STUDY ON BUILDING ENERGY EFFICIENCY USING NUMERICAL SIMULATIONS AND IN SITU MEASUREMENTS

Teză destinată obținerii
titlului științific de doctor inginer
la
Universitatea Politehnica Timișoara
în domeniul Inginerie Civilă și Instalații
de către

Cristina-Mariana Tănasă

Conducător științific:	prof.univ.dr.ing. Valeriu STOIAN
Referenți științifici:	prof.univ.dr.ing. Daniel DAN
	prof.univ.dr.ing. Stefano CORGNATI
	prof.univ.dr.ing. Marcela PRADA

Ziua susținerii tezei: 25 Iulie 2018

Seriile Teze de doctorat ale UPT sunt:

1. Automatică
2. Chimie
3. Energetică
4. Ingineria Chimică
5. Inginerie Civilă
6. Inginerie Electrică
7. Inginerie Electronică și Telecomunicații
8. Inginerie Industrială
9. Inginerie Mecanică
10. Știința Calculatoarelor
11. Știința și Ingineria Materialelor
12. Ingineria sistemelor
13. Inginerie energetică
14. Calculatoare și tehnologia informației
15. Ingineria materialelor
16. Inginerie și Management

Universitatea Politehnica Timișoara a inițiat seriile de mai sus în scopul diseminării expertizei, cunoștințelor și rezultatelor cercetărilor întreprinse în cadrul Școlii doctorale a universității. Seriile conțin, potrivit H.B.Ex.S Nr. 14 / 14.07.2006, tezele de doctorat susținute în universitate începând cu 1 octombrie 2006.

România, 300159 Timișoara, Bd. Republicii 9,
Tel./fax 0256 403823
e-mail: editura@edipol.upt.ro

Preface

The doctoral thesis was elaborated during my research activity in the Department of Civil Engineering and Building Services, Faculty of Civil Engineering, „Politehnica" University of Timişoara.

First and foremost, I would like to express my grateful acknowledgement to Prof. Valeriu Augustin Stoian, for his trust in my capabilities, for his guidance and support, for being an example as a professor, engineer and person and for all the opportunities that he offered me in all these years.

I would like to express my sincere gratitude to Prof. Daniel Dan, for his contribution in my development as a researcher, for all his help and support, for his example of professionalism and for giving me the chance of working in a research project.

I would like to thank to architect Dan Stoian for providing all the information related to the case study building and access to all the monitoring data.

My sincere thanks go to all the colleagues in the Civil Engineering and Building Services Department, for their help and support. Special thanks to Silviana Brata for her help and advices related to my research.

Special thanks to Prof. Stefano Paolo Corgnati and Cristina Becchio, for guiding me and giving me the opportunity of enriching my knowledge, experience and research perspective during my internship at Politecnico di Torino. Thanks to all the colleagues from the office in Politecnico Di Torino for making me feel like part of their team.

My sincere thanks also go to the guiding committee Prof. Dan Tudor, Prof. Sevastean Ianca and Prof. Ioan Sarbu.

I am grateful to the doctoral committee Prof. Daniel Dan, Prof. Stefano Paolo Corgnati, Prof. Marcela Prada and Conf. Sorin Dan.

I am thankful to my friends, for their understanding, empathy and encouregments.

Dedicated to my beloved Alex, for all his love and support and for everything that he is.

To my parents, for their love, endless support, encouragement and sacrifices.

Timișoara, 2018 Cristina-Mariana TĂNASĂ

This work was partially supported by a grant of the Romanian National Authority for ScientificResearch,CNDI–UEFISCDI; project number PN-II-PT-PCCA-2011-3.2-1214-Contract 74/2012.

Tănasă, Cristina Mariana

Study on building energy efficiency using numerical simulations and in situ measurements

Teze de doctorat ale UPT, Seria X, Nr. YY, Editura Politehnica, 2018, 211 pagini, 117 figuri, 51 tabele.
ISSN:

ISBN:

Keywords: energy efficiency, monitoring, building energy model, energy simulations, global cost

Abstract:
In the context of achieving the European Union climate targets, investigations on highly energy efficient buildings through measurements and numerical simulations can lead to the validation and improvement of technical solutions for nealy zero-energy buildings. Moreover, life cycle cost analyses, based on global cost calculations, are crucial towards the identification of cost optimal solutions. The studies performed in this thesis are based on an existing highly energy efficient building, which is continuously monitored in terms of energy consumption and environmental parameters. A full year monitoring data is used to create a building energy model that reflects real operation conditions, for hourly dynamic simulations. The simulations results show very small differences between measured and simulated energy consumption and interior air temperature. The study is extended on investigating, in terms of global cost and primary energy consumption, several energy efficiency scenarios applied to the case study building. The proposed energy efficiency scenarios are either upgrades that can be implemented in the existing building or different other configurations of thermal envelope and technical systems, including on-site renewable energy production. This last study is in compliance with the current requirements at European Union level, with respect to the cost-optimal levels of energy performance for nearly zero-energy buildings.

TABLE OF CONTENTS

SYMBOLS AND ABBREVIATIONS

Symbols

ψ	linear thermal transfer coefficient
$U - value$	thermal transmittance
R'_{min}	minimum corrected thermal transfer resistance
U_{max}	minimum thermal transmittance
$q_{an,max}$	maximum admissible specific primary energy consumption for heating from non-renewable energy
q_{an}	specific primary energy consumption for heating from non-renewable energy
G	global coefficient of thermal insulation
GN	normalised global coefficient of thermal insulation
A/V	area to volume ratio
EP_P	primary energy indicator
$E_{P,nren}$	non-renewable primary energy
$E_{del,i}$	delivered (imported) energy on site or nearby fo energy carrier i
$f_{del,nren,i}$	non-renewable primary energy factor for the delivered energy carrier i
$E_{exp,i}$	exported energy on site or nearby for energy carrier i
$f_{exp,nren,i}$	non-renewable primary energy factor for the delivered energy compensated by the exported energy for energy carrier i
A_{net}	useful floor area
RER_P	renewable energy ratio based on the total primary energy;
$E_{ren,i}$	renewable energy produced on site or nearby for energy carrier i
$E_{del,i}$	delivered energy on site or nearby for energy carrier i
$f_{del,tot,i}$	total primary energy factor for the delivered energy carrier i
$f_{del,nren,i}$	the non-renewable primary energy factor for the delivered energy carrier i;
$E_{exp,i}$	exported energy on site or nearby for energy carrier i

$f_{exp,tot,i}$	total primary energy factor of the delivered energy compensated by the exported energy for carrier i
$NMBE$	normalised mean bias error
$CVRMSE$	coefficient of variation of the root mean square error
$\tilde{y}_i$	is the simulated result at time i
y_i	is the measured data at time i
$\bar{y}$	is the average value of y_i
V_{ac}	domestic hot water demand volume per day
a	specific demand of domestic hot water
N_u	the number of persons that use domestic hot water
$n_{V,Res}$	infiltration air change rate at atmospheric pressure
n_{50}	fan pressurization test result
e	wind screening coefficient
V_{n50}	net air volume – reference volume for the fan pressurization test
V_{RAX}	air exchange volume
$E(m,h)$	average hourly household appliances electricity consumption in month *m* hour *h*
$L(m,h)$	average hourly lighting electricity consumption in month *m* hour *h*
$T(m,h)$	average hourly temperature in month *m* hour *h*
$l(d,h)$	hourly lighting electricity in day *d* hour *h*
$e(d,h)$	hourly household appliance electricity in day *d* hour *h*
m	month
h	hour
n	number of days in a month
d	day
EL_{m_i}	the monthly energy consumption from category *i*
EL_{m_i}	recorded electricity power from category *i*
$v(d,h)$	average hourly value for a particular measured parameter

Abbreviations

IPCC	International Panel on Climate Change
COP21	21st Conference of Parties
UNFCCC	United Nations Framework Convention on Climate Change
EU	European Union
GHG	Grennhouse gases
Mtoe	Million Tonnes of Oil Equivalent
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
nZEB	nearly zero-energy building
Low-E	low emissivity
DOE	United States Department of Energy
DOD	United States Department of Defence
BWM	Box and Whiskers Mean
BEM	Building Energy Modelling
IWEC	International Weather for Energy Calculations
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 General aspects related to energy consumption

1.1.1 The climate change phenomena

One of the most significant concerns of nowadays society is related to the energy use and its effects on the climate change phenomena. The energy sector needs a major change, as it is the source of at least two-thirds of greenhouse-gas emissions [2]. According to the International Energy Outlook 2016 (IEO2016), between 2012 and 2040 there will be a 48% increase in the worldwide energy need. A major part of this growth is assigned to the Asian non-OECD countries (outside the Organization for Economic Cooperation and Development) where the strong economic development and increase of population is assumed to lead to a 45% increase of the energy need in 2040 compared to 2012 [3]. With this prevision ahead, solutions of decoupling the economic growth and development from the energy requirements should be implemented.

The already high worldwide energy consumption from fossil fuels and also the previsions of future growth of energy need, implies the increase of environmental pollution through the greenhouse gas emissions. Researches made by NASA show that the melting of ice cap occurs at a rate of 9% in a decade and the Arctic Ocean temperature increases by 1.2 ° C over a decade.

The climate change phenomena is a consequence of the human activities that generate greenhouse gas emissions (burning fossil fuels, emissions from the transport sector etc.), which due to their high concentration lead to heat-trapping in the atmosphere and increasing the global temperature. According to the Intergovernmental Panel on Climate Change (IPCC) the global average surface temperature has increased by almost 0.6°C throughout the 20th century.

The concentration of CO2 in the atmosphere increased with approximately 80% emissions 1970 and 2004 (28% between 1990 and 2004) [5]. According to the forth Report of the Intergovernmental Panel on Climate Change (2007), the highest increase of the greenhouse gases emissions was registered between 1970 and 2004 (145%) in the energy sector followed by the transport sector (120%) [5]. Increase of the amount of CO2 in the atmosphere due to the burning of fossil fuels is a serious environmental problem. The data recorded by the observer Mauna Loa shows an increase in the amount of CO2 by 35% compared to the amount before the industrial revolution, and an increase of 6% in the last 19 years [7].

The first policy action of fighting the climate change process was taken in 1992 in Rio De Janeiro when the United Nations Framework Convention on Climate Change was signed and more than 150 countries agreed to take long term measures in order to stabilize the concentration of greenhouse gases in the atmosphere at a level that would prevent dangerous influences on the climate [8]. The climate change combat action took a higher amplitude five years later, when in Kyoto, Japan, the developed countries engaged to limit and reduce the greenhouse gas emissions between 1998 and 2012 [9]. During the 21st Conference of Parties (COP21) in Paris, on 12 December 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have established a new agreement to prevent and combat the climate change and also to enhance the actions necessary for a sustainable and clean future of the natural environment [1]. Within the Paris Agreement, Parties to the UNFCC aim at maintaining the increase in the global average temperature well below 2°C above pre-industrial levels and following efforts to keep the temperature increase even further to 1.5° in order to diminish the negative effects of climate change [1]. The Paris Agreement entered into force on 4 November 2016 and requires to all Parties to enhance their efforts in achieving the goals of the agreement. Governments have agreed to submit their contributions every five years in order to establish future objectives. The European Union (EU) agreed to continue providing funding for climate change to support developing countries to reduce emissions and strengthen their resilience to climate change. The Paris Agreement is in fact a document that strengthens the existing strategic plans [1] [11].

1.1.2 European Union perspectives to combat climate change

In order to cope with the global energy challenge and climate change consequences, energy efficiency improvements and use of a higher share of energy from renewable sources are necessary. In March 2007, the European Union adopted the 2020 Climate and Energy Package which aimed three major targets, well known as the '20-20-20' targets:

1. A 20% reduction in greenhouse gas emissions (GHG) from 1990 levels;
2. Increasing the share of energy consumption produced from renewable sources to 20%;
3. 20% increase in the energy savings compared to projections.

Besides the ambitions with respect to 2020, the European Commission (EC) proposed a long-term policy plan as the EU climate action. The targets to be achieved by 2050 consist in reducing the GHG emissions by 80-95% compared to 1990 levels [131].

In 2014, an intermediate policy framework for climate and energy in the period from 2020 to 2030 was released [132]. This comes with new perspectives and aims as follows: reducing the greenhouse gas emissions by 40%, increasing the share of renewables production of more than 27% and increasing the energy efficiency with 27%, all relative to 1990 levels.

Figure 1.1 shows the greenhouse gas emissions trend in the European Union starting with 1990 levels until 2014. In the first years after 1990, the greenhouse gas emissions reduction is visible, with a peak in 1996 due to the higher heating requirements in that year [17]. The graph in Figure 1.1 shows the trend in total human-made emissions of greenhouse gases starting with the baseline year 1990. The following six greenhouse gases are considered: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and the so-called F-gases (hydrofluorocarbons, perfluorocarbons, nitrogen triflouride (NF3) and sulphur hexafluoride (SF6)). These gases are aggregated into a single unit using gas-specific global warming potential (GWP) factors [4].

Through the entire period (1990-201) the graph shows a general downward trend. Therefore, in 2014 the greenhouse gas emissions in the European Union were with almost 23% lower compared with 1990 levels. The 2014 data on greenhouse gas emissions and also the downward trend registered in past, puts the EU in the position of surpassing its 2020 target.

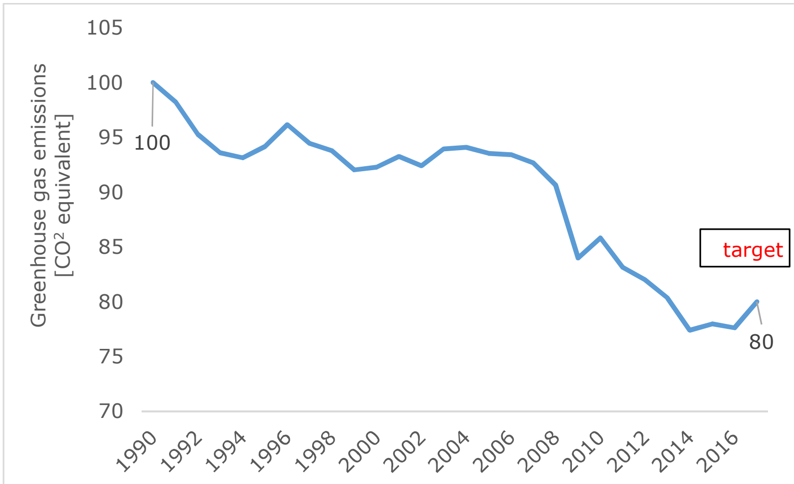


Figure 1.1 - Greenhouse gas emissions trend in the European Union, 1990–2014
Data Source: EUROSTAT [4]

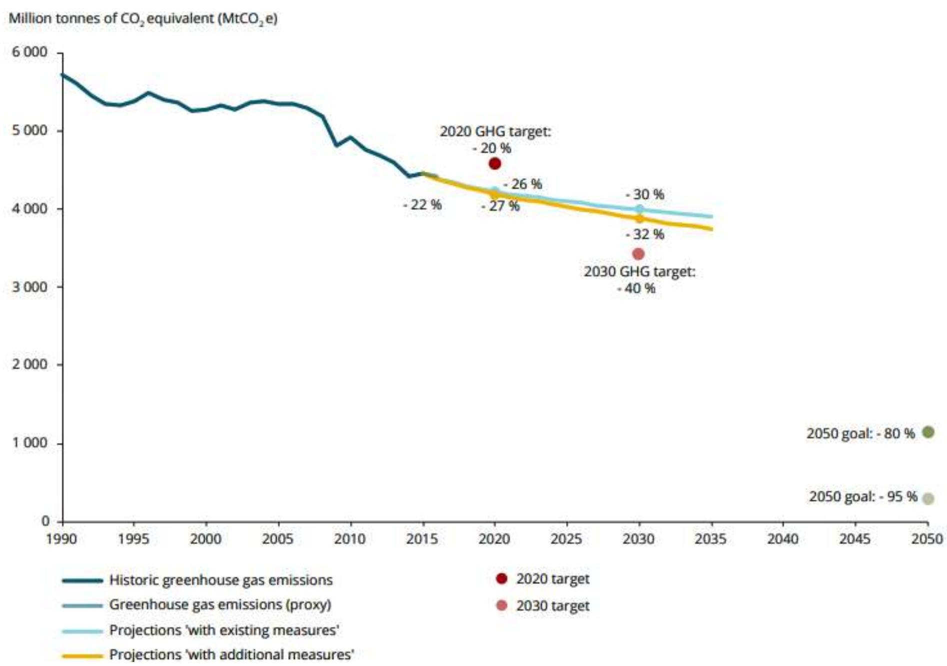


Figure 1.2 – GHG emissions trends, future projections and targets in the EU. Data Source: EEA report 2017 [133]

Figure 1.2 shows the current progress within EU towards the GHG emission reduction targets. It is noticeable that while for the short-term targets (2020), the Member States are well on track, for the long-term objectives the perspectives are not very optimistic.

Figure 1.3 shows the progress of the European Union towards the '20-20-20' climate and energy goals. As mentioned earlier, the GHG emissions target is already achieved since 2015. The use of renewable energy increase is noticeable every year, representing 16.7% of gross final energy consumption in 2015 and getting closer to the 20% target for 2020. The promotion of the renewable energy use was made under the Directive 2009/28/EC [18] of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. The Renewable Energy Directive [18] is a framework policy for the production and promotion of energy from renewable sources in the EU and establishes national renewable energy targets for each country, considering its starting point and potential for renewables. The targets for each country can be seen in Figure 1.4. The lowest target is 10% for Malta and the highest is 49% for Sweden. In Figure 1.4 we can also see the share of energy from renewable sources in 2004 and 2015 for the EU and each Member State. For several countries, among which is Romania as well, the 2020 target was already achieved in 2015.

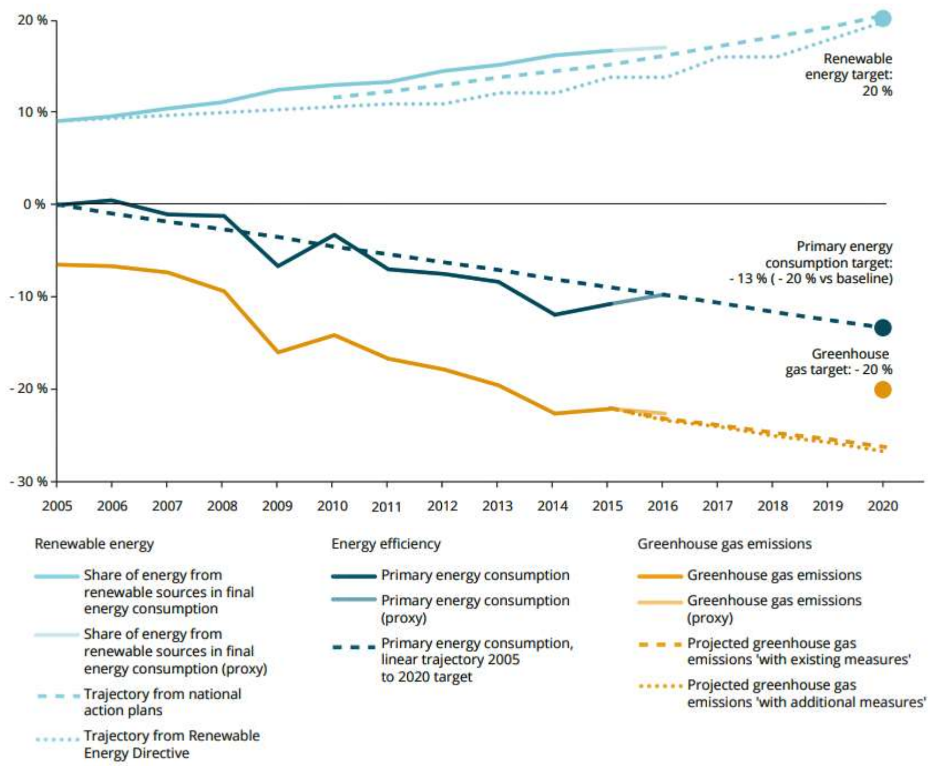


Figure 1.3 – EU progress towards 2020 climate and energy goals. Data source EEA report 2017 [133]

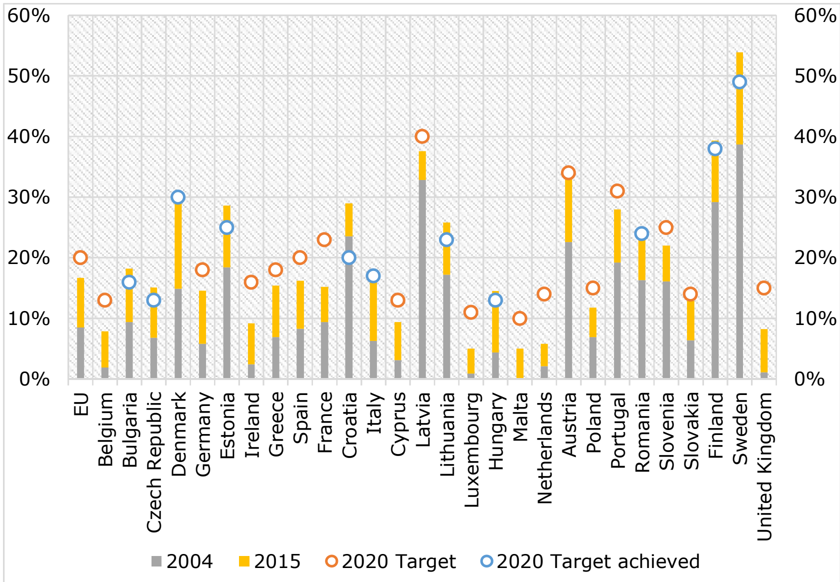


Figure 1.4 - Share of energy from renewable resources in the European Union, 2004 – 2015
Data source: EUROSTAT [4]

As noticed in Figure 1.3, the primary energy consumption in EU has been decreasing in the past decade. If the decrease rate is sustained, the 20% energy efficiency target can be achieved.

In 25 October 2012, the EU adopted the Energy Efficiency Directive (EED) 2012/27/UE [12], amending Directives 2009/125/EC [13] and 2010/30/EU [14] and annulling Directives 2004/8/EC [15] and 2006/32/EC [16]. The Energy Efficiency Directive came as a response to the EU need of increasing energy efficiency in order to achieve the 20% energy savings of the EU's primary energy consumption until 2020 compared to projections [12]. The projections made in 2007 indicated a primary energy consumption of 1 842 Mtoe in 2020. This means that a 20% reduction of primary energy consumption compared to projections will result in 368 Mtoe [12]. In 2015, the final energy consumption in the EU was 1 082 Mtoe, almost equal with the final energy consumption in 1990 (Figure 1.5). The highest final energy consumption was registered in 2006, the consumption then was 11% higher than the one in 2015. In order to fulfil the energy efficiency objective of 20% energy saving, the final energy consumption in 2020 should not increase with more than 390 Mtoe above the 2015 consumption (36% increase). However, according to Eurostat data [4], the final energy consumption target not to be over headed by 2020 is 1086 Mtoe.

To better understand the energy consumption actors within EU, the final energy consumption is represented by sectors in Figure 1.6. The evolution of the final energy consumption by sector in the European Union between 1990 and 2015 shows an increase of the consumption in the residential-tertiary sector and transport and a decrease in the industry and agriculture sectors (Figure 1.6) [4]. The continuous development of transport infrastructure and transport in recent years led to a significant increase of energy consumption in this sector (from 26.24% in 1990 to 33.14% in 2015). Significant as well is the decrease of energy consumption in the industry sector. In 2015, the energy consumption in the building sector represented

39% of the total energy consumption in the European Union, registering an increase of almost 4% compared to 1990.

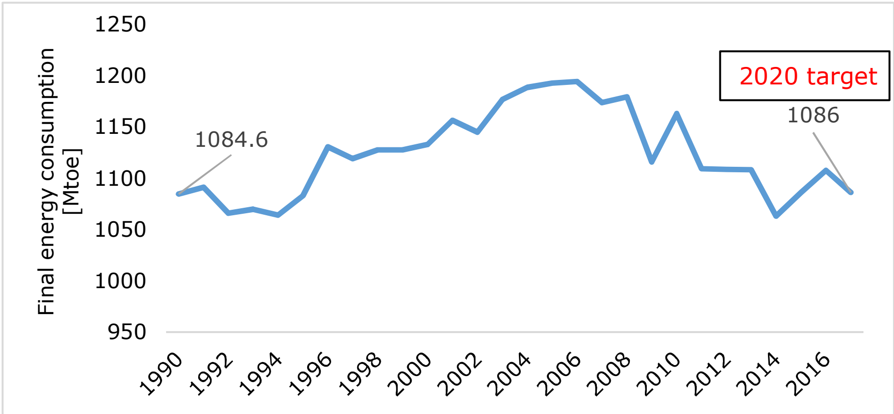


Figure 1.5 - Final energy consumption trend in the European Union, 1990 to 2015
Data source: EUROSTAT [4]

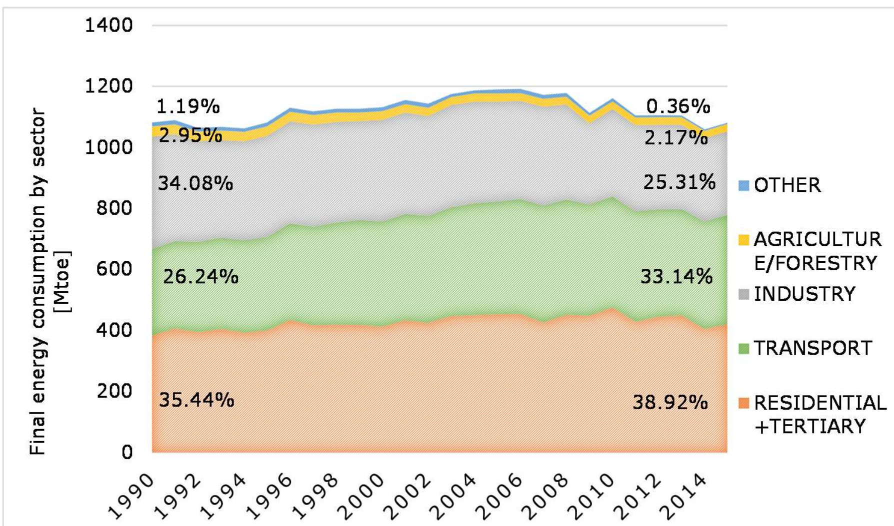


Figure 1.6 - Final energy consumption by sector in the European Union between 1990 and 2015
Data source: EUROSTAT [4]

EED requires that each Member State shall set an individual national energy efficiency target, considering national circumstances influencing primary energy consumption [12]. In 2016, the European Commission came with an update of the Energy Efficiency Directive, proposing a new target of 30% energy efficiency by 2030 [19] [24]. In Article 5 of EED, rules for the renovation of public buildings are imposed – renovation of 3% of the total area of "heated and/or cooled buildings owned and occupied by their central government" [12]. In Article 8 and Article 9, Member States are required to introduce energy audits and energy management systems and also meters that provide information on the actual energy consumption and time of use of the final consumer [12].

Not only in the EU but worldwide, the building sector has the largest share of energy consumption from the total energy consumption (40%) and therefore is responsible for a high amount of greenhouse gas emissions. Different studies indicate that the highest potential of reducing the energy consumption from fossil fuels and the related greenhouse gas emissions lies in the building sector [10]. Improving the energy efficiency of buildings is crucial in order to achieve the EU objective of reducing the greenhouse gas emission by 80-95% until 2050, compared to 1990 [12].

1.1.3 Energy use in the European Union building sector

Energy consumption in the EU building sector represents approximately 40% of the total energy consumption, above the consumption in the transport and industry sectors. The significant share of energy consumption of the building sector in the total energy consumption makes it responsible for 36% of CO2 emission in the European Union. Figure 1.7 shows how the energy consumption in the building sector evolved since 1990 until 2015 in the EU countries. As we can see, Germany has the highest energy consumption in the building sector, followed by France, Italy and United Kingdom. This consumption varies significantly among EU countries due to very different climatic conditions.

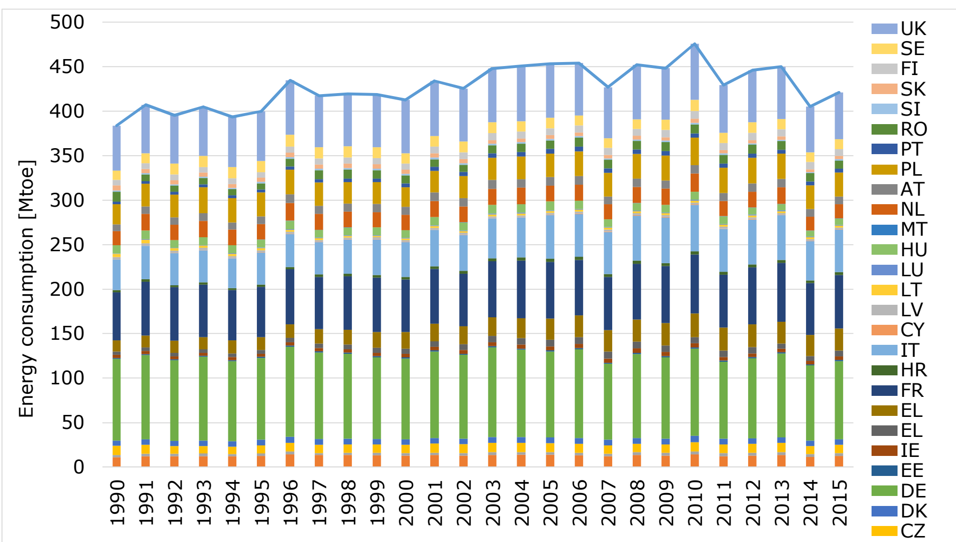


Figure 1.7 - Building energy consumption in the EU countries, 1990 – 2015
Data Source: EUROSTAT [4]

In the European Union, the annual average energy consumption was 210 kWh/m^2 in 2010, with a significant difference between residential (185 kWh/m^2) and non-residential (286 kWh/m^2). In the EU, space heating has the largest share in the total final energy consumption in residential buildings (approximately 67%) but this share is continuously decreasing in the last decade. The energy consumed for domestic hot water represents 13% and is a stable value in time. Electricity consumption for household appliances and lighting has increased with 3% in the last years. According to ENERDATA, the energy efficiency for households in the EU has improved with 18% since 2000. The most significant improvement is for space heating (20%) and is followed by domestic hot water and large appliances (15%). The energy need for space heating has decreased due to the development of more energy efficient new buildings that use efficient systems for heating. Also, the use of new electrical appliances that have very high energy efficiency are used [6]. The energy efficiency improvement rhythm slowed down since 2008 along with the beginning of the economic crisis [6].

In 2002, the EU launched the Energy Performance of Buildings Directive (EPBD) 2002/91/EC [20] as a legal framework and action plan to reduce the energy consumption in the building sector. EPBD is focused on promoting the improvement of building's energy efficiency using cost optimal solutions and establishes key points to be transposed in actions by the Member States. EPBD encompasses the following main requirements:

- ''the general framework for a methodology of calculation of the integrated energy performance of buildings;
- the application of minimum requirements on the energy performance of new buildings;
- the application of minimum requirements on the energy performance of large existing buildings that are subject to major renovation;
- energy certification of building;
- regular inspection of boilers and of air-conditioning systems in buildings and in addition an assessment of the heating installation in which the boilers are more than 15 years old.'' [20]

In 2009, the Recast on the Energy Performance of Buildings Directive Directive 2010/31/EU (EPBD recast) [21] was launched in order to strengthen the energy performance requirements and clarify some aspects in the initial Directive 2002/91/EC. The EPBD recast highlights the need to establish more specific actions in order to reach the high potential of energy savings in the building sector. All Member States have to set minimum energy efficient requirements considering cost optimal solutions and life cycle analysis. Directive 2010/31/EC introduces the concept of ‚nearly zero energy building' (nZEB) that have a nearly zero primary energy consumption from fossil fuels and very low level of CO_2 emissions. The European Union published the Energy Performance of Buildings Directive (EPBD) as a common legislation related to the energy performance of buildings for the European member states and aims to promote improvements in the energy efficiency of a building. The recast on the EPBD introduced in Article 9 the concept of nearly zero energy building as a future requirement to be applied to all new buildings [21]. The EPBD defines the nZEB as "a building that has a very high energy performance […]. 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" [21]. Nevertheless, the recast on EPBD does not establish a uniform methodology in order to implement this type of buildings causing each individual Member State to develop its own definitions complying with their national particularities. However, throughout Europe there are many other concepts of energy efficient buildings such as passive house, active house or zero energy building. Broadly, all these concepts imply a certain level of energy efficient measures for the building envelope combined with renewable energy technologies. Thus, the challenge is to find the balance between energy efficiency measures and implementation of renewable energy. In the case study by Marszal and Heiselberg [26], on a multi-story residential net zero energy building, the authors concluded that it is crucial to reduce first the energy use to a minimum, and afterwards implement renewable energy technologies to compensate the remaining energy demand. However, regardless of the level of energy efficient measures or renewable energy technologies, the design and construction of such a house implies a higher initial investment. Generally, building owners take in consideration only the initial costs of a new building without thinking of the future costs for operation and maintenance. Thus, the investors lack the overall approach leading to the choice of an unprofitable solution throughout the life cycle of a building. Buildings are long term investments, which assume that the initial decision on the quality of the investment has long term consequences [27].

According to Directive 2010/31/EU [21], Member State have to conform to the following requirements:

- ''by 31 December 2020, all new buildings are nearly zero energy buildings; and
- after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings.'' [21]

Member States have to draw national plans in order to promote and increase to number of nZEBs. Each Member State has to develop a detailed methodology on how to design and implement these kind of buildings in accordance with the EPBD requirements [21].

In 2016, a new proposal for a directive amending Directive 2010/31/EU on the energy performance of buildings was published [22]. This proposal comes as an update of the Energy Performance of Buildings Directive [21] with the following:

- ''integrating long term building renovation strategies (Article of 4 Energy Efficiency Directive), supporting the mobilization of financing and creating a clear vision for a decarbonized building stock by 2050;
- encouraging the use of ICT and smart technologies to ensure buildings operate efficiently; and
- streamlining provisions where they have not delivered the expected results.''

In 2016, a report on the implementation of the Energy Performance of Buildings Directive was published and provides the current status of the developments and achievements related to the relevant topics of the EPBD. The report has two key objectives: share an overview of existing solutions and provide an analysis of topics that Member States should pay more attention to [23]. An important chapter of the report presents the overview and outcomes regarding the energy performance requirements using cost-optimal levels. Also, the report presents an overview regarding the current status in each Member State on developing national definitions for nZEB based on national plans for increasing this number of buildings. Approximately 40% of the Member States do not provide yet an accurate for nZEB. About 60% of the Member States have developed detailed definitions but few of them highlight the fact that the proposed definition are drafts that might be updated in the future. By April 2015, approximately 60% of the Member States have developed their detailed nearly zero energy building definition in a legal document and the vast majority of Member States use a primary energy indicator in kWh/m^{2}year [23].

1.1.4 Energy in the Romanian building sector

1.1.4.1 Energy consumption trends

In Romania, the energy saving potential and energy waste reduction is estimated to be 27.7% of the final energy consumption, according to the latest evaluations of the Energy Minister [28]. Table 1.1 shows the share of each sector in the total final energy consumption and also the energy efficiency potential that lies in each of the sectors. The building sector is responsible for about 36% of the total final energy consumption and produces yearly about 56.1 Mtoe of CO2 equivalent. Thus, a very high energy efficiency potential lies in buildings (41.5%). The energy efficiency of the building sector in Romania must be addressed on a priority basis because the energy losses in buildings from Romania are three times higher than the European average [29].

Table 1.1 - Share of consumption and potential to reduce final energy consumption

Sector	Share in the total final energy consumption	Energy consumption reduction potential
Building	36%	41.5%
Transport	22%	31.5%
Services	11%	14%
Industry	31%	13%

A significant part of the Romanian residential building stock was constructed between 1960 and 1990, when there were no regulations regarding the thermal insulation of buildings. The final energy consumption in these buildings varies between 150 and 400 kWh / (m^2 year). The buildings built in the first years after 1990 also have a low energy performance (150-350 kWh / (m^2 year)). An improvement on the energy performance can be noticed in buildings built after 2000 (120-230 kWh / (m^2 year)) [30]. The residential buildings represent the greatest part of the building sector in Romania and 52% of them were built before 1970. Recently, the total energy consumption associated to the residential buildings was estimated to be about 86% from the total energy consumption in the Romanian building sector (Figure 1.8).

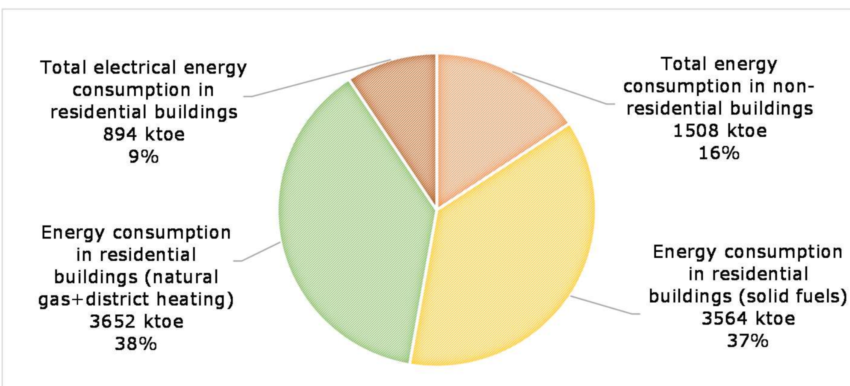


Figure 1.8 - Categories of energy consumption in buildings: average 2005 – 2010 (residential), approximation for non-residential [30]

Figure 1.9 shows the energy consumption variation in residential buildings by energy type. We can notice a constant decrease of the energy consumption since 2000, with some slight increases in some years [134].

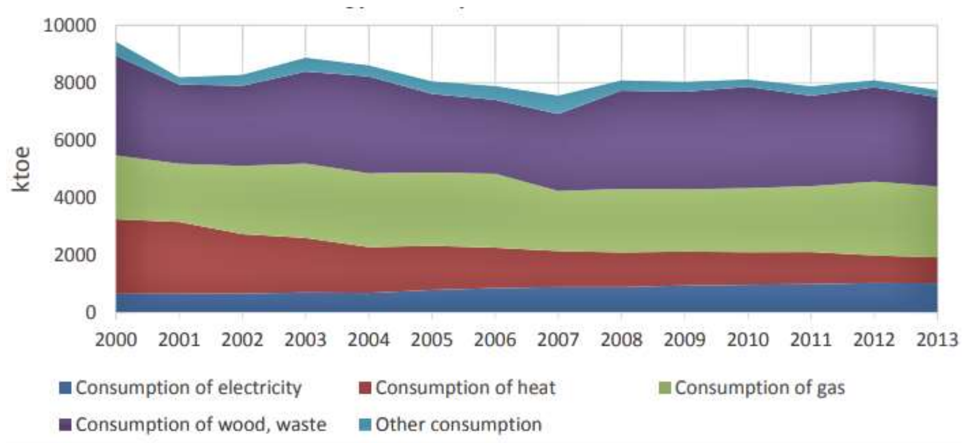


Figure 1.9 – Residential buildings energy consumption by energy type. Source: Romanian Statistical Yearbook [134]

1.1.4.2 Energy efficiency policies

Although in the last decades, interest in the energy consumption in buildings increased, the energy efficiency requirements for new or rehabilitated buildings in Romania are still not very restrictive at the moment. Generally, the limitations related to energy efficiency consisted in respecting the minimum thermal transfer resistances of the envelope elements as required by the Romanian normative C107 – 2005 - 'Normative regarding the thermal calculation of construction elements of buildings' [31] and the global coefficient of thermal insulation.

Table 1.2 contains the values for the thermal transfer resistances R'_{min} and thermal transmittance U'_{max}, required for the common envelope elements of the buildings in Romania.

Table 1.2 - Minimum thermal transfer resistance requirements of the envelope elements for buildings in Romania [31], [32]

Envelope element	Residential buildings designed after 1.06.2010	
	R'_{min} [m²K/W]	U'_{max} [W/m²K]
Exterior walls	1.80	0.56
Windows	0.77	1.30
Roof	5.00	0.20
Ground floor	4.50	0.22

In April 2017, a new legal document was released in order to modify and complete de technical regulation 'Methodology for calculating the energy performance of buildings' MC001 [32], [33]. Order No. 2641 [33] form April 2017, establishes conditions that are required to be fulfilled when designing a new building or renovating and old building. For residential buildings, the requirements are:

a) minimum thermal transfer resistance for envelope elements as listed in Table 1.2;
b) global thermal insulation coefficient G, G≤GN [W/(m^{3}K)], where GN is the normalised global thermal insulation coefficient and depends on the Area to Volume ratio of a building and number of floors (Table 1.3);
c) the specific primary energy consumption for heating from non-renewable energy q_{an} has to be lower than a maximum value $q_{an,max.}$ The maximum value imposed by the standard is 153 kWh/m^{2}year for building with less than five floors and 117 kWh/m^{2}year for buildings with more than five floors.

Table 1.3 – Maximum admissible values for the normalised global coefficient of thermal insulation [31], [32].

Number of floors	A/V [m^2/m^3]	GN [W/m^{2}K]	Number of floors	A/V [m^2/m^3]	GN [W/m^{2}K]
	0.80	0.55		0.25	0.33
	0.85	0.58		0.30	0.36
	0.90	0.62		0.35	0.39
1	0.95	0.63	4	0.40	0.42
	1.00	0.66		0.45	0.44
	1.05	0.67		0.50	0.46
	≥1.10	0.68		≥0.55	0.47
	0.45	0.41		0.20	0.31
	0.50	0.4		0.25	0.34
	0.55	0.48		0.30	0.37
2	0.60	0.50	5	0.35	0.40
	0.65	0.52		0.40	0.42
	0.70	0.53		0.45	0.44
	≥0.75	0.54		≥0.50	0.45
	0.30	0.35		0.15	0.30
	0.35	0.38		0.20	0.32
	0.40	0.41		0.25	0.35
3	0.45	0.44	≥10	0.30	0.38
	0.50	0.47		0.35	0.40
	0.55	0.48		0.40	0.42
	0.35	0.49		≥0.45	0.42

Several laws and action plans were published and launched in the last years with the purpose of increasing the energy performance of buildings in Romania. Law No. 372/2005 on Energy Performance of Buildings promotes the increase of the energy performance of buildings, considering the climate conditions, interior temperature requirements and economic efficiency [34]. In 2013, Law No. 372/2015 was republished [35] in order to comply with the Energy Performance of Buildings Directive [21]. The nearly zero-energy building concept was introduced in the law but without providing yet an accurate definition for it. The republished law on Energy Performance of Buildings [35] requires that starting with 31 December 2020 all new buildings must have a nearly zero-energy consumption from conventional sources. In February 2016, Ordinance no. 13/2016 [36] for amending and completing the Law no. 372/2005 on the energy performance of buildings [34], [35] was published. A more specific definition for nZEB is provided: 'nearly zero-energy building – a building with very high energy performance for which the energy consumption is very low or almost zero and the very low amount of energy need is covered with at least 10% of renewable energy produced on site or nearby' [36]. In March 2016, Order no. 308/2016 [37] was published for amending and supplementing normative C107-2005

'Normative regarding the thermal calculation of construction elements of buildings'. Through this legislative act, a new division in climate zones is established for the Romanian territory (Figure 1.10) as well as maximum values for primary energy consumption and CO_2 emissions for nZEB, depending on the climate zone and type of building (Figure 2.8). [37].

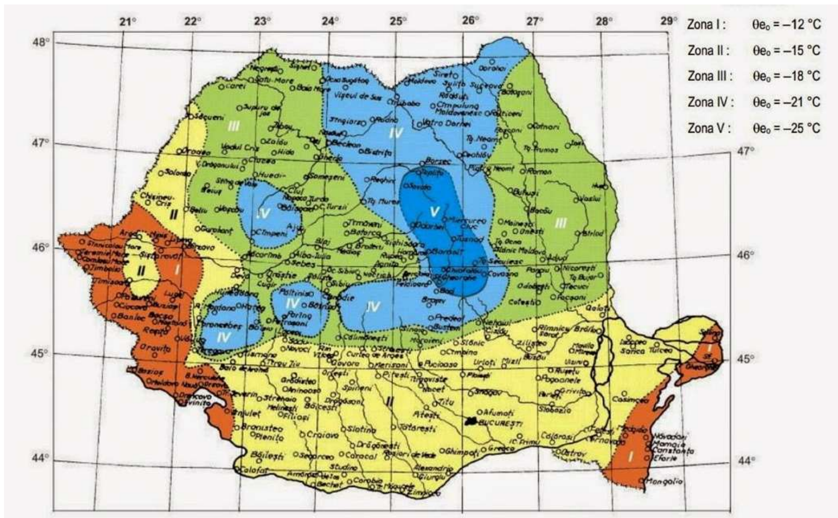
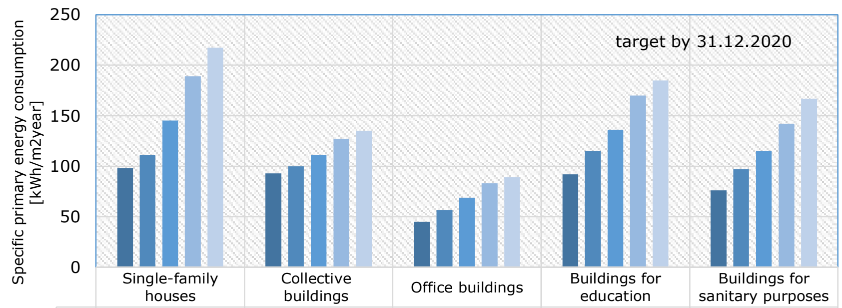


Figure 1.10 - Climate zones in Romanian territory for winter season

Each climatic zone has a corresponding conventional value for the exterior air temperature used in determining the heating energy need of a building and sizing the heating system. The graphs in Figure 1.11 shows the maximum specific primary energy consumption form conventional sources for nZEB in Romania starting with 31 of December 2020. Figure 1.12 shows the maximum values for CO_2 emissions acceptable for nearly zero energy buildings after 31 December 2020.



	Single-family houses	Collective buildings	Office buildings	Buildings for education	Buildings for sanitary purposes
I	98	93	45	92	76
II	111	100	57	115	97
III	145	111	69	136	115
IV	189	127	83	170	142
V	217	135	89	185	167

Figure 1.11 - Maximum primary energy consumption for nearly zero-energy building in Romania depending on building category and climate zone

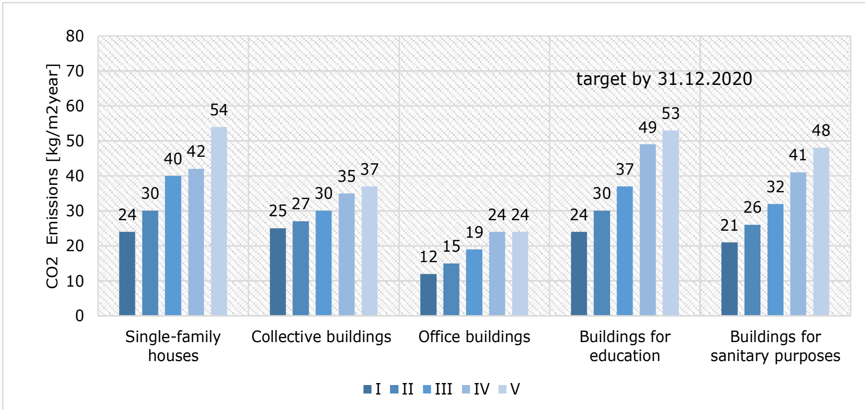


Figure 1.12 - Maximum CO_2 emissions for nearly zero-energy building in Romania depending on building category and climate zone

The maximum limits of primary energy and CO_2 emissions were defined by approaching the economic efficiency as a criteria of acceptability for constructing nearly zero-energy buildings in Romania. Economic efficiency refers to the period of time needed to recover the additional investment in a nZEB compared to the reference building (as defined by normative C107) [30].

1.2 Research motivation and objectives

The development of a sustainable built environment is becoming a necessity in the European Union construction landscape. Therefore, engineers and architects all over started using innovative technologies and design methods in order to improve the energy performance of new and existing buildings. The main challenge in achieving the targets set by the Energy Performance of buildings Directive consists in providing highly energy efficient solutions that at the same time have life cycle cost efficiency. At present, both in Romania and in other developing countries, pilot projects of energy efficient buildings that are monitored in real time in terms of energy consumption, indoor comfort parameters, user behaviour, represent an effective path to decrease the gap between the theoretical performance and real performance of a building. Real-time tracking of an energy-efficient building over an extended period of time is a practical and transparent way to investigate the real performance of such a building. Based on monitoring data, improvements can be made to energy efficiency solutions in buildings, which can then be extended to other buildings.

The research in this thesis deals with investigations on a pilot energy efficient building (passive house standard), constructed in west side of Romania. A study made on the existing residential building stock in Romania, shows that almost 61% are single family houses. The heating energy consumption in these houses represents approximately 80% from the total energy consumption [128]. Romania is characterized by a temperate climate, having high differences between winter and summer in terms of outdoor environmental conditions. Therefore, energy is needed to provide comfortable indoor environment in both winter and summer conditions. New solutions for highly energy efficient buildings are rarely used in Romania because of the higher initial investment. In order to raise the attention of the investors on the long-term performances on buildings with high energy efficiency, pilot projects are necessary that provide real-time monitoring on the energy performance and real response of such buildings. At the Politehnica University Timisoara, an experimental program was developed to demonstrate that applying passive house and nearly zero-energy design principles could be an alternative solution for energy-efficient buildings, reflecting the Romanian local climate conditions, materials, and construction techniques. An energy-efficient house was built following the passive house design principles and perspectives of achieving the nearly zero-energy building.

The main objectives of this thesis can be summarised in the following:

- Processing and analysis of the monitoring data of the investigated energy efficient building
- Implement measured data in the building energy model in order to achieve a calibrated simulation.
- Validate the theoretical results from the numerical simulations against measured data in terms of energy consumption and interior air temperature.
- Investigate changes in the building operation parameters that might increase or decrease the energy consumption of the buildings, through numerical simulations.
- Investigate several energy efficiency scenario applied to the case study building with the aim of identifying those solutions that lead to the achievement of nearly zero energy buildings and, at the same time, identifying the optimal cost solutions.

1.3 Overview of the thesis

This thesis is structured on seven chapters from 1 to 7 and four appendices A, B, C and D. The content of the seven chapters and four appendices has a total number of 195 pages. The research in this thesis follows a series of studies on the energy efficiency of buildings. The studies are based on an existing energy efficient residential building for which on site measurements were performed through a monitoring system.

Chapter 1, named ″Introduction″, presents a frame of reference through some general aspects related to energy consumption on international and national levels. After that, the thesis motivation and objectives are presented and an overview of the thesis.

Chpater 2, entitled ″Research method″, presents an overview on the concepts applied in this thesis based on the existing international research.

In Chapter 3, entitled ″Case study building″, the building which is the case study of this research is described and presented.

Chapter 4, named ″Building monitoring and registered data processing and analysis″ presents a detailed description of the monitoring system implemented of the case study building. The registered data processing procedure is presented and the analysis of the monitoring process results.

Chapter 5, named ″Building energy model simulation″ presents a detailed description of the building energy model development and simulation using a dynamic simulation software. All the input data for the building geometry and equipment is presented. The procedure for calibrating and validating the simulation with monitoring data is presented as well. The simulation results are assessed against registered data, in terms of energy consumption and interior air temperature. Model performance is investigated through the calibration criteria, in accordance to the existing international guideline. Two other simulations are performed on the validated building energy model. One scenario investigates the energy consumption of the building if different user behaviour scenarios are considered. The second scenario analysis the simulated interior air temperature in the hypothesis of shading devices installed on some of the windows.

In Chapter 6, the thesis studies are extended on investigating, in terms of global cost and primary energy consumption, several energy efficiency scenarios applied to the case study building. The proposed energy efficiency scenarios are presented in terms of configurations of thermal envelope and technical systems, including on-site renewable energy production. The energy consumption is assessed for each scenario and the results are presented comparatively. Further, the global cost analysis is presented. The last part of the chapter presents the cost-optimal analysis of the proposed scenarios.

Chapter 7 summarizes the conclusions of the studies performed in this thesis.

The appendices contain supplementary information consisting in tables, graphs, geometry description and calculation sheets. Appendix A presents the thermal properties of the materials that compose the case study building envelope. Appendix B presents in detail the comparison between the simulated and measured energy consumption through comparative graphs plotted for each month. Appendix C contains the building surfaces coordinates as they were used to create the geometry of the building energy model. Appendix D contains the global cost calculation sheets for each scenario investigated, as well as the global cost reports.

2 RESEARCH METHOD

2.1 Energy efficient buildings concepts

Building norms and energy efficiency standards in buildings set minimum energy efficiency requirements for all new buildings. In many situations it is possible and cost-effective to build energy-efficient buildings much higher than minimum requirements, thus increasing long-term energy savings. At European and even global level, there are a number of types of buildings that tend to have a much higher energy efficiency than the minimum requirements imposed by national standards. This chapter presents energy efficient building concepts that are increasingly popular in the past years such as passive house, nearly zero-energy building, net zero-energy building.

2.1.1 Passive house

2.1.1.1 Definition and criteria

Passive houses are, as a general description, buildings where the desired interior thermal comfort can be obtained without the need for a traditional heating or cooling system. The concept was initiated as an energy efficient construction concept for residential buildings in Central Europe [38]. According to Passipedia – The Passive House Resource [38], the passive house should not be regarded as an energy standard but more as an integrated approach in building design, assuring a high level of thermal comfort. The exact definition provided is *"A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air."* [39], [40].

The first passive house project was developed in 1991 in Darmstadt, under the coordination of Wolfgang Feist. In 1996, Wolfgang Feist established the Passive House Institute, which is an independent research institute that had a continuous growth and development ever since, currently having interdisciplinary teams of employees [38]. The Passive House Institute had a leading position in the development of the passive house concept. The main activities were focused on research and development of construction concepts, building components, planning tools and quality assurance for highly energy efficient buildings.

Along with design strategies and recommendations, the Passive House Institute established a set of criteria to be achieved by a passive house [41] (Table 2.1).

Table 2.1 - Passive House criteria

Specific space heating/cooling energy demand	< 15 kWh/m^{2}y
Specific primary energy demand	<120 kWh/m^{2}y
Pressurization test result n_{50}	< 0.6 air changes per hour at a pressure of 50 Pascal
Overheating	During summer months, excessive temperatures may not occur more than 10 % of the time.

2.1.1.2 Principles, characteristics, design

In order to conform to the passive house criteria presented in Table 2.1, the passive house is assumed to follow several design principles and construction rules that lead to the low heating energy demand. Figure 2.1 illustrates the basic principles that guide the design of a passive house. We can see that it is not all related to the high quantity of thermal insulation. There are several other aspects to be considered: advantageous orientation, thermal bridges reduction, and good airtightness, mechanical ventilation with heat recovery, efficient windows glazing and frames [41].

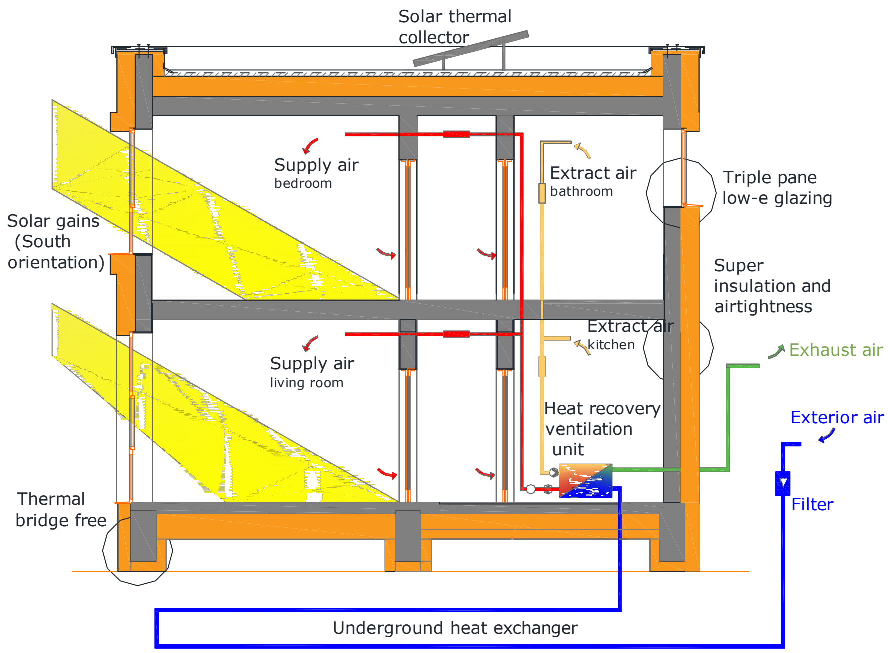


Figure 2.1 - Basic principles for passive house standard

The first step in the design of a passive house consists creating the building architecture and establishing the most advantageous orientation related to the site availability. A proper orientation is one of the key elements in a passive house because it can have a high impact on the heating and cooling energy need. During summer, the sun is higher in the sky than in winter, as it can be seen in Figure 2.2. Therefore, in passive house deign is recommended to have large facades with fenestration oriented to south. This allows the lower winter sun to provide heat gains in the building, while in the summer, the higher position of the sun allows shading through overhangs, shading devices, trees. Considering these facts, it is recommended that the building facades that have large fenestration surfaces to be south oriented and on the northern facades, the windows surfaces to be as small as possible. Besides the benefit of solar heat gains, having large windows properly oriented also provides natural light, reducing the energy consumption for Interior lighting.

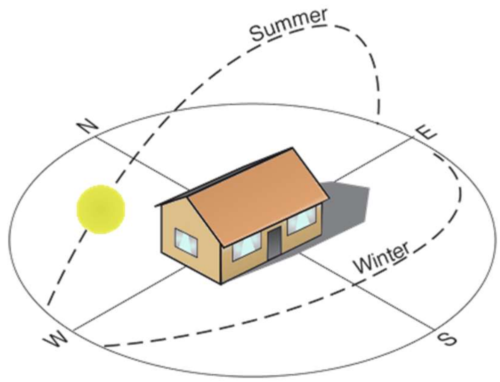


Figure 2.2 - Variation of the sun position in the sky in summer and winter [42]

Regarding the building shape and architecture, it is important that the ration between the envelope area and volume to be as low as possible. A compact building shape assures minimum heat losses through the building envelope. Buildings with a high ratio between envelope surfaces (A) and building volume (V) have a higher energy consumption than buildings with a lower envelope area reported at the same volume. Therefore, the more compact the building envelope, the easier and cost-effective it is to obtain a passive house. [43].

The building envelope represents all the construction parts of a building that separate the interior climate from the outdoor environment. In a passive house, the purpose is to design an envelope that assures minimum heat losses and maximum solar heat gains and internal gains during winter. The key elements in obtaining a highly efficient thermal envelope are [45]:

- *qualitative and thick thermal insulation*
- *thermal bridge-free design and construction*
- *reducing air infiltration by achieving an airtight envelope*
- *efficient windows and exterior doors*
- *solar heat gains optimization.*

Choosing the thickness and thermal properties of the insulation materials depends on the climatic conditions of the area where the house is constructed. The existing passive houses in Northern and Central Europe have envelope elements with thermal transfer coefficients (U-values) between 0.09 and 0.15 W/(m^{2}K). These U-values correspond to an insulation thickness between 250 and 300 mm, depending on the thermal conductivity coefficient [44].

Edges, corners, connections and penetrations of the building envelope must be carefully planned in order to avoid thermal bridges. The general rule in thermal bridge-free design is to reduce effect of thermal bridges to a limit that allows to neglect them in the energy balance of the building. The limit is related to the linear thermal bridge coefficient ψ. The effect of a thermal can be ignored if its linear coefficient ψ value is below 0.01 W/(mK) [38]. In order to verify if this criteria is fulfilled, all the relevant thermal bridges details have to be calculated. Nowadays, there are specialized software tools that allow an easy and accurate thermal transfer analysis for building details. Besides the thermal bridge-free characteristic, the envelope of a passive house must also be airtight. In a highly insulated building with qualitative and performant windows, air infiltration and uncontrolled air changes can have a great influence on the building energy balance. These aspects have to be considered in the design phase, through an accurate planning, and especially in the construction phase, when the risk of low quality execution might occur. An airtight envelope means and undisturbed and continuous layer of thermal insulation. Existing research shows that building airtightness is important for energy efficiency, thermal comfort and also indoor air quality [46], [47] and [48]. The measures that have to be considered in order to achieve an airtight and thermal bridge-free envelope are the following [45]:

- The thermal insulation layer has to enclose entirely the exterior surface of the building, without any loopholes and as far as possible it must have the same quality and thickness;
- Besides the insulation layer, it is recommended to use a sealing layer (foil placed at the interior side of the thermal insulation), which usually has a high resistance to vapour diffusion;
- The sealing layer must be continuous and well stretched. Infiltrations and air leakages cannot be avoided by overlapping multiple layers;
- Joints, overlaps and perforations of the thermal insulation layer must be reduced to minimum;
- All connections should be checked before applying the finishing;
- Infiltration measurements through a pressurization test (usually a Blower Door Test) in a construction phase that allows access to all joints and connections;
- Avoid construction elements that pass through the thermal envelope, such cantilevered structures, and balconies;
- As much as possible, the window frames will be covered by the thermal insulation layer.
- In passive houses, windows are an essential component because they influence both, the amount of solar heat gains the heat losses. In other words, windows must allow the penetration of solar energy as much as possible and, at the same time, energy losses must be minimum in the absence of sun. Thus, depending on the positioning of the windows, their dimensions and their quality, the energy performance of a house can vary significantly. According to the Passive House Institute, the heat transfer coefficient of the windows should not exceed 0.8 $W/(m^2K)$ [41]. The main features of windows used in passive houses are:
- triple glazed windows and low thermal conductivity spacers;
- high total solar energy transmittance, allowing solar radiation to penetrate through glass and contribute to space heating;
- a low-emissivity (Low-E) layer, placed on the interior surface of the exterior glass layer;
- gas filling in the spaces between the glass panes (argon or krypton) to help reduce the heat loss through the glass;
- insulated window frame.

Solar heat gains through windows must overcome the heat losses through windows in the heating season. In order to optimize and balance the solar heat gains with heat losses, the proper orientation is the key element. As mentioned earlier in this chapter, building facades with large windows have to be south oriented. Although this is advantageous during winter, during summer windows shading might be necessary in order to avoid overheating. However, the south-facing windows do not represent a major problem in terms of sun protection during summer. Research shows that the south-facing glazing have self-regulation feature in terms of sun protection. In the period when sun radiation is at its highest (summer), the sun is very high above the horizon, causing the incidence of sunlight on the south-facing glazed surfaces to make a sharp angle with these surfaces, and much of the solar radiation is reflected.

However, the shading features have a beneficial effect on the protection during hot summer days [45]. A special attention is needed for the windows that have east and west orientations. In this case, the sun radiation might penetrate the building in the morning and evening, when its position is lower. These windows need shading measures in order to avoid building overheating.

The Passive House Institute recommends that windows to be installed in the thermal insulation layer, at the exterior face of the wall. Studies and analyses show that the effect of the thermal bridges related to windows installation increases or decreases depending on the position in the wall thickness. Also, it is recommended that the window frame to be included in the walls insulation as much as possible.

Passive houses have as main objective, besides energy efficiency, to ensure a quality, healthy and comfortable indoor environment to its occupants. This objective can only be achieved if the indoor air is regularly exchanged with outdoor fresh air. In order to minimize the heat losses through ventilation, passive houses have mechanical ventilation systems with heat recovery. As seen in Figure 2.1, polluted air has to be extracted from kitchen, bathrooms and all rooms with significant air pollution and fresh air is to be supplied to the living room, bedrooms, and offices. The ventilation system will supply outdoor air and not recirculated air. Both, the fresh air and the polluted air will pass through a heat exchanger in which the fresh air will be preheated with the energy from the polluted air (Figure 2.3). In addition to the heat exchanger, earth tubes can be used to preheat the outdoor fresh air. During winter, the ground has a higher temperature than the outdoor air. During summer, the ground has temperatures between 8°C and 12°C depending on the depth. Therefore, it is effective to preheat or precool the fresh air by using ducts buried in the ground.

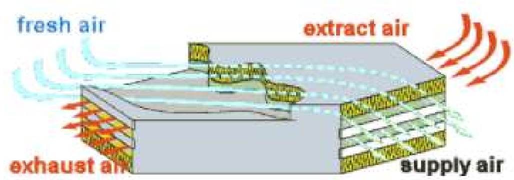


Figure 2.3 - Heat exchanger counter flow [38]

The passive house main principles have the aim at reducing as much as possible the energy need of a building, by using design techniques, optimizing internal heat gains, heat recovery. Due to its highly energy performance and reduced energy need, a passive house does not require the use of a conventional heating or cooling system. Among the most used systems are the heat pumps that can have reversible cycle to be used for cooling during summer time. For domestic hot water preparation, besides the heat pumps, solar panels are generally used.

2.1.2 Nearly zero-energy buildings (nZEB)

2.1.2.1 Nearly zero-energy building definition and principles according to EPBD

As mentioned in the introductive section of this thesis, within the recast of the EPBD, according to Article 2 "a 'nearly zero-energy building' is a building that has a very high performance, as determined in accordance with Annex I. 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" [21]. In Annex I of the EPBD recast in written that "The energy performance of a building shall be determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs." [21]. The EPBD also introduces the ‚cost optimal' or ‚cost-effective' notions to be considered when developing nearly zero-energy buildings.

Based on the above statements, Member States of the European Union are required to develop National Plans to increase the number nZEB. Article 9 of EPBD states that the national plans must include nZEB definition reflecting national, reginal or local conditions, and a primary energy use boundary condition. Thus, the EPBD leaves open for each Member State the possibility to define and detail the 'very high performance' and 'a very significant extent by energy from renewable sources' by considering their specific conditions and national context [50].

2.1.2.2 Nearly zero-energy building definitions within EU Member States

In the last years, progress has been made among the EU Member States related to nZEB definitions development. In 2016, the European Commission published a report that summarizes the national plans and progress for nZEB definitions and implementation in the EU Member States [50]. The mentioned report says that more than 50% of the Member States have established a nZEB definition that give a numerical indicator for primary energy use. Several Member States also give a value for the share of energy to be covered from renewable energy sources. The definitions are specific for residential and non-residential buildings and include subcategories such as single family houses, collective family buildings, office buildings, educational buildings etc. Most of EU Member States consider in their plans both new and retrofitted buildings. In their definitions, most of the Member States provide a numeric indicator for primary energy in kwh/m^2/y not to be exceeded by nearly zero-energy buildings [50]. In Romania, these values range depending on building type and climate zone between 93-117 kwh/m^2/y for residential new buildings and 50-102 kwh/m^2/y for non-residential new buildings. The limit is higher when it comes to retrofit buildings: 120-230 kwh/m^2/y for residential buildings and 120-400 kwh/m^2/y for non-residential buildings [50]. In other EU countries, the definitions related to primary energy numerical indicator are: 20 kwh/m^2/y for residential buildings and 25 kwh/m^2/y for non-residential buildings Denmark; 33-41 kwh/m^2/y for residential new buildings in Croatia; 50-72 kwh/m^2/y for residential new buildings in Hungary; 30-75 kwh/m^2/y for residential new buildings in Sweden and 30-105 kwh/m^2/y for non-residential new buildings; approximately 44 kwh/m^2/y for residential new buildings in United Kingdom; 100 kwh/m^2/y for residential new buildings and 125 kwh/m^2/y for non-residential buildings in Cyprus [50].

The implementation of renewables is different within the Member States. However, the most preferred solution include on-site generation such as photovoltaics, solar thermal, air source heat pumps, ground source heat pumps, biomass, heat recovery, passive solar, passive cooling [50]. Some Member States have defined the percentage of renewable energy to cover the energy need of nZEB. Percentages vary from 10%- 25% (Romania, Cyprus) up to 56 % (Denmark) and 60% (Germany) [50].

As mentioned earlier, the authorities in Romania provide the definition for nZEB, in line with the Romanian economic and climatic context. All the information related to the characterization of nZEB in Romania are presented in the document entitled ‚Plan For Increasing the Number of Nearly Zero Energy Buildings – Romania' [30]. The definition refers to both energy performance (through primary energy numerical target) and share of energy from renewable energy sources (percentages). The primary energy numerical target is defined for different types of buildings from residential and non-residential categories, and for the five climatic zones of Romania. In order to comply with the second part of nearly zero-energy definition in the EPBD, renewable energy sources (non-fossil) must cover at least 10% of the calculated total primary energy of the building. Renewable energy sources must be used according to their technical, economic and environmental feasibility and can be located either on-site or nearby. In existing buildings where major renovation works are being carried out, the maximum admissible level of primary energy from conventional sources shall be met to the extent where the investments are technically and economically justified on the basis of a cost-effectiveness analysis during the normal operating building.

2.1.2.3 From passive house to nearly zero energy building

The nZEB is generally defined by the EPBD [21] as a building that has a very low energy demand that is largely covered by renewable energy generated on site or nearby. As deducted from this definition, the energy efficiency represents the primacy in achieving a nearly zero energy consumption, because renewable energy is not available in the same amount and variety for every location [49].
EPBD's main objective is to reduce the energy consumption related to buildings, considering the local climate condition, particularities of the economic situation and cost effectiveness and indoor climate. Studies performed by the Passive House Institute prove that the passive house concept, which is nowadays a well-known building standard with numerous implementations worldwide, can be a basis in defining the nZEB [49]. Furthermore, in a study performed by the Passive House Institute it was concluded that the passive house is a solution for implementing EPBD [51]. It can easily be stated that nZEB standard can be achieved by applying the passive house design principles and afterwards implementing renewable energy production systems to cover the remaining energy demand (Table 2.2). It should not be concluded that a passive house is necessarily a nZEB building or vice versa but a passive house can be a nZEB and vice versa.

Table 2.2 - Synthesis of the passive house characteristics and nZEB perspective

<table>
<tr><td rowspan="9">Nearly zero-energy building</td><td rowspan="9">Passive house</td><td colspan="2">Measure/solution</td><td>Recommendation</td></tr>
<tr><td rowspan="4"><u>Thermal envelope, very good thermal insulation</u></td><td>Thermal insulation for opaque envelope elements</td><td>U-values≤0.15 W/(m^{2}K)</td></tr>
<tr><td>Windows and exterior doors</td><td>U-values≤0.80 W/(m^{2}K)</td></tr>
<tr><td>Thermal bridges</td><td>ψ≤0.01 W/(mK)</td></tr>
<tr><td>Air tightness</td><td>Number of air changes per hour n50≤0.6 h^{-1}</td></tr>
<tr><td rowspan="4"><u>Heat recovery/ energy efficient heating system/ indoor air quality</u></td><td>Ventilation with heat recovery</td><td>Heat recovery efficiency ≥ 75%</td></tr>
<tr><td>Reducing heating energy demand</td><td>Preheating the fresh air using a subsoil heat-exchanger</td></tr>
<tr><td>Efficient heating systems</td><td>Heat pumps, biomass etc.</td></tr>
<tr><td>Ensuring air quality through ventilation rate</td><td>Min. 30 m^3/per/h</td></tr>
</table>

Domestic hot water preparation using efficient systems		Solar collectors, heat pumps
Solar heat gains	Performant windows	
	Orientation	Large glazed surfaces facing south, avoiding north oriented windows
Use of energy efficient electrical equipment		
Complex design of the building using Passive House Planning Package	Heating energy demand	15 kWh/(m^2year)
	Heating load	10 W/m^2
	Total primary energy	120 kWh/(m^2year)
Implementation of systems for producing energy from renewable sources to cover the energy demand of the house		

2.1.3 Net zero-energy buildings

Historically, the concept of ”net zero energy” came from the intentions of achieving zero-heating energy demand by means of solar heat gains [130]. Currently, the most known approach of ″net zero energy″ consists in the annual energy balance between the energy imported from the grid and the energy exported to the grid. According to the existing research, the net zero energy building (NZEB) is a complex building concept, mainly identified in buildings that have low energy needs that can be supplied with technologies that use renewable energy sources [129]. Depending on the method through which the energy use is accounted, there are several ways a NZEB can be defined [129]. The four definitions are [129]:

- **Net-Zero Site Energy -** implies a building which, on a yearly basis, it produces at least as much energy as it consumes, when accounted for at the site.
- **Net-Zero Source Energy –** a building that, on a yearly basis, produces at least as much energy as it consumes, when accounted for at the source. In this situations, primary energy conversion factors must be used to multiply the imported and exported energy.
- **Net-Zero Energy Cost –** in this case, the amount of money paid for the energy purchased from the grid is less than or equal to the amount of money repaid for the energy exported to the grid.
- **Net-Zero Energy Emissions –** this type of building produces at least as much emission-free renewable energy as it uses from emission-producing energy sources.

As we saw in the previous section and can be observed in this section, is that the idea of nZEB, earlier presented, is not far from the net-zero energy building concept. Researchs agree that even though a building might be designed to be NZEB, in certain circumstances, this might not happen every year, thus becoming a near NZEB [129].

2.2 Primary energy

Primary energy (PE) is defined as the energy that has not suffered any conversion of transformation process. The conversion of final energy of a building (electricity, natural gas, wood etc.) to primary energy is made by means of a primary energy factors, which indicates the amount of primary energy used to provide a unit of end use energy.

The framework and methodologies established through EPBD requires that the energy performance of buildings to be expressed in terms of primary energy. Primary energy can be renewable primary energy and non-renewable primary energy. The total primary energy of a building includes both.

The nZEB definition includes two aspects to be considered: energy consumption from non-renewable sources and share of renewable energy from the total primary energy consumption. Thus, the characterization of nZEB expressed in terms of primary energy, as required by the EPBD, is to be made with the use of two indicators: primary energy indicator and share of renewable energy from the total energy consumption. According to the technical definition of nZEB presented by Kurnitski [123], the primary energy indicator is calculated based on the sum of all imported and exported energy (calculated using national level primary energy factors) and useful floor area. The formula for primary energy calculation is presented in Equation 2.1 and for primary energy indicator in Equation 2.2.

$$E_{P,nren} = \sum_i (E_{del,i} \times f_{del,nren,i}) - \sum_i (E_{exp,i} \times f_{exp,nren,i}) \qquad \text{Eq. 2.1}$$

$$EP_P = \frac{E_{p,nren}}{A_{net}} \qquad \text{Eq. 2.2}$$

Where:
EP_P – primary energy indicator in kWh/m^{2}year
$E_{P,nren}$ – non-renewable primary energy in kWh/year
$E_{del,i}$ – delivered (imported) energy on site or nearby fo energy carrier i, in kWh/year
$f_{del,nren,i}$ – non-renewable primary energy factor for the delivered energy carrier i
$E_{exp,i}$ – exported energy on site or nearby for energy carrier i, in kWh/year
$f_{exp,nren,i}$ – non-renewable primary energy factor for the delivered energy compensated by the exported energyfor energy carrier i (is equal o the factor of the imported energy, if not definer in other way)
A_{net} – useful floor area in m^2

The renewable energy share is to be determined based on total primary energy consumption. The total primary energy consumption is calculated based on all energy consumption of the building, including solar thermal, electricity from photovoltaic panels and/or wind, renewable energy from heat pumps etc. As presented in [123], the following formula (Eq. 2.3) is to be used for the renewable energy ratio calculations:

$$RER_P = \frac{\sum_i E_{ren,i} + \sum_i (E_{del,i} \times (f_{del,tot,i} - f_{del,nren,i}))}{\sum_i E_{ren,i} + \sum_i (E_{del,i} \times f_{del,tot,i}) - \sum_i (E_{exp,i} \times f_{exp,tot,i})} \qquad \text{Eq. 2.3}$$

Where:
RER_P – renewable energy ratio based on the total primary energy;
$E_{ren,i}$ – renewable energy produced on site or nearby for energy carrier i [kWh/year]
$E_{del,i}$ – delivered energy on site or nearby for energy carrier i [kWh/year];
$f_{del,tot,i}$– total primary energy factor for the delivered energy carrier i;
$f_{del,nren,i}$ – the non-renewable primary energy factor for the delivered energy carrier i;
$E_{exp,i}$ – exported energy on site or nearby for energy carrier i [kWh/year]
$f_{exp,tot,i}$ – total primary energy factor of the delivered energy compensated by the exported energy for carrier i.

2.3 Methods in buildings energy modelling

As stated in the previous chapters, the design and construction of energy efficient buildings and use of renewable energy plays an important role in the transition to a more sustainable energy future. On one hand, implementing energy efficiency measures in the existing building stock has limitations (architectural, functional or economic reasons). On the other hand, new buildings that are designed and constructed from now on have a great potential of energy efficiency and optimization. The use of building energy simulations models is suitable for both, the design of energy efficient buildings and design of renovation solutions for the existing building stock and allows an accurate and detailed calculation of the building energy need in order to provide comfortable and healthy indoor environment under the effect of external factors such as weather, occupant behaviour, airtightness and infiltration. Although the main interest in using whole building energy simulation tools is in the design phase, in the last years, simulations have become increasingly significant in post-construction phases of the buildings. Currently, BEM is increasingly used throughout the life cycle of a building for commissioning, operation and optimization [53], [72]. Moreover, with the use of data from monitoring systems related to energy use, indoor environment parameters, internal heat gains, calibrated simulations can be performed. This plays a significant role in order to reduce the gap between the actual energy performance of the building and the predicted through simulation. Post-construction calibrated simulations can lead to an optimized energy use of the building and also can identify the building control parameters that can reduce the energy consumption of a building. In this chapter, a review on building energy modelling is presented, emphasizing the uncertainties related to modelling along with calibration procedures developed by different researchers.

2.3.1 Whole building energy modelling

Building energy modelling (BEM) represents the computational simulation, performed to estimate and evaluate the energy consumption of a building. A building energy model is created in a simulation tool that calculates the thermal load and energy consumption of a building. BEM represents the most effective way of predicting the energy use of a building and is extremely useful when different design aspects and systems are under question, in order to determine the most efficient solution [52]. The energy performance of a building can be analysed by means of steady-state or dynamic simulation. Regardless of the used simulation type, the steps of building energy modelling are mainly the same (Figure 2.4). Depending on the type of simulation and used software, the volume of input data and complexity and accuracy of the results might vary significantly. The process of whole building energy modelling (BEM) for dynamic energy simulations is a complex activity that requires detailed information related to the building envelope, systems and operation. Usually, building energy models are used in the design of new buildings and design of renovation projects to predict the energy need of the building based on the design information related to building architecture, heating, ventilation and air conditioning (HVAC) systems. Nevertheless, the interest in building energy modelling in post-construction phases has gained much interest and is frequently used to optimize the building operation and for savings determination [73].

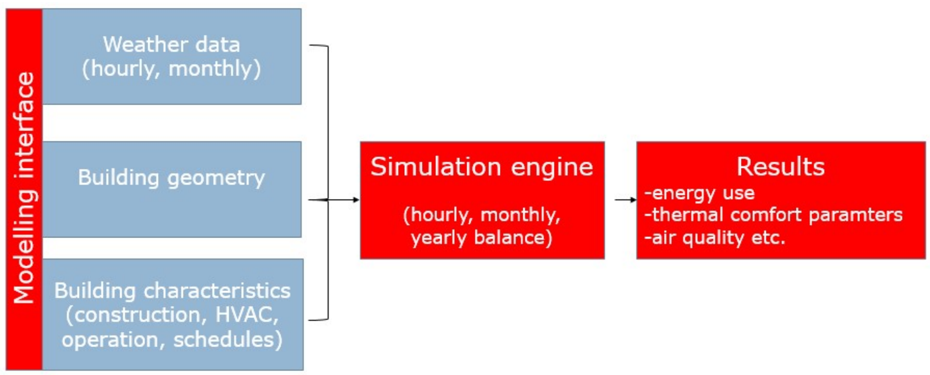


Figure 2.4 - Whole building energy modelling steps

The amount of data necessary for creating an energy model for an existing building is quite high and providing it with a high level of accuracy is the key in achieving a reliable and calibrated simulation. The Measurements and Verification Guidelines [78] presents the categories of data that are typically required in building energy simulation (Table 2.3).

Table 2.3 - Required data for accurate building energy model [78]

Category	Details
Utility bill records	A minimum a 12 consecutive months of utility bills
Architectural, mechanical and electrical drawings	As-built drawings
Site survey data	Comprehensive equipment and system data: - HVAC systems capacities, characteristics, design flow rates, ventilation airflow rates, type of controls, efficiencies, operating schedules etc. - HVAC system controls – temperature set-points - Lighting systems characteristics and schedules - Building occupancy - Infiltration rates – measurements if possible - Building envelope and thermal mass – dimensions, thickness of envelope elements, shadings from nearby objects etc.
Short-term monitoring - spot measurements of specific equipment	- Recorded building system data over time Lighting power, plug load, HVAC equipment
Operator interviews	Building occupants or operators can provide a major part of the information mentioned earlier.
Weather data	For calibration, representative site weather data ate required.

2.3.2 Uncertainties in building energy modelling

Through building energy modelling and analysis, specialists can accurately predict building energy consumption [54]. However, many experiences show that there are considerable differences between the predicted energy consumption and real measured energy consumption. According to several studies, buildings do not have the same energy performance in reality as it is predicted in the design phase [73], [74], [75]. When compared to measured values, building energy simulations generally underappreciate or over appreciate the energy consumption of a building [55]. Some studies show that there are several reasons that contribute to the differences between estimated and actual energy consumption, such as occupancy patterns, user behaviour and internal loads [56], [57], and [58].

Buildings can be seen as a complex system that has several sub systems that interact and influence the behaviour of the entire system. In order to model the complexity of a building and the interaction of its components, building energy models require detailed and accurate parameters to be defined as input data [53].

In order to accurately create a building energy model for dynamic simulation, one must define the building geometry and characteristics, HVAC system, internal heat gain sources (occupancy, lighting, electric equipment) and weather conditions. Many of the input parameters have theoretical values that might differ from reality and is impossible to have direct measurements for each parameter. The complexity of a building when it comes to creating a building energy model comes from the multitude of parameters including material properties, infiltration, uncontrolled ventilation, HVAC specifications and operation, occupancy and occupancy schedules, temperature set points, equipment and lighting schedules, weather etc. All these parameters are vast sources of a building energy model uncertainty [59].

According to the publication of De Wit and Augenbroe [60], the types of uncertainties in a building energy model can be described as:

- **Specification uncertainty** – caused by an incomplete or inaccurate specification of the building or systems that are modelled;
- **Modelling uncertainty** – comes from simplifications and assumptions of complex physical processes. The modelling uncertainties can be associated to the modeller (Ex: thermal zone division of the building) or can be hidden within the software (calculation algorithm);
- **Numerical uncertainty** – errors in the discretization and simulation;
- **Scenario uncertainty** – outdoor weather conditions and building operation and occupancy schedules;
- A classification of uncertainties by their source is presented by Ramallo-González [61] in a doctoral thesis, as it follows:
- **Environmental –** uncertainty in weather predictions;
- **Workmanship and quality of building elements** –poor execution (infiltration, thermal bridges) or false thermal properties of the construction materials: conductivity of insulation layers, U-values for windows.
- **Behavioural –** this includes all the parameters that are related to occupant behaviour – uncontrolled opening of windows and doors, temperature set points, lighting schedules, cooking habits etc.

  Heo [80] also made a classification of uncertainties on source categories that is similar with the previous two and are presented in Table 2.4 [80].

Table 2.4 - Categories of uncertainty sources in building energy models [80]

Category	Factors
Scenario uncertainty	Outdoor weather conditions Building usage/occupancy schedules
Building physical/operational uncertainty	Building envelope characteristics Internal gains HVAC systems Operational and control settings
Model inadequacy	Modelling assumptions Simplifications in the model algorithm Ignored phenomena in the algorithm
Observation error	Metered data accuracy

Norford et al. [62] made a research related to the differences between the estimated energy consumption by using BEM in the design phase, and actual measured energy consumption in the operation phase of the building. According to their study, the building energy model underappreciated the energy consumption by 150% and 64% of the underestimation was due to different than expected occupant behaviour and use of electronic equipment. Other causes identified by Norford et al [62] are related to the equipment performances not corresponding to the manufacturer's specifications and HVAC operation schedules. In their study, Norford et al. [62] managed to calibrate their building energy model and foretell the energy consumption within 94% of the measured values. The calibration procedure included occupant behaviour and HVAC operation effects on the energy consumption [52], [62].

In order to better understand how different changes in the parameters of the building components affect the overall energy consumption of a building, several studies have been made over time. These studies emphasize the sensitivity of the results to the change of different parameters. In a study made by Wang et al. [63], the authors investigate the uncertainties in energy consumption of a building due to actual weather and building operation schedules on the energy consumption of medium size office buildings. On one hand, the results show that the influence of yearly weather fluctuations have a relatively small impact on the energy consumption, ranging -4% to 6% changes for different scenarios. On the other hand, changes in the building operation parameters have a greater impact on the energy consumption, uncertainties ranging from -27.7% to 79.2%. Martinaitis et al. [64] studied the influence of occupants on the energy demand of an energy efficient house. They concluded that the use of different occupancy profiles results in changes on the total building energy consumption and thus, the use of actual occupancy information in building simulation improves the accuracy of the results [64]. In the study made by Yang et al. [65], personalized occupancy profiles were used in the building energy simulation. The results show a reduction of 9% in energy consumption when compared to the case of conventional profiles.

2.3.3 Calibration of building energy models

Calibrating a building energy model is the process of adjusting or 'tuning' the various input parameters in a model in order to achieve predictions of energy use that closely match the measured energy use of a building [53], [71]. In various researches, this process is called calibrated simulation [73], [76]. A calibrated simulation is important for building operation and control strategies optimization and for further predictions of energy savings [76]. An accurate estimation of energy savings and energy performance through a calibrated simulation allow building owners to obtain higher levels of energy savings and reduced variability of savings [77]. Also, a calibrated simulation of a building energy model represents a way of evaluate other potential energy savings [78], such as building operation or behaviour of the occupants. The International Performance Measurements and Verification Protocol (IPMVP) [79] provides a series of techniques for verifying the energy performance of new buildings. IPMVP [79] introduces Option D that involves whole building calibrated simulation, which is a building simulation calibrated with building measured energy data. In order to apply Option D, the building energy model must reflect the as-built building. Also, the building energy model must be adjusted so that it reflects real operation conditions (schedules and occupancy). Another important adjustment is the weather and on-site weather measurements can be used. After the mentioned adjustments are made, the simulation is ran and the energy consumption results are compared with the real measured energy use of the building [79].

Although the calibration of building energy models is a topic of great interest amongst researchers in the field of building energy performance [68-70], currently there is no common and certified guideline and methodology for this process [76]. Therefore, calibrating a building energy model is a process that mostly depends on the user's knowledge and experience [76].

As presented in the previous subchapter, there are a lot of uncertainties and interacting variables that can affect the accuracy of the simulation results in a building energy model. The use of building energy performance simulation in the operational phase of a building can lead to the detection of potential failures and performance optimization, when comparing measured data with simulation results [66]. This might reduce the actual energy use [67] and also the discrepancy between actual measured and predicted energy use.

Raftery e al. [68] presents a methodology for calibrating a whole building energy model to hourly energy consumption data, using measured lighting and plug load data in the simulation at hourly intervals. The results prove the effectiveness of the method, the simulated energy consumption being close to the measured energy consumption. However, the authors acknowledge that the calibration of a building energy model to a high level of detail takes significant time and resources. Kim et al. [56] developed a method for building energy models calibration by using operation schedules derived from measured electrical energy consumption data. The results show a significant improvement on the accuracy of the building energy model simulations. Paliouras et al. [69] performed the calibration of a building energy model using measured indoor environment data for temperature, relative humidity and carbon dioxide concentration. The model was considered calibrated after 10 iterations and refining the input data of the ventilation system, window opening and solar shading devices. According to Royapoor et al. [70], the accuracy of building energy models can be improved nowadays due to the accessible monitoring equipment. In their research paper [70], Royapoor et al. examine the precision of a building energy model by using calibrated environmental sensors and a weather station. In this situation, the energy model of the building predicted the hourly air temperature in a year with a precision of ±1.5ºC for 99.5% of the time and ±1ºC for 93.2% of the time. They concluded that the calibration of an Energy Plus building energy model can lead to more accurate predictions related to energy use and environmental parameters [70].

Coakley et al. [59] made a review of existing methods for correlating building energy simulation results to real metered data that present the current approaches related to model development and calibration. According to Coakley et al. there is no explicit standard for calibration criteria and the existing guides only provide acceptable error ranges. In general, the process of building energy model calibration can be manual or automated [59], [53].

2.3.4 Assessing calibration performance

A building energy model is considered calibrated when the differences between simulated and measured are below the accepted calibration tolerances. Currently, the validation of a building energy simulation model is based on standardized statistical indices that represent the performance of a model [81], [59]. The Coefficient of Variation of the Root Mean Square Error (CVRMSE) and the Normalized Mean Bias Error (NMBE) are the calibration metrics and are defined by equations 2.4 and 2.5 [56]:

$$NMBE = \frac{\sum_{i=1}^{n}(y_i - \tilde{y}_i)}{n \times \bar{y}} \times 100 \qquad \text{Eq. 2.4}$$

$$CVRSME = 100 \times \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \tilde{y}_i)^2}}{\bar{y}} \qquad \text{Eq. 2.5}$$

In equations 2.1 and 2.2 the following parameters were used:

- n is the number of measured data points;
- $\tilde{y}_i$ is the simulated result at time i;
- y_i is the measured data at time i;
- $\bar{y}$ is the average value of y_i ;

According to [81] the calibration can be performed on an hourly or monthly time basis. When monthly time basis is considered, the number of data points is 12, and when hourly calibration is assessed n has the value of 8760 points corresponding to the number of hours in a year. Building energy simulations can be called calibrated if they meet the accepted criteria proposed by ASHRAE Guideline 14 [81], presented in Table 2.5.

Table 2.5 - Accepted calibration tolerances for building energy model calibration [78], [81]

Calibration Type	Statistical indices	Acceptable value
Monthly	NMBE	±5%
	CVRMSE	15%
Hourly	NMBE	±10%
	CVRMSE	30%

2.3.5 Available energy simulation tools

Along the years, building energy modelling has improved and expanded to a level where it can simulate the actual structure and materials of a building, complex HVAC systems, energy saving techniques (such as shading devices for windows) and renewable energy systems [74]. Currently there are several available energy simulation tools that have different levels of complexity and capabilities. The most common and widely used are Energy Plus [82] and TRNSYS [83]. EnergyPlus is a whole building energy simulation software that is used to model energy consumption in buildings (heating, cooling, ventilation, lighting, hot water use) and process loads, on an hourly basis. The targeted audience of the software are design engineers or architects that want to size heating ventilation and cooling (HVAC) equipment, perform energy rehabilitation of buildings studies, optimize energy performance, perform parametric studies and investigate different building operation scenarios or different energy efficiency measures on the same building. Energy Plus program was developed in 2001 as an innovative software out of two building energy software simulations: DOE-2 and BLAST, developed by the United States Department of Energy (DOE) and Department of Defence (DOD) [84]. The simulation software EnergyPlus is in fact a simulation engine that was designed to be a component in a complex software that includes a graphical user interface to define the building. Although, there are several user friendly graphical interfaces available to be used with EnergyPlus, this software can be run stand-alone without such an interface. The process of creating a building energy model in EnergyPlus, without the use of a graphic interface, can be more difficult compared to other exiting software [85]. The software is freely available worldwide and also provides climate date for multiple locations all over the globe.

The TRNSYS software, with the complete name Transient Simulation Software, was developed more than 35 years ago. TRNSYS is a graphically based software used to simulate the behaviour of transient systems. The software has two components: the engine that reads and processes the input file and an extensive library of components. Among the system's applications, the most relevant are: central plant modelling, building simulation, solar thermal processes, ground coupled heat transfer, geothermal heat pump systems, optimization, coupled multizone thermal/airflow modelling etc. This software has a component-based approach, referred to as 'Types'. A 'Type' can have a simple component, such as a pump or pipe or it can be a multi-zone building model [85].

Another available building simulation software is WUFI Passive, which was developed by Fraunhofer IBP in collaboration with Passive House Institute in the United States. This tool is a user-friendly software, developed to improve the design process of passive houses. WUFI Passive combines passive building energy modelling with hygrothermal analysis [86]. With this tool, a double analysis of a building can be performed based on the same building model:

- Monthly energy balance – for the design and verification of buildings meeting the passive house criteria based on EN 13790 [87].
- Dynamic building simulation.

2.4 Building monitoring systems

Implementing a monitoring system in a building represents a way of evaluating the real performances of a building, which is an important aspect to be considered when dealing with new technical solutions and high expected energy performance. The data from monitoring allows the analysis of the building's real energy consumption and energy performance characteristics. Energy savings in a building can be increased if one can locate when and where exactly the energy consumption occurs [89]. There are various drivers related to the implementation of monitoring systems in buildings but the most representative ones are: improvement of the building energy management; identifying and obtaining potential energy and cost savings; verify the design [94].

The International Energy Agency published a report that presents the Measurement and Verification Protocol for net zero energy buildings [92]. The report aims on guiding the design, implementation and data assessment for net zero energy buildings monitoring. Table 2.6 contains the relevant steps to be followed when dealing with net zero energy building monitoring [92].

Table 2.6 - Relevant steps for building monitoring process [92]

Measurement and Verification Protocol	1. Building data collection 2. Monitoring boundaries 3. Metrics and relevant data 4. Frequency and duration of measurements 5. Suitable sensors and data acquisition system 6. Planning of the monitoring equipment and installation 7. Definition and implementation of data post-processing 8. Definition of standard reporting

Capozzoli et al. [90] uses data from the monitoring campaign of two nearly zero-energy buildings to assess the real operational parameters of the buildings in order to perform 'tailored' calculations, using both quasi-steady-state and hourly model. The monitoring system presented in [90] collects data related to energy consumption and indoor environment and allows real-time visualization of the monitored parameters. The monitoring campaign was conducted for the periods 2010-2011 and 2011-2012. Capozzoli et al. [90] concluded that even though the monitoring process is a post-construction activity, it can help detect operational or technical issues that lead to a lower than expected energy performance.

Zhao et al. [89] presents the structure of a monitoring system platform implemented in a building located in a climate with extreme temperatures for summer and winter. The monitoring system presented in [89] consists of an electrical power system and components for measuring the quantity of heat and cold provided by the air conditioning system. Zhao et al. propose a method of error analysis of sensors meters as a first step to be made when developing an energy consumption monitoring platform.

The Measurements and Verification Guidelines [78] the use and installation of monitoring system as a way to track and assure energy savings persistence in buildings. According to [78], an accurate performance monitoring leads to the optimization of the energy conservation measures implemented in a building.

Garcia et al. [91] proposes a framework to help the improvement of energy efficient behaviour through 'activity and context monitoring'. The system recommended in [91] identifies the pattern in the user behaviour related to energy consumption and promotes a more efficient use of energy. The results show that such a system can lead to energy savings between 17% and 22%. However, the authors acknowledge that the installation of such a system in residential buildings is expensive at the moment.

Raftery et al. [93] presents investigations performed on energy monitoring systems in multiple case study buildings. The research concluded that the energy monitoring system can contribute to identify energy saving possibilities. Also, the authors emphasize the issues encountered with energy monitoring systems such as sensor specification and installation and data quality.

Ahmad et al. [94] published a research paper in which is presented a state-of-the-art in building energy and environmental monitoring, along with its advantages and limitations. The authors present monitoring technologies and their principle of functioning, types and costs for various meters and sensors. The authors appreciate that nowadays there are multiple solutions for metering equipment that provide accuracy, robustness and data storage. The available technology allows the development of low cost metering and monitoring solutions for homes through wireless area networks. Ahmad et al. [94] concluded that the selection of the appropriate monitoring solution is a challenge and depends on various factors: accuracy, costs, availability, communication protocol etc. When it comes to policies and regulations related to building monitoring systems, Ahmad et al. appreciate that there are only a few countries that address the need of monitoring technologies in buildings [94].

2.5 Reviews on the occupant behaviour effects on energy consumption

In the previous subchapters, remarks were made related to discrepancies between simulated and real energy consumption of buildings, advances in building energy models calibration and building energy monitoring. Several authors concluded that the building operation and the behaviour of its occupants represents a major source of uncertainty when predicting the energy need of a building [62], [63] and [64]. This situation derives from the fact that the real operational parameters of the building (temperature set point, ventilation rates, lighting, electric equipment plug loads etc.) are far from the scenarios considered in the design phase.

Fabio et al. [95] investigated different occupant behaviour scenarios and building automation effects in a high energy performance building. The study analysed two different user behaviour scenarios defined as „standard lifestyle'' and „sustainable lifestyle''. The authors concluded that a combination between a sustainable lifestyle with conscious users and automation of building operation can lead to considerable energy savings. Andersen et al. [96] tested several models of occupant behaviour against measurements for five apartments. The authors acknowledge that although the simulated and monitored values are in the same ranges, the models are unable to generally predict the actual indoor environmental conditions. Also, in order to have a reliable building energy performance prediction, one must include realistic interactions between the occupants and the building (thermostats, window openings, shadings etc.) [96]. A study made by Hong et al. [97] shows the advances and issues related to occupant behaviour modelling and its impact on building energy consumption. The study encompasses methods to monitor and collect data on occupant behaviour, occupant behaviour models and the implementation of the models in building simulation tools.

Yu et al. [98] proposed a methodology for improving the occupant behaviour in residential buildings based on data mining techniques, through which the energy inefficient comportment of the occupants is detected. Thus, the behaviour that needs to be improved in order to reduce energy consumption is identified. Using this methodology, the awareness of the occupants on the energy saving potential related to their comportment can increase and can also represent a strong motivation for them to adapt their everyday activities accordingly [98].

Although in theory it is proven that an inefficient user comportment leads to a higher energy consumption, in practice most of the people do not give the deserved importance to this aspect. A possible approach that can motivate people on becoming energy efficient users of their buildings might lay in performing economic analyses on different user behaviour scenarios, to see just how much the operation of a building can modify the yearly costs on energy. Moreover, life cycle cost analyses for different user behaviour scenarios can show how different user comportment can influence the energy and economic performance of a building throughout its life span.

2.6 Energy efficiency and economic analysis

2.6.1 Cost optimal methodology

Along with the recast on the EPBD and nZEB requirements, a methodological framework for determining economical aspects related to the energy performance of buildings was established. The framework requires to the European Union Member States to determine the energy performance of buildings and connect it to the economic aspects with the purpose of identifying cost optimal solutions.

Thus, Directive 2010/31/UE introduces the "cost optimal" or "cost-effective" notions to be considered when developing nearly zero-energy buildings. In Article 2 paragraph 14 the ‚cost-optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where:

- the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced), where applicable, and disposal costs, where applicable; and
- The estimated economic lifecycle is determined by each Member State. It refers to the remaining estimated economic lifecycle of a building where energy performance requirements are set for the building as a whole, or to the estimated economic lifecycle of a building element where energy performance requirements are set for building elements." [21].

In 2012, the Delegated Regulation no. 244 [101] was published as guidelines for calculating cost-optimal levels of building performances. This guideline establishes the steps that need to be followed in cost-optimal analyses, as follows:

1. ***Definition of reference buildings***, which has to be made for several representative buildings categories such as single-family buildings, office buildings and multifamily buildings;
2. ***Identification of the energy efficiency measures***, which includes packages composed of envelope solutions, technical systems and renewable energy.
3. ***Calculation of primary energy consumption*** for each energy efficiency package using the primary energy conversion factors that are established at national level. Prior to the primary energy calculation, the energy performance of the building is determined in terms of end use energy consumption for heating, cooling, and ventilation, lighting and domestic hot water.
4. ***Global cost calculation*** is performed in terms of net present value for each energy efficiency package applied to the reference building. The categories of costs included in global cost calculations are: initial investment, running costs, energy costs and disposal costs (if applicable).
5. ***Sensitivity analysis*** with the purpose of identifying the effect of discount rate on the cost-optimal calculations.
6. ***Derivation of cost-optimal level of energy performance***. This step consists in comparing the global cost and primary energy of the different energy efficiency packages. If two or more solutions have the same global cost but different energy performance, the solution having lower energy consumption is preferred.

In Romania, some studies have already been made with regard to the nZEB implementation. In a study made by BPIE [99], nZEB solutions were proposed for single family houses, multifamily houses and office buildings. Also, the Ministry of Local Development and Public Administration, published a document where cost-optimal analyses were performed for several building categories [30].

In Europe, several other studies on cost-optimal methodologies applied to different types of buildings were performed. A study made by Becchio et al on cost-optimal solutions for a single family house, found as cost-optimal an energy efficiency package which includes a medium level of thermal insulation, solar collector shading systems, condensing gas boiler for heating, solar collectors, direct expansion cooling system and a small size photovoltaic plant [100].

2.6.2 Global cost methodology

According to Delegated Regulation no.244/2012 [101], the calculation of the global cost is performed considering the following categories of costs:

- *Initial investment cost C_I;*
- *Annual costs C_a (energy costs, operational costs, maintenance costs, replacement costs);*
- *Disposal costs (if applicable);*
- *Costs related to the greenhouse gas emissions (only for macroeconomic calculations);*

The global cost calculations should also include the residual value of the building at the end of the analysis period. The calculation of the global cost implies the sum of all the above mentioned costs, all referred to the starting year of the analysis. In addition to costs, the discount rate, price evolution and the analysis period are important in calculating the global cost. In mathematical terms, the formula for calculating the global cost from a financial perspective can be written as presented in Equation 2.6 [101]:

$$C_g(\tau) = C_I + \sum_j [\sum_{t=1}^{\tau} (C_{a,i}(j) \times R_d(i)) - V_{f,\tau}(j)] \qquad \text{Eq. 2.6}$$

τ – calculation period
$C_g(\tau)$ – global cost on the considered calculation period (referred to starting year τ_0)
C_I – initial investment cost
$C_{a,i}(j)$ – annual cost during year i for measure or set of measures j
$R_d(i)$ – discount factor for year i based on discount rate r
$V_{f,\tau}(j)$ – residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year τ_0)

The discount factor is calculated using the Equation 2.7.

$$R_d(p) = \left(\frac{1}{1 + \frac{r}{100}} \right)^p \qquad \text{Eq. 2.7}$$

r – real discount rate [%]
p – number of years passed from the starting year of the analysis.
As in [no 244], the calculation period represents the time period expressed in years for the calculation. The calculation period may be less than the expected lifetime of

the building. The decision on the analysis period takes into account the technical functioning of the building elements. At the same time, the analysis period can be determined by the renovation cycle of the building, which is the time period after which the building undergoes a series of major renovations and improvements. Refurbishment cycles differ from one type of building to another but are almost never less than 20 years [102]. In Annex I of Delegate Regulation no. 244 [101], a calculation period of 30 years is recommended for residential buildings.

The global cost is in fact the sum of the initial investment costs and of the net present value of all future costs during the period of analysis. The present value of future costs is determined using the discount factor, which is calculated based on the discount rate. The discount rate does not only consider the time value of money but also the risk or unpredictability of future cash flows. According to some authors, this is determined by several factors including: interest rate, profit rate, the rate of increase of the national income and can be assimilated to them [103]. Real discount rate is to be used in calculations, which means that the inflation is not considered. Delegate Regulation no. 244, states that Member States have to establish national values for discount rates, with the mention that a sensitivity analysis will be performed for at least two other values of which on is 3%.

In the calculation of the global cost, the future development of prices can also be considered by means of price escalations rates in real terms (excluding inflation). In this case, the annual costs must be multiplied with a price escalation factor calculated considering the price escalation rate. The residual value at the end of the calculation period is calculated considering the remaining lifetime of the building components. Based on EN 15459 [105], the residual value of building components is calculated following the mathematical formula in Equation 2.8:

$$V_{f,\tau}(j) = V_0(j) \cdot (1 + R_p)^{n \cdot \tau_n(j)} \cdot \left(\frac{(n+1) \cdot \tau_n(j) - \tau}{\tau_n(j)}\right) \cdot \frac{1}{(1 + {}^{r}/_{100})^{\tau}} \qquad \text{Eq. 2.8}$$

Where:

$V_{f,\tau}(j)$	– final value of component j;
$V_0(j) \cdot (1 + R_p)^{n \cdot \tau_n(j)}$	– price of component j considering the evolution of products costs;
$\left(\frac{(n+1) \cdot \tau_n(j) - \tau}{\tau_n(j)}\right)$	– straight-line depreciation;
$(1 + {}^{r}/_{100})^{\tau}$	– discount factor value at the end of the calculation period.
n	– number of replacements during the calculation period;
$\tau_n(j)$	- lifespan for building component j.

3 CASE STUDY BUILDING

3.1 General information

The research in this thesis is focused on a residential energy efficient building, which is in use and continuously monitored for several years now. The investigated building is part of duplex building, constructed near the city of Timisoara (Dumbravita), Romania (Figure 3.1). The design and construction of this duplex came as a challenge for the design team because it was one of the very first highly energy efficient buildings in the area. Therefore, the design team along with researchers at the Politehnica University Timisoara developed an experimental program around this building with the purpose of improving the existing experience and knowledge in Romania on designing and constructing highly energy efficient buildings. Thus, the studied building is a pilot project that seeks to contribute on meeting the challenges from the European Union of increasing the energy efficiency of buildings and development of nZEB. The house is located in the west side of Romania, in climate zone II, according to the Romanian climate zone division map [37].

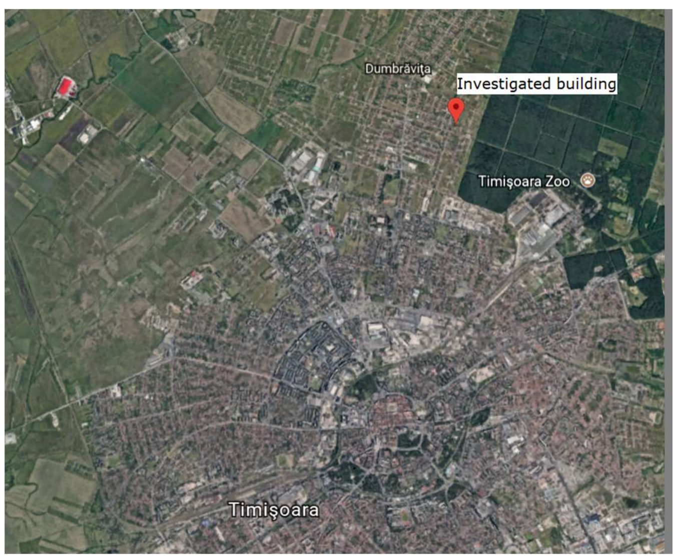


Figure 3.1 - Building location
Source: Google maps

The premise of this project was to build a house following the passive house design principles and using materials and technologies specific to residential constructions in the area, so that the investment costs would be comparable to the costs of a regular house in Romania. Thus, this project also serves as an example for future energy efficient constructions in this area, taking into account the local tradition and construction techniques, simple and easily adaptive architecture, combined with perspectives related to energy saving and renewable energy.

Besides the experience related to energy efficient design and construction techniques, this project offers information related to the real response of the building post-occupancy, due to the data collection available from several years of building monitoring. The monitoring data is used to verify the energy performance of the building, investigate its efficiency and optimize the energy use. Also, the monitoring data is extremely valuable in calibrating and validating the building energy model.

3.2 Design concept

As presented earlier, the investigated house is part of a duplex building. The two buildings of the duplex share the same structural and architectural features, have different orientation, building equipment and functionality. The construction of the building started in 2010 and was finished in 2011. One of the two semidetached houses is inhabited by a family composed of three persons (4 persons from 2017) from the end of 2011 and is continuously monitored ever since. The other side of the duplex was put in use at the beginning of 2015 and is currently functioning as an architectural studio. The investigations in this thesis target the residential house (Figure 3.2).

Figure 3.2 - General view of the investigated house

The building was designed by the architectural studio SDAC from Timisoara and the design team was leaded by an architect that followed the passive house designer courses held at the Passive House Institute in Darmstadt. Therefore, special attention was paid to the architectural and structural details in order to obtain an efficient thermal envelope and strict control of the air exchange between the interior and exterior environments. The main features of the investigated building are summarized in Table 3.1.

The energy design of the house was performed using Passive House Planning Package Tool (PHPP), developed by the Passive House Institute in Darmstadt [106]. The Darmstadt Passive House Institute has developed PHPP to help determine the energy balance of a passive house. With the help of the PHPP program, the following objectives where achieved:

- sizing the building's individual components and their influence on the energy balance of the building both in the cold season and in the hot season
- determining the thermal load and cooling load

- sizing, mechanical systems for the entire building (heating, cooling, ventilation, domestic hot water supply.

Table 3.1 - Summary of the investigated building characteristics

<table>
<tr><th>Characteristic</th><th colspan="3">Description</th></tr>
<tr><td>Building type</td><td colspan="3">Residential</td></tr>
<tr><td>Planned number of occupants</td><td colspan="3">4</td></tr>
<tr><td>Treated floor area</td><td colspan="3">141 m^2</td></tr>
<tr><td>Passive features</td><td colspan="3">-compact form
-highly insulated envelope U-values ≤ 0.15 W/(m^{2}K)
-ventilation with heat recovery
-compactness: the thermal envelope surface area to volume (A/V) ratio of 0.89 m^2/m^3 and the heat loss form factor of 2.77*</td></tr>
<tr><td rowspan="5">Building envelope</td><td>Element</td><td>Insulation material</td><td>Insulation thickness [mm]</td></tr>
<tr><td>-exterior walls</td><td>polystyrene</td><td>300</td></tr>
<tr><td>-ground floor</td><td>polystyrene</td><td>400</td></tr>
<tr><td>-roof terrace</td><td>polystyrene + mineral wool</td><td>425</td></tr>
<tr><td>-cantilevered floor</td><td>polystyrene + mineral wool</td><td>500</td></tr>
<tr><td>Structural system</td><td colspan="3">-masonry walls with reinforced concrete columns and belts
-foundation blocks connected with reinforced concrete beams
-roof terrace</td></tr>
<tr><td>Windows</td><td colspan="3">-triple glazed windows with low-e coating
-U-value 0.9 W/(m^{2}K)</td></tr>
<tr><td>Heating, ventilation and hot water</td><td colspan="3">-air to water pump (the rooms are heated through fan coils installed in the ceiling)
- solar collector for domestic hot water, installed on the roof
-ventilation unit with heat recovery featured by an underground heat exchanger</td></tr>
<tr><td>Air change rate n_{50}**</td><td colspan="3">0.6 h^{-1}</td></tr>
</table>

* The heat loss form factor is an alternative to the A/V ratio and describes the ratio of the thermal envelope surface area to the treated floor are. Achieving a heat loss form factor of ≤ 3 is a useful guideline when designing an energy efficient house such as the passive house [109].
**n_{50} represents the air change rate of the building at a pressure of 50 Pa and was determined through a pressurization test using the Blower Door procedure according to BS EN 13829 [105].

Energy design with PHPP is divided into two stages. First, surfaces and heat transfer coefficient values for envelope elements, window specifications, shading, and values for ventilation system design were introduced. Based on these data, the heat demand, thermal load, frequency of overheating times and cooling demand were determined. The second step is to introduce all relevant data for determining the total primary energy consumption: domestic hot water, household equipment, auxiliary energy, etc. Designing a passive house is a thorough process that involves an overall approach and sometimes requires testing and analysing multiple variants for the most effective choice. Table 3.2 presents the house energy demands as estimated in the design phase.

Table 3.2 - House energy demand determined using PHPP

Indicator	**Value**	**Passive House institute criteria**
Heating energy demand	14 kWh/(m^{2}an)	<15 kWh/(m^{2}an)
Total primary energy demand	104 kWh/(m^{2}an)	<120 kWh/(m^{2}an)

3.3 Architecture, structural system, envelope

From architectural perspective, the investigated building is a two floors building with a rectangular horizontal plan and prismatic volume. The simple architecture comes from the intention of achieving a low area to volume ratio and therefore limit the thermal bridges and heat transfer through the building envelope. Thus, the area to volume ration (A/V) is 0.89 m^2/m^3, which is significantly below the maximum value recommend in the design of a passive house [103]. The house has an advantageous orientation, with the south-facing facades having large windows, and presents a very compact form. The proper orientation of the windowed facades has a beneficial influence during winter, ensuring passive solar heating. The regular shape and compact volume of the house were designed in a way that achieves an air-tight envelope and minimizes thermal bridges. The house was built as a semidetached house and has approximately 141 m^2 of living space, corresponding to the needs of an average family (4 member's family). The space division of the house is listed in Table 3.3.

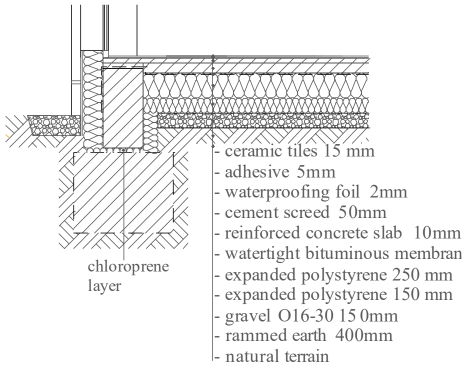
Table 3.3 - Structure of the space in the building

Room type	Floor area [m^2]	Total useful floor area [m^2]
Living room	47.4	~141
Technical room/Service bathroom	7.68	
Kitchen	14.94	
Bedroom 1	14.78	
Bedroom 2	14.44	
Bedroom3	14.16	
Office	18.57	
Bathroom	7.15	

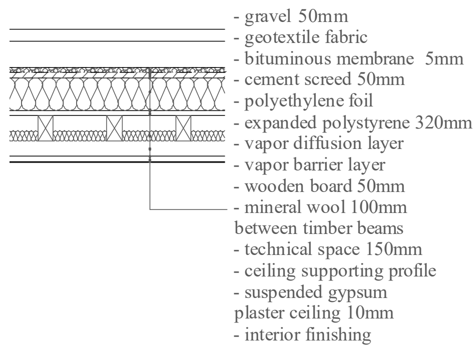
The structural system of the building is composed of masonry structural walls of 250-mm-thinkness, confined with reinforced concrete horizontal and vertical ties to meet seismic regulations. The over-structure was designed to conform to the P100/2006 [107] Romanian standard. The infrastructure system of the house consists of isolated concrete blocks connected with foundation beams to comply with the seismic building requirements.

The thermal insulation layer of the envelope elements positioned externally with the advantage of reducing the effect of the thermal bridges in the joining zones of the structural elements. The roof is terrace type and was insulated with a layer of 32 cm of polystyrene and 10 cm of mineral wool arranged between the wooden beams of the floor (Figure 3.3.b)). The foundation system reduces the amount of concrete used and facilitates the thermal insulation of the entire ground floor, the polystyrene plates being applied from the foundation beams upwards. The ground floor was thermally insulated with two layers of polystyrene having a total thickness of 400 mm of insulation. The foundation beams were also thermally insulated with 150 mm thick polystyrene and 200 mm on the exterior perimeter (Figure 3.3.a)).

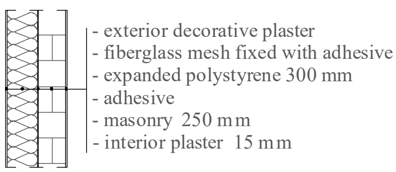
The exterior walls insulation consists of polystyrene plates of 300-mm thickness, while only 150 mm of thermal insulation was provided for the upper part of the parapet (Figure 3.3c) and d)). Triple-glazed windows were used.



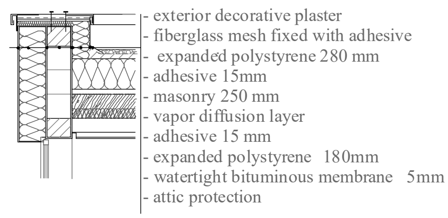
a) Ground floor



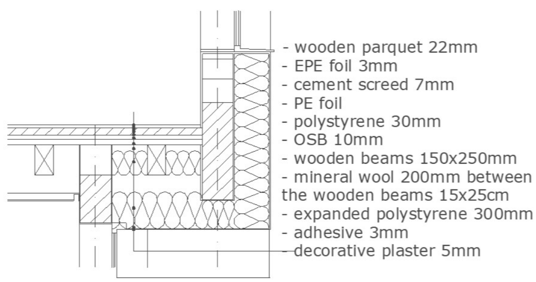
b) Roof



c) Exterior wall



d) Attic



e) Cantilevered floor

Figure 3.3 - Detail and stratification of the envelope elements

The doors for access in the building are positioned on the side façade. The first floor is extended with 1 m compared to the ground floor. The height of the ground floor is 2.66 m and of the first floor is 2.6. Figure 3.4 and Figure 3.5 shows the horizontal plans of the house. The simple geometrical features can be observed, that offer the benefits of solar heat gains due to their high glazed surfaces and limited heat loss limited due to the compact form. Figure 3.6 shows a longitudinal section of the house. It can be observed how the thermal insulation layer is continuous, without interruption, assuring a thermal bridge free and airtight envelope.

The interior finishing of the passive house is quite simple: laminated parquet in rooms, ceramic tiles and faience in bathrooms, kitchen and access hole; watersolvent wall plaster paint and wood panel interior doors. The interior compartment walls of 150-mm thickness are gypsum plaster boards on cold-formed steel profiles.

Table 3.4 summarizes the geometrical characteristics of the envelope elements. The areas were calculated using the exterior dimensions of the construction elements.

Table 3.4 - Envelope elements characteristics

Envelope element	Area [m^2]	Total thickness [m]
Exterior walls	151.70	0.588
Ground floor	89.42	0.887
Roof terrace	96.22	0.924
Floor over air	6.80	0.680
Windows	41.87	-

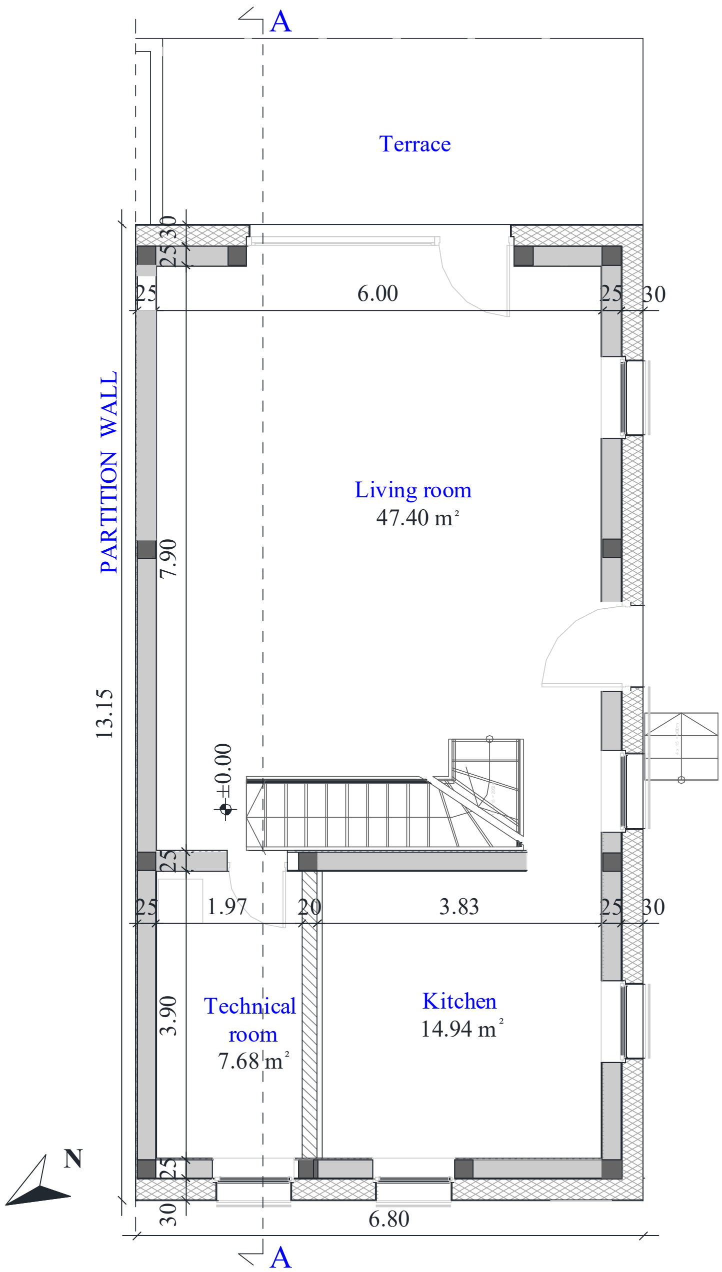


Figure 3.4 - Ground floor plan

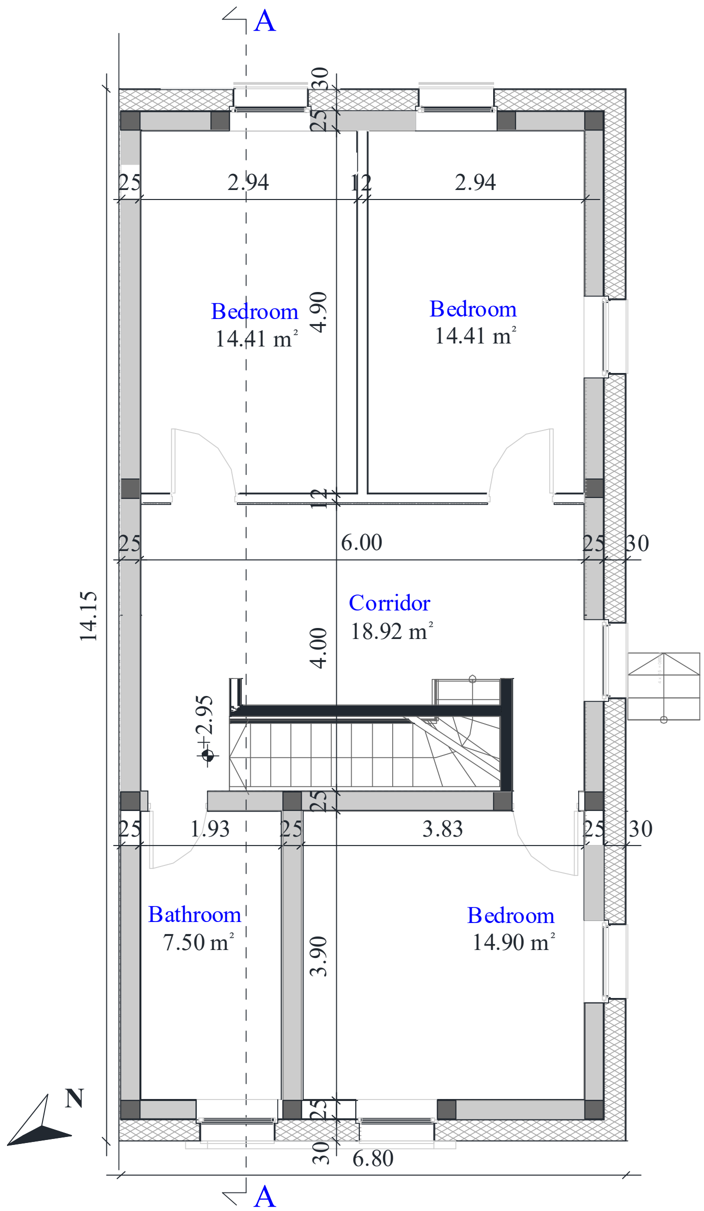


Figure 3.5 - First floor plan

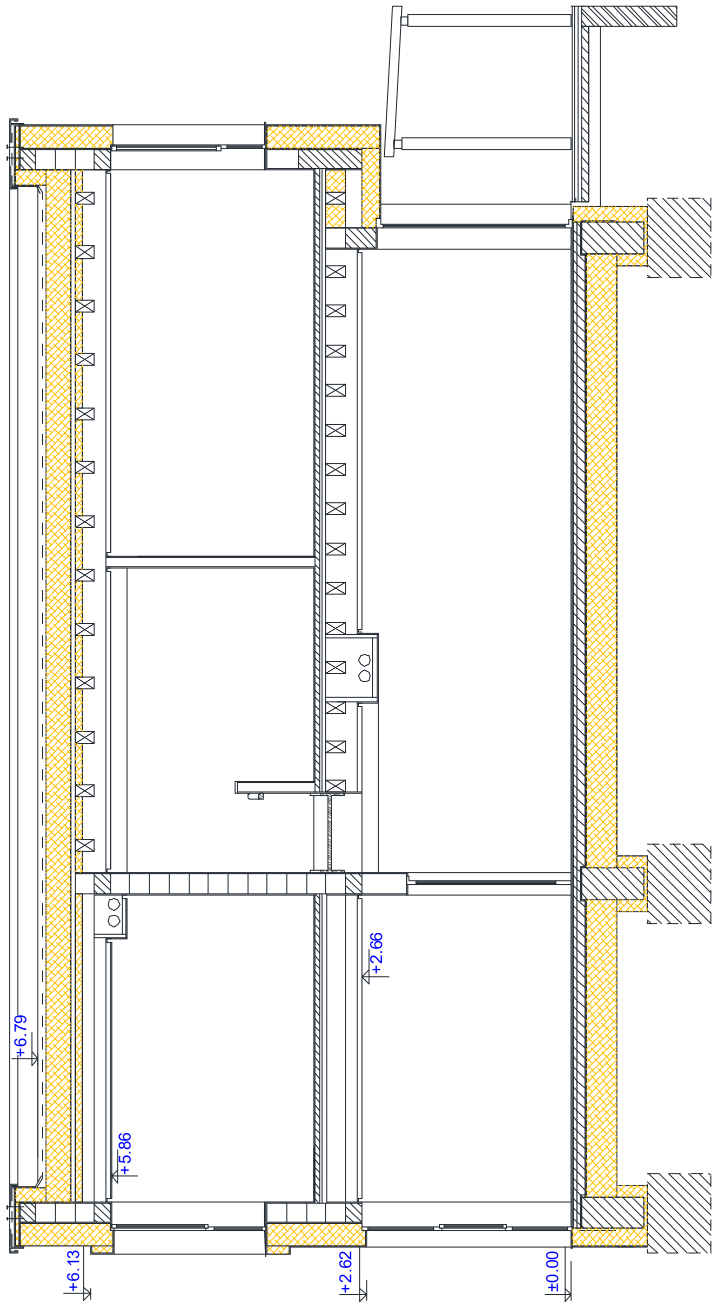


Figure 3.6 - Longitudinal section A-A

3.4 Building systems

The house has a complex system providing heating, ventilation, cooling and domestic hot water. The scheme presented in Figure 3.7 illustrates how the utilities of the investigated house operate. The key components of the system are a heat recovery ventilation and an underground heat exchanger for fresh air input, a 5.21 kW air-to-water heat pump and a solar collector for domestic hot water. The house is equipped with a hot water boiler and a heating buffer for thermal energy storage. The heat is distributed throughout the rooms through convectors installed in the ceiling. In the periods when the solar panel does not cover the domestic hot water demand, it is covered with the heat pump. The house is all electric, all the equipment use electrical energy from the grid.

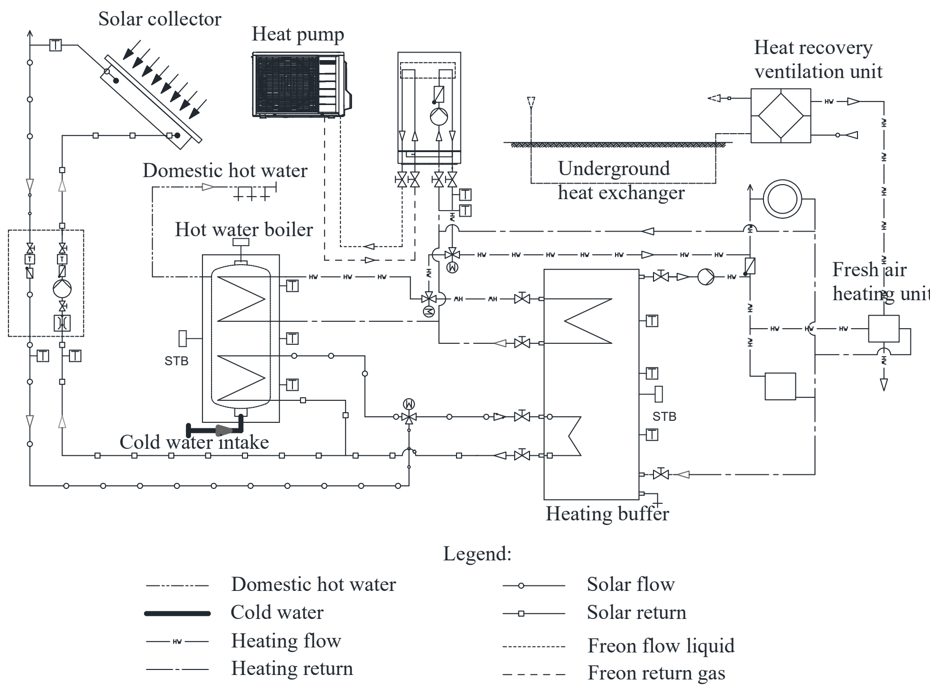


Figure 3.7 - Schematic representation of the building's heating, cooling and ventilation system

The heating energy need, as estimated in the design phase, is very low. Therefore, the house did not require the use of a traditional heating system. Air to water heat-pumps are widely used in residential heating because they have easy commissioning and low installation costs. However, these pumps have the disadvantage of decreasing it's coefficients of performance towards very low outdoor temperatures. In this situation, the choosing of this kind of heat pump was the safest decision considering the lack of experience and knowledge at the moment related to heat pumps behaviour in residential buildings. The water storage buffer for space heating is provided with an electrical resistance that goes into operation when the heat pump fails to cope. The heat pump works on an electrically driven vapour-compression cycle and pumps energy from the air in the environment to water in a storage tank, thus raising the temperature of the water. Thus, the heat is taken from the outside air through an outdoor unit in which the refrigerant circulates in a closed duct system and which transfers the heat from the source to the indoor unit. The heat distribution in the rooms is made by means of fan coils installed in the ceiling.

The ventilation system of the building has a heat recovery ventilation unit with 85% efficiency of heat recovery. The vicious air is extracted from the bathrooms and the kitchen, and the fresh, preheated air is introduced in the living room and bedrooms. The ventilation system with heat recovery is a key element alongside the performance and airtight thermal envelope as it has two main roles: to ensure indoor air quality through an appropriately controlled air exchange; to recover heat from the vicious air to reduce the energy demand for heating. Thus, the ventilation system is provided with a ventilation unit in which there is a heat exchanger. The fresh air flow is passed through the heat exchanger along with the vaporous airflow, thus recovering heat from the vicious air and transferring it to fresh air. Before being introduced into the heat recovery ventilation unit, the air is passed through the ground-to-ground heat exchanger at a varying depth of 1.5 to 3 m. The passive house underground heat exchanger consists of a single PVC pipe having the thermal and geometric characteristics presented in Table 3.5. The pipe system is buried at an approximately 2 m distance from the house, following the house perimeter. The ground-air heat exchanger has the usual features used for residential buildings with floor areas between 150 and 200 m^2 This system is useful to preheat the air during winter and precool the air during summer.

Table 3.5 - Characteristics of the ground-air heat exchanger

Parameter	Value
Pipe thermal conductivity [W/(mK)]	0.30
Exterior diameter [m]	0.200
Interior diameter [m]	0.185
Length [m]	35

As mentioned earlier, for the domestic hot water preparation, the house is equipped with a vacuum tubes solar panel and a boiler for hot water storage. The solar panel is installed on the roof, the collector tubes face south and the hot water is stored in a 150 l container. During the design phase an annual production of 1400 kWh/year was estimated.

The house's passive heating strategy is based on solar passive heating, internal heat gains and the ground-to-air heat exchanger (Canadian shaft). With regard to the summer cooling strategy, the designer proposed the use of the air-to-ground heat exchanger and night cooling by opening the windows.

3.5 Building construction

The construction of the house has been carefully managed to assure the quality of the thermal insulation system, avoiding any potential thermal bridge and ensuring the airtightness of the construction. Figure 3.8 presents a series of photos taken during construction of the house.

a) Foundations

b) Masonry

c) Terrace roof

d) Windows

e) Technical room

f) Technical room

g) Ground-air heat exchanger

h) South-West and South-East facades

i) South-West and North-West facades

j) North-West facades

Figure 3.8 - Pictures of the building

4 BUILDING MONITORING: REGISTERED DATA PROCESSING AND ANALYSIS

4.1 Monitoring system

In a developing country such as Romania, high energy efficiency measures are not very widespread and therefore it is important that along with their implementation, a complex monitoring to be installed as well, in order to investigate and validate these solutions, optimize the energy use and also improve and optimize the solutions for application in future projects. The building under investigation is one of the few highly energy efficient buildings in Romania. Implementing a monitoring system in this building represents a way of optimizing the real energy consumption and also offers necessary data for building performance analysis, energy model calibration and validation. The data from monitoring allows the analysis of the building's real energy consumption and energy performance characteristics. Through monitoring, it is also possible to optimize the parameters related to building use and thus reducing even more the energy consumption. The design and implementation of the monitoring system were performed by the research team at the Politehnica University of Timisoara. The design and implementation process are accurately presented in several scientific papers [108].

4.1.1 System components

The monitoring system is composed of the central unit Web Energy Logger (WEL) and ambient energy flow meters. The WEL collects measurements from the sensors every minute and posts the data to a webserver. The data collection unit has internet connection to upload readings to the database. The internet connection is provided through router featuring a USB port that was in turn connected to a 3G access modem offering access to the internet at all hours and days of the year. The router in turn provides an Ethernet connection to the WEL. Also, an internet connection monitoring module was set-up and configured to reset the power to the router anytime a connection time-out is detected and also provides local data display. The measuring components are: temperature sensors, humidity sensors, atmospheric pressure sensors, solar radiation silicon pyranometers with amplified output, for the heating agent, flow volume meters were used and interfaced directly with the impulse counting inputs of the WEL., anemometer, electric meters with impulse outputs were directly interfaced to the impulse counting inputs of the WEL, state sensors After several years in use, there were some short-term unavailability due to the disconnection of the internet modem, power problems. Some sensors failed due to high temperatures.

Figure 4.1 shows the schematic representation of the monitoring system implemented in the passive house.

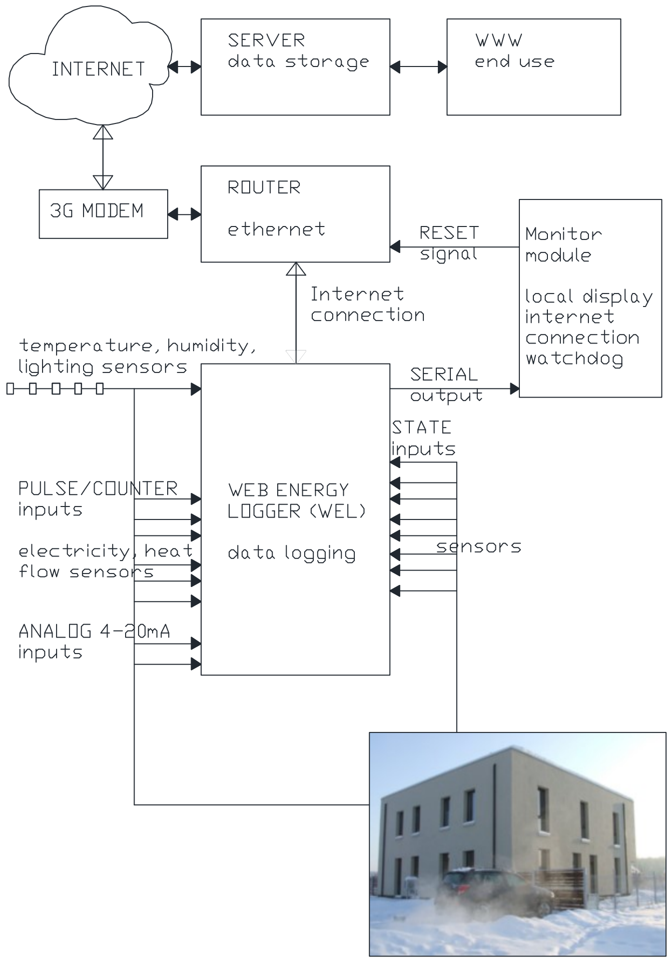


Figure 4.1 - Monitoring system scheme

4.1.2 Monitoring strategy

The structure and components of the monitoring system come from the categories of parameters that have been proposed to be monitored: indoor comfort and environmental conditions and indoor air quality, exterior environment parameters, energy consumption of the building, plant and equipment parameters. Each measurement component has a unique ID. The registered data is stored on a server and can be downloaded as Excel files for each month. The measurements are made at one minute interval, thus allowing an easy and accurate identification of errors or possible malfunctioning of the system. Table 4.1 contains the components of the monitoring system related to indoor and outdoor environment conditions as well as indoor air quality parameters.

Table 4.1 - List of monitored environment parameters

Measurement category	Component ID	Measured parameter
Indoor environment and air quality parameters	T_1	air temperature in the living room
	T_4	air temperature in the living room
	Tair_D1	air temperature in bedroom 1
	Tair_D2	air temperature in bedroom 2
	Tair_H	air temperature in the corridor
	Tair_D3	air temperature in bedroom 2
	Hair_D3	air relative humidity in bedroom 3
	Hair_Liv	air relative humidity in the living room
	CO_2ppm_D3	CO_2 concentration in bedroom 3
	CO_2ppm_Liv	CO_2 concentration in bedroom 3
Outdoor environment parameters	TEXT	exterior air temperature
	Tair_roof	exterior air temperature
	Tair_grdn	exterior air temperature
	Hair_roof	exterior air relative humidity
	Hbox_roof	exterior air relative humidity
	Hair_grd	exterior air relative humidity
	Vwind	wind speed
	Dwind	wind direction
	Psun_V	solar irradiation on vertical surface West
	Psun_E	solar irradiation on vertical surface East
	Psun_S	solar irradiation on vertical surface South

The temperature sensors are positioned in different parts of the house: living room (2 sensors), corridor (1 sensor), bedrooms (3 sensors, 1 for each bedroom). The CO_2 concentrations is measured in the living room and one of the bedrooms. The air relative humidity is also measured in the living room and in one of the bedrooms. These position of these sensors can be seen in the scheme in Figure 4.2.

Table 4.2 contains the components of the monitoring system related to the energy consumption of the building. The energy consumption of the building is monitored separately for different consumer categories. Also, the total energy consumption of the building is measured through a separate measuring component. This thing is possible due to the fact that the building is all electric.

Table 4.2 - List of monitored parameters related to energy consumption

Measurement category	Component ID	Measured parameter
Electrical energy	EL_1	household electricity power
	EL_2	lighting electricity power
	EL_3	technical room electricity power
	EL_4	exterior lighting electricity power
	ELis_tot	instantaneous total power consumption
	ELds_tot	total annual electricity consumption
	Elms_tot	total monthly electricity power

A shortcoming of the energy consumption monitoring process consists in the fact that the energy consumption of the technical room is not broken down on consumers, and only registers the total energy consumption. This aspect makes it difficult to determine the exact energy consumption for each type of consumption:

heating, ventilation, cooling and domestic hot water. However, the system has some state sensors for the equipment in the technical room. These sensors were installed with the purpose of knowing when and how long each equipment in technical room functioned. Unfortunately, during the several years of monitoring, the state sensors often had malfunctioning and false indications.

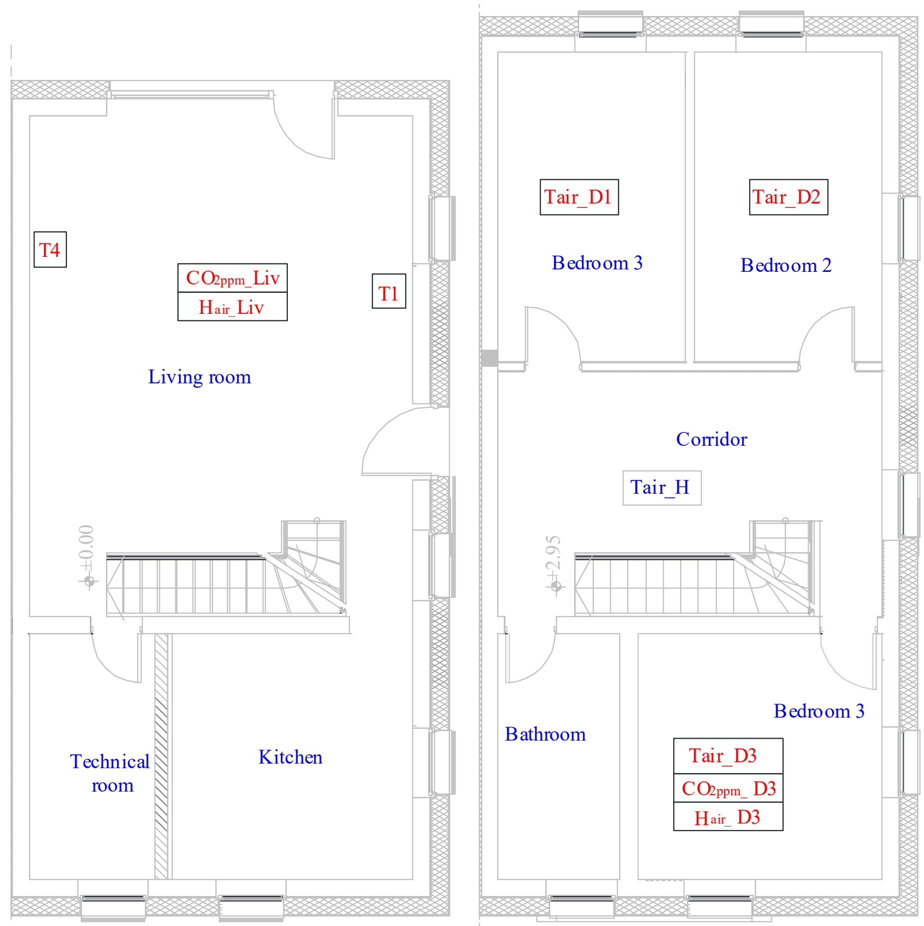


Figure 4.2 - Location of the sensors for indoor air temperature and quality measurements

Table 4.3 contains the components of the monitoring system that measure water and air temperatures related to heating, ventilation and cooling systems. These parameters are relevant in order to assess the real efficiency of the equipment. The data related to the ventilation system is useful to determine the real efficiency of the underground heat exchanger and of the heat recovery ventilator. Also, the data is used to identify the periods when the heat exchanger from the mechanical ventilation unit should be bypassed in order to avoid heating the air during the cooling season.

Figure 4.3 shows the scheme of the building equipment and the positions of the sensors listed in Table 4.3.

Table 4.3 - List of monitored parameters related to heating, ventilation and cooling

Measurement category	**Component ID**	**Measured parameter**
Air temperature	TAIR_intk	Fresh air temperature after underground heat exchanger
	TAIR_exha	Evacuated air temperature
	TAIR_supp	Fresh air temperature after heating coil
	TAIR_extr	Air temperature absorbed from the rooms
	Tair_D1inlHRV	Fresh air temperature in bedroom 1
	Tair_D1inlFCU	Recirculated air temperature in bedroom 1
	Tair_D2inlHRV	Fresh air temperature in bedroom 2
	Tair_D2inlFCU	Recirculated air temperature in bedroom 2
	Tair_D3inlHRV	Fresh air temperature in bedroom 3
	Tair_D3inlFCU	Recirculated air temperature in bedroom 3
	Thex_supp	Fresh air temperature after heat recovery
	Thex_extr	Extract air temperature
	Thex_exh	Exhaust air temperature
Water temperature	Thfc_re	freon flow temperature - heat pump
	Thfc_fl	freon return temperature - heat pump
	Thea_fl	flow water temperature – bathroom radiator
	Thea_re	return water temperature – bathroom radiator
	Tcoil_fl	flow water temperature – heating coil
	Tcoil_re	return water temperature – heating coil
	Tfl_FCUe	flow water temperature – fan convector
	Tre_FCUe	return water temperature – fan convector
	THP_fl	water flow temperature – heat pump
	THP_re	freon return temperature - heat pump
	THW_lo	domestic hot water boiler – lower part
	THW_mid	domestic hot water boiler – middle part
	THW_hi	domestic hot water boiler – higher part
	TBUF_hi	heating buffer – higher part
	TBUF_mid	heating buffer – middle part
	TBUF_lo	heating buffer - lower part
	TSOL_fl	solar panel - flow
	TSOL_re	solar panel - return

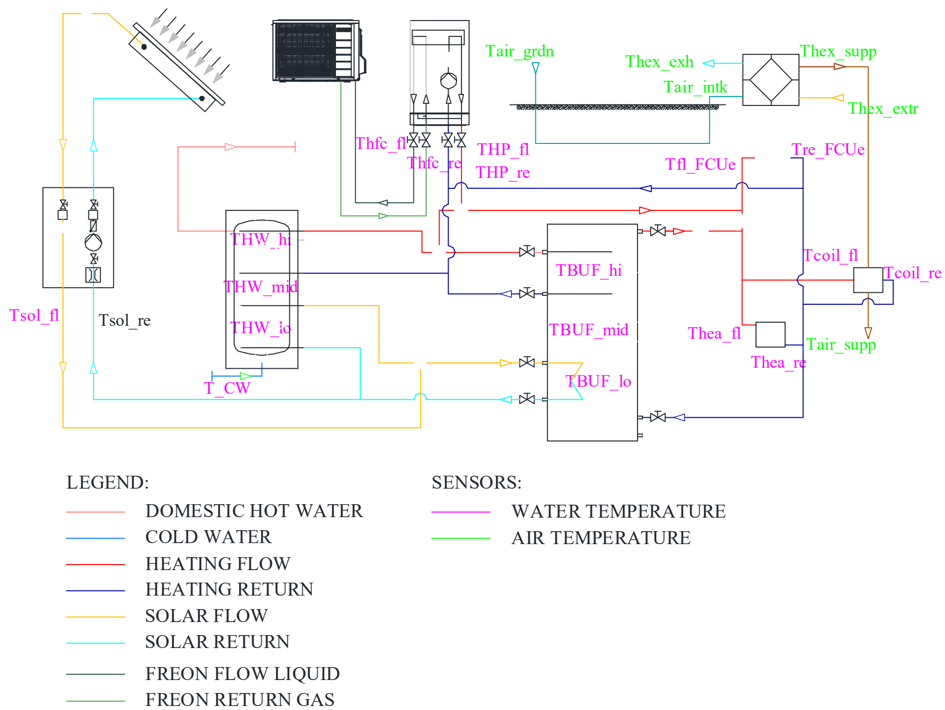


Figure 4.3 - Location of the sensors for equipment parameters monitoring

4.2 Monitoring data processing

The monitoring process was initiated at the end of 2011. The system registers values at each minute and stores them on a server. The data files can be downloaded from the server as spreadsheets files for each month. Each monthly file contains approximately 44000 lines of values for each measuring component. The processing of the monitoring data was performed using Microsoft Excel tool. A set of data from 2015 was used in this research.

4.2.1 Missing data and out of range values

During the monitoring years, there were a few short outages due to the internet modem disconnection, blackouts, maintenance and sensor network works. In these situations, the data lines display "?" or "0" in case of environmental parameters measurements. In order to cope with this situation, a ‚IF’ function was used in Excel to detect and replace missing values displayed as "0" and errors displayed as "?". The procedure is presented in the flowchart in Figure 4.4.

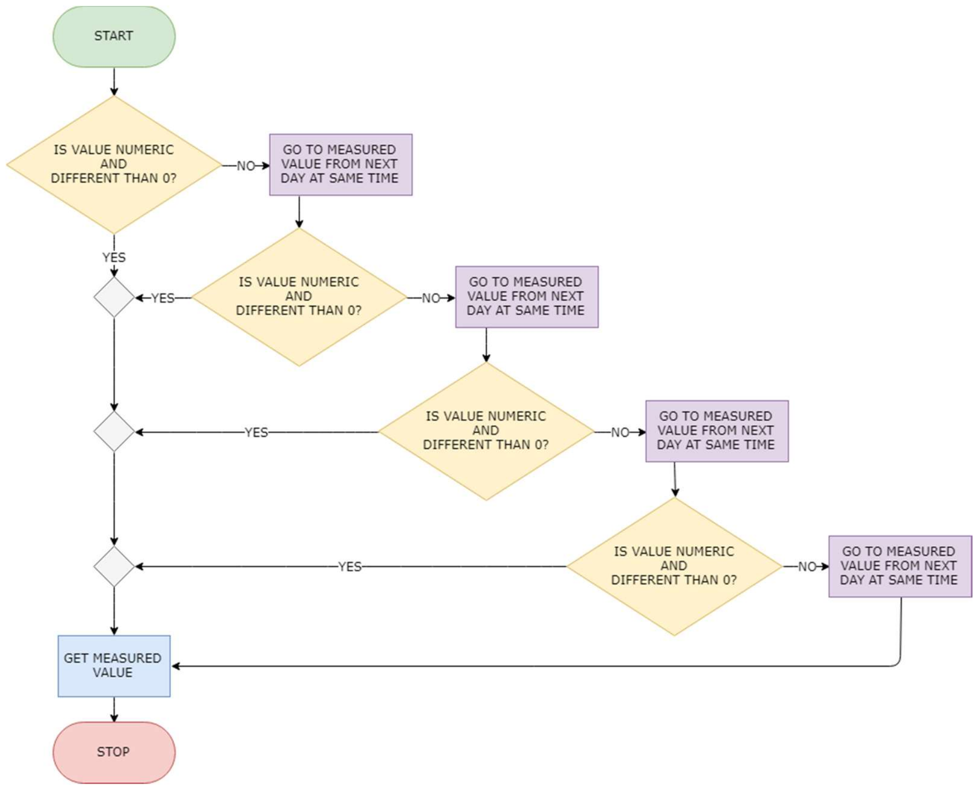


Figure 4.4 - Procedure for detecting and replacing missing data and non-numeric values for environmental parameters

Thus, for each column of data, another column was generated containing a formula that detects lines that have "?" and "0" instead of values and replaces them with data from the next day at the same time, according to the procedure presented in the flowchart in Figure 4.4.

The following step consisted in detecting unusual peak values for each set of data (temperature, air relative humidity and CO_2 concentration). These points were identified by plotting graphs of the measured data for each sensor. Considering that the measurements were performed at every minute, any significant variation of values from one minute to another was obviously considered as erroneous and removed. The peak points were manually removed and replaced with the value from the previous minute. The flow chart presented in Figure 4.4 and rest of the procedure was used in case of the environmental parameters. This procedure was necessary in order to proceed with monitoring data processing to hourly, monthly and yearly values.

In case of energy consumption measurements, the measured data for power consumption was plotted in graphs in order to see the variation and peaks over the monitoring period. From the visual analysis of the data sets, no non-numeric lines were identified. The identified peaks were assumed to be normal and attributed to the number of electricity consumers in the building, which can vary dramatically from one minute to another, depending on the electricity consumers.

4.2.2 Processing monitoring data to hourly values

As mentioned earlier, the monitoring system registered lines of data at every minute. Thus, the data was processed to obtain hourly values that were further analysed and used in the hourly building energy simulations. The monitoring data is available in Excel files generated for each month. Each monthly file contains columns of all measured parameters and corresponding recorded values in a single sheet. Thus, it was necessary to develop a formula that automatically calculated the average hourly values of the measured parameters.

The mean hourly value of a particular parameter in a particular day between two particular consecutive hours was calculated by making the average of the valid values from every minute between those two hours. To do so, a formula following Equation 4.1 was implemented in the Excel files containing monitoring data and applied to each parameter needed for the research.

$$v(d,h) = \frac{\sum_{m=h\ in\ minutes}^{(h+1)\ in\ minutes} v(d,m)}{nvv} \qquad \text{Eq. 4.1}$$

In Equation 4.1: *d* is the day, *h* is the hour, *m* is the minute, *nvv* represents the number of valid values in an hour, *v(d,h)* is the average hourly value for a particular measured parameter.

4.2.3 Processing monitoring data to monthly values

The processing of monitoring data to obtain monthly values for environmental parameters such as temperature, air relative humidity, CO_2 concentrations consisted in a simple procedure of simply using an 'Average' function for each parameter.

The energy consumption of the building has been monitored through a series of 7 electric data recorders as presented in Table 4.7. Using the measured data, the monthly energy consumption on categories can be determined as well as total monthly energy consumption. In order to obtain the monthly energy consumption for the 4 monitored categories, the average power consumption is determined for each recorded category, using recordings by EL_1, EL_2, EL_3 and EL_4. The monthly average value of each recorder is multiplied with the number of hours in a day and number of days in the month, as presented in Equation 4.2:

$$EL_{m_i} = \frac{Average(EL_i) \times n \times 24}{1000} [kWh] \qquad \text{Eq. 4.2}$$

In Equation 4.2: *i* is the consumption category (as presented in Table 4.7), *Elm_i* is the monthly energy consumption from category *i, EL_i* recorded electricity power from category *i,* n is the number of days in month *m*.

The total monthly energy consumption can be further obtained in two ways. The first one consists in summing-up the values for all consumption categories for each month. The second one is using the readings of the recorder Elms_tot, which is a counter that resets itself every month to zero.

4.2.4 Processing monitoring data to yearly values

The process of obtaining average yearly values for the environmental measured parameters was an easy process and was performed by simply using the

‚Average' function in Excel. The annual energy consumption was obtained by summing up the monthly energy consumption values.

4.3 Monitoring data analysis

4.3.1 Interior air temperature and air relative humidity

The interior air temperature was measured through 6 temperature sensors placed in different locations of the house as presented earlier in Figure 4.2. Thus, the air temperature was measured with two sensors (T_1 and T_4) in the ground floor and 4 sensors in the first floor (Tair_D1, Tair_D2, Tair_D3, Tair_H). The graph in Figure 4.5 shows the hourly temperature throughout the monitoring year, registered by the 2 sensors in the ground floor spaces. It is noticeable that the temperature T_4 is slightly higher and the hourly variation is also greater than temperature T_1. The graph in Figure 4.6 shows the hourly temperature throughout the monitoring year, registered by the 4 sensors in the first floor rooms. We can observe in both graphs the increase of interior air temperature from the winter months to the summer months.

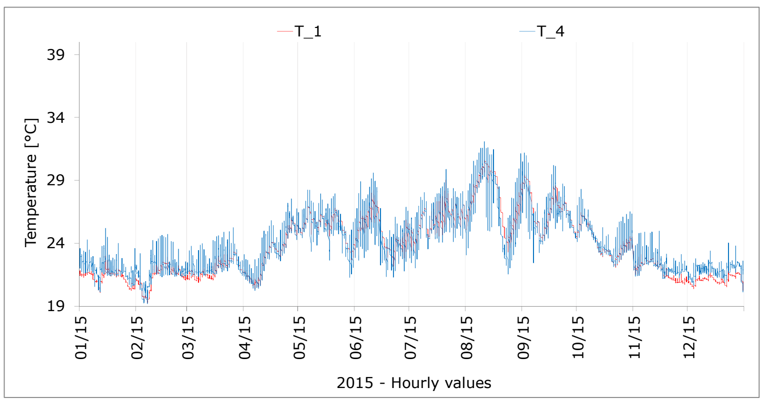


Figure 4.5 - Hourly measured temperature in ground floor spaces

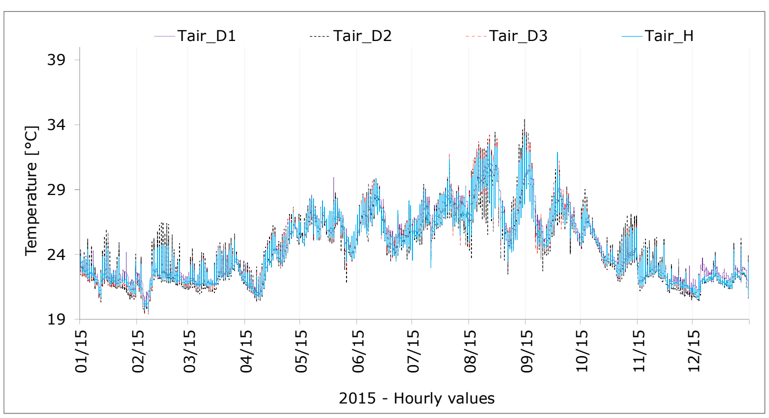


Figure 4.6 - Hourly measured temperature in the first floor rooms

A histogram was plotted in Figure 4.7 for the average interior air temperature in the house. We can see what temperatures were experienced the most throughout the year. The most frequent values are within the range 22℃ - 23℃.

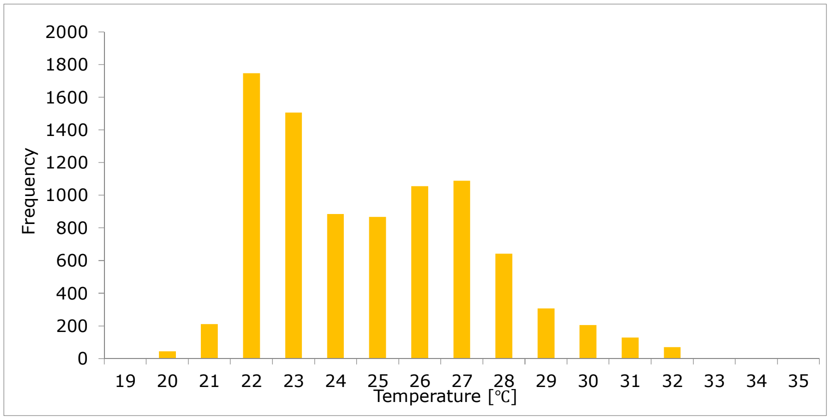


Figure 4.7 – Histogram of hourly average interior air temperature

The graph in Figure 4.8 shows a summary of the measurements performed by the 6 sensors. The average and minimum values have close values in case of all sensors but obviously are higher for the sensors placed in the first floor rooms. There is a more obvious diversity in the maximum recorded temperature. The maximum temperature was recorded by sensor Tair_D3 which is located in the first floor in the bedroom that has two windows, one oriented to south-west and the other one oriented to south-east. The graph in Figure 4.9 shows the average monthly temperature recorded by each sensor. It is noticeable that the highest average is registered by sensor Tair_D1, located in one of the first floor bedroom. Throughout the year, the temperature in the first floor rooms is slightly higher than the temperature in the ground floor.

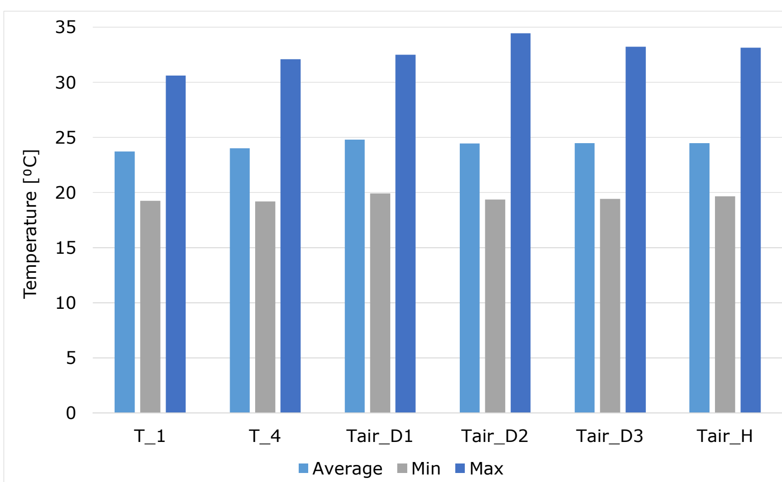


Figure 4.8 - Temperature diversity recorded by the 6 sensors

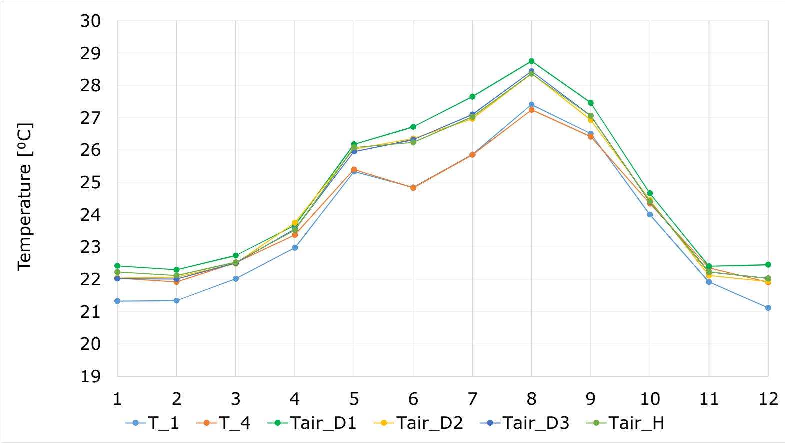


Figure 4.9 - Monthly average temperature recordings

A comparative Box and Whiskers Mean (BWM) plot was created for the measured interior temperature by each sensor in order to better see the distribution of temperature values (Figure 4.10). This type of graph is useful to see the shape of the data distribution, central values and variability. The red line in the two plots unites the median values corresponding to each month. The medians are the middle values for each set of data points that divides the data set into two parts. It is the point at which exactly 50% of the values lie below and above this value. The lines extended vertically from the boxes indicate the variability of the data sets outside the upper and lower quartiles, representing the minimum and maximum values. The upper lines of the boxes represent the 3rd Quartile for each data set which indicates that 75% of the hourly temperature values are less than this value. The lower lines of the boxes are the 1st Quartiles. The 1st Quartiles indicate that 25% of the measured and simulated values are less than this value.

A quick look at the comparative graphs in Figure 4.10 shows that the median values has a slight variation from a sensors to another, with a visible increase for the first floor rooms sensors measurements.

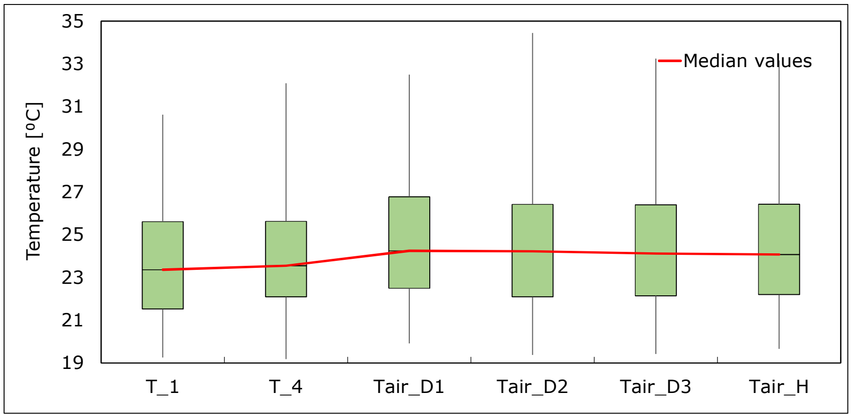


Figure 4.10 - BWM plot for the temperature measurement in different building rooms

From the interior air temperature analysis it is noticeable that the building faced overheating during some hours in the summer, when the indoor temperature overcame 30ºC in some rooms. The Passive House Institute recommends a limit for the frequency of summer overheating events when indoor temperature is higher than 25°C. Thus, it is recommended that the frequency of overheating events to be less than 10% of the total number of occupied hours in a year. According to EN ISO 7730 [40], the recommended temperature for winter is from 20° C to 24° C, and for summer from 23° C to 26° C, in order to keep the amount of dissatisfied occupants below 10%. In order to provide an indicator of the overheating times, the frequency of overheating events was calculated for a range of temperatures between 26°C and the maximum value recorded by each sensor. The number of overheating hours, when the temperature inside the house overcame the earlier mentioned values, were determined based on the hourly monitoring data of the interior temperature. The frequency of overheating is expressed as a percentage of the total hours of the year. The results are plotted in the graph in Figure 4.11. The frequency of overheating events at 25ºC is the highest in Bedroom 1 (Tair_D1) from the first floor, where the interior temperature was higher than this value for approximately 40% of the total number of hours in the year. The frequency of overheating is noticeable higher for the first floor rooms for all the investigated temperature limits. The main cause of overheating is the lack of shading systems for the windows. For the considered monitoring year, the cooling system was available for only a limited number of hours every day during August as it was the preference of the building occupants.

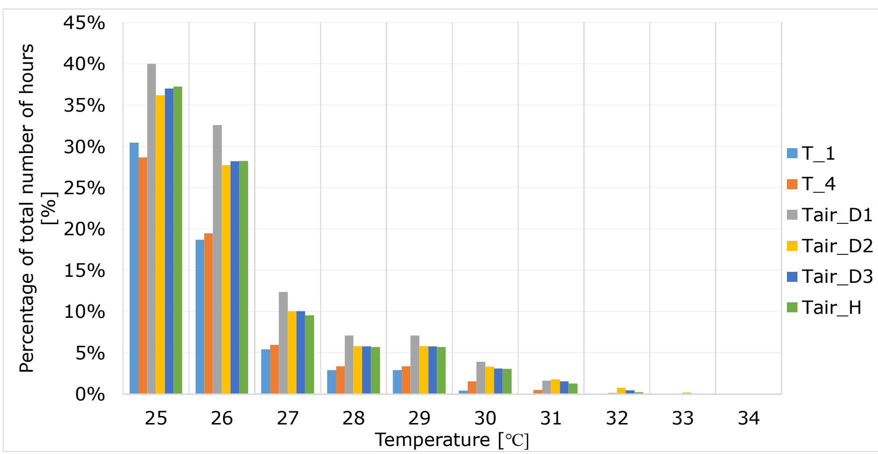


Figure 4.11 - Frequency of overheating at different temperature values

Figure 4.12 shows diagrams of the monitoring campaign in 2015. This graphs shows the hourly average house temperature and the hourly interior air humidity registered in the monitoring period. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) [46] provides guidelines that recommend a relative humidity of 30% to 60%. Levels less than 30% in the winter and greater than 60% in the summer should be unacceptable. Analysis of the graph in Figure 4.12 shows that the humidity levels are maintained within the comfort limits, with lower values during winter and higher values during summer. The maximum registered values are 62.82%, registered in July and the minimum is 31.64%, registered in February.

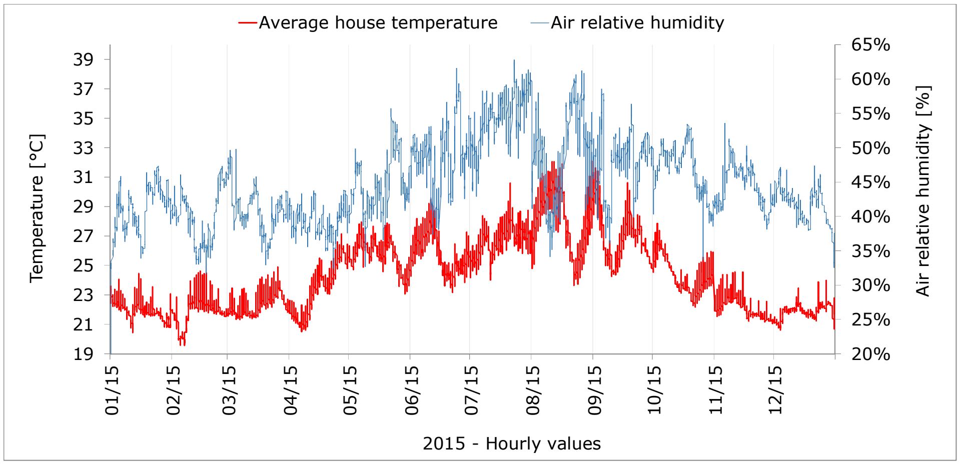


Figure 4.12 - Hourly average house temperature and air humidity measurement over the monitoring period

4.3.2 CO_2 measurements

Indoor air quality in houses depends of many factors such as the number of persons and time of occupation, emissions from activities, emissions from furnishing, construction materials, cleaning products etc. [110]. Among the pollutants in the indoor air that represent a health risk are: nitric oxides, nitrogen monoxide, formaldehyde and ozone [110]. These pollutants have to be measured if specific complaints such as smell or sick building symptoms persist and ventilation measurements show that the requirements for fresh air supply are met [110]. Also, in some areas, the soil might represent a risk due to increased levels of radon concentrations but this issue is avoided in passive houses through an air tight envelope and controlled ventilation [111].

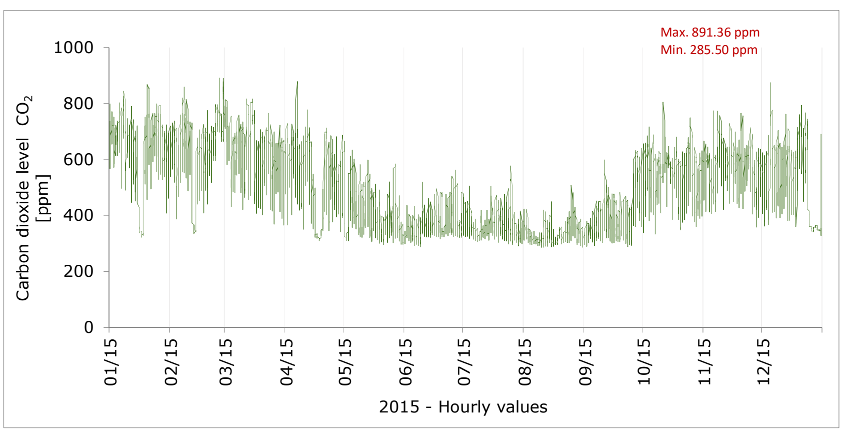


Figure 4.13 - Hourly measured CO_2 over the monitoring year

The CO_2 concentration can be used as an indicator for the degree of indoor air quality in buildings where people are the main pollution sources. According to European

Standard 15251 [110] new buildings should have the CO_2 concentrations lower than 500 ppm above the outdoors for most of the time. For the studied house, CO_2 sensor was mounted in the living room. Even though the house occupancy was not monitored, it is known that the house is constantly inhabited/used by 3 persons and the number of people increases occasionally during guests' visits. Figure 4.13 shows the hourly measured CO_2 concentration fin the living room in the considered monitoring year. With the average outdoor concentration in Timisoara of 350 ppm, it can be noticed that the indoor CO_2 concentration has in general an acceptable level during the year, lower than 850 ppm (acceptable CO_2 concentration). However, it can be noticed that there were some hours when the CO_2 concentration of the interior air overcame the acceptable limit. The number of hours when the CO_2 concentration was higher than 850 ppm is 18 hours throughout the year.

4.3.3 Energy consumption

The energy consumption of the house is monitored through a series of electric data recorders as presented in Table 4.3. All equipment installed in the building uses solely electricity, which facilitates an accurate and clear evaluation of the building's total energy use. Using the data registered with the electric recorders, the actual energy use of the building is obtained, broken down by consumer categories. For the considered monitoring campaign (2015), the monthly energy consumption is presented in Figure 4.14. It is noticeable how during the heating period, the energy consumption recorded by EL_3 is significantly higher compared to the other categories. The energy consumption for lighting (EL_2) is visibly decreasing from April until October, due to the higher quantity of natural light. The energy consumption associated to household appliances (EL_1) has similar values for all months of the year.

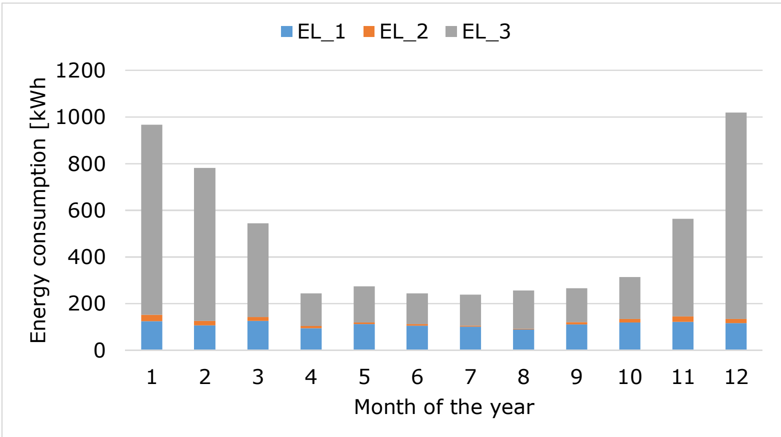


Figure 4.14 – Monthly measured energy consumption on categories

The total energy consumption of the building registered in 2015 is 5713.4 kWh, which represents 40.52 kWh/m^2 of total specific energy consumption of the building.

5 BUILDING ENERGY MODEL SIMULATION

5.1 Description of the energy simulation tool EnergyPlus

5.1.1 Software capabilities

One of the main benefits of having building monitoring data related to the energy consumption, environmental parameters and equipment parameters, consists in the fact that it offers precise input data to develop an accurate energy calculation model that can be further calibrated and validated. Once a model is calibrated, it can be further used to assess the change in the building energy performance under changing conditions such as climate and occupants comportment.

In the last decades, the applications and research related to energy requirement calculations have constantly increased from steady state calculations to annual energy requirement using monthly average values and in the last decade to dynamic thermal energy simulations for buildings.

EnergyPlus is a whole building energy simulation software that is used to model energy consumption in buildings (heating, cooling, ventilation, lighting, hot water use) and process loads, on an hourly basis. The targeted audience of the software are design engineers or architects that want to size heating ventilation and cooling (HVAC) equipment, perform energy rehabilitation of buildings studies, optimize energy performance, perform parametric studies and investigate different building operation scenarios or different energy efficiency measures on the same building. Energy Plus program was developed in 2001 as an innovative software out of two building energy software simulations: DOE-2 and BLAST, developed by the United States Department of Energy (DOE) and Department of Defense (DOD). Some of the most important capabilities of this software are:

- **Integrated, simultaneous solution** of thermal zone conditions and HVAC system response that does not assume that the HVAC system can meet zone loads and can simulate un-conditioned and under-conditioned spaces.
- **Heat balance-based solution** of radiant and convective effects that produce surface temperatures thermal comfort and condensation calculations.
- **Sub-hourly, user-definable time steps** for interaction between thermal zones and the environment; with automatically varied time steps for interactions between thermal zones and HVAC systems. These allow EnergyPlus to model systems with fast dynamics while also trading off simulation speed for precision.
- **Combined heat and mass transfer** model that accounts for air movement between zones.
- **Advanced fenestration models** including controllable window blinds, which calculate solar energy absorbed by window panes.
- **Component-based HVAC** that supports both standard and novel system configurations.
- **A large number of built-in HVAC and lighting control strategies** and an extensible runtime scripting system for user-defined control.

- **Standard summary and detailed output reports** as well as user definable reports with selectable time-resolution from annual to sub-hourly, all with energy source multipliers. [84]
- **Atmospheric pollution calculations** that predict CO_2, SO_2, NO_2, CO, particulate matter, and hydrocarbon production for both on site and remote energy conversion.

Energy Plus is therefore a thermal load and energy analysis simulation tool that calculates heating and cooling loads needed to maintain the temperature control set points year round, coil loads, the energy consumption of primary plant equipment. The calculations are made based on user input data related to building physical composition, associated mechanical systems, operation schedules and temperature set points.

5.1.2 Weather data

Along with the software download, hourly weather data are available for many locations all over the globe (1042 locations in the USA, 71 locations in Canada, and more than 1000 locations in 100 other countries throughout the world) (Figure 5.1).

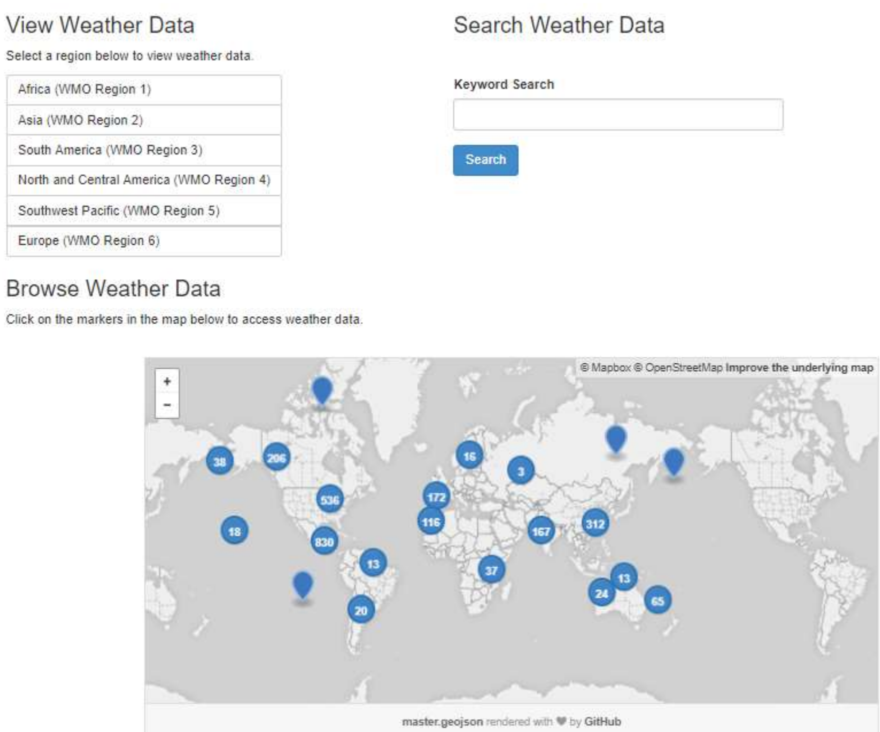


Figure 5.1 - EnergyPlus weather data map
Source [112]

The weather data freely available for Romania is provided by ASHRAE IWEC2 (International Weather for Energy Calculations). The IWEC2 files contain 'typical' year data to be used in building energy simulation programs [112]. A 'typical' year weather data is obtained from combining multiple years weather data for a certain location in order to best represent the pattern and range of weather parameters for the location on the long term. This type of weather data is generally used in building simulations instead of a single year weather data which might not represent long-term typical weather conditions over a year [84, [112]. The available data can be used for the design and sizing of heating, ventilation and air conditioning (HVAC) equipment and for other energy-related analyses in buildings.

5.1.3 Using EnergyPlus

EnergyPlus is characterized by flexibility and is not limited to predefined system configurations. The software has HVAC templates to be used for standard system structures that can be adapted for each situation in order to match the real building system that has to be simulated. HVAC templates feature is very useful for beginners because they ease the process of implementing building system in the model, which can be quite difficult for engineers or architects that use the software for the first time.

The simulation software is in fact a simulation engine that was designed to be a component in a complex software that includes a graphical user interface to define the building. Although, there are several user friendly graphical interfaces available to be used with, this software can be run stand-alone without such an interface. The process of creating a building energy model in this software, without the use of a graphic interface, can be more difficult compared to other exiting software. In order to run EnergyPlus, the EP-Launch program is used (Figure 5.2). EP-Launch is available for Windows users and represents a simple way of selecting a file with a building model and run a simulation. This auxiliary program works like an assistant that gathers all the input files needed to run the simulation, runs the simulations and offers access to the output files. Thus, EP-Launch allows: selecting the input file and weather file, running the simulation, opening a text editor for the input file, opening results files, opening an internet browser for the results file, opening errors file and a viewer for the building geometry drawings.

The error output file is the first thing to be verified after running a simulation. Right after the simulation is finished, a status message appears on the screen that offers an overview of the correctness of the model. The status includes the number of warnings (things that need to be verified), severe errors (the model should be fixed) and/or fatal errors (the model must be fixed). In case of a fatal error, the simulation is stopped and no results can be viewed. The error output file can be opened from EP Launch. The advantage of this file is the fact that it indicates exactly where the problem is, thus facilitating the correction and improvement of the model.

The input file that describes the building is an IDF file and is created in a separate tool of the main software, called IDF Editor (Figure 5.3). The IDF Editor comes along with the installation and allows creating or editing input file that represents the building energy model. IDF editor does net verify the input data correctness but some numeric fields are highlighted if the input is out of range and text files are highlighted if the data is invalid. Through the IDF Editor, all the input data related to a building is defined: geometry, orientation, building materials and thermal properties, heating, cooling and ventilation systems, temperature set points schedules, equipment schedules, lighting schedules etc.

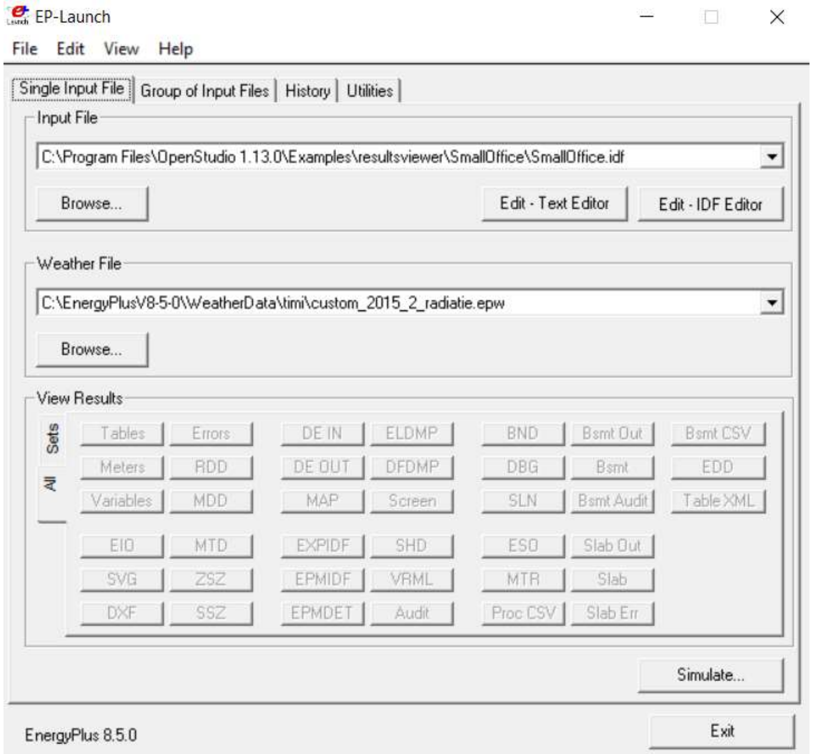


Figure 5.2 - EnergyPlus component - EP-Launch

Creating the building energy model by solely using the IDF Editor could require a lot of time and labour for a building with many thermal zones and a sophisticated architecture and equipment. In the last years, several graphical interfaces were developed. The most used is Open Studio that uses the Google Sketch up Plug-In. These two programs, offer the possibility of a simplified and comprehensive process for data input. Google Sketch up is extremely useful in creating the geometry of the building with envelope details: windows, doors, shadings. Open Studio is useful in defining all parameters and characteristics of the building envelope elements and building equipment [113].

If the model is generated without using a graphical interface, the building geometry is defined using coordinates, as well as the building thermal zones. The coordinates are introduces considering the user defined global geometry rules. The building geometry can be visually verified afterwards by using the DXF option (in EP Launch) that generates an AutoCAD file containing the building geometry. To each envelope element is assigned a surface type, construction layers and boundary conditions. These steps that include the building geometry, construction layers characteristics define the building envelope that separates the indoor environment from the outdoor environment.

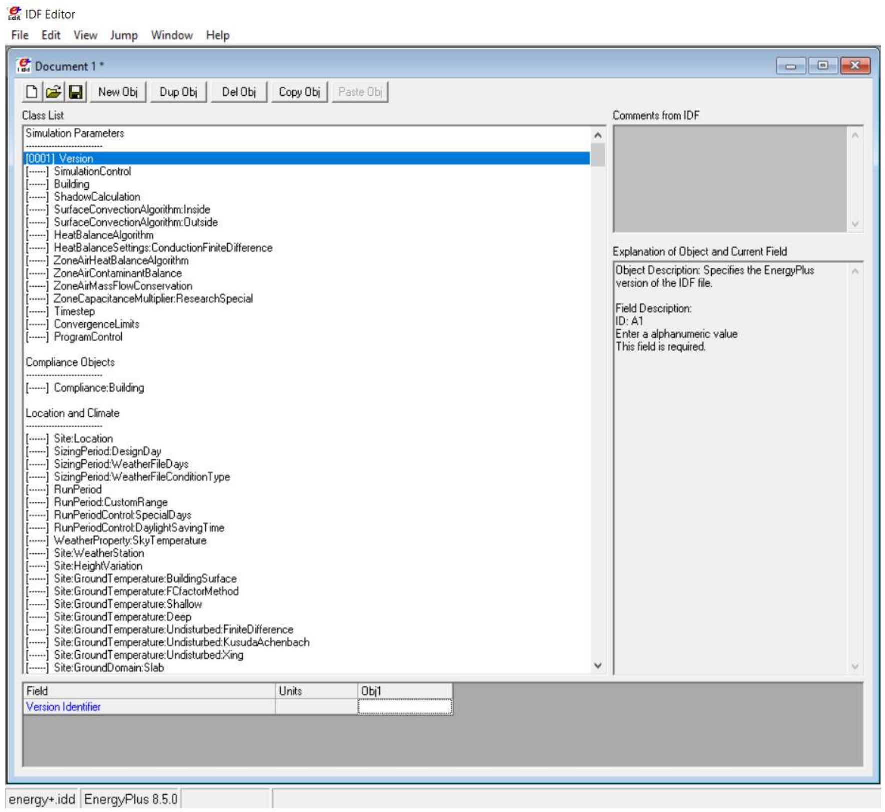


Figure 5.3 - EnergyPlus component – IDF Editor

The energy consumption of the building can vary greatly influenced by internal heat gains, heat losses and by the way it is operated. The software allows defining the input related to the building internal heat gains (occupancy, human activity, lights, electric equipment etc.), infiltration, natural ventilation etc. Once the building envelope is designed, the building equipment can be accurately defined.

An extremely important feature of EnergyPlus software consists in the accuracy with which the building operation can be defined. In order to do this, the program allows the user to define schedules that influence many items such as occupancy, lighting, thermostatic controls, human activity, shadings, ventilation etc. Also, the programme allows defining day types used for sizing building equipment (SummerDesignDay, WinterDesignDay).

The possibility of creating custom and accurate building operation schedules is extremely useful for the research developed in this thesis because it allows generating schedules based on hourly building monitoring data. This is a first step in creating a calibrated energy model for the studied building. The objective of the calibration is to see if the energy model can provide energy related results that closely match the measured values using actual building operation inputs (occupancy schedule, lighting and equipment schedules and densities, and the HVAC system parameters and controls), including weather.

For the simulations performed in this thesis EnergyPlus version V8.5.0. The building geometry was defined using coordinates and AutoCAD and GoogleSketchup were solely used to verify the correctness of the geometry.

5.2 Development of the building energy model

This subchapter follows the analysis of the building energy model performance by using monitoring data as input in order to calibrate the simulation to match the measured energy consumption of the building. The procedure consists in using real operation conditions to calibrate the simulation. The following measured parameters were used for the building energy model: hourly interior temperature for heating and cooling temperature set points schedules, hourly exterior temperature, measured infiltration rate, hourly lighting and electric equipment energy consumption for internal loads. A set of data from 2015 was used for the calibration.

5.2.1 Methodology

The proposed methodology for building energy model calibration is presented in Figure 5.4. The first step in the methodology is to define the building physical parameters. The building geometry was defined using as-built drawing of the building. Construction materials were defined according to as-built construction drawings as well. The second step of the proposed methodology consists in defining the building operation schedules. Thus, based on the monitoring data, hourly schedules are defined for heating and cooling set point, interior equipment and lighting power consumption, cold water intake. Besides the building operation parameters and physical characteristics, real condition weather data is essential to use in order to calibrate the simulation. A custom weather data file is generated using hourly measured values for the exterior temperature. When the building energy model is complete and has all the information, the first simulation is ran. The calibration is an iterative process that consists in adjusting the building parameters until the normalized mean bias error (NMBE) and the coefficient of variation of the root mean square error (CVRMSE) are within the acceptance criteria. Thus, at each stage in the model iteration, an error verification is carried out in order to validate the results of the simulation. The NMBE and CVRMSE are calculated for monthly energy consumption values using the results of the simulation and the monthly energy consumption of the building measured in 2015. If the results of the simulation meet the acceptance criteria, then the building energy model is considered calibrated. If the calibration acceptance criteria is not met, further improvements and adjustments of the building energy model are required. The iterative process of improving and adjusting the building energy model is the most difficult part of the process because it requires expertise in order to identify the parameters that need to be modified. For the case study in this thesis, a major source of uncertainty, which is related to the internal loads, is reduced due to the fact that real measured data is used as input. Nevertheless, the following sources of uncertainty are still left:

- outdoor weather conditions: solar radiation;
- building envelope real characteristics;
- HVAC system operation and real performance;
- metered data accuracy;
- modelling assumptions.

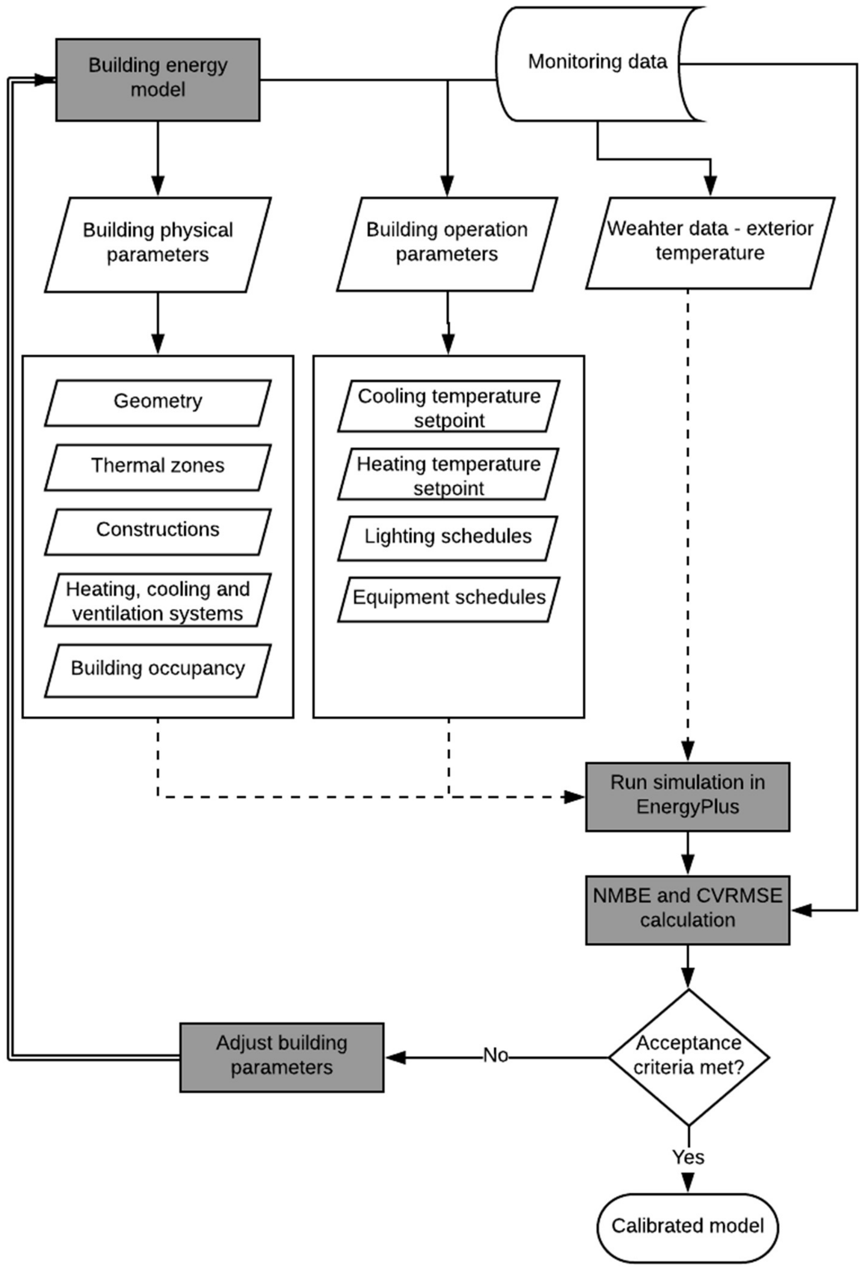


Figure 5.4 - Building energy modelling and calibration procedure

5.2.2 Initial input data

The energy model of the investigated building was created using the IDF Editor platform from EnergyPlus version V8.5.0. In the following subchapters, the most relevant steps in creating the building energy model are presented.

The first steps in creating the model consists in defining the data related to the building orientation, terrain and other data related to the simulation (Figure 5.5). The 'North Axis' field represents the deviation of the building in degrees from the true north. The 'Terrain' field is helpful for the software to determine the wind exposure (as well as the building height). The 'Solar Distribution' determines how the software treats solar radiation from exterior surfaces that reach the building and enter the zone. In the 'Building' section, the parameters related to warmup convergence are defined. These values used in these fields are the default values recommended by EnergyPlus documentation and tutorials. The maximum number of warmup days is set to 25 which is the default value in EnergyPlus. In the software documentation it is specified that this number is generally enough to achieve convergence [114].

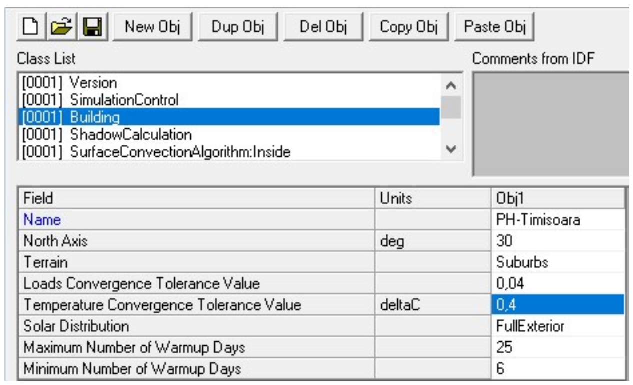


Figure 5.5 - Defining building orientation – IDF Editor

The minimum number of warmup days was set to 6 which also the default value in EnergyPlus. The EnergyPlus documentation states that this number is generally enough to avoid false predictions of convergences and generate enough temperature and flux history to start the simulation [114].

Figure 5.6 shows the input data related to building location. The latitude and longitude were determined using Google Maps. Also the time zone is defined relative to the Greenwich Mean Time (+2). The field 'Elevation' refers to the elevation of the building in meters relative to the sea level. The building geometry is defined using coordinates specified in the IDF Editor. In order to properly define the building geometry (zones and surfaces), firstly the geometry rules have to be established (Figure 5.7).

EnergyPlus uses a three dimensional (3D) Cartesian coordinate system for surface vertex specification. For this building model, the starting position of inserting the vertices of a surface is the upper left corner. The coordinates are always specified considering that the surfaces are viewed from the exterior of the zone to which they belong. The direction for entry the coordinates is selected to be counter clockwise form the starting position. Also, the vertices are specified using relative coordinate system.

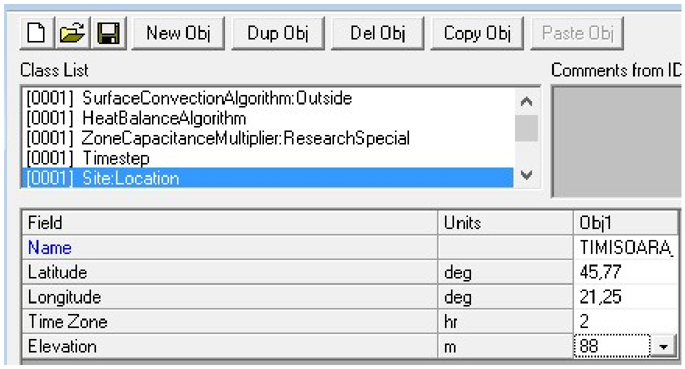


Figure 5.6 - Defining building location – IDF Editor

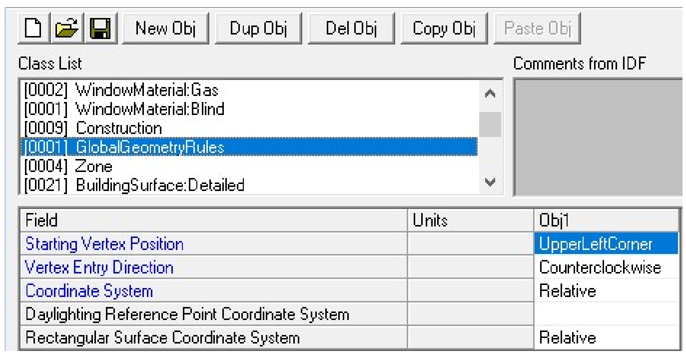
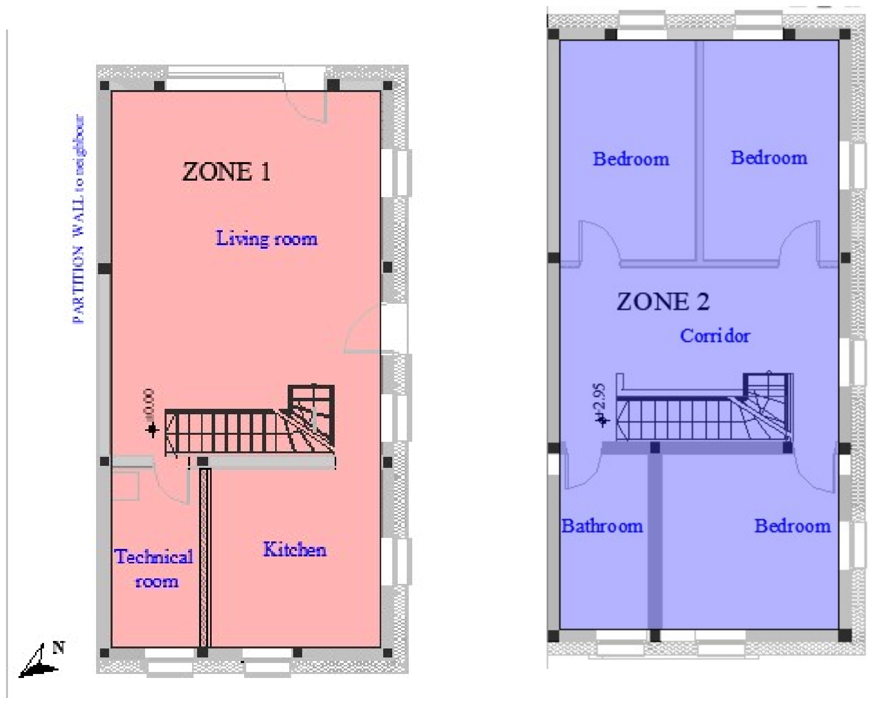


Figure 5.7 - Rules related to geometry

5.2.3 Division of the building into thermal zones

In order to create the geometry of the building, the first step is to divide the building into thermal zones. A thermal zone must not be confused with a geometric concept. A thermal zone is the space in the building enclosure characterized by the same set-point temperature and that has negligible temperature variation inside the zone. A thermal zone can be composed from multiple rooms of the building. The software determines the necessary energy to maintain each zone of a building at a specified temperature for each hour of the day. According to EnergyPlus documentation, the general rule in zoning a building is to use the number of fan systems (and radiant systems) not the number of rooms to determine the number of zones in the building [115]. The studied building is divided into 2 thermal zones as it is represented in Figure 5.8.



a) Ground floor b) First floor

Figure 5.8 - Building division in thermal zones

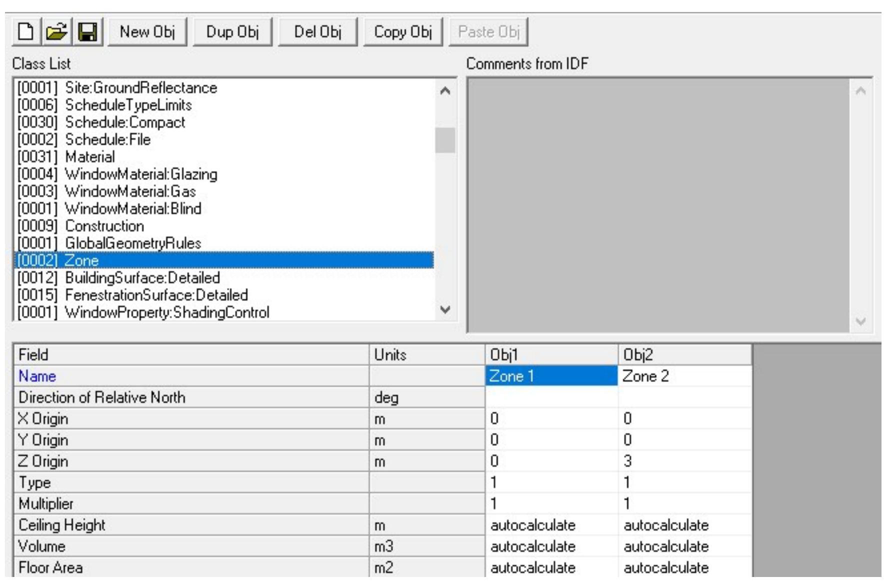


Figure 5.9 - Thermal zones specification in EnergyPlus IDF Editor

The decision was made to separate the ground floor rooms from the first floor room, each of them being served by an individual fan system. Zone 1 and Zone 2 are part of the conditioned building area through heating and cooling thermostat set-points. Zone 1 is on the ground floor and is composed from the living room, kitchen and technical room. Zone 2 is on the first floor and is composed of three bedrooms, a corridor and a bathroom. The zones were specified in the IDF Editor using coordinates that define the starting point of each zone (Figure 5.9).

5.2.4 Building geometry, envelope and construction layers

Building surfaces

The geometry of the building was created directly in the IDF Editor by using coordinates. The geometry of the building was defined using centreline dimensions. The envelope elements were defined as surfaces and each building surface was assigned to the belonging thermal zone. In order to verify the building geometry, the input file was exported in Google Sketchup and the results can be seen in Figure 5.10. For each type of surface, a different colour was assigned: yellow for vertical opaque surfaces, blue for windows and maroon for horizontal surfaces.

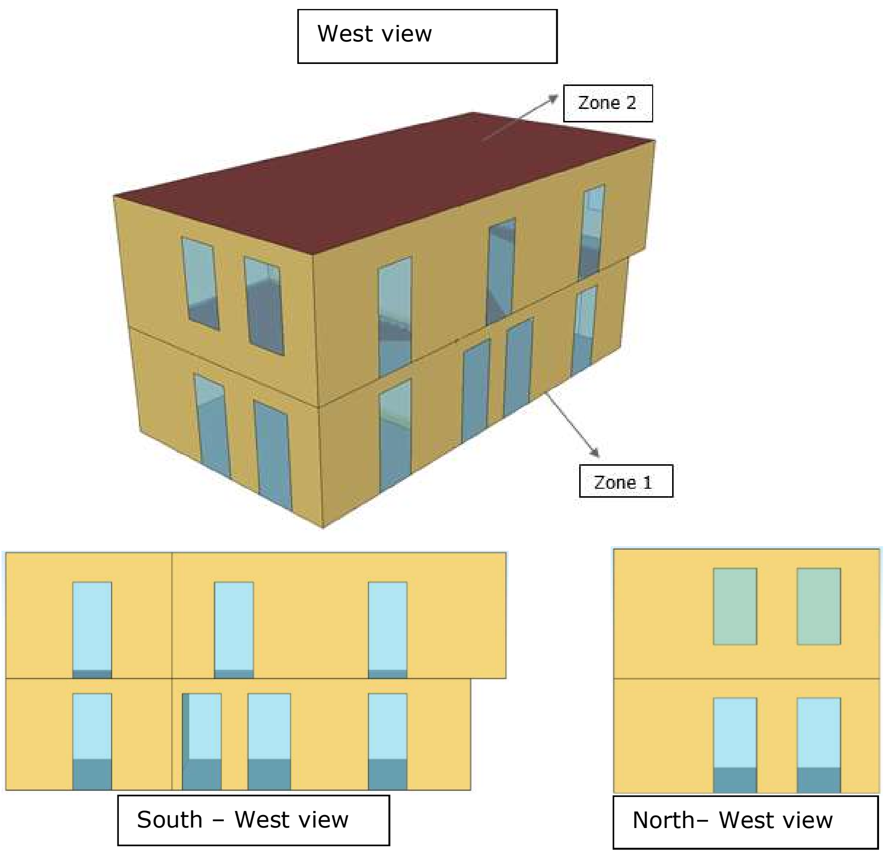


Figure 5.10 - Building geometry exported in Google Sketchup

The opaque building surfaces were defined in the IDF Editor, field 'BuildingSurface:Detailed' (Figure 5.11) and for each surface a unique name was assigned. In order to perform heat transfer calculations, construction layers were defined for each type of surface. The building surfaces coordinates are presented in Appendix C for each thermal zone.

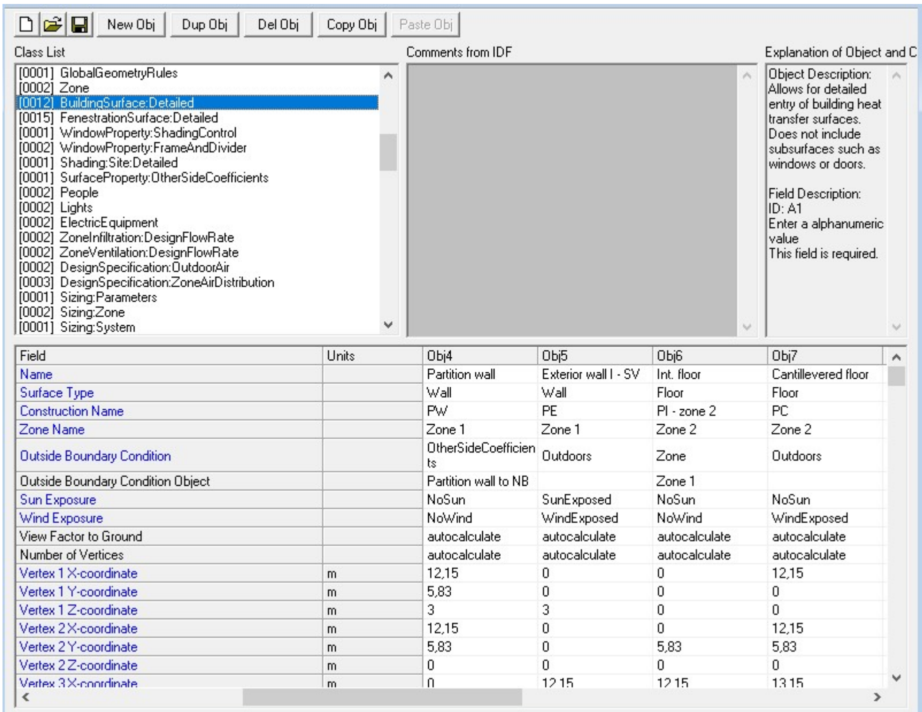


Figure 5.11 - Building opaque surfaces – coordinates specification in IDF Editor

Based on the coordinates, the software automatically calculates the surfaces for each envelope elements and displays the results in the tabular output report in HTM format. The information presented in Table 5.1 are taken from the report created by Energy Plus at the end of the simulation.

Table 5.1 - Opaque envelope elements summary

Envelope elements		Net Area [m^2]
Exterior wall	South-East	27.07
	South-West	64.27
	North-West	27.07
Partition wall		74.81
Ground floor		76.88
Cantilevered floor		6.25
Roof		83.13

Windows surfaces and characteristics were specified in the section 'FenestrationSurface:Detailed', similarly to the opaque surfaces (Figure 5.12). Each window was assigned to its corresponding opaque surface and the coordinates were defined relatively to the corresponding opaque surface. Table 5.3 contains the characteristics of the windows.

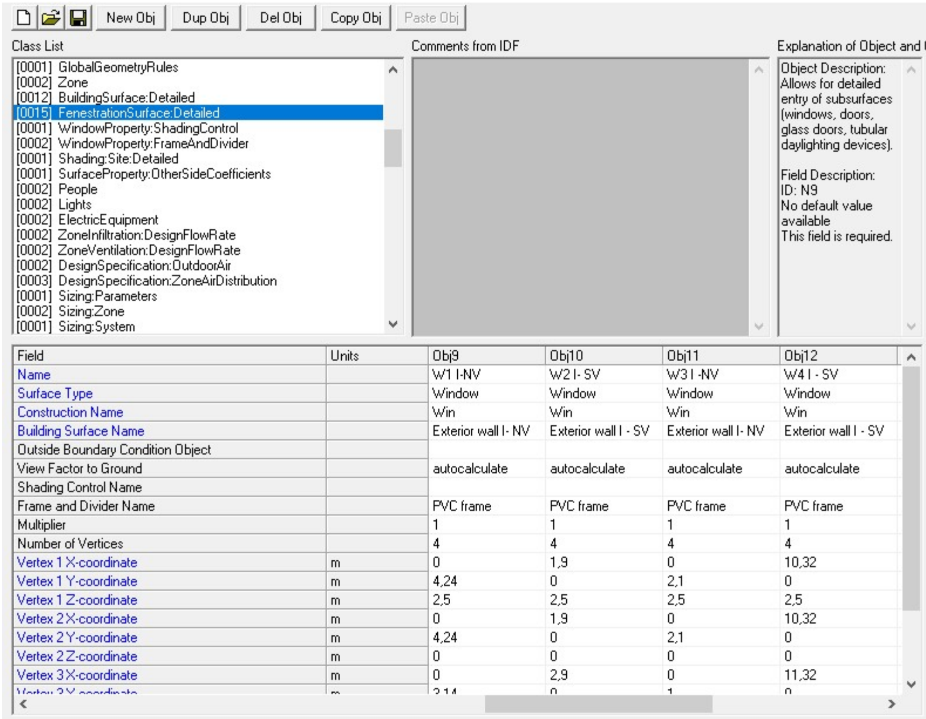


Figure 5.12 - Building windows surfaces – characteristics specification in IDF Editor

Table 5.2 - Windows characteristics summary

Window Area Orientation	Window area	Glazing area
	m^2	m^2
South-East	12.69	9.5
South-West	16.50	11.7
North-West	9.68	6.8

Boundary conditions
Also, in this field, the outside boundary conditions were selected. The exterior walls, windows and roof are exposed to outdoors as boundary conditions and the ground floor is exposed to the ground. For the partition wall that separates the two apartments, the boundary conditions were defined in order to consider that in the other apartment the temperature was lower because the space was not heated during the considered period of analysis, thus leading to thermal transfer between the two apartments. The outside boundary condition was defined as 'OtherSideCoefficients' which has an associated object 'SurfaceProperty:OtherSideCOefficients'. By referencing the Other Side Coefficients statement in the surface statements, the temperature of the outer plane of a surface is controlled through a temperature schedule. All heat transfer surfaces are simulated in the same manner through

conduction transfer functions. The only difference between the various types of heat transfer surfaces is the environment on the other side of the surface [114]. Thus, a monthly average temperature schedule was defined based on the measured interior temperature in the other apartment of the duplex. The values for the average monthly temperature used as boundary condition for the partition wall are presented in Table 5.3.

Table 5.3 - Monthly average temperature – boundary conditions for partition wall

Month	Monthly average temperature [ºC]
January	20.89
February	19.07
March	21.99
April	23.39
May	24.94
June	25.46
July	28.22
August	27.62
September	25.94
October	23.41
November	18.74
December	18.35

Construction layers and material properties

The construction layers for the envelope elements were defined in the field 'Construction' using materials that were previously defined in field 'Materials'. The construction layers were specified starting with the outside layer. For each layer were specified the thickness, thermal conductivity, density and specific heat. A more detailed description of the composition of the building envelope elements defined in EnergyPlus are presented in Chapter 3, Figure 3.6. The characteristics of the materials that compose the envelope elements of the building are presented in Appendix A. For some of the materials, the characteristics were provided by the manufacturer and for those who not, the characteristics were taken from Appendix B of Mc 001/1 – 2009 – Methodology for the energy performance calculation of buildings part IV [116]. Figures 5.13 and 5.14 exemplify the procedure of defining the construction layers and materials in the IDF Editor.

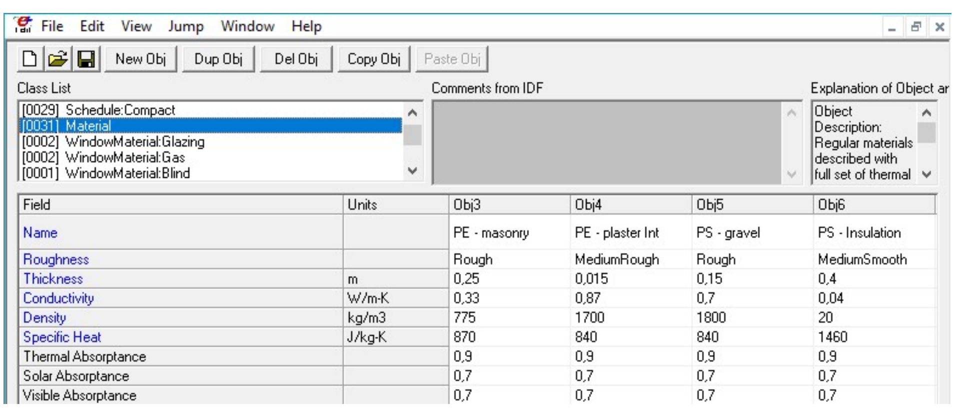


Figure 5.13 - Materials

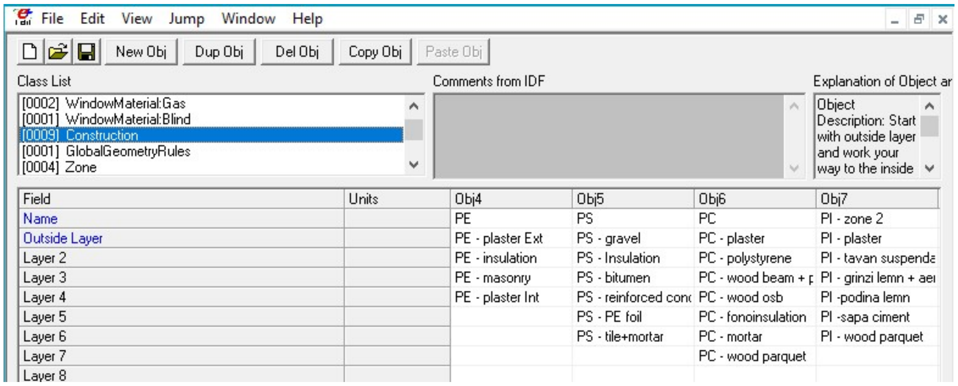


Figure 5.14 - Construction layers

5.2.5 Input data for heating, cooling and domestic hot water

Heating, cooling and ventilation system features
The building systems were modelled considering the features and efficiencies specified in the technical books provided by the manufacturers. The air to water heat pump has a COP of 2.98, according to the technical sheet. The hot water storage buffer for heating has a volume of 500 l and a 3 kW electric heating element as a back-up source of heat. The rated heating capacity of the fan coils was set to 2740 Watts and the rated cooling capacity to 2800 Watts.

Heating and cooling system availability
The heating system is scheduled to be available from the 15th of October until the 15th of April. According to the monitoring data, the cooling system was solely active in August (Figure 5.15). The state sensors that indicate the cooling system activity indicate that it was available solely in August between 14:00 and 20:00 (Figure 5.16).

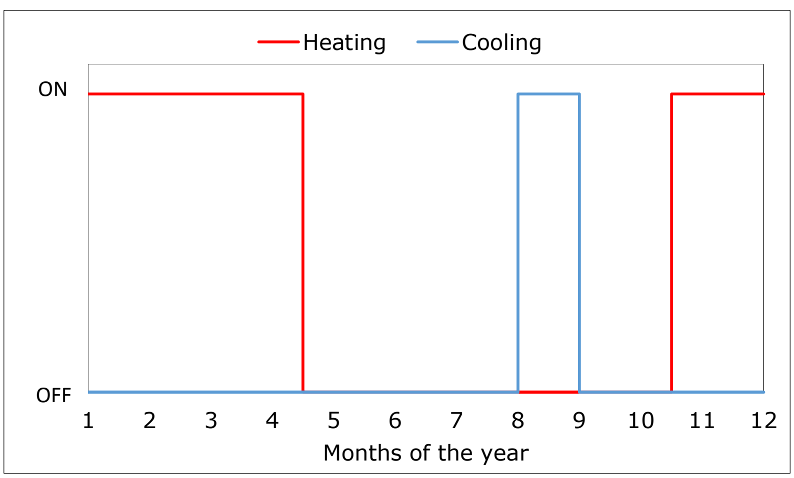


Figure 5.15 - Heating and cooling system availability throughout the year

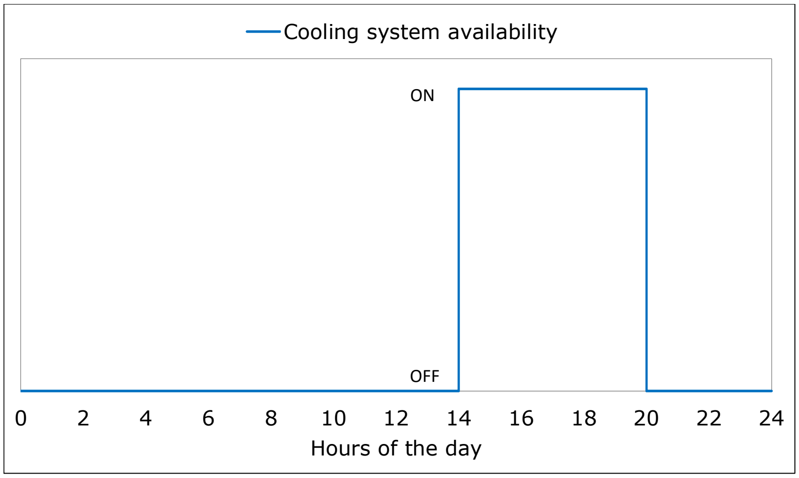


Figure 5.16 Cooling system availability throughout the day

Cold water supply temperature

The cold water supply temperatures was defined using the „Site:WaterMainsTemperature" object in EnergyPlus. A monthly temperature schedule was created using data measured in 2015 for the cold water supply temperature. The obtained values are presented in Table 5.4.

Table 5.4 - Monthly average cold water temperature

Month	Monthly average temperature [ºC]
January	15.96
February	15.94
March	16.91
April	18.63
May	21.24
June	22.13
July	24.51
August	25.95
September	24.11
October	21.02
November	17.49
December	17.82

Domestic hot water parameters

The domestic hot water consumption and energy were not monitored. Therefore, the needed volume of domestic hot water was calculated according to the Romanian regulations [117], using the formula in Equation 5.1.

$$V_{ac} = \frac{a \cdot N_u}{1000} \quad [m^3/day]$$ Eq. 5.1

In Equation x, V_{ac} is the domestic hot water demand volume per day, a is the specific demand of domestic hot water at 60ºC, for the considered use and period and is determined according to Annex II.3.A in MC001/3 [117], N_u is the number of persons that use domestic hot water (number of occupants of the building).

Table 5.5 - Input data for domestic hot water demand

Parameter	Value
a	75 liters/person/day [117]
N_u	3 persons
V_{ac}	0.225 m^3 / day

In order to calculate the energy consumption for domestic hot water, the software Energy Plus requires the peak demanded hot water flow rate in m^3/s. The value for V_{ac}, presented in Table 5.5 is converted resulting 2.6×10^{-6} m^3/s.

The domestic hot water is provided by a solar collector that has a surface area of 4.92 m^2 and is placed on the roof. The domestic hot water is stored in a 150 litres electric boiler.

5.2.6 Mechanical ventilation parameters

As presented in the previous chapter, the ventilation of the building is controlled through a mechanical ventilation system with heat recovery. The mechanical ventilation unit is a centralised unit with fans and constant volumetric flow regulation. The air flow is adjustable between 100 m^3/h and 250 m^3/h. Based on the information received from the building occupants, the ventilation rate of the mechanical ventilation system is different for summer and winter. From the 15^{th} of October until the 15^{th} of April the outdoor air flow volume was set to 0.0277 m^3/s and for the rest of time to 0.0694 m^3/s. The efficiency of heat recovery, according to the technical sheet is 92%. The heat exchanger of the mechanical ventilation unit is on from 15^{th} of September until the 15^{th} of May. The heat exchanger is off during summer in order to avoid heating the fresh air from the exhaust air.

The ventilation system is equipped with an underground heat exchanger to preheat and precool the air before entering the mechanical ventilation unit. The temperature of the air leaving the underground pipes was measured, thus being possible to use the hourly values as input data in the building energy model. The hourly measured values of the air temperature leaving the underground pipes are presented in the graph in Figure 5.17. These temperatures were introduced in the building energy model to serve as air intake for the mechanical ventilation system, replacing the outdoor air intake. A .cvs schedule file was created using the monitored temperatures presented in Figure 5.17. With the help of 'EnergyManagementSystem' routines available in Energy Plus, the dry bulb and wet bulb temperatures in the weather file were replaced with the values found in the .cvs file, but only for the outdoor air intake node of the mechanical ventilation system. The underground heat exchanger is on all year long.

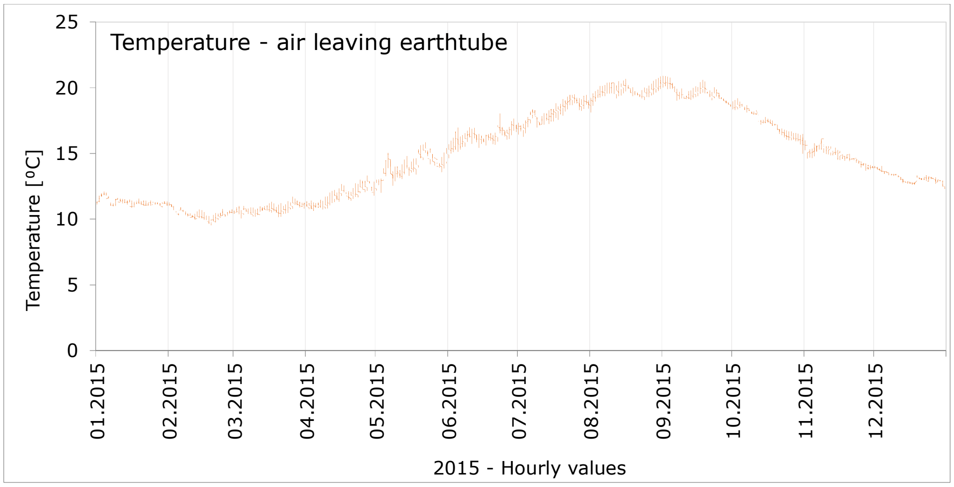


Figure 5.17 - Hourly measured air temperature after passing through underground pipes

5.2.7 Infiltration and natural ventilation

A fan pressurization test at 50 Pa was carried out in order to determine the real infiltration rate of the building. The measured building's air change rate at 50 Pa was approximately 0.6 h^{-1}. The conversion from the measured building's air change rate to infiltration rate at atmospheric pressure was made according to [39], based on EN 13790 [87], using Equation 5.2 and the parameters presented in Table 5.6.

$$n_{V,Res} = n_{50} \cdot e \cdot \frac{V_{n50}}{V_{RAX}} \qquad \text{Eq. 5.2}$$

Table 5.6 - Air infiltration rate calculation parameters

Parameter	Value	Reference
n_{50}	0.60 [h^{-1}]	measured using a pressurization test
e	0.07 [-]	determined according to EN832, moderate screening building
V_{n50}	370 [m^3]	it is derived by doing a room by room air volume measurement
V_{RAX}	354 [m^3]	effective air volume, calculated by multiplying the treated floor are by a standardized ceiling height of 2.5 m
$n_{V,Res}$	0.044 [h^{-1}]	Calculated using Equation (4.1)

In equation 5.2 the following parameters were used:
n_{50} - fan pressurization test result; e - wind screening coefficient according to EN832 [118];
V_{n50} – net air volume – reference volume for the fan pressurization test;
V_{RAX} – air exchange volume.

The input for the infiltration rate of the building was set to 0.044 h^{-1}. Besides the infiltration rate of the building, natural ventilation associated to windows night opening was considered during summer, as a passive cooling strategy. Although the building occupants could not give precise information with the exact number of hours the windows were opened, a schedule for night ventilation through windows opening was defined from June until September, between hours 20:00 and 7:00.

The area of the window opening was defined using the object in EnergyPlus ,,ZoneVentilation:WindandStackOpenArea'', where two windows considered for the ground floor space and two windows of for first floor space.

5.2.8 Building occupancy and activity

The input data for building occupancy is based on the information received from the occupants. The house is inhabited by a young family: two adults and one children (two children from 2017). The data related to people in the building is specified in the field 'People'. Here, the data necessary for calculating the internal heat gains related to human activity is defined.

The occupancy schedule was defined for weekdays and weekends, considering the information received from the occupants and is defined as fraction from the total number of occupants. Thus, a typical occupancy schedule was defined for weekday and weekend, considering the information received from the occupants. The daily occupancy profile can be seen for each of the two zones in Figure 5.18 and Figure 5.19. During weekdays, between 23:00 and 07:00, the bedrooms are considered fully occupied (Zone 2), while the living room and kitchen (Zone 1) were occupied by two persons between 09:00 and 18:00 and fully occupied between 18:00 and 22:00.

Table 5.7 presents the data related to the metabolic rates for the human activity considered for this building. The human activity is as well defined through schedules. The activity profile was defined considering three types of activities carried out in the building, as presented in Table 5.7. Combining building occupancy and activity schedules, the internal heat gains related to people in the building are accounted in the building simulation.

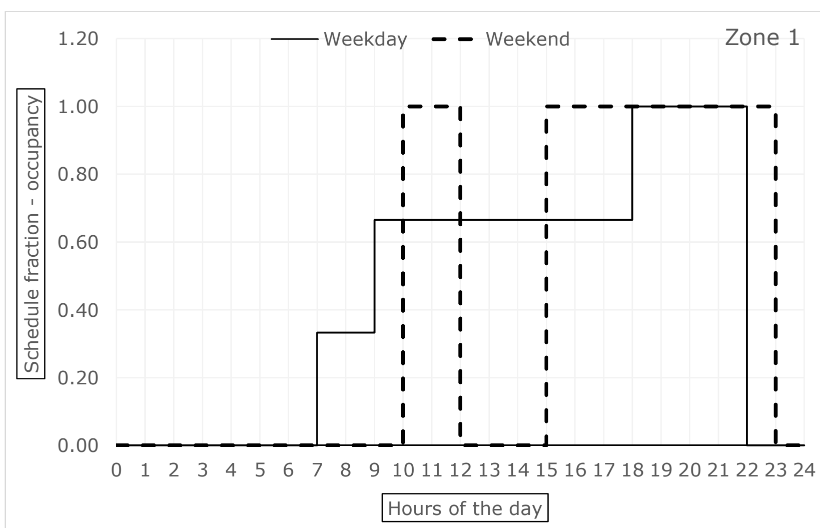


Figure 5.18 - Occupancy schedules for weekend days and weekdays ZONE 1

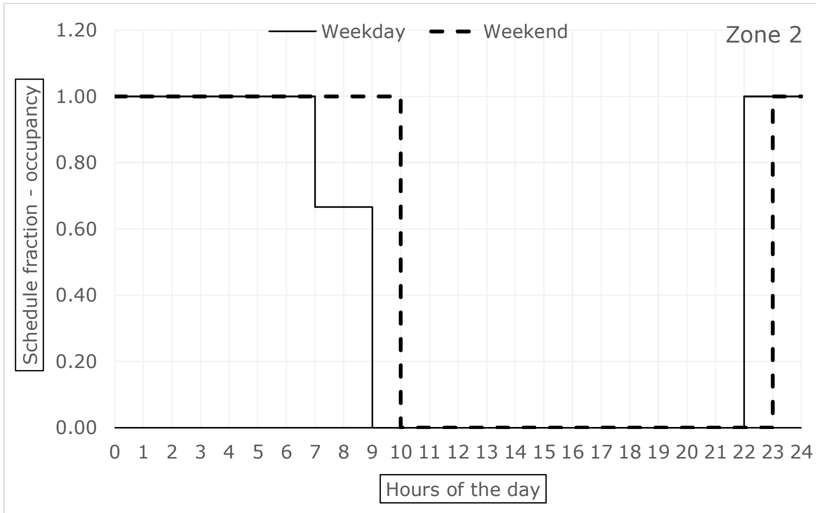


Figure 5.19 - Occupancy schedules for weekend days and weekdays – ZONE 2

Table 5.7 - Metabolic rates for the human activity considered in the building model

Activity	Metabolic rate** [W/m^2]	Metabolic energy per person [W]
Reclining	46	78.2
Sedentary activity	72	122,4
Standing, medium activity	116	197.2

** The metabolic rate was defined according to ISO 7730, Annex A, Table A.1. [40]

5.2.9 Interior equipment and lighting

A major part of the energy consumed by the interior electrical equipment and interior lighting in the building becomes a heat gain and influences the building energy balance. In order to define as accurate as possible the internal loads associated to interior lighting and electrical equipment, the electricity consumption periods were defined using schedules generated based on hourly monitoring data.

For each month of the year, an hourly consumption day profile was generated for interior equipment energy consumption, based on the formula in Equation 5.3.

$$E(m,h) = \frac{\sum_{h=1}^{n} e(d,h)}{n} \quad [W] \qquad \text{Eq. 5.3}$$

In Equation 5.3 *m* is the month of the year, *h* is the hour, *n* is the number of weekend days/weekdays in month *m*, *E(m,h)* is the average hourly consumption in month *m* at hour *h in* Watts, *e(d,h)* is the hourly consumption at hour *h* in day *d* in Watts.

The decision to create an hourly day profile schedule for each month instead of an average value for all days in each month, was taken with the purpose of simulation a more accurate distribution of the internal loads along the day.

The lighting and electrical equipment schedules were created as fractions of the maximum hourly registered power consumption in 2015 for each category. In order to determine the maximum power, first the day consumption profile was determined for each month and afterwards the hour that had the higher consumption was selected. The selected value was then divided to the building conditioned area. The fraction schedule was determined by dividing the hourly consumption *E(m,h)* to the maximum hourly value registered in the considered month.

The input data for interior equipment is specified in the field 'ElectricEquipment'. This section models equipment in the building which consume electrical energy (computers, cooking equipment, televisions etc.) and allows to input the information related to a zone's electric equipment such as power and operation schedule. The maximum electrical input to equipment was set to 3.96 W/m^2, which is the maximum value measured in 2015. The maximum electrical input value is modified by the electric equipment operation schedule. Thus, the actual electrical input for the equipment in the building is the product between the maximum power and the value of the schedule. The graphs in figures from 5.20 to 5.31 show the hourly schedule of equipment electricity consumption for each month as a fraction of 3.96 W/m^2.

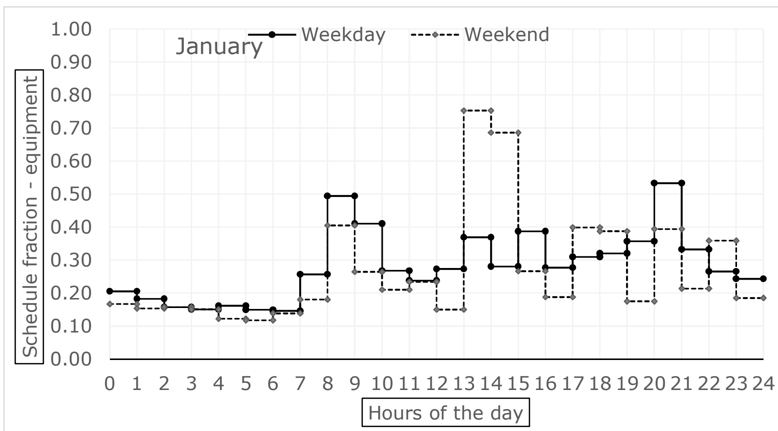


Figure 5.20 - Interior equipment consumption schedule for January

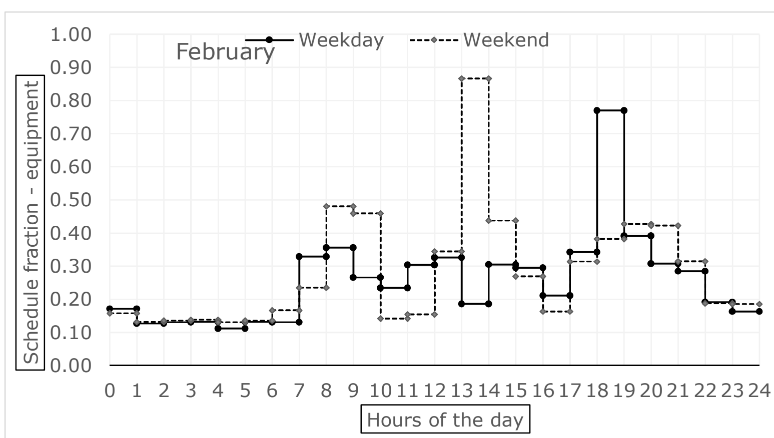


Figure 5.21 - Interior equipment consumption schedule for February

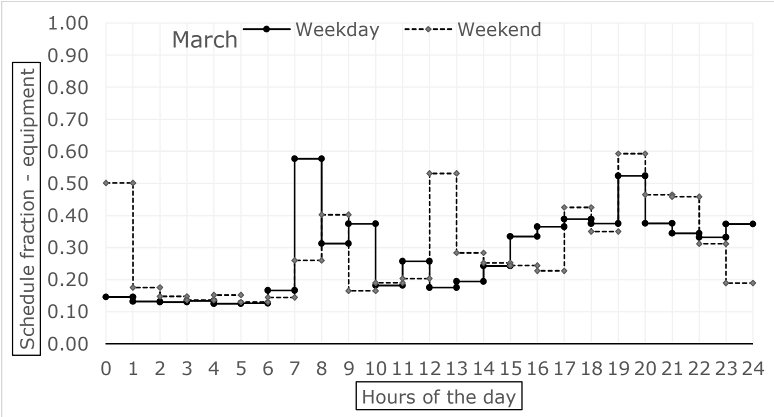


Figure 5.22 - Interior equipment consumption schedule for March

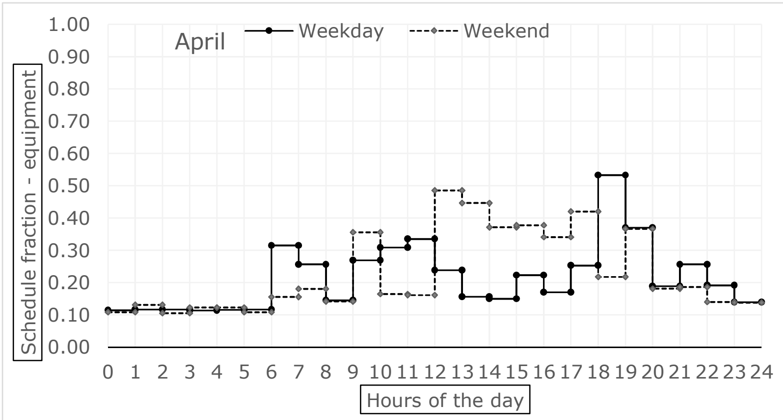


Figure 5.23 - Interior equipment consumption schedule for April

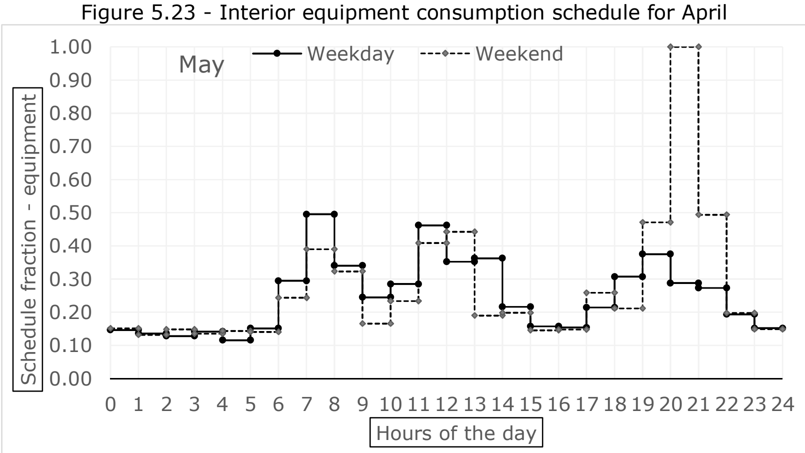


Figure 5.24 - Interior equipment consumption schedule for May

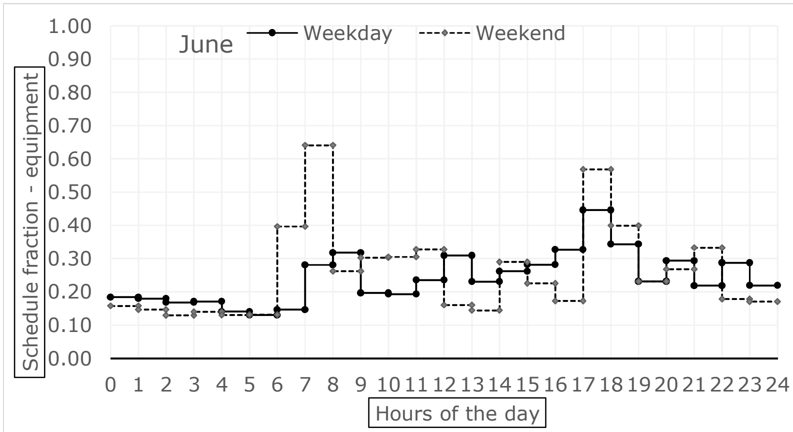


Figure 5.25 - Interior equipment consumption schedule for June

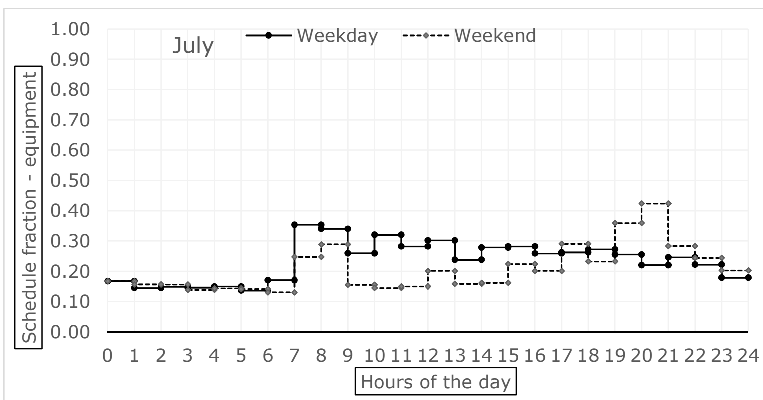


Figure 5.26 - Interior equipment consumption schedule for July

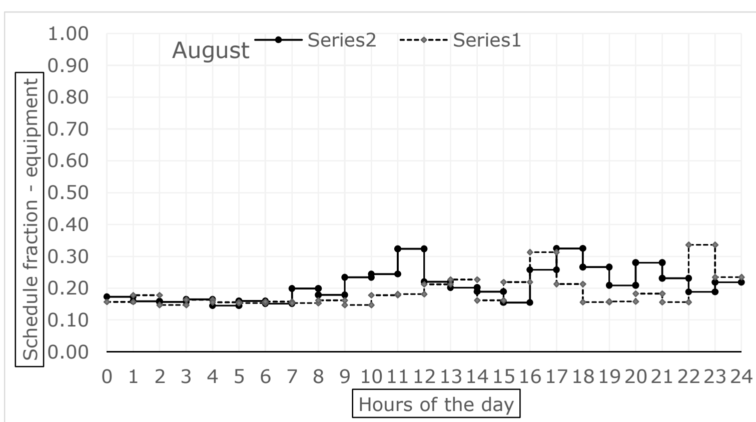


Figure 5.27 - Interior equipment consumption schedule for August

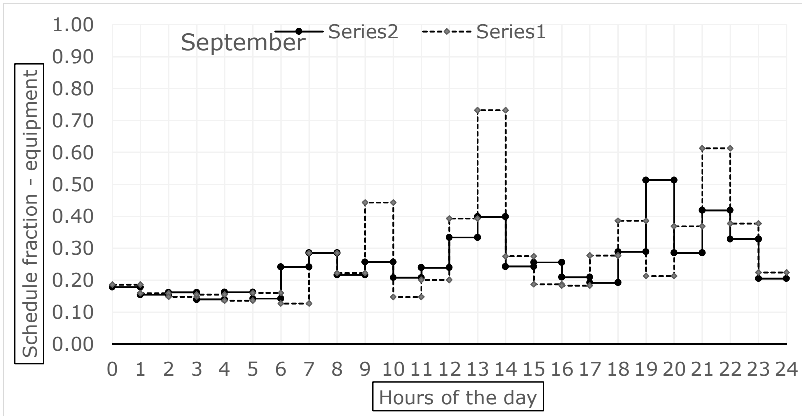


Figure 5.28 - Interior equipment consumption schedule for September

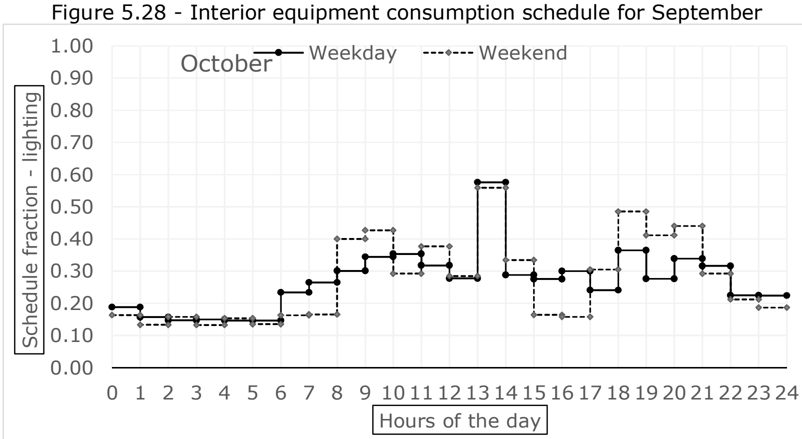


Figure 5.29 - Interior equipment consumption schedule for October

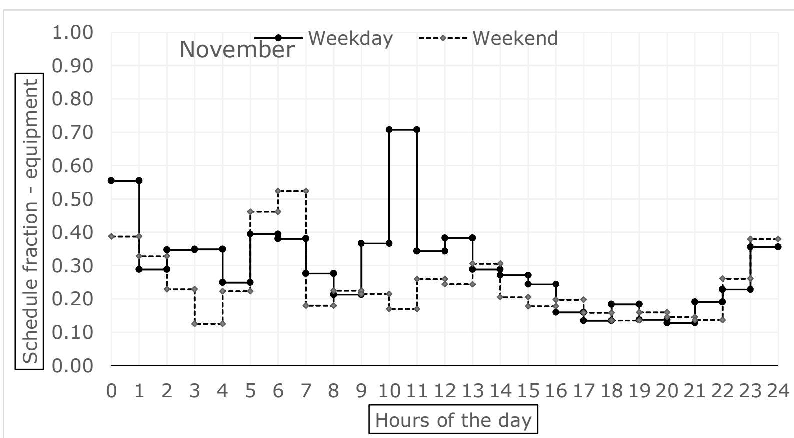


Figure 5.30 - Interior equipment consumption schedule for November

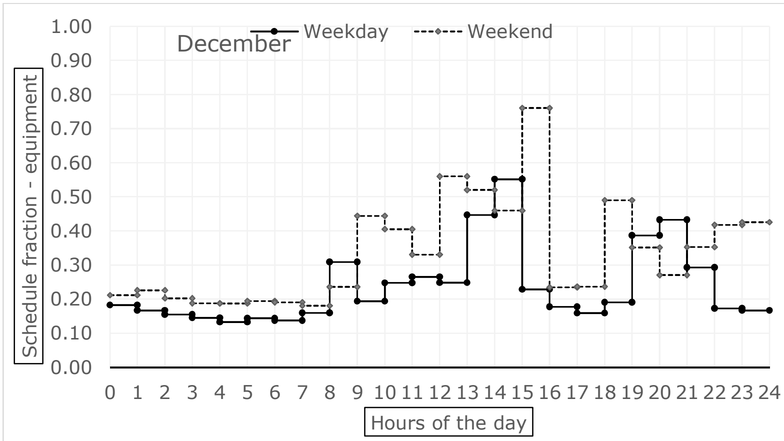


Figure 5.31 - Interior equipment consumption schedule for December

The input data for lighting is specified in the field 'Lights'. This section allows to input the information related to a zone's electric lighting system such as power, operation schedule and the way in which the heat is distributed.

For each month of the year, two hourly consumption profile was generated for interior lighting energy consumption for weekend and weekdays, based on the formula in Equation 5.4.

$$L(m,h) = \frac{\sum_{h=1}^{n} l(d,h)}{n} \quad [W] \qquad \text{Eq. 5.4}$$

In Equation 5.4 *m* is the month of the year, *h* is the hour, *n* is the number of weekend days/weekdays in month *m*, *L(m,h)* is the average hourly consumption in month *m* at hour *h in* Watts, *l(d,h)* is the hourly consumption for lighting at hour *h* in day *d* in Watts. The decision to create an hourly day profile schedule for each month instead of an average value for all days in each month, was taken with the purpose of simulation a more accurate distribution of the internal loads along the day.

The hourly schedules for Interior lighting were also created as fraction of the maximum registered power load for lighting in 2015. The maximum electrical input to equipment was set to 1 W/m^2, which is the maximum value measured in 2015. The maximum electrical input value is modified by the lighting operation schedule. Thus, the actual electrical input for lighting in the building is the product between the maximum power and the value of the schedule. The graphs in figures from 5.32 to 5.43 show the hourly schedule of interior lighting consumption for each month as a fraction of 1 W/m^2.

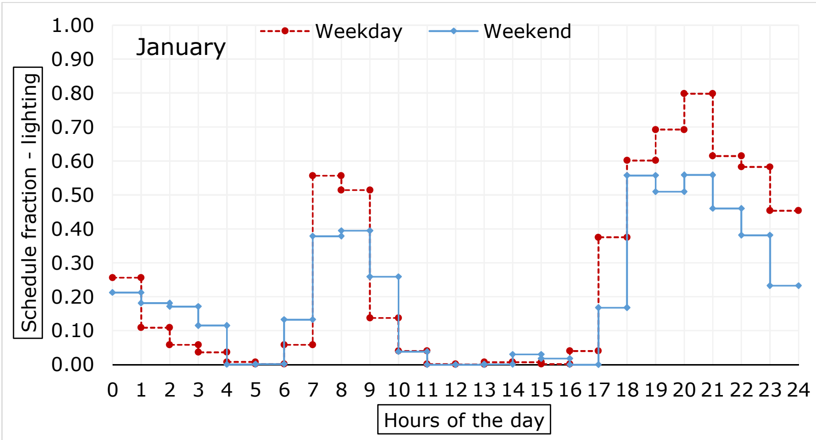


Figure 5.32 - Interior lighting consumption schedule for January

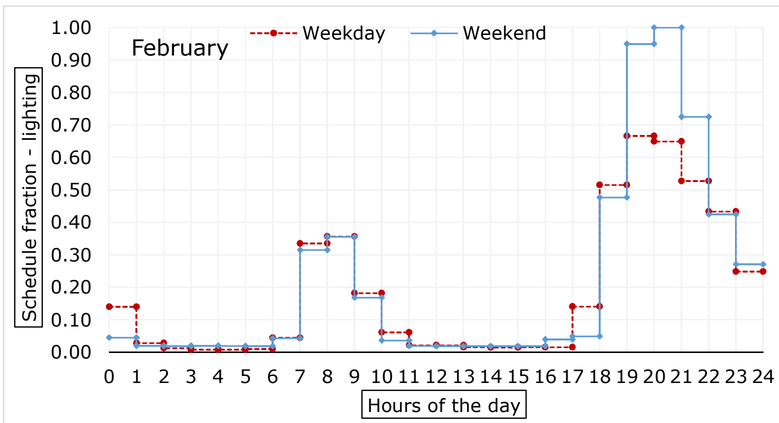


Figure 5.33 - Interior lighting consumption schedule for February

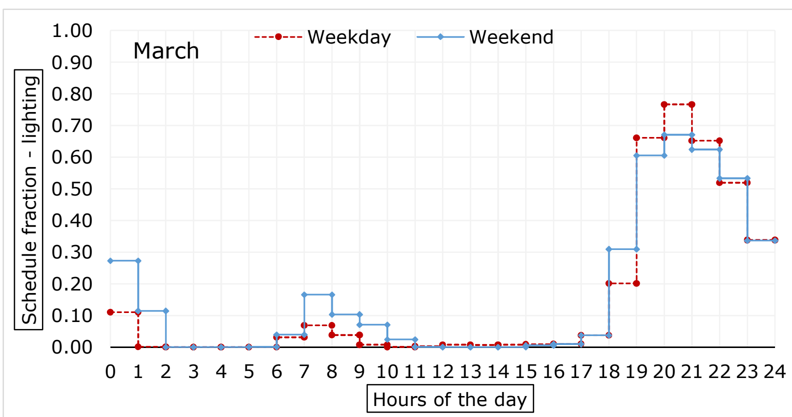


Figure 5.34 - Interior lighting consumption schedule for March

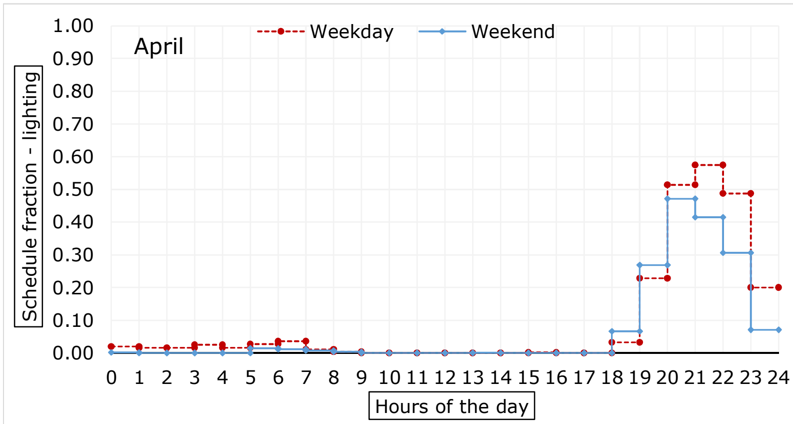


Figure 5.35 - Interior lighting consumption schedule for April

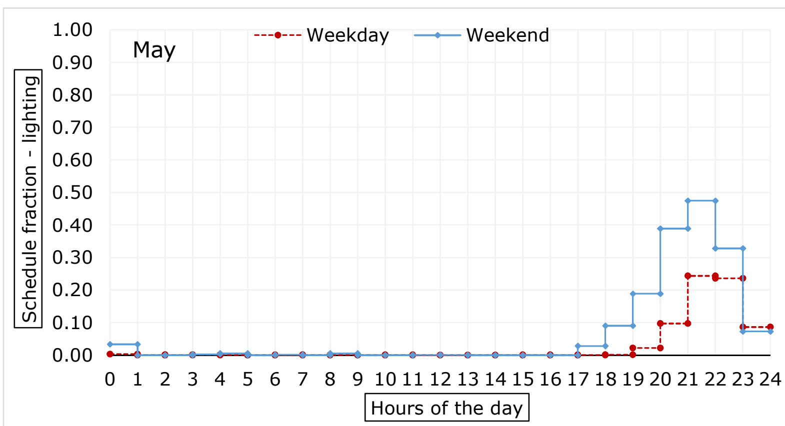


Figure 5.36 - Interior lighting consumption schedule for May

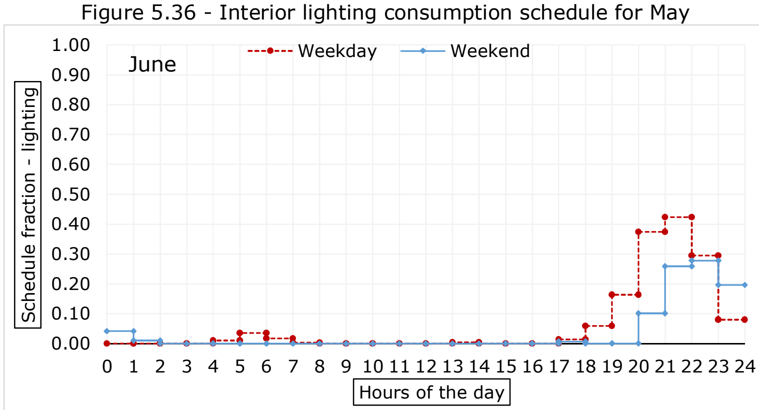


Figure 5.37 - Interior lighting consumption schedule for June

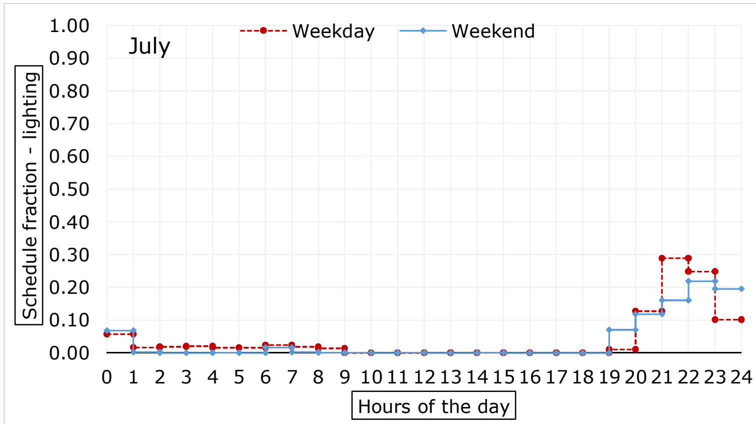


Figure 5.38 - Interior lighting consumption schedule for July

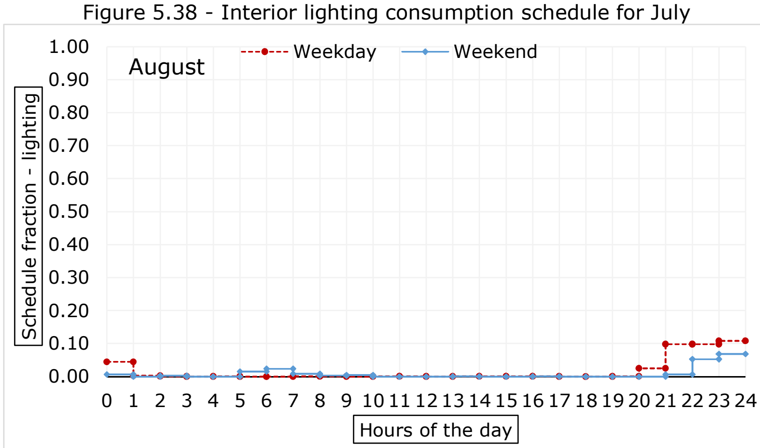


Figure 5.39 - Interior lighting consumption schedule for August

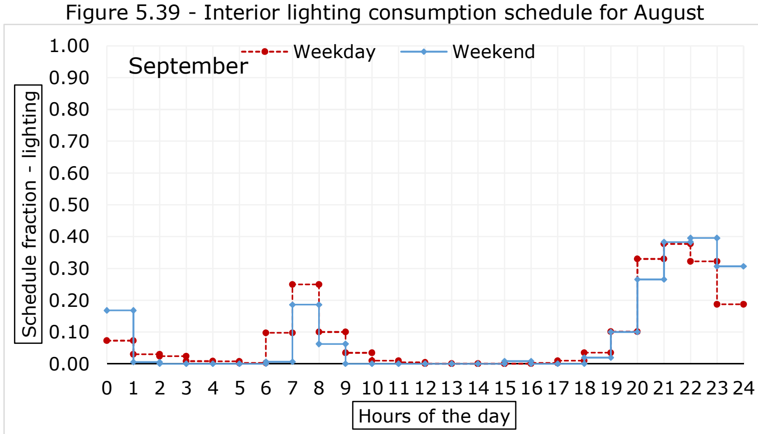


Figure 5.40 - Interior lighting consumption schedule for September

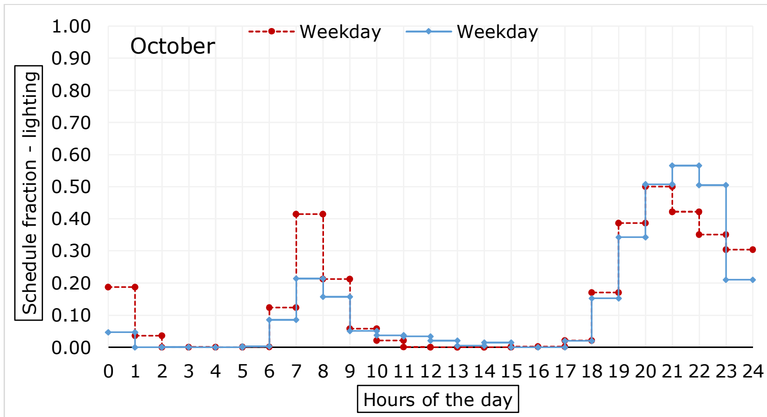


Figure 5.41 - Interior lighting consumption schedule for October

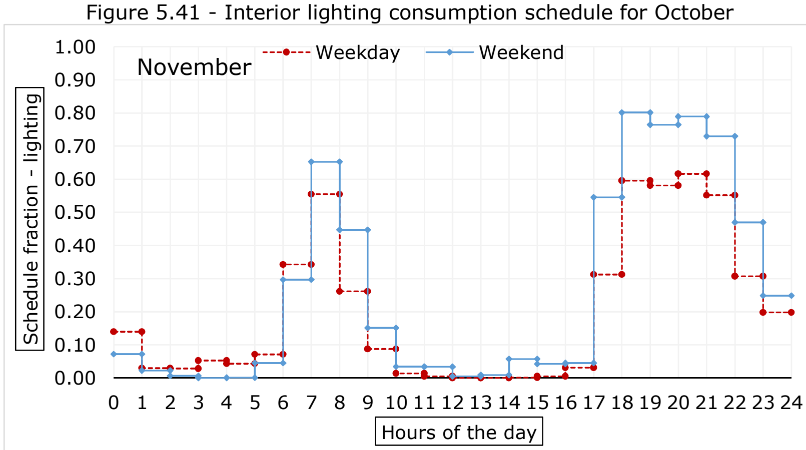


Figure 5.42 - Interior lighting consumption schedule for November

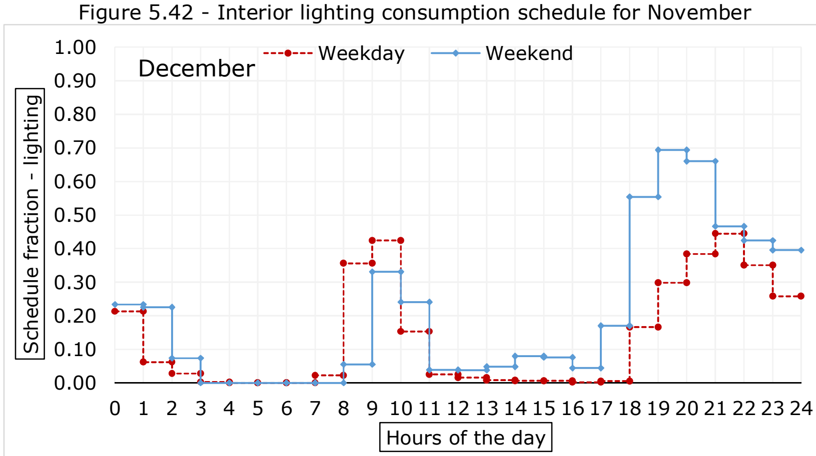


Figure 5.43 - Interior lighting consumption schedule for December

5.2.10 Interior temperature set point

The temperature control of the building is made through thermostat. Also, in the building energy model it was possible to implement a thermostatic control of the interior temperature through the object „ZoneControl:Thermostat''. This object references a control type schedule which has assigned temperature set point schedules.

The heating and cooling set points schedules were defined using the measurements made on the interior temperature through monitoring. For each month of the year, an hourly temperature profile was generated based on the formula in Equation 5.5.

$$T(m,h) = \frac{\sum_{d=1}^{n} t(d,h)}{n} \quad [^0C] \qquad \text{Eq. 5.5}$$

In Equation 5.5 *m* is the month of the year, *h* is the hour in day *d*, *n* is the number of days in a month, *T(m,h)* is the average hourly temperature in month *m* at hour *h*, *t(d,h)* is the hourly temperature at hour *h* in day *d.*

The heating system is available from the 15th of October until the 15th of April. The cooling system is available from May until September. The graph in figure from 5.44 shows the hourly temperature set point for the months when the heating system was active.

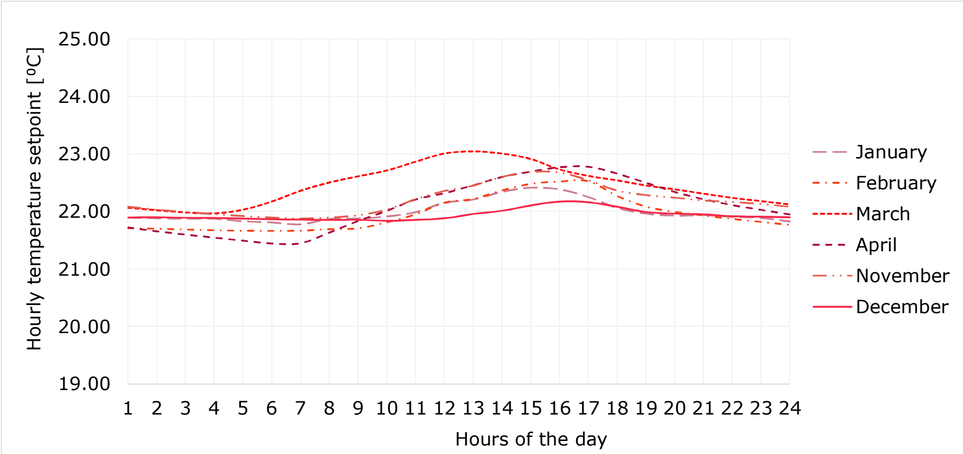


Figure 5.44 - Hourly temperature set point for heating

The graph in figure from 5.45 shows the hourly temperature set point for August, when the cooling system was available.

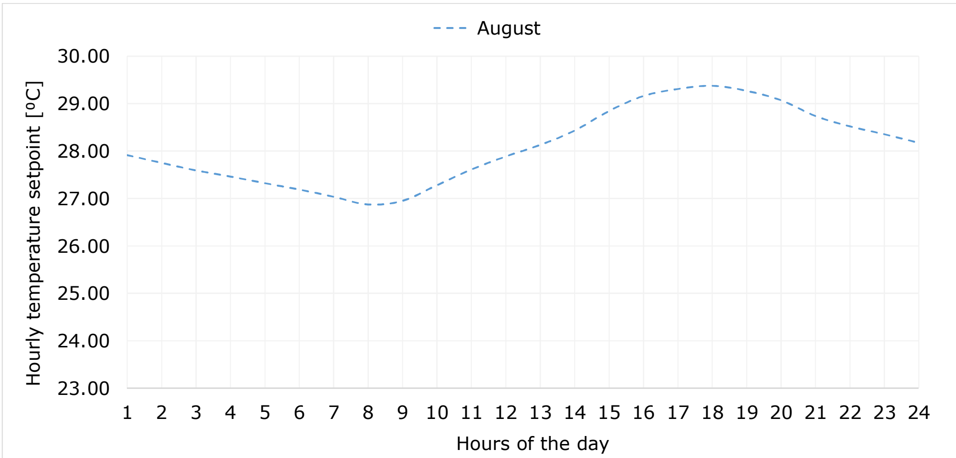


Figure 5.45 - Hourly temperature set point for cooling– cooling system available in August

5.2.11 Weather data

Besides the data related to building operation condition, accurate weather data is necessary in order to match the building's response to external conditions from simulation with the real behaviour of the building. For this purpose, weather data registered by the monitoring system is available. Unfortunately, not all the relevant parameters were measured by the monitoring system but just the following: exterior temperature, wind speed and air relative humidity.

The custom weather file was created using Elements software tool [120] which is a free programme for creating and editing weather files for building energy modelling. Because not all the required weather data was available from monitoring, the file was created from an existing weather file for Timisoara, downloaded from the EnergyPlus software web page in section Weather [112]. The weather file is freely available and is provided by ASHRAE IWEC2 (International Weather for Energy Calculations). The IWEC2 file contain 'typical' year data for Timisoara to be used in building energy simulation programs [112]. A 'typical' year weather data is obtained from combining multiple years weather data for the location in order to best represent the pattern and range of weather parameters for the location on the long term.

Figure 5.46 shows the file created using Elements based on the IWEC2 file, where the dry bulb temperature, air relative humidity and wind speed were replaced with hourly values determined based on data measured in 2015 by the monitoring system.

The following figures (5.47, 5.48 and 5.49) show the graphs for air temperature variation, air relative humidity and wind speed for the year 2015. The data presented in these graphs were implemented in the weather data file and were further used in the simulations.

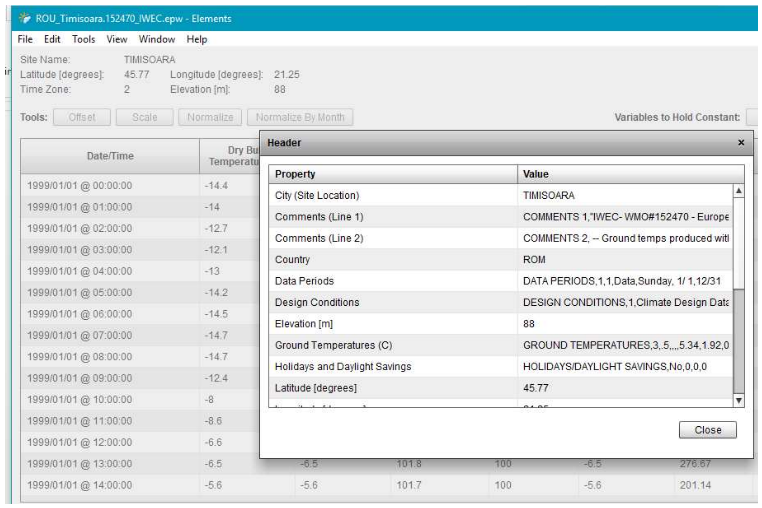


Figure 5.46 - Weather data file used in the building energy simulation

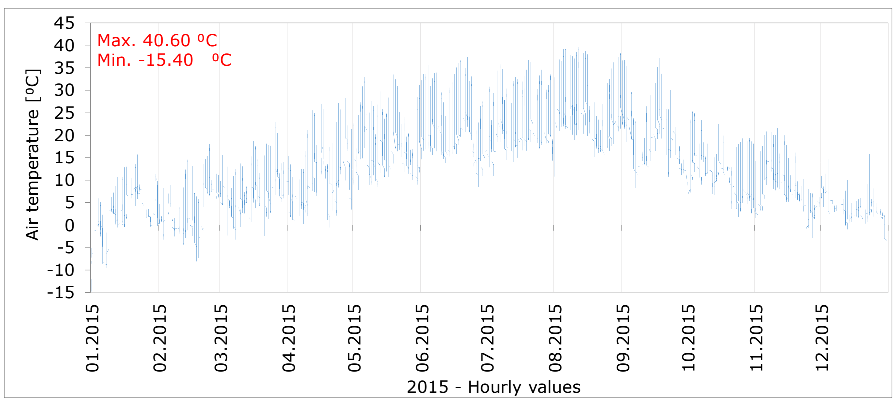


Figure 5.47 - Hourly outside air temperature used in the simulations – year 2015

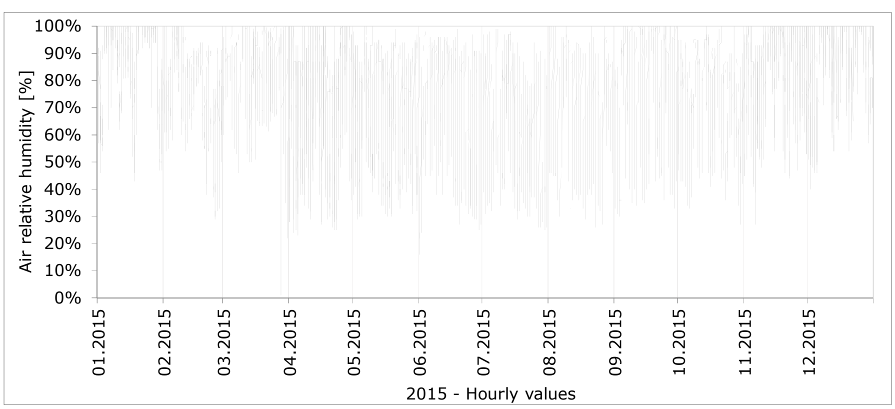


Figure 5.48 - Hourly outside air relative humidity used in the simulations – year 2015

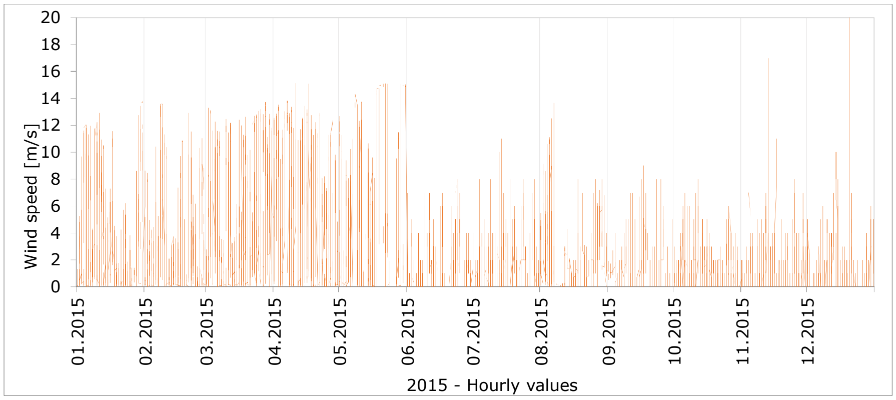


Figure 5.49 - Hourly wind speed values used in the simulations – year 2015

5.3 Building energy simulation results and comparison to measured data

5.3.1 Calibration data

The calibration of the building energy model was performed using monitoring data from 2015 monitoring campaign. The monitoring data is used firstly for creating the building operation pattern and further the monthly measured energy consumption will be compared to simulated energy consumption in order to assess the performance of the building energy model. In other words, model calibration data is the measured data that is used to calibrate and validate the building energy model. Since the building is all electric, the validation related to energy consumption is made of course for electrical energy consumption. In this case, the model will be validated for:

A) Energy consumption:

- total electrical energy consumption, *kWh* (monthly);
- electrical energy consumption for lighting, *kWh* (monthly and hourly);
- electrical energy consumption for interior equipment, *kWh* (monthly and hourly)
- electrical energy consumption for heating, cooling, ventilation and domestic hot water, *kWh* (monthly).

B) Space temperature, ºC (hourly values).

This data is obtained from processing the data measured by the monitoring system in 2015. The monitoring data processing process is described in Chapter 3 of the thesis.

5.3.2 Assessing calibration performance

A building energy model is considered calibrated when the differences between simulated and measured are below the accepted calibration tolerances. Currently, the validation of a building energy simulation model is based on standardized statistical indices that represent the performance of a model [81], [59]. The Coefficient of Variation of the Root Mean Square Error (CVRSME) and the Normalized Mean Bias Building energy simulations can be called calibrated if they meet the accepted criteria proposed by ASHRAE Guideline 14 [81], presented in Table 4.8.

Table 5.8 - Accepted calibration tolerances for building energy model calibration [78], [81].

Calibration Type	Statistical indices	Acceptable value
Monthly	NMBE	±5%
	C_v(RSME)	15%
Hourly	NMBE	±10%
	C_v(RSME)	30%

In the process of simulating complex phenomena, such as the behaviour and response of a building, errors or residual values can be identified by subtracting the simulated values from the measured values [70], [121]. In this research, for the five categories of data under analysis presented in the previous subchapter, errors were calculated using Equation (5.6).

$$\varepsilon_i = m_i - s_i \qquad \text{Eq. 5.6}$$

5.3.2.1 Energy consumption

The total annual measured energy consumption of the building in 2015 was 5713.4 kWh and the building energy model predicted a value of 5776.7 kWh, resulting that the simulation over-predicted the total energy consumption of the building with 1.11%. A comparison between the monthly total measured and simulated energy consumption is presented in Figure 5.50. Figures from 5.51 to 5.53 show the comparison between the measured and simulated values on category of consumption.

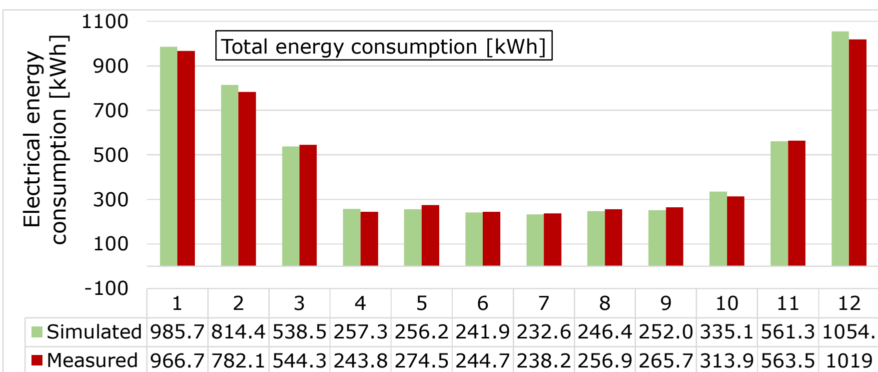
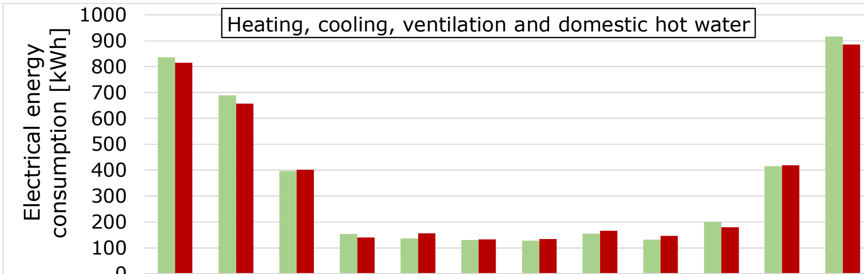
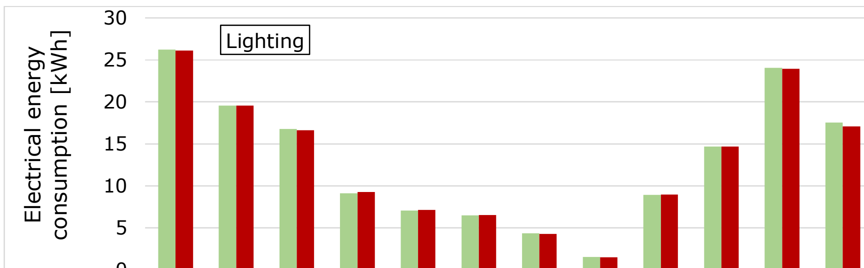


Figure 5.50 - Monthly total electricity consumption comparison



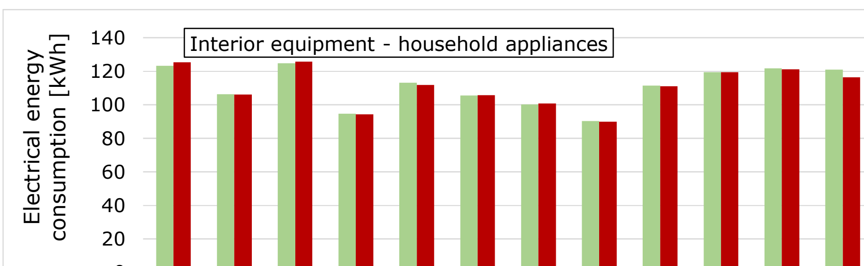
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Simulated	836.2	688.6	396.9	153.5	136.1	129.8	128.0	154.5	131.7	200.9	415.5	916.3
Measured	815.2	656.4	402.1	140.2	155.6	132.4	133.0	165.6	145.7	179.7	418.4	885.7

Figure 5.51 - Monthly HVAC electricity consumption comparison



	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Simulated	26.2	19.6	16.8	9.1	7.1	6.5	4.4	1.6	8.9	14.7	24.0	17.5
Measured	26.1	19.5	16.6	9.3	7.1	6.5	4.3	1.5	9.0	14.7	23.9	17.1

Figure 5.52 - Monthly lighting electricity consumption comparison



	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Simulated	123.4	106.3	124.8	94.7	113.2	105.6	100.3	90.4	111.4	119.6	121.8	120.9
Measured	125.3	106.2	125.6	94.3	111.8	105.8	100.9	89.9	111.1	119.5	121.2	116.4

Figure 5.53 - Monthly interior equipment consumption comparison

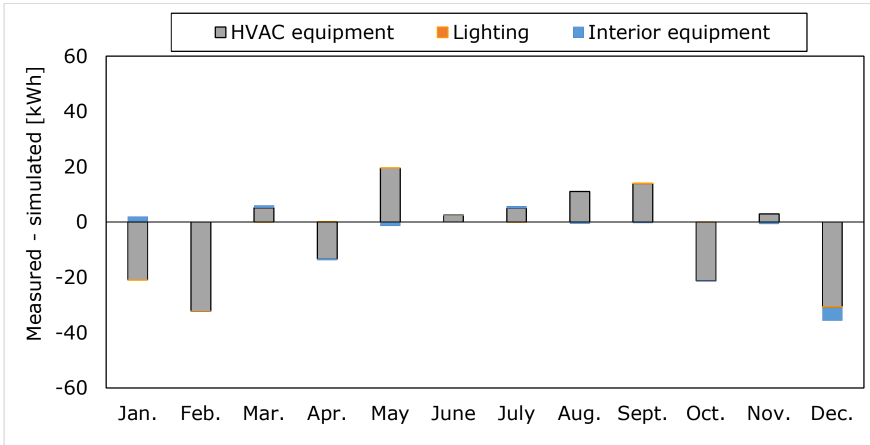


Figure 5.54 - Difference between measured and simulated energy consumption values

As we can see in Figures from 5.51 to 5.54 the differences between the measured and simulated energy consumption are relatively small. Still, there is an amount of discrepancy left between measured and simulated values, especially in case of the energy consumption of HVAC system. The graph in figure 5.55 shows the monthly difference in energy consumption between the measured and simulated values. As said earlier, the differences related to energy consumption of the HVAC system are the highest and the ones related to lighting energy consumption are the lowest. It is noticeable that the simulation over-predicted more the energy consumption for the months when the house required heating. This fact indicates that the some uncertainties of the model are related to the heating system. The highest difference between measured and simulated is identified in December, when the simulation over-predicted the total energy consumption with 35 kWh.

The Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Mean Square Error were calculated using Equations 5.6 and 5.7, on a monthly basis. The results presented in Table 5.9 show that the NMBE and CVRMSE values for monthly data are within the acceptance limit recommended by ASHRAE Guideline [81]. The analysis and comparison of the simulated and measured energy consumption and calibration of the building energy model was performed on a monthly basis.

Table 5.9 – NMBE and CVRMSE energy consumption values for the final building energy model

Category	NMBE*	CVRMSE**
Total energy consumption	-1.107 %	3.843 %
Heating, cooling, ventilation and domestic hot water	-1.376 %	5.054 %
Lighting	0.487 %	1.234 %
Interior equipment	-0.327 %	1.385 %

* NMBE acceptance limit ≤ ± 5% [81]
** CVRMSE acceptance limit ≤ +15% [81]

The discrepancies between measured and simulated energy consumption are within the acceptance limits and the building energy model is considered calibrated to monthly values. These differences can be attributed in the first place to the lack of complete real weather data measurements. Although the weather file contains the measured exterior temperature, wind speed and air relative humidity, the measured solar radiation is missing. For the simulation, solar radiation values corresponding to the typical meteorological year in Timisoara were used. A 'typical' year weather data is obtained from combining multiple years weather data for a certain location in order to best represent the pattern and range of weather parameters for the location on the long term. The relatively close values between the measured and simulated energy consumption, despite the lack of measured solar radiation data, indicate that on a monthly basis, the typical year weather data for the building location managed to closely simulate the real environmental conditions.

5.3.2.2 Interior temperature

The air temperature inside the building was measured using 5 temperature sensors located in different rooms of the house. Using the measured temperature values, cooling and heating temperature set-points profiles were created. This section analyses the ability of the Energy Plus software to predict zone temperature. Figure 5.55 shows the NMBE and CVRMSE verification for temperature using hourly values, for each month and overall. The CVRMSE and NMBE values have the highest values in June and August, but still they remain under the acceptance limit of 30% (CVRMSE), respectively ±10% (NMBE) for hourly values calibration [81].

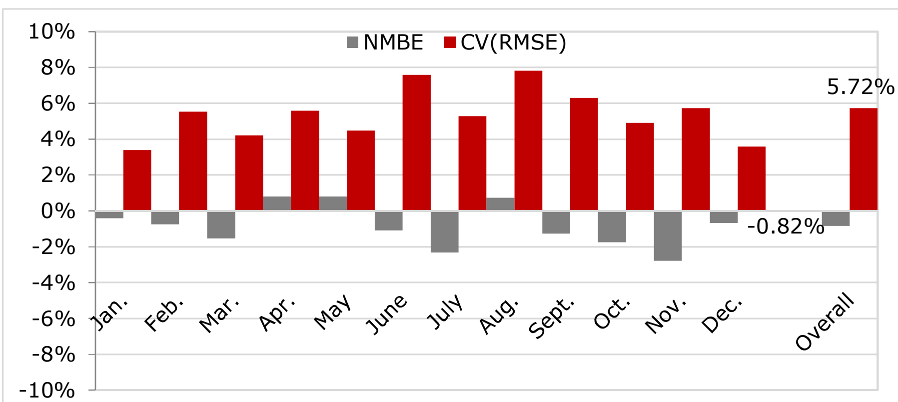


Figure 5.55 - NMBE and CVRMSE results for interior temperature (hourly basis)

A comparative Box and Whiskers Mean (BWM) plot was created for the measured and simulated interior temperature in order to better see the distribution of temperature values in both situations (Figure 5.56). This type of graph is useful to see the shape of the data distribution, central values and variability. The red line in the two plots unites the median values corresponding to each month. The medians are the middle values for each set of data points that divides the data set into two parts. It is the point at which exactly 50% of the values lie below and above this value. The lines extended vertically from the boxes indicate the variability of the data sets outside the upper and lower quartiles, representing the minimum and maximum values. The upper lines of the boxes represent the 3rd Quartile for each data set which indicates that 75% of the hourly temperature values are less than this value. The lower lines of the boxes are the 1st Quartiles. The 1st Quartiles indicate that 25% of the measured and simulated values are less than this value. A quick look at the comparative graphs in Figure 5.56 shows that for most of the months, the median values of simulated data set closely matches the median values of the measured data set. In order to better identify the differences in values for each month, comparative BWM plots were made for each month, containing both measured and simulated hourly temperature values. Appendix C contains the comparative BWM plots for measured and simulated hourly interior temperature for each month and the percent change from measured to simulated values. An approximately 2% difference between measured and simulated median values is identified in April, May, August and November. For the rest of the months, the difference is below±1% for median values. A significant difference is identified in February, when the minimum measured value for interior temperature is 10% lower than the simulated one. Also, in November, the maximum measured value is 12% lower than the simulated.

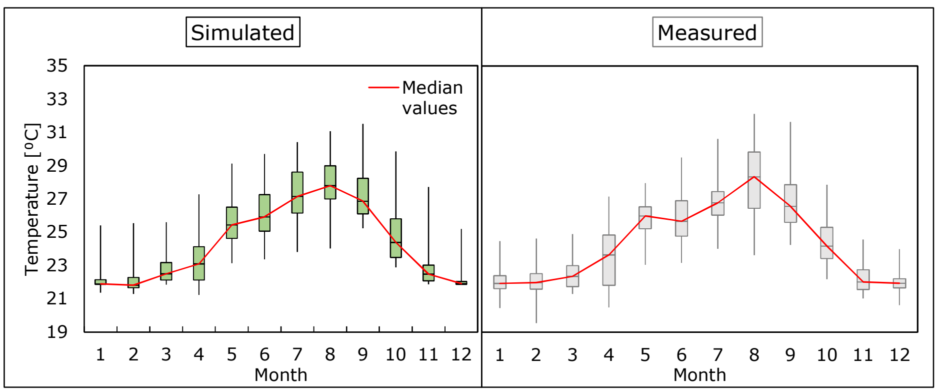


Figure 5.56 - BWM comparative plot for measured and simulated interior temperature (hourly values)

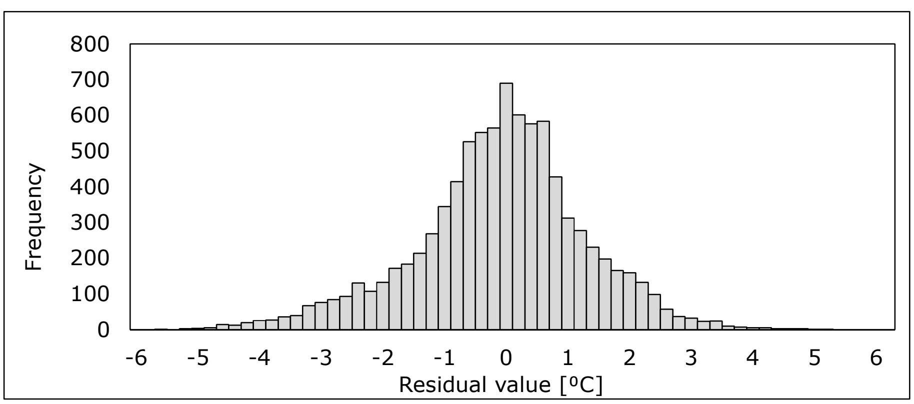


Figure 5.57 - Histogram of temperature residuals (hourly values)

Figure 5.57 shows the histogram of the residual values calculated with Equation 5.6. The histogram shows the frequency of each residual value and the distribution and the centre of the histogram is somewhere around 0ºC. The histogram has a normal distribution but with a slight asymmetry. It can be observed that for the situation presented in this research (higher frequency of negative residuals) that the software tends to over-predict the values of the air temperature slightly more often than under-predicts.

Figure 5.58 shows the variance of the residuals values within the full range of simulated temperatures. The spread of residuals generally shows a constant trend with a slight increase of residuals with the increase of simulated temperatures. A similar distribution was obtained by Royapoor et al. [70].

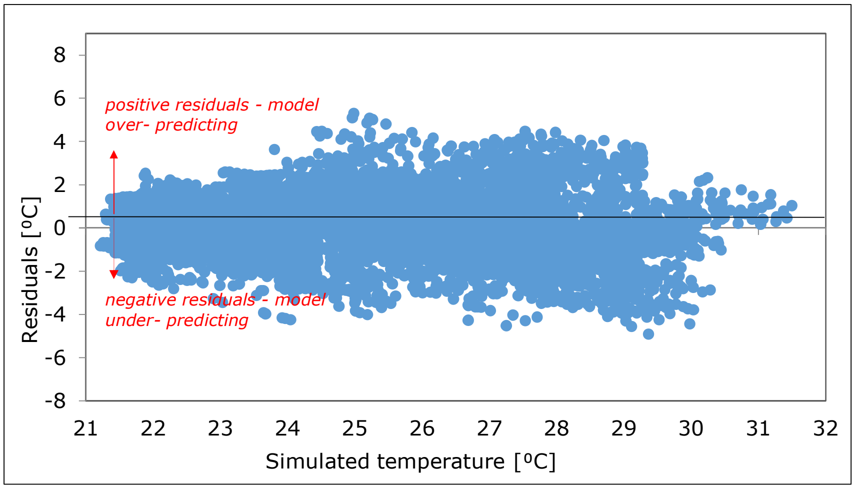


Figure 5.58 - Simulated temperatures and residuals scatterplot

Over the entire year, the measured indoor air temperatures are lower with and average value of 0.20ºC. The comparative analysis of measured temperature values against simulated ones indicate an overall good prediction of the building energy model. However, differences have been identified and the main cause can be the fact that in the simulation was not used measured solar radiation data. When it comes to comparing hourly measured values of space temperature with simulated values, the differences can be noticeable for some instances of time, because of a different distribution of real solar radiation than the one used in the simulation. It is unlikely that the hourly and daily solar radiation distribution from the typical weather data to reproduce exactly the real situation in 2015. This lead to a slightly different hourly and daily distribution of space temperature. Of course, a major cause of uncertainty can be attributed to the modelling assumptions.

5.3.3 Discussion

The development of a building energy model requires a great amount of information on one hand related to the building composition (envelope and systems) and one the other hand related to the building operation. Thus, in the simulation of a building energy model the uncertainty sources are multiple. The purpose of this research was to present the methodology that aimed at calibrating the building energy model for the case study building. In this research occupant related operation of the building was defined using monitoring data for a year of occupancy. Weekdays and weekend days electricity use for lighting and interior equipment were created using hourly energy consumption measured data. The validation of the building energy model was performed using monthly energy consumption values and hourly interior temperature.

The NMBE and CVRMSE values of -1.11% and 3.84% for total energy consumption are within the acceptance limit of ±5% and 15%. The CVRMSE gives an overall evaluation of the difference between the measured and simulated values while the NMBE characterizes the bias of the difference. The accuracy of the building energy model in predicting air temperature was assessed as well. The overall NMBE and CVRMSE values calculate for hourly instances of time are -0.82%, respectively 5.72% and follow the calibration criteria to hourly values (±10%, 30%). Over the entire year, the measured indoor air temperatures are lower with and average value of 0.20ºC.

5.4 Heating temperature set point and energy consumption

Along with a calibrated building energy model, an analysis of the effect of different parameters variation on the energy consumption of the building can be investigated. For this case study, the impact of heating temperature set points on overall energy consumption is studied. The occupant behaviour feature that has a great influence on the energy consumption of the building is its perception related to indoor environment comfort temperature. Although the indoor comfort temperature is often a subjective matter, investigating its impact on the overall energy consumption might increase the user awareness towards a more effective use of the building. Using the calibrated building energy model, referred to as scenario S0, 4 other simulation scenarios were performed using lower and a higher temperature set-point for heating. The calibrated building energy model, which represents in this situation the real occupant behaviour related to heating temperature set point, is to be referred in this research as the average consumer type. In the first two scenarios (S1 and S2) the heating temperature set-point of each month, used in the calibrated model is reduced with 1ºC and 2ºC (15th October – 15th April), as shown in Figure 5.59. These two scenarios will be referred in this research as low consumer types. In the other two scenarios (S3 and S4), the heating temperature set-point is increased with 1ºC and 2ºC. These two scenarios will be referred as the high consumer types.

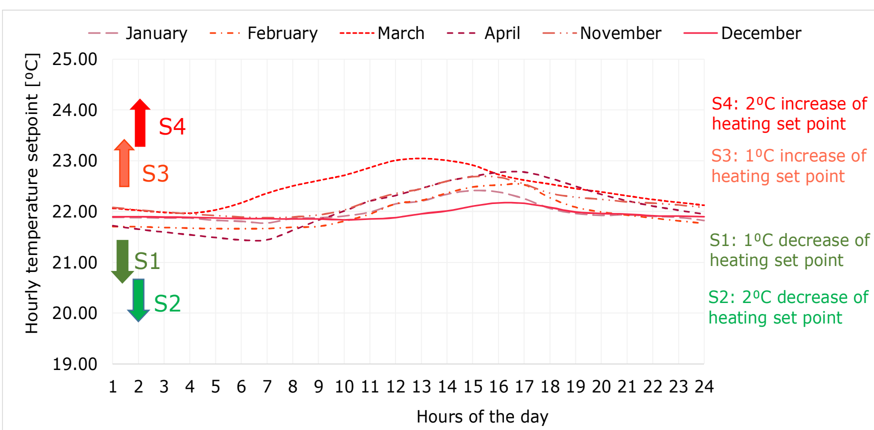


Figure 5.59 – Heating temperature set points scenarios

The change in total energy consumption is highlighted in Figure 5.60. For scenarios S1 and S2, the total annual energy consumption decreases from 40.97 kWh/(m^{2}y) to 38.39 kWh/(m^{2}y), respectively 35.40 kWh/(m^{2}y). In case of S3 and S4, the total energy consumption increases from 40.97 kWh/(m^{2}y) to 45.38 kWh/(m^{2}y), respectively 48.44 kWh/(m^{2}y). Thus, a decrease of the heating temperature set with 1ºC, respectively 2ºC, leads to a decrease of the total energy consumption of 6.30%, respectively 13.59%. An increase of the heating temperature set point with 1ºC, respectively 2ºC, leads to an overall increase of the energy consumption of 10.77%, respectively 18.24%.

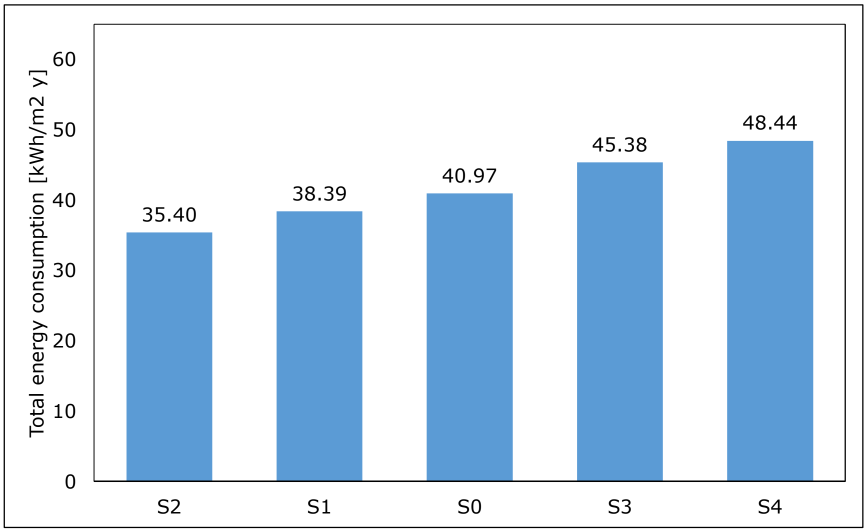


Figure 5.60 - Total energy consumption for the investigated scenarios

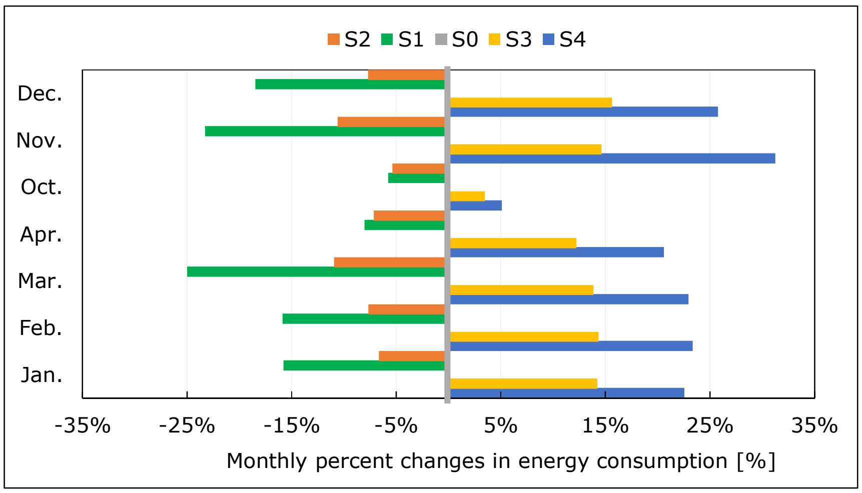


Figure 5.61 - Percent change in monthly energy consumption

The results of the simulations show a change in the monthly energy consumption of the building for the months when the heating system is on. Figure 5.61 shows the percent change of monthly energy consumption for the investigated scenarios with reference to the base case scenario (S0). It is noticeable that in October, the energy consumption decrease and increase percent have close values for all scenarios. In April and October, we can notice that for scenarios S1 and S2 the percent change in energy consumption is almost the same. In this situation it can be concluded that the set-point temperature for scenario S1 can be maintained without much higher heating energy consumption than for scenario S2.

Scenarios S3 and S4 which represent higher consumer types consider an energy-wasting attitude of the user. However, there might be situations when the occupants preferences with respect to heating temperature set-points might be even more demanding, leading to an even higher energy consumption for heating the building. Scenarios S1 and S2 which represent the lower consumer types with reference to the base case scenario (S0). The average heating set-point temperature for scenario S1 is approximately 21ºC, and leads to an 8% reduction of the annual heating energy consumption. In case of scenario S2, the average heating set point temperature is approximately 20ºC, and is the temperature usually used in the design phase of a residential building. For this case study, this scenario represents the most sustainable behaviour related to heating set-point temperature, resulting in a 17.26% reduction of the annual heating energy consumption.

The main purpose of this study is to enhance the effect of the user behaviour with respect to the heating temperature set point on the overall energy consumption of the building. The results show that with reference to the base case scenario, which represents the real operation conditions of the building, the energy consumption for heating can decrease with 8% and 17.26% for the lower consumer types and can increase to with 13.67% and 23.17% for the higher consumer types. The results presented in this study can be a reference for building users and increase their energy related consciousness because it reveals how a small increase or decrease of the preferred temperature in the house during the heating season, might affect the overall consumption of the building and in consequence the energy consumption costs.

The results of this research emphasize the sensitivity of the overall energy consumption of a building to the heating temperature set-point. Therefore, in order to reduce the gap between the designed and real energy consumption of a building, several scenarios for temperature set point can be investigated in the design phase of a building. This kind of analysis could be a reference for building owners and their use of the house.

5.5 Simulation considering shading devices

The analysis of the interior air temperature during summer, both simulated and measured, shows that in several times the building faced overheating. The main cause of overheating is the lack of shading systems for the windows. Moreover, according to the building user preferences, the cooling system was only active in August, for the rest of the time the house being solely cooled during night hours through windows opening. This subchapter investigates the effect of shading devices on the interior air temperature during summer. Also, the change in energy consumption for the period when the cooling system was active is investigated.

5.5.1 Shading system features

Exterior shading devices for windows were implemented in the building energy model previously created in EnergyPlus. The proposed shading systems consist in exterior venetian blinds with horizontal slats. This type of system has small dimensions when closed and can be installed subsequently to the façade construction works. The horizontal slats have 60 mm width and 60 mm separation space between the slats. The slat angle was set to 45º (Figure 5.62).

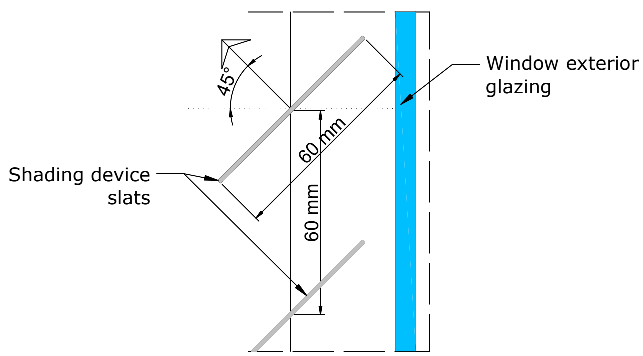


Figure 5.62 - Exterior shading device with horizontal slats

The exterior venetian blinds were implemented for windows place on the south-west and south-east facades, except for the windows and exterior door on the south-east façade that is already shaded by the cantilevered floor. Shading systems are active from May until the end of September, between 8:00 and 20:00.

5.5.2 Simulation results

5.5.2.1 Energy consumption for cooling

The results of the simulation show that building with shading system active reduces the energy consumption for cooling from 35.75 kWh to 5.87 kWh. In other words, the energy consumption for cooling is reduced almost completely. However, this reduction is possible only if the same cooling temperature set point is used as in the original building energy model.

5.5.2.2 Interior air temperature

The results of the simulation show a significant reduction of the interior air temperature if shading devices are implemented in the building. In the situation of the original building energy model, the maximum average interior air temperature was 31.50ºC. The results of the simulation considering the shading devices show a maximum average interior air temperature of 29.24ºC. Figure 5.63 shows a histogram for the simulated interior air temperature in both situations. We can see what temperatures were experienced the most during the summer months (including May and September). The most frequent values are below 27℃ in case of the building with exterior shadings. For the other situation, the most frequent interior temperature values are above 26℃.

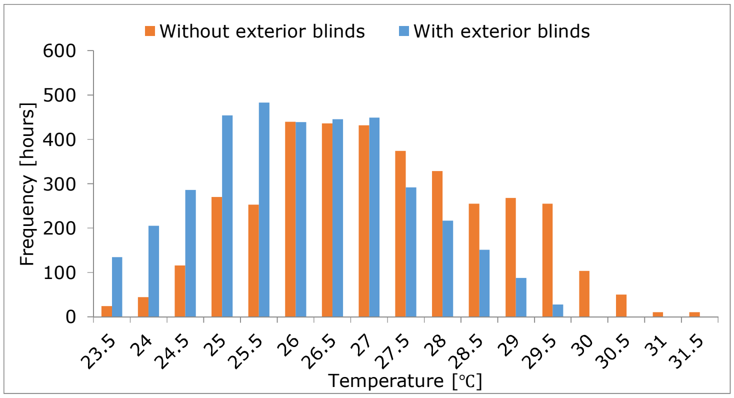


Figure 5.63 - Histogram of hourly interior air temperature

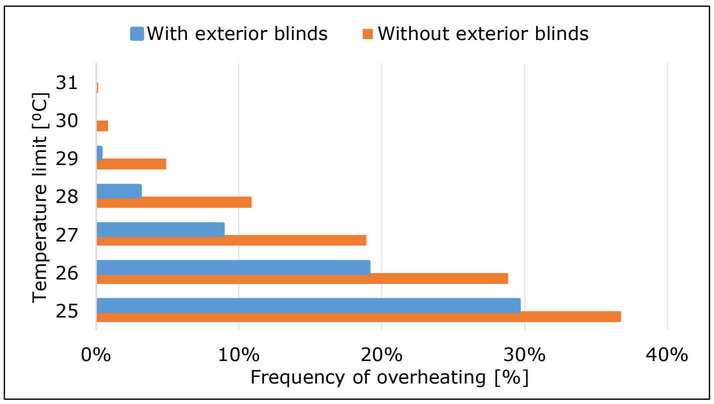


Figure 5.64 - Frequency of overheating at different temperature limits

To better understand the effect of the shading devices, the frequency of overheating was calculated at different temperature limits, for both situation (with and without shading systems). The number of overheating hours was determined based on the hourly simulated interior temperature. The frequency of overheating is expressed as a percentage of the total hours of the year. Figure 5.64 shows the frequency of overheating at temperature limits between 25ºC and 31ºC. It is noticeable a significant reduction of the overheating hours for all considered temperature limits.

This study emphasizes the importance of the shading devices in case of very well insulated and airtight buildings. It can be concluded that with shading devices available during the summer and night hours cooling, the interior air temperature can be maintained in acceptable limits without the use of an active cooling system.

6 TOWARDS NEALRY ZERO-ENERGY BUILDINGS: COST OPTIMAL ANALYSIS

6.1 Introduction

The publication of EPBD recast launched the nZEB concept as a future requirement for new and refurbished buildings in the European Union. Each Member State has to define minimum energy performance requirements with respect to certain cost optimal levels.

In Romania, the maximum admissible primary energy from fossil fuels has been defined for different building categories, depending on the climatic zones of Romania. The building investigated in this thesis is located in the Romanian climatic zone II. For all new residential buildings located in climatic zone II the maximum admissible specific primary energy from conventional sources is 111 kWh/m^{2}year, in order to be considered nZEB. Also it has been decided that in order to assure the total energy consumption of a nZEB in Romania, the renewable energy must cover at least 10% of the total primary energy of the building.

The construction of a highly energy efficient building implies higher investment costs compared to the construction of a traditional/conventional building, which leads to a situation where most of the investors or buildings owners are reluctant on whether to invest or not the extra amount of money.

The general approach when it comes to the energy efficiency of a building is divided in two elements:

- building thermal envelope characteristics, which is ultimately translated into energy demand for heating and cooling
- building heating, cooling, ventilation and domestic hot water systems features.

The above mentioned elements, which ultimately define the energy efficiency of the building must be balanced so that the initial investment cost is minimum. As it is required through EPBD recast, the energy performance of buildings must be connected to the economic aspects with the purpose of identifying cost optimal solutions. Nowadays there are a multitude of possible solutions in terms of energy efficiency, for both building envelope and building systems. Therefore, it is important to investigate various solutions in terms of energy performance and costs, in order to choose the solutions that brings the best benefits in terms of energy savings but is also cost-effective. This chapter presents the global cost analysis of the case study building in comparison to the global cost of several other proposed energy conservation measures under the form of energy efficiency packages applied to the building with the same architectural, structural and functional features. All the scenarios are compared with the reference building in Romania, composed according to C107/2010 [122]. The proposed scenarios will be assessed in terms of both global cost and primary energy consumption, according to the methodology presented in Chapter 2.5.

The proposed energy efficiency packages aim at a supplementary reduction of the energy consumption of the real building but also at investigating how other systems and envelope configurations impact the overall energy efficiency of this building. Also, this study proposes to provide reference solutions that can lead to nearly zero and net zero energy residential buildings in Romania or even more, to buildings that produce more energy than consume.

The energy assessment was made using the dynamic energy simulation software EnergyPlus. The operation conditions of the building lighting and household appliances, occupancy and activity are the same that were used in the energy performance simulations of the real building, based on monitoring data. However, because this chapter is purely theoretical, the heating and cooling temperature set points will be according to the conventional values used for the design of the buildings. Also, instead of the custom weather data, the typical year weather file is used.

6.2 Energy efficiency scenarios

6.2.1 Reference building according to Romanian standards

This study aims at investigating scenarios that could be solutions for achieving nZEB in Romania. In order to emphasize the energy and economic performance of the proposed solutions, the assessment is performed in comparison to a reference building. According to Part III – Mc 001/3- 2006 [117], the reference building is the building that has the same geometrical characteristics, volume and envelope elements areas as the real building. The envelope elements of the reference building must comply with the minimum requirements for thermal transfer resistances in Romania as presented in Table 1.2 in Chapter 1.
Table 6.1 contains the proposal of reference building characteristics and features, which were defined for the case study building in compliance with C107/2010 – C107-1 [122] and [117]. The geometrical and architectural characteristics of the reference building are identical to the real building and were presented in the previous chapters. The envelope elements composition were defined in such a manner as to achieve, in terms of U-values, the maximum values imposed by the Romanian normative.

Table 6.1 - Reference building (RB) features and characteristics according to [117], [122]

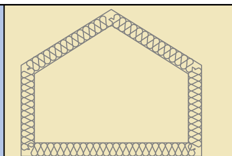
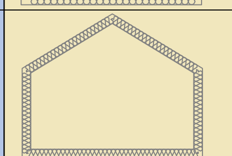
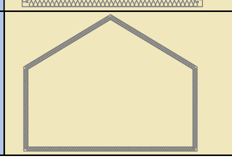
Characteristic	**Description**	
Building type	Residential	
Building envelope	Element	U-value [m^2K/W]
	-exterior walls	0.560
	-ground floor	0.220
	-roof terrace	0.200
	-cantilevered floor	0.200
	-windows/exterior doors	1.300
Building systems	-condensing gas boiler for space heating and radiators for heat distribution -gas boiler for domestic got water -multi split cooling (+night hours cooling through natural ventilation)	
Natural ventilation	0.6 h^{-1}	

6.2.2 Thermal envelope

As mentioned earlier, the energy efficiency of a building is defined by two elements: thermal envelope and building systems. The configuration of the thermal envelope determines the heating and cooling energy needs of a building. In other words, depending on how well insulated and airtight an envelope is, the heating and cooling energy needs might vary significantly. Beside the reference building envelope, two other envelope scenarios are proposed for this research. The first one, which will be referred to as PH, is the real building thermal envelope that is specific to passive house level. The second envelope scenario, which will be referred to as EE, proposes a lower level of insulation than passive house recommendation and higher than minimum requirements in Romania, being considered as energy efficient envelope.

The composition of the envelope elements is the same for all three scenarios, except for the thermal insulation layers, Table 6.2 summarizes the thermal insulation characteristics of the envelope elements for the three envelope scenarios.

Table 6.2 - Insulation material properties for the proposed scenarios

Scenario		Description
PH		- **Exterior wall:** 30 cm polystyrene - **Ground floor:** 40 cm polystyrene - **Roof:** 32 cm polystyrene, 10 cm mineral wool - **Cantilevered floor**: 30 cm polystyrene, 20 cm mineral wool - **Windows:** triple glazing windows with Low-E coating
EE		- **Exterior wall:** 15 cm polystyrene - **Ground floor:** 25 cm polystyrene - **Roof:** 25 cm polystyrene - **Cantilevered floor:** 25 cm polystyrene - **Windows:** triple glazing windows with Low-E coating
RB		- **Exterior wall:** 5 cm polystyrene - **Ground floor:** 20 cm polystyrene - **Roof:** 20 cm polystyrene - **Cantilevered** floor: 20 cm polystyrene - **Windows:** double glazing windows

The characteristics of the materials that compose the envelope elements of the buildings are presented in Appendix A.

A supplementary measure proposed for the building envelope consists in exterior shading systems (S) for the windows. The proposed shading systems consist in exterior venetian blinds with horizontal aluminium slats. The horizontal slats have 60 mm width and 60 mm separation space between the slats. The slat angle was set to 45º.

6.2.3 Building systems

6.2.3.1 Heating, cooling, ventilation and domestic hot water

In order to define energy efficiency packages, two building system configuration are investigated in combination with different sizes of photovoltaic plants. The first system is the real building system (I). The second configuration (II) replaces the air to water heat pump with a soil-water heat pump. The technical configuration II has the same heating terminals, solar collector type and mechanical ventilation features as technical system I, only the heat pump is different. Table 6.3 summarizes the building system components for the two scenarios.

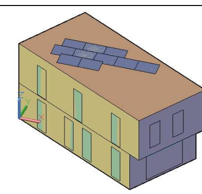
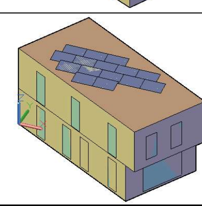
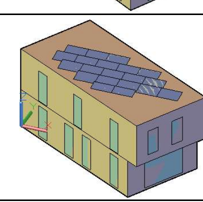
Table 6.3 - Technical systems components for the two scenarios

	I - Real building system	**II -** Alternative solution
Heating	Air to water heat pump – rated heating capacity 5.2 kW Fan coils installed in the ceiling	Soil-water heat pump with rated heating capacity of 7 kW Fan coils installed in the ceiling
Cooling	Air to water heat pump with reversible cycle	Soil-water heat pump with reversible cycle
Domestic hot water	solar collector 4.92 m^2 Domestic hot water boiler – 0.15 m^3	solar collector 4.92 m^2 Heating buffer - 0.5 m^3
Ventilation	Mechanical ventilation with heat recovery Soil-air heat exchanger for preheating/precooling the fresh air	Mechanical ventilation with heat recovery Soil-air heat exchanger for preheating/precooling the fresh air

6.2.3.2 On-site renewable energy production

Two different sizes of photovoltaic (PV) panels systems are proposed in this research. The first system includes a number of 20 polycrystalline PV panels and covers the maximum available space on the roof. The other two systems have 15 respectively 10 PV panels. The nominal power of one panel is 240 W and the module efficiency is 14.74%. Table 6.4 presents the three photovoltaic systems configurations used in this research.

Table 6.4 - On-site electricity production systems configuration

Power	Description
2.4 kW	- 10 polycrystalline PV panels with a 14.74% module efficiency and 240 W power - inverter 3 kW nominal power - total PV surface 17 m^2 
3.6 kW	- 15 polycrystalline PV panels with a 14.74% module efficiency and 240 W power - inverter 4 kW nominal - total PV surface 25 m^2 
4.8 kW	- 20 polycrystalline PV panels with a 14.74% module efficiency and 240 W power - inverter 5 kW nominal power - total PV surface 33 m^2 

Investigating different sizes of photovoltaic power allows the identification of different solutions in terms of primary energy and global cost, as photovoltaic panels still have an increased price and building owners are reluctant in implementing these types of systems.

6.2.4 Definition of energy efficiency packages

The proposed energy efficiency measures for technical systems aim at promoting the use of renewable energy. Therefore heat pumps, solar collectors and photovoltaic panels were the options proposed in this thesis.

Table 6.5 summarizes the energy efficiency packages that are investigated in this chapter. The packages are based on combinations between envelope measures, building technical systems and on-site renewable energy production earlier presented.

Table 6.5 - Energy efficiency packages description

Package name	Description
PH_I	Real building envelope (PH) and real technical system (I)
PH_I_S	Real building envelope (PH) and technical system (I) + shadings (S)
PH_I_S+2.4kW	Real building envelope (PH) and technical system (I) + shadings (S)+ 10 photovoltaic panels (2.4 kW power)
PH_I_S+3.6kW	Real building envelope (PH) and technical system (I) + shadings (S) +15 photovoltaic panels (3.6 kW power)
PH_I_S+4.8kW	Real building envelope (PH) and technical system (I) + shadings (S) +20 photovoltaic panels (4.8 kW power)
PH_II_S	Real building envelope and systems + technical system II + shadings
PH_II_S+2.4kW	Real building envelope + technical system (II) + shadings+10 photovoltaic panels (2.4 kW power)
PH_II_S+3.6kW	Real building envelope (PH) and technical system (II) + shadings (S) +15 photovoltaic panels (3.6 kW power)
PH_II_S+4.8kW	Real building envelope (PH) and technical system (II) + shadings (S) +20 photovoltaic panels (4.8 kW power)
EE_I	Energy efficient envelope (EE) + technical system (I)
EE_I_S	Energy efficient envelope (EE) + technical system (I)+ shadings
EE_I_S+2.4kW	Energy efficient envelope + technical system (I)+ shadings+10 photovoltaic panels (2.4 kWp)
EE_I_S+3.6kW	Energy efficient envelope + technical system (I) + shadings+15 photovoltaic panels (3.6 kW power)
EE_I_S+4.8kW	Energy efficient envelope + technical system (I)+ shadings+20 photovoltaic panels (4.8 kW power)
EE_II_S	Energy efficient envelope + technical system (II) + shadings
EE_II_S+2.4kW	Energy efficient envelope + technical system (II)+ shadings+10 photovoltaic panels (2.4 kWp)
EE_II_S+3.6kW	Energy efficient envelope + technical system (II) + shadings+15 photovoltaic panels (3.6 kW power)
EE_II_S+4.8kW	Energy efficient envelope + technical system (II)+ shadings+20 photovoltaic panels (4.8 kW power)
RB	Reference building

6.3 Energy consumption evaluation

6.3.1 Energy models simulation parameters

The energy consumption evaluations of the energy efficiency packages earlier presented was performed using the dynamic building simulation software EnergyPlus. The construction of the models started from the already existing building energy model of the real building by modifying the features to match each of the energy efficiency packages. The simulations were conducted using the typical year weather data file for Timisoara from International Weather for Energy Calculations (IWEC), available on EnergyPlus software web page in section Weather [112].

For all building energy models the following operation conditions were set:

- Heating system availability: 15th October – 15th April
- Cooling system availability : 15th May – 15th September
- Heating set point: 20ºC – conventional interior temperature for calculations
- Cooling set point: 26ºC between hours 9:00 and 20:00; 28ºC for the rest of the hours.
- Occupancy: 3 persons.

The lighting and interior equipment parameters and schedules are the same as in the real building energy model (see Chapter 5). The shadings are scheduled to be active from 15th of May until 15th September. The outdoor air flow rate for the mechanical ventilation was set to 0.4 air changes per hour. Also, night ventilation was considered during summer months for all scenarios, as presented in section 5.2.7.

The technical systems were mainly modelled with the help of "HVAC Template" feature available in EnergyPlus, which allows configuring of different common technical systems. An "expanded" file is generated subsequently to the simulation containing the HVAC templates. The expanded files were modified and adapted for each technical system.

The sizing of the heating and cooling systems was made using the simulation software EnergyPlus, based on the "WinterDesignDay" and "SummerDesignDay" from the weather data file.

6.3.2 End use primary energy consumption for envelope and technical systems packages

Table 6.6 presents the end use energy consumption for the investigated building packages for envelope and technical systems. In order to better compare the end use energy of the proposed energy efficiency packages with the energy consumption of the reference building, the end use energy consumption was also converted to primary energy. The conversion to primary energy was made considering the Romanian conversion factors for each type of energy: 1.17 for natural gas and 2.62 for electricity [33]. The graph in Figure 6.1 shows the primary energy consumption for each end use without considering the on-site electrical energy production and aims at enhancing the differences in energy consumption for the envelope and technical systems packages. As it can be seen in the graph in Figure 6.1 and also in Table 1, the energy consumption for lighting and interior equipment is constant for all scenarios because no energy efficiency measures were considered for these two end uses. Differences can be seen with respect to energy consumption for heating, cooling and domestic hot water. For all energy efficiency packages, the energy consumptions for heating, cooling and domestic hot water are lower than the primary energy consumption of the reference building. The energy consumption for domestic hot water has close values for all energy efficiency packages, excluding the reference building, since they all have the same type of solar collector.

Table 6.6 - End use energy consumption for selected packages

End use \ Package		PH_I	PH_I_S	PH_II_S	EE_I	EE_I_S	EE_II_S	RB
Heating [kWh/m^{2}y]	Electric	13.00	13.05	4.45	19.86	19.86	8.03	-
	Natural gas	-	-	-	-	-	-	95.70
Cooling [kWh/m^{2}y]		2.87	1.12	0.22	2.64	1.00	0.21	5.61
Domestic hot water kWh/m^{2}y	Electric	4.50	4.51	4.41	4.53	4.54	4.42	-
	Natural gas	-	-	-	-	-	-	19.59
Interior equipment (kWh/m^{2}year)		9.45	9.45	9.45	9.45	9.45	9.45	9.45
Lighting [kWh/m^{2}y]		1.11	1.11	1.11	1.11	1.11	1.11	1.11
Fans [kWh/m^{2}y]		5.76	5.74	4.63	5.86	5.83	5.33	-
Circulation pumps [kWh/m^{2}y]		5.70	5.75	7.71	5.94	5.95	8.02	6.55

We can notice the reduction of energy consumption for cooling by comparing the packages that do not include shading systems (PH_I, EE_I) with the packages that have available shading systems during the cooling season (PH_I_S, EE_I_S). The primary energy consumption is reduced with more than 50%.

With respect to the primary energy consumption for heating, it is noticeable that the highest energy use is the one of the reference building. Differences can be seen between the packages that have different envelope configuration but the same technical systems. The primary energy consumption for heating increases with approximately 50% for EE_I and EE_I_S compared to PH_I and PH_I_S.

The primary energy consumption for heating is more than 50% lower for envelope packages PH than EE. Also, the differences in primary energy consumption for heating are also visible between packages that have the same envelope but different technical systems. In all situations, technical system II leads to a lower energy consumption for heating, regardless of the envelope package.

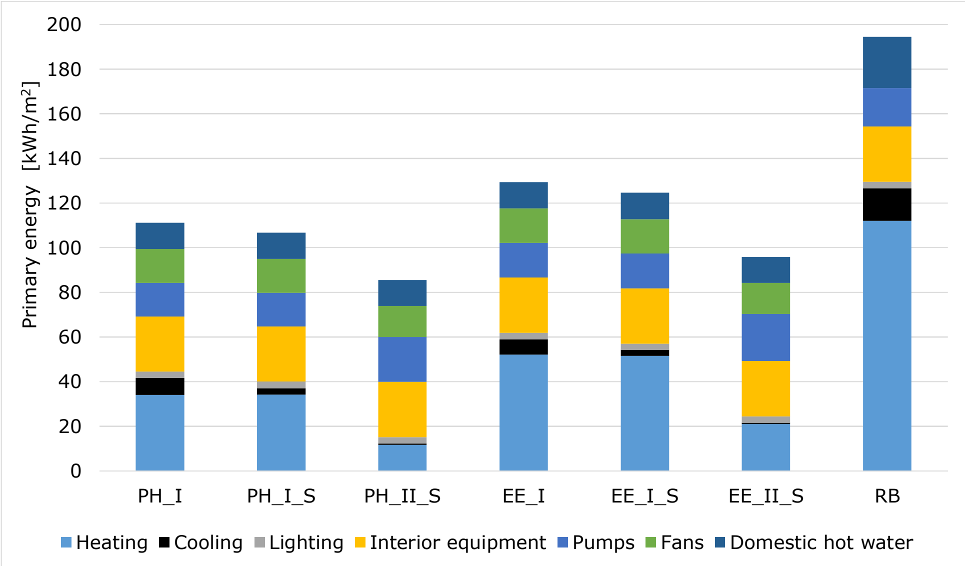


Figure 6.1 – Primary energy consumption for each end use

6.3.3 On-site electricity production using photovoltaic panels

Three different sizes of PV systems were implemented in combination with the building envelope measures and technical systems. This section presents the energy consumption and production evaluation for the packages that include photovoltaic systems.

Figure 6.2 shows the annual energy consumption of each package against annual total electricity produced on-site. The energy used for power conversion was subtracted from the total energy production. It is noticeable that for packages PH_I_S+4.8kW, PH_II_S+4.8kW and EE_II_S+4.8 kW the energy production is higher than the energy consumption. Table 6.7 shows the ratio between total electricity production and total electricity use. Obviously, the highest total PV production to total electricity consumption is achieved by the earlier mentioned packages (ratio greater than 1). Also, the ratio of surplus electricity production that is exported to the grid to total electricity production is presented for each package in Table 6.7.

The graph in Figure 6.3 shows the total final energy consumption of each package broken down in the energy consumed from the grid and the energy used on-site from the photovoltaic system production. The on-site energy use from photovoltaic systems production was determined using the EnergyPlus results file, by subtracting from the total energy production the surplus energy exported to the grid and the energy used for power conversion.

Figure 6.4 shows the percentage of electricity produced and consumed on site from the total electricity production and from the total electricity consumption. It’s worth mentioning that the packages that have a smaller photovoltaic systems have greater on site use percentage of total electricity production. However, the on-site PV use percentage of total electricity consumption does not go above 35%.

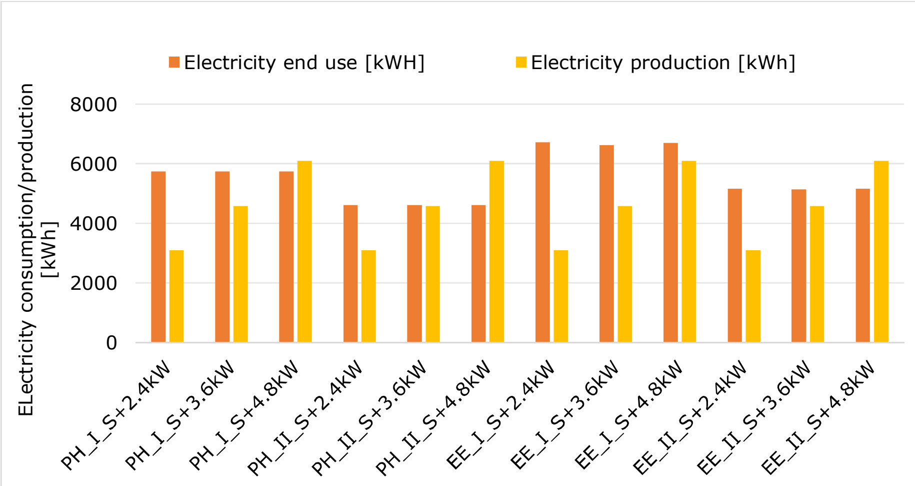


Figure 6.2 - Annual electricity consumption and on-site production

Table 6.7 – PV electricity production ratios

Package name	Total electricity production/ total electricity consumption ratio [-]	Surplus exported electricity/ total PV production ratio [-]
PH_I_S+2.4kW	0.54	0.54
PH_I_S+3.6kW	0.80	0.66
PH_I_S+4.8kW	1.06	0.73
PH_II_S+2.4kW	0.67	0.56
PH_II_S+3.6kW	0.99	0.68
PH_II_S+4.8kW	1.32	0.74
EE_I_S+2.4kW	0.46	0.54
EE_I_S+3.6kW	0.69	0.67
EE_I_S+4.8kW	0.91	0.73
EE_II_S+2.4kW	0.60	0.56
EE_II_S+3.6kW	0.89	0.67
EE_II_S+4.8kW	1.18	0.74

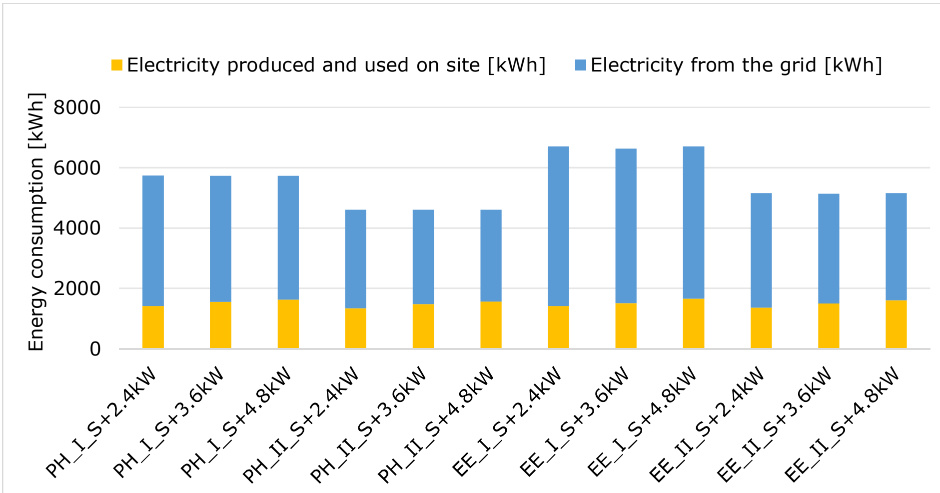


Figure 6.3 – End use energy consumption divided by source

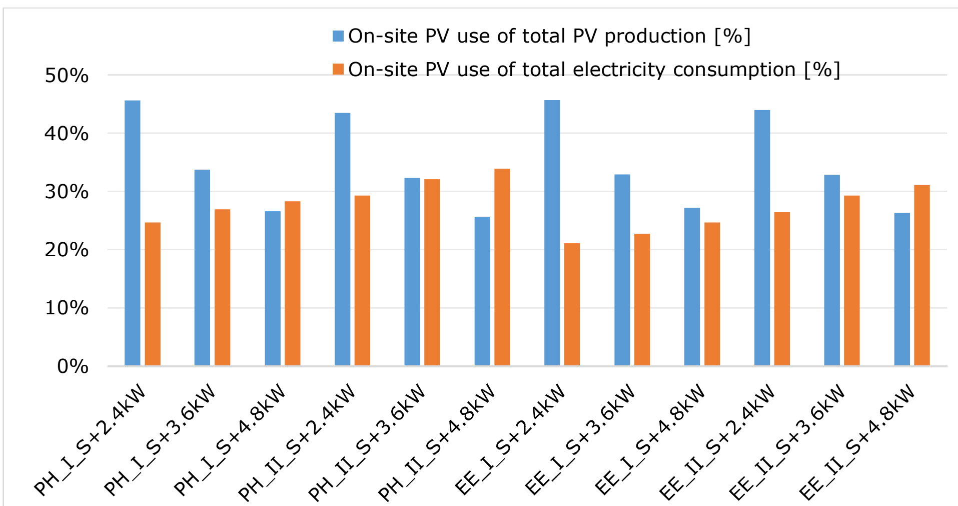


Figure 6.4 – On-site PV use of total PV production and total electricity consumption

6.3.4 Primary energy calculation

As mentioned earlier, the Romanian authorities have established requirements related to nZEB primary energy consumption from fossil fuels, depending on the type of building and climate zone. Thus, for the nZEB located in Romania in climate zone II (where the investigated building is located), the specific primary energy consumption from conventional sources must be lower than 111 kWh/m^{2}year. In order to identify the packages that respect the above mentioned requirement, the primary energy consumption from non-renewable sources (also called net primary energy) is calculated for each package.

According to [101] the primary energy from non-renewable sources is calculated based on the delivered and exported energy, using primary energy conversion factors. Thus, the primary energy from non-renewable sources is calculated as the difference between the primary energy corresponding to the energy imported from the grid and the primary energy corresponding to the energy exported to the grid. In Romania, the most recent values for primary energy factors depending on the energy source are provided in [33] and presented in Table 6.8. The specific net primary energy consumption or primary energy consumption form non-renewable sources is plotted in the graph in Figure 6.5 for each of the investigated building packages.

Table 6.8 - Primary energy conversion factors [33]

Energy source	Factor	
	Non-renewable	Renewable
Electrical energy from national grid	2.62	0.00
Natural gas	1.17	0.00
Electrical energy produced with photovoltaic panels	0.00	2.62

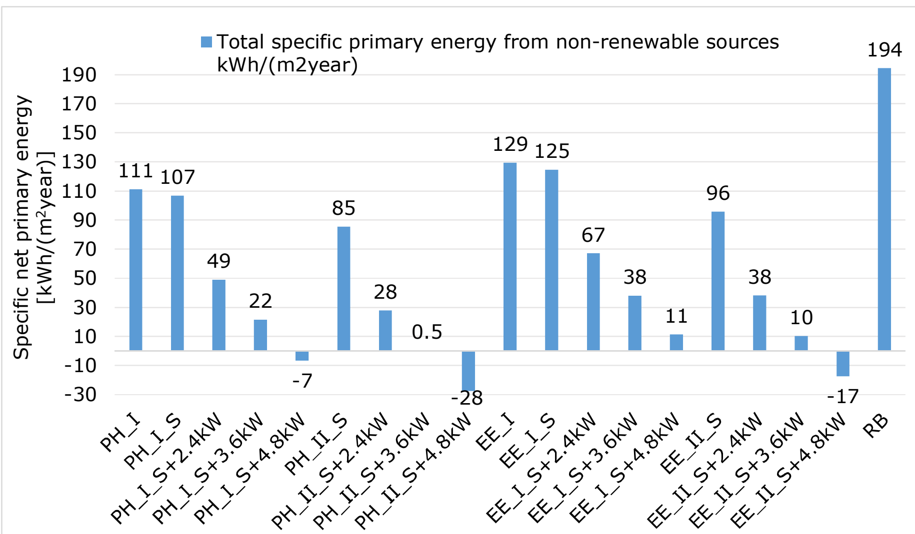


Figure 6.5 – Net specific primary energy consumption

There are some situations when the net primary energy has negative values, which means that on an annual basis, the building packages lead to a higher energy production than consumptions (PH_I_S+4.8kW, PH_II_S+4.8kW, EE_II_S+4.8kW). The packages that lead to a surplus of energy are the ones including the on-site electricity production system composed of 20 photovoltaic panels.

Building package PH_II_S+3.6kW leads to a net specific primary energy consumption of 0.5 kWh/m^{2}year and it can be considered a net zero-energy building.

The primary energy of the real building envelope and system configuration PH_I is at the primary energy consumption limit that defines nZEB in Romania. Packages EE_I and EE_I_S have a higher primary energy consumption than the requirements, which means that these two options are not suitable for nZEB. All other packages respect the primary energy requirements imposed by the Romanian authorities with respect to nearly zero-energy buildings, with primary energy ranging from 10 to 96 kWh/m^{2}year.

6.3.5 Renewable energy ratio

The second part of the nZEB definition, as it is stipulated in the EPD recast and also in the Romanian documents, is related to the share of renewable energy from the total primary energy consumption. According to the EPBD recast, the energy need of nZEB must be covered to a high extent from renewable sources. In Romania, the authorities have established that the percentage of renewable energy of total primary energy consumption must not be lower than 10%.

If the net primary energy is calculated considering only the imported and exported energy, the total primary energy calculation must be performed including all the renewable energy sources such as: thermal energy from solar collectors, thermal energy captured by heat pumps from air, ground or water etc.

According to [123], when calculating the total primary energy, it is considered that the exported energy compensates the imported energy. Also, the on-site renewable energy production is weighted with renewable energy conversion factor 1 and non-renewable factor 0. The calculation of the total primary energy is made based on the above principles and using the formula given in [123].

The primary energy corresponding to the thermal energy provided by heat pumps is determined according to [124]. For the calculations, Equation 6.1 and 6.2 are used, in accordance with Annex VII of the EPDD recast [21].

$$E_{RES} = Q_{usable} \cdot (1 - {}^{1}/_{SPF}) \qquad \text{Eq. 6.1}$$

$$Q_{usable} = H_{HP} \cdot P_{rated} \qquad \text{Eq. 6.2}$$

Where:
E_{RES} – energy supplied by heat pump technologies
H_{HP} - equivalent full load hours of operation
Q_{usable} – the estimated total usable heat delivered by heat pumps
P_{rated} - rated heating capacity
SPF – the estimated average seasonal performance factor

Default values for H_{HP} and SPF were used, in compliance with [124]. Thus, for cold climates the H_{HP} values are: and for air to water heat pump and 2470 for soil-water heat pump. The default values for the seasonal performance factor is 2.5 for the air to water heat pump and 3.5 for the soil-water heat pump. The renewable energy from the two types of heat pumps used in this research are listed in Table 6.9.

Table 6.10 presents the total primary energy consumption, which is the sum between the non-renewable primary energy and renewable primary energy. The renewable primary energy includes the thermal energy provided by solar collectors and also the thermal energy provided by the heat pumps. The renewable energy ratio was calculated based on total primary energy consumption. The minimum ratio is achieved for packages EE_I and while the maximum is achieved by package PH_IIS+4.8kW (higher than 1).

Table 6.9 - Renewable energy from heat pumps

Type of heat pump	H_{HP} [h]	SPF	P_{rated} [kW]	Q_{usable} [kWh/m²year]	E_{RES} [kWh/m²year]
Air to water (technical system I)	1710	2.5	5.21	63.20	37.90
Soil-water (technical system II)	2470	3.5	7	122.6	87.60

Table 6.10 - Total primary energy based on non-renewable and renewable energy

	Non-renewable primary energy [kWh/m²year]	**Renewable primary energy [kWh/m²year]**	**Total primary energy [kWh/m²year]**	**Renewable energy ratio [-]**
PH_I	111	47	158	0.298
PH_I_S	107	47	154	0.306
PH_I_S+2.4kW	49	69	118	0.585
PH_I_S+3.6kW	22	80	101	0.787
PH_I_S+4.8kW	-7	90	84	1.079
PH_II_S	85	97	182	0.531
PH_II_S+2.4kW	28	119	147	0.809
PH_II_S+3.6kW	1	129	130	0.996
PH_II_S+4.8kW	-28	140	112	1.245
EE_I	129	47	177	0.267
EE_I_S	125	47	172	0.274
EE_I_S+2.4kW	67	69	136	0.507
EE_I_S+3.6kW	38	80	118	0.677
EE_I_S+4.8kW	11	90	102	0.888
EE_II_S	96	97	193	0.503
EE_II_S+2.4kW	38	119	157	0.756
EE_II_S+3.6kW	10	129	140	0.925
EE_II_S+4.8kW	-17	140	123	1.141
RB	194	0	0	0.000

Figure 6.6 shows the percentage of renewable energy from the total primary energy consumption. It is noticeable that all packages have a higher renewable share than the minimum requirement in Romania of 10%, which means that packages that accomplish both conditions (primary energy consumption below 111 kWh/m²year and share of renewable energy higher than 10%) can be considered nZEBs following the Romanian definition. Packages EE_I and EE_I_S don't respect the first condition and therefore cannot be considered nZEB. However, the energy consumption reduction is significant for these two packages with respect to the reference building.

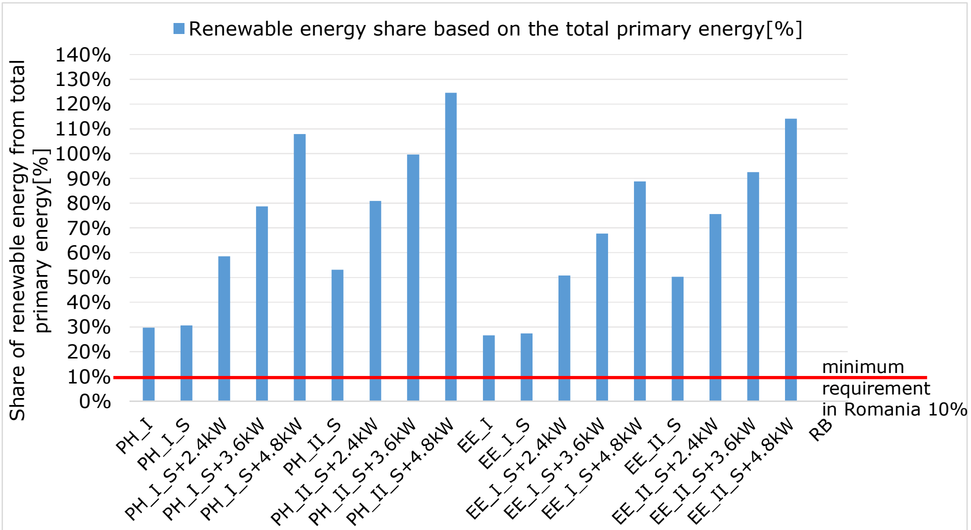


Figure 6.6 – Renewable energy share from the total primary energy consumption

6.4 Economic analysis based on global cost

6.4.1 Calculation period and discount rate

The global cost calculation was conducted following the guidelines provided in Delegated Regulation no. 244 and standard EN 15459 [104] using the priniples and matemathical equations presented in Chapter 2.5. As recomended, a period of analysis of 30 years was used in this thesis. A discount rate of 3% was used, as it is the same rate used by the Romanian authorities in global cost and cost optimal calculations [30].

6.4.2 Initial investment

The initial investment of the real building was evaluated using real the real costs of the building construction and technical systems, provided by the building owner. The costs include all taxes and VAT. The costs were broken down on: building structural system, thermal insilation, windows, technical systems (heating and cooling equipment, ventilation, domestic hot water, heating terminal etc.). Futher, these costs were adapted to match each of the other energy efficiency packages. The costs for the building construction and structural system are the same for all the packages, including for the reference building. The calculation sheet of the initial investment costs and categories breakdown for each package are presented in Appendix D. The initial investment costs are centralised and presented in the graph in Figure 6.7.

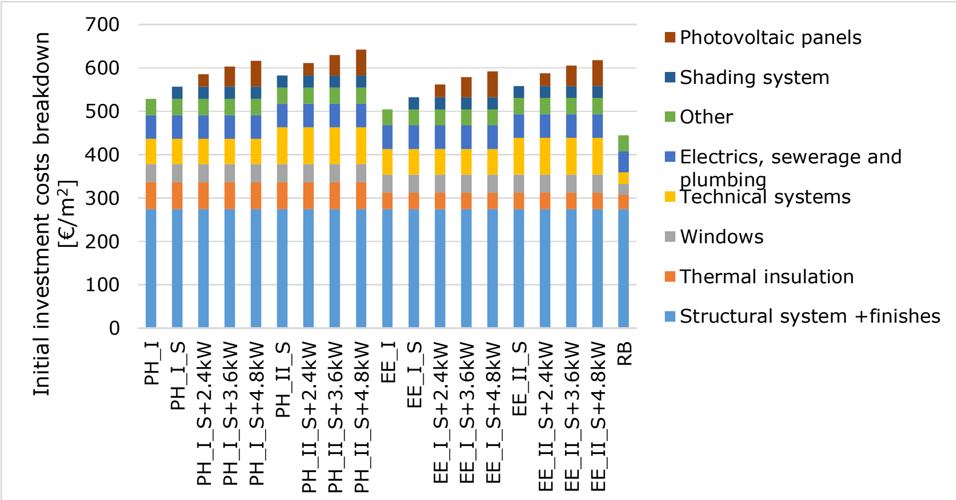


Figure 6.7 – Initial investment costs breakdown

The highest investment costs is for is for package PH_II_S+4.8kW, which corresponds to real building envelope with shadings, soil water heat pump and 20 photovoltaic panels. Obviously, the lowest investment cost is the one of the reference building. We can see how the initial investment for structural system and finishes remains constant among the building packages. Variations of the initial investment for technical systems can be observed betwenn technical system II, whose costs are slightly higher than for technical system I. The technical system of the reference building is the lowest and also the costs of thermal insulation and windows. The cost of thermal insulation is the highest for PH envelope and the lowest for RB.

6.4.3 Replacement and maintenance costs

The replacement costs depend on the lifespans of the different building systems components, which were established using Annex A of EN 15459 [104]. For each component that has a lifespan shorter than the calculation period, a replacement cost is considered in the year of the replacement. The replacement cost is actualized at present value using the discount rates.

The maintenance costs include those cost necessary for the quality conservation of the building systems in time. The costs refer to inspection costs, adjustments, repairs and preventive maintenance. Thus, the global cost is calculated considering that the equipment and building systems are properly maintained and periodically inspected. The maintenance costs were established in compliance to EN 15459-2006 [104], which offers data related to maintenance costs for different types of building components, expressed as percentage of the initial investment of each component. The replacement and maintenance costs for each package are presented in Appendix D. Table 6.11 shows the data established according to EN 15459 [104] for calculating the replacement and maintenance costs.

Table 6.11 - Lifespan and data for maintenance costs calculation [104]

Component	Life span [years]	Annual maintenance cost in % of the initial investment
Thermal insulations	50	-
Structural system	50	-
Windows	30	-
Condensing boiler	20	1-2
Fan coils	15	4
Expansion vessels	30	1
Ventilation fans	15	6
Heat pumps	20	2-4
Heat recovery units	20	4
Circulation pumps	20	2
Radiators, water	30	1-2
Tank storage for hot water	20	1
Wiring	30	1
Solar collector	25	0.5
Piping system	30	0.5
Photovoltaics	25	1
Split AC	20	4

6.4.4 Energy costs

The price for electricity was determined using the information available on the National Authority for Regulation in Energy domain [125], where electricity tariffs for household consumers are listed depending on the supplier. An average price of electricity of 0.12 €/kWh was used, including taxes and VAT. The price escalation rate of electricity energy prices was established by determining the average growth rate of electricity prices for household consumers in the past 10 years, using data for Romania provided by Eurostat [4]. Thus, a price escalation rate of 1.5% was used for the electricity prices.

The natural gas price in Romania is the lowest in Europe at the moment, according to EUROSTAT [4]. Regarding the natural gas price increase in Romania, the things are not very stable at the moment, since the Government has set a timetable for natural gas price liberalization by June 2021. However, this calendar does not establish a certain price to be achieved on the natural gas market for household consumers. For the timetable June 2011 – January 2017, the price for natural gas acquisition for household consumers increased with approximately 20.75% [126]. Considering the information available on the National Authority for Regulations in Energy field, a natural gas price of 0.060 €/m^2 (including acquisition, transport, distribution, taxes and VAT) was used in the calculations. In lack of other reliable information, the price escalation rate of natural gas was set to 5%, as in [30].

In the energy costs calculation, the benefits from electricity exported to the grid were accounted. It was assumed that the electricity exported in the grid is sold with a price of 0.043 €/kWh, even though an official value for the feed-in tariff has not yet been imposed at national level. This value was established as being equal to the one the distributors pay for the energy they buy from the market to ensure their own technological consumption [127].

6.4.5 Residual value

The residual value was calculated based on the remaining lifetime of the building components at the end of the calculation period. The residual value of the structural system was excluded from the calculations since is the same for all packages. The residual values were calculated according to Equation 2.5 presented in Chapter 2.5. Appendix D contains the residual values at the end of the calculation period for each package.

6.4.6 Global cost calculation

The global cost was calculated following Equation 2.3 in Chapter 2.5 and based on the costs evaluation and calculation assumptions earlier presented. The results of the global cost calculations are presented in Figure 6.8.

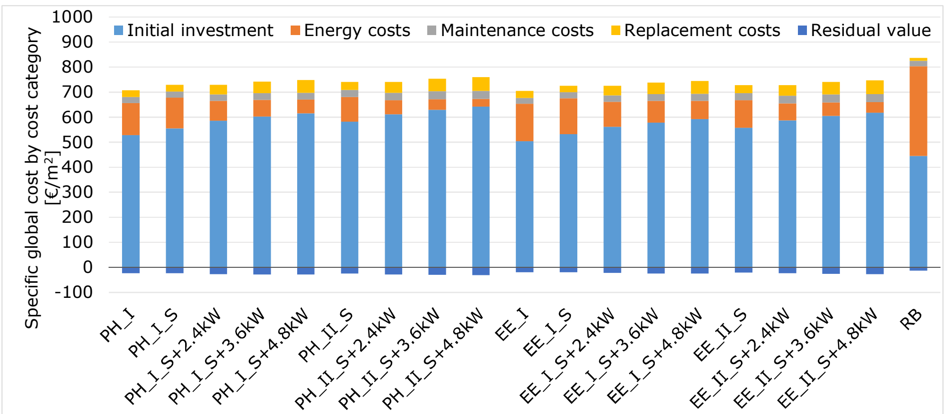


Figure 6.8 – Specific global cost in net present value of investigated building packages

As expected, the highest global cost is the one of the reference building due to the high energy costs, even though all the other costs categories are lower compared to the other building packages. The maintenance costs have the lowest values from the considered categories of costs, followed by replacement costs and energy costs. The energy costs decrease proportional with the energy consumption, meaning that the building packages with the lowest energy consumption from the grid, the energy costs are the lowest. The global costs calculation results are presented individually for each building package in Appendix D.

6.4.7 Derivation of cost-optimal level of energy performance

Subsequently to the primary energy and global cost calculations of each of the proposed building packages, a graph is plotted to detect which are the cost optimal solution but also to see the economic and energy performance of each solution compared to the others. Thus, the graph in Figure 6.9 displays the specific primary energy and global cost values for each investigated energy efficiency scenario. On the graph is also plotted the specific primary energy requirement for residential nZEB in climate zone II, Romania.

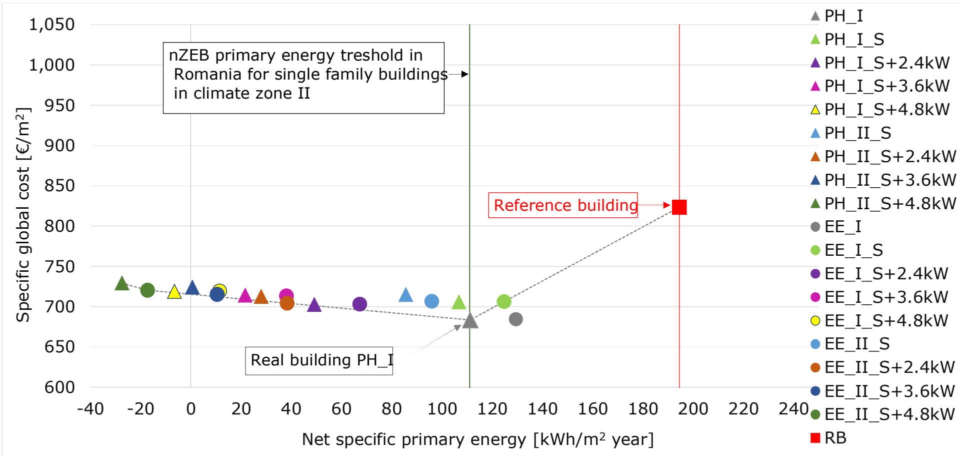


Figure 6.9 – Specific primary energy and global cost graph

The lowest global cost is achieved by the scenario of the real building PH_I and EE_I. However, the specific primary energy of package EE_I overcomes the maximum threshold defined for nZEB in Romania. In case of the real building, the specific primary energy is at the exact limit of primary energy consumption. Nevertheless, it can be said that the real building configuration is a cost-optimal solution. In other words, the lowest global cost is achieved at a primary energy consumption of 111 kWh/m^{2}year. This fact emphasizes that the primary energy requirements for nZEB established by the Romanian authorities are reliable for achieving cost-effective solutions. The derivation of real building package PH_I to PH_I_S, by implementing a shading system leads to a small reduction of the primary energy consumption but to an increase of the global cost due to the higher initial investment. However, even though the impact of the shading system is not so high on the overall energy consumption and global cost, its advantages are relevant with respect to indoor comfort parameters. An important primary energy reduction is encountered in case of PH_I_S+2.4KW, which as well derives from real building by including shading systems and 10 photovoltaic panels. The achieved primary energy reduction is about 55% (compared to PH_I_S) while the global cost increase due to the higher initial investment is only 2.8%. The difference in global cost is very small, thus both solutions can be considered cost-optimal.

It can be noticed that all the proposed solutions have a significantly lower global cost and primary energy consumption compared to the reference building. The global cost for the investigate solutions varies between €/m^2 and 729 €/m^2, excluding the reference building. Among the proposed energy efficiency packages, excluding the reference building, the highest global cost is achieved by PH_II_S+4.8kW, which has at the same time a surplus of primary energy. This solution can be considered the most energy efficient among the ones investigated. It is noticeable that the investigated solutions that have the maximum number of photovoltaic panels lead to a surplus of energy (PH_II_S+4.8kW, EE_II_S+4.8kW and PH_I_S+4.8kW), except for EE_I_S+4.8kW. Net zero-energy balance is achieved through energy efficiency package PH_II_S+3.6kW.

It is worth mentioning, that if two or more solutions have the same global cost but different energy performance, the solution having lower energy consumption is preferred.

6.4.8 Sensitivity analysis to the discount rate values

The sensitivity analysis will be performed for two other values of the discount rate, one higher (5%) and one lower (1%). This analysis investigates the way in which the global cost is affected by the uncertainties which are included in the discount rate estimations. Thus, the global cost calculation was performed for discount rate vales of 1% and 5%. The results are plotted in Figure 6.10, comparatively to the base case situation (discount rate 3%).

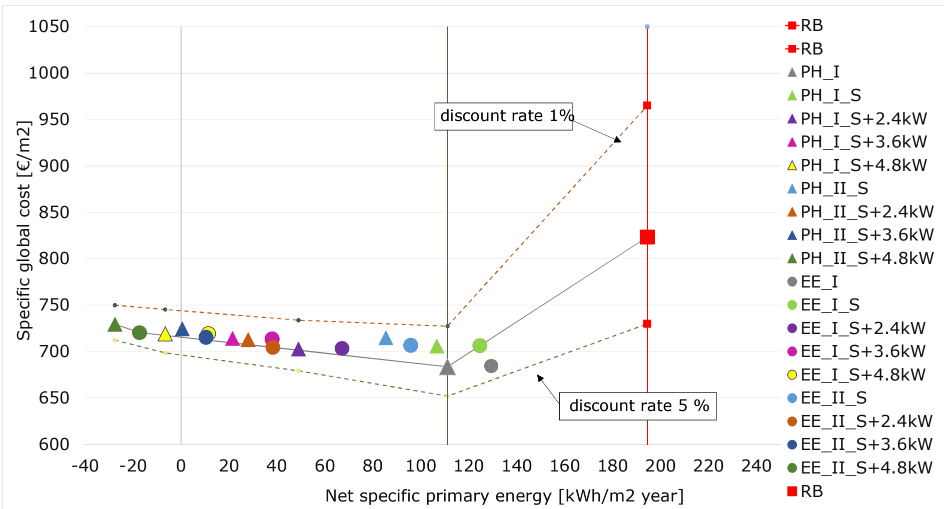


Figure 6.10 – Analysis of sensitivity to the discount rate

We can notice that a reduction of the discount rate leads to an overall increase of the global cost, which means that with a lower discount, the effect of the future costs on the global costs is higher. The global cost increase is significant in case of the reference buildings, due to the high annual costs related to energy. An increase of the discount rate leads to a reduction of the overall global cost, especially in case of the reference building, when the global cost decreases from 823 €/m^2 to 729 €/m^2, being comparable with the global cost of the most energy performant package PH_II_S+4.8kW, which is 712 €/m^2. The global cost of the real building stays below the one of the reference building in both investigated situations.

It is noticeable that the difference between the base case scenario and the two other scenarios of discount rates decreases with the decrease of the energy consumption, which means that packages with a low energy consumption are not so vulnerable to the discount rate variation as the packages with higher energy consumption. In other words, a building that has a low energy consumption is not so sensitive to the changes that financial market might encounter throughout the life-cycle.

The sensitivity analysis shows that for different values of the discount rate, the energy efficiency packages maintain similar positions on the cost-optimal curve relatively one to another.

6.4.9 Sensitivity analysis to the future development of the energy prices

The calculations of the global cost were performed considering an estimated price escalation rate for electricity of 1.5% and 5% for natural gas. Two other scenarios will be investigated, following the recommendations in [101] to perform sensitivity analysis to the energy prices development rates. Considering that for the base case scenario, price escalation rates were taken into account, one of the proposed scenarios assumes that the energy price development rate is 0%, for both natural gas and electricity. The results are plotted in Figure 6.11 and we can notice that in this situation the global cost of almost all proposed energy efficiency packages is higher than the global cost of the reference building. However, the real building still maintains a slightly lower global cost than the reference building.

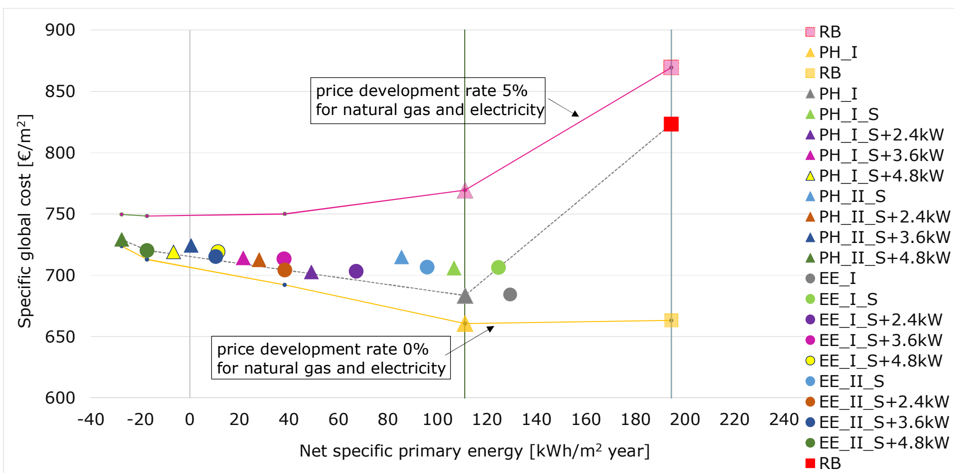


Figure 6.11 – Cost-optimal sensitivity analysis – energy price development rate

A second scenario was considered when the energy price escalation rate was set to 5% for both types of energy. In this situation we can see how the global cost for the most energy efficient solutions is lower than for the reference building and the energy efficiency packages that have a higher energy consumption. As expected, the sensitivity analysis on the price development rate reveals that the energy efficiency packages with the lowest energy consumption are the least influenced by the future evolution of energy prices. It is noticeable that the real building is not cost optimal in this scenario.

Another global cost analysis was performed considering that the surplus energy produced by the photovoltaic panels and exported to the national grid is not repaid. The results are plotted in Figure 6.12 and compared to the base case situation. In this situation, the global cost increases for the energy efficiency packages that include photovoltaic panels, but still remains below the global cost of the reference building. The highest global cost increase is of 5% for PH_II_S+2.4kW.

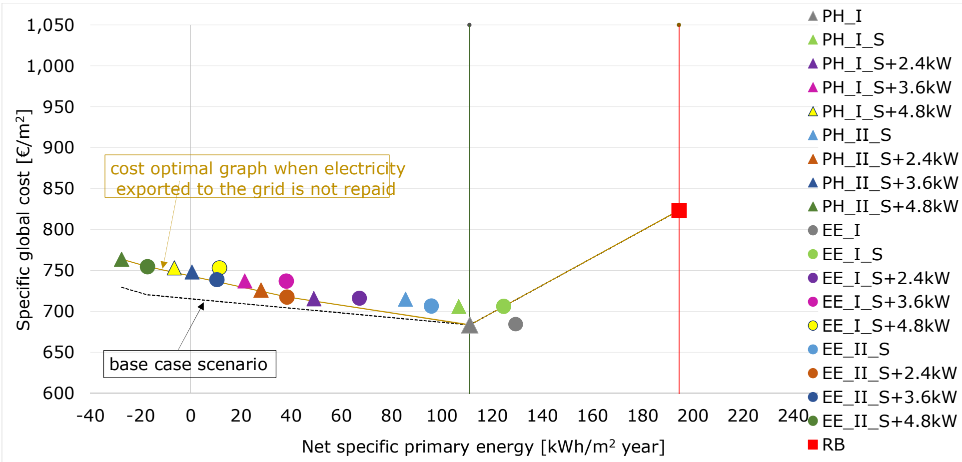


Figure 6.12 – Cost-optimal analysis – energy exported to the grid is not repaid

7 CONCLUSION

7.1 Conclusions of the research

This chapter summarizes the main conclusions of the research work developed in this thesis. As the title of the thesis says, the research followed a series of studies on the energy efficiency of buildings. The studies are based on an existing energy efficient residential building, which was built in compliance with the Passive House Standard and for which on site measurements were performed through a monitoring system. Thus, the first part of the research is focused on the monitoring data processing and analysis. A procedure for monitoring data processing was proposed. The aim of this part of the research is to investigate the real behaviour of the building in terms of energy consumption and indoor air parameters. The second part of the research is focused on the development of the building energy model using the hourly dynamic simulation software EnergyPlus and calibration of the building energy model using the monitoring data. The building energy model simulation results were assessed against real building data in terms of monthly energy consumption and interior air temperature. Subsequently, some analyses were performed on the building energy model. In the last part of the research, the study is extended on investigating, in terms of global cost and primary energy consumption, several energy efficiency scenarios applied to the case study building. The proposed energy efficiency scenarios are either upgrades that can be implemented in the existing building or different other configurations of thermal envelope and technical systems, including on-site renewable energy production. This last study was conducted following the cost-optimal methodology defined through Directive EPBD and Delegated Regulation 244 [21], [101].

Following the research and the analysis of the obtained results, the following main conclusions can be drawn:

1. The existing studies and research related to energy consumption throughout the world reveal that the building sector has the highest potential of reducing the energy consumption from fossil fuels and the related greenhouse gas emissions, as it is the sector with the highest share on the total global energy consumption.
2. The main challenge in achieving high levels of energy performance in buildings consists in providing solutions that lead to low energy consumption but at the same time are cost-effective.
3. Implementing a monitoring system in a building represents a way of optimizing the real energy consumption and also offers necessary data for building performance analysis, energy model calibration and validation.
4. At present, in Romania and in other developing countries, pilot projects of energy efficient buildings that are monitored in real time in terms of energy consumption, indoor comfort parameters, represent an effective path to decrease the gap between the theoretical performance and real performance of a building.
5. The monitoring data processing was a very laborious process because of the very high amount of registered data and lack of automated tools to ease the work. However, a procedure was developed using various functions and formulas implemented in Excel spreadsheets that reduced the workload.

6. The analysis of the hourly interior air temperature shows that throughout the year, the most frequent values are within the range 22℃ - 23℃. Only for 2.91% of the total number of hours, the interior air temperature falls below 22℃.

7. The temperature measurements over a year time period indicated that the building faced overheating several times during summer. The frequency of overheating events is noticeable higher for the first floor rooms at all temperature limits. The main cause of overheating is the lack of shading systems for the windows. The cooling system was available for only a limited number of hours every day in August, as it was the preference of the building occupants.

8. The total energy consumption registered in 2015 was of 40.52 kWh/m2. The corresponding primary energy is of 106.16 kWh/m2, which is below the passive house standard requirement (120 kWh/m2) and also below the primary energy limitation for residential nearly zero-energy buildings in Romania (111 kWh/m2). It can be said that the investigated building is a good practice example for achieving nearly zero-energy building standard in Romania, in terms of primary energy.

9. The development of a building energy model for dynamic hourly simulations is a very laborious process due to the complexity and accuracy of the required input data. The modelling process requires a great amount of information to the building composition (envelope and systems) and also related to the building operation. Thus, in the simulation of a building energy model the uncertainty sources are multiple.

10. A methodology for calibrating the building energy model for the case study building was proposed. Occupant related operation of the building was defined using monitoring data for a year of occupancy. Weekday and weekend day electricity use patterns for lighting and interior equipment were created using hourly energy consumption measured data. The validation of the building energy model was performed using monthly energy consumption values and hourly interior temperature.

11. The performance of the building energy model was assessed by means of NMBE and CVRME. The NMBE and CVRMSE values of -1.107% and 3.843% for total energy consumption are within the acceptance limit of ±5% and 15%. The monthly total energy consumption comparison between simulated and measured, as shown in Figure 7.1, shows that the building energy model managed to predict very closely the measured values.

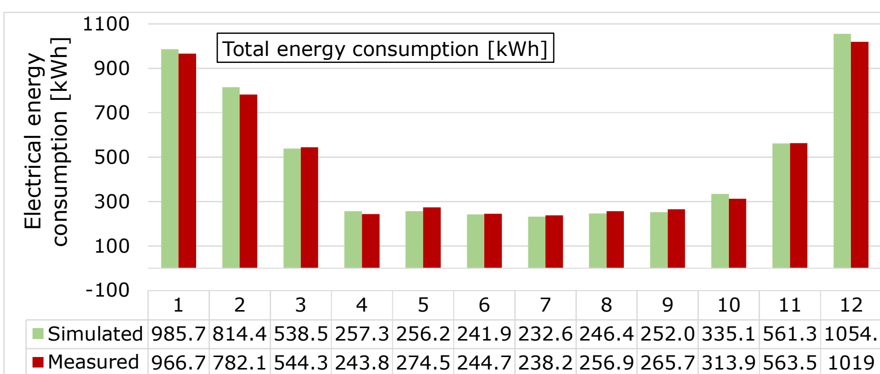


Figure 7.1 - Monthly total electricity consumption comparison

12. The accuracy of the building energy model in predicting air temperature was assessed as well. The overall NMBE and CVRMSE values calculate for hourly instances of time are -0.82%, respectively 5.72% and follow the calibration criteria

to hourly values (±10%, 30%). Over the entire year, the measured indoor air temperatures are lower with and average value of 0.20ºC.

13. A study was investigating the effect of the interior air temperature set point for heating on the total energy consumption of the building. The results show that with reference to the base case scenario (S0), which represents the real operation conditions of the building, the energy consumption for heating can decrease with 8% (S1) and 17.26% for the lower heating set-points and can increase with 13.67%(S3) and 23.17%(S4) for the higher heating set-points. The results of this study emphasize the sensitivity of the overall energy consumption of a building to the heating temperature set-point. Therefore, in order to reduce the gap between the designed and real energy consumption of a building, several scenarios for temperature set point should be investigated in the design phase of a building. This kind of analyses could be a reference for building owners and their use of the house.

14. Another simulations investigating the effect of shading devices on the interior air temperatures show a significant reduction of the interior air temperature if shading devices are implemented in the building. In the situation of the original building energy model, the maximum average interior air temperature was 31.50ºC. The results of the simulation considering the shading devices show a maximum average interior air temperature of 29.24ºC.

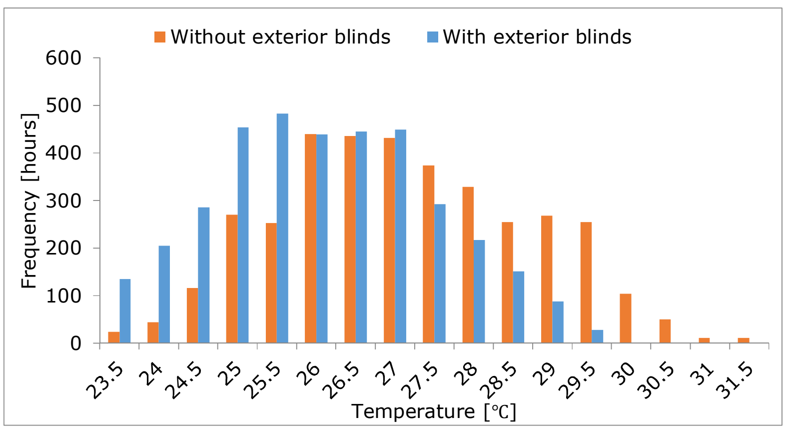


Figure 7.2 - Histogram of hourly interior air temperature

If shading devices are considered, the most frequent values of the interior air below 27℃ (Figure 7.2). For the other situation, the most frequent interior temperature values are above 26℃. This study emphasizes the importance of the shading devices in case of very well insulated and airtight buildings. It can be concluded that with shading devices available during the summer and night hours cooling, the interior air temperature can be maintained in acceptable limits without much use of an active cooling system.

15. The study investigating different energy efficiency packages implemented to the case study building shows as the most energy efficient the scenario when the current heating/cooling system of the building (air- water heat pump) is replaced with a soil-water heat pump and shading systems and 20 photovoltaic panels are implemented (PH_II_S+4.8kW).

16. The cost optimal-analysis shows that the lowest global cost is achieved by the scenario of the real building PH_I (Figure 7.2), for which the specific primary

energy is at the exact limit of primary energy consumption. It can be concluded that the real building configuration is a cost-optimal solution. In other words, the lowest global cost is achieved at a primary energy consumption of 111 kWh/m2year. This fact emphasizes that the primary energy requirements for nearly zero-energy buildings established by the Romanian authorities are reliable for achieving cost-effective solutions.

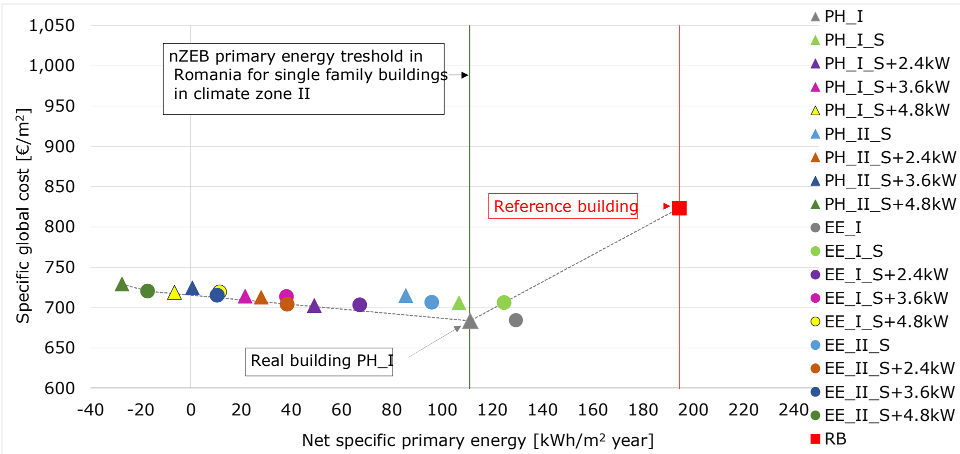


Figure 7.3 – Specific primary energy and global cost graph

17. An important primary energy reduction is encountered in case of PH_I_S+2.4KW, which as well derives from real building by including shading systems and 10 photovoltaic panels. The achieved primary energy reduction is about 55% (compared to PH_I_S) while the global cost increase due to the higher initial investment is only 2.8%. The difference in global cost is very small, thus both solutions can be considered cost-optimal.

18. All the proposed energy efficiency packages lead to a significantly lower global cost and primary energy consumption compared to the reference building. The global cost for the investigate solutions varies between 683 €/m² and 729 €/m², excluding the reference building. The solutions that have the maximum number of photovoltaic panels lead to a surplus of energy (PH_II_S+4.8kW, EE_II_S+4.8kW and PH_I_S+4.8kW), except for EE_I_S+4.8kW. Net zero-energy balance is achieved through energy efficiency package PH_II_S+3.6kW.

19. The cost optimal analysis shows that the nearly zero energy building can be achieved also with a lower insulation level than passive house level, if it is combined with efficient technical system and/or renewable energy production.

20. The sensitivity analyses performed for different discount rates and energy price escalation rates indicate that the scenarios that have very low energy consumption are not so sensitive to the future evolution of the prices or discount rates, which means that they can be considered safer solutions in front of the uncertainty that lies in the energy market evolution.

21. Even though on a long time perspective, the highly energy efficient buildings proves to be more cost-effective than the reference buildings, the higher initial investment is an impediment for most of the building owners. However, in case of the identified cost optimal solutions (PH_I and PH_I_S+2.4kW), the initial

investment is higher with 19%, respectively 32% compared to the reference buildings. Higher differences occur along with the increase of photovoltaic systems or change of the heating/cooling system.

22. The range of the investigated energy efficiency package is not very wide, as it include only two types of technical systems (excluding the reference building) and two envelope configurations. Therefore a more comprehensive study including different configurations might lead to even better cost-optimal solutions of energy performance.

7.2 Personal contributions

The author consider as personal contributions the following:

1. **Study and synthesis of a large number of research papers and thesis** following the current international situation on energy consumption and energy performance of buildings.
2. **Development of a strategy and procedure for processing a large amount of data registered by the monitoring system**. The author established a strategy to cope with the large amount of data provided by the monitoring system, which performed measurements at every minute for almost 100 sensors and meters.
3. **Analysis and interpretation of the processed monitoring data.**
4. **Generating customised input data based on monitoring for** performing a tailored simulation of the energy performance of the case study building, with the purpose of calibrating a numerical simulation. The author generated interior air hourly temperature schedules patterns for each month. Also, hourly schedules were determined for lighting consumption and household appliances.
5. **Development of a complex building energy model**, based on real operation condition of the case study building, as built geometry and characteristics.
6. **Established a calibration procedure of the building energy model** in order to obtain simulation results that comply with the real measured energy performance of the building. The results of the tailored calculations lead to a very small difference between the measured data and simulated data.
7. **Investigated the influence of different changes related to the building operation** on the total energy consumption. The author concluded that the energy consumption can vary greatly depending on the heating temperature preferred by the user.
8. **Investigated the possibility of reducing the interior air temperature in the building** during summer, without the use of an active cooling system. The author performed a simulation on the case study building, including shading systems for the windows. This measure reduces the frequency of hours when temperature was above 27℃ in the house.
9. **Proposed 19 energy efficiency scenarios applied to the case study building and investigated each scenario in terms of primary energy consumption and global cost.** The author identified energy efficiency packages that lead to net-zero energy balance as well as plus energy balance. Also, it was concluded that with an extra investment in the case study building, even greater energy performance can be achieved than the present one.
10. **Applied the cost-optimal methodology to the investigated energy efficiency scenarios.** The author identified cost-optimal solutions for nearly zero-energy buildings among the investigated scenarios. These scenarios comply with the

Energy Performance of Buildings Directive as well as with the national requirements with respect to nearly zero-energy buildings.
During her time as a Ph.D. student, the author was enrolled in a three months internship financed through the ERASMUS mobility, at Politecnico di Torino, where she has been working under the coordination of Prof. Stefano Paolo Corgnati and Ph.D. architect Cristina Becchio. In that period, the author gained knowledge that was further applied in her research and studies.
The author was part of the research team in a research grant at the Politehnica University Timisoara, grant of the Romanian National Authority for Scientific Research,CNDI–UEFISCDI; project number PN-IIPT-PCCA-2011-3.2-1214-Contract 74/2012.
During her studies, the Ph.D. student published 19 scientific papers that follow the topic of the thesis, from which 2 papers are ISI journal, 3 papers ISI proceedings and several other are indexed in international database. A list of selected papers is as follows:

D. Dan, **C. Tanasa**, V. Stoian, S. Brata, D. Stoian, T. Nagy-Gyorgy, S.C. Florut, "Passive house design-An efficient solution for residential buildings in Romania", Energy For Sustainable Development, vol. 32, pp. 99-109, June 2016, ISSN: 0973-0826.

C. Tanasa, M. Fofiu, D. Stoian, V. Stoian, D. Dan, "Air Tightness Measurements for an Energy Efficient Residential House Using the Blower Door Procedure", Proceedings of the 15th National Technical-Scientific Conference on Modern Technologies for the 3rd Millennium Nov. 27-28 2015, Oradea, Romania, pp. 169-174, 2016, ISBN 978-88-7589-724-8. Printed in February 2016.

I. Boros, **C. Tanasa,** V. Stoian, D. Dan, " Life cycle assessment and life cycle cost analysis of a nearly zero energy residential building - a case study", Environmental Engineering and Management Journal, vol. 16, Issue 3, pp. 695-704, March 2017.

S. Brata, V. Cotorobai, S. Brata, **C. Tanasa,** "Thermal performances of a ground-air heat exchanger integrated in a mechanical ventilation system of a residential building – daily and hourly models", Proceedings of the 16th National Technical-Scientific Conference on Modern Technologies for the 3rd Millennium, Mar. 23-24 2017, Oradea, Romania, pp. 133-138, ISBN 978-88-87729-42-2. Printed in June 2017.

C. Maduta, S. Brata, S. Pescari, **C. Tanasa,** V. Stoian, "Renovation solutions for collective residential buildings – case study", Proceedings of the 16th National Technical-Scientific Conference on Modern Technologies for the 3rd Millennium, Mar. 23-24 2017, Oradea, Romania, pp. 185-190, ISBN 978-88-87729-42-2. Printed in June 2017.

C. Tanasa, C. Sabau, D.Dan & V. Stoian, "Energy consumption and thermal comfort in a passive house built in Romania", PORTUGAL SB13, CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS Conference Proceedings P.161-166, Guimaraes 2013.

C. Tanasa, C. Maduta, V. Stoian, D. Dan, D. Stoian, S. Pescari, „Study on energy efficiency requirements in buildings", International Conference On Urban Sustainability, Cultural Sustainability, Green Development, Green Structures And Clean Cars (Uscudar '14), Ediția A 5-A, 22-24 Noiembrie 2014, Florența, Italia, Paper Id Number: 71804-157.

C. Tanasa, C. Sabau, D. Stoian, D. Dan, V. Stoian, „Study on the life cycle cost of energy efficient buildings", International Conference On Environment Technologies And Equipment (Eeete '14) – Advances In Environmental Technology And

Biotechnology, Ediția A 3-A, 26-28 Iunie 2014, Brașov, România Issn 2227 - 4359, Pag. 173 – 179.

C. Tanasa, V. Stoian, D. Stoian, D. Dan, "Concept and monitoring strategy of a residential building designed as a nearly zero-energy building'', YRSB16 – iiSBE Forum of Young Researchers in Sustainable Building 2016, 21st June 2016, Praga, Cehia, ISBN 978-80-01-05979-1, pp. 280-289.

I. Boros, **C. Tanasa,** V. Stoian, D. Dan, "Thermal studies of specific envelope solutions for an energy efficient building", International Conference on Innovative Research, ICIR 2015; Iasi; Romania; 14 May 2015 through 16 May 2015, Key Engineering Materials, vol. 660, pp 192-197, 2015.

I. Boros, K. Schmiedt, **C. Tanasa**, T. Nagy-Gyorgy, D. Dan, V. Stoian, "Real time thermal analysis of an exterior wall solution used as envelope for an energy efficient building'', International Journal of Energy and Environment 2016, Volume 10, 2016, pp. 243-247, ISSN: 2308-1007 (INASE Conferences in Rome, Italy, November 5-7, 2016).

S. Brata, V. Cotorobai, **C. Tanasa**, "Differences between the five climatic zones of Romania regarding the design and energy requirements of an energy efficient house", Revista Română de Inginerie Civilă, Numărul 2/2016, Volumul 7(2016), Nr. 2, ISBN:20683987.
D. Stoian, D. Dan, V. Stoian, T. Nagy-György, **C. Tănasă**, "ECONOMIC IMPACTS OF A PASSIVE HOUSE COMPARED TO A TRADITIONAL HOUSE", JOURNAL OF APPLIED ENGINEERING SCIENCES Vol. 1 p135-140, Oradea 2013.

7.3 Future work

This thesis follows a topic that is of great interest at an international level, among researchers, national authorities but also for the construction market and building owners. Therefore, research activities have still a long run to go in order to ensure an energy efficient built environment, which is cost-effective at the same time and provides comfort conditions to the occupants.
The author proposes the following future research activities to be developed:

1. Statistical processing and analysis of the monitoring data using the several years of recorded data.
2. Completing the monitoring system with some new measuring components that allows the breakdown of the energy consumption of the technical room. This will allow to better evaluate the performance of each component of the building technical systems.
3. Installment in the building of measuring components that determine the mean radiant temperature in the building, which will facilitate the indoor comfort parameters assessment.
4. Extending the cost-optimal studies by investigating other energy efficiency measures for both, thermal envelope and technical systems, in order to provide a wider range of solutions.

5. Extending the cost-optimal studies for all climate zones in Romania, considering the weather specific of each zone but also the national primary energy requirements in Romania for each climate zone.

BIBLIOGRAPHY

[1] United Nations, Framework Convention on Climate Change (2015) Adoption of the Paris Agreement, 21st Conference of the Parties, Paris: United Nations, Available from: https://treaties.un.org/.

[2] International Energy Agency, World Energy Outlook 2016 Executive Summary, 2016, Available from: http://www.iea.org .

[3] United States Energy Information Administration (EIA), The International Energy Outlook 2016, Available from: https://www.eia.gov.

[4] Eurostat-The statistical office of the European Union, Online at: http://ec.europa.eu/eurostat.

[5] The Intergovernmental Panel on Climate Change (IPCC), Available from: http://www.ipcc.ch/ipccreports/tar/wg1/index.php?idp=5.

[6] Enerdata, Energy Efficiency Trends in Buildings in the EU – Lessons from the ODYSSEE MURE, September 2012.

[7] Earth System Research Laboratory, National Oceanic and Atmospheric Administration – Mauna Loa Observatory, Available at: <https://www.esrl.noaa.gov/gmd/obop/mlo/>.

[8] United Nations, United Nations Framework Convention on Climate Change (UNFCCC), 1992.

[9] United Nations, Kyoto Protocol To The United Nations Framework Convention On Climate Change, 1998.

[10] Schneider Electric, Energy Efficicency Drivers in Europe - Regulations and other instruments open new horizons for Energy Management in buildings, October 2009.

[11] http://www.consilium.europa.eu/ro/meetings/international-summit/2015/11/30/.

[12] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directive 2004/8/EC and 2006/32/EC.

[13] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast).

[14] Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products.

[15] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC.

[16] Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC.

[17] http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics.

[18] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable

sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.
[19] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.
[20] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings.
[21] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.
[22] COM (2016) 765: Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2010/31/EU on the energy performance of buildings.
[23] Implementing the Energy Performance of Buildings Directive 2016, Intelligent Energy Europe Programme of the European Union.
[24] Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC.
[26] Marszal, A.J., Heiselberg, P., Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark, Journal Energy, Vol. 36, No.9, 2011, pp.5600-5609, doi:10.1016/j.energy.2011.07.010.
[27] Sterner, E., Life-cycle costing and it use in the Swedish building sector, Journal of Building Research & Information, Vol. 28, No. 5-6, 2010, pp. 387- 393, doi: 10.1080/096132100418537.
[28] Bankwatch Romania, Decuplarea creșterii economice de consumul de energie în România, Iulie, 2016.
[29] Ministerul Energiei, Analiza stadiului actual, February 2016, Available from: http://energie.gov.ro/wp-content/uploads/2016/03/Actualizare-Analiza-sistem_draft-final_19-feb-2016-1.pdf.
[30] Ministerul Dezvoltării Regionale și Administrației Publice, Nearly Zero Energy Buildings (NZEB) Romania – Plan de creștere a numărului de clădiri al căror consum de energie este aproape egal cu zero, July 2014. Available from: http://www.mdrap.ro/userfiles/metodologie_calcul_performanta_energetica_iulie2014.pdf.
[31] C107/3 -2005 - Normativ privind calculul termotehnic al elementelor de construcţie ale clădirilor.
[32] Mc 001/2006 - Metodologie de calcul al performanței energetice a clădirilor.
[33] ORDIN nr. 2641 din 4 aprilie 2017 privind modificarea şi completarea reglementării tehnice "Metodologie de calcul al performanţei energetice a clădirilor", aprobată prin Ordinul ministrului transporturilor, construcţiilor şi turismului nr. 157/2007.
[34] Legea 372 – 2005 - Lege privind performanța energetică a clădirilor.
[35] Legea 372 – 2005 - Lege privind performanța energetică a clădirilor, Republicată, 2013.
[36] O.G. 13/2016 - Ordonanță pentru modificarea și completare Legii 372/2005 privin performanța energetică a clădirilor.
[37] Ordinul nr. 386/2016 pentru modificarea şi completarea Reglementării tehnice "Normativ privind calculul termotehnic al elementelor de construcţie ale clădirilor", indicativ C 107-2005, aprobată prin Ordinul ministrului transporturilor, construcţiilor şi turismului nr. 2.055/2005.
[38] Passipedia – the Passive House resource, Available at: https://passipedia.org.

[39] Feist, W.; Pfluger, R.; Kaufmann, B.; Schnieders, J.; Kah, O.: Passive House Planning Package 2007, Technical information, PHI-2007/1, Passive House Institute, Darmstadt 2007.

[40] ISO 7730 - Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

[41] The Passive House Institute (PHI), Available at: http://www.passiv.de.

[42] The importance of building orientation. Online article available at: <https://www.ecowho.com/articles/6/The_importance_of_building_orientation.html>.

[43] International Passive House Association, Available at: <https://www.passivehouse-international.org>.

[44] Passive homes – Guidelines for the design and construction of passive house dwellings in Ireland, UCD ERG and MosArt Architecture, Sustainable Energy Authority of Ireland, Dublin, 2007. Available online at: <https://www.seai.ie/>.

[45] Pregizer, D., Casa energetic pasivă – Fundamente și construcție, Editura MATRIX ROM, ISBN: 978-973-755-881-7, București, 2013.

[46] Jokisalo, J., Kurnitski, J., Vinha, J., Building leakage, infiltration and energy performance analyses for Finnish detached houses, 9th REHVA World Congress Clima 2007 "WellBeing Indoors" - Helsinki, Finland, 10 -14 June 2007.

[47] Pan, W. (2010), Relationships between air-tightness and its influencing factors of post-2006 new built dwellings in the UK," Building and Environment, vol. 45, 2387-2399.

[48] Sherman, M.H., Matson, N.E., Reducing indoor residential exposure to outdoor pollutants, Lawrence Berkley National Laboratory, 2003, Berkeley, California.

[49] Defining the nearly zero-energy building: Passive House + renewables, the PassREg Project – Passive House Regions with Renewable Energies, Passive House Institute, 2015.

[50] European Comission, JRC Science for Policy Repor – Synthesis Report on the National Plans for NEalry Zero Energy Buildings (NZEBs), Progress of Member States towards NZEB. Available from: sthttp://publications.jrc.ec.europa.eu/repository/bitstream/JRC97408/reqno_jrc97408_online%20nzeb%20report%281%29.pdf

[51] Krick, B., Nearly Zero Energy Building? The Passive House provides answear, Passive House Institute, Germany, 2013.

[52] Ryan, M. E., Sanquist, F. T. (2012), “Validation of building energy modeling tools under idealized and realistic conditions”, Energy and Buildings, vol. 47, 375-382.

[53] Chong, Zhun Min Adrian, ”Bayesian calibration of building energy models for large datasets” (2017), Dissertations. 1006. Available at: <http://repository.cmu.edu/dissertations/1006>.

[54] Hoes, P., Hensen, J.L.M., Loomans, M.G.L.C., de Vries, B., Bourgeois, D. (2009), ”User behaviour in whole building simulation”, Energy and Buildings, vol. 41, issue 3, 295-302.

[55] Sullivan, R. (1998), ”Validation Studies of the DOE-2 Building Energy Simulation Program”, Lawrence Berkeley National Laboratory.

[56] Kim, Y-S., Heidarinejad, M., Dalhausen, M., Srebric, J. (2017), "Building energy model calibration with schedules derived from electricity use data", Applied Energy, vol. 190, 997-1007.

[57] Bordass, B., Cohen, R., Standeven, M., Leaman, A. (2010), "Assessing building performance in use 3: energy performance of the Probe buildings", Building Research and Information, vol. 29, issue 2, 114-128.

[58] Haberl, JS. Bou-Saada, TE. (1998), "Procedures for calibrating hourly simulation models to measured building energy and environmental data", Journal of Solar Energy Engineering, vol. 120, issue 3, 193-204.

[59] Coakley, D., Raftery, P., Keane, M. (2014), "A review of methods to match building energy simulation models to measured data", Renewable and Sustainable Energy Reviews, vol. 37, 123-141.

[60] De Wit, S., Augenbroe, G. (2002), "Analysis of uncertainty in building design evaluations and its implications", Energy and Buildings, vol. 34, issue 9, 951-958.

[61] Ramallo-Gonzales, A. P. (2013), "Modelling, simulation and optimisation methods for low-energy buildings", University of Exeter, Ph.D. Thesis.

[62] Norford, L.K., Socolow, R.H., Hsieh, E.S., Spadaro, G.V. (1994), "Two-to-one discrepancy between measured and predicted performance of a 'low-energy' office building: insights from a reconciliation based on the DOE-2 model", Energy and Buildings, vol. 21, issue 2, 121-131.

[63] Wang, L., Mathew, P., and Pang, X. (2012), "Uncertainties in energy consumption introduced by building operations and weather for a medium-size office building", Energy and Buildings, vol. 53, 152-158.

[64] Martinaitis, V., Zavadskas, E. K., Motuzienė, V., & Vilutienė, T. (2015),"Importance of occupancy information when simulating energy demand of energy efficient house: a case study", Energy and Buildings, vol. 101, 64-75.

[65] Yang, B., Becerik-Gerber, B. (2014), "The coupled effects of personalized occupant profile based HVAC schedules and room reassignment on building energy use", Energy and Buildings, vol. 78, 113-122.

[66] Maile, T., Bazjanac, V., Fischer, M. (2012), "A method to compare simulated and measured data to assess building energy performance", Building and Environment, vol. 56, 241-251.

[67] Wei, G., Martinez, J., & Verdict, M. (2006), "Embedding continuous commissioning in an energy efficiency retrofit program", Proceedings of the Sixth International Conference for Enhanced Building Operations (ICEBO2006), Shenzen, China.

[68] Raftery, P., Keane, M., Costa, A. (2011), "Calibrating whole building energy models: Detailed case study using hourly measured data", Energy and Buildins, vol. 43, 3666-3679.

[69] Paliouras, P., Matzaflaras, N., Peuhkuri, R.H., Kolarik, J. (2015), "Unsing measured indoor environment parameters for calibration of building simulation model – a passive house case study", Energy Procedia - 6th International Building Physics Conference (IBPC 2015), vol. 78, 1227-1232.

[70] Royapoor, M, Roskilly, T., (2015), "Building model calibration using energy and environmental data", Energy and Buildings, vol. 94, 109-120.

[71] Reddy, T. A. (2006), "Literature review on calibration of building energy simulation programs: uses, problems, procedures, uncertainty, and tools", ASHRAE transactions, 112, 226-240.

[72] Augenbroe, G., ”Trends in building simulation”, Building and Environment, vol. 37, issue 8-9, 891-902.
[73] Claridge, D.E. (2011), ”Building simulation for practical operational optmization”, Article In Building Performance Simulation for Design and Operation, 1st ed.; Hensen, J.L.M., Lamberts, R., Eds.; Spon Press: Oxfordshire, UK.
[74] Emily, M.; Ryan, E.M.; Sanquist, T.F. (2012), ”Validation of building energy modeling tools under idealized and realistic conditions”, Energy and Buildings, vol. 47, 375–382.
[75] Dall'O', G., Sarto, L., Sanna, N., Martucci, A. (2012), ”Comparison between predicted and actual energy performance for summer cooling in high-performance residential buildings in the Lombardy region (Italy)”, Energy and Buildings, vol. 54, 234–242.
[76] Fabrizio, E., Monetti, V., (2015), ”Methodologies and advancements in the calibration of building energy models”, Energies, vol. 8, 2548-2574.
[77] International Performance Measurement & Verification Protocol Committee (2002), International Performance Measurement & Verification Protocol: Concepts and Options for Determining Energy Savings and Water Savings, Volume I, Washington, DC: Department of Energy.
[78] Federal Energy Management Program (FEMP), M&V Guidelines: Measurement and Verification for Federal Energy Projects Version 4.0; U.S. Department of Energy Federal Energy Management Program: Washington, DC, 2015.
[79] International Performance Measurement & Verification Protocol Committee (2003), International Performance Measurement & Verification Protocol: Concepts and Options for Determining Energy Savings for New Construction, Volume III, Washington, DC: Department of Energy.
[80] Heo, Y., (2011), ”Bayesian calibration of building energy models for energy retrofit decision-making under uncertainty”, Georgia Institute of Technology, Atlanta, USA. Ph.D thesis, Available at: <https://smartech.gatech.edu/bitstream/handle/1853/42878/Heo_Yeonsook_201112_phd.pdf?sequence=1&isAllowed=y>.
[81] ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2002.
[82] <http://www.eere.energy.gov/buildings/energyplus/>.
[83] <http://www.trnsys.com/>.
[84] <http://energyplus.net/>.
[85] Crawley, D.B., Hand, J.W, Kummert, M., Griffith, B.T., (2008), ”Contrasting the capabilities of building energy performance simulation programs”, Building and Environment, vol. 43, issue 4, 661-673.
[86] <https://wufi.de/en/software/wufi-passive/>.
[87] ISO 13790:2008 Energy performance of buildings -- Calculation of energy use for space heating and cooling.
[88] ISO 13790:2008 Energy performance of buildings -- Calculation of energy use for space heating and cooling.
[89] Zhao, L., Liang, L., Zhang, J., (2015), ”The Typical Application of Building Energy Consumption Monitoring and Energy Management: A Case Study”, International Journal of Smart Home, vol. 9, no. 1, 177-188.
[90] Capozzoli, A., Berra, L., Russo, R., Corrado, V., (2013), ”Design and verification of a zero energy building: evaluation of real energy performance and

comparison with a tailored calculation", CLIMAMED VII - Mediterranean Congress of Climatization, Istanbul, 3-4 October, 2013.
[91] Garcia, O., Prieto, J., Alonso, R.S., Corchado, J.M., (2017), "A Framework to Improve Energy Efficient Behaviour at Home through Activity and Context Monitoring", Sensors, vol. 17 (8). Available from: http://www.mdpi.com/1424-8220/17/8/1749 .
[92] International Energy Agency (IEA), (2013), "Measurement and Verification protocol for Net Zero Energy Buildings", A report of Subtask A, IEA Task 40/Annex 52 Towards Net Zero Energy Solar Buildings.
[93] Raftery, P., Keane, M., O'Donnell, J., Costa, A. (2010), "Energy Monitoring Systems: value, issues and recommendations based on five case studies", Proceedings of Clima 2010 conference, Antalya, Turkey.
[94] Ahmad, M.W., Mourshed, M., Mundow, D., Sisinni, M. (2016), "Building energy metering and environmental monitoring – A state-of-the-art review and directions for future research", Energy and Buildings, vol. 120, 85-102.
[95] Fabi, V., Barthelmes, V.M., Schweiker, M., Corgnati, S.P. (2017), "Insighs into the effects of occupant behaviour lifestyles and building automation on building energy'', AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy, Energy Procedia, vol. 140, 48-56.
[96] Andersen, R.K., Fabi, V., Corgnati, S.P. (2016), "Predicted and actual indoor environmental quality: Verification of occupants' behaviour models in residential buildings'', Energy and Buildings, vol. 127, 105-115.
[97] Hong, T., Taylor-Lange, S.C., D'Oca, S., Yan, D., Corgnati, S.P. (2016), "Advances in research and applications of energy-related occupant behaviour in buildings'', Energy and Buildings, vol. 116, 694-702.
[98] Yu (Jerry), Z., Haghighat, F., Fung, B.C.M., Morofsky, E., Yoshino, H. (2011), "A methodology for identifying and improving occupant behaviour in residential buildings'', Energy, vol. 36, 6596-6608.
[99] Buildings Performance Institute Europe (BPIE), Implementing nearly zero-energy buildings (nZEB) in Romania – Towards a definition and roadmap, August 2012. BPIE.
[100] Becchio, C, Dabbene, P., Fabrizio, E., Monetti, V., Filippi, M. (2015), "Cost optimality assessment of a single family house: Building and technical solutions for nZEB target'', Energy and Buildings, vol. 90, 173-187.
[101] Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings.
[102] European Commission, Official Journal of European Union C115 – Romanian version, 2012.
[103] Jana Șuler, Guidelines for applying global cost method in construction sector, INCERC National Institute for Research in Construction, Bucharest
[104] EN 15459 -European Standard EN 15459:2006, Energy Efficiency for Buildings. Standard economic evaluation procedure for energy systems in buildings, 2006.
[105] EN 13829 -European Standard EN 13829:2001, Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method, 2001.
[106] Feist, W. et. al. 2007. Passive house Planning Package 2007 - Technical information. Darmstadt: Passive House Institute.

[107] P100/2006. Cod de proiectare seismică – partea I - Prevederi de proiectare pentru clădiri (in Romanian), Ministerul Transportului Construcțiilor și Turismului; 2006.
[108] Stoian, D., Stoian, V., Daniel, D. (2013). P100/2006. "A monitoring system as applied in a passive house and a nearly zero energy house" Buletinul AGIR, Supliment 1/2013, 150-153.
[109] BRE - Passivhaus Primer – Designer's Guide: A guide for the design team and local authorities. Available at: http://www.passivhaus.org.uk/filelibrary/Primers/KN4430_Passivhaus_Designers_Guide_WEB.pdf.
[110] EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2006.
[111] Passivhaus Dienstleistung GmbH, Certified European Passive House Designer: Building Services-Ventilation, 2012.
[112] https://energyplus.net/weather.
[113] https://www.openstudio.net/
[114] U.S. Department of Energy. EnergyPlus Version 8.5 Documentation. Input Output Reference.
[115] U.S. Department of Energy. EnergyPlus Version 8.5 Documentation. Getting started.
[116] Mc 001/4 - 2009 - Metodologie de calcul al performanței energetice a clădirilor. Partea a IV-a – Breviar de calcul al performanței energetice a clădirilor și apartamentelor.
[117] Mc 001/3 - 2006 - Metodologie de calcul al performanței energetice a clădirilor. Partea a III-a – Auditul și certificatul de performanță a clădirilor.
[118] BS EN 832:2008 -European Standard EN 13829:2001, Thermal performance of buildings. Calculation of energy use for heating. Residential buildings.
[119] BS EN 832:2008 -European Standard EN 13829:2001, Thermal performance of buildings. Calculation of energy use for heating. Residential buildings.
[120] https://bigladdersoftware.com/projects/elements/
[121] Christie, M.A., Glimm, J., Grove, J.W., Higdon, D.M., Sharp, D.H., Wood-Schultz, M.M. (2005). "Error analysis and simulations of complex phenomena'', Los Alamos Science, No. 29.
[122] C107/1 -2010 - Normativ privind calculul termotehnic al elementelor de construcţie ale clădirilor Partea I - Normativ privind calculul coeficienților globali de izolare termică la clădirile de locuit.
[123] Kurnitski, J. (2013), "Technical definition for nearly zero energy buildings'', REHVA Journal, May 2013, Vol. 50, Issue 3, 22-28.
[124] COMMISSION DECISION 2013/114/UE of 1 March 2013 establishing the guidelines for Member States on calculating renewable energy from heat pumps from different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC of the European Parliament and of the Council (notified under document C(2013) 1082).
[125] http://www.anre.ro/ro/comparator-tarife
[126] Autoritatea Nationala de Reglementare in Domeniul Energiei (ANRE), Evolutii ale pietei gazelor in Romania – Consumuri, client, preturi, tarife si preturi reglementate, grdul de deschidere a pietei. Available from: http://www.energynomics.ro/wp-content/uploads/2017/08/Grafice-evolutie-piata-gaze-2011-2017.pdf

[127] Autoritatea Nationala de Reglementare in Domeniul Energiei (ANRE), Proiect de Ordinpentru aprobarea preturilor de vanzare a E-SRE produsa in centrale electrice din surse regenerabile cu putere electrica instalata sub 100 kW apartinand persoanele fizice.

[128] Ministerul Dezvoltării Regionale și Administrației Publice, Strategia pentru mobilitatea investițiilor în renovarea fondului de clădiri rezidențiale și comerciale, atât publice cât și private, existente la nivel național, 2014. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_ro_romania.pdf.

[129] Pless, S., Torcellini, P. (2010). ”Net-Zero Energy Buildings: A classification system based on renewable energy supply options'', Technical Report, National Renewable Energy Laboratory.

[130] Hernandes, P., Kenny, P. (2010). ”From net zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)”, Energy and Buildings, vol. 42(6), 815-821.

[131] European Commission, 2011. COM (2011) 112 final - Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A Roadmap for moving to a competitive low carbon economy in 2050.

[132] European Commission, 2014. COM (2014) 15 final -Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A policy framework for climate and energy in the period from 2020 to 2030.

[133] European Environment Agency EEA (2017). Trends and projections in Europe 2017 - Tracking progress towards Europe’s climate and energy targets, EEA Report No. 17/2017.

[134] Romanian Energy Regulatory Authority (2015). Energy efficiency trends and policies in Romania.

Appendix A – Materials characteristics

Table 0.1.A1 - Materials characteristics for the envelope elements layers – real building

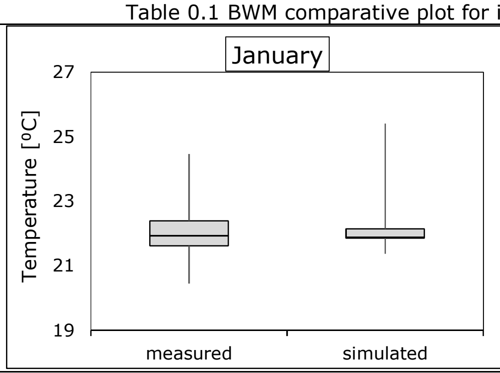
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
EXTERIOR WALL				
plaster	0.870	15	1700	840
masonry	0.330	250	770	870
mortar	0.870	15	1700	840
polystyrene	0.031	300	20	1460
mortar	0.870	8	1700	840
ROOF				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
gypsum plasterboard	0.410	12	1100	840
mineral wool	0.040	100	70	840
wooden board	0.180	50	550	2510
expanded polystyrene	0.044	320	20	480
cement screed	0.970	50	1800	840
bitumen isolation	0.170	5	1100	840
sand/gravel	0.700	50	1800	840
FLOOR OVER GROUND				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
tile+mortar	0.970	18	1800	840
cement screed	0.970	50	1800	840
concrete	1.620	100	2400	840
bitumen isolation	0.170	5	1100	840
expanded polystyrene	0.044	250	20	480
expanded polystyrene	0.044	150	20	480
gravel	0.700	300	1800	840
CANTILEVERED FLOOR				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
wood parquet	0.094	22	400	2510
mortar	0.970	70	1800	840
polystyrene	0.037	30	20	480
wood osb	0.180	10	350	2510
Mineral wool	0.040	200	70	840
polystyrene	0.044	300	20	480
mortar	0.970	8	1800	840

Table 0.2.A2 - Materials characteristics for the envelope elements layers – energy efficient envelope EE

EXTERIOR WALL				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
plaster	0.870	15	1700	840
masonry	0.330	250	770	870
mortar	0.870	15	1700	840
polystyrene	0.044	150	20	1460
mortar	0.870	8	1700	840
ROOF				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
gypsum plasterboard	0.410	12	1100	840
wooden board	0.084	50	400	2510
expanded polystyrene	0.044	250	20	480
cement screed	0.970	50	1800	840
bitumen isolation	0.170	5	1100	840
sand/gravel	0.700	50	1800	840
FLOOR OVER GROUND				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
tile+mortar	1.400	180	1800	840
cement screed	0.970	50	1800	840
reinforced concrete	1.620	100	2400	840
bitumen isolation	0.170	5	1100	840
expanded polystyrene	0.044	250	20	480
gravel	0.700	150	1800	840
CANTILEVERED FLOOR				
Layers	λ [W/(mK)]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg·K]
wood parquet	0.094	22	400	2510
mortar	0.970	70	1800	840
polystyrene	0.037	30	20	480
wood osb	1.400	10	350	2510
polystyrene	0.044	250	20	480
mortar	0.970	8	1800	840

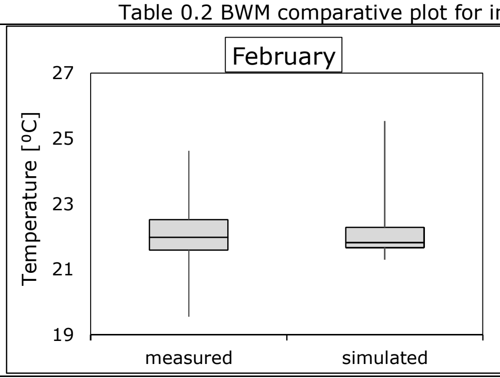
Appendix B – Comparative BWM plots

Table 0.1 BWM comparative plot for interior temperature in January



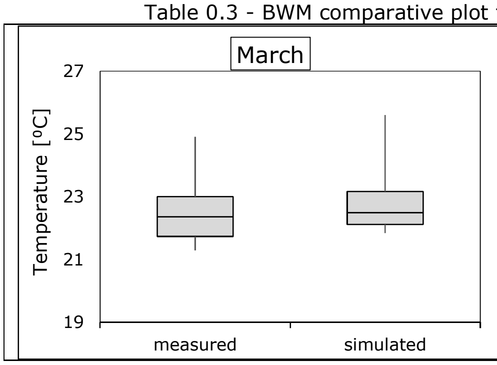
	m	s	Percent change [%]
Minimum	20.45	21.37	4.49
1st Quartile	21.62	21.86	1.11
Median	21.94	21.89	-0.20
3rd Quartile	22.39	22.15	-1.08
Maximum	24.47	25.41	3.86

Table 0.2 BWM comparative plot for interior temperature in February



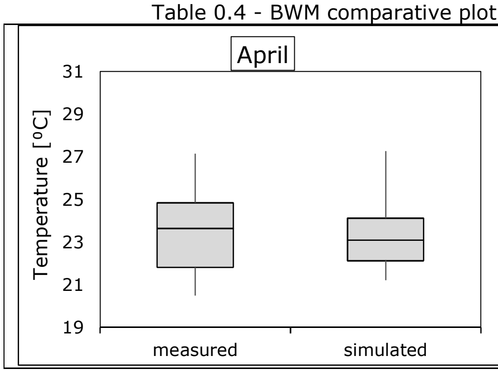
	m	s	Percent change [%]
Minimum	19.55	21.29	8.93
1st Quartile	21.59	21.66	0.33
Median	21.98	21.82	-0.75
3rd Quartile	22.52	22.29	-1.04
Maximum	24.62	25.54	3.71

Table 0.3 - BWM comparative plot for interior temperature in March



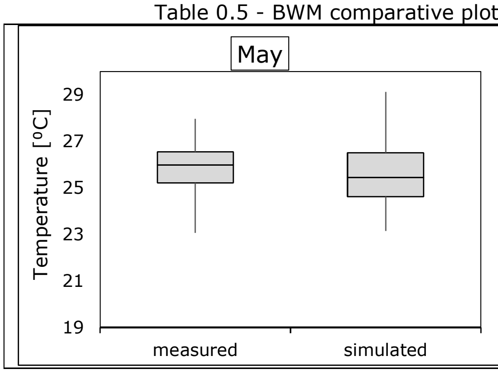
	m	s	Percent change [%]
Minimum	21.29	21.29	2.57
1st Quartile	21.74	21.74	1.78
Median	22.36	22.36	0.59
3rd Quartile	23.01	23.01	0.70
Maximum	24.91	24.91	2.80

Table 0.4 - BWM comparative plot for interior temperature in April



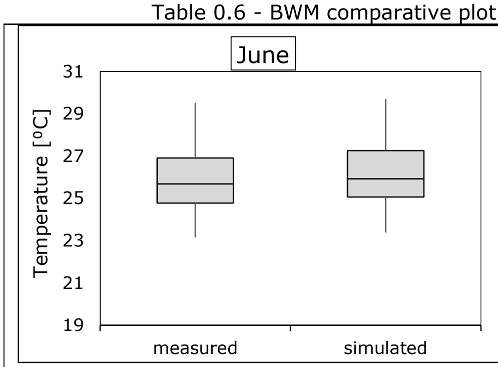
	m	s	Percent change [%]
Minimum	20.49	21.22	3.57
1st Quartile	21.82	22.12	1.40
Median	23.64	23.09	-2.33
3rd Quartile	24.84	24.12	-2.90
Maximum	27.15	27.27	0.43

Table 0.5 - BWM comparative plot for interior temperature in May



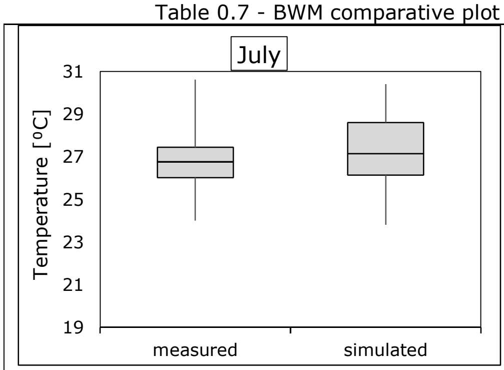
	m	s	Percent change [%]
Minimum	23.05	23.14	0.39
1st Quartile	25.22	24.62	-2.36
Median	25.99	25.44	-2.11
3rd Quartile	26.54	26.50	-0.13
Maximum	27.96	29.13	4.18

Table 0.6 - BWM comparative plot for interior temperature in June



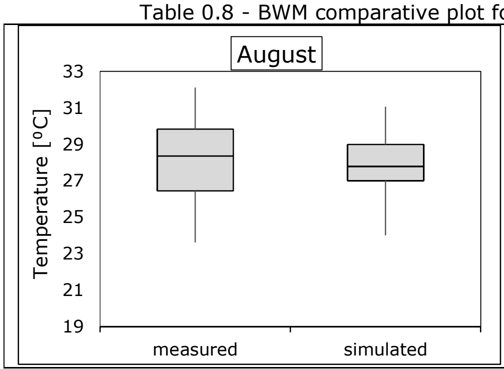
	m	s	Percent change [%]
Minimum	23.16	23.38	0.95
1st Quartile	24.77	25.06	1.15
Median	25.67	25.92	0.96
3rd Quartile	26.90	27.25	1.30
Maximum	29.50	29.69	0.62

Table 0.7 - BWM comparative plot for interior temperature in July



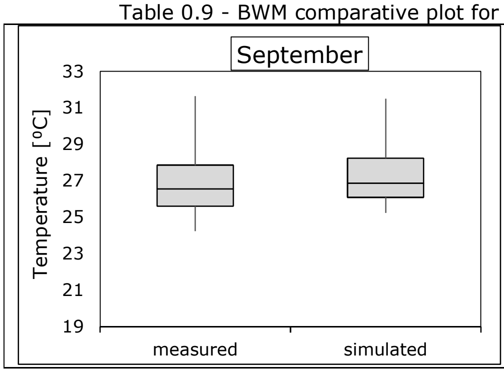
	m	s	Percent change [%]
Minimum	24.00	23.81	-0.82
1st Quartile	26.03	26.14	0.45
Median	26.77	27.15	1.41
3rd Quartile	27.45	28.60	4.22
Maximum	30.62	30.41	-0.67

Table 0.8 - BWM comparative plot for interior temperature in August



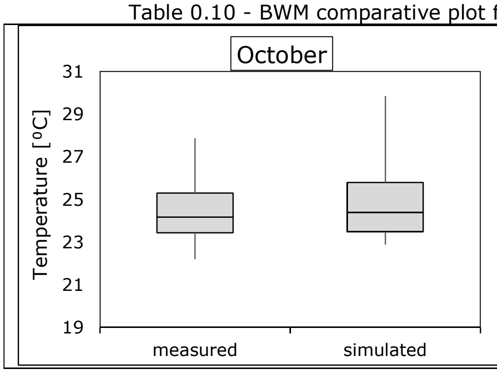
	m	s	Percent change [%]
Minimum	23.62	24.01	1.66
1st Quartile	26.45	27.00	2.08
Median	28.35	27.79	-1.95
3rd Quartile	29.83	28.99	-2.82
Maximum	32.11	31.07	-3.27

Table 0.9 - BWM comparative plot for interior temperature in September



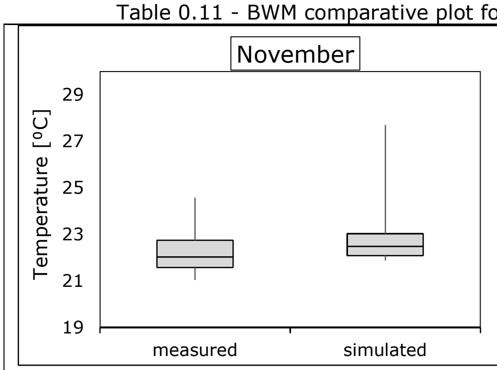
	m	s	Percent change [%]
Minimum	24.24	25.24	4.12
1st Quartile	25.61	26.10	1.90
Median	26.56	26.87	1.17
3rd Quartile	27.87	28.24	1.34
Maximum	31.64	31.50	-0.45

Table 0.10 - BWM comparative plot for interior temperature in October



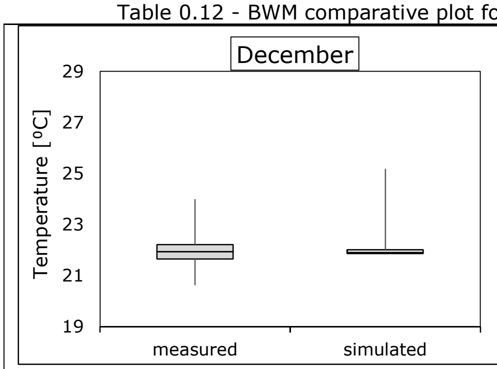
	m	s	Percent change [%]
Minimum	22.19	22.88	3.09
1st Quartile	23.43	23.49	0.25
Median	24.18	24.39	0.88
3rd Quartile	25.30	25.80	1.97
Maximum	27.87	29.85	7.13

Table 0.11 - BWM comparative plot for interior temperature in November



	m	s	Percent change [%]
Minimum	21.03	21.87	3.98
1st Quartile	21.57	22.08	2.35
Median	22.03	22.49	2.09
3rd Quartile	22.75	23.02	1.18
Maximum	24.57	27.71	12.78

Table 0.12 - BWM comparative plot for interior temperature in December



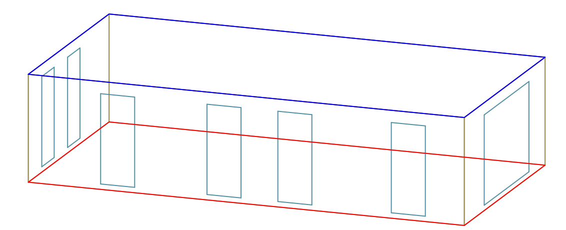
	m	s	Percent change [%]
Minimum	20.63	21.82	5.81
1st Quartile	21.66	21.87	0.98
Median	21.95	21.91	-0.17
3rd Quartile	22.22	22.02	-0.90
Maximum	24.00	25.19	4.96

Minimum – the smallest value in the data set
1st Quartile – 25% of the measurement are less than the this value
Median - is the middle value of a set of numbers. It is the point at which exactly half of the data lies below and above the central value
3rd Quartile - 75% of the values are less than this value.

Appendix C – Building surfaces coordinates

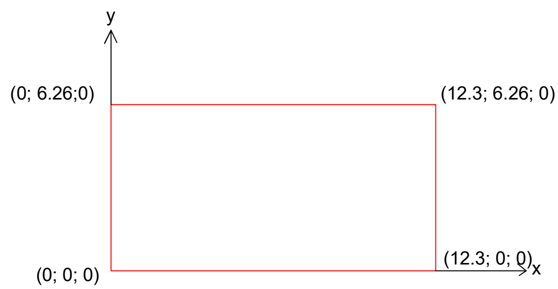
This Appendix contains the coordinates through which the building surfaces were defined in the software Energy Plus. The coordinates were defined relatively to the zone and counterclockwise, as seen outside the zone.

Building surface coordinates for ZONE 1 (ground floor space)

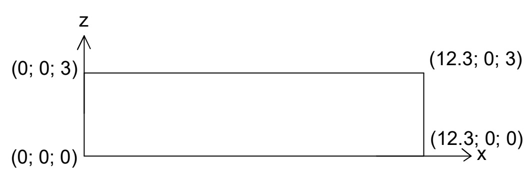


ZONE 1

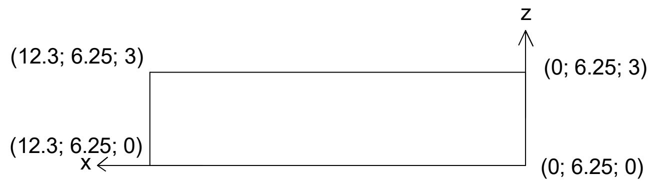
Ground floor



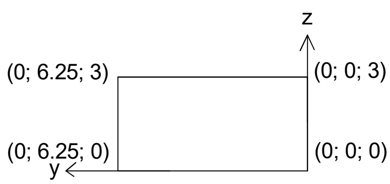
South west wall



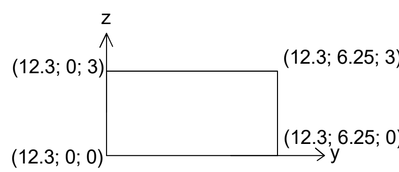
Partition wall to neighbour



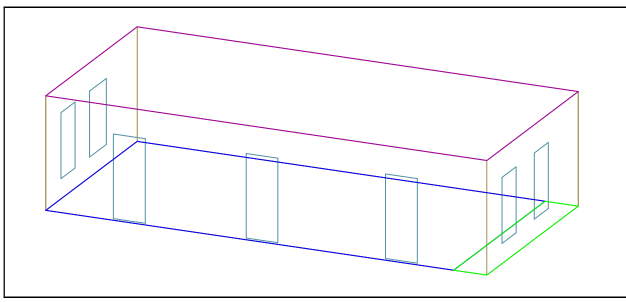
North- west wall



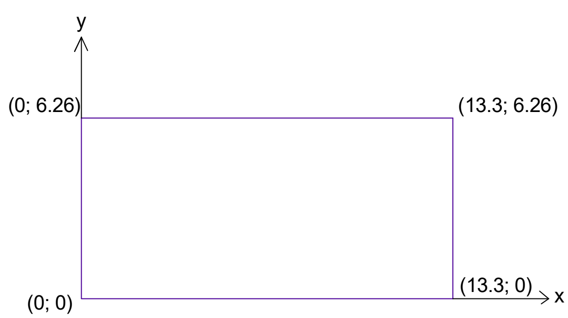
South-east wall



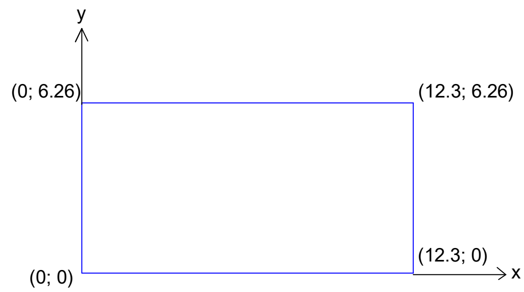
Building surface coordinates for ZONE 2 (first floor space)

	ZONE 2

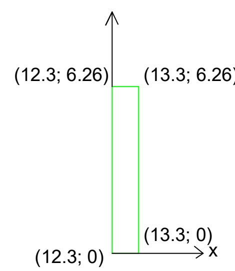
Roof



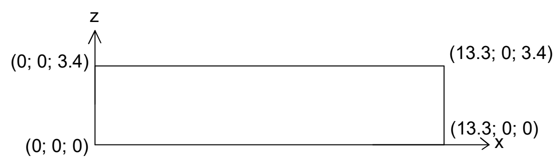
Intermediate floor



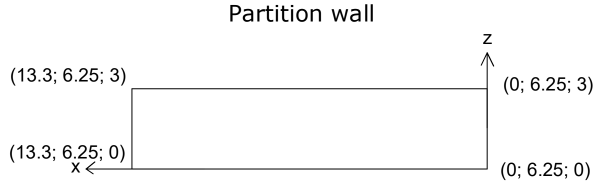
Cantillevered floor



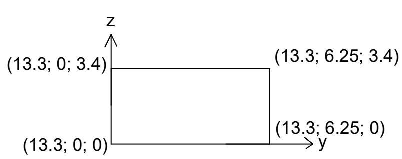
South west wall



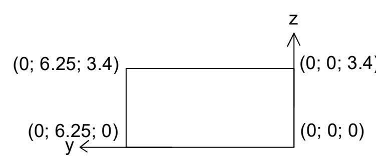
Partition wall



South-east wall



North-west wall



Appendix D – Global cost calculation sheets

D.1. Costs evaluations

Real building PH_I			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
										-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53302.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other component		403.01							-
										-
Total building systems			15940.84			376.81	5698.03	838.77	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			74527.40	163.55		376.81	5698.03	838.77	0.00	3338.75

PH_I_S			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	7787.00							1283.3
Exterior works		50	3672.98							605.3
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems		30	3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0.00	0.00	0.00	0.00	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			515.0
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.5
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.2
DHW boiler		20.00	916.61	9.17			916.61			188.8
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.5
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.2
	Other components		403.01							-
										-
Total building systems			15940.84			376.81	5698.03	838.77	0.00	
Other expenses			5284.21							
TOTAL [EURO]			78397.40	163.55		376.81	5698.03	838.77	0.00	3338.8

PH_I_S+2.4kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	0.00
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	10 Panels	20	1894.34	9.47			1894.34			390.22
	Inverter	15	755.58495	3.78		755.58				-
	Bidirectional meter	15	152.17			152.17				-
	Other expenses		1318.20							-
						0.00				-
										-
										-
										-
Total building systems			20061.14			1284.566	7592.37	838.7714	0	-
Other expenses			5284.21							0.00
										0.00
TOTAL [EURO]			82517.70	176.80		1284.57	7592.37	838.77	0.00	3728.97

BUPT

PH_I_S+3.6kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
		50								-
		50								-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	15 Panels	20.00	3125.66	15.63			3125.66			643.86
	Inverter	15.00	1347.96	6.74		1347.96				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		1977.30							-
										-
										-
										-
										-
Total building systems			22543.93			1876.94	8823.685	838.7714	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			85000.49	185.92		1876.94	8823.68	838.77	0.00	3982.61

PH_I_S+4.8kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
		50								-
		50								-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems		30	3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	20 Panels	20.00	3788.67	18.94			3788.67			780.44
	Inverter	15.00	1840.00	9.20		1840.00				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		2636.40							-
										-
										-
										-
										-
Total building systems			24358.09			2368.9811	9486.70253	838.77143	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			86814.65	191.69		2368.98	9486.70	838.77	0.00	4119.19

PH_II_S			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
			0.00							-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
				0.00			0.00			-
				0.00		0.00				-
						0.00				-
										-
										-
										-
										-
										-
Total building systems			19630.27			376.80714	6787.4619	838.7714	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			82086.84	194.86		376.81	6787.46	838.77	0.00	3563.17

PH_II_S+2.4kW			**Initial investment (euro)**	**Annual maintenance costs (euro)**	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
PV - system	10 Panels	20.00	1894.34	9.47			1894.34			390.22
	Inverter 2.4 kW	15.00	755.58	3.78		755.58				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		1318.20							-
										-
										-
										-
										-
										-
Total building systems			23750.57			1284.57	8681.8	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			86207.13	208.11		**1284.57**	**8681.80**	**838.77**	**0.00**	**3953.39**

PH_II_S+3.6kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	15 Panels	20.00	3125.66	15.63			3125.66			643.86
	Inverter	15.00	1347.96	6.74		1347.96				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		1977.30							-
										-
										-
										-
										-
Total building systems			26233.36			1876.94	9913.12	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			88689.92	217.23		1876.94	9913.12	838.77	0.00	4207.03

PH_II_S+4.8kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	7787.00							1283.26
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			57172.35			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							0.00
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	20 Panels	20.00	3788.67	18.94			3788.67			780.44
	Inverter	15.00	1840.00	9.20		1840.00				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		2636.40							-
										-
										-
										-
										-
Total building systems			28047.52			2368.98	10576.14	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			90504.08	223.00		2368.98	10576.14	838.77	0.00	4343.61

EE_I			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	4400.50							725.2
Exterior works		50	3672.98							605.3
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
										-
Windows and glazing		30	5888.58						0.00	-
Total building construction			49915.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			515.0
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.5
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.2
DHW boiler		20.00	916.61	9.17			916.61			188.8
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.5
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.2
	Other components		403.01							-
										-
Total building systems			15940.84			376.8071	5698.029	838.77143	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			71140.91	163.55		376.81	5698.03	838.77	0.00	2780.7

EE_I_S			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other component		403.01							-
										-
Total building systems			15940.84			376.807	5698.03	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			75010.91	163.55		376.81	5698.03	838.77	0.00	2780.67

EE_I_S+2.4kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
		50								-
		50								-
Thermal insulation		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	10 Panels	20.00	1894.34	9.47			1894.34			390.22
	Inverter	15.00	755.58	3.78		755.58				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		1318.20							-
						0.00				-
										-
										-
										-
Total building systems			20061.14			1284.566	7592.366	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			79131.20	176.80		1284.57	7592.37	838.77	0.00	3170.89

EE_I_S+3.6kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural		50	24522.97							-
										-
										-
Thermal		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.84			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	0.00
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	15 Panels	20.00	3125.66	15.63			3125.66			643.86
	Inverter	15.00	1347.96	6.74		1347.96				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other		1977.30							-
										-
										-
										-
										-
Total building systems			22543.93			1876.94	8823.68	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			81613.98	185.92		1876.94	8823.68	838.77	0.00	3424.54

EE_I_S+4.8kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading systems			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump		20.00	2500.00	50.00			2500.00			514.98
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1374.91	13.75			1374.91			283.22
DHW boiler		20.00	916.61	9.17			916.61			188.82
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27						0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	20 Panels	20.00	3788.67	18.94			3788.67			780.44
	Inverter	15.00	1840.00	9.20		1840.00				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		2636.40							-
										-
										-
										-
										-
Total building systems			24358.09			2368.98	9486.7	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			83428.15	191.69		2368.98	9486.70	838.77	0.00	3561.12

EE_II_S			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	21821.57							-
		50								-
Walls	Masonry	50	2701.41							-
	Thermal insulation	50	4400.50							725.18
	Exterior works	50	3672.98							605.29
	Exterior plaster	30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.86			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other component		403.01							-
										-
				0.00			0.00			-
				0.00		0.00				-
						0.00				-
										-
										-
										-
										-
										-
Total building systems			19630.27			376.807	6787.462	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			78700.34	194.86		376.81	6787.46	838.77	0.00	3005.09

EE_II_S+2.4kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
Thermal insulation		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
PV - system	10 Panels	20.00	1894.34	9.47			1894.34			390.22
	Inverter	15.00	755.58	3.78		755.58				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		1318.20							-
										-
										-
										-
										-
										-
Total building systems			23750.57			1284.57	8681.8	838.771	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			82820.64	208.11		1284.57	8681.80	838.77	0.00	3395.31

EE_II_S+3.6kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
		50								-
		50								-
Thermal insulation		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	15 Panels	20.00	3125.66	15.63			3125.66			643.86
	Inverter	15.00	1347.96	6.74		1347.96				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		1977.30							-
										-
										-
										-
										-
Total building systems			26233.36			1876.94	9913.12	838.7714	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			85303.43	217.23		1876.94	9913.12	838.77	0.00	3648.95

EE_II_S+4.8kW			Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building		Lifespan								-
Structural systems		50	24522.98							-
										-
										-
Thermal insulation		50	4400.50							725.18
Exterior works		50	3672.98							605.29
Exterior plaster		30	946.95						0.00	-
										-
Interior finishes			7694.71							-
										-
Papers and authorizations			2789.15							-
Shading system			3870.00							-
Windows and glazing		30	5888.58						0.00	-
Total building construction			53785.85			0	0	0	0	-
Building systems										-
										-
Electric wiring		30.00	3582.20	17.91					0.00	-
Sewerage		30.00	689.46	3.45						-
Plumbing		30.00	3370.21	16.85					0.00	-
Heat pump and drills	soil-water heat pump	20.00	4500.00	90.00			4500.00			926.97
	drills		2600.00							-
Ventiltion with heat recovery+Hexcg		20.00	711.36	28.45			711.36			146.53
Undeground heat exchanger		30.00	941.08	4.71						-
Fan convectors		15.00	376.81	15.07		376.81				-
Heating buffer		20.00	1380.95	13.81			1380.95			284.47
DW system-solar	Solar panel	25.00	838.77	4.19				838.77	0.00	276.45
	Expansion vessel	30.00	41.27	0.41					0.00	-
	Pump	20.00	195.15				195.15			40.20
	Other components		403.01							-
										-
PV - system	20 Panels	20.00	3788.67	18.94			3788.67			780.44
	Inverter	15.00	1840.00	9.20		1840.00				-
	Bidirectional meter	15.00	152.17			152.17				-
	Other expenses		2636.40							-
										-
										-
										-
										-
Total building systems			28047.52			2368.98	10576.14	838.7714	0	-
Other expenses			5284.21							-
										-
TOTAL [EURO]			87117.59	223.00		2368.98	10576.14	838.77	0.00	3785.53

RB		Initial investment (euro)	Annual maintenance costs (euro)	Replacement costs (euro)	Lifespan - 15 years	Lifespan - 20 years	Lifespan - 25 years	Lifespan - 30 years	Residual value
Building	Lifespan								-
Structural systems	50	24522.98							-
									-
									-
Thermal insulation	50	3561.08802							586.85
Exterior works	50	3672.98							605.29
Exterior plaster	30	946.95						0.00	-
									-
Interior finishes		7694.71							-
									-
Papers and authorizations		2789.15							-
									-
Windows and glazing	30	3552.67						0.00	-
Total building construction		46740.53			0	0	0	0	-
Building systems									-
									-
Electric wiring	30.00	3582.20	17.91					0.00	-
Sewerage	30.00	689.46	3.45						-
Plumbing	30.00	3370.21	16.85					0.00	-
Heating systems (Condensing boiler)	20.00	1075.27	21.51			1075.27			221.50
Radiators	30.00	881.72	17.63						0.00
Split cooling	20.00	1827.96	73.12			1827.96			376.55
					0.00	0.00			-
						0.00			-
							0.00	0.00	-
								0.00	-
						0.00			-
									-
									-
						0.00			-
					0.00				-
					0.00				-
									-
									-
									-
									-
									-
Total building systems		11426.82			0	2903.23	0	0	-
Other expenses		5284.21							-
									-
TOTAL [EURO]		63451.56	150.47		0.00	2903.23	0.00	0.00	1790.18

D.2. Global cost reports

Global Cost REPORT		Real Building PH_I
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**74,527**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	377
Replacement cost 2		
Year	year	20
Cost	Euro	5,698
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**164**
3. Annual costs for energy		
Annual costs for natural gas		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	5,982
Price including VAT	Euro/kWh	0.120
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,339
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	96,368
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 2%)	Euro	102,536
GLOBAL COST (higher discount rate 5%)	Euro	91,914

Global Cost REPORT		**PH_I_S**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**78,397**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	377
Replacement cost 2		
Year	year	20
Cost	Euro	5,698
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**164**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	5,745
Price including VAT	Euro/kWh	0.120
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,339
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	99,523
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,454
GLOBAL COST (highest discount rate 5%)	Euro	95,228

Global Cost REPORT		PH_I_S+2.4kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**82,518**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,285
Replacement cost 2		
Year	year	20
Cost	Euro	7,592
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**177**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	4,325
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	1,686
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,729
Results		
GLOBAL COST (3% - discount rate)	Euro	99,064
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	103,446
GLOBAL COST (highest discount rate 5%)	Euro	95,758

Global Cost REPORT		PH_I_S+3.6kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**85,000**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,877
Replacement cost 2		
Year	year	20
Cost	Euro	8,824
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**186**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	4,192
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	3,034
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,983
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	100,687
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	104,765
GLOBAL COST (highest discount rate 5%)	Euro	97,554

Global Cost REPORT		PH_I_S+4.8kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**86,815**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	2,369
Replacement cost 2		
Year	year	20
Cost	Euro	9,487
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**192**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	4,114
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	4,468
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	4,119
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	101,384
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,080
GLOBAL COST (highest discount rate 5%)	Euro	98,486

Global Cost REPORT		**PH_II_S**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**82,087**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	377
Replacement cost 2		
Year	year	20
Cost	Euro	6,787
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**195**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	4,601
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,563
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	100,793
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,886
GLOBAL COST (highest discount rate 5%)	Euro	97,037

Global Cost REPORT		PH_II_S+2.4kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**86,207**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,285
Replacement cost 2		
Year	year	20
Cost	Euro	8,682
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**208**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,257
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	1,751
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,953
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	100,491
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	104,088
GLOBAL COST (highest discount rate 5%)	Euro	97,689

Global Cost REPORT		**PH_II_S+3.6kW**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**88,690**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,877
Replacement cost 2		
Year	year	20
Cost	Euro	9,913
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**217**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,128
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	3,100
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	4,207
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	102,124
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,419
GLOBAL COST (highest discount rate 5%)	Euro	99,492

Global Cost REPORT		PH_II_S+4.8kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**90,504**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	2,369
Replacement cost 2		
Year	year	20
Cost	Euro	10,576
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**223**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,046
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	4,528
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	4,344
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	102,817
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,729
GLOBAL COST (highest discount rate 5%)	Euro	100,421

Global Cost REPORT		EE_I
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**71,141**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	377
Replacement cost 2		
Year	year	20
Cost	Euro	5,698
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**164**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	6,964
Price including VAT	Euro/kWh	0.120
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	2,781
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	96,494
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	104,090
GLOBAL COST (highest discount rate 5%)	Euro	91,138

Global Cost REPORT		EE_I_S
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**75,011**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	377
Replacement cost 2		
Year	year	20
Cost	Euro	5,698
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**164**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	6,707
Price including VAT	Euro/kWh	0.120
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	2,781
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	99,592
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	106,932
GLOBAL COST (highest discount rate 5%)	Euro	94,408

Global Cost REPORT		**EE_I_S+2.4kW**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
ate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**79,131**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,285
Replacement cost 2		
Year	year	20
Cost	Euro	7,592
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**177**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	5,298
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	1,684
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,171
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	99,166
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	104,967
GLOBAL COST (highest discount rate 5%)	Euro	94,963

Global Cost REPORT		EE_I_S+3.6kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**81,614**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,877
Replacement cost 2		
Year	year	20
Cost	Euro	8,824
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**186**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	5,118
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	3,071
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,425
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	100,607
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	106,043
GLOBAL COST (highest discount rate 5%)	Euro	96,617

Global Cost REPORT		**EE_I_S+4.8kW**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**83,428**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	2,369
Replacement cost 2		
Year	year	20
Cost	Euro	9,487
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**192**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	5,050
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	4,437
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,561
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	101,408
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	106,498
GLOBAL COST (highest discount rate 5%)	Euro	97,631

Global Cost REPORT		**EE_II_S**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**78,700**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	377
Replacement cost 2		
Year	year	20
Cost	Euro	6,787
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**195**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	5,157
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,005
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	99,637
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,732
GLOBAL COST (highest discount rate 5%)	Euro	95,264

Global Cost REPORT		EE_II_S+2.4kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**82,821**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,285
Replacement cost 2		
Year	year	20
Cost	Euro	8,682
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**208**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,799
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	1,737
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,395
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	99,308
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	103,902
GLOBAL COST (highest discount rate 5%)	Euro	95,897

Global Cost REPORT		EE_II_S+3.6kW
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**85,303**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	1,877
Replacement cost 2		
Year	year	20
Cost	Euro	9,913
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**217**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,635
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	3,074
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,649
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	100,851
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,108
GLOBAL COST (highest discount rate 5%)	Euro	97,629

Global Cost REPORT		**EE_II_S+4.8kW**
Calculation period τ (years)	30	
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**87,118**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	2,369
Replacement cost 2		
Year	year	20
Cost	Euro	10,576
Replacement cost 3		
Year	year	25
Cost	Euro	839
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**223**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,555
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	4,485
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	3,786
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	101,567
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	105,451
GLOBAL COST (highest discount rate 5%)	Euro	98,576

Global Cost REPORT		
Calculation period τ (years)	30	RB
Financial data		
Discount rate r (%)	3.0%	
Rate of development of cost for electricity (%)	1.5%	
Rate of development of cost for energy type 1 (%)	5.0%	
Rate of development of operation/maintenance costs (%)	0.0%	
Initial investment C_I		
Initial costs including VAT	Euro	**63,452**
Annual costs $C_{a,i}(j)$		
1. Replacement costs (Periodic costs)		
Replacement cost 1		
Year	year	15
Cost	Euro	0
Replacement cost 2		
Year	year	20
Cost	Euro	2,903
Replacement cost 3		
Year	year	25
Cost	Euro	0
Replacement cost 4		
Year	year	30
Cost	Euro	0
2. Annual maintenance/running costs		
Total	**Euro/year**	**150**
3. Annual costs for energy		
Annual costs for energy type 1		
Annual energy consumption	kWh/year	16,255
Price including VAT	Euro/kWh	0.060
Annual costs for electricity		
Annual electrical energy consumption	kWh/year	3,207
Price including VAT	Euro/kWh	0.120
Annual benefits for electricity delivered to the grid		
Annual electrical energy consumption	kWh/year	0
Price including VAT	Euro/kWh	0.043
Residual value $V_{f,\tau}(j)$		
Residual value at the end of the analysis period, including VAT	Euro	1,790
Results $C_g(\tau)$		
GLOBAL COST (3% - discount rate)	Euro	116,969
Sensitivity analysis to discount rate r		
GLOBLA COST (lower discount rate 1%)	Euro	136,968
GLOBAL COST (highest discount rate 5%)	Euro	103,748