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NEARLY ZERO ENERGY DETACHED SINGLE FAMILY HOUSES IN PORTUGAL AND HUNGARY

Dissertação no âmbito do Mestrado em Engenharia Mecânica, na especialidade de Energia e Ambiente, orientada pelo Professor Doutor Adélio Manuel Rodrigues Gaspar e pelo Professor László Zsolt Gergely e apresentada ao Departamento de Engenharia Mecânica da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

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Nearly Zero Energy Detached Single Family Houses in Portugal and Hungary

A dissertation submitted in partial fulfilment of the requirements for the degree of Master in Mechanical Engineering in the specialty of Energy and Environment

Moradias Unifamiliares Isoladas com Consumo de Energia quase Nulo em Portugal e na Hungria

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Abstract

Energy consumption associated with the European residential sector accounts for a significant portion of total end-use energy consumption in the European Union. To reduce the energy demand from the residential sector, the Energy Performance of Buildings Directive (EPBD) introduced the concept of Nearly Zero-Energy Building (NZEB), however, there is still a huge problem related to the existing building stock and their high energy consumption.

The present dissertation, using Building Energy Modeling (BEM), aims to investigate retrofit measures to turn typical buildings from the existing Hungarian and Portuguese single family residential stock into NZEBs. To achieve this goal, two representative detached single family buildings models were created based on statistical data about the national residential building stock of both countries. Two construction periods were selected to determine the challenges faced by the older (before 1940) and the newer building stock (1990-2000). These buildings were simulated in two different climate zones, Coimbra, and Budapest.

After that, retrofit measures were applied to improve the buildings' exterior envelope, to improve the buildings' technical systems, and renewable energy sources were implemented. In the end, the buildings' energy performance was obtained and compared to the requirements imposed in each legislation for NZEBs.

In this work, after being retrofitted, three out of the four buildings modeled complied with the NZEBs requirements from the respective national legislations. The older buildings primary energy consumption was reduced by 93% and 86% in Coimbra and Budapest, respectively. Meanwhile, the newer buildings reduced their primary energy consumption by 86% and 77% in Coimbra and Budapest, respectively. This study allowed to conclude that Portugal, when compared to Hungary, faces an easier task meeting NZEB requirements due to the warmer temperatures felt throughout the heating season, which results in lower energy consumption associated to space heating, and higher solar radiation levels, which increase the efficiency of renewable energy systems.

Keywords: Energy efficiency, Nearly Zero Energy Building, Building Energy Modeling, Retrofit, Energy Performance of Buildings Directive.

Resumo

O consumo de energia associado ao sector residencial europeu representa uma percentagem significativa do consumo de energia na União Europeia. Para reduzir o consumo de energia associado a este setor, a *Energy Performance of Buildings Directive (EPBD)* introduziu o conceito *Nearly Zero-Energy Building (NZEB)*, no entanto, existe um enorme problema associado ao parque imobiliário existente e ao seu elevado consumo de energia.

Com esta dissertação, através de *Building Energy Modeling* (*BEM*), teve-se como objetivo a investigação de medidas de reabilitação para transformar edifícios típicos do parque residencial unifamiliar existente Húngaro e Português em NZEBs. Para isso, com base em dados estatísticos sobre o parque imobiliário de ambos os países, foram concebidos dois modelos de habitações típicos. Foram selecionados dois períodos de construção para representar os desafios enfrentados pelo parque edificado mais antigo (antes de 1940) e mais recente (1990-2000). Os edifícios modelados foram simulados em Coimbra e Budapeste.

Posteriormente, foram aplicadas medidas de reabilitação com vista a melhorar a envolvente exterior dos edifícios, os sistemas técnicos e a integração de fontes de energia renovável. No final, o desempenho energético de cada edifício foi determinado e comparado aos requisitos impostos em cada legislação para NZEBs.

Após terem sido reabilitados, três dos quatro edifícios modelados cumpriram os requisitos NZEB impostos nas respetivas legislações nacionais. O consumo de energia primária dos edifícios mais antigos foi reduzido em 93% em Coimbra e 86% em Budapeste. Nos edifícios mais recentes, o consumo de energia foi reduzido em 86% e 77% em Coimbra e Budapeste, respetivamente. Este estudo permitiu concluir que Portugal, quando comparado com a Hungria, enfrenta menos dificuldades para cumprir os requisitos impostos aos NZEBs. Isto deve-se às temperaturas mais quentes sentidas durante a estação de aquecimento, que resultam num menor consumo de energia associado ao aquecimento, e aos níveis radiação solar mais elevados, que aumentam a eficiência dos sistemas de energia renováveis.

Palavras-chave: Eficiência energética, *Nearly Zero Energy Building*, Modelação Energética de Edifícios, Reabilitação, *Energy Performance Building Directive*.

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF SIMBOLS, ACRONYMS/ABBREVIATIONS

List of Symbols

$\theta_{ext,v}$ – Average outdoor air temperature during heating season (ºC)

Ψ – Linear thermal bridge heat transfer coefficient (W/(m.ºC))

ΔT – Temperature differential (ºC)

A_N – Useful floor area (m^2)

c_p – Specific heat capacity (J.(kg.K))

$E_{Primary}$ – Primary energy consumption (kWh)

E_{Final} – Final energy consumption (kWh)

g – Glazing solar heat gain coefficient (-)

HDD – Heating Degree Days (ºC)

N_i – Reference building heating needs (kWh)

N_{ic} – Predicted building heating needs (kWh)

N_v – Reference building cooling needs (kWh)

N_{vc} – Predicted building cooling needs (kWh)

P_{PV} – Solar panel peak power (Wp)

P_{load} – Average daily electricity consumption (W)

q – Specific heat loss coefficient (W/(m^3.K))

q_{DHW} – Domestic hot water net thermal energy demand (kWh/(m^2. year))

Q_{sd} – Solar heat gains during the heating season (W)

R_{NT} – Energy class ratio in residential buildings (-)

Ren_{Hab} – Renewable primary energy indicator in residential buildings (-)

U – Opaque envelope heat transfer coefficient (W/(m^2.ºC))

U_g – Glazing heat transfer coefficient (W/(m^2.ºC))

U_r – Opaque envelope heat transfer coefficient after accounting for the effect of thermal bridges (W/(m2.ºC))

Acronyms/Abbreviations

AB – Apartment Block

AWHP – Air to Water Heat Pump

BEM – Building Energy Modeling

COP – Coefficient of Performance

CO_2 – Carbon Dioxide

DHW – Domestic Hot Water

EER – Energy Efficiency Ratio

EPBD – Energy Performance of Buildings Directive

EU – European Union

GHG – Greenhouse gases

IAQ – Indoor Air Quality

INE – *Instituto Nacional de Estatística*

LNEC – *Laboratório Nacional de Engenharia Civil*

MFH – Multifamily House

NZEB – Near Zero Energy Building

PSH – Peak Sun Hour

PV – Photovoltaic

SCE – *Sistema de Certificação Energética*

SHGC – Solar Heat Gain Coefficient

SCE – *Sistema de Certificação Energética*

TMY – Typical Meteorological Year

ZEB – Zero Emission Building

1. INTRODUCTION

Global warming is a serious environmental concern that has received a lot of attention in recent decades. This problem is related to the rise in the average surface temperature on the Earth, which is principally driven by the accumulation of greenhouse gases in the atmosphere. The earth's surface temperature increased by around 0.9 degrees Celsius between the 1950s and the 2000s [1]. The most recent carbon dioxide (CO_2) emissions have been recorded to track the high end of emission scenarios, posing challenges to keep global warming below two degrees Celsius [2].

With the increasing concerns about global warming and carbon CO_2 emissions across Europe, several energy and climate policy packages have been released to make the EU energy performance more efficient, enabling a fast reduction of fossil fuel consumption. As stated in the European Green deal, the goal is to reduce greenhouse gas emissions by at least 80% by 2050 compared to 1990 levels and to achieve a climate neutral continent by 2050 [1,2].

The high energy consumption associated with the European residential sector imposes a huge concern. Buildings are estimated to account for approximately 40% of primary energy consumption and 36% of the energy related greenhouse gas emission [3]. Space heating and domestic hot water are the main uses of energy by households in the European Union, accounting for 64.4% and 14.5% respectively [4].

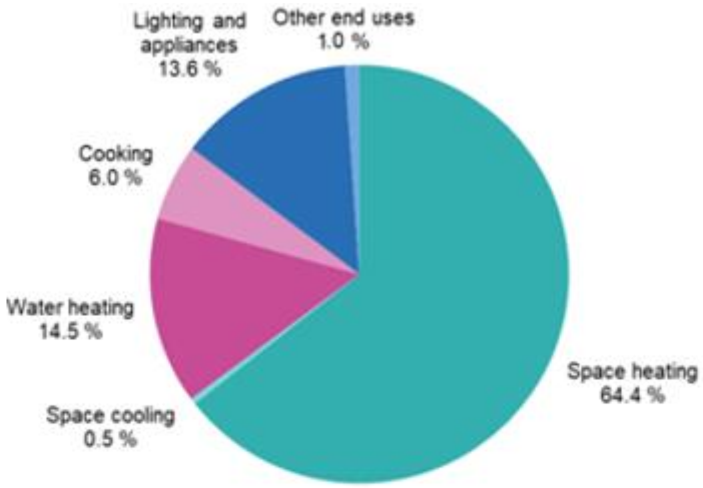

Figure 1.1. Final energy consumption in the residential sector by use [4].

In Figure 1.2 the main energy products used for each type of end-use in the residential sector are described. Energy consumed for space heating comes mostly from natural gas and renewable energy sources (respectively 39.3% and 29.2%). For water heating the energy mainly comes from natural gas (43%), electricity (19.2%) and renewable energy sources (13.9%) [4].

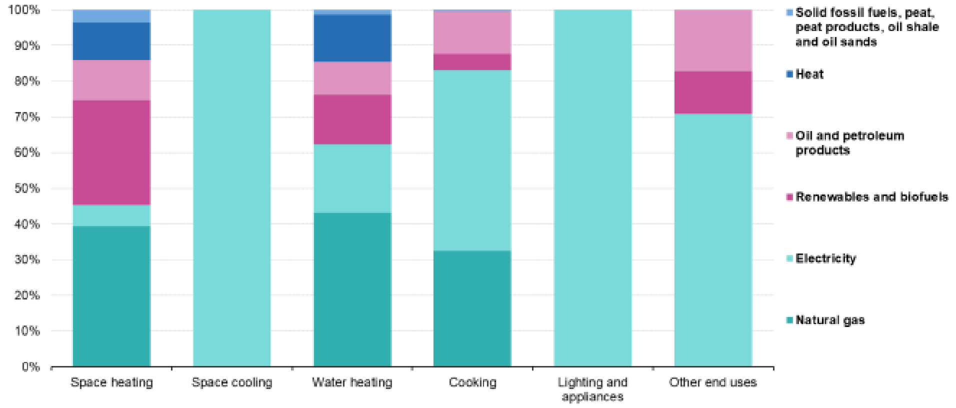

Figure 1.2. Final energy consumption in the residential sector by use [4].

To reduce the energy demand from the residential sector in 2010, the Energy Performance of Buildings Directive 2010/31/EU was agreed to show the main pathways towards an EU decarbonized building stock. According to this Directive, new buildings occupied by public authorities and properties should be NZEBs by December 31, 2018, and all new buildings by December 31, 2020 [5].

A Nearly Zero-Energy Building means a building that has a very high energy performance, and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produce on-site or nearby [5]. This directive does not advocate a uniform approach for implementing NZEBs throughout Europe, leaving some flexibility for Member states to detail their NZEB definitions, to account for different building types and climates, and including a numerical indicator of primary energy use [6].

Even with these requirements for new buildings to be very energy efficient there is still a huge problem related to the existing building stock and their high energy consumption. In Europe, 35% of buildings are over 50 years old and 90% were built before 1990 [7]. Renovating both public and private buildings is an essential action and has been referenced in the European Green Deal as a key driver for achieving the energy reduction goals [8].

In the 2018 amendment of the EPBD, it is pointed out that each Member state must establish a comprehensive strategy aimed at achieving a highly efficient decarbonised building stock by 2050 and a cost-effective transformation of existing buildings into NZEBs [9].

Besides all these measures and requirements, due to the variety of climates, market and local conditions across Europe, the implementation of NZEBs hasn’t been an easy task [10]. Buildings are central in the decarbonisation process of Europe, but current efforts and trends are not enough to achieve carbon neutrality by 2050 [11]. To solve this, in December 2021, the Commission proposed a revision of the EBPD. It upgrades the existing regulatory framework to reflect higher ambitions, more ambitious concepts of new buildings as well as a renovation plan that sets how Europe can achieve a zero-emission and fully decarbonised building stock by 2050 [12].

Renovation can offer numerous opportunities and generate huge social, environmental, and economic benefits. Investing in buildings renovation can also inject a stimulus in the broader economy. Europe has now the opportunity to turn the renovation wave into a win-win situation for climate neutrality and recovery. The goal is to at least double the annual energy renovation rate and to encourage deeper energy renovations [13].

1.1. Motivation

As climate change and the problems associated with it increasingly affect us, and since energy consumption associated with the European residential sector accounts for a considerable portion of total energy end-use in the European Union [14], research have been directed towards reducing the energy consumption associated with the building’s operation [15].

Buildings have the highest energy saving and toxic waste reduction potential [16]. Governments and international organizations have been putting significant effort towards the development of energy efficiency programs and policies related to building retrofitting and refurbishing projects aimed at reducing the building’s energy demand without sacrificing the thermal comfort of the occupants [17].

The development of goals, targets, and action plans is essential for a sustainable retrofitting strategy for the European existing housing stock to achieve high performance dwellings in terms of energy consumption and occupant thermal comfort. Retrofitting can also add value to properties, reduce building operational costs, and provide stability when changes in energy prices and regulatory costs occur [18,19].

Retrofitting is a complex process that faces a lot of constraints and uncertainties such as different physical condition of properties, regulation updates, human behavior, market transformation and different financial limitations [20]. Therefore, determining appropriate retrofit measures to achieve meaningful improvements is a complex process that requires deep knowledge of thermodynamics and consumption practices of occupants.

To access the energy performance of buildings and to determine the energy savings associated with retrofitting measures, Building Energy Modeling (BEM) is one of the most important and advanced technology [21]. With BEM it is possible to predict the effect of one or more hypothetical energy efficiency measures on a building and plan the optimal energy retrofitting scenario [22].

To quantify the energy savings, the energy consumption of the building before and after the retrofit solution must be determined. To conduct this comparison, a model of a building energy consumption must be created in order to access the energy savings associated with retrofit measures [22]. If the base model of the building is constructed using data from an existing building, it is possible to design a plant to convert an existing building into a NZEB.

1.2. Aim and research objectives

The present dissertation uses BEM to evaluate retrofit solutions for typical buildings from the Hungarian and Portuguese residential building stock. The building models were created based on established common typologies and reference buildings based on statistical data from each countries' residential building. A reference building is a theoretical building designed to represent the most common building types in a specific construction period.

In this work, two building energy models were conceived and simulated under two different climate zones, Coimbra, and Budapest. Two construction periods were selected to determine the challenges faced by the older (before 1940) and the newer building stock (1990-2000). The buildings models were created in accordance with the construction solutions and the most common technical systems used during the construction periods chosen.

With this, the main goals were to analyze the energy savings potential associated with the retrofitting of typical buildings from each country and to better understand the main challenges associated to the retrofitting of the existing building stock. Therefore, this study intends to:

- Study the NZEB concept and the legislation for accessing their energy performance.
- Study the most common retrofit measures and technical building systems installed to enhance a building energy performance.
- Study the national regulations from Portugal and Hungary to characterize energy consumption in residential buildings.
- Describe the Hungarian and Portuguese residential building stock.
- With DesignBuilder, create building energy models for typical buildings from each country and access the energy savings associated with different retrofit measures and different technical building systems.
- Access the energy performance of the retrofitted buildings and test the requirements specified in each national legislation for NZEBs.

1.3. Dissertation structure

According to the aim of this study, the present dissertation has been structured into five distinct chapters, which are represented as follows:

Chapter 1 introduces the topic of this dissertation and describes the motivation and objectives of this work.

Chapter 2 reviews the literature of the most important concepts for this study, including the NZEB concept, the European legislation that characterizes these buildings, and the national legislation for accessing the energy performance of residential buildings in Portugal and Hungary. Following that, the best practices and most common technical buildings systems used to enhance building energy performance were studied. This chapter concludes with a description of the national residential building stock from Portugal and Hungary.

Chapter 3 describes the methodology used to conceive the reference building models that were responsible for representing a typical dwelling from each country's residential building stock. After this, the retrofit measures, technical building systems, and renewable energy sources applied are described.

Chapter 4 showcases the results obtained by building energy simulation through Designbuilder. The results obtained were discussed and suggestions were made in order to reach conclusions. At the end of this chapter, the buildings' energy performance was calculated and compared to the requirements imposed in each legislation for NZEBs.

Chapter 5 summarizes the main conclusions reached with this study and provides recommendations for future studies.

2. LITERATURE REVIEW

2.1. Nearly Zero Energy Building

According to the Energy Performance of Building Directive recast a Nearly Zero Energy Building is a building that has a very high energy performance and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby [5].

The energy performance of a building, according with the Directive 2018/844 amending the 2010/31/EU Directive, shall be determined in the basis of calculated or actual energy use and shall reflect typical energy use for space heating, space cooling, domestic hot water, ventilation, built-in lighting, and other technical building systems [9].

The energy performance of a building is required to be expressed by a numeric indicator of primary energy use in kWh/(m^2.y) and the calculation of primary energy shall be based on primary energy conversion factors, which may be based on national, regional, or local conditions [9].

The definition given in the EPBD recast is still a little bit vague and it is necessary for Member states to give a quantitative definition of "very high energy performance" and "a very significant extent by energy from renewable sources" [10]. It is also necessary to identify the primary energy to be used in the numerical performance indicator (total, non-renewable or renewable), as well as the definition of "nearby" in each country.

Another important provision established in the EPBD is related to cost-optimal levels of minimum energy performance requirements for new and existing buildings [3]. The cost-optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle" [5]. The Delegated Regulation No 244/2021 supplementing the EPBD provides a comparative methodology framework for achieving cost-optimal levels of minimum energy performance requirements for building and building elements [23,24]. This methodology requires the definition of reference buildings, the definition of energy efficiency measures aimed at reducing the primary energy consumption, and the comparison of various strategies in order to select most economically advantageous one [25–27].

Due to differences across countries from Europe in relation to building and climate types, different cost-optimal levels and energy efficient measures can be used [28,29]. According to the EPBD recast, flexibility is also needed to account for the influence of climatic conditions on heating and cooling needs, and on the cost-effectiveness of different measures for reducing the primary energy consumption [5].

Member states have in place a certification system to classify their buildings in terms of energy performance. In this certificate, information about the building’s energy performance and reference values such as minimum energy performance are included. The amount of renewable energy used relative to overall energy consumption, as well as the annual energy consumption can also be included in this certificate. Additionally, recommendations for cost-effectively enhancing a building´s energy performance must be made. These recommendations may also provide an estimation of the range of payback time or potential benefits throughout the course of the building´s economic lifecycle [5].

2.1.1. NZEB definitions across EU

As mentioned earlier, cost optimality varies across Member states due to variables such as climate, local conditions, energy and labor costs, material prices, policy frameworks, building types, available renewables and technologies, calculation methods, etc. As a result, national plans need to be adjusted according to national implementation which is reported on regularly to comply with EU directives [30].

The European Union grants Member states the flexibility to define various aspects related to NZEBs. These include building typology, classification, balance, physical boundary, period of balance, metric, normalization, and time dependent weighting [10].

By analyzing the scenario across Europe, it is possible to understand that for energy consumption calculation the main sources to consider are heating, cooling, domestic hot water, ventilation, and lighting [31].

The difference between the primary energy demand and the energy generated on-site by renewable energy is the most common approach for determining the energy balance of a building. Usually, the calculation is conducted over a year and incorporates constant factors (e.g. primary energy and CO_2 emission conversion factors, etc.) throughout the period [10].

In terms of boundaries for analysis, the focus is primarily on individual building or units. This allows for a more detailed understanding of energy use within specific structures.

When it comes to energy generation from renewable sources, most member states consider only on-site energy generation, but some nations also consider external and nearby sources of energy generation [10].

Despite all the differences between the European member states, a numeric indicator of energy performance expressed as primary energy in kWh/(m^2.y) is used to represent the energy efficiency of a building. Due to the non-homogeneous calculation methods and the differences in definitions across member states, the requirements for the numeric indicator of energy performance across Europe can be greatly varied.

2.1.2. NZEB implementation across EU

The number of NZEBs and high-performance buildings in Europe increased significantly from 2012 to 2016, as can be seen in Figure 2.1 [3]. During this period, 1,238,184 buildings were built or renovated to NZEBs standards. Residential buildings accounted for the largest share (95.6%) of the total NZEBS built. New constructions accounted for 52% of NZEBs built between 2012 and 2016, while 48% were the result of renovations [32].

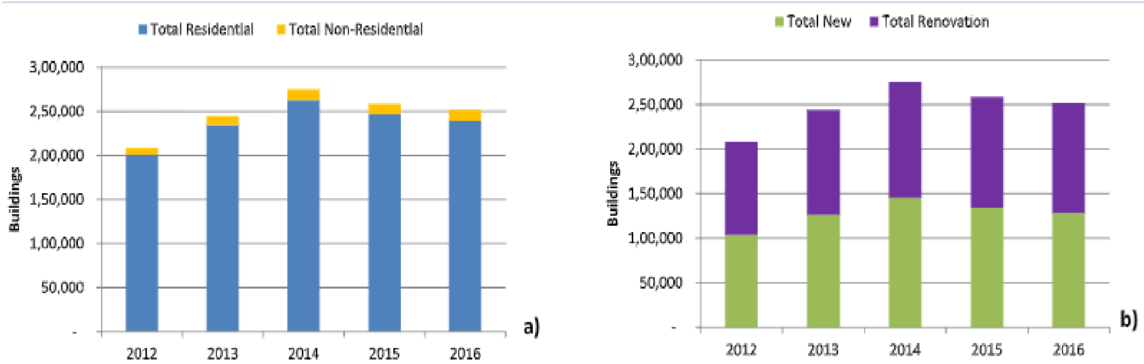

Figure 2.1. a) NZEBs in Europe by building use (2012-2016); b) NZEBs in Europe (2012-2016) (new and renovated) [3].

Another important parameter to evaluate the NZEBs development is the share of NZEBs within the total construction market. This share increased from 14% in 2012 to 20% in 2016 [32]. The share of NZEBs in the total construction market across the different European Member States is described in Figure 2.2.

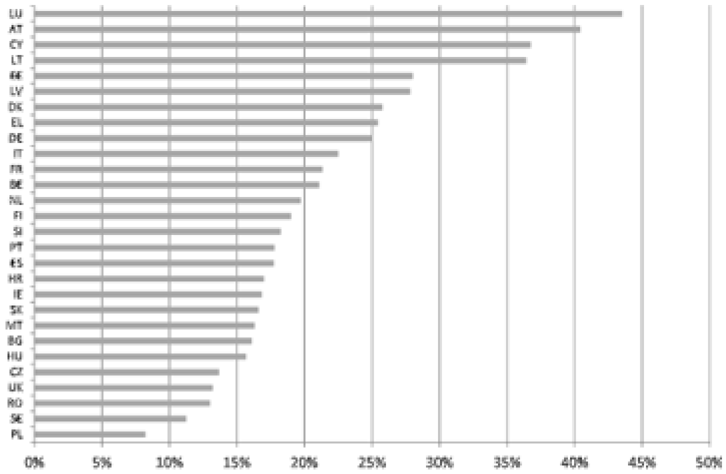

Figure 2.2. Share of NZEBs in the total construction market per Member State. Adapted from [3].

Most member states have implemented a variety of initiatives to encourage the development of NZEBs. These measures can be classified as [9]:

- Regulatory actions - setting energy standards and defining NZEB requirements through the adoption of regulations and laws.
- Financial measures - subsidies, grant for renovations, operation initiatives, and fiscal incentives to support NZEB projects are all important financial measures that need to be incentivized by member states.
- Educational measures - training courses for engineers must be granted and research projects must be incentivized for those who want to improve their knowledge and abilities in NZEB design and construction.

2.2. Zero Emission Buildings

Despite all current trends and efforts made by all Member states in achieving carbon neutrality by 2050, current efforts and trends are not enough to achieve this goal [33]. In 2021, through the EBPD provision recast, more ambitious concepts of new buildings were introduced, and the existing regulatory framework was improved to reflect the higher ambitions [12].

With this revision the focus is on reducing buildings' greenhouse gas (GHG) emissions and final energy consumption by 2030 and setting a long-term vision for buildings towards EU-wide climate neutrality in 2050. The initiative is built around a few specific goals, including speeding up and deepening building renovations, improving knowledge of building's energy efficiency and sustainability, and ensuring that all structures will meet the 2050 climate neutrality requirements.

The new building concept is designated by Zero Emission Building (ZEBs), and these buildings must have a very high energy performance, where the very low amount of energy still required is fully covered by energy from renewable sources generated on-site, from a renewable energy community, or district heating and cooling systems [12]. According to article 7, as of 1 January 2027, new buildings occupied or owned by public authorities must be zero emission buildings, and new buildings as of 2030. The timeline for NZEBs and ZEBs is demonstrated in Figure 2.3.

Besides the introduction of this new concept, the EPBD recast requires that the worst performing residential buildings be renovated and improved to at least class F by 2030, and to at least class E by 2033. This focus on the worst performing classes ensures that efforts are directed into buildings with the highest potential for decarbonization, energy poverty alleviation and economic benefits [12].

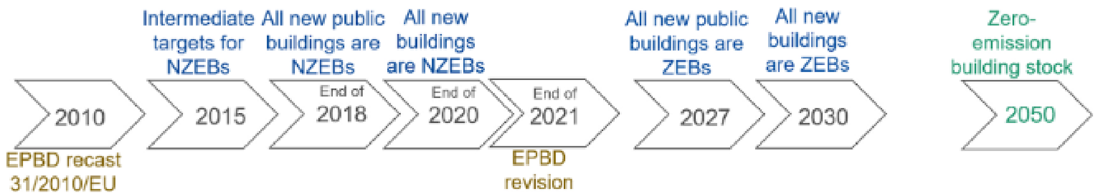

Figure 2.3. Timeline for NZEB and ZEB [34].

With the introduction of ZEBs, the focus goes beyond the GHG emissions associated with the operation of the building. The whole life-cycle emission of buildings should be considered not only in new construction but also in renovations. This implies the definition of which stages, over the lifetime of a building, are included in the calculation of GHG emissions [35].

Commonly, a first disaggregation is made dividing the system boundary into two main parts, the operational and the embodied. The operational part focuses on the stage at which the building operates, while the embodied refers to the stages before and after the operation, such as the product stage, the construction process, and the end of life [36]. In Figure 2.4 the different life cycle stages are represented.

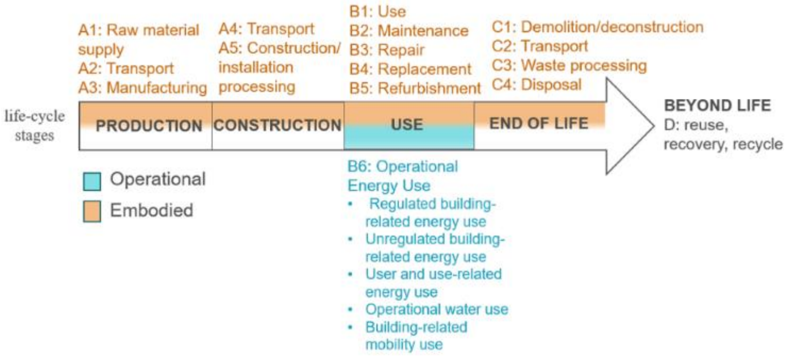

Figure 2.4. Life cycle stages with operation and embodied impacts [34].

2.3. NZEB and ZEB toughest challenge

The main issue that Europe is facing is the renovation of old residential and non-residential buildings. The building stock in Europe is old and the current renovation rate is around 0.5% and 2.5%. From the EU's building stock, 85% of the buildings were built before 2001, and 85-95% of the buildings that exist today will be standing in 2050 [7]. Another concern raised by the current slow renovation rate is that the buildings built between 1945 and 1980 have the highest energy demand [37].

In the Climate Target Plan, the Commission proposes reducing greenhouse gas emission by at least 55% by 2030 compared to 1990. To meet this goal, the European Union should reduce greenhouse gas emissions from building by 60% by 2030, energy consumption by 14% and energy consumption for heating and cooling by 18% (compared to 2015 levels) [7].

Nowadays, only 11% of the EU existing building stock is renovated each year, and very rarely renovation works address energy performance of buildings. Deep renovations that lower energy use by at least 60% are carried out in only 0.2% of the EU's building stock each year [38].

Renovation is held back by barriers at different points throughout the value chain – from the initial decision stage to engage in renovation, to financing and completion of the project. The three main barriers can be classified as technical, financial, and social barriers [39].

Key technical barriers to energy renovations include the absence of consistent and standardized solutions to meet various building standards requirements on energy saving, lack of skilled labor, and long processes that discourage owners. Financial barriers arise from the high up-front costs and insufficient funding for energy renovation purposes, and long pay-back times for retrofitting interventions. As for the social barriers the decision-making processes are long and complex, there is a lack of understanding and support from the inhabitants, and low awareness about energy efficiency and non-energy benefits of the retrofit interventions [40].

Renovation can open numerous possibilities and generate far-reaching social, environmental, and economic benefits. Investing in buildings can also stimulate the construction ecosystem and the broader economy. Renovation works are labor intensive, create jobs and investments, can generate demand for highly energy and resource-efficient equipment and bring long-term value to properties. By 2030 an additional 160,000 green jobs could be created in EU construction sector through a renovation wave [41].

Europe now has a unique chance to make renovation a win-win for climate neutrality and recovery. The goal is to at least double the annual energy renovation rate in residential and non-residential buildings by 2030, as well as to encourage deep energy renovations [13].

The EU needs to adopt an encompassing strategy based on key principles to address climate and energy challenges. One of these principles is prioritizing energy efficiency to ensure that we only produce the energy we truly need. This strategy must also emphasize decarbonization and the integration of renewable sources, with a focus on accelerating building renovations to allow the integration of local renewable sources [7].

2.4. Energy saving measures

The NZEB target can be achieved using the appropriate technologies and best practices [42]. Although buildings represent a huge opportunity for reducing global energy consumption and GHG emission, the real challenge is to achieve these savings without sacrificing thermal comfort [43].

There are two main strategies that need to be implemented: reducing energy demand through energy saving measures and increasing energy supply with renewable energy systems [44–46]. To go from a reference building to a NZEB, measures to reduce the demand for energy have a higher priority since it is easier to save energy than to produce it [47].

To choose the most efficient measures, it is important to talk about the balance of heating and cooling energy needs. This is an important topic for high performance buildings to limit unnecessary space conditioning systems and distribution. In heating dominated climates, for example, the focus should be on eliminating the cooling thermal needs of the building. This is attainable in Northern European countries since summer comfort conditions are easy to maintain. This allows the use of a single technical building system which would result in substantial cost savings [37].

In Southern Europe, higher summer temperatures and solar radiation result in an equilibrium of heating and cooling energy needs, this results in the need to solve potential conflicts between winter and summer comfort objectives, and a higher likelihood of having to install both heating and cooling systems and bear the associated costs [37].

However, according to data from the Intergovernmental Panel on Climate Change’s most recent reports, the average global temperature is predicted to increase by more than 1.5 ºC in the next 20 years compared to the pre-industrial period [48]. As a result of the effects of global warning, the demand for higher levels of indoor thermal comfort, and the improvement in the quality of the external envelope of a building, energy use for cooling is becoming a larger share in the building energy balance [49–51].

2.4.1. Opaque envelope

The energy performance of a building is greatly influenced by the building envelope thermal transmittance properties and geometric configuration [52,53]. Therefore, it is of great significance to enhance the thermal performance of the external envelope to improve a building’s energy efficiency.

To determine the rate of heat transfer through an opaque element of a building the heat transfer coefficient or *U*-value is used. The *U*-value ($W/m^2.ºC$) quantifies the amount of energy transferred per unit of time through one square meter for a temperature difference of 1ºC across the element [54].

There are two ways to optimize the opaque envelope of a building, one is to apply design type measures to reduce the building surface area, the other is to increase the thermal resistance of the building’s construction solutions in order to reduce their *U*-value. Increasing the total thermal resistance of the core layer of opaque envelopes is a critical direction in improving building energy efficiency [55–58].

Building insulation is regarded as a basic yet extremely energy efficient measure. A thermal insulator is made up of a material with high thermal resistance which reduces the heat flow rate with the surroundings [59]. As a result, the building heating and cooling needs are greatly reduced [60].

2.4.2. Glazing areas

Windows are useful multifunctional construction components that offer passive solar gains, air ventilation, and natural lighting. However, windows are considered the weakest components in the building envelope [61,62], and account for 20% to 50% of the building energy losses [63] . Glazing is usually characterized by the thermal transmittance (U_g), and the solar heat gains coefficient (SHGC), also called the g factor [64].

Thermal heat transmission, solar heat gains, air leakage, and daylighting are the four basic ways by which windows influence building energy use. As a result, by using glazing and shading strategies to control solar heat gains to supplement heating and minimize cooling requirements, specifying low-air-leakage windows, integrating windows into natural ventilation strategies that can reduce energy use for cooling and outdoor air requirements, and using daylight to offset lighting requirements, windows can have a positive impact on a building's energy performance [65].

One of the most commercialized solutions is multilayer glazing, which is defined as the combination of glazing layers with air, Argon, or Krypton gas fill [65]. The number of glazing layers and the inert gas type remarkably affects the thermal performance of multilayer glazing. The space between the glazing layers is normally filled with air since it is the cheapest [66].

To control the solar heat gains, e-coating or low-emissivity coatings are usually applied on one or both surfaces of the glazing. These coatings are thin, transparent layers of metal or metallic oxide that are applied to improve the glazing thermal performance. These coatings are intended to diminish the glass ability to emit thermal radiation. By doing this, low-e coatings minimize heat transmission through the glass, resulting in increased energy efficiency and thermal comfort in buildings [67].

2.4.3. Building airtightness

Building energy consumption can increase due to inadequate airtightness known as air leakage, which can be caused by outside gusting winds or by pressure differences across the building envelope resulting from the temperature differential between indoor spaces and surroundings [68].

Infiltrations can account for up to 40% of the total heat losses from buildings, and poor building airtightness can also have an influence on indoor air quality (IAQ) and thermal comfort [42]. As a result, maximum infiltration-level criteria have been incorporated into the building codes of many European countries (e.g., in Belgium, Denmark, France, Germany, Sweden, and the United Kingdom) [69].

2.4.4. Ventilation

Acceptable IAQ is achieved through ventilation, which can be supplied by natural means (open windows or doors) or mechanical ventilation (exhaust fans or heat recovery devices). However, the energy required to condition the outside air may account for a large portion of the total space thermal load, which is one reason to keep air change rate to the minimum required. In a modern building that meets ventilation requirements, the air exchange rate typically contributes 20-50% of the heat load [65].

Natural ventilation reduces the reliance on mechanical cooling and ventilation systems, resulting in energy savings while improving thermal comfort and indoor air quality [70]. Passive ventilation strategies can reduce the thermal load of the building, thereby lowering the building’s energy consumption [71]. One of these passive ventilation techniques is night ventilation which has the potential to reduce energy demand in buildings [72].

Furthermore, while super-insulated buildings provide good conditions in the colder seasons, they may end up with very high internal temperatures in the summer, falling outside the comfort standards during these times. To solve this, the utilization of natural ventilation is becoming more popular as an optimal passive strategy to avoid overheating during the warm seasons [73,74].

However, in climate zones with severe winters, supplying unconditioned outdoor air straight into occupied spaces may induce thermal discomfort if no further heating is applied and warming it to standard supply temperatures might result in substantial heating demands [75]. As a result, mechanical ventilation has emerged as the most common type of ventilation for ensuring IAQ and thermal comfort in most newly constructed residential buildings located in cold climate regions [76]. Because heat loss from the exhaust air accounts for a significant portion of total heat loss in cold climates, heat recovery technologies have been commonly used in recent years to reduce the heating demands of residential buildings [77]. In residential buildings, the heat loss from mechanical ventilation systems can reach 35-40 kWh/m^2 [78], however, 60-95% of this ventilation heat loss can be recovered using a heat recovering system [79].

2.4.5. Technical building systems

A technical building system, according to the EPBD, is a technical equipment used for space heating, space cooling, ventilation, domestic hot water, lighting, building automation and control, on-site renewable energy, and storage. Among the EPBD provisions, the directive introduced energy performance requirements for technical building systems [9] and, in the last revision, introduced the goal to shift towards emission free heating systems [12].

Heat pumps are the most commonly installed technical systems for space heating in NZEBs, accounting for 49% share in the space heating technologies [76]. This type of systems can also be used for domestic hot water and can supply the cooling needs of the building, which is becoming increasingly more important due to the expected global temperature increases [80].

Once all the technically and economically possible building energy saving measures have been implemented to reduce the energy demand, renewable energy sources must be installed to balance the demand for residual energy. The most used renewable technologies in NZEBs are PV, solar thermal, geothermal and biomass [3].

2.5. Energy assessment regulations

As previously stated, Member States have flexibility in establishing reference buildings and criteria for calculating energy consumption due to differences in building types, climatic zones, and cost optimal levels across the European Member States [28,29].

2.5.1. Hungarian regulation

In Hungary, for determining the energy performance of buildings the decree 7/2006 TNM is used. The scope of this decree covers the buildings and building elements specified in the government decree on the certification of the energy characteristics of buildings.

To access the energy demand for space heating and cooling for residential buildings, the internal temperatures during the heating and cooling season must be the ones specified in Table 2.1.

Table 2.1. Heating and cooling setpoint for Hungarian residential buildings. Adapted from [81].

Function of the building	Function of the room	Minimum internal temperature for heating [ºC]	Maximum internal temperature for cooling [ºC]
Residential building	Long-term stays (dining room, bedroom, etc.)	20	26
	Other rooms (kitchen, storage, etc.)	16	-

In Annex 3 of the 7/2006 TNM decree, for residential buildings, the minimum air change rate, the net thermal energy demand for domestic hot water (DHW), and the average value of internal heat gains are defined according to Table 2.2.

Table 2.2. Residential requirements for the Hungarian residential buildings. Adapted from [81].

Function of the building	Air exchange rate n [ach]	Domestic hot water net thermal energy demand q_{DHW}[kWh/(m^2. year)]	Average value of internal heat gains [W/m^2]
Residential building	0.5	30	5

The DHW thermal energy demand specified in the previous table is only valid for buildings with a useful floor area (A_N) of less than 80 m^2. According to the 7/2006 TNM decree, the following equation shall be used for bigger buildings.

$$q_{DHW} = \frac{80*30+(A_N-80)*15}{A_N} \left[\frac{kWh}{m^2.year}\right]. \quad (2.1)$$

The thermal transmittance requirements for the external building envelope are given in Appendix 5 of the 7/2006 TNM decree, and these values are specified in Table 2.3.

Table 2.3. Hungarian building elements thermal transmittance requirements. Adapted from [81].

Building boundary structure	U_{ref} **[W/(m²·ºC)]**
Exterior wall	0.24
Flat roof	0.17
Heated attic delimiting structures	0.17
Slab under attic	0.17
Wooden or PVC framed glazed window and door (>0.5 m^2)	1.15
In new buildings, floor laying on the ground	0.3

For accessing the energy performance of a residential building, it must only be accounted the primary energy consumption of the building technical systems (heating, cooling, domestic hot water, mechanical ventilation), and lighting systems per unit of heated floor area.

According to Annex 6 of the 7/2006 TNM standard, for a residential building to be considered a NZEB, the required value for the primary energy consumption (not including lighting energy demand) is 100 kWh/(m^2.year). To determine the primary energy needs and CO_2 emission of buildings, the conversion factor specified in Table 2.4 are used.

Table 2.4. Primary energy and CO_2 emission conversion factors. Adapted from [81].

Energy	**Primary energy conversion factor** $[kWh_{PE}/kWh]$	**CO_2 emission conversion factor** $[kgCO_2/kWh_{PE}]$
Electricity	2.5	0.455
Natural gas	1	0.297
Renewable (solar, water energy, wind, etc.)	1	0

Another requirement specified for buildings to be considered NZEBs is that, if the technical and economic conditions are suitable, 25% of the building's energy demand must be supplied by renewable energy sources that are generated in the building, from nearby sources, or taken from the national grid.

2.5.2. Portuguese regulation

In Portugal, the requirements for accessing the energy performance of a building are ruled by the *Manual do Sistema de Certificação Energética de Edificios* (SCE) [54] approved by *Despacho nº.6476-H/2021* [82].

For residential buildings, to determine the energy demand for space heating and cooling, the indoor temperatures must be the ones specified in Table 2.5.

Table 2.5. Heating and cooling setpoints for Portuguese residential buildings. Adapted from [54].

Function of the building	Minimum internal temperature for heating [ºC]	Maximum internal temperature for cooling [ºC]
Residential building	20	25

Requirements for residential ventilation and average value of internal heat gains are also specified, and these values are described in Table 2.6.

Table 2.6. Portuguese residential buildings requirements. Adapted from [81].

Function of the building	Air exchange rate n [ach]	Average value of internal heat gains [W/m²]
Residential building	0.5	4

The average daily domestic hot water consumption is calculated according to the number of conventional occupants in the building (n_{oc}) and the existence of water efficiency systems (f_{eh}) in shower or shower systems, as per the following equation.

$$M_{AQS} = 40 * n_{oc} * f_{eh} \ [\frac{l}{day}]. \qquad (2.2)$$

The energy performance assessment varies according to the climate zone and the respective variables that influence it. In Portugal, there are three types of climatic zones defined for each season (I1, I2, I3, for winter, and V1, V2, V3 for summer). The climate zone for winter is defined by the number of heating degree days (HDD) during heating season with a reference temperature of 18ºC, while the summer climate zone is defined by the average outdoor air temperature during the heating season ($\theta_{ext,v}$). The ranges that characterize each climate zone are represented in Table 2.7 and Table 2.8.

Table 2.7. Portuguese winter climate zones. Adapted from [54].

Criteria	**HDD ≤ 1300 ºC**	**1300 ≤ HDD ≤ 1800 ºC**	**HDD ≥ 1800 ºC**
Winter climate zone	I1	I2	I3

Table 2.8. Portuguese summer climate zone. Adapted from [54].

Criteria	$\boldsymbol{\theta_{ext,v}} \leq$ **20 ºC**	**20 ºC ≤** $\boldsymbol{\theta_{ext,v}} \leq$ **22 ºC**	$\boldsymbol{\theta_{ext,v}} \geq$ **22 ºC**
Summer climate zone	V1	V2	V3

The thermal transmittance requirements are specified according to the climatic zone, and their values are described in the Table 2.9.

Table 2.9. Portuguese building elements thermal transmittance requirements. Adapted from [54].

<table>
<tr><th colspan="2" rowspan="2">$U_{ref}[W/(m^2.ºC)]$</th><th colspan="3">Climatic Zone</th></tr>
<tr><th>I1</th><th>I2</th><th>I3</th></tr>
<tr><td rowspan="2">Outer boundary condition</td><td>Vertical opaque elements</td><td>0.50</td><td>0.40</td><td>0.35</td></tr>
<tr><td>Horizontal opaque elements</td><td>0.40</td><td>0.35</td><td>0.30</td></tr>
<tr><td rowspan="2">Inner boundary condition</td><td>Vertical opaque elements</td><td>0.80</td><td>0.70</td><td>0.60</td></tr>
<tr><td>Horizontal opaque elements</td><td>0.60</td><td>0.60</td><td>0.5</td></tr>
<tr><td colspan="2">Glazed aperture</td><td>2.8</td><td>2.4</td><td>2.2</td></tr>
<tr><td colspan="2">Elements in contact with the ground</td><td colspan="3">0.5</td></tr>
</table>

The primary energy consumption is determined according to the energy needs for space heating and cooling, domestic hot water preparation, mechanical ventilation, and the contribution of energy from renewable energy sources for self-consumption in these uses.

To determine the primary energy needs and CO_2 emission of buildings the conversion factors specified in Table 2.10.

Table 2.10. Primary energy and CO_2 emission conversion factors. Adapted from [54].

Energy	**Primary energy conversion factor $[\mathbf{kWh_{PE}/kWh}]$**	**CO_2 emission conversion factor $[\mathbf{kgCO_2/kWh_{PE}}]$**
Electricity (non-renewable)	2.5	0.144
Natural gas	1	0.267
Electricity (renewable)	2.5	0
Thermal energy from renewable sources	1	0

Buildings are classified according to their energy performance based on the ratio (R_{NT}) of the expected and reference building energy consumption. This ratio is classified according to the values specified in the Table 2.11.

Table 2.11. R_{NT} value ranges for residential buildings. Adapted from [54].

Energy class	$\boldsymbol{R_{NT}}$
A+	≤ 0.25
A	$0.25 \leq R_{NT} \leq 0.5$
B	$0.5 \leq R_{NT} \leq 0.75$
B-	$0.75 \leq R_{NT} \leq 1.0$
C	$1.0 \leq R_{NT} \leq 1.5$
D	$1.5 \leq R_{NT} \leq 2.0$
E	$2.0 \leq R_{NT} \leq 2.5$
F	$R_{NT} > 2.5$

The primary energy consumption in the reference building is determined according to the energy needs for the regulated uses and considering the absence of renewable systems and mechanical ventilation, i.e., that ventilation is done by natural means.

To access the thermal energy needs of the reference building, the interior temperatures to be considered are 20ºC for the heating season, and 25ºC for the cooling season. The heat transfer coefficient of the opaque building envelope and the glazing areas should be equal to the reference values specified in Table 2.9. For the opaque building envelope, this should be achieved by adding or changing the thickness of the insulation layer in the construction solution. For glazing areas there must not be any protection from mobile or fixed solar protection devices.

The thermal needs for domestic hot water are determined the same way as for the modeled building, considering that the water efficiency factor of the shower system is equal to 1.

The Portuguese requirements for buildings to be considered NZEBs are outlined in *Despacho n. º 6476-E/2021* [83], and buildings must meet the conditions described in Table 2.12. According to *Decreto Lei n. º 101-D/2020* [84], on December 7, new residential buildings or those undergoing major renovation must present a minimum level of renewable primary energy (Ren_{Hab}). This value is determined by the ratio of total renewable primary energy for self-consumption in the building's regulated uses to total primary energy use for domestic hot water.

Besides the energy performance requirements, NZEBs must also meet thermal comfort conditions. These conditions are determined by the thermal needs for space heating and cooling of the predicted and reference buildings. The heating need parameter is determined by the ratio of the predicted building's heating needs (N_{ic}) to the reference building's heating needs (N_i). Meanwhile, the cooling thermal parameter is determined by the ratio of the predicted building's cooling needs (N_{vc}) to the cooling needs of the reference building (N_v).

Table 2.12. Portuguese residential NZEB requirements. Adapted from [83].

Type of requirement	Evaluation Parameters	Climatic Zone		
		I1	I2	I3
Thermal comfort	Heating needs	$\frac{N_{ic}}{N_i} \leq 0.75$	$\frac{N_{ic}}{N_i} \leq 0.85$	$\frac{N_{ic}}{N_i} \leq 0.90$
	Cooling needs	$\frac{N_{vc}}{N_v} \leq 0.85$		
Energy performance	Energy class	Equal or higher than class A		
	Total primary energy	$R_{NT} \leq 0.50$		
	Renewable primary energy	$Ren_{Hab} \geq 0.50$		

2.6. Residential building typology

The development of goals, targets, and action plans for energy policy is fundamentally dependent upon having access to sufficient information regarding the energy use of the building stock. To help this task, two European research projects Tabula (2009-2012) and EPISCOPE (2013-2016) were developed to focus on improving energy efficiency in buildings.

These projects aimed at assisting policymakers, building experts, and stakeholders in reaching energy efficiency goals and reducing the environmental impact of buildings by fostering the development of a coherent framework for the sector of residential buildings, focusing on the energy use for space heating and domestic hot water [85].

During both projects, 21 national building typologies were built with the objective of describing the national building stock in terms of building energy performance. Buildings energy consumption depends on a variety of factors, including envelope construction, age distribution of existing building stock, exterior weather conditions, building size, type, age, and efficiency of the systems used [86].

The building's construction year provides useful information on the envelope's composition. Every construction era has its typical construction technologies, therefore, the structures of buildings built during the same period are identical in terms of heat losses. The construction year also gives information about the technical building systems installed [86].

Each national building typology classifies buildings, in terms of energy performance, by age and size. The distinction between building sizes is made by four different categories, single family house (SFH), terraced house (single family), multifamily house (MFH), and apartment block (AB) [87].

For each construction period and for each building size, a reference building is created, and information is given about the building elements and the systems installed. Regarding the building elements (walls, roofs, floors, and windows), their constitution is described as well as their heat transfer coefficient, and solar factor values for glazing. About the systems, information is given about the heat generator, storage, and distribution system types for space heating and DHW [88].

2.6.1. Hungarian residential building typology

According to the Hungarian typology of residential building, there are three main groups according to the size of the buildings:

- Single Family Houses;
- Multi-Family Houses with 4-9 flats;
- Apartment Blocks containing 10 or more flats.

Within each of these groups, there are more subgroups which were developed based on the building's construction year. In total, 15 different types of buildings were created, and a reference building was assigned to each. For every reference building, a photo is assigned, and the thermal properties of the building envelope and technical building systems are described.

The available statistical data from the Hungarian Statistic Office based on the census in 2001 describes the frequency of building types according to Table 2.13.

Table 2.13. Total number of residential buildings in Hungary. Adapted from [88].

<table>
<tr><th rowspan="2">Construction period</th><th colspan="2">Single family house</th><th colspan="2">Multifamily house</th></tr>
<tr><th>Below 80 m² (1-3 flats)</th><th>Above 80 m² (1-3 flats)</th><th>4-9 flats</th><th>10 + flats</th></tr>
<tr><td>-1944</td><td>400,537</td><td>269,508</td><td rowspan="5">43,981</td><td>10,819</td></tr>
<tr><td>1945-1960</td><td rowspan="2">449,213</td><td rowspan="2">672,128</td><td rowspan="4">59,356</td></tr>
<tr><td>1961-1979</td></tr>
<tr><td>1980-1989</td><td colspan="2">378,942</td></tr>
<tr><td>1990-2001</td><td colspan="2">198,938</td></tr>
<tr><td>2001-2011</td><td colspan="2">157,885</td><td>6,285</td><td>3,770</td></tr>
</table>

Almost all residential buildings in Hungary have space heating, which is typically supplied by a room-by-room heating system or a dwelling heating system. For single family houses, gas boilers, gas convectors, and wood stoves are the most common heat generators, as can be seen in Table 2.14.

Table 2.14. Space heating systems in Hungarian residential buildings. Adapted from [87].

Single family houses (1-3 flats)		Multifamily houses			
		4-9 flats		10 + flats	
Gas boiler	36.6 %	District heating	6.7 %	District heating	14.6 %
Gas convector	21.6 %	Central gas boiler	3.4%	Central gas boiler	7.8 %
Wood stove or boiler	30.3 %	Gas boiler flatwise	35.2 %	Gas boiler flatwise	19.8 %
Other	11.5 %	Gas convector	18.0 %	Gas convector	27,4 %
		Mixed	30.4 %	Mixed	26.7 %
		Other	6.3 %	Other	3.7 %

Natural gas is the most consumed energy source for space heating, followed by wood or coal. The distribution of the Hungarian building stock energy consumption by energy source is depicted in Figure 2.5.

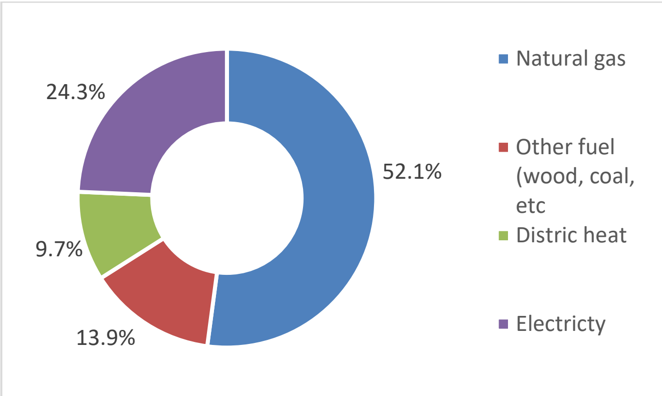

Figure 2.5. Primary energy use by energy source in Hungarian residential buildings. Adapted from [87].

2.6.2. Portuguese residential building typology

Portugal did not participate in the TABULA or EPISCOPE project so there is no national building typology in place. The only available data is given by the *Instituto Nacional de Estatística* (INE).

The high growth rate of the Portuguese housing stock during the last few decades meant that, in 2011, a significant part of the existing buildings was relatively recent. Of the total number of existing buildings in 2011 (3,544,389), 63.1% were built after 1971. The buildings built between 1946 and 1970 accounted for 22.5% of the national building stock, and the ones built before 1946 accounted for 14.4%. In 2011, the Portuguese housing stock was mainly made up mostly of low-rise buildings, with 84.9% of all buildings having one or two floors.

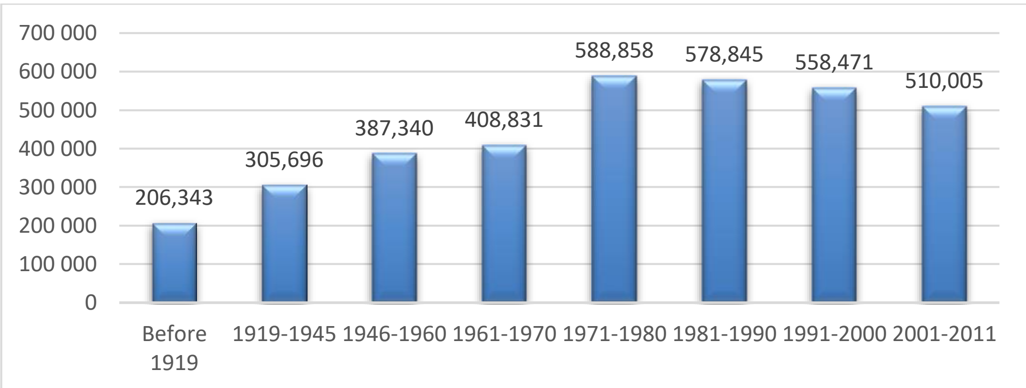

Figure 2.6. Portuguese residential buildings built until 2011. Adapted from [89].

In 2011, almost half of the conventional dwellings had heating provided through mobile appliances. However, in recently constructed buildings, the proportion of conventional dwellings with central heating, stoves, and fixed appliances has gradually increased. In contrast, the proportion of dwellings with an open fireplace and mobile appliances decreased in newer buildings, as can be seen in Figure 2.7.

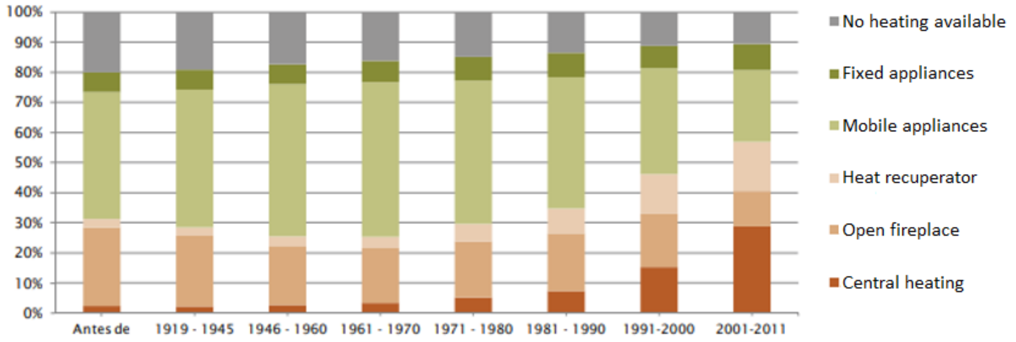

Figure 2.7. Space heating in Portuguese dwellings by construction period. Adapted from [89].

In newer buildings, the proportion of dwellings where electricity was the primary source of energy for heating has gradually decreased. On the other hand, the proportion of dwellings that use natural gas and other gaseous fuels has increased especially in buildings constructed after 1991, as can be seen in Figure 2.8.

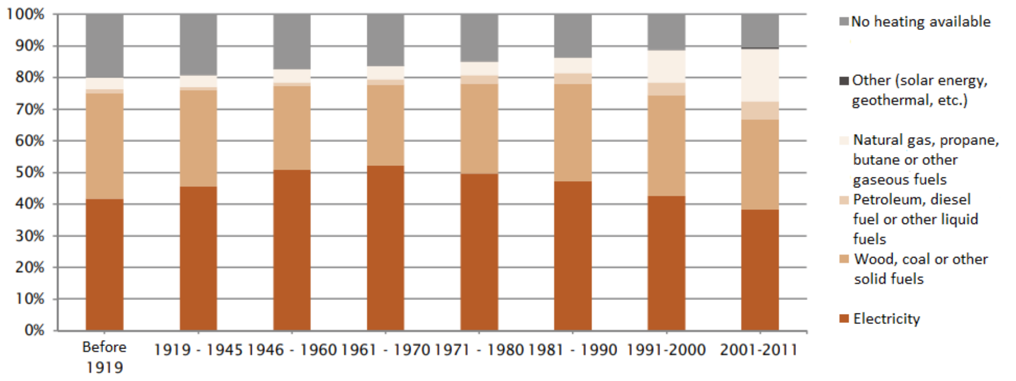

Figure 2.8. Number of Portuguese dwellings by type of heating. Adapted from [89].

3. METHODOLOGY

This chapter opens with a brief overview and justification of the buildings chosen to represent both countries' national stock. Then the procedure of designing the geometric model is described, as well as the characterization of the constructive solutions, the modeled mechanical systems, and the characterization of the building energy model.

In the second part of this chapter the studied retrofitting measures were described. First, measures to lower the building's energy consumption were implemented, followed by measures to improve the building's technical systems efficiency, and ultimately, renewable energy generation systems were integrated.

All the work described in this chapter was done with the help of BEM, which is a computational technique used to model and analyze the energy performance of buildings. It involves using specialized software tools to simulate and predict the energy consumption, thermal comfort, and environmental impacts of a building throughout its annual operation. This technology has increasingly become practical for energy efficient designs [90], operations [91], and retrofitting of buildings [92], with the aim of increasing the energy performance and reducing the carbon emissions of buildings.

The simulation software uses mathematical algorithms and computational models to simulate the behavior of the building and its systems over time. To calculate the behavior of the building it uses a set of well-defined laws, such as energy balance, mass balance, conductivity, heat transfer, etc. [93]. By simulating the building's energy use under different scenarios, such as varying insulation levels, different HVAC systems, or renewable energy integration, it allows designers and owners of buildings to evaluate the impact of each choice and make informed decisions to achieve a higher energy efficiency.

To access the energy performance of a building it is necessary to consider various building specification and characteristics, including internal heat loads and schedules, climatic conditions, thermal properties of the envelope, technical building systems efficiency, etc. [94]. The building energy simulation process is summarized in Figure 3.1.

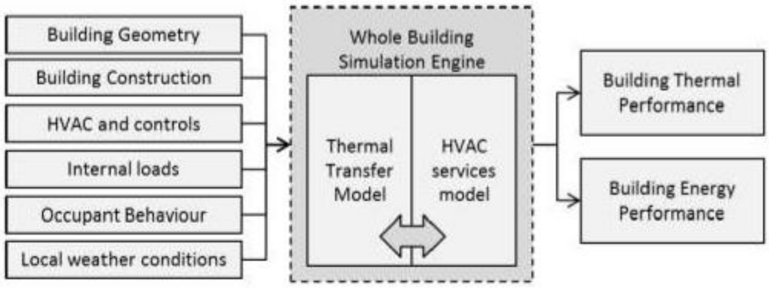

Figure 3.1. Building energy simulation process [95].

Due to the high number of inputs required and the complexity of the models required to access the energy performance of a building, simulation tools, like Energyplus, DOE2, Transys, etc., are broadly used to determine building energy performance. The user´s ability to enter inputs that produce a good model of the real energy consumption of buildings determines how accurate these simulation programs can be [95].

DesignBuilder, a third-party graphical user interface for the EnergyPlus thermodynamic simulation engine, was utilized for energy simulation. EnergyPlus is a modular and structured code program developed by the U.S. Department of Energy (DOE). This program combines the most popular features and capabilities of BLAST and DOE-2 whole-building energy simulation engines [96].

Users can benefit from a visually intuitive interface when using DesignBuilder with the EnergyPlus engine to design building models, define numerous input parameters, simulate energy usage, and analyze the results. The EnergyPlus engine allows engineers, architects, and researchers to model a building energy consumption associated with heating, cooling, domestic hot water, ventilation, lighting, and electric appliances [97].

3.1. Building selection and modeling

As previously said, when describing the national residential building typology of a country the most important parameters are the construction period and size. For each one of these parameters, it is defined a reference building that represents an average building of the stock under consideration.

One theory regarding this approach is that, even if a representative building does not perfectly replicate a specific building, it will respond to an intervention in the same manner as other buildings with similar use or form. After selecting the fundamentals such as building geometry, construction solutions, technical building systems, and internal loads, a reference building can be modeled with building energy simulation software.

To represent the challenges faced in the renovation of the existing residential building stock of each country, two single family buildings from two construction periods were selected based on the high number of residential buildings built during those years. The two periods and the number of buildings built during those periods in each country are described in Table 3.1.

Table 3.1. Single family buildings distribution according to construction period [88,89].

	Number of buildings in Hungary	**Number of buildings in Portugal**
Before 1940	670,045	512,039
Between 1990-2000	198,938	864,167

Buildings from these periods were built before the first EPBD recast was released. This means that these buildings were built without any thermal requirements for their construction solutions. Analyzing the periods just before the first EPBD recast, and the oldest existing building class allows to understand the challenges faced by the worst performing building class and how the evolution in the construction technologies helped reducing the energy consumption of buildings.

3.1.1. Local weather

Accurate BEM is dependent on precise input data, and one crucial input is the weather data of the location to be considered, including humidity, wind speed, dry bulb temperature, solar radiation and so on. While it is possible to simulate a building using actual weather data from a specific period, building energy retrofit optimization often requires average weather data.

For this purpose, typical meteorological year files (TMY) were developed, and they generate a year of representative weather data by assembling the database's most typical month for each calendar month. For each month, a weighted average of important parameters is created, and the month that most closely fits the average is chosen [98].

The modeled buildings were analyzed under the climatic zone of Budapest and Coimbra, allowing to study the influence of both climatic zones in the building's energy consumption. In Table 3.2 the cooling degree days, with a reference temperature of 25ºC, and the heating degree days, with a reference temperature of 20ºC, are specified for both cities. Additionally, the average monthly outdoor air temperature in Budapest and Coimbra can also be seen in Figure 3.2. ºC

Table 3.2. Cooling and heating degree days in Budapest and Coimbra.

	Cooling Degree Days [ºC]	Heating Degree Days [ºC]
Coimbra	13	1825
Budapest	25	3142

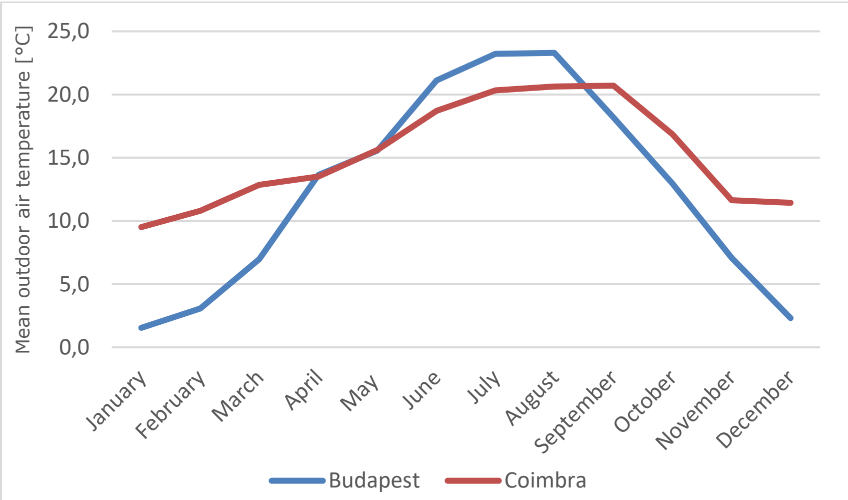

Figure 3.2. Mean outdoor air dry-bulb temperature in Budapest and Coimbra.

To meet the thermal transmittance requirements specified in the Portuguese legislation it was necessary to determine the climate zone of the buildings in Coimbra. According to the methodology outlined in *Manual SCE* [54], and considering that both buildings are located near the University of Coimbra campus, the parameters described in Table 3.3 were obtained.

Table 3.3. Coimbra climate characterization parameters.

	Building altitude [m]	HDD [ºC]	$\theta_{ext,v}$ [ºC]
Coimbra	140	1304	20.9

According to the criteria specified in Table 2.7 and Table 2.8 the buildings are located in winter climatic zone I2 and summer climatic zone V2.

3.1.2. Building modeling

Geometric information about the reference buildings responsible for characterizing the building typologies that make up the national building stock of both countries was only found for the Hungarian reference buildings. This information was given in a database provided by the Budapest University of Economics and Technology. Therefore, the creation of the geometric models of the buildings was based on this information, and the buildings modeled in Coimbra and Budapest have the same design.

In this database each of the reference buildings created to characterize the Hungarian residential building stock are described based on their dimensions, number of floors, glazing areas, among other important parameters to be considered when describing a building design. The general building data taken from the database to describe both reference single family buildings is showcased in Table 3.4 and the detailed information is given in appendix A.

Table 3.4. Hungarian reference building general data.

Building data	**Construction period**	
	Before 1940	**Between 1990-2000**
Number of floors	1	1
Total heated floor area [m^2]	69.9	99.2
Building dimensions	13.7 x 7.3	13.0 x 9.3
Typical location	Detached	
Floor plan shape	Rectangular	
Vertical division	First floor and Unheated attic	
Heated building volume [m^3]	178.9	351.6

The resulting characteristics are the means of surveys concluded in building typification. As the averaging process makes it impossible to have a definite building geometry, the specific heat loss coefficient (*q*), is used to create a geometry as close to the specific types as possible. According to decree 7/2006 TNM [81], this coefficient is the sum of the transmission losses and the utilized solar gains for the heating season (Q_{sd}) for 1ºC temperature difference, divided by the heated volume of the building, V. This coefficient is calculated according to the following equation:

$$q = \frac{1}{V} * (\sum A_i U_{R,i} * \sum l_i \psi_i - \frac{Q_{sd}}{72}) [\frac{W}{m^{3o}C}], \quad (3.1)$$

where A_i is the construction element i area in m^2, $U_{r,i}$ is the heat transfer coefficient after accounting for the effect of thermal bridges in W/(m^2.ºC), l_i is the linear thermal bridge development in m, Ψ_i is the linear thermal bridge heat transfer coefficient W/(m.ºC).

The building modeled to represent the buildings before 1940 (Building 1) is a detached single-family dwelling with two bedrooms, one living room, one kitchen and one bathroom. The one modeled to represent the buildings built between 1990 and 2000 (Building 2) is a detached single-family dwelling with three bedrooms, one kitchen, one living room and one bathroom. The buildings floor plans and 3D models are described in Figure 3.3.

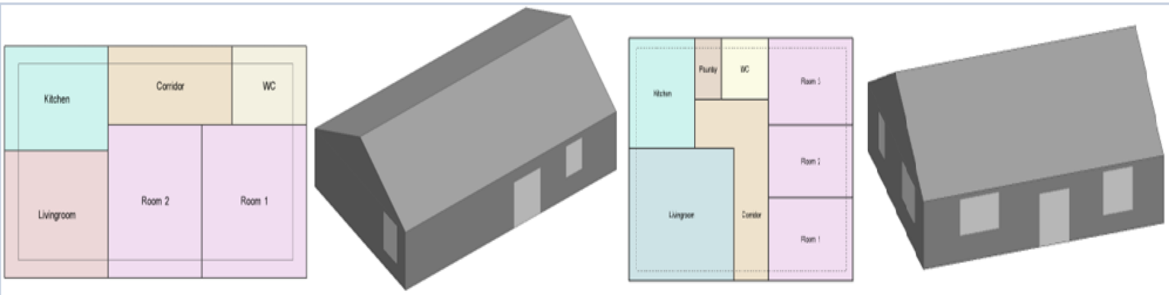

Figure 3.3. Floor plan and 3D view of the buildings modeled.

The general building data obtained for the modeled buildings is described in Table 3.5 and the detailed geometric information is given in appendix A.

Table 3.5. Modeled buildings general data.

Building data	**Construction period**	
	Before 1940	**Between 1990-2000**
Number of floors	1	1
Total heated floor area [m^2]	69.99	111.4
Ceiling height [m]	2.8	2.8
Building dimensions	12.0 x 7.3	13.0 x 10
Typical location	Detached	
Floor plan shape	Rectangular	
Vertical division	First floor and Unheated attic	
Heated building volume [m^3]	196.0	311.9

Regarding the construction solutions and their thermal characteristics, for the Portuguese buildings the information was taken from ITE 54 [99] and ITE 50 [100], both published by the *Laboratório Nacional de Engenharia Civil* (LNEC). For the Hungarian buildings, the construction technologies and their thermal characteristics were taken from the database provided by the Budapest University of Economics and Technology. The heat transfer coefficient of the construction elements used in each building are described in Table 3.6 and the layer-by-layer constitution can be seen in annex A.

Table 3.6. Heat transfer coefficient of the modeled buildings' construction elements.

Construction period	Construction element	Heat transfer coefficient W/(m^2.°C)	
		Portugal	Hungary
1940	Exterior wall	2.52	1.11
	Attic slab	2.32	1.09
	Ground floor	2.27	1.56
	Window	3.96	3.18
1990 - 2000	Exterior wall	1.10	0.63
	Attic slab	2.80	0.41
	Ground Floor	2.51	0.9
	Window	3.96	1.81

Since the objective was to analyze a building that thermally behaves like the reference building, the difference between the specific heat loss factor of the reference buildings and the buildings modeled must be small. This means that both buildings will lose the same amount of heat under the same weather conditions.

The specific heat loss factor was calculated according to the 7/2006 TNM standard [81], and the calculations were only performed for the Hungarian buildings. The results obtained for the specific heat loss factor for the reference buildings and for the modeled buildings are described in Table 3.7.

Table 3.7. Specific heat loss factor for the Hungarian modeled and reference buildings.

Construction period	Reference building specific heat loss factor [$\frac{W}{m^3 °C}$]	Modeled building specific heat loss factor [$\frac{W}{m^3 °C}$]	Deviation
Before 1940	1.43	1.47	2.6 %
1990 – 2000	0.62	0.61	0,8 %

3.1.3. Technical systems

In Hungary, buildings built before 1940 and those built between 1990 and 2000 already had a central heating system with radiators installed in each room. The equipment used for providing thermal energy for space heating and for domestic hot water is a natural gas water boiler. This equipment produces water at 70ºC, and the heating system is sized to work with a temperature difference of 20ºC (70ºC/50ºC). The Designbuilder configuration of this system is described in Figure 3.4.

In Portugal, buildings built before 1940 didn't had a central heating system for space heating, instead, the thermal energy for space heating is supplied by mobile electric appliances. The thermal needs for DHW were supplied by a natural gas water boiler with an operating temperature of 60ºC. The visual configuration of this system in Designbuilder is depicted in Figure 3.4.

Between 1990 and 2000, Portuguese buildings began to have a central heating system with radiators installed in each room. The heating needs for space heating and DHW were supplied by a natural gas water boiler. The radiator heating system was sized with a temperature difference of 20ºC (60ºC/40ºC).

The natural gas water boiler modeled has a heating capacity of 24 kW and its efficiency is determined in accordance with the part load factor curve "Circa1975HighTempBoiler" taken from the DesignBuilder templates.

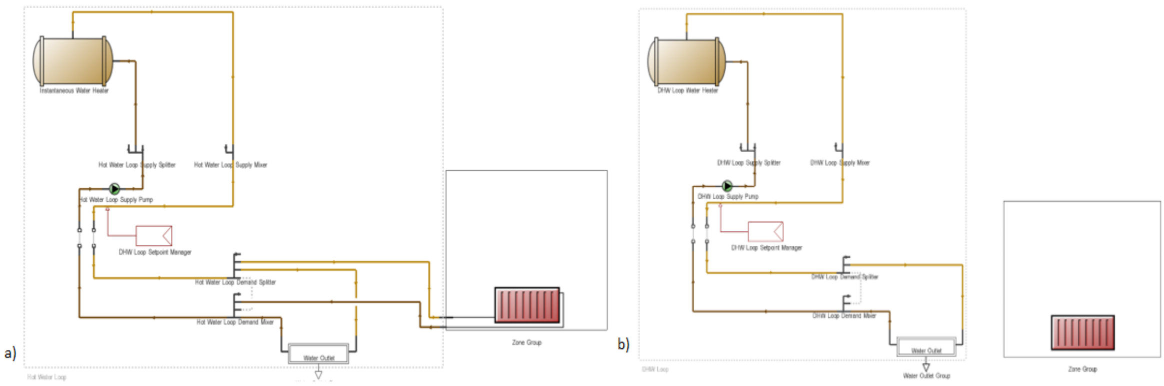

Figure 3.4. a) System modeled for Building 2 in Coimbra, and Buildings 1 and 2 in Budapest; b) System modeled for Building 1 in Coimbra.

3.1.4. Domestic hot water

Hot water consumption in buildings for hygiene activities can account for a sizable portion of total building energy consumption. In the European Union, DHW production accounts for around 14.5% [4]. In DesignBuilder the hot water consumption is defined in liters per square meter per day.

To comply with the requirements for domestic hot water consumption described in subchapter 2.5.1 and 2.5.2, the following two equations were used to calculate the DWH consumption in l/m^2.day. Equation 3.2 was used to determine the consumption from the buildings located in Budapest, while equation 3.3 was used to determine the consumption from the buildings located in Coimbra.

$$\dot{m}_{DHW,HU} = \frac{q_{DHW}*3600*1000}{c_p*\Delta T*365} \; [\frac{l}{(m^2.day)}], \tag{3.2}$$

$$\dot{m}_{DHW,PT} = \frac{40*n_{oc}*f_{eh}}{A_N} \; [\frac{l}{(m^2.day)}], \tag{3.3}$$

where c_p is the specific heat capacity of the water in J.(kg.K), and ΔT is the temperature increase required for DHW preparation in ºC.

According to the methodologies described in each legislation to determine the DHW needs and using the previous equations, the hot water consumption values obtained for each building are described in Table 3.8.

Table 3.8. Domestic hot water consumption.

Country	Building	Water mains supply temperature [ºC]	Consumption temperature [ºC]	Domestic hot water consumption [l/(m^2.day)]
Portugal	1	15	60	1.381
	2			1.056
Budapest	1	10	70	1.174
	2			1.009

3.1.5. Energy simulation assumptions

The energy required to keep the modeled buildings in thermally acceptable range for 24 hours per day was used to access the building's energy performance. Total heating and cooling demand were calculated to keep all the internal spaces within the thermal comfort range of 20°C to 25°C, for the Portuguese case, and 20ºC to 26ºC, for the Hungarian case.

It is a challenge to explore the effect of internal heat gains on the thermal performance of residential buildings and general rules, schedules, and design values are usually considered as general criteria. In this study, the DesignBuilder templates were used to characterize the internal heat gains from occupancy, lighting, and appliances. This software presents templates of various residential spaces (kitchen, living room, bedrooms, etc.), where all the parameters required for the dynamic characterization of the internal heat gains are defined. Despite using the templates, some adjustments were made in order to have the same average internal heat gains as specified in both legislations (5 W/m^2 for the Hungarian legislation and 4 W/m^2 for the Portuguese legislation).

Building airtightness was defined with a constant air change rate. The air change rate value was taken from the information given for the Hungarian reference buildings. For the modeled building built before 1940 the air change rate per hour defined was 0,7 ach, while for the other building it was used a 0,6 ach. Both buildings' infiltration rates are above the minimum ventilation requirement specified in both legislations so no extra ventilation was considered.

3.2. Building retrofit

Every building is unique, with distinct characteristics that influence energy consumption and the success of potential retrofit strategies. In this subchapter the measures applied were focused on reducing the building thermal needs, improving the system's efficiency, and integrating on-site renewable energy sources.

3.2.1. Energy saving measures

Since the energy consumed for space heating and cooling in buildings account for 65% of the total consumed energy [4], building retrofit focused on reducing the thermal needs of the building is an effective measure to reduce the building's energy consumption.

The thermal insulation of the exterior walls and the horizontal slab of the roof deck was the first step for reducing the energy consumption of the buildings under investigation. The insulation on the walls was applied to the outside surface, and the thickness applied in both constructive elements was the minimum required to satisfy the requirements of thermal transmission of both legislations. The insulation thickness added and the heat transfer coefficient after the retrofit are described in Table 3.9.

Table 3.9. Thermal properties of the opaque envelope after retrofit.

	Construction element	Insulation added [m]		Heat transfer coefficient after retrofit [W/(m^2.ºC)]	
		Portugal	Hungary	Portugal	Hungary
Building 1	Exterior wall	0.09	0.13	0.40	0.24
	Attic slab	0.1	0.20	0.34	0.17
Building 2	Exterior wall	0.07	0.11	0.40	0.23
	Attic slab	0.1	0.22	0.35	0.16

The second measure focused on replacing the windows and exterior door with more energy-efficient solutions. This intervention aimed at reducing the building's energy consumption by increasing the thermal quality of the building envelope and lowering the infiltration rate. Both constructive solutions were chosen in order to comply with the reference values given in both legislations, and their thermal properties are presented in Table 3.10.

Table 3.10. Thermal properties of the glazing after retrofit.

	Description	Heat transfer coefficient after retrofit [W/(m^2.ºC)]	SHGC
Portugal	Double glazing with air filling	2.1	0.75
Hungary	Triple glazing, low-e coating, and argon gas filling	1.06	0.58

As a consequence of improving the building airtightness by insulating the opaque envelope and changing the glazing solutions from the existing buildings, it was necessary to ventilate the building to respect the minimum air change rate requirements. The ventilation is done by natural means (open doors or windows) and a ventilation rate of 0,5 air changes per hour throughout the day was defined.

The final passive measure applied aimed at reducing solar radiation gains through the glazing envelope of the building. External blinds opaque to sunlight were modeled and were activated during the cooling season when the building is generally empty. Figure 3.5

describes the time when the solar protection devices are active. In this schedule, a value of one indicates that they are completely active.

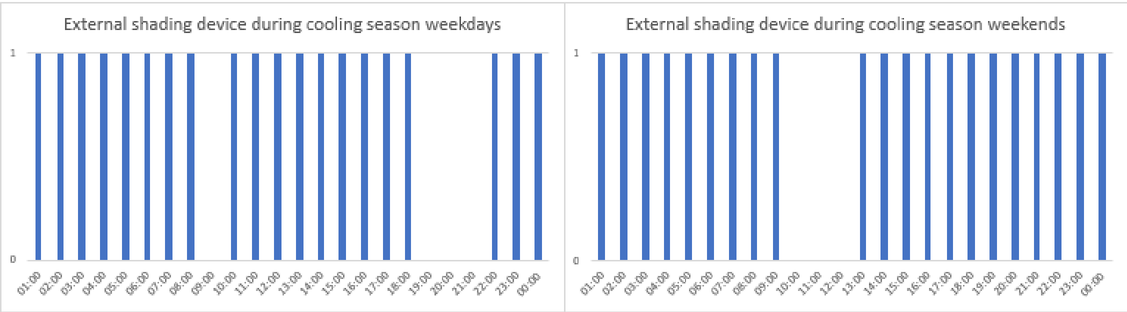

Figure 3.5. External shading schedule for the cooling season.

3.2.2. Technical building systems

After all the measures to reduce the building's thermal load were applied, three different systems for space heating and cooling were tested. The first system was a Multisplit system with wall mounted units installed in the kitchen, living room and bedrooms. When modeling this system, it was important to manually specify the cooling and heating capacity, as well as the Energy Efficiency Ratio (EER) and Coefficient of Performance (COP), respectively.

Table 3.11. Multisplit exterior unit performance data.

	Nominal Heating Capacity [kW]	COP	Nominal Cooling Capacity [kW]	EER
Building 1	7.80	4.82	6.60	4.79
Building 2	10.0	4.25	7.50	4.85

The cooling and heating capacity were sized to always respect the cooling and heating setpoint temperatures, and the values described in the preceding table were taken from the technical features of the heat pump described in annex B. For DHW an electrical instantaneous water heater with a heating capacity of 24 kW and an operative temperature of 60ºC was modeled. The efficiency of this equipment is determined in accordance with the part load factor curve "New style low temperature boiler" taken from the DesignBuilder templates.

In the second system the old boiler was replaced by a condensing boiler which is responsible for supplying the thermal needs for space heating and DHW. To modulate this system, it was not possible to apply the same configuration as the one described in Figure 3.4 because the EnergyPlus WaterHeater:Mixed object only accepts quadratic curves as a function of Part Load Ratio (PLR). The condensing boiler performance curve defined in EnergyPlus is a bi-quadratic curve. For this reason, two separate systems were modeled, one for space heating and one for DHW. After running a simulation only with the space heating system working, it was possible to determine the condensing boiler efficiency. The efficiency value obtained was used as constant value for the instantaneous water heater throughout the whole year.

In the third system, thermal energy will be produced by an air to water heat pump (AWHP) which will be responsible for supplying the DHW and space heating needs of the building. This unit produces water at 55ºC and operates with a temperature differential of 5ºC. A water tank with a heating coil was modeled to store the hot water needed throughout the day.

The visual configuration of the three systems previously described is represented in Figure 3.6.

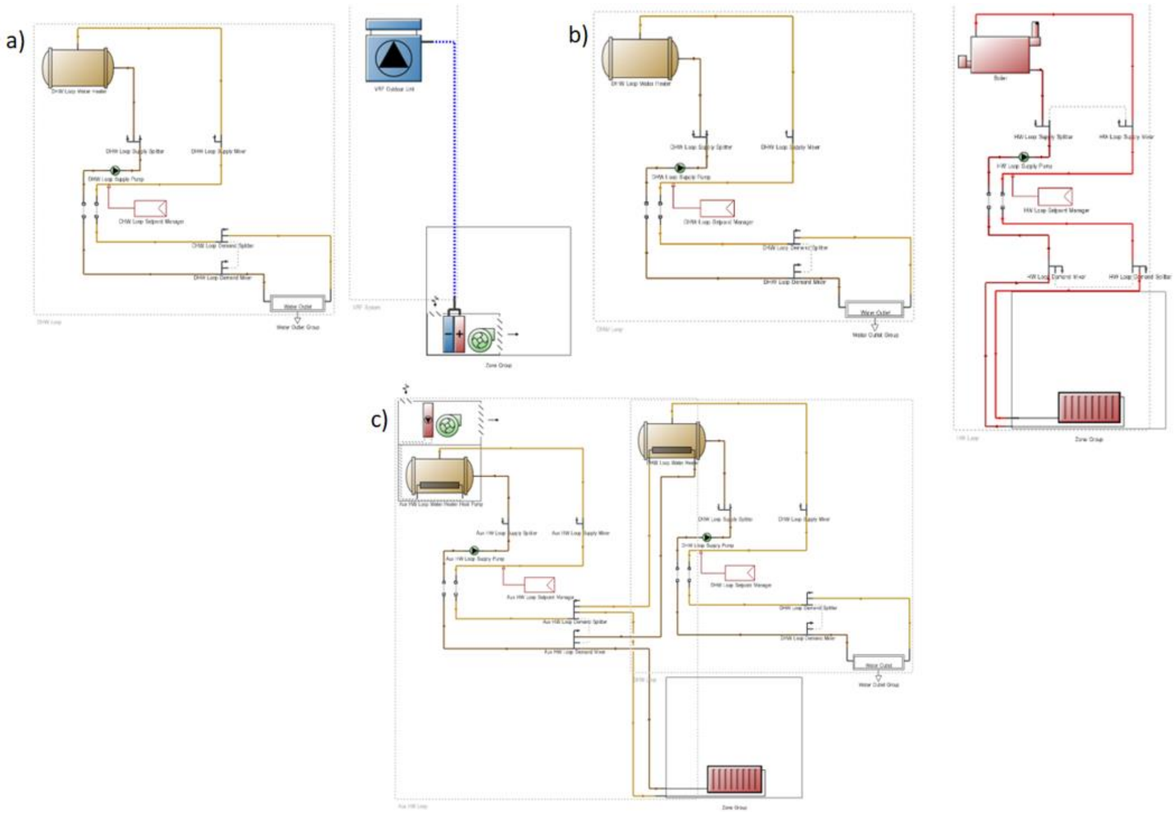

Figure 3.6. a) Multisplit system with electric instantaneous water heater b) Condensing boiler system c) Air to water heat pump system.

3.2.3. Renewable energy generation

Following the implementation of all the rehabilitation measures described in the preceding sections, the integration of renewable energy systems was studied. In both legislations, for a building to be considered a NZEB, minimum energy consumption from renewable sources is specified.

The systems modeled were a solar thermal system to reduce the energy consumption for DHW and a photovoltaic (PV) system to reduce the building's electricity demand. Since both systems use solar energy, their efficiency is greatly reliant on the levels of solar radiation in each zone. The monthly incident solar radiation per square meter in the roof surface of both buildings is described Table 3.12.

Table 3.12. Monthly solar radiation in Budapest and Coimbra.

	Solar Incident Radiation [kWh/m^2]	
	Budapest	**Coimbra**
January	64.2	103.0
February	90.6	97.5
March	143.1	154.5
April	167.0	174.3
May	182.0	179.8
June	178.7	194.0
July	187.5	208.8
August	180.9	207.9
September	141.2	166.6
October	113.4	136.2
November	69.0	85.6
December	47.3	80.2

The sizing of the solar system was done by dynamic simulation and the systems were sized to achieve a solar fraction between 0.6 and 0.8. The system's main components are the solar water tank, the solar collector field, and the pump that will force the circulation of the water from the collectors to the solar tank.

The modeled PV system was an on-grid system, and to obtain an estimate size of the PV system capacity, a simple deterministic method using the Peak Sun Hour (PSH) concept was used. PSH is defined as the equivalent number of hours per day when solar irradiance averages 1000 W/m^2 [101]. According to the data showcased in Table 3.12, the average daily solar radiation in Budapest and Coimbra is 4.29 kWh/m^2 and 4.9 kWh/m^2, respectively. This means that the average daily PSH in Budapest and Coimbra is 4.29 hours and 4.9 hours, respectively.

To calculate the PV system capacity with the PSH method, the following equation was used.

$$P_{PV} = \frac{P_{load}}{PSH * \eta_{system}}, \tag{3.4}$$

where P_{PV} is the PV panel nominal peak power, P_{load} is the average daily electricity demand, and η_{system} is the overall system efficiency. The system efficiency considers factors such as connection losses, dust factor, and inverter efficiency.

The average daily electricity demand for each building was obtained by dynamic energy simulation and without considering the winter months energy consumption. During these months, solar radiation levels are low and energy consumption associated with space heating is at its peak. If we consider these months into the calculation of the average daily demand, the PV system will be oversized. To avoid this error only the months with similar energy consumption were considered.

In the first round of simulations, most of the energy produced was sent back to the grid because of the mismatch between energy production and energy consumption. To avoid this, a battery was incorporated into the photovoltaic systems.

4. ENERGY SIMULATION RESULTS

This chapter shows the results of the simulations performed and described in the preceding chapter. The thermal needs, final energy consumption, and primary energy consumption of existing buildings are first displayed. In terms of energy consumption, an analysis of energy consumption by end use and energy source is also presented.

Following that, the results obtained after applying the envelope retrofit measures, improving the technical building systems, and integrating renewable energy sources into the building are presented. To evaluate the envelope retrofit measures the data selected was the building thermal needs, meanwhile, for the technical building systems and renewable energy sources, the data selected was primary energy consumption and CO_2 emissions.

Finally, the energy performance assessment of the buildings after all the retrofit measures were applied is presented. Here the NZEB target specified in both legislations is compared to the results obtained and comments were made for each case.

4.1. Exisiting buildings

In this subchapter the results shown are related to the modeled buildings before applying any retrofit measures. Figure 4.1 presents the thermal needs of both buildings modeled in Coimbra and Budapest.

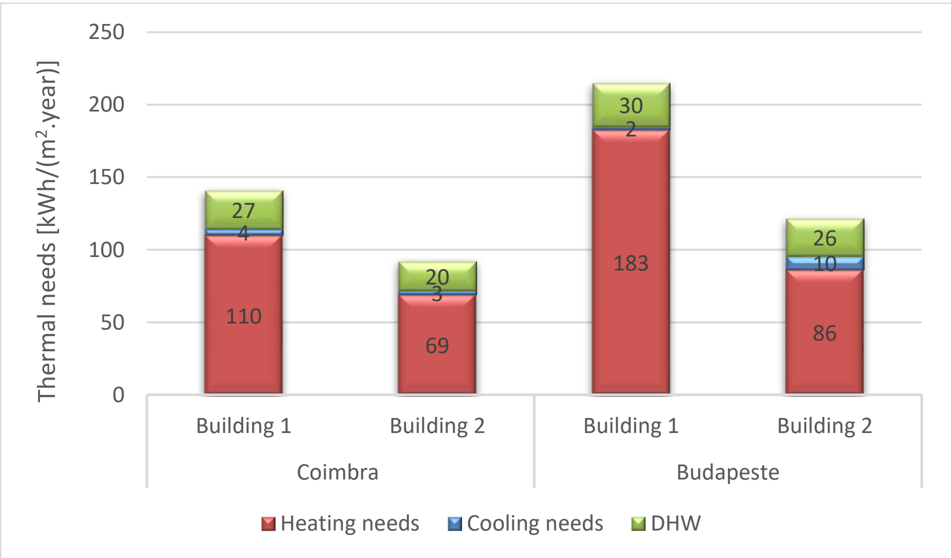

Figure 4.1. Existing buildings thermal needs.

As expected, according to the cooling degree days and heating degree days calculated in Table 3.2, the heating needs obtained were much higher than the cooling needs.

When comparing the buildings under the same climatic conditions, it is also possible to see how construction technologies have evolved. The buildings built between 1990 and 2000 had lower thermal needs per square meter than those constructed prior to 1940. The reduction in thermal needs caused by improvements in construction solutions was greater in Hungary (48%) than in Portugal (37%).

Despite the higher thermal resistance of the construction solutions used for the buildings in Budapest, as shown in Table 3.6, the space heating needs obtained were still higher than the ones obtained for the buildings in Coimbra. This is explained by the colder temperatures felt in Budapest during the heating season, as seen in Figure 3.2.

According to both countries' methodologies for calculating DHW consumption for residential buildings, Portuguese buildings consume less energy to meet the hot water needs of the building's occupants. Despite differences in calculation methodologies, one reason for this is the difference in the temperature of the water supplied, in Portugal, a yearly average of 15ºC is considered, whereas in Budapest a temperature of 10ºC is considered.

With the technical building systems described in subchapter 3.1.3 the final energy consumption (E_{Final}) results by regulated end uses and by energy source are described in Figure 4.2 and Figure 4.3, respectively.

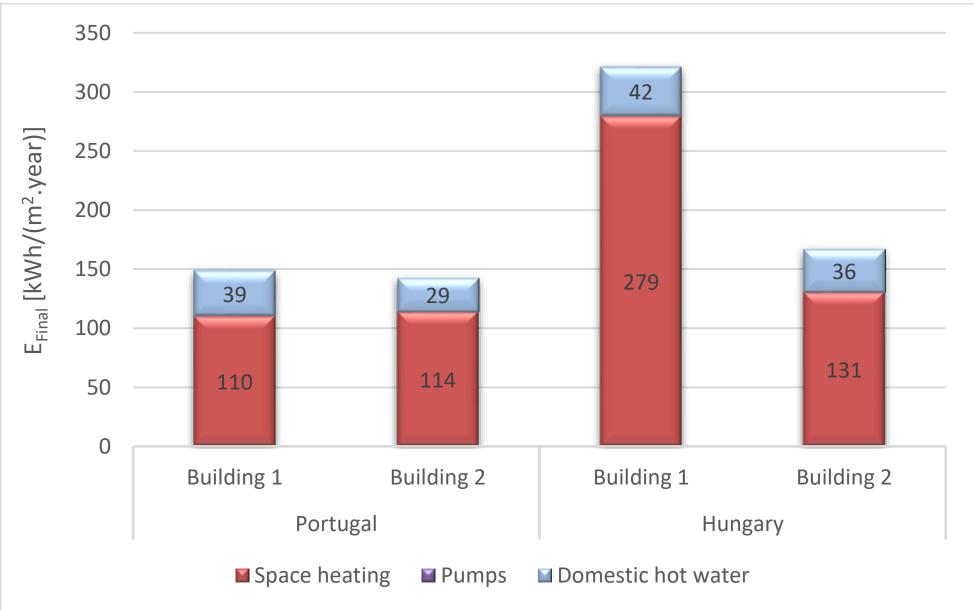

Figure 4.2. Existing buildings final energy consumption by end use.

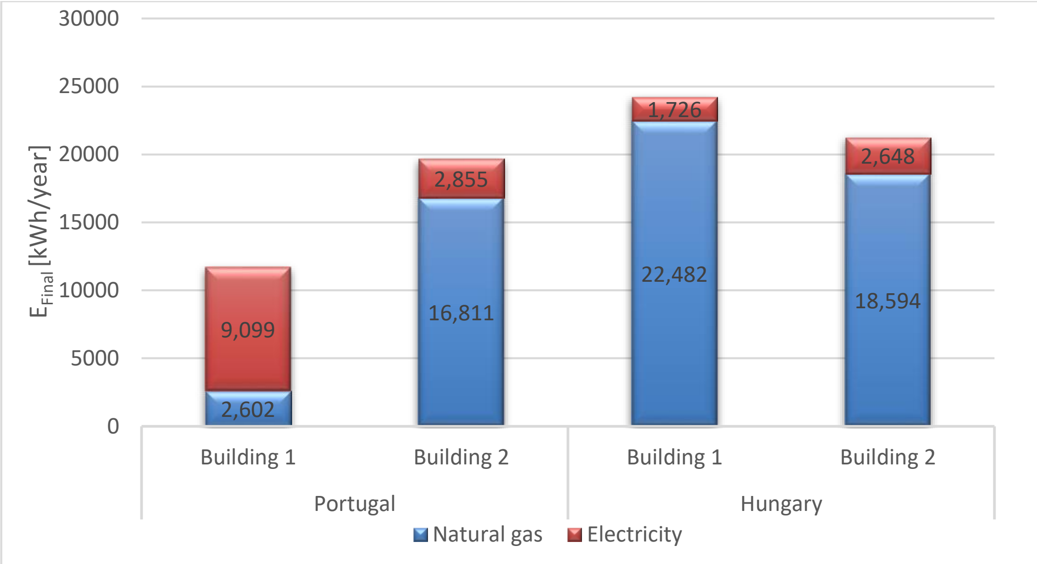

Figure 4.3. Existing buildings final energy consumption by energy source.

Despite having lower thermal needs per square meter than Building 2, Building 1 in Coimbra consumed nearly the same amount of final energy per square meter as Building 2. This was due to the different space heating systems modeled for each case and the efficiencies associated with each system. Table 4.1 shows the efficiencies obtained for the technical building systems modeled.

Table 4.1. Existing buildings technical systems performance.

	Coimbra		**Budapest**	
	Building 1	**Building 2**	**Building 1**	**Building 2**
Space heating	100 %	69 %	66 %	67 %
DHW	69 %			

The primary energy consumption ($E_{Primary}$) and CO_2 emissions from the existing buildings were calculated using the conversion factors described in Table 2.4 and Table 2.10, and the results are shown in Figure 4.4.

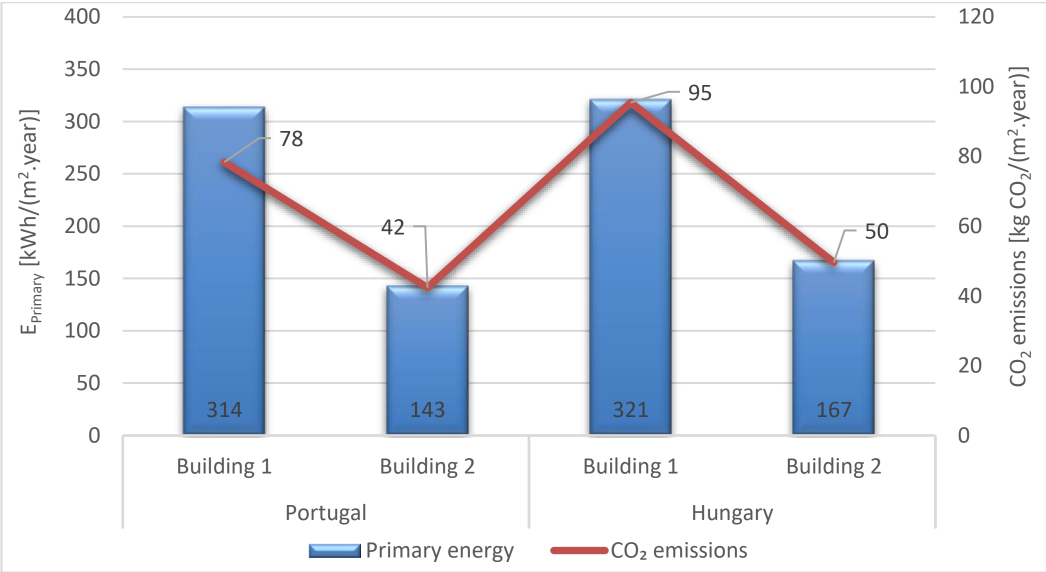

Figure 4.4. Regulated primary energy consumption and CO_2 emissions from existing buildings.

In Budapest, natural gas is heavily used to meet the thermal needs of buildings, however, in Portugal, buildings built before 1940 do not have a central heating system, so they rely on electric mobile appliances for space heating. This is why, as shown in Figure 4.3, the primary energy consumption of Building 1 in Portugal was higher than all the other buildings.

4.2. Retrofitting results

4.2.1. Exterior envelope retrofit

The results obtained after implementing the retrofit measures described in subchapter 3.2.1 are highlighted in this subsection. Figure 4.5 depicts all the measures applied to each building and their impact on the thermal needs of the buildings.

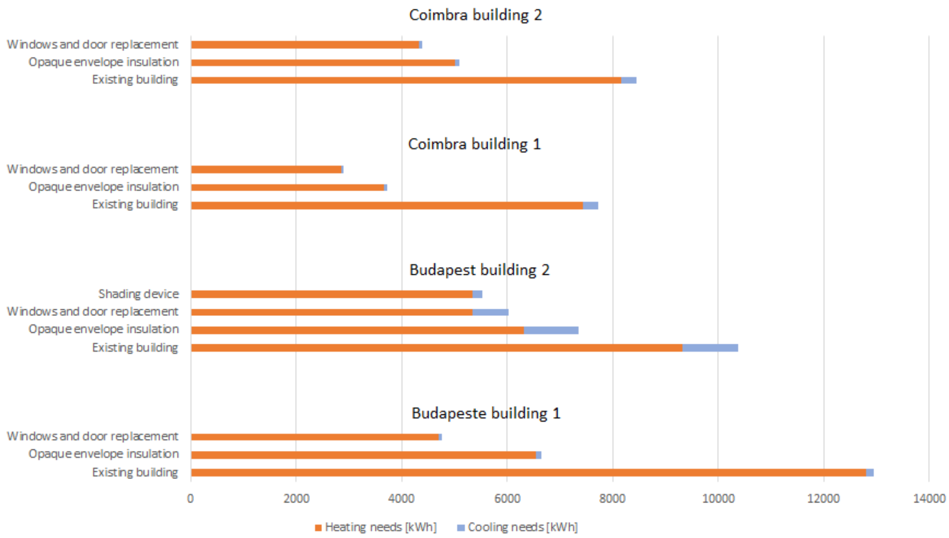

Figure 4.5. Thermal needs after each retrofit measure.

Analyzing the buildings under Coimbra climatic zone, Building 1 reduced its thermal needs by 51% and Building 2 by 49% after implementing the retrofit measures to the external building envelope. Building 1 and 2 located in Budapest reduced their thermal needs by 49% and 47%, respectively. The thermal needs of each building before and after applying all the retrofit measures are described in Table 4.2.

Table 4.2. Thermal needs before and after retrofit measures.

		Building 1		**Building 2**	
		Heating needs [kWh]	**Cooling needs [kWh]**	**Heating needs [kWh]**	**Cooling needs [kWh]**
Coimbra	Existing building	7,442	275	8,165	297
	Retrofitted building	2,824	51	4,262	69
Budapest	Existing building	12,805	140	9,314	1 061
	Retrofitted building	6,554	92	5,337	190

As a result of reducing the building's thermal needs, primary energy consumption was also reduced. Figure 4.6 and Figure 4.7 show a comparison of the primary energy and CO_2 emissions of the existing buildings and retrofitted buildings in Coimbra and Budapest, respectively.

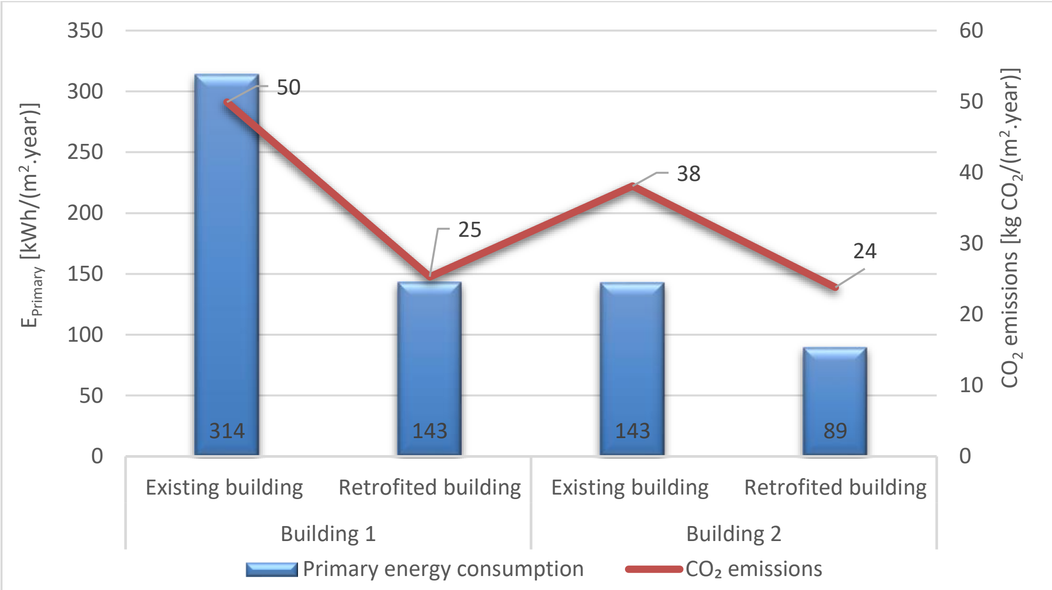

Figure 4.6. Primary energy consumption and CO_2 emissions after envelope retrofit of buildings in Coimbra.

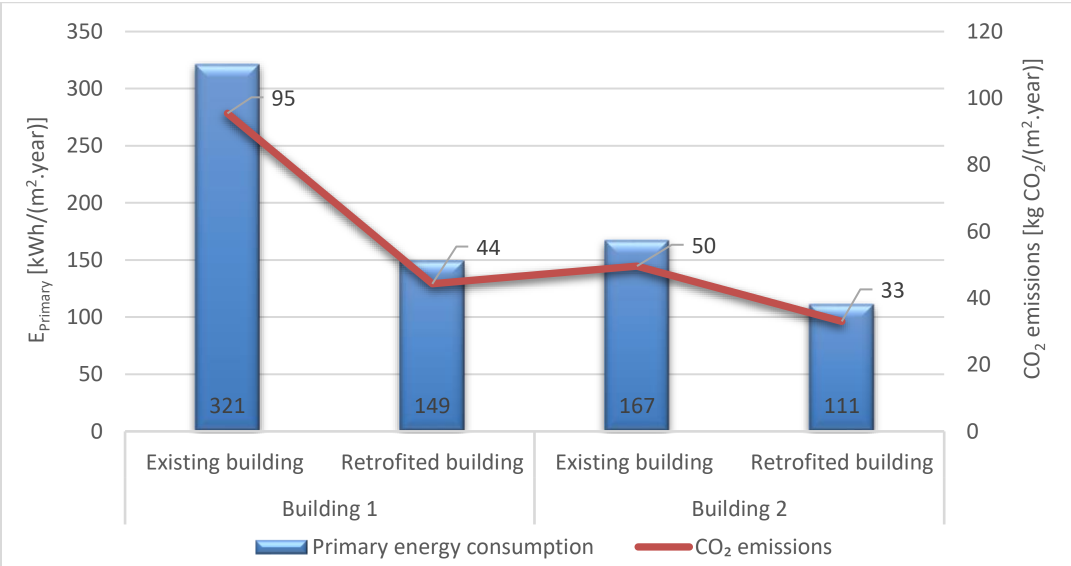

Figure 4.7. Primary energy consumption and CO_2 emissions after envelope retrofit of buildings in Budapest.

When comparing the energy savings from the newer and older buildings it is possible to see that the energy savings associated with retrofitting the older buildings were much higher. This demonstrates the enormous energy savings potential associated with retrofitting the worst performing building class in terms of energy performance.

4.2.2. Technical building systems

This subchapter showcases the primary energy consumption and CO_2 emissions for the retrofitted buildings with the different technical systems described in subchapter 3.2.2. Table 4.3 demonstrates the system's performance obtained in the energy simulations.

Table 4.3. Technical building systems performance.

		Coimbra		Budapest	
		Building 1	**Building 2**	**Building 1**	**Building 2**
Condensing boiler efficiency		91 %	90 %	92 %	93 %
AWHP COP		2.39	2.51	1.90	1.94
Multisplit	COP	3.65	3.28	3.4	2.88
	EER	2.97	3.14	3.2	3.49

The Multisplit and AWHP systems had a better performance under the climatic zone of Coimbra. The reason for this is the warmer temperatures felt in Coimbra during the colder months. Because the temperature differential between the outdoor air and the desired indoor temperature is smaller in warmer climates, heat pumps typically perform better in this type of climate.

As shown in Figure 4.8, the AWHP system had the best performance in terms of primary energy consumption for the buildings located in Coimbra. However, the AWHP system did not perform so well in Budapest's climate, and the condensing boiler was the best performing system in the Hungarian buildings.

The Multisplit system had the worst energy performance despite having the higher efficiency in terms of space heating and cooling, as shown in Table 4.3. This outcome was brought about by DHW's high energy consumption. In these cases, an instantaneous electric water heater with an efficiency under 1 was used to meet the DHW. Additionally, the conversion factor of final energy into primary energy associated with electricity consumption of 2.5, makes the primary energy needs for DHW high when compared to the condensing boiler system and AWHP system.

However, with the application of renewable energy sources the DHW energy consumption can be greatly reduced, making this system the one with the highest energy reduction potential from the application of renewable energy systems.

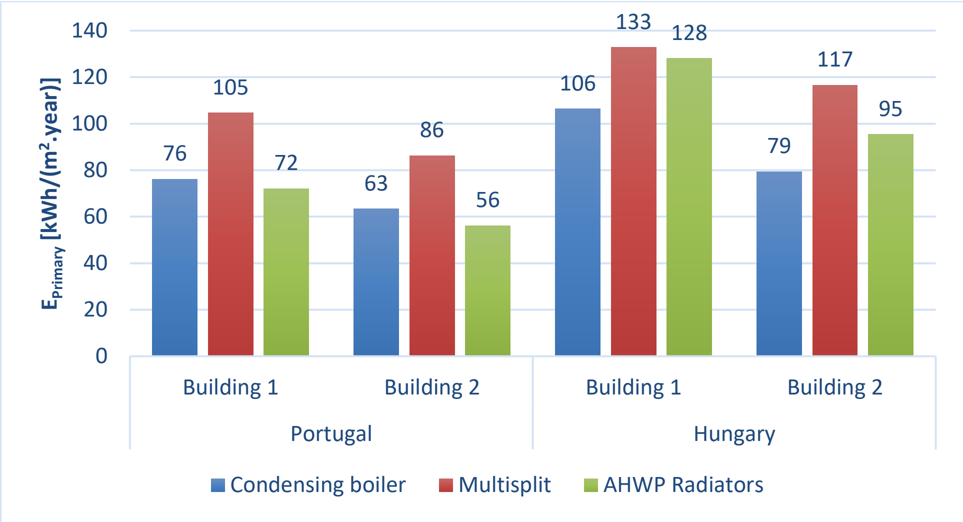

Figure 4.8. Primary energy consumption from the systems modeled.

When converting the primary energy consumption into the equivalent CO_2 emissions, in Portugal the worst performing system in terms of CO_2 emissions was the condensing boiler. Meanwhile, in Budapest the worst performing system remained the Multisplit. This might show the importance of changing the focus from primary energy consumption to CO_2 emissions to account for the grid efficiency and energy mix of different countries.

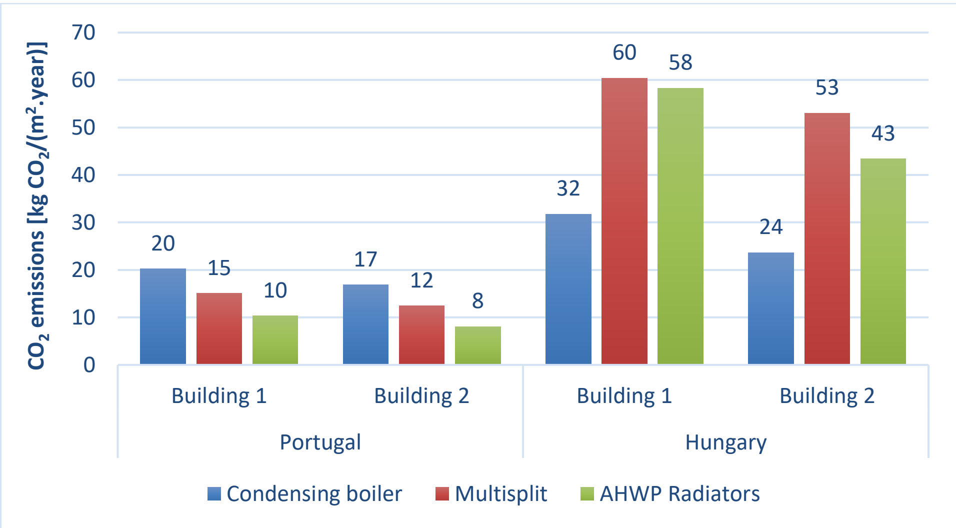

Figure 4.9. CO_2 emissions associated with the primary energy consumption from the systems modeled.

4.2.3. Renewable energy systems

Table 4.4 displays the performance and efficiency of the different solar thermal systems modeled for each situation. While sizing these systems, the goal was to achieve a solar fraction of roughly 0,7 and, as can be seen from the results obtained, the solar systems modeled in Coimbra required less solar collector area. These was expected since, as Table 3.12. shows, the average solar radiation is higher in Coimbra.

Higher solar fractions were obtained by the solar systems linked to the AWHP systems due to the inability of Designbuilder to model a water tank with two heating coils. For this system, it was necessary to size two separate tanks, one for the solar collectors and one for the heat pump system. By having a larger volume of water available for thermal storage, it became possible to capture and store a higher quantity of solar thermal energy over time.

Table 4.4. Solar thermal systems characteristics.

		Building 1			Building 2		
		Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Coimbra	Solar collector [m2]	1.9307			2.5987		
	Solar thermal energy [kWh]	1230.9		1303.9	1661.6		1752.6
	Auxiliary energy [kWh]	530.6		446	692.3		583.4
	Solar fraction [%]	69.9		74.5	70.6		75.0
Budapest	Solar collector [m2]	2.965			3.8164		
	Solar thermal energy [kWh]	1480.5		1476.6	1862.8		1958
	Auxiliary energy [kWh]	660.7		584.5	872.1		855.9
	Solar fraction [%]	68.1		71.6	68.1		69.6

The PV systems were sized in accordance with the methodology described in subchapter 4.2.3 and the main characteristics of the modeled PV systems are described in Table 4.5. The methodology and the initial sizing estimates obtained are described in annex C.

Table 4.5. Photovoltaic systems characteristics.

		Building 1			Building 2		
		Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Coimbra	PV panels	2	3	3	4	5	5
	Battery storage [kWh]	2.5	4		4	5	
	Energy produced [kWh]	875	1327	1300	1774	2255	2212
	Energy consumed [kWh]	839	1279	1226	1562	1989	1912
	Energy wasted [kWh]	36	49	74	212	266	301
Budapest	PV panels	3	4		5	6	
	Battery storage [kWh]	4			5		
	Energy produced [kWh]	1162	1584	1569	1941	2392	2368
	Energy consumed [kWh]	1084	1430	1342	1789	2084	1967
	Energy wasted [kWh]	78	154	227	153	309	401

Regarding the contribution of renewable energy sources, only energy consumed in regulated building uses can be accounted as savings when calculating the building's primary energy consumption. As a result, not all the energy generated by the PV system can be included in the calculation of the building's primary energy consumption.

To determine the electric energy consumed by regulated uses from renewable sources, it was necessary to assume that the energy consumption for regulated uses would be prioritized. Taking this into account, the energy savings were calculated using the following methodology:

$$E_{reg.uses} = E_{building} - E_{lighting} - E_{equip.} [kWh], \tag{4.1}$$

where $E_{reg.uses}$ is the building electric consumption for regulated uses, $E_{building}$ is the total building electric consumption, $E_{lighting}$ is the lighting electric consumption, and $E_{equip.}$ is the consumption from electric appliances. The monthly value of all these variables were computed using dynamic energy simulation.

Therefore, to determine the monthly energy savings two options were possible:

$$If\ E_{produced} < E_{reg.uses} \Rrightarrow E_{savings} = E_{produced}\ [kWh]. \tag{4.2}$$

$$If\ E_{produced} > E_{reg.uses} \Rrightarrow E_{savings} = E_{reg.uses}\ [kWh]. \tag{4.3}$$

This process was performed for every system modeled in each one of the buildings, and the energy savings obtained are described in Table 4.6.

Table 4.6. Energy savings from the PV system.

		Building 1			Building 2		
		Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Coimbra	Energy produced [kWh]	875	1327	1300	1774	2255	2212
	Energy consumed by regulated uses [kWh]	30.5	752.3	626.1	32.5	1193.2	976.9
	Energy consumed by non-regulated uses [kWh]	844.5	574.7	673.9	174.5	1061.8	1235.1
Budapest	Energy produced [kWh]	1162	1584	1569	1941	2392	2368
	Energy consumed by regulated uses [kWh]	37.8	785.3	691.5	30.5	1179.3	864.7
	Energy consumed by non-regulated uses [kWh]	1124.2	154	877.5	1910.5	1212.7	1503.3

As previously mentioned, and corroborated by the results obtained in the previous table, the Multisplit system had the highest energy savings following the integration of renewable energy systems. The system with the lowest energy reduction was the condensing boiler. Buildings with these systems do not have electric regulated energy consumption, therefore, the electricity generated by the PV system is not considered in the building's primary energy consumption.

The building's primary energy consumption after accounting for energy produced by renewable sources is described in Figure 4.10. As a result of the bigger energy savings associated with the Multisplit and AWHP system, the condensing boiler had the worst energy performance.

The Multisplit system had the best performance in every building, however the AWHP system, for the buildings in Coimbra, had a very similar performance. However, for the buildings located in Budapest the AWHP system had a much worst performance. This was related to the low system efficiency obtained, as can be seen in Table 4.3, which is probably a little bit unrealistic, and a further look should be taken to the modeled outdoor AWHP unit.

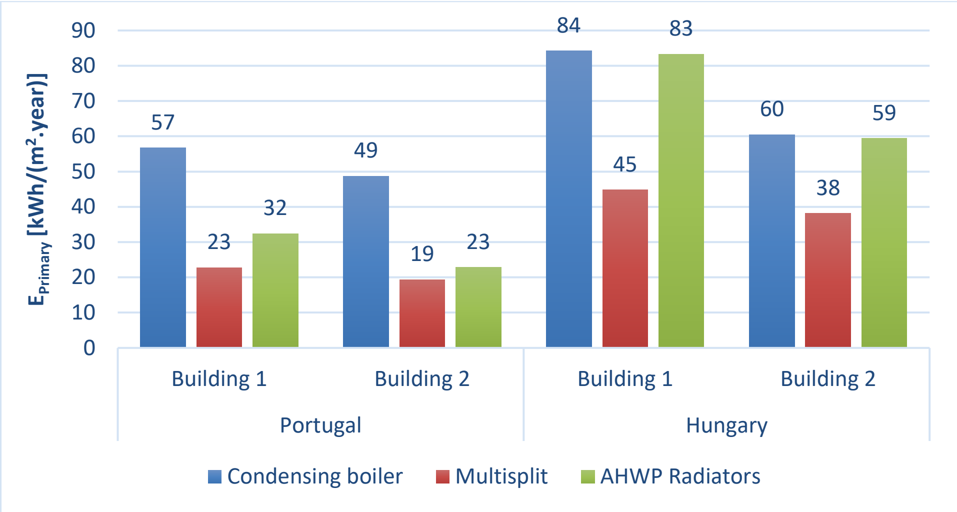

Figure 4.10. Primary energy consumption after renewable energy sources.

When converting the primary energy into CO_2 emissions, in Budapest the worst performing system was the AWHP. This again might show the importance of changing the focus from primary energy consumption to CO_2 emissions.

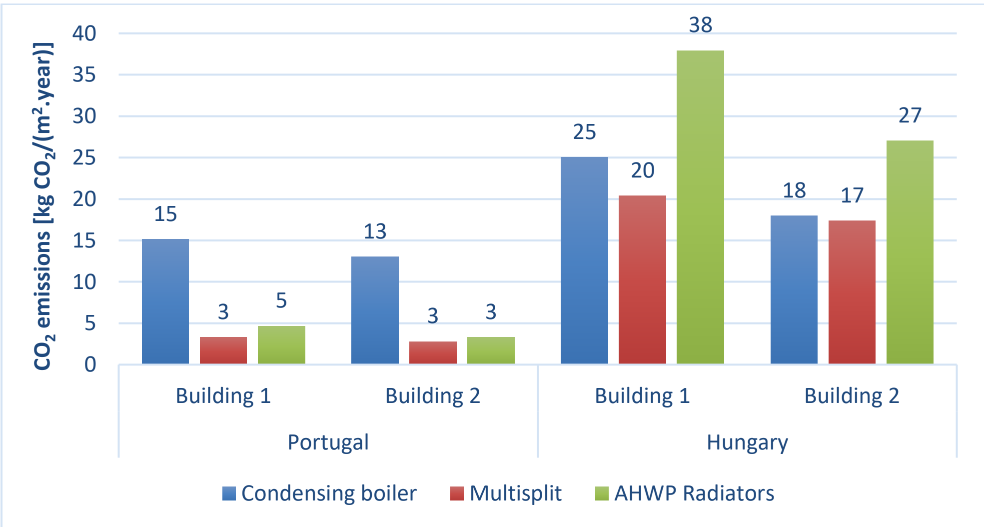

Figure 4.11. CO_2 emissions after renewable energy sources.

4.3. NZEBs requirements

As previously described in subchapter 2.5.1, a residential building in Hungary must have a primary energy consumption of 100 kWh/(m^2.year) or less (excluding lighting energy demand) in order to be deemed a NZEB. Renewable energy generated on-site is not accounted for in the calculation of the building's primary energy consumption. Therefore, to access the energy performance of the Hungarian buildings the primary energy considered were the ones described in Figure 4.8.

In addition to this requirement, 25% of the building's energy needs must be met by on-site renewable energy production. In Table 4.7 the primary energy consumption and the renewable energy percentage for each system modeled in the buildings located in Budapest are described.

Table 4.7. Primary energy consumption from buildings in Budapest without considering renewable energy sources.

	Building 1			Building 2		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Primary energy consumption [kWh/m^2]	106	133	128	79	117	95
Renewable energy [%]	20.4	24.4	24.2	21.4	23.4	26.6

The primary energy requirement specified in the Hungarian legislation was not meet by any system for Building 1. This could be an indication that, for this type of building, the ground floor must be insulated to meet the NZEB requirements. For Building 2, the condensing boiler and AWHP system primary energy consumption was lower than the requirement. However, only the AWHP system had a renewable share greater than 25% of the building primary energy consumption.

The lowest primary energy consumption obtained in both buildings was obtained by the condensing boiler system. However, when taking into account on-site renewable energy generation, Figure 4.8 shows that this system had the worst energy performance. This led to the conclusion that, to determine the energy performance of a building, the energy balance (energy consumed minus energy generated) should be considered when assessing a building's energy performance.

After accounting for renewable energy savings, both buildings had the lowest primary energy consumption with the Multisplit system. When equipped with this system, and after being retrofitted, the primary energy consumption from Building 1 and 2 was reduced by 86% and 77%, respectively. In Figure 4.12 a comparison between the primary energy consumption and CO_2 emissions of the existing buildings and the buildings after applying all the retrofit measures is showcased.

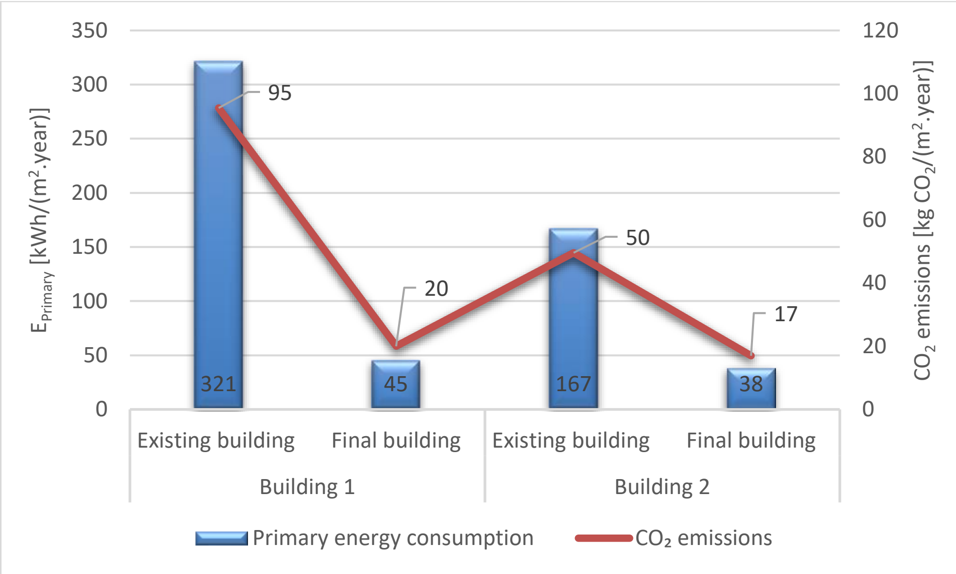

Figure 4.12. Primary energy consumption and CO_2 emissions of the existing building and retrofitted building in Budapest.

For the buildings located in Coimbra, to access their energy performance, it was necessary to first calculate the energy consumption by the reference buildings. The energy consumption of the reference buildings was determined according to the assumptions listed in subchapter 2.5.2, and the results obtained are displayed in Table 4.8.

Table 4.8. Primary energy consumption from Portuguese reference buildings.

	Reference Building 1			**Reference Building 2**		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Heating needs [kWh]	1994.3			3862.1		
Cooling needs [kWh]	580.4			185.82		
DHW [kWh]	1780.31			2372.6		
Final Energy consumption [kWh/m^2]	63	39	19	59	31	18
Primary energy consumption [kWh/m^2]	63	98	48	59	78	45

Two types of requirements are used to determine if a residential building in Portugal is considered a NZEB, as shown in Table 2.12. The first requirement is associated with thermal comfort and is related to the building heating and cooling needs. This requirement can be accessed independently of the building technical systems and the values obtained for each parameter are described in Table 4.9.

Table 4.9. NZEB thermal comfort requirements for the buildings in Coimbra.

Evaluation parameters	Building 1	Building 2
Heating needs	$\frac{2823.7}{1994.3} = 1.4 \leq 0.85$	$\frac{4261.9}{3862.1} = 1.1 \leq 0.85$
Cooling needs	$\frac{50.5}{580.4} = 0.09 \leq 0.85$	$\frac{68.8}{185.8} = 0.37 \leq 0.85$

Both buildings met the cooling thermal requirement, however, the heating thermal requirement was not met. The reason for this is that no thermal insulation was added to the ground floor of the retrofitted buildings. Meanwhile, for the reference building the thermal resistance of the ground floor was enhanced and for that reason, heating needs were greatly reduced.

By applying an insulation layer to the floor, the heat transfer between the indoor spaces and ground floor was reduced, however, during the cooling season, it prevents the heat from escaping through the floor. This resulted in the higher cooling needs obtained for the reference buildings.

The higher cooling needs of the reference Building 1 when compared to the reference Building 2 are associated with the thermal resistance of the ground floor used for each case. According to the methodology described in *Manual SCE* [54] to determine the heat transfer coefficient of construction elements in contact with the soil, Building 1 ground floor has to have a higher thermal resistance in order to comply with the requirements described in Table 2.9. The methodology and the thermal resistance obtained for each ground floor are described in annex D.

Regarding the energy performance requirements, these were calculated for each one of the systems modeled. As previously described in subchapter 2.5.2, to determine the energy class of a building in Portugal, the ratio (R_{NT}) between the primary energy consumed by the predicted building and the primary energy consumed by the reference building is used.

For the predicted building primary energy consumption, renewable energy generated on-site must be considered. Therefore, to access the energy performance of the buildings in Coimbra, the primary energy consumption considered were the ones described in Figure 4.10.

In addition to this requirement, NZEBs must present a minimum level of renewable primary energy (Ren_{Hab}) determined by the ratio of total renewable primary energy for self-consumption in the building's regulated uses to the total primary energy use for DHW. The primary energy and the renewable energy ratios obtained for each system modeled are described in Table 4.10.

Table 4.10. Portuguese NZEB energy performance requirements

	Building 1			Building 2		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
R_{NT}	0.9	0.23	0.67	0.82	0.25	0.5
Ren_{Hab}	0.51	1.2	1.19	0.51	1.37	1.31

According to the energy performance requirements specified in Table 2.12, for Building 1 in Coimbra, the only system that met the primary energy consumption requirement was the Multisplit. Building 1, after being retrofitted and equipped with the Multisplit system sized during this work, would have an energy class A+.

For Building 2, the AHWP and the Multisplit system met the primary energy consumption requirement. However, the Multisplit system had the best performance and when equipped with this system, Building 2 is also classified with an energy class of A+.

Regarding the minimum renewable primary energy requirement, every system met the requirement specified in the Portuguese legislation.

According to the results described in Table 4.10, both buildings had the best energy performance with the Multisplit system. When equipped with this system, and after being retrofitted, the primary energy consumption from Building 1 and 2 was reduced by 93% and 86%, respectively. In Figure 4.13 a comparison between the primary energy consumption and CO_2 emissions of the existing buildings and the buildings after applying all the retrofit measures is showcased.

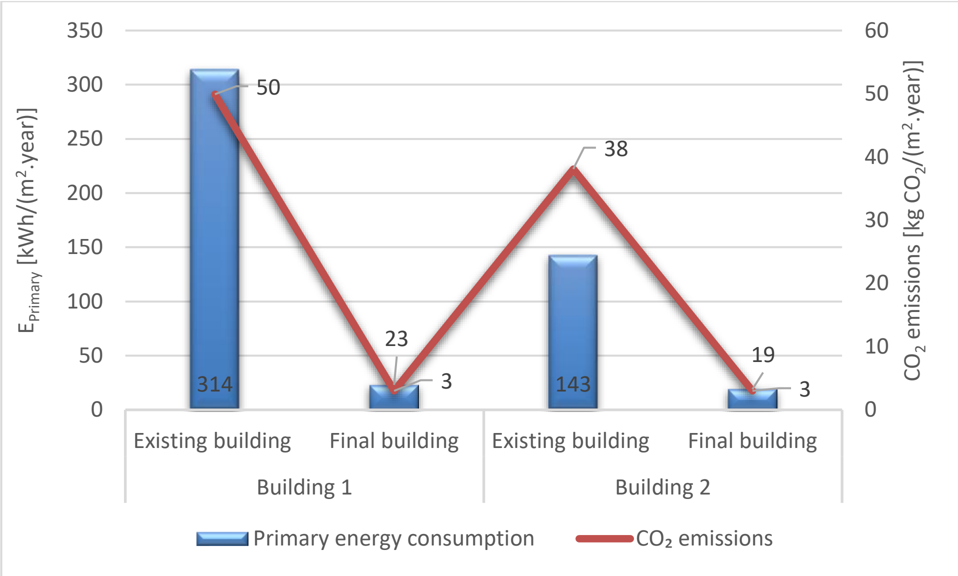

Figure 4.13. Primary energy consumption and CO_2 emissions of the existing building and retrofitted building in Coimbra.

5. CONCLUSION

This dissertation aimed at analyzing different retrofit measures to improve the energy efficiency of typical existing buildings in Portugal and Hungary. To achieve this goal, two representative detached single family buildings models were created based on statistical data about the national residential building stock of both countries. The building energy models were conceived based on the data found for single family buildings built before 1940 and between 1990 and 2000.

During this work, retrofit measures to improve the exterior building envelope, the building's technical systems, and the installation of renewable energy generation systems were tested to determine their impacts on the buildings' energy consumption. The energy savings associated with each measure implemented were calculated by dynamic energy simulation with the help of Designbuilder.

After applying all the retrofit measures, three out of the four buildings modeled complied with the NZEB requirements specified in the respective country legislation. In percentual terms, the older buildings' primary energy consumption was reduced by 93% and 86% in Coimbra and Budapest, respectively. Meanwhile, for the newer buildings, primary energy consumption was reduced by 86% and 77% in Coimbra and Budapest, respectively.

Analyzing the energy savings obtained in absolute terms, it was possible to realize the energy saving potential associated with retrofitting the older single family building stock. For the single-family buildings modeled based on the data obtained for this type of buildings built before 1940, the primary energy consumption was reduced by 296 kWh/m^2 and 276 kWh/m^2 in Coimbra and Budapest, respectively. When comparing the energy savings from the older modeled buildings and the newer modeled buildings, the older buildings' energy savings were 2.35 and 2.15 times bigger in Coimbra and Budapest, respectively.

Comparing the results from the buildings in Coimbra and Budapest, it is possible to conclude that Hungary has a much tougher challenge than Portugal. This is due to the substantially colder outside temperatures felt in Hungary throughout the heating season. This results in higher energy consumption related to space heating in order to maintain thermal comfort conditions in indoor spaces.

Another key factor that works in Portugal's favor is the solar radiation. Portugal has a higher average solar radiation than Hungary making renewable energy systems more profitable. It was also possible to draw the following conclusions concerning the energy assessment process of buildings:

- Energy consumed minus energy produced locally should be used instead of energy consumption to assess the primary energy consumption of a building.
- Switching the focus from primary energy consumption to CO_2 emissions should be done to account for the energy grid efficiency and energy mix from different countries.
- There is a need to strengthen the regulation related to the dynamic energy characterization for residential buildings in both nations. This is a crucial step to properly assessing the energy consumption from the existing residential building stock and developing adequate retrofit plans.

5.1. Future research

As proposals for future research, an economic analysis of the measures applied to the buildings' exterior envelope, technical building systems proposed, and the renewable energy systems modeled could be done. This would allow to understand which measures had the lowest payback period and which retrofit scenario would benefit the homeowners.

Aside from that, a more detailed analysis of the systems modeled might be performed, particularly for the systems responsible for meeting the thermal needs for space heating, space cooling and DHW. A careful review of the performance curves for each technical equipment modeled, as well as changing the performance curves from the DesignBuilder templates to those found on technical equipment data sheets, would improve the quality of the results.

It will be also interesting to study the rehabilitation of multi-family buildings and evaluate the differences in primary energy consumption between apartments and detached single-family buildings. Another interesting comparison may be the primary energy consumption between apartments on different floors of the same multifamily building.

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ANNEX A – Typical Construction Solutions

The layer-by-layer constitution, as well as the thermal properties of each construction element used to model the representative buildings described in this dissertation are described in Figure A.1., Figure A.2., Figure A.3. and Figure A.4.

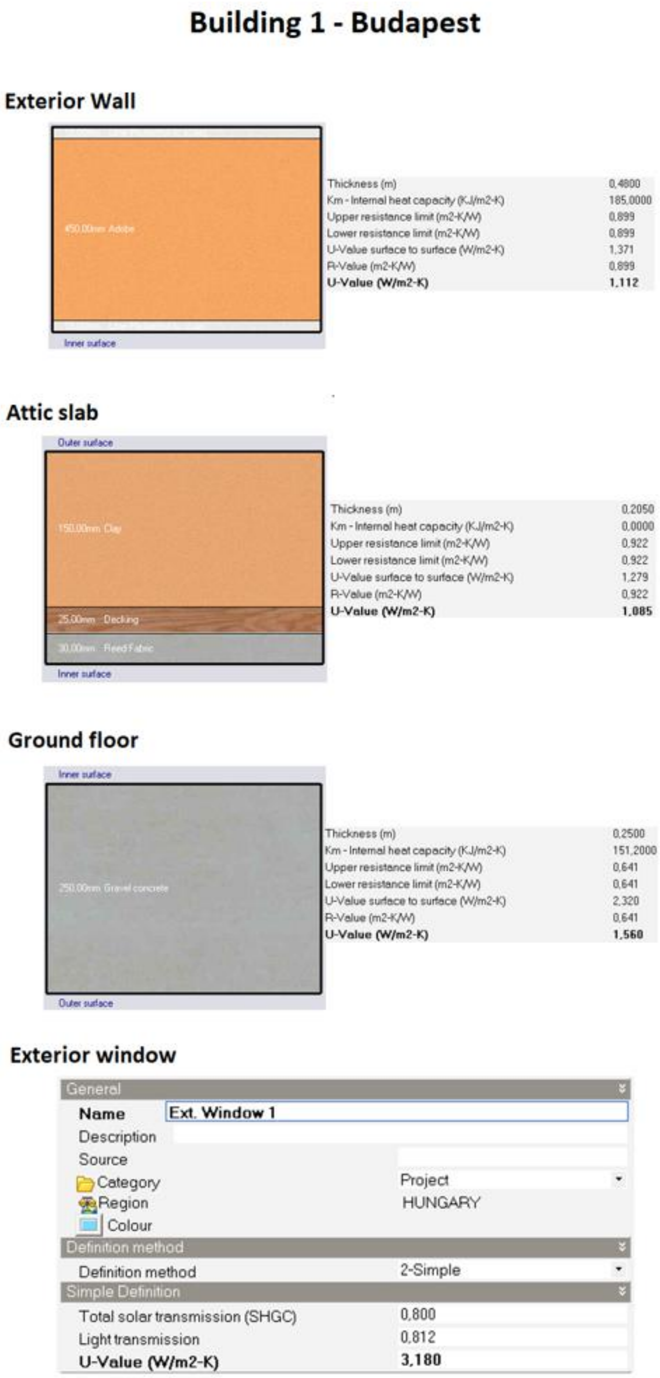


Figure A.1. Hungarian buildings built before 1940 construction solutions.

Building 2 - Budapest

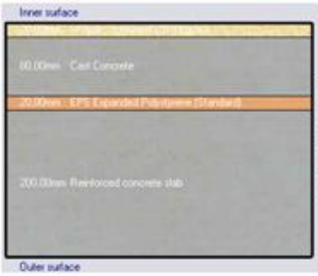
Exterior wall

Thickness (m)	0,4200
Km - Internal heat capacity (KJ/m2-K)	101,5680
Upper resistance limit (m2-K/W)	1,583
Lower resistance limit (m2-K/W)	1,583
U-Value surface to surface (W/m2-K)	0,708
R-Value (m2-K/W)	1,583
U-Value (W/m2-K)	**0,632**

Attic slab

Thickness (m)	0,2750
Km - Internal heat capacity (KJ/m2-K)	187,9960
Upper resistance limit (m2-K/W)	2,416
Lower resistance limit (m2-K/W)	2,416
U-Value surface to surface (W/m2-K)	0,439
R-Value (m2-K/W)	2,416
U-Value (W/m2-K)	**0,414**

Ground floor



Thickness (m)	0,3200
Km - Internal heat capacity (KJ/m2-K)	174,0760
Upper resistance limit (m2-K/W)	1,114
Lower resistance limit (m2-K/W)	1,114
U-Value surface to surface (W/m2-K)	1,106
R-Value (m2-K/W)	1,114
U-Value (W/m2-K)	**0,898**

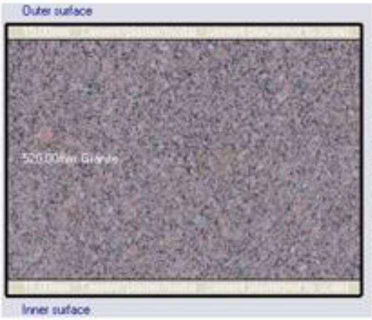
Exterior window

General	
Name	**Glazing**
Description	
Source	
Category	Project
Region	HUNGARY
Colour	
Definition method	
Definition method	2-Simple
Simple Definition	
Total solar transmission (SHGC)	0,750
Light transmission	0,738
U-Value (W/m2-K)	**1,810**

Figure A.2. Hungarian buildings built between 1990-2000 construction solutions.

Building 1 - Coimbra

Exterior wall



Thickness (m)	0,5500
Km - Internal heat capacity (KJ/m2-K)	243,1760
Upper resistance limit (m2-K/W)	0,397
Lower resistance limit (m2-K/W)	0,397
U-Value surface to surface (W/m2-K)	4,398
R-Value (m2-K/W)	0,397
U-Value (W/m2-K)	**2,516**

Attic slab

Thickness (m)	0,0350
Km - Internal heat capacity (KJ/m2-K)	12,3165
Upper resistance limit (m2-K/W)	0,432
Lower resistance limit (m2-K/W)	0,432
U-Value surface to surface (W/m2-K)	3,429
R-Value (m2-K/W)	0,432
U-Value (W/m2-K)	**2,317**

Ground floor

Thickness (m)	0,4100
Km - Internal heat capacity (KJ/m2-K)	139,8500
Upper resistance limit (m2-K/W)	0,440
Lower resistance limit (m2-K/W)	0,440
U-Value surface to surface (W/m2-K)	4,352
R-Value (m2-K/W)	0,440
U-Value (W/m2-K)	**2,274**

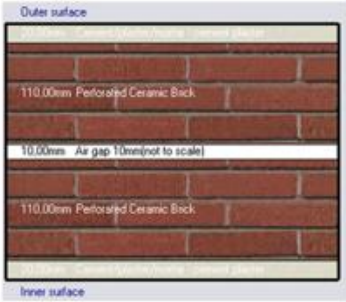
Exterior window

General	
Name	**Ext. Window 1**
Description	
Source	
Category	Project
Region	HUNGARY
Colour	
Definition method	
Definition method	2-Simple
Simple Definition	
Total solar transmission (SHGC)	0,850
Light transmission	0,812
U-Value (W/m2-K)	**3,960**

Figure A.3. Portuguese buildings built before 1940 construction solutions.

Building 2 - Coimbra

Exterior wall



Thickness (m)	0,2700
Km - Internal heat capacity (KJ/m2-K)	103,4880
Upper resistance limit (m2-K/W)	0,912
Lower resistance limit (m2-K/W)	0,912
U-Value surface to surface (W/m2-K)	1,347
R-Value (m2-K/W)	0,912
U-Value (W/m2-K)	**1,096**

Attic slab

Thickness (m)	0,1700
Km - Internal heat capacity (KJ/m2-K)	103,4880
Upper resistance limit (m2-K/W)	0,358
Lower resistance limit (m2-K/W)	0,358
U-Value surface to surface (W/m2-K)	4,595
R-Value (m2-K/W)	0,358
U-Value (W/m2-K)	**2,796**

Ground floor

Thickness (m)	0,2200
Km - Internal heat capacity (KJ/m2-K)	176,9000
Upper resistance limit (m2-K/W)	0,398
Lower resistance limit (m2-K/W)	0,398
U-Value surface to surface (W/m2-K)	5,322
R-Value (m2-K/W)	0,398
U-Value (W/m2-K)	**2,513**

Exterior window

General	
Name	**Ext. Window 1**
Description	
Source	
Category	Project
Region	HUNGARY
Colour	
Definition method	
Definition method	2-Simple
Simple Definition	
Total solar transmission (SHGC)	0,850
Light transmission	0,812
U-Value (W/m2-K)	**3,960**

Figure A.4. Portuguese buildings built between 1990-2000 construction solutions.

ANNEX B – Multisplit Outdoor Unit

In Figure B.1. the outdoor unit technical features of the Multisplit system are described.

Outdoor unit			Unit	2MXM40M	2MXM50M9	3MXM40N	3MXM52N	3MXM68N	4MXM68N	4MXM80N	5MXM90N
Dimensions	Unit	HeightxWidthxDepth	mm	550x765x285		734x958x340					
Weight	Unit		kg	36	41	57		62	63	67	68
Sound power level	Cooling		dBA	60		59		61			64
	Heating		dBA	62		59		61			64
Sound pressure level	Cooling	Nom./High	dBA	-/46	-/48	46/-		48/-		49/-	52/-
	Heating	Nom./High	dBA	-/48	-/50	47/-		48/-		49/-	52/-
Operation range	Cooling	Ambient Min.~Max.	°CDB	-10~46							
	Heating	Ambient Min.~Max.	°CWB	-15~18							
Refrigerant	Type			R-32							
	GWP			675							
	Charge		kg/TCO2Eq	0.88/0.60	1.15/0.78	1.80/1.2		2.00/1.4		2.40/1.6	
Piping connections	Liquid	OD	mm	6.4		6.35					
	Gas	OD	mm	9.5							
	Piping length	OU - IU Max.	m	20		25					
	Additional refrigerant charge		kg/m	0.02 (for piping length exceeding 20m)		0.02 (for piping length exceeding 30m)					
	Level difference	IU - OU Max.	m	15.0							
Power supply	Phase/Frequency/Voltage		Hz/V	1~/50/220-230-240		1~/50/220-240					
Current - 50Hz	Maximum fuse amps (MFA)		A	20		25					

Contains fluorinated greenhouse gases | See separate drawing for electrical data | See separate drawing for operation range | For one room

Building 1 Outdoor unit

Outdoor unit	Indoor unit	Cooling capacity (kW)				Total capacity (kW)			Power input (kW)			Total current (A)			Power factor (%)	EER	Energy label	AEC (kWh)	Seasonal data			
		A room	B room	C room	D room	Min.	Nom.	Max.	Min.	Nom.	Max.	Min.	Nom.	Max.					Label	SEER	Pdesign	AEC
4MXM68N2V1B	1.5+1.5+1.5+1.5	1.65	1.65	1.65	1.65	1.97	6.60	7.09	0.38	1.38	1.63	1.73	6.32	7.45	95	4.79	A	690	A+++	8.54	6.6	271

Outdoor unit	Indoor unit	Heating capacity (kW)				Total capacity (kW)			Power input (kW)			Total current (A)			Power factor (%)	COP	ENERGY LABEL	Seasonal data				
		A room	B room	C room	D room	Min.	Nom.	Max.	Min.	Nom.	Max.	Min.	Nom.	Max.				label	SCOP	Pdesign	AEC	Back-up heater capacity at -10°C
4MXM80N2V1B	1.5+1.5+1.5+1.5	1.83	1.83	1.83	1.83	2.23	7.30	10.10	0.39	1.61	2.13	1.76	7.37	9.75	95	4.56	A	A+	4.04	6.23	2157	1.40

Building 2 Outdoor unit

Outdoor unit	Indoor unit	Cooling capacity (kW)					Total capacity (kW)			Power input (kW)			Total current (A)			Power factor (%)	EER	Energy label	AEC (kWh)	Seasonal data			
		A room	B room	C room	D room	E room	Min.	Nom.	Max.	Min.	Nom.	Max.	Min.	Nom.	Max.					Label	SEER	Pdesign	AEC
5MXM90N2V1B	1.5+1.5+1.5+1.5+1.5	1.50	1.50	1.50	1.50	1.50	2.48	7.50	7.79	0.48	1.55	1.79	2.19	7.10	8.19	95	4.85	A	775	A++	7.90	7.5	333

Outdoor unit	Indoor unit	Heating capacity (kW)					Total capacity (kW)			Power input (kW)			Total current (A)			Power factor (%)	COP	ENERGY LABEL	Seasonal data				
		A room	B room	B room	C room	D room	Min.	Nom.	Max.	Min.	Nom.	Max.	Min.	Nom.	Max.				label	SCOP	Pdesign	AEC	Back-up heater capacity at -10°C
5MXM90N2V1B	1.5+1.5+1.5+1.5+1.5	2.00	2.00	2.00	2.00	2.00	2.77	10.00	10.90	0.42	2.14	2.47	1.94	9.80	11.30	95	4.68	A	A+	4.25	6.46	2127	1.25

Figure B.1. Multisplit outdoor unit technical features.

ANNEX C – PV System Sizing

The monthly energy consumption from the buildings modeled in Budapest is described in Table C.1.

Table C.1. Monthly energy consumption from buildings in Budapest.

	Building 1 – Monthly energy consumption [kWh]			Building 2– Monthly energy consumption [kWh]		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
January	153.6	552.5	845.6	230.1	823.2	1101.7
February	138.1	436.6	652.6	207.9	632.0	821.4
March	152.0	363.9	521.0	230.3	507.4	620.1
April	142.7	211.2	232.5	217.0	285.2	266.2
May	146.7	198.5	192.9	223.6	284.4	244.9
June	143.1	172.8	149.7	220.4	281.5	224.0
July	145.9	172.8	145.9	223.4	271.8	230.1
August	146.7	170.8	150.0	225.3	269.3	225.4
September	142.4	191.5	160.1	218.5	299.3	234.1
October	147.7	278.6	292.8	224.4	388.3	361.1
November	146.6	415.9	519.9	222.0	599.3	664.3
December	154.7	594.7	879.8	232.5	882.5	1158.9

According to the monthly energy consumptions described in the previous table, with the average daily radiation obtained for Budapest, and using equation 3.4, the systems' capacity described in Table C.2. were obtained. Besides this, the following assumptions were made: η_{system} = 80% and PV panel nominal peak power of 450 Wp.

Table C.2. PV system sizing results for buildings in Budapest.

	Building 1			Building 2		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Average daily consumption [kWh]	4.7	6.0	5.5	7.2	9.0	7.7
System capacity sizing [kW]	1.38	1.75	1.62	2.1	2.62	2.2
Number of PV panels	3.1	3.9	3.6	4.7	5.8	5.0

The monthly energy consumption from the buildings modeled in Budapest is described in Table C.3.

Table C.3. Monthly energy consumption from buildings in Coimbra.

	Building 1 – Monthly energy consumption [kWh]			Building 2– Monthly energy consumption [kWh]		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
January	146.2	380.1	471.6	247.2	626.0	694.7
February	131.5	312.5	353.1	223.4	509.5	533.2
March	145.0	277.0	312.0	248.0	450.5	472.0
April	138.3	228.5	257.5	236.1	378.8	389.3
May	141.5	210.3	200.9	242.1	341.2	319.7
June	137.7	166.1	143.1	237.6	277.0	244.3
July	140.4	165.6	143.3	241.0	276.7	244.2
August	141.2	164.1	141.2	242.9	277.4	246.3
September	136.8	170.5	142.2	235.6	282.4	244.9
October	141.1	219.0	190.2	242.0	358.8	314.0
November	140.9	341.1	367.2	240.0	551.7	554.7
December	146.4	387.3	426.9	248.4	621.3	631.8

According to the monthly energy consumptions described in the previous table, with the average daily radiation obtained for Coimbra, and using equation 3.4, the systems' capacity described in Table C.4. were obtained. Besides this, the following assumptions were made: η_{system} = 80% and PV panel nominal peak power of 450 Wp.

Table C.4. PV system sizing results for building in Coimbra.

	Building 1			Building 2		
	Boiler	**Multisplit**	**AWHP**	**Boiler**	**Multisplit**	**AWHP**
Average daily consumption [kWh]	4.5	5.9	5.2	7.8	9.8	8.7
System capacity sizing [kW]	1.15	1.50	1.32	1.98	2.49	2.2
Number of PV panels	2.6	3.3	2.9	4.4	5.5	4.9

ANNEX D - Ground Floor Thermal Resistance

The heat transfer coefficient for construction elements in contact with the ground is determined in function of three parameters: the height difference between the ground floor and the soil (z_{soil}), the thermal resistance of the ground floor, and the characteristic size of the floor in contact with the ground (*B'*). This last variable is determined according to the following equation:

$$B' = \frac{A_{p,soil}}{0{,}5 * P}\,[m],$$

where $A_{p,soil}$ is the useful internal floor area in contact with the ground, measured from inside, and P is the floor perimeter in contact with the ground. In Table D.1. the ground floor parameters from Building 1 and 2 in Coimbra are described.

Table D.1. Ground floor parameters.

	Building 1	Building 2
Floor area [m^2]	67.58	117.87
Floor perimeter [m]	34.52	43.84
z_{soil} [m]	0.26	0.44
B'	4	5.4

According to the values described in the previous table and with Figure D.1. it is possible to calculate the thermal resistance of the ground floor to comply with the thermal transmittance requirement described in Table 2.9.

B'	U_{bf} [W/(m².ºC)]											
	z_{solo} ≤ 0,5 m				0,5 m < z_{solo} ≤ 1,0 m				1,0 m < z_{solo} ≤ 2,0 m			
	R_f [(m².ºC)/W]				R_f [(m².ºC)/W]				R_f [(m².ºC)/W]			
	0,5	1	2	≥ 3	0,5	1	2	≥ 3	0,5	1	2	≥ 3
3	0,65	0,57	0,32	0,24	0,57	0,44	0,30	0,23	0,51	0,41	0,29	0,22
4	0,57	0,52	0,30	0,23	0,52	0,41	0,28	0,22	0,47	0,37	0,27	0,21
6	0,47	0,43	0,27	0,21	0,43	0,35	0,25	0,20	0,40	0,33	0,24	0,19
10	0,35	0,32	0,22	0,18	0,32	0,28	0,21	0,17	0,30	0,26	0,20	0,17
15	0,27	0,25	0,18	0,15	0,25	0,22	0,18	0,15	0,24	0,21	0,17	0,14
≥ 20	0,22	0,21	0,16	0,13	0,21	0,18	0,15	0,13	0,20	0,18	0,15	0,13

Figure D.1. Ground floor without insulation heat transfer coefficient [54].

By linear interpolation, the Building 1 and Building 2 ground floor thermal resistance obtained was 1.1 (m^2.ºC)/W and (0.5 m^2.ºC)/W, respectively.

APPENDIX A – REFERENCE AND MODELED BUILDINGS DESCRIPTION

	Type	Building 1 Reference	Building 1 proposed	Error
Building data - general	Number of levels	1	1	-7%
	Number of heated levels	1	1	-1%
	Floor area (with unheated space, corridors, basement with attic) [m^2]	101.7		-100%
	Total heated floor area (including common areas) [m^2]	69.9	70.0	0%
	Building dimensions - A direction [m]	13.7	12.0	-13%
	Building dimensions - B direction [m]	7.3	7.3	0%
	Typical Location	Detached	Detached	
	Floor plan division of a building	Rectangular	Rectangular	
	Vertical division of a building	First floor + Unheated attic	First floor + Unheated attic	
	A (Surface delimiting heated building volume) [m^2]	237.2	248.1	5%
	V (Heated building volume) [m^3]	178.9	196.0	10%
	n (Average number of air changes in the heating season) [1/h]	0.7	0.7	4%
Exterior Wall	Wall surface [m2]	77.5	108.1	39%
	Structure *U* value [W/m2K]	1.12		
Attic floor	Floor slab surface [m^2]	69.6	70.0	1%
	Uninsulated structure *U* value [W/m^2K]	1.08		
Floor (laid on the ground)	Floor (laid on the ground) surface [m^2]	71.0	70.0	-1%
	Floor perimeter	26.9	29.9	
	Uninsulated structure *U* value [W/m^2K]	1.54		
	Average "z" level difference [m]	-0.26		
Window (wood and PVC)	Gross surface area of window (wood and PVC) [m^2]	9.3	9.5	1%
	Net area of window (wood and PVC) [m^2]	6.7		
	Average *U* value [W/m^2K]	3.18		
	Average *g* factor	0.80		
	Northern, northeastern	16.8%		
	Eastern, Western	27.4%		
	Southeast, southwest	36.5%		
	Southern	19.4%		
Door (external, unglazed)	Door (external, unglazed)	3.3	3.3	0%
	Average *U* value[W/m^2K]	3.5		

	Type	Building 2 Reference	Building 2 proposed	Error
Building data - general	Number of levels	1	1	
	Number of heated levels	1	1	
	Floor area (with unheated space, corridors, basement with attic) [m^2]	146.8		
	Total heated floor area (including common areas) [m^2]	99.2	111.4	12%
	Building dimensions - A direction [m]	13.0	13.0	
	Building dimensions - B direction [m]	9.3	10.0	
	Typical Location	Detached	Detached	
	Floor plan division of a building	Rectangular	Rectangular	
	Vertical division of a building	First floor + Unheated attic	First floor + Unheated attic	
	A (Surface delimiting heated building volume) [m^2]	305.7	351.6	15%
	V (Heated building volume) [m^3]	272.3	311.9	15%
	n (Average number of air changes in the heating season) [1/h]	0.6		
Exterior Wall	Wall surface [m2]	99.8	105.8	6%
	Uninsulated structure *U* value [W/m2K]	0.62		
Attic floor	Floor slab surface [m^2]	89.5	111.4	24%
	Uninsulated structure *U* value [W/m^2K]	0.44		
Basement slab	Basement slab surface [m^2]	10.9	0	
	Uninsulated structure *U* value [W/m^2K]	0.86		
Floor (laid on the ground)	Floor (laid on the ground) surface [m^2]	68.5	93.6	37%
	Floor perimeter	28.0	34.7	24%
	Uninsulated structure *U* value [W/m^2K]	0.87		
	Average "z" level difference [m]	0.44		
Windows	Gross surface area of window (at roof level) [m^2]	19.8	19.5	
	Net area of window (at roof level) [m^2]	14.9		
	Average *U* value [W/m^2K]	1.81		
	Average *g* factor	0.75		
	Northern, northeastern	23.3%		
	Eastern, Western	31.9%		
	Southeast, southwest	26.3%		
	Southern	18.5%		
	Southern	0.0%		
Door (external, unglazed)	Door (external, unglazed)	3.5	3.5	0%
	Average *U* value[W/m^2K]	2.1		