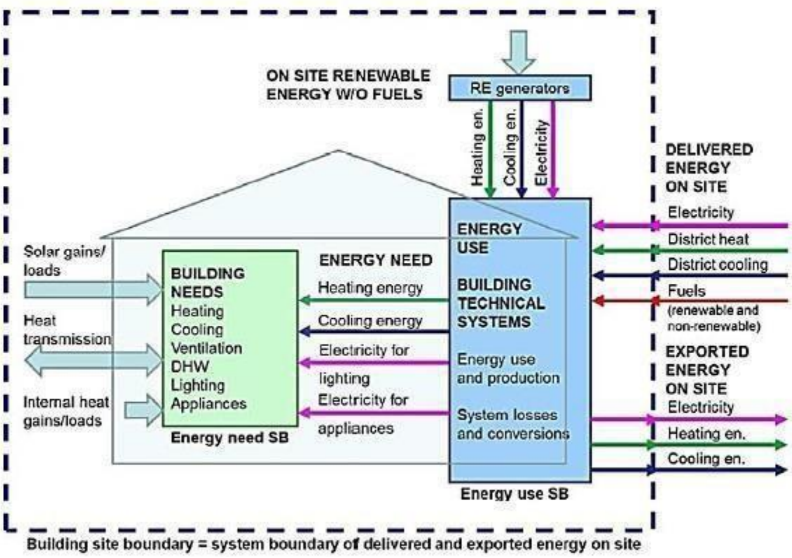

Figure 6 System boundaries for on site assessment and energy flow calculation [14]

Equation (3) displays the renewable energy ratio (RER), which is the share of renewable energy use and accounts for all renewable energy sources on and off site: solar thermal, solar PV, wind, hydro, ambient heat sources of heat pumps and free cooling and renewable fuels). The renewable energy ratio to the total primary energy is calculated relative to all energy use in the building and accounts that exported energy compensates the delivered energy. For on-site and nearby renewable energy, the total primary energy factor is 1.0 and the non-renewable primary energy factor is 0.

$$RER_P = \frac{\sum_i(E_{ren,i}+\sum_i((f_{del,tot,i}-f_{del,nren,i})E_{del,i})}{\sum_i(E_{ren,i}+\sum_i(E_{del,i}f_{del,tot,i})-\sum_i E_{exp,i}f_{exp,tot,i}} \qquad (3)$$

Where

RER_P is the renewable energy ratio based on the total primary energy;

$E_{ren,i}$ is the renewable energy produced on site or nearby (kWh/year) for energy carrier i;

$f_{del,tot,i}$ is the total primary energy factor (-) for the delivered energy carrier i;

$f_{del,nren,i}$ is the non-renewable primary energy factor (-) for the delivered energy carrier i;

$f_{exp,tot,i}$ is the total primary energy factor (-) of the delivered energy compensated by the exported energy for energy carrier i;

$E_{del,i}$ is the delivered energy on site or nearby (kWh/year) for energy carrier i;

$E_{exp,i}$ is the exported energy on site or nearby (kWh/year) for energy carrier i.

Besides the indicators of primary energy and renewable energy, there is another relevant indicator to be used for the specification of nZEB: the specific CO_2 equivalent emissions. This indicator is a good way to ensure the coherence and consistence between the long-term energy use and environmental goals of the EU. The emissions depend on the CO_2 content of the energy that is used in the building and can be calculated using the national CO_2 conversionfactors.

$$EP_{CO_2} = \frac{mCO_2}{A_{net}} \quad (\frac{KgCO_2}{m^2 year}) \qquad (4)$$

Where:

mCO_2 Is the mass equivalent emissions (KgCO_2)

A_{net} Useful floor area (m^2) calculated according to national definition.

In order to maximize the use of renewable sources and therefore limit the environmental impact caused by ventilation, lighting, heating or cooling, these strategies need to be properly planned through national calculation methods and requirements to suit the specific needs of the building according to its geographical location and climate. Each country has specific national requirements and some of them put more emphasis in encouraging the use of renewable energy, while others do not [15].

The current EU approach to foster nZEB through the EPDB implementation allows Member States to use separate national nomenclatures and definitions, sometimes even within different regions of a Member State. This creates a market barrier for saving in energy through envelope materials and components, efficient technical building systems and design strategies for new constructions and retrofits. Nevertheless, the application of these standards enacted by National Parliaments will stimulate innovative energy saving solutions that can be applied everywhere in Europe, tuned to the local climate, because they can be evaluated according to the same principles in a transparent way.

2.4 Building Energy Management Systems

The importance of energy analysis of buildings has grown over time, but still is often done using simple static calculations. Building Energy Management Systems (BEMS) are known as advanced methods used to monitor, control and optimize the building's energy requirements and performance. When the performance is efficient, this concept is closely linked with the nZEB application as it reduces the energy requirements and optimizes the energy efficiency of the existing systems to save energy and reduce the greenhouse gas emissions. This makes BEMS solutions a powerful tool to improve the energy performance of buildings.

The prediction of the building energy dynamics is a big challenge as it helps to determine the optimal schedule of thermal and electrical appliances, which requires accurate information about parameters that are constantly changing. Those values are among others, the ambient temperature, relative humidity, occupancy, wind speed or solar radiation.

Their main role of an BEMS is to achieve comfort in the building while using at the maximum efficiency the energy resources. By monitoring the energy flows, it is possible to control and analyze the energy consumption, identify weaknesses and therefore, be able to make changes in the energy loads over time or implement more efficient energy measures. There are significant opportunities to decrease energy demand for heating and cooling and to improve occupant's comfort by developing common constructive solutions according to common climatezones.

The installation of building management systems leads to energy savings by up to 30% [16]. Often, BEMS include the management of thermal energy storage tanks thatcan be used as flexible sources using power- to-heat devices as the electrical heat pumps (HPs) that can interact with thermal appliances such as Thermal Energy Storage (TES)systems.

In [17], M. Hannan et al (2018), the authors conduct a rigorous review of the potential of an Internet of Energy (IoE), which combines the smart grid and Internet of Things (IoT) characteristics. The study applies the concept to reinforce the energy performance of future building generations and criticizes that many existing BEMS have data loss and network problems mainly due to static set points. The results highlight that efficient energy management systems require advanced controllers integrated with IoE-based technologies.

Accurate dynamic models used for advanced control techniques could significantly contribute to reduce the energy demands for HVAC systems. Additionally, the application of suitable Energy Management Systems according to precise climatology conditions will be crucial to transform today's world into a competitive, sustainable and low-carbon economy. Of the various RES that can be installed in the building sector to cover energy requirements, solar energy systems are currently the most widely used, especially for locations with high annual solar radiation and temperatures. Solar energy systems are already a viable alternative to fossil energy systems and are expected to become even more efficient and cost-competitive in the future.

2.5 HVAC Systems

Within residential buildings, HVAC is responsible for the largest share of energy use. It also plays an important role in broader the implementation of nZEB. HVAC refers to an assembly of various types of equipment installed together, able to move air between indoor and outdoor areas and provide heating and cooling along with indoor climate control. The working principle of heating and cooling in HVAC systems follows the basic principles of heat transfer: a) heat always flows from areas of high temperature to areas of low temperature and b) heat is transferred to and from these areas either via conduction, radiation or convection.

Nevertheless, HVAC systems are able to reverse the heat transfer natural flow, removing hot air from buildings in the hot summers and placing it in buildings in the cold winters. Heated or cooled air is distributed within buildings either through forced air (electrically powered fan), gravity (hot air rising) or radiation (heated floor, walls or ceilings).

Some of these HVAC systems are heat pumps or air conditioners, which include Heat Exchangers (HE) to increase the efficiency of heating and cooling processes, reduce refrigerant charge and save space. Heat exchangers are devices used to transfer thermal energy from one fluid to another. Those fluids can be single or two phase and, depending on the exchanger type, may be separated or in direct contact. The fluids must be at different temperatures for heat to flow. Normally, HE for HVAC purposes use convection and conduction (radiation does occur but only in a small percent). Most HE follow either coil or plate designs.

Commonly, there are two approaches to classify HE: considering a) the flow configuration: counter flow, co-current low, crossflow or hybrids such as cross counterflow and multi pass flow, as depicted in Figure 7,and b) the equipment construction: regenerative or recuperative [18].

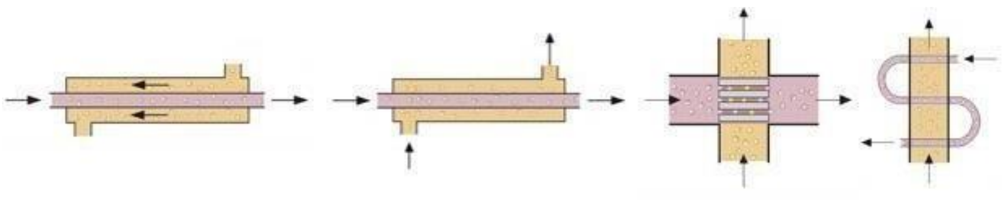

Figure 7 Counter flow, co-current flow, cross flow and cross/counter flow types of HE [18]

There are different examples of heat exchangers used in HVAC units such as condensers, evaporators or earth coils. In case of HVAC systems powered by renewable sources, the role the HE is often coupled with two of the most common types of HVAC equipment, the air conditioner and the heat pump.

All air-conditioning systems rely on the refrigerants pressure-temperature relationship. When a refrigerant evaporates or boils it absorbs heat at a very high rate as is the case with all liquified gases. Normally refrigerants have lower boiling points than most liquids and it can be easily manipulated so that the only heat source needed is room-temperature air. The boiling point can be controlled by altering the pressure placed upon the liquid. This is a very effective and cost-effective method for HVAC in buildings.

During the summer mode, the compressor, which is the heart of the heat pump, receives cool and low-pressure refrigerant vapor which is pumped into the high-pressure side of the system. This hot air pressure gas travels through a routing valve (reversing valve) to the outside coil which works as the condenser. Here the heat is removed from the refrigerant by an outdoor fan causing its condensation into a liquid. The liquid refrigerant passes through a one direction valve (check valve) and travels to the indoor unit (evaporator) where it is forced through the second expansion valve, which restricts the refrigerant flow decreasing the pressure and causes its evaporation. As the refrigerant evaporates, it absorbs heat from the passing air. In addition, the cold evaporator collects moisture which provides dehumidification for the home. Then, the refrigerant travels back to the compressor where the process is repeated over and over again.

During the winter mode, the reversing valve reroutes the refrigerant path, thereby the outside coil functions as the evaporator and the indoor coil as the condenser. The heat is absorbed from the outside air by the evaporator, brought inside and release by the condenser to heat the home air. This process is depicted in Figure 8.

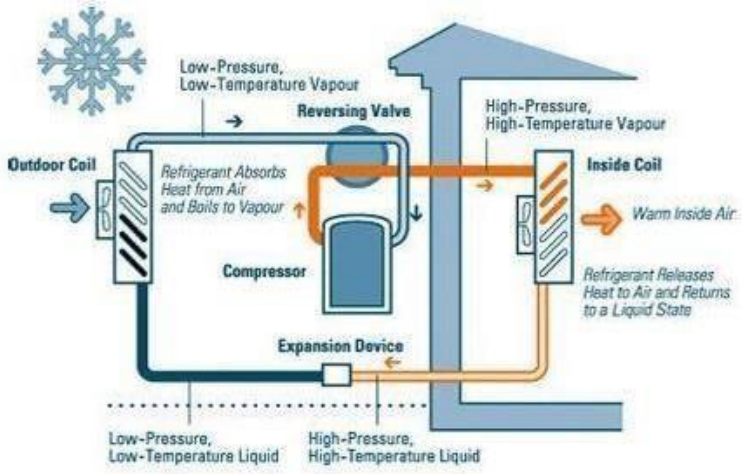

Figure 8 Air source heat pump scheme; Energies [Ref????]

The HVAC market faces an innovative future as a result of continuous advances in intelligent technology. These include systems for monitoring building's energy consumption and controlling the energy output of a HVAC system.

2.6 Solar thermal systems for HVAC

It has been shown that to achieve the nZEB approach is not enough by reducing energy consumption through passive measures. Therefore, the active systems, as those that allow harvesting the solar energy to partially replace the use of non-renewable energy, are one of the best solutions to consider. At this level, solar thermal solutions together with electricity production through PV systems play an important role, mainly in countries with high levels of solar radiation, as in the Southern European countries.

The employment of solar energy for heating and cooling purposes is widely used. Although the primary application during the last decades remains hot water production for sanitary uses, space heating and cooling from solar energy is gaining ground in several countries. Solar thermal systems are considered a mature technology that has gone through markets all over the globe with the highest total installed capacity among other renewable energy technologies [19]. According to the European Solar Thermal Industry, in Germany represents almost 40% of the European market, followed by Italy (10%), Poland (9%), France and Greece with 7% each[20].

For water heating, solar thermal systems take advantage of the free heat supplied by the sun to warm up either water or different working fluids to later produce hot water services throughout the year. There are different devices by which the solar water heating system is usually formed, these are the following: the solar collectors, the storage tank, the pump and the piping system for water transport. For continuous supply of warm water, temperature controllers and either electric or gas back-up systems are also integrated with solar thermal systems. Figure 9 gives a scheme of the general components of solar water heating systems.

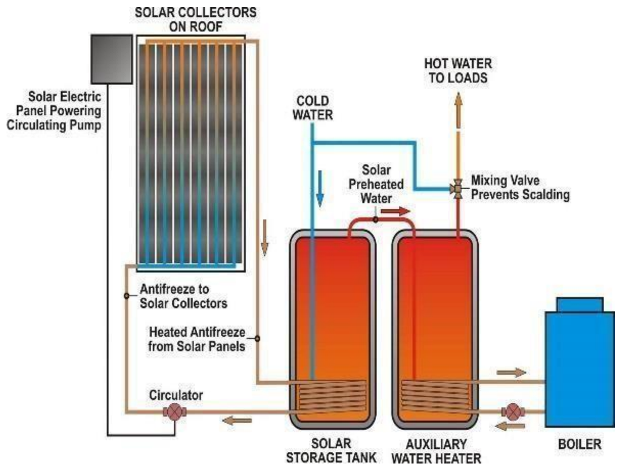

Figure 9 Layout of a conventional solar water heating system [21].

Solar collectors collect the energy from solar irradiation to heat up the working fluid. Good optical properties will make them absorb as much heat as possible. The heat absorbed by the working fluid can then be used not only for DHW loads, but also for other different purposes including indoor comfort, HVAC or thermal energy storage through different thermochemical processes.

In spite of the future of solar thermal systems appear to be very positive, there are still barriers to its widespread deployment. These mainly include technical problems, focused on the space availability for the installation of the collectors and its accompanying equipment, as well as the requirement of high energy density thermal storage materials. Nevertheless, there are other barriers as economic, legal, educational, and behavioral issues. Two of the main issues regarding the implementation of solar water heating systems are: the high dependency on the variable weather conditions and the lack of materials with high latent heat storage density[22].

2.7 Europe climate zones

As it has been reviewed, subjects such as eco-design requirements, energy performance and compliance regarding energy efficiency are expanding towards the European level. This leads to the necessity of defining zones which share common climatic characteristics and will further improve the estimation of building energy performance.

There are different ways to harness solar energy. The amount of energy that the sun provides annually to Earth's atmosphere is enormous, it is estimated to be approximately 10.000 times the world energy consumption. Although only a smaller fraction goes through the atmosphere, the average value of solar radiation that reaches the Earth's surface is about 1000 W/m^2. The solar radiation that reaches the earth´s surface can be used both for power generation and heat production at different levels as dwelling, public services and industrial purposes.

When analyzing the energy consumption of buildings, it is convenient to evaluate whether the different energy use of the building is climate dependent or not. The variables that depend on the climate are those that affect the specific energy consumption of the building, which increases when climate becomes more severe. These variables can be shorted out as external air temperature, wind velocity and direction and both solar and infrared radiation. Likewise, the energy uses that are affected by climate are space heating and space cooling.

It is well recognized the relevance of the sun as an energy resource within Southern Europe countries. However, many of these countries account for strong climate variations and different energetic resource profiles throughout their territory. These situations concern regional and more adaptive requirements able to address the heating and cooling seasons more properly. The geographical analysis of the availability of the primary solar energy resource can improve our understanding of the potential contribution to the future energy and economic structures and therefore, contribute to setting up effective policies. Figure 10 shows the Global Horizontal Irradiance (GHI) in Europe and the vast potential of solar energy.

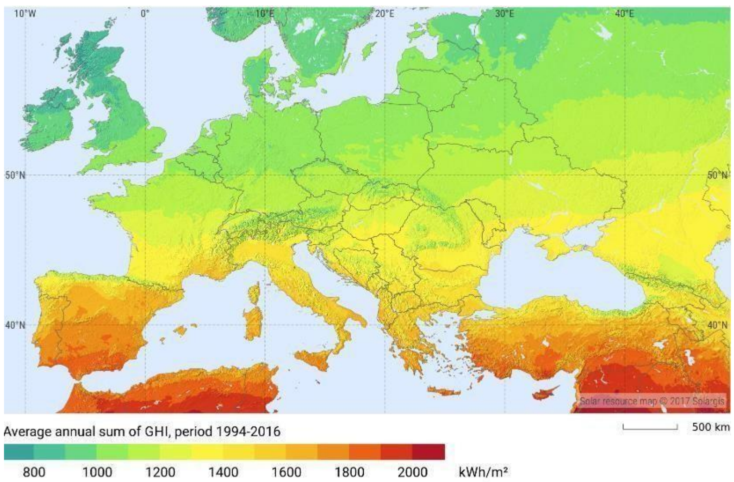

Figure 10 Global Horizontal Irradiation in Europe; Solar resource map © 2019 Solargis

There are different irradiation levels associated with different orientations for each geographic situation. The yearly sum of global irradiation is specific to the location and it can be obtained from databases, measurements, computer programs or irradiance maps. To limit investment costs and minimize the area of the solar collectors, solar systems are usually oriented where the yearly solar radiation is maximized.

Climatic zones are understood as those with similar climate characteristics (outside temperature, solar radiation, humidity, etc). There are many countries with different climate zones classification but similar regulations. Climate borders are different and independent from political borders and, unfortunately, nowadays is the political border the one that divide climates zones and implements national regulations on them. There are a wide variety of climatic conditions that buildings may bear affecting the energy performance of its systems. This subject must be addressed in order to determine the most appropriate technologies for each different region.

Nevertheless, over the past decade, the EU has been focusing on the requirements for the different climate zones, in order to build a regulatory framework able to include local standards as input. The main goal within the regulation side of the climate requirements is to achieve climate-specific nZEB building concepts.

According to Köppen-Geiger climate classification [23], there are four prevailing climatic zones in Europe (Table 1). Withal, countries may have more than one climatic zone and it can be difficult to establish the prevailing climate within this classification. To facilitate the comparison of different national approaches for the definition and implementation of nZEB, Ecofys created a 'nZEB zoning' by dividing the European countries in 5 European climate zones based on global radiation, heating degree-days, cooling degree-days and cooling potential by night ventilation (Table 2). By taking the general climate classification of the Köppen-Geiger system as a starting point, combined with the European Heat Index (EHI), the European Cooling Index (ECI), developed by Ecoheatcool (2005) and showed in Figure 11, and the nZEB zoning, PVSITES [24] proposes in its publication an updated and new zoning map for nZEB.

Table 1 The prevailing climatic zones in Europe by Köppen-Geiger climate classification [23]

Csa	Warm Mediterranean: Temperate with dry, hot summer
Cfb	Temperate oceanic: Temperate without dry season and warm summer
Dfb	Temperate continental: Humid continental climate without dry season and with warm summer
Dfc	Cool continental: Cold, without dry season and with cold summer.

Table 2 The five prevailing climatic zones by Ecofys [25]

Zone	Main cities	Köppen
1	Athens- Lamaca-Luga-Catania-Seville-Palermo	Csa
2	Lisbon-Madrid-Marseille-Rome	Csa Cfb
3	Bratislava-Budapest-Ljubljana-Milan-Venice	Dfb
4	Amsterdam-Berlin-Brussels-Copenhagen-Dublin-London-Macon-Nancy-Paris-Prague-Waszawa	Cfb/Dfb
5	Helsinki-Riga-Stockholm-Gdansk-Tovarene	Dfc

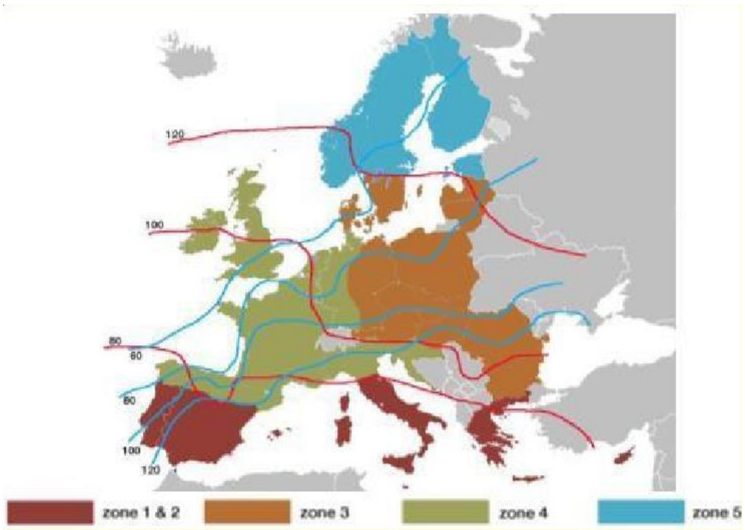

Figure 11 Alternative NZEB climate zones based on Köppen-Geiger and the EHI and ECI; [26]

S. Attia et al [27], have conducted a cross-comparative study of the climatic, societal and technical barriers to implement the nZEB target through 7 Southern European countries. The objective is to identify both the challenges and possible synergies between these regions with similar climate. Simultaneously, the research attempts to help create a common approach for the future development of high-performance, climate-adaptive buildings. Their assessment show that there are no clear functional concepts but a lack of understanding of the nZEB's performance. The conclusions postulate that "most Southern European countries are poorly prepared for nZEB implementation" mainly due to insufficient funding of human infrastructure (problem root cause) and that the European Union and their own governments are only supporting the targets financially but no enforcing and enabling human infrastructure.

The transition of the European building environment to energy efficient and nearly zero-energy buildings is a great challenge and it has become clear that studies from different climatic regions can not be directly compared. Some may require distinct design strategies to minimize the energy consumption. Likely, the definition of climate change scenarios and its correlation with the overheating risk at a scale of the different countries and regions is not properly addressed yet. To culminate with the disparity within the nZEB concept in the Southern Europe countries, the definition of performance indicators should be tightly tuned to their individualclimates.

The corresponding descriptive parameters should be clearly identified to be able to engineer a cost-efficientstrategies, able to meet the desired targets. It is essential to adapt and detail the technical and constructive solutions for different regions thus, different national regulatory and policy instruments need to address the complex energy efficiency issue in the building sector.

More in detail, an overview of the status of different energy measures, policies and legislations within the countries of Southern Europe related to the IMPROVEMENT project (Portugal, Spain and France) [28], will be addressed in this part of the document. Table 2 provides a summary of the main points regarding the nZEB requirements, implementations and performances in these three countries.

Table 3 Main nZEB status and if detailed definition is fixed in a legal documents [29][30]

Country	Legislaton and Definition available	Subsidy Retrofitting towards nZEB	Thermal comfort Standard	Very significant extent of renewable energy	Primary energy indicator in kWh/m^2year
Portugal	National Plan is in place but, numerical indicators were exactly stated only in 2019 and they depend on several variables	Unspecified	Yes, adaptive comfort model based on ASHRAE ST 55 AND EN 15251. The nZEB heating needs area at the most 75% of the reference building	The requirement is at least 50% of the total primary energy	Min. energy performance requirements is a A certificate(50% or less of the reference building)
Spain	Still to be approved. A draft of nZEB indicators for Spain was published in December 2016, without specifying their limits.	Yes, e.g. projects FARO, REMOURBAN,RePublicZEB, ECOCITY	Yes, indoor limits based on Fanger model and ISO7730	No requirements. Min. energy performance and direct requirements for certain buildings included in current legislation	Min. energy performance requirements not directly included in current legislation
France	National Plan *"Energy transition for green economic growth"*. Min. threshold for cooling and heating set (50 kWh/m2.a). The PE ranges from 70 to 110 kWh/m2/a. Positive Energy Buildings and Low Carbon label	No, (Only credit tax per replacement action 30%, max 8000€/a.person	Yes, adaptive comfort model based on EN15251 and ISO7730	For RT2012 (Min.-Max.): 5-12 $kWh/m^2.a$ for single and multi-family houses, futher updates in RT 2020	Yes

2.7.1 Portugal

According to Köppen-Geiger climate classification, Portugal accounts with warm Mediterranean climate (Csa) in the center and north of the country and temperate Mediterranean climate (Csb) within the southern regions.

The Portuguese regulation has been adapted with the last EPBD updates and presents a definition of nZEB. This is considered as all building that uses envelope cost-optimal solutions and where the remaining energy need are covered by on-site or nearby renewable production. This definition is now more or less complete, and states as follows: NZEB is a building where the consumption is below 75% of the reference (buildings B or less), [Portaria 42/2019]. In 2010, the Portuguese National Laboratory of Civil Engineering (LNEC) have developed an adaptation to the Portuguese context of the thermal comfort model [31], specified in both the American ASHRAE Standard and the European one EN 15251.

During the last decades, all temperature related climate indices have shown dramatic increases in the climate change scenario. Due to the mild winters within a significant portion of the country (Figure 12), there is an overheating risk when using passive measures of nZEB requirements with additional control limitations in the case of existing buildings. The economic constraints, cultural habits and climatic conditions, have led to low tech nZEB solutions.

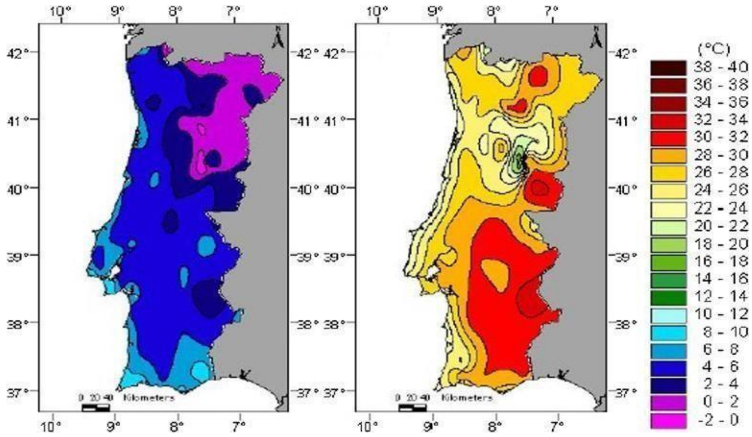

Figure 12 Climatic zones of Portugal, (left) Mean minimum temperature in winter and (right) Mean maximum temperature in summer. Data from 1961 to 1990 [32].

The Portuguese government has created funds to finance innovation research and technological development in the field of renewable energy, as well as to support campaigns that raise awareness on RES issues. The PV sector has been mainly driven by small installations, but over the last decade, the feed-in tariff (FIT) experimented significant cuts with the aim of bringing FIT prices down to market prices. Now is the self-consumption regime the one that experiments the main incentives by facilitating its installation [33].

Regarding the building sector, policies obligate to use solar thermal collectors for heating water and regulate the performance and durability of installations and its components. Within the heating sector, there are not any direct support scheme for RES in the heating sector, only indirect. Nevertheless, the Energy Efficiency Fund (FEE) provided a subsidy for solar thermal installations for heating water through "Efficient Buildings 2016".

2.7.2 Spain

Given the wide geographical typology of the Spanish territory, it has a great variety of Köppen-Geiger climate indicators among which predominate the following ones: warm and temperate mediterranean (Csa, Csb); temperate oceanic (Cfb) and cold semi-arid (Bsk) climates, all of them depicted in Figure 13. Concurrently, the Basic Document HE0 of the Spanish Technical Building Code (CTE), distinguishes four geographical areas depending on the climate severity in summer (indicated from lowest to highest: 1, 2, 3 and 4 from lowest to highest) and five geographical areas depending on the severity of the climate in winter (from lowest to highest: A, B, C, D and E).

Figure 13 Spanish climate zones (based on data from CTE DB-HE of 2013 [34])

This broad difference between the climate zones constitutes one of the major challenges of nZEB implementation and therefore, different indicators are required to evaluate the different performance of nZEB in Spain's varying climate. Other barriers, as the socio-economic aspect or the slow development, are also limiting the progress of nZEB implementation.

The nZEB concept is defined and regulated within Spanish legislation 'Documento Básico de Ahorro de Energía' (DBHE) [35], as those new or existing buildings which satisfies the basic requirements of the current technical building code. The mentioned minimum requirements are the following: the limitation of energy consumption and demand, the thermal performance, the energy efficiency of lighting systems and the minimum of both solar contribution to DHW and photovoltaic contribution to electricity production.

The new regulations have been separated into two main features: a) the energy needs of the building, represented by the total Primary Energy (PE) consumption and b) the quality of the envelope, evaluated through three new parameters that respond to the three forms of energy transmission - the global thermal transmittance (conduction), the solar gains (radiation) and the building permeability (convection).

In this way, all new buildings constructed in accordance with DBHE2019 will be nZEB. The existing buildings that meet new buildings in PE consumption indicators will also be considered nZEB. Furthermore, from the year 2021 all new residential buildings should have a PE consumption 70% lower than buildings constructed under the previous regulations and 85% less than the buildings representing the stock for 2006.

In Spain, the last update of the main support scheme for renewable energy sources, the "Régimen Retributivo Específico", was established in 2014 under the aim of granting specific remuneration regimes for new renewable energy plants, located within the mainland electricity system. However, a contribution mechanism that established charges on existing and new self-consumption RES plants, both on capacity and generation levels, was in place until October 2018. Under the new regulation self-consumption of RES is free from these charges and the procedures for RES self-consumption have been simplified. Currently, no support schemes for heating and cooling RES are placed in Spain.

2.7.3 France

The vast French territory also covers several climate indicators among which temperate oceanic (Cfb), cool continental (Dfc), temperate continental (Dfb) and temperate mediterranean (Csb) can be highlighted due to its major extension. Figure 14 shows how the French building standard divides the country into four summer areas (a,b,c and d) for the non-heating period and three main zones for the heating period (H1, H2 and H3).

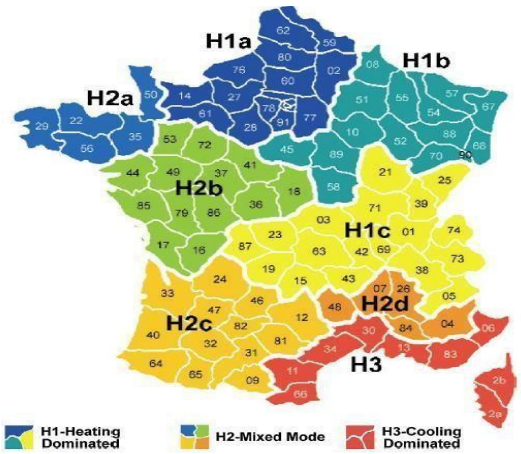

Figure 14 Climatic zones of France based on cooling or heating dominance [36]

The French legislation has shifted for a new building thermal regulation, which promotes Positive Energy Buildings (BEPOS, Bâtiment à énergie positive), targeting all building consumption from the pure energy approach to an environmental assessment one. It also strives to balance the energy consumption of the building with renewable energy resources. Within the new regulations, there is a standard for Low Carbon Buildings, taking into account the environmental impact of building construction, operation, greenhouse gases emissions, energy systems and even considers the transport means used to access the building. This new approach allows the definition of the E+C− (Energy positive and Low Carbon) label [37].

There are various policies aiming at promoting the development, installation and usage of RES in France, including certification schemes (PV installations, solar thermal plants, wood-heating systems and heat pumps), RD&D and training programmes as well as building obligation for the use of renewable heating. Electricity from RES is promoted through different tariffs (feed-in tariff, premium tariff) and through tenders [37].

Concerning heating and cooling, the public distribution is a competence of the local or regional authorities and the generation of heat through renewable energy plants is promoted through several energy subsidies as tax regulations mechanisms or zero percent-interest loans. Furthermore, territorial communities must ensure that heating networks are classified and supplied with at least 50% of heat from renewable energy sources.

3 Case study

The case study consists of a specific area that belongs to “Laboratório Nacional de Energia e Geologia” (LNEG), a large office building in Lisbon built in the1980’s decade where research activities related to renewable energy systems and smart grids are carried out. Figure 15 shows the delimited area within the pilot building that has been selected for the implementation and validation of the proposed energy efficiency measures to perform the nZEB conversion.

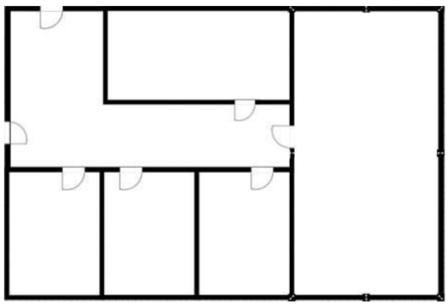

Figure 15 Layout of the delimited office area

The developed model has been used to evaluate the thermal performance with a useful floor area of 156 m^2. The state of the art of the pilot section has some aspects that have been already defined, for instance the external envelope already include external insulation and it is not possible to introduce significant changes on the outside part of the building.

The preliminary work associated with the case study consisted in the characterization of the condition of the building before any retrofit action and the calculation of the energy and comfort needs of the different rooms. These measures were carried out by LNEG and IST to be able to specify the new equipment to be acquired and the building modernization works to be performed.

3.1 Main components of the energy system

The pilot building has been planned to be installed with a solar trigeneration system (electricity, heating and cooling). The electrical system (Figure 16), is planned to be powered by PV modules (4.6 kW), two hybrid PV-T liquid collectors of 3 m^2 and a total power of 0.7 kW and a small urban wind turbine (2.5 kW). The power system could be installed on the roof of the building and connected to the AC grid by grid-commuted inverters adapted to the energy source. In this case, a battery bank could be used to balance the variable generation.

Originally, the proposed thermal system includes two thermal flat solar collectors of 4m^2 each connected in series, a DHW thermal storage (300 l + 200 L heat tanks) to be supplied to taps and appliances and an air/water 2.4 kW Heat Pump for space heating and cooling through fan coils, using a 1000 L water tank as an inertial element. The layout of the mentioned system is shown in Figure 17. The operation period of the heat pump is a function of the available renewable electricity production (PV and wind), the thermal load of the building and the volume of the storage.

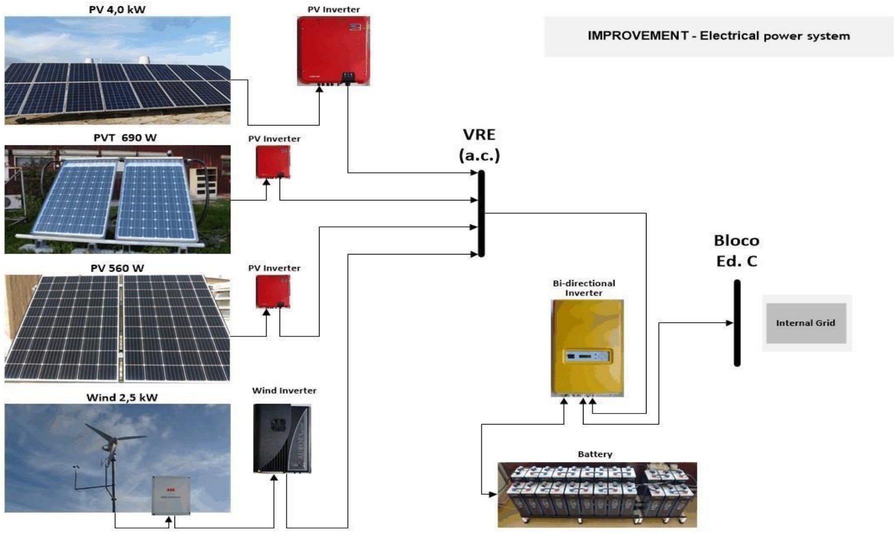

Figure 16 LNEG pilot plant power system

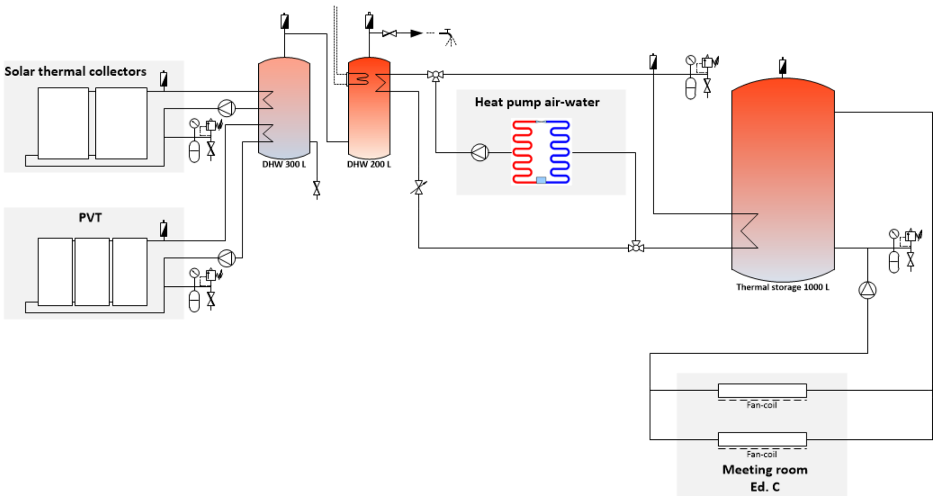

Figure 17 LNEG pilot plant thermal system

Despite of the mentioned state-of-the-art of the proposed electrical and thermal systems, the modelling of the thermal system has been carried out only for air conditioning purposes and specifically for heating. The developed model includes the solar thermal collectors, the thermal storage tank and a pump that connects them. The model will also account with a back-up unit which will be activated if the solar generation is not enough for the heating requirements.

The basic geometric and thermal details of the case study building used to run the simulation are given in Table 4. The heat transmission coefficients and the thermal capacity were determined in [38], in accordance with ISO 13789.

Table 4 Main thermal parameters of the simulated office

Parameter	Value
Orientation	N-S
Htr,op	80.6 W/K
Htr,w	19.1 W/K
Htr,is	2283.7 W/K
Htr,ms	3981.0 W/K
Htr,em	82.3 W/K
C_m	37.58 MJ/K

Where:

$H_{tr,op}$ Transmission heat transfer coefficient of the opaque building elements, (W/K)

$H_{tr,em}$and $H_{tr,ms}$ Transmission heat transfer coefficients ofthe external and internal part of $H_{tr,op}$, respectively, (W/K)

$H_{tr,is}$ Transmission heat transfer coefficient between the air node Ti and the surface node Ts, (W/K)

$H_{tr,w}$ Transmission heat transfer coefficient of doors, win-dows, curtain walls and glazed walls, (W/K)

H_{ve} Transmission heat transfer coefficient of ventilation air,(W/K)

C_m Internal thermal capacity of the building,(J/K)

Furthermore, the internal heat gains schedule has been set up as shown in the following table 5

Table 5 Schedule for the weekly internal heat gains

Period	*Hours*	*Internal heat gains (W)*
Weekdays (Mon.-Fri.)	6.00-8.00, 15.00-22.00	800
	22.00-6.00	300
	8.00-15	0
Weekends (Sat.-Sun.)	All day	400

By last, the modelled thermal energy system has been simulated for three different cities that belong to the South European climate region: Lisbon (1), Madrid (2) and Marseille (3), as it is shown in Figure 18. The results for each city will be presented in Chapter 5.

Figure 18 Southern Europe test locations

3.2 Global Irradiation on sloped surfaces

The amount of solar radiation incident either on solar thermal collectors or photovoltaic panels is strongly affected by its installation angle and orientation [39]. Therefore, finding the optimum tilt angle to receive maximum solar radiation on a photovoltaic module is the best way to take full advantage of the solar radiation.

Generally, global solar radiation is measured on horizontal surfaces, although due to the inclination of the Earth, the maximum amount of incident solar radiation is measured on inclined surfaces. In [40], Maleki et al. have reviewed the estimation of the most accurate model (or models) for computing solar radiation components for a selected location. Their conclusions show that one of the most accurate models is the Liu-Jordan.

For the case study, the selected collectors are oriented to the south and with an inclination approximately equal to the latitude. The annual global irradiation of the three studied cities, has been computed following the Liu-Jordan isotropic model [40][41]. The three cases are depicted in Figure 19, Figure 20 and Figure 21, where the irradiation is measured in kWh/m^2 and the 8760 hours of the year have been grouped by months. Table 6 shows the computed annual global irradiation on a sloped surface facing south for each city: Lisbon, Madrid and Marseille, with its respectives latitudes and the selected tilt angle.

Table 6 Annual global irradiation, latitude and tilt angle of the study cases

	Latitude (°C)	*Tilt angle (°C)*	*Global Irradiation (kWh/m2)*
Lisbon	38.74	40	671.90
Madrid	40.42	40	977.20
Marseille	43.30	45	581.53

The simulation of the model was carried out according to detailed weather data. The data was firstly downloaded from the EnergyPlus website [42] and then utilized to compute, the hourly values of global solar irradiance on a sloped surface of any orientation and slope. As mentioned before, this has been calculated through simple Liu-Jordan method.

The very same procedure was followed for the three European cities: Lisbon, Madrid and Marseille. These calculations were done in different excel files whose data were imported to MATLAB/Simulink and simulated independently.

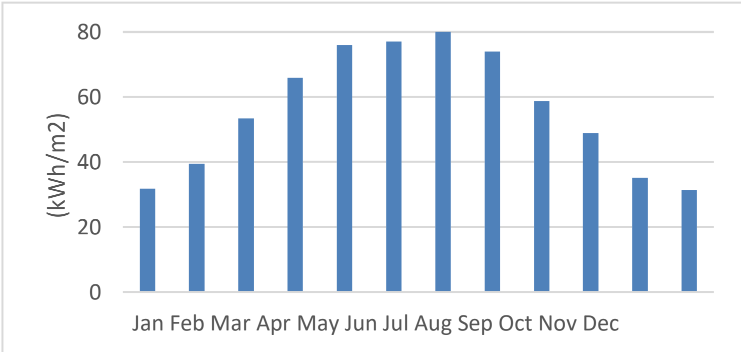

Figure 19 Lisbon'sannual solar irradiation

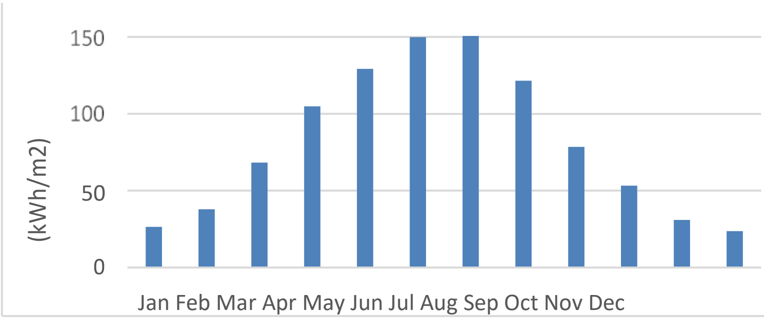

Figure 20 Madrid's annual solarirradiation

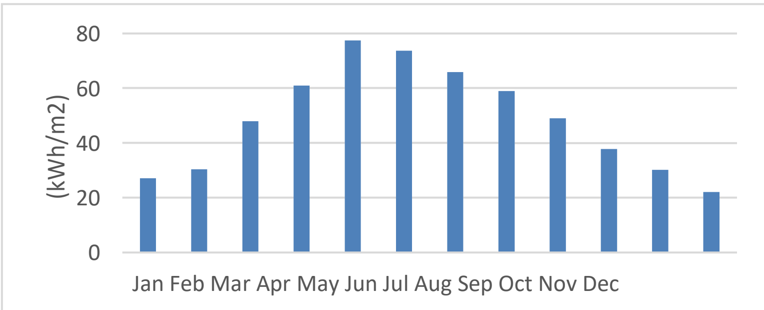

Figure 21 Marseille's annual solar irradiation

3.3 Simulation tool selection

The implementation of the solar active systems for heating and cooling in buildings are one of the main solutions for the nZEB conversion. However, although solar irradiance, consumption and thermal storage are naturally transient processes, it is commonly seen that the design rules of the involved parameters are based only in steady state models.

The production of Domestic Hot Water (DHW) based on solar thermal collectors is a classic example of HVAC system characterized by substantial variations of the thermal load during the day and the different seasons. In order to achieve more accurate and reliable results, the significant parameters of the model should be analyzed through an hourly evolution. This is possible when following a dynamic approach, able to evaluate hour by hour the energy absorbed by the solar collectors and the temperature of the hot water produced by the system

Wetter [43] remarks that developing building energy simulation with Simulink has essential advantages, as the capacity to perform frequency domain analysis or automatic inversion of the defined models. These features can not be achieved by other traditional energy simulation software as EnergyPlus or TRNSYS. Evenly, MATLAB/Simulink framework is very well known and widely applied both in professional and academic environment, meaning a very large potential user's audience able to add new components and examples to the library.

Simulink, integrated with MATLAB, is a platform for Model-Based Design through a block-diagram environment that allows virtual validation and verification. This software provides immediate access to a broad range of analysis and design tools by means of which users can easily combine, both dynamic building thermal simulation and multi-objective optimization, avoiding "co-simulations" that involves different software platforms. Therefore, Simulink has become suitable and interactive tool for modelling, simulating, and analyzing dynamic systems as the complex control systems currently used in HVAC systems.

The prediction of the building management dynamics is a big challenge as it is the determination of the optimal schedule of thermal and electrical appliances, which requires accurate information about parameters whose values are constantly changing. Dynamic energy management is a key enabler for the integration of renewable power generation into the grid.

Controling Energy Management Systems are one of the biggest challenges in the 'smart energy society'. With MATLAB/Simulink it is possible to overcome these challenges as the software allows users to: Access and preprocess both engineering and business data, build data-driven and physics-based models, model and simulate equipment performance, design algorithms to optimally control equipment and many other features. This is possible due to Simulink interface accounts with an end-to-end work flow that enables data processing, prediction, optimization, system simulatioon and integration, which is very useful for any modeling project.

4 Modelling and simulation

The model of the energy management system of the heating and cooling generation and system of the case study has been developed taking into account the dynamic approach, which is based on the analysis of the hourly evolution of the significant status parameters. There are two principal reasons to follow such approach. Firstly, the thermal loads strongly depend on time (hourly basis) and the performance of HVAC systems based on renewable sources varies significantly during the day and the season. By following this approach, it is possible to give an accurate evaluation of the thermal performance of the office. This section covers the explanation of how the system has been built and modelled.

MATLAB/Simulink environment can be efficiently used to build the components of a thermal system and offers considerable simulation advantages for the dynamic modelling of buildings. Any component is modelled through specific sub-blocks which contains the lumped formulation of the conservation equations.

Figure 22 depicts the layout of the thermal energy management system modelled for the office's case study. It has been built through MATLAB/Simulink environment. Four principal sub-systems have been employed for the modelling of the thermal performance of the office. These are:

- The *Solar System,* composed by the collectors, the storage tank and the auxiliary equipment such as the pump.
- *The Room*, which simulates the thermal conditions of the case study by considering the heat gains and losses through the envelope, infiltration and ventilation, solar gains and internal gains.
- The *Fan Coil Unit* system, which allows the heat exchange between the *Solar System* and the Room.
- The *Back-up* unit, that will be activated when the energy provided by the collectors does not meet the thermal needs of the office.

Each block and their respective sub-blocks are described more in detail in the following sections.

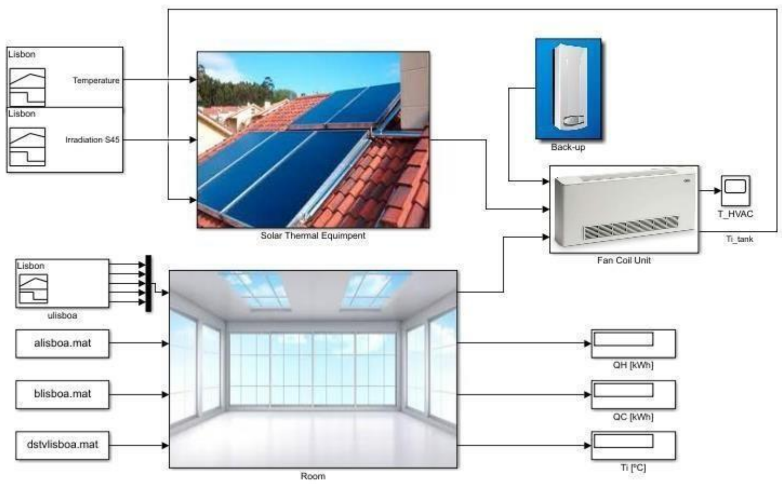

Figure 22 Layout of the complete thermal system model

4.1 The *Room* block

The *Room* sub-system is based on the solution that Piotr Michalak proposes in [38], which introduces a novel Linear Time-Varying (LTV) simulation model of thermal network of a building. It has been developed through the Simulink S-function stvmgain (i.e. continuous time varying matrix gain). Through this function block, it is possible to build a state-space model of the building in the form of state-space matrices with time-varying parameters as inputs. These can be generated according to the user's requirements.

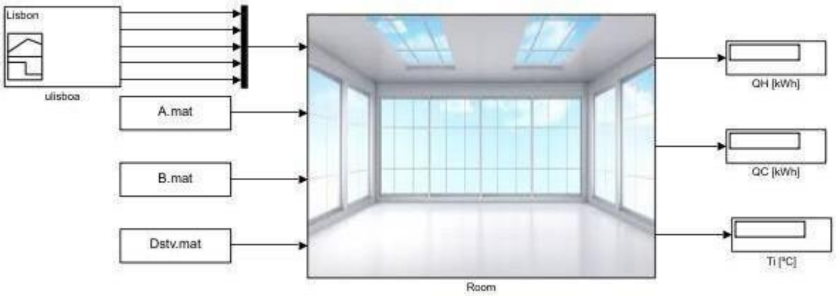

Figure 23 Room's Layout with its inputs and outputs variables

Figure 23 depicts the *Room* sub-system, by means of which the main thermal loads (gains and losses) of the office are calculated. The hourly values of the heating and cooling needs have been calculated through a simple hourly model: the five resistances, one capacitance (5R1C). This model is described in ISO 13790:2008 Standard [44] and enables the calculation of the energy consumption and use of the space heating in residential and non-residential buildings. (See Appendix A: 5R1C model). The inputs that constitutes this system belong to different files composed by four different time-varying matrices, generated according to the heat transfer/thermal specifications of the building (*A, B, C and D*), the input signal '*u'*, the *Dead Zone* and the saturation blocks. This will be applied for each studied city.

Since the model of the *Room* is able of calculating the thermal needs for space heating, the simulation of this sub-system will be the first to be carried out. Once the thermal needs are known, the rest of the sections will be developed to know if these requirements can be fully provided by the solar collectors or if a back-up unit will be needed. The inputs of the system are:

- The 'u' block, that has been created by means of the Signal Builder Simulink's block, which containsthe hourly values of the external air temperature (T_e), the supply air temperature (T_{sup}) and the heat fluxes to the internal mass (Φ_m), to the central node (Φ_{st}) and to the internal gains (Φ_{ia}).

- The *A.mat, B.mat, C.mat, Dstv.mat* blocks are the system, input, output and input-output matrices respectively, composed by the different transmission heat transfer coefficients within the building and the internal thermal capacity of the building and (See [38] for full set of equations).

- The *Dead zone* block allows the temperature control for the heating and cooling, according to EN ISO 13790 requirements. This block is coupled with the gain block *FHC*, which is used as temperature error gain.
- The *Saturation* block is used to limit the maximum heating and cooling power. Furthermore, two display blocks (H and C) have been used for the measurement of the respectively heating and cooling energy needs to be delivered to the building zone.

The outputs of the Room are the heating needs (QH), the cooling heeds (QC) and the internal temperature (T_i). As described above, Figure 24 depicts the layout of the Room sub-system.

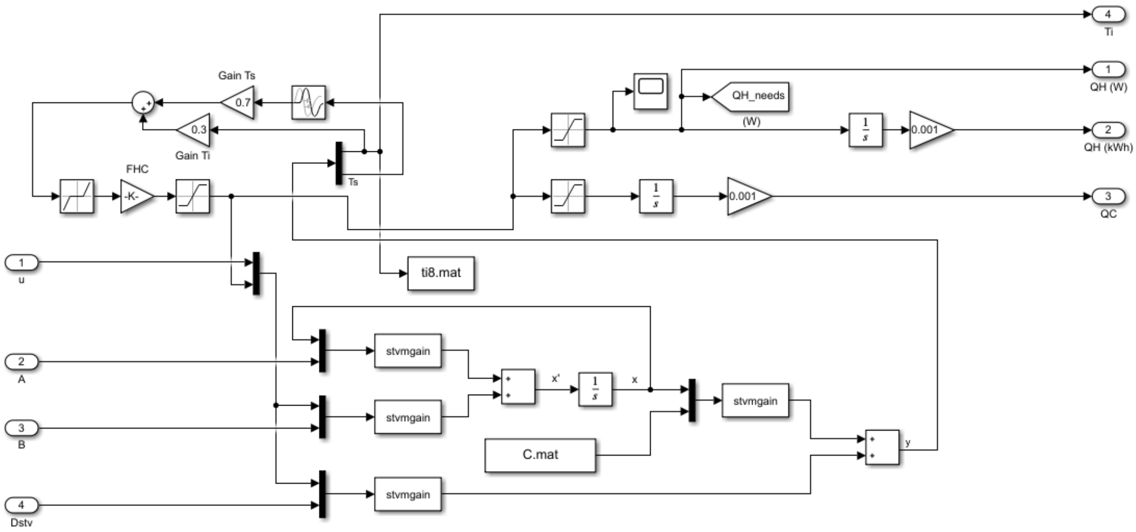

Figure 24 Layout of the Room sub-system

Both the Room and Solar sub-systems are connected to each other through the FCU which allows the heat transfer process.

4.2 The Solar thermal block

The *Solar thermal* sub-system has been adapted from [45] where Matteo Dongellini et al. have developed a dynamic simulation of solar thermal collectors for DHW production. The adaptation of the mentioned model is showed in Figure 25 . This sub-system is composed by a series of lumped sub- blocks, named as: *Collectors, Pump, Back-up unit and Solar thermal storage.* The simulation of this model allows the hourly evaluation of the energy collected by the solar panels and the temperature of the hot water produced by the system.

The inputs of the *Solar* sub-system are the external temperature and the hourly solar radiation. These external signals come from weather data files downloaded from EnergyPlus and have been independently computed for each studied European city (Lisbon, Madrid and Marseille). These hourly climatic inputs have been selected within a reference year for each of the mentioned European cities.

The outputs of this sub-system are two: the warm water that goes to the FCU and the cold glycol that comes back to the collectors.

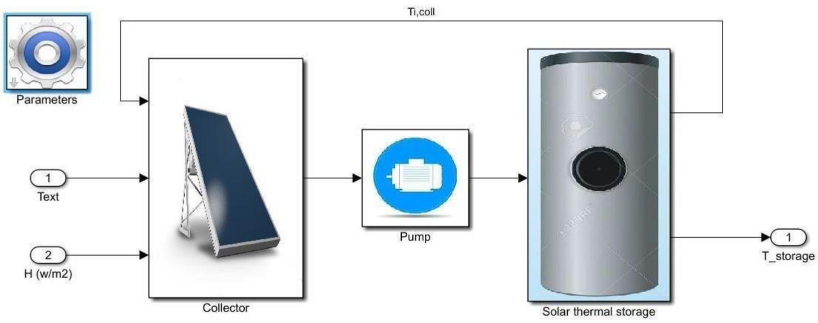

Figure 25 Layout of the Solar thermal sub-system

The sub-blocks that compose the *Solar thermal* sub-system are the following:

- The *Collector* block is a simulation of the solar thermal collectors' performance that constitutes the heating system. This sub-system receives as input, the total incident solar radiation and the hourly value of the outdoor temperature, both computed externally, as well as the inlet working fluid temperature, which is an output of the storage tank.

- The *Pump* block contains the pump governing equations that compute the fluid temperature raise caused by de pump itself and its electrical consumption.

- The *Solar thermal storage* block evaluates the thermal loads within the hot water storage tank. In this case, it has been considered as a completely mixed tank with an inner heat exchanger coil. The storage tank connects the *Solar thermal* and the *Fan Coil Unit* sub-systems through a water mass flow that has been heated up by the solar collectors and stored until needed. The required mass flow of water is computed as shown in the next section and can be modified according to different requirements.

Separately, there is an extra block within this category, called the *Parameters* block, which contains all the values of the main physical and geometrical properties required in the modelling of the *Solar Thermal* sub-system. Some of these attributes are the collector's geometry and efficiency values, the latitude and longitude where the collectors are located, the fluid properties, the storage tank volume, etc. The *Parameter*s writer block changes the specific values within the same model to simulate different scenarios.

4.3 The *FCU* block

The *FCU* sub-system simulates the performance of a Fan Coil Unit through a cross-flow heat exchanger, which allows the heat transfer process between the collector's working fluid (water) and the air mass flow of the room. It is assumed that the heat exchange is based on the specific heat of the fluid with less heat exchange (i.e. the air) and depends on the temperature difference of both fluids of interest with a certain efficiency, the layout of this unit is shown in Figure 26. The general equation of the process can be written as (1).

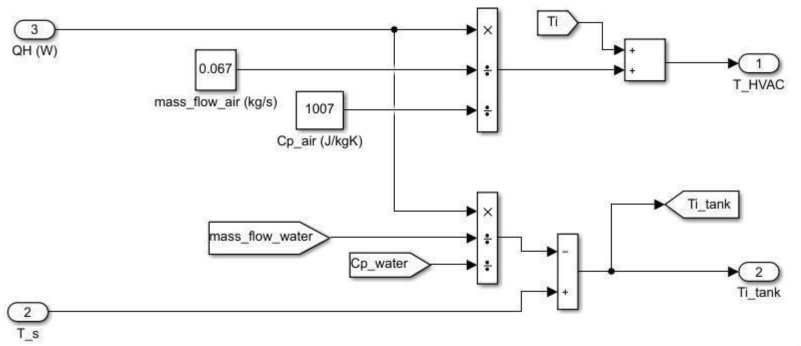

Figure 26 Layout of the FCU sub-system

As is shown in Figure 27, the hot water cools down by transferring the heat to the air mass flow. The equations of the process are (1) and (2) respectively. From these equations, it is possible to compute the temperature of the cold water (T_{i_tank}) that has to be returned to the thermal storage (3) and the air temperature to be supplied into the room (T_{HVAC}) (4). Furthermore, by considering a HE's efficiency value of 0.7, an air mass flow ($\dot{m}_a$) of 0.067 (kg/s) and the air's heat capacity, it is possible to compute the required water mass flow by equation (6).

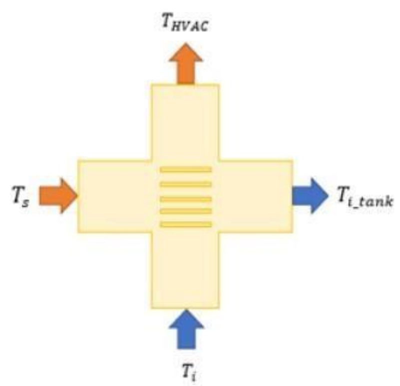

Figure 27 General Layout of a cross-flow HE

$$Q = \eta Cp_a(T_{w\_h} - T_i) \quad (1)$$

$$Q = \dot{m}_w Cp_w\left(T_s - T_{i\_tank}\right) \quad (2)$$

$$Q = \dot{m}_a Cp_a(T_{HVAC} - T_i) \quad (3)$$

$$T_{i\_tank} = T_s + \frac{Q}{\dot{m}_w * Cp_w} \quad (4)$$

$$T_{HVAC} = T_i + \frac{Q}{\dot{m}_a * Cp_a} \quad (5)$$

$$\eta = \frac{\dot{m}_a * Cp_a}{\dot{m}_w * Cp_w} \quad (6)$$

Table 7 Nomenclature and units of the Heat Exchanger variables

η	Efficiency	Cp_w	Specific heat of water (J/kgK)
T_{HVAC}	Air supply temperature (ºC)	Cp_a	Specific heat of air (J/kgK)
T_i	Internal air temperature (ºC)	$\dot{m}_w$	Water mass flow (kg/s)
T_{i_tank}	Cold water temperature (ºC)	$\dot{m}_a$	Air mass flow (kg/s)
T_s	Hot water temperature (ºC)	Q	Instantaneous Exchanged heat (W)

Associated to this subsystem we find the back-up unit, which will be switched on if the heat provided by the collectors is not enough to meet the thermal requirements of the office. It works by means of an electric heater (COP=1). This operation is supervised by a controller characterized by an on-off logical control that is implemented within the block.

5 Results and Discussion

As mentioned in the previous section, the first variable to be known is the heating needs for space heating, these will be computed through the Room sub-system. Once the total annual amount of heat to be provided is known, this will try to be provided through the modelling of the Solar thermal sub-system, which is formed by the solar collectors, the thermal storage tank, the pump and the back-up unit. The union of both sub-systems has been implemented through a water-air FCU unit. Both the results of each sub-system independently as well as the result of the fully coupled system are shown in this chapter.

The following sub-sections will show the results of the different subsystem working independently as well as the whole model functioning as a grouped model. All the simulations have been performed within MATLAB/Simulink environment. The simulations are carried out in identical conditions for all three European cities. The results obtained from simulations were performed to determine if the originally proposed thermal system is suitable for the space heating within the study case.

5.1 The Room

The annual heating needs, from now (QH), that have been calculated by the presented model, have been also compared with benchmark results of the annual energy needs for each city. The reference values were taken from the EnergyPlus, which detailed simulations that follow the csv format (comma separated values), show satisfactory similitudes with the developed model.

As mentioned in section 4, the thermal performance of the office uses the time-varying parameters of its thermal network as well as other independent variables as the temperature or the internal gains. To study the Room as an independent system, the model has been simulated with hourly samples during a reference year (8760 hours).

5.1.1 Lisbon

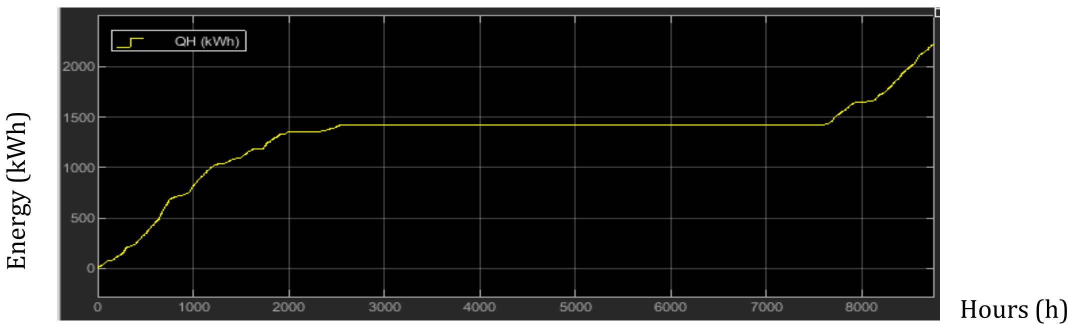

Figure 28 Lisbon's accumulated heating needs (kWh)

Figure 28 shows the heating needs to be provided if the office's study case would be located in Lisbon. It can be noticed that the results are shown as an accumulated value during the refence year. During the first 2500 hours, which correspond from January to mid-April, the heating needs go up to 4000 kWh. All along the summer, there is no need of space heating in the office and therefore, the accumulated value for heating purposes remains constant until the months of November and December, in which the needs grow up to 2220 kWh.

Similarly, Figure 29 shows the instantaneous power requirements to be supplied to the office for space heating. Following the same working principle, the thermal performance of the office only requires heating during the cold seasons that is, from November to mid-April in the case of Lisbon.

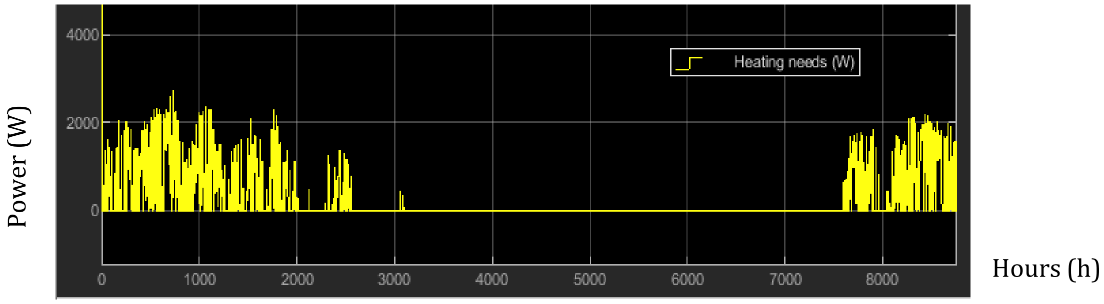

Figure 29 Lisbon instantaneous power needed for heating purposes

5.1.2 Madrid

Due to the difference in climate conditions, Figure 30 shows how the annual heating needs required in Madrid are slightly more than twice of those required in Lisbon. In this case, an amount of 3170 kWh are needed to heat up the office from January to the beginning of May. Furthermore, there will not be more energy needs for space heating until mid-October, when an amount of about 2000 kWh will be needed until the end of the year.

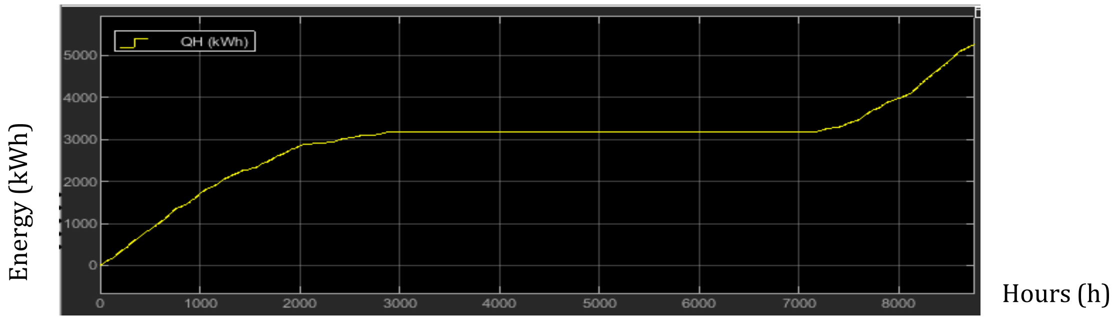

Figure 30 Madrid's accumulated heating needs (kWh)

The instantaneous power needs required for Madrid's case study are shown in Figure 31. Here, it can be appreciated that the power requirements are considerably higher, exceeding the 2000 (W) from the month of November until March, both included. There will also be heating needs but at lower levels during the months of April andOctober

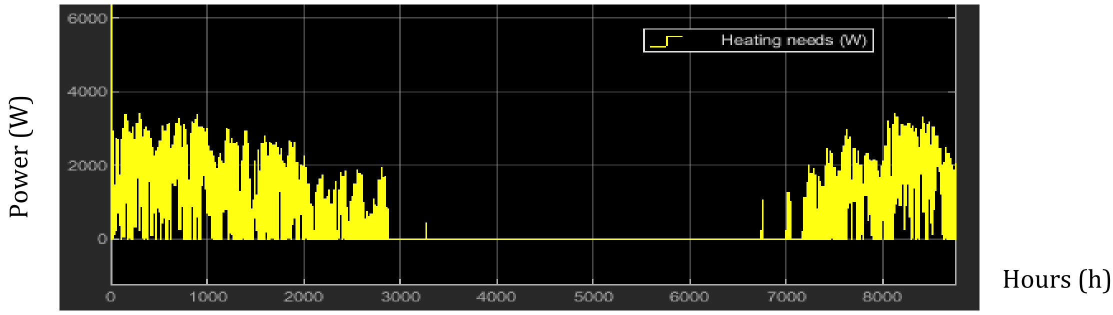

Figure 31 Madrid's instantaneous power required for heating purposes

5.1.3 Marseille

Following the same trend, Figure 32 and 33 show respectively, the accumulated energy needs and instantaneous power required for space heating during the cold season. The peak power needs reach values of about 4000 (W) during the winter period (December to March), while the in the months of April and October these values are within the range of 2000 (W) and present small periods where no space heating is needed.

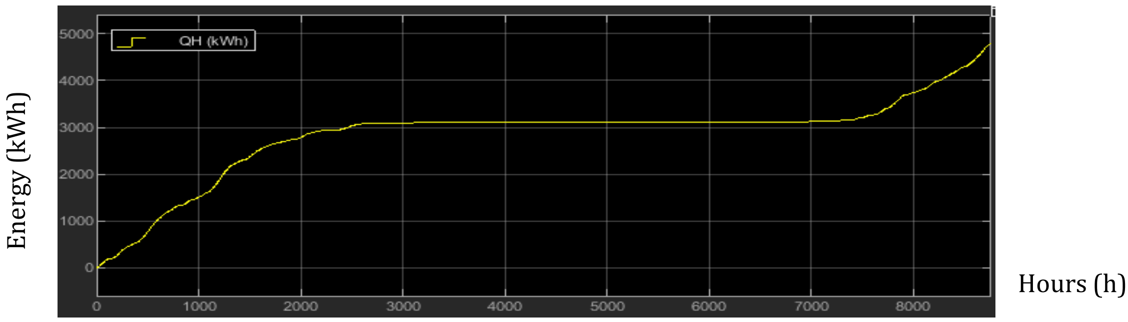

Figure 32 Marseille's accumulated heating needs (kWh)

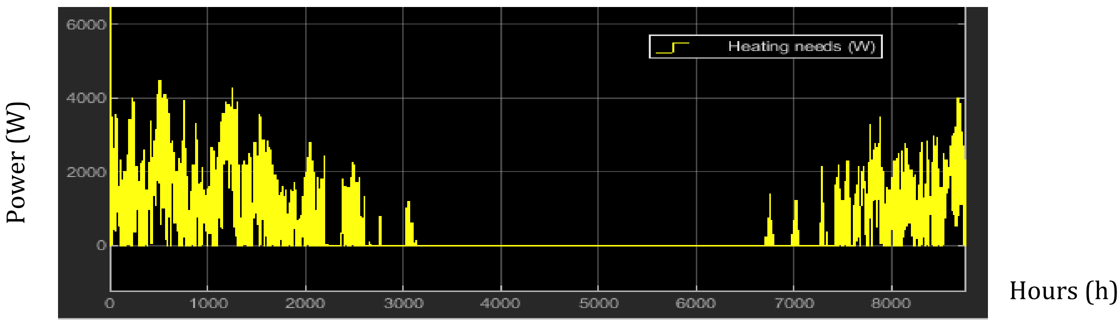

Figure 33 Marseille instantaneous power required for heating purposes

The next table 8 shows a comparison of the mentioned energy consumption for space heating in kWh by means comparing the results obtained by running the simulation within MATLAB/Simulink environment and those collected fromEnergyPlus.

Table 8 Accumulated energy consumption MATLAB/Simulink vs EnergyPlus

	MATLAB/Simulink	*EnergyPlus*	
	Heating needs (kWh)	**Heating needs** (kWh)	**Total Energy needs** (kWh) (heating+cooling)
Lisbon	2219.54	2212.41	4457.36
Madrid	5254.3	5615.67	8405.52
Marseille	4781.84	5263.32	7719.42

According to EN 15265 the annual energy needs calculated for the given test cases, should be compared

Table 9 Values of errors from the comparison of the heating needs

Case study	$r\,QH$
Lisbon	0.0016
Madrid	0.043
Marseille	0.062

The mentioned standard defines three levels of accuracy to evaluate such comparisons. These are:A (the best), if rQH≤ 0.05 and rQC≤ 0.05; B, where rQH≤ 0.10 and rQC≤ 0.10 andC (the worst), if rQH≤ 0.15 and rQC≤ 0.15. Nevertheless, to stablish a level of accuracy and carry out a full evaluation of the thermal needs of the model, values of errors from the computation of the cooling needs should also be taken into consideration.

In any case, from this comparison can be stated that the considered method (MATLAB/Simulink), provides results with a very good accuracy. The best results are given by the calculations of the heating needs for Lisbon case study with a very small error. The value of error for the case of Madrid also shows very good certainty as it has a numerical value below 0.05. By last, Marseille example presents the bigger value of error of 0.062 which might be rated with medium accuracy.

5.2 The Solar thermal block

As mentioned in chapter 3, the simulated solar thermal equipment accounts with two flat solar collectors with an absorber area of 4 (m^2) each, an electric pump with a nominal power of 65 (W), a thermal storage with a volume of 500 (L) and an electrical back-up unit with a nominal power of 2000 (W).

This section presents a comparison of the main studied variables of the three case study cities. Notice that these results belong to the Solar thermal block working as an independent system (not yet connected to the FCU).

5.2.1 Lisbon

Figure 34 shows the annual useful thermal power collected by the solar panels in Watts. It can be appreciated how during the spring and summer periods these values are higher, reaching and even overtaking the 2000 (W). During the fall and winter seasons these numbers are clearly smaller, with a range between 500-1300(W).

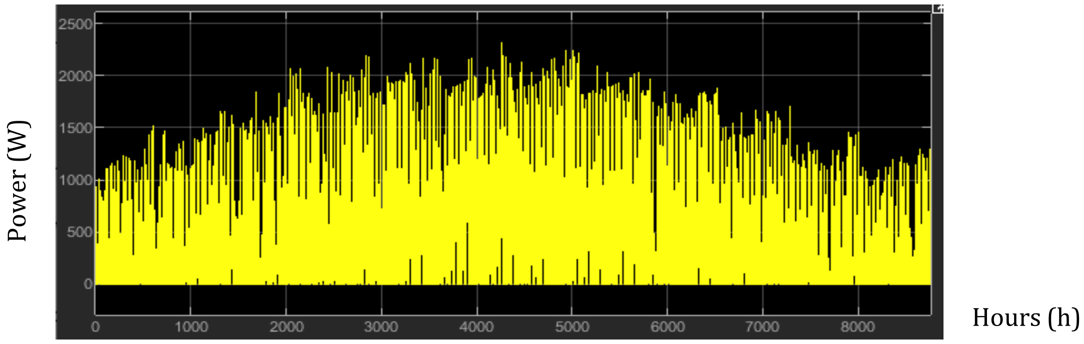

Figure 34 Useful thermal power collected by the solar panels

Figure 35 represents the glycol temperature at the outlet of the collector and at the outlet of the electric pump, which in this case, it mainly takes values between approximately 35 and 43 degrees Celsius.

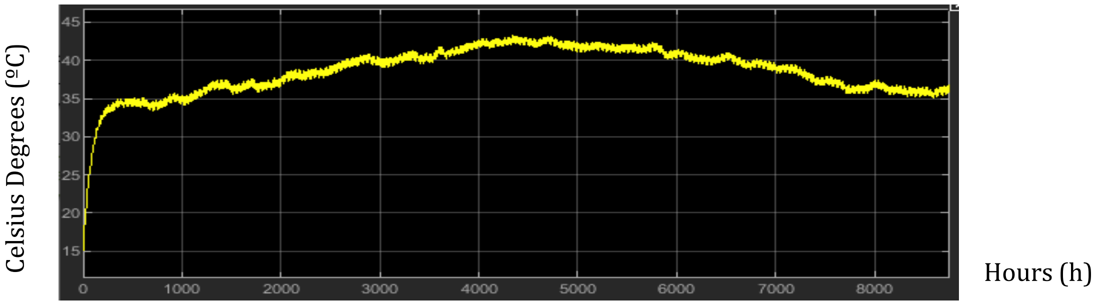

Figure 35 Temperature at the collector outlet: Tu,coll (°C)

The figure 36 represents the water temperature within the storage tank. Under the mentioned conditions, the thermal energy provided by the solar collectors is only able to raise the water temperature by two degrees Celsius along the whole year.

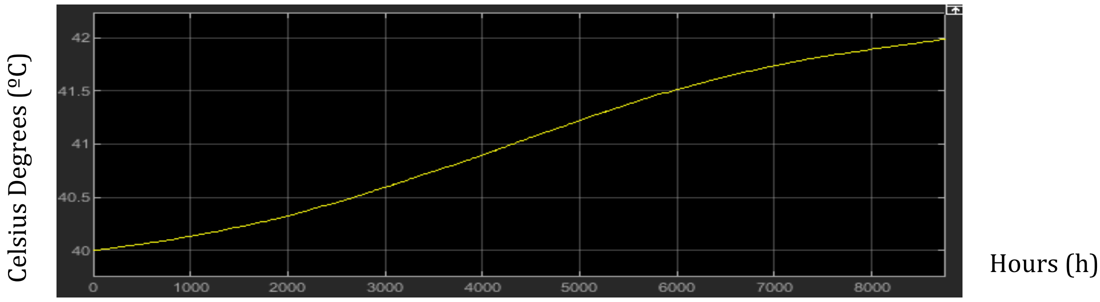

Figure 36 Temperature in the storage tank: Ts (°C)

Figure 37 represents the glycol temperature that is going to be returned to the solar collectors after transferring the heat to the water in the storage tank. By last.

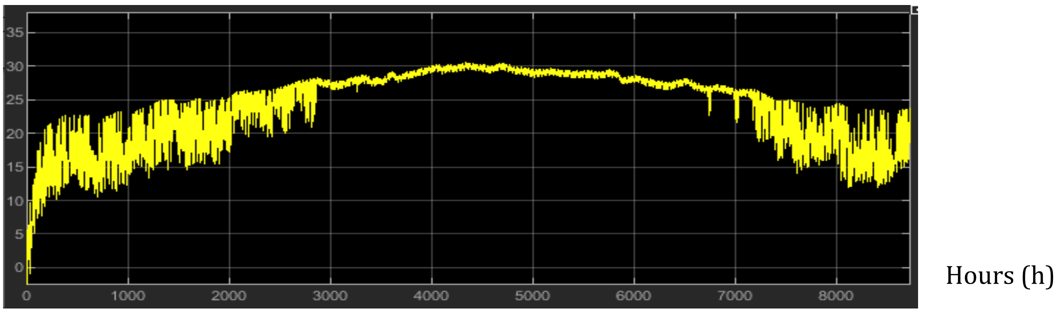

Figure 37 Return temperature to the collector: Ti,coll (°C)

5.2.2 Madrid

Due to Madrid's specific location and climate conditions, the shape of the annual useful thermal energy collected by the solar panels is very different. It can be appreciated how in the peak period (from May to September), the recorded values are almost twice as high as those obtained in Lisbon. On the other hand, during the winter months, the available power values barely reach 1000 (W). The curve for the useful thermal power collected by the solar panels (Figure 38) is much more pronounced in this example than in the Portuguese one, where the variation is much smoother.

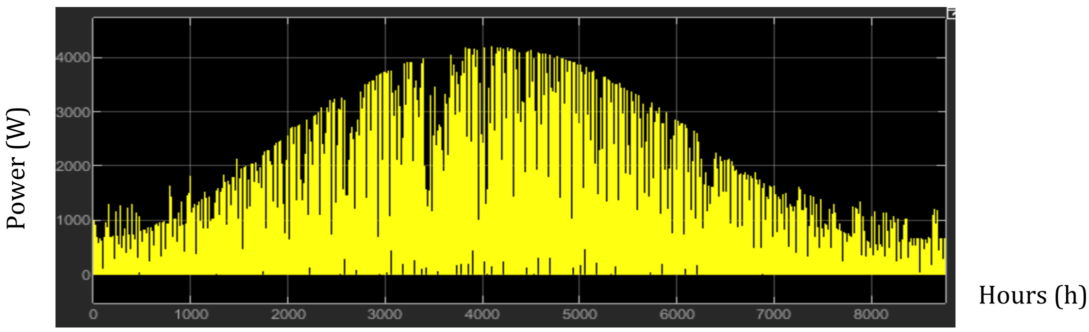

Figure 38 Useful thermal power collected by the solar panels

Due to higher values of solar irradiation but following the same trend, the glycol temperature at the collector's outlet has its maximum values about five degree Celsius above the Portuguese case as depicted in Figure 39.

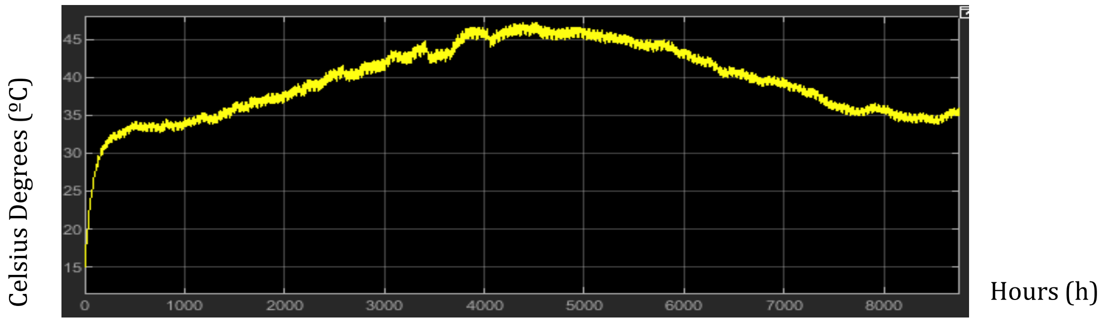

Figure 39 Temperature at the collector outlet: Tu,coll (°C)

With the storage tank not being connected to any external heat exchange equipment, the hot glycol is able to raise the water temperature by up to almost three degrees throughout the year (Figure 40).

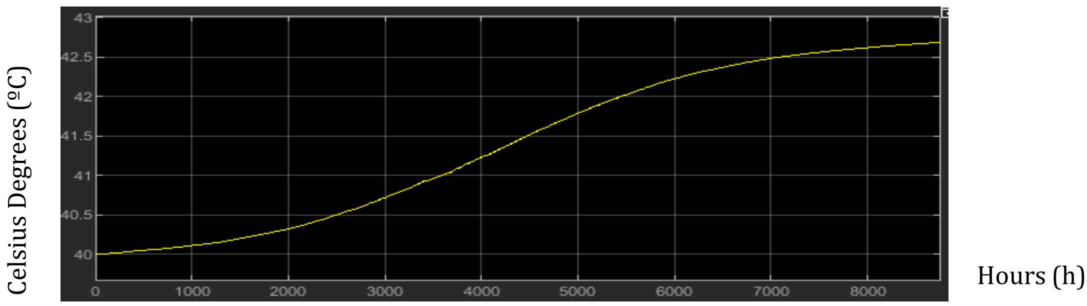

Figure 40 Temperature in the storage tank: Ts (°C)

The glycol temperature at the outlet of the storage tank oscillates between 10-22 degrees Celsius during the winter months while during fall and spring increases in a range of up to 10 (°C). During the summer months these values go from 30-34 (°C) as is shown in Figure 41.

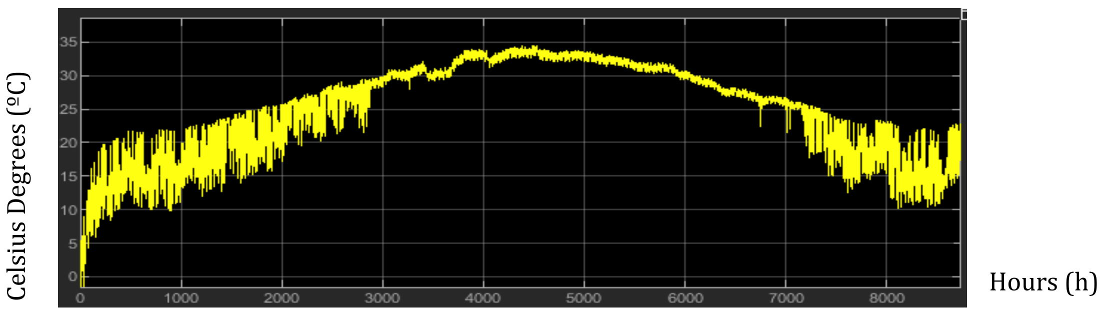

Figure 41 Return temperature to the collector: Ti,coll (°C)

5.2.3 Marseille

The useful energy obtained by the solar collectors in Marseille's case study is shown in Figure 42. The graph illustrates how most of these values oscillate between 500-1000 (W) during most of the year although during the hottest months these values reach peaks of around 2000-2400 (W).

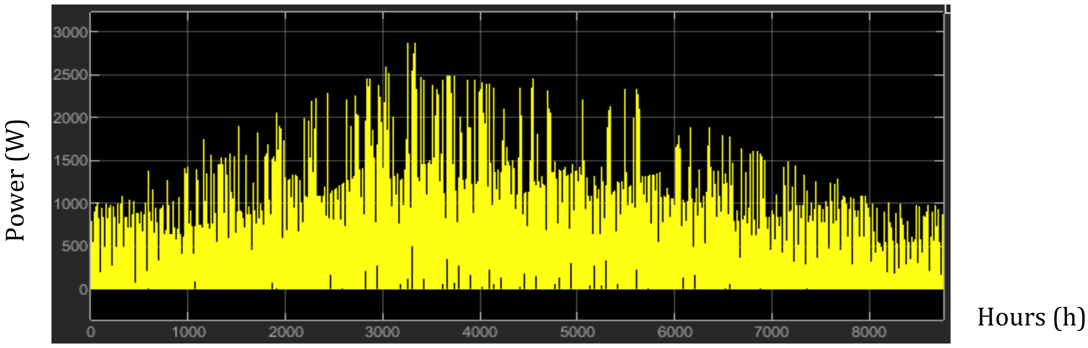

Figure 42 Useful thermal power collected by the solar panels

Accordingly, Figure 43 shows the temperature of the heat transfer fluid is between 35 and 43 degrees Celsius for most of the year, except for the months of December, January and February.

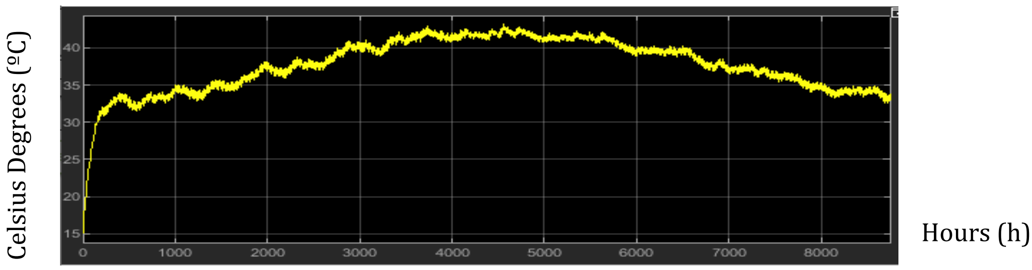

Figure 43 Temperature at the collector outlet: Tu,coll (°C)

The following figure 44 represents the water temperature within the storage tank. For this case, the thermal energy provided by the solar collectors is only able to raise the water temperature by nearly two degrees Celsius along the whole year.

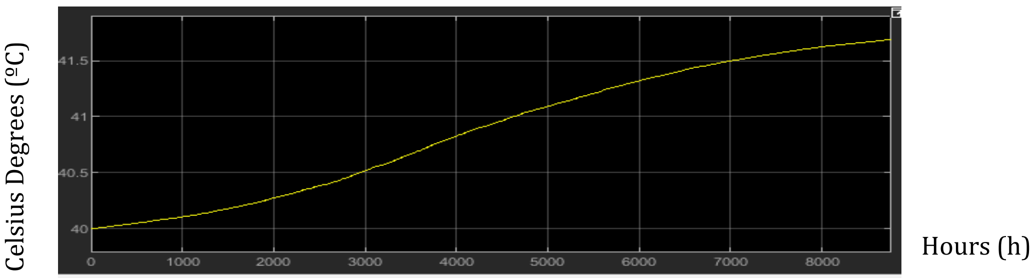

Figure 44 Temperature in the storage tank: Ts (°C)

The French example represents the lowest values acquired by heat transfer fluid for the three cities studied. The glycol temperature at the exit of the tank presents values up to 25 (°C) maximum during the heating needs period, as is illustrated in Figure 45,

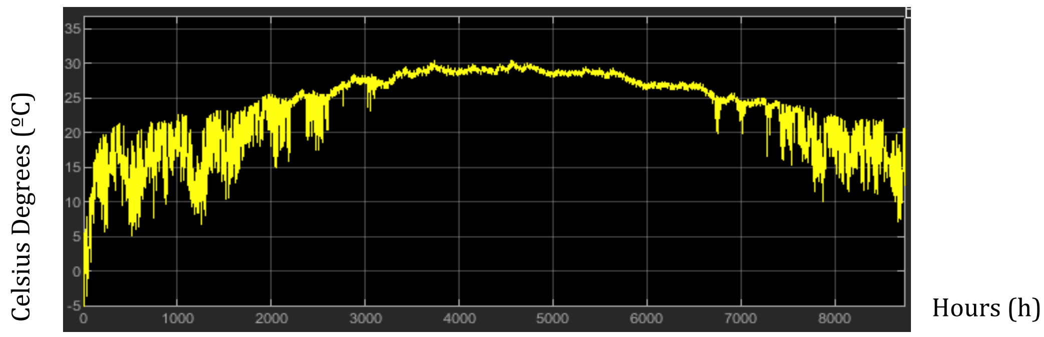

Figure 45 Return temperature to the collector: Ti,coll (°C)

5.3 The complete model: Solar thermal + HVAC

The next paragraphs detail the result of the main studied variables for the four different sub-systems (The room, the solar thermal equipment, the fan coil unit and the back-up) working together as a complete system. As in the previous paragraphs the results of the principal variables illustrated for each one of the case study cities.

5.3.1 Lisbon

In first place, Figure 46 shows the water temperature required in the storage tank to meet the energy needs for the office space heating. As can be seen, the graph shows the temperature in cumulative values during the months with heating needs while it remains constant (no need of space heating) for the hot months.

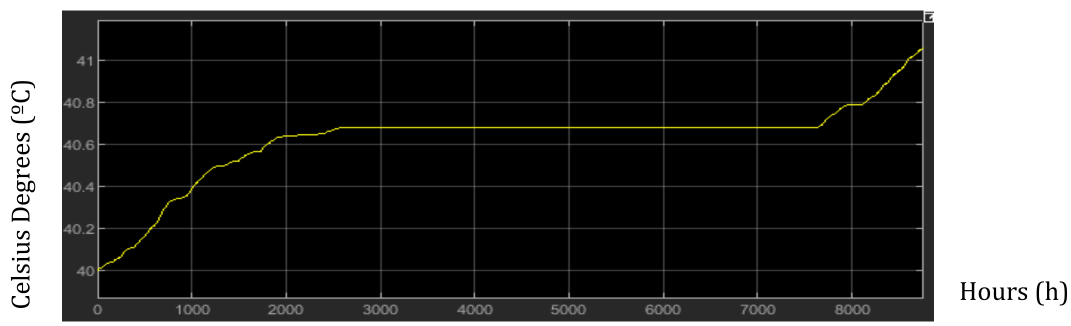

Figure 46 Temperature in the storage tank: Ts (°C)

As the storage tank is now connected to the FCU, the heat within the water is transferred to the air that is going to be supplied into the room through a water-air heat exchange process. The mentioned supply temperature required for space heating in the room has been called HVAC temperature and is shown in Figure 47. Since a very low airflow has been selected for comfort reasons, the temperature range between the office interior temperature and the space heating temperature is considerably large. Thus, for the given conditions, the air supply temperature is also very high.

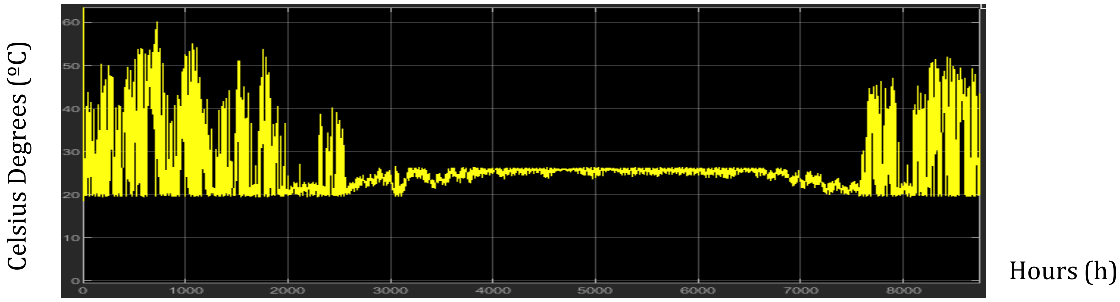

Figure 47 Required HVAC Temperature (°C) in Lisbon

Once the air has been heated up by the warm water, this last one returns to the storage tank to be heated up again when needed. The 'cold' water that goes back to the tank has been called T_{i_tank} and is shown in Figure 48.

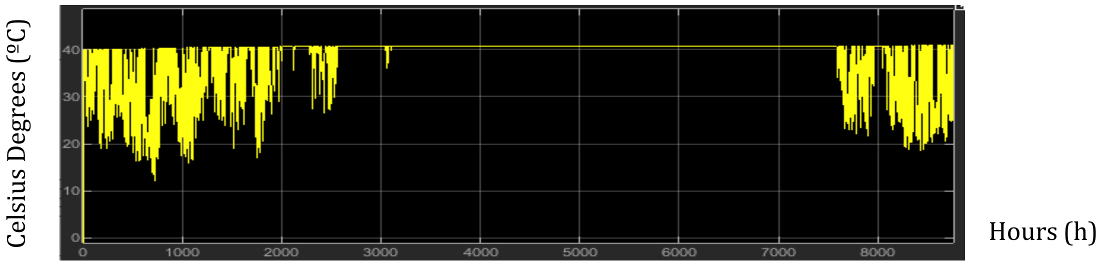

Figure 48 Return temperature to the storage tank: Ti_tank (°C)

While being connected to the fan coil unit, the heat exchange process that occurs in this sub-system makes that water temperature within the storage tank cool down. For this reason, the glycol temperature that leaves the water tank and returns to the collector has lower temperature values that those obtained in the previous section Figure 49.

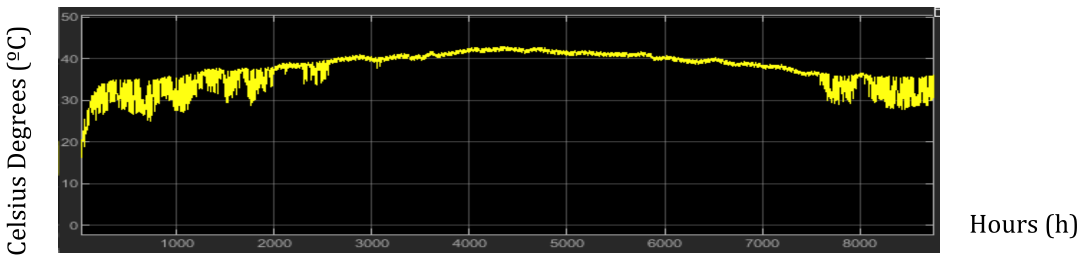

Figure 49 Return temperature to the collector: Ti,coll (°C)

Now that the systems are connected it is possible to compare the heating needs required in the office with the useful thermal energy provided by the collector. The comparison between these two magnitudes will explain when it is necessary to switch up the back-up unit. The theoretical performance of the back-up unit is shown in Figure 50.

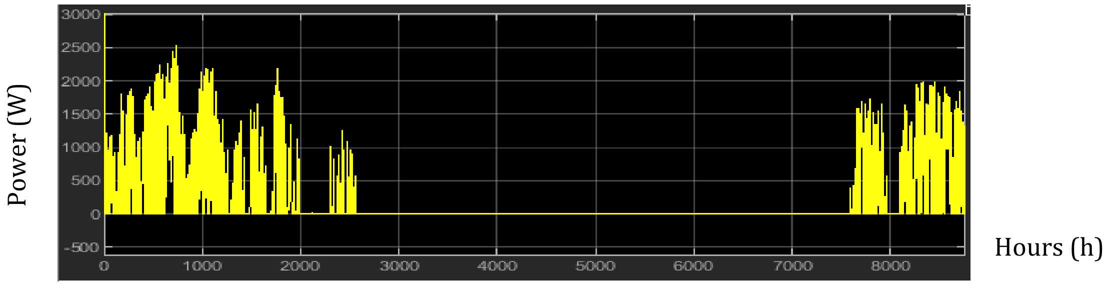

Figure 50 Theoretical back-up power requirements (W)

5.3.2 Madrid

Figure 51 depicts the water temperature in the storage tank while being this unit connected to the fan coil one. The temperature values are represented in cumulative terms reaching a temperature rise of 1.5 degrees Celsius during the months of January, February and March and a single degree from October to the end of the year.

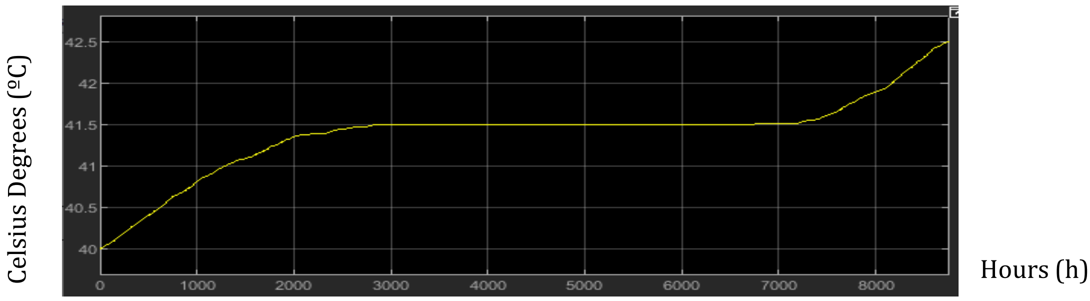

Figure 51 Temperature in the storage tank: Ts (°C)

During the cold season, Madrid presents much lower external temperatures that the ones recorded in Lisbon. For this reason, required HVAC temperature for space heating takes significantly higher values compared with those for Lisbon. For example, from mid-November until February these numbers usually exceed the 60 °C as it is shown in Figure 52. The water temperature that goes back to the storage tank after transferring its heat capacity to the air is shown in Figure 53.

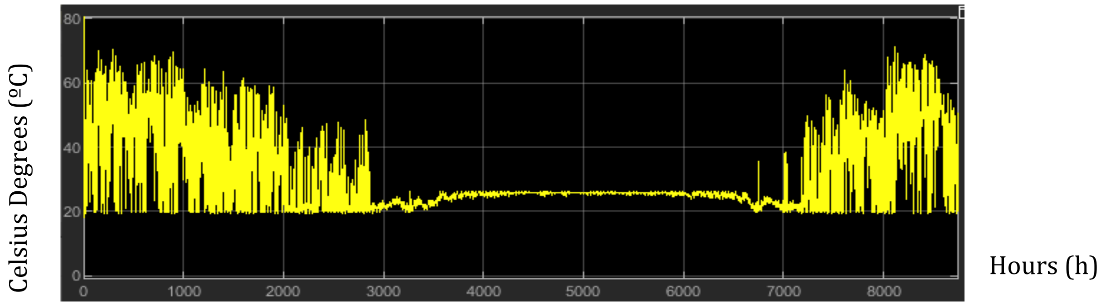

Figure 52 Required HVAC Temperature (°C) in Madrid

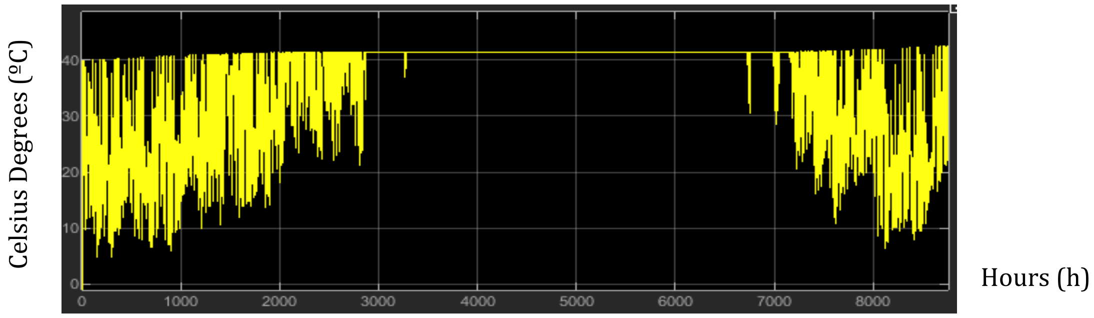

Figure 53 Return temperature to the storage tank: Ti_tank (°C)

Lastly, the changes within the glycol temperature that goes back from the storage tank to the collector. During the period where space heating is needed, these values go from 20-42 degrees Celsius as shown in Figure 54. Figure 55 illustrates the back-up theoretical performance for the complete model in the case study of Madrid.

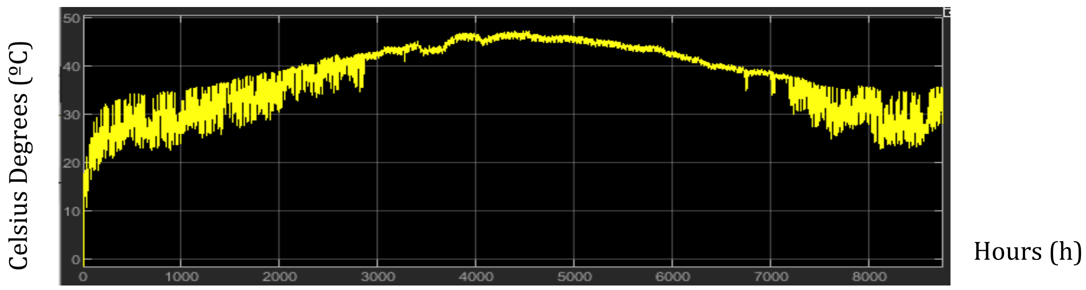

Figure 54 Return temperature to the collector: Ti,coll (°C)

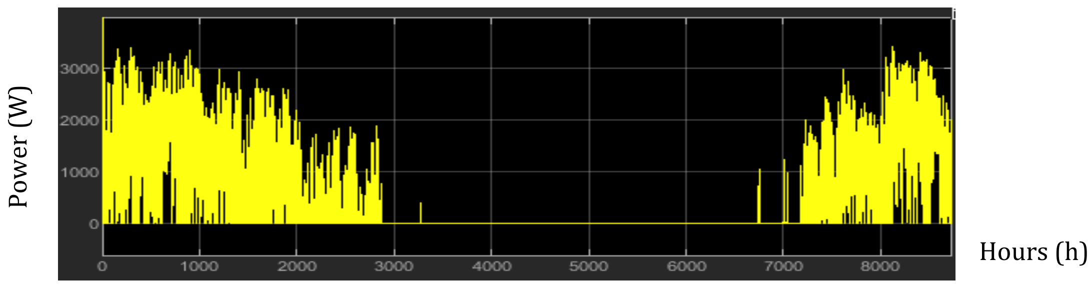

Figure 55 Theoretical back-up power requirements (W)

5.3.3 Marseille

This last section shows the results for Marseille's scenario. The first image shows the water temperature raise in the storage tank, which takes a cumulative value of 1.5 (°C) until April, remains constant during the months where there is no need of space heating and raises up to nearly one more degree from November to the end of the year. This is illustrated in Figure 56.

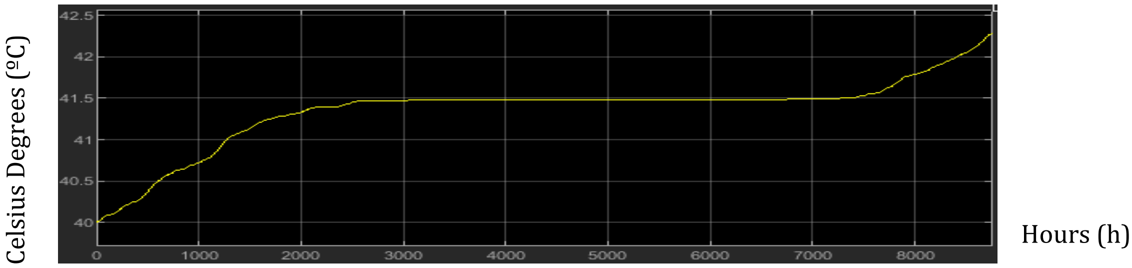

Figure 56 Temperature in the storage tank: Ts (°C)

The required HVAC temperature for space heating in Marseille's prototype office are much higher that any of the other two cases. Figure 57 illustrates how these values might reach up to even 80 (°C) during the winter period in order to accomplish the thermal comfort in the studied room for the given conditions. In the case of spring and fall seasons this values are considerably lower but still within a really high range.

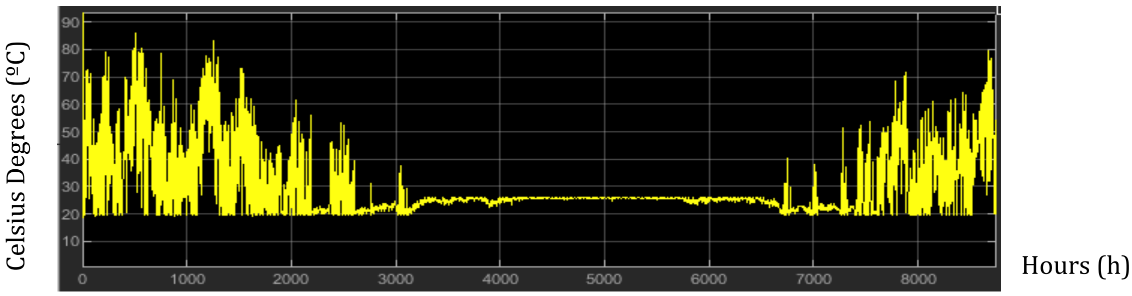

Figure 57 Required HVAC Temperature (°C) in Marseille

As in the Lisbon and Madrid examples, the Figure 58, Figure 59 and Figure 60 detail the behavior of the following variables: the water temperature that goes back to the tank, the glycol temperature that goes back to the collector and the theoretical back-up performance respectively.

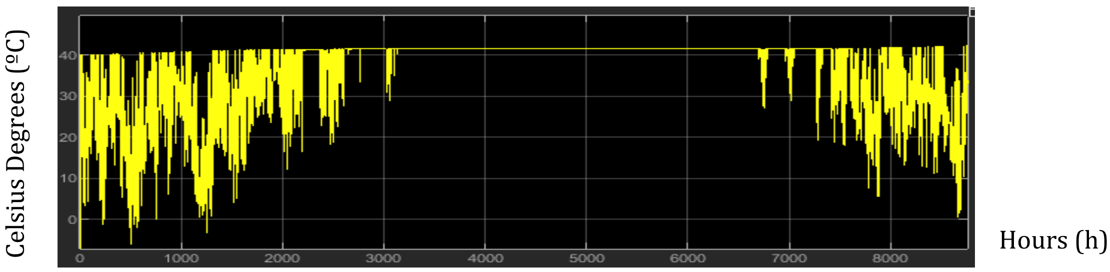

Figure 58 Return temperature to the storage tank: Ti_tank (°C)

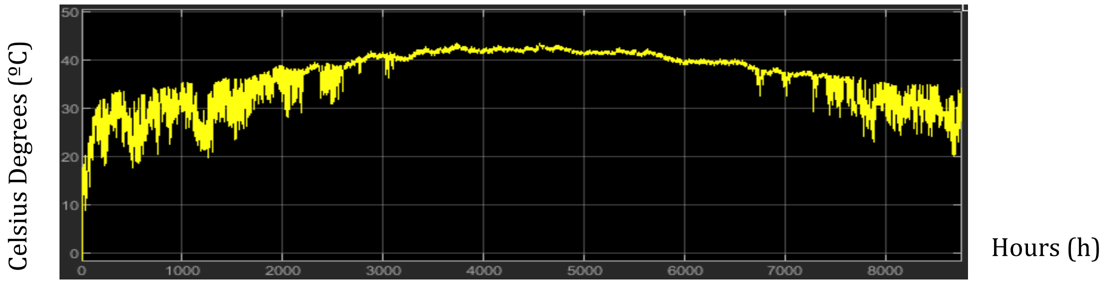

Figure 59 Return temperature to the collector: Ti,coll (°C)

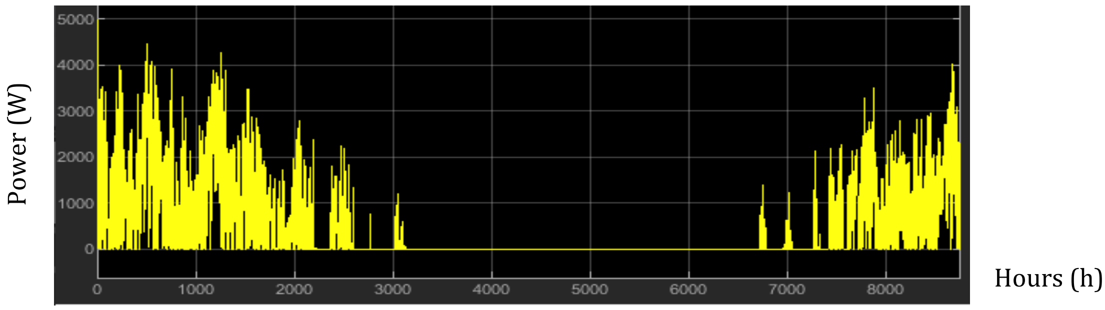

Figure 60 Theoretical back-up power requirements (W)

6 Conclusions and future recommendations

In the past few decades, an extensive research has been made in the field of thermal energy storage. A reliable assessment of the heating and cooling energy demands requires advanced simulation techniques. Furthermore, it is worldwide known that this field has a huge potential to increase the sustainability of our lifestyles and to significantly reduce our carbon footprint.

The potential for the development of innovative new building technologies is huge. It has been shown that new approaches to improve energy performance in buildings are essential and that it is indispensable to promote the integration of renewables such as solar thermal. Together with the implementation of innovative concepts for buildings and urban districts, Renewable Energy Systems are a very important contribution for reaching the nZEB goals. However, the thermal behavior and energy efficiency of buildings depend on many factors as building design and use. As it has been highlighted in the literature review, this fact the needs for more studies that group and specify climate zones and building types.

The Member States need more advice and leadership to be able of setting consistent and comparable nZEB values with balanced ambition levels. The existing low-energy buildings definitions within the different countries have common approaches and differences and there is a need to harmonize them to the nZEB requirements as indicated by the European directives. Moreover, the classification of climatic zones considering both heating and cooling degree days leads to more realistic results, especially in the Southern Europe regions.

The application of nZEB concepts adapted to the different climatic zones within each country, will make the energy needs and electricity consumption develop further on the roadmap to sustainability.

In this research, an integrated simulation model of the EMS within an office building was carried out using MATLAB/Simulink. This model was then used to predict the thermal performance of a specific office-prototype building for the South European cities of Lisbon, Madrid and Marseille. For this purpose, the model of each city has been simulated by means of its respective location and weather features.

As far as the model has been developed, the HVAC system can only provide space heating through a Fan Coil Unit (hot air from the heated water by the solar panels) and therefore, the model can only cope with the 'cold-season' heating requirements and not with cooling needs. Furthermore, for satisfying both heating and cooling needs, a heat pump would be needed.

It is concluded that an accurate estimation of the energy needs for space heating to meet the specified comfort targets for winter, requires a detailed hourly simulation (mainly due to the significant daily fluctuations of temperature and solar irradiation). Accordingly, the results strongly depend on the climatic conditions as well as on the configuration of the thermal energy management system. It is hoped that the findings of the present study can help to establish procedures to optimize energy demand and thermal comfort in nZEB buildings in warm regions.

This model highlights the almost continuous need of a back-up unit during the cold months. Taking into account the imposed conditions of using a rather low airflow to heat the office, the supply air temperature in the FCU is very high and this limits the need for back-up action most of the time. A possible solution would be to increase the number of collector or the collector area with the intention of increasing the temperature of the working fluid.

Considering that the model provides an accurate calculation of both energy needs and solar radiation on inclined surfaces, possible improvements should be made to both the solar thermal and the FCU sub-systems more adjusted to specific needs.

It can be stated that the main disadvantage of using solar energy for heating is that the main heating demand occurs during a few months of the year and these coincide with the months with less solar radiation, which limits the performance of these installations and evidences the back-up requirements. This is one of the reasons of why it is very common to share the use of the mentioned systems together with the production of DHW, with the appropriate control systems that prioritize the most convenient use in each case.

In this thesis, only technical aspects have been mentioned and it would be better if a complete techno-economic analysis is carried out to see the investment return period. Moreover, it will be interesting to see the economic viability of incorporating different EMS to such building concept. Renewable energy technologies needed in nZEB may or may not be cost-effective, depending on available national financial incentives. The Commission has established a comparative methodology framework for the calculation of the mentioned cost-optimal levels.

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APPENDICES

Appendix A: 5R1C model

The five resistors and one capacitor model is one of the simple hourly methods given by the EN ISO 13790 standard. It appears as an alternative to the monthly method with the main advantage that the hourly time intervals enable direct input of hourly patterns with the same level of transparency and robustness. This method, as well as other models of similar complexity, uses an hourly time step and allows all building and system input data to be modified each hour using schedule tables. Figure 61 illustrates the scheme of the 5R1C method while Table 10 contains the nomenclature and units of the main heat transfer variables.

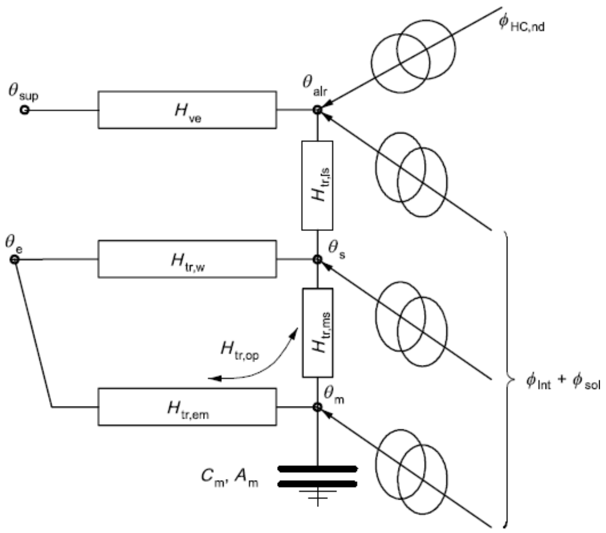

Figure 61 Five resistances, one capacitance (5R1C) model; EN-ISO 13790 standard

Table 10 Nomenclature and units of the main heat transfer variables

$H_{tr,op}$	Transmission heat transfer coefficient of the opaque building elements, (W/K)
$H_{tr,em}$ and $H_{tr,ms}$	Transmission heat transfer coefficients ofthe external and internal part of $H_{tr,op}$, respectively, (W/K)
$H_{tr,is}$	Transmission heat transfer coefficient between the air node Ti and the surface node Ts, (W/K)
$H_{tr,w}$	Transmission heat transfer coefficient of doors, windows, curtain walls and glazed walls, (W/K)
H_{ve}	Transmission heat transfer coefficient of ventilation air, (W/K)
C_m	Internal thermal capacity of the building, (J/K)
A_m	Area of the thermal mass, (m^2)
$\Phi_{HC,n}$	Actual heating or cooling need, (W)
Φ_{sol} and Φ_{int}	Heat flow rate from solar heat sources and nternal heat sources in thebuilding respectively, (W)
Θ_{sup} and Θ_{air}	Supply air temperature node and internal air node respectively
Θ_s and Θ_m	Central and internal mass nodes respectively

The calculation method of this model makes a distinction between the internal air temperature and the mean temperature of the internal surfaces which enables thermal comfort checks and increases the accuracy of accounting the solar, lighting and internal heat gains. The building elements are discretized into a set of nodes connected by thermal resistances and capacitance. These parameters can be identified analytically, by model order reduction or by tuning the model to a temperature and energy consumption dataset.

The nodes are used to evaluate the needs to be supplied to or extracted from and to compute de heating and/or cooling energy needs to maintain the set-point temperature. The heat transfer by ventilation (H_{ve}) connects the supply air temperature node (Θ_{sup}) with the internal air node (Θ_{air}), from which is possible to compute the actual heating and cooling needs. The coupling conductance ($H_{tr,is}$) links the air and central nodes. The heat transfer by transmission is split into the glazed elements ($H_{tr,w}$), taken as having zero thermal mass, and the opaque builiding elements ($H_{tr,op}$), containing the thermal mass which is successively split into two parts: $H_{tr,em}$ and $H_{tr,ms}$.

The solar and internal gains, Φ_{sol} and Φ_{int} respectively, are distributed through the $\Theta_{air,}$ the central node Θ_s (a mix of Θ_{air} and mean radiant temperature $\Theta_{r,mn}$) and Θ_m, that represents the mass of the building zone. The main energy storage ability is related to the thermal mass and its capacity to store energy. It is located between $H_{tr,ms}$ and $H_{tr,em}$, and represented by a single thermal capacity (C_m), the internal heat capacity. The heat flow rate due to solar heat sources (Φsol), and the heat flow rate due to internal heat sources (Φint), are splitted along these three nodes.

The hourly energy needs for heating and/or cooling ($\Phi_{HC,nd}$), expressed in megajoules, are obtained by unit conversion by multiplying ($\Phi_{HC,nd}$), expressed in watts, by 0,036. Similarly, the internal (Q_{int}) and solar heat gains (Q_{sol}), are obtained by using Φint and Φsol respectively. Furthermore, the monthly heating and cooling energy needs are obtained by summing the hourly heating and cooling energy needs.

This method is generally classified as a low complex model, but it can properly estimate the indoor air temperature or the space heating and cooling needs. Furthermore, is a good basis for the development of more complicated models or be alternatively coupled with the MATLAB/Simulink environment.

It is possible to follow the calculation of the simple hourly method with the full set of equations within the EN ISO 13790 standard, (Annex C), [44]. However, this structure can be modified to create different structures to simulate complicated building systems or achieve better results regarding the HVAC system presence in buildings.

Moreover, the ISO 52016-1:2017 is a new standard that supersedes the ISO 13790:2008. It describes as well as the calculation procedure for the energy needs of heating and cooling and how to calculate the internal air temperature by using a more complex and extensive RC network model to perform the hourly calculation. The main difference is that the building elements are not aggregated to a few lumped parameters but kept separate in the model. This makes the computations more transparent and widely usable.