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From energy refurbishment of existing buildings to Nearly Zero-Energy ones: Set-up, experimental measures, performance gap and numerical modelling

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Doctoral Thesis

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To whom always supported me,

and to whom taught me to dream

CONTENTS

ABSTRACT

The world is faced with challenges in all three dimensions of sustainable development—economic, social and environmental. Continued unabated, anthropogenic pollution and greenhouse gas emissions will further increase global warming, ocean acidification, desertification and changing climate patterns. Aggravated by pollution, overexploitation of natural resources and environmental degradation, these will lead to severe, pervasive and irreversible changes for people, assets, economies and ecosystems around the world.

Energy-related CO_2 emissions from buildings have risen in recent years after flattening between 2013 and 2016. Direct and indirect emissions from electricity and commercial heat used in buildings rose to 10 $GtCO_2$ in 2019, the highest level ever recorded. Several factors have contributed to this increase, including growing energy demand for heating and cooling with rising air-conditioner ownership and extreme weather events. Enormous emissions reduction potential remains untapped due to the continued use of fossil fuel-based assets, a lack of effective energy-efficiency policies and insufficient investment in sustainable buildings. However, for instance, the most recent Eurostat data confirm that the building sector, that in EU-28 accounted almost 27% of final energy consumption[3], has the highest potential in achieving energy savings.

About this matter, a lot of worldwide international committees, intergovernmental energy policies and international directives have been promoted with the aim to reduce the energy consumption, the costs, and the environmental impact of buildings, without compromising or even improving occupants' comfort conditions.

The legislative frame will be extensively detailed in the first chapter of this Thesis, in terms of overview on climate change phenomena and building sector impact on global energy consumption, as well as in terms of international and national actions and resolutions put in place to "developing a sustainable, competitive, secure and decarbonised energy system" by 2050.

In this context, researchers are making many efforts to optimize the design and operation of buildings and their systems by means of new materials, technologies, solutions, design criteria and managements strategies. All these efforts could be summarized in the achievement of new high-efficient construction standard, both for new than for the refurbishment of existing buildings and introduced for the first time by the European Directive 2010/31/EU: Nearly Zero-Energy Buildings (nZEBs). It is defined as a building that has a very high energy performance, which means 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. In northern European countries, standards and guidelines for designing and constructing passive houses and high energy efficient buildings started to be enacted already during the 90s. Their design had to meet detailed criteria about space energy demand and airtightness with a strong attention to the building envelope, thermal dispersion through it and to the air ventilation system to meet the comfort conditions inside the building and meanwhile minimize the energy consumption. Now, the introduction of nZEBs is based on a new concept of high-performance design, based on the energy balance between consumption and generation from renewable sources. So, over the building envelope and plant systems, the exploitation and integration of renewable systems assumes considerable importance.

Considering that in the current scientific literature is possible identify some challenges that are still open about the achievement of “nZEB target”, the present PhD Thesis has been focused on two main interconnected aspects on the energy performance of new and existing buildings: the performance investigation of building energy performance in real operational mode, and the optimization of building/HVAC performance.

I) <u>Performance investigation on building energy performance in real operational mode</u>

The analysis of scientific literature allows to highlight that there is a limited availability of studies about real monitored data on Nearly Zero-Energy Buildings, concerning in-field monitoring campaigns about the stationary and dynamic behaviour and energy performance of building during the real occupation. Indeed, only the knowledge-transfer and exchange of experience, often resulting from pilot programs, could allow to avoid further mismatch between the expected energy performance and the real ones, and could allow to export strategies of management, design logic and information about the operational energy performances of devices and systems in countries with comparable climate conditions. Moreover, the available studies are focused only on long-term energy balance, without considering the energy exchangers at smaller time scale.

In this perspective, the PhD's research activity has been supported by the use of a real-scale test facility, designed and built in a middle-size city with typical Mediterranean climate, Benevento (south Italy) and thus named "BNZEB" (where the first "B" means Benevento). This innovative prototype, besides being one of the first example of nZEB for Mediterranean climates, is a perfectly working "thermodynamic lab" where both "life" and "studies" are allowed. Indeed, this is a laboratory in which real and comfortable life is allowed, and thus the innovative topic is that, contextually, "experiments" can test how comfortable can be the "life" inside new high-efficient buildings. The aim of the research followed during the Ph.D program, is the provision of real data, information and guidelines about the operational performance of a nZEB building in a real context. A methodology for real-time nZEB performance analysis is proposed by taking into consideration the implications of the continuous interplay between external conditions and indoor occupant requirements as well as between on-site generation and the building loads with the resulting interaction with the energy grid. The interpretation of data from in-field monitoring campaign could support the integration of efficient solution sets and renewable energy systems, in a form that fits with the development of smart energy communities. Indeed, only in this way, it could be possible to understand and solve the problem of performance gap between real behaviour of the buildings and design expectation that can determine management problem of the national power systems. In other words, the use of data from in-field monitoring campaign could drive the develop of energy policies, the spread of zero-energy districts, the energy services design and be a reference to the export of management and design strategies in regions with similar climate conditions.

Load matching and grid interaction are key aspects to be analysed for the diffusion of nearly zero energy building together with the fulfilment of the yearly energy balance and of the comfort requirement. At present time, there is a poorness of experimental measures about behaviour of nZEB in real operation mode. About it, by means of data elaboration and some numerical analysis, the aim of the research activity is the discussion about the possible optimization of the hourly operational performance of a real nearly zero energy building in by means of detailed monitoring campaign. This research theme is a crucial in-coming objective for researcher and designers.

Another important topic developed during the short-term mobility at the Technology Campus Ghent of KU Leuven (Belgium) has been the optimization of the control and management strategies for achieving energy saving during the operation of HVAC system in an educational nZEB.

II) <u>Methodological approach for the optimisation of building/HVAC performance</u>

The optimization of the whole building/HVAC system energy performance of the new and existing building stock is a key strategy to achieve tangible results in the reduction of worldwide energy consumption and, thus, polluting emissions. However, the path is very challenging, and the purposes could be several, like increase the comfort conditions inside building, reduce the energy request and then the environmental impacts of the building use.

According to the literature, the "performance gap" between operational energy performance of a building and the expected one, forecasted during the design phase, could be generally due to the different behaviour of occupants or the use of non-optimized control logic and HVAC's parameters. Moreover, sometimes although a building has high energy performance, these could often be further improved by implementing more advanced control logic or by setting different operating parameters. Indeed, changing the programming and control strategies of the active systems, or implement some retrofit measure on building envelope and HVAC system, could allow to significantly increase the performance of a building like a complex system, both in terms of improving the conditions of comfort, and decreasing of energy requests and therefore the environmental impact.

For this reason, the research activity has been aimed to introduce a methodological approach for selecting energy refurbishment measures, mainly for educational buildings, by means of accurate energy diagnoses that allow the characterization of building/HVAC system and the indoor conditions. Indeed, high performance and economical effective refurbishments can be obtained only if in the early design stage, designers have appropriate building information. According to this aim, two aspects have been exhaustively examined by using some case studies: a) the importance to use validated energy models for estimating the present building performance; b) the environmental benefits and the economic implications of a deep energy refurbishment of educational building.

The organization of the present Thesis is the following one: first of all, an overall overview about the aforementioned legislative frame, and about the current situation in term of existing buildings renovation and nZEB definition in the European context (detailed in the chapter 1) is presented. Then, the research activity has been focused on the definition of most appropriate approach to study and meet the above-described purposes of the PhD. In general, two different methodological approach can be used: a) the numerical approach, based on mathematical model implemented, in most cases, in simulation software; b) experimental approach in real or controlled environment. Obviously, they both could be carried out for an in-depth evaluation, based on the availability/costs of experimental and computational resources, time available for experimentation/simulation and availability of necessary human resources.

The importance to select the adequate method for the research investigation is fully described in the chapter 2 of this Thesis, together with a detailed description of purposes and motivations of the research topic. More in detail, the adopted methodological approach is based on a deep correlation between the experimental approach and the numerical one, that will be combined between themselves in a more or less interconnected way, depending on the aim of each performed analysis. Concerned the dynamic thermo-energetic simulation, two modelling approaches are analysed and used: building energy simulation (BES) with nodal network model and computational fluid dynamics (CFD) tools. Meanwhile, regarding the experimental investigations on whole building or single elements, during the PhD, the performed activities have been supported by the use of full-scale test facilities, and also some existing educational buildings have been used as case studies for energy refurbishment investigations and for evaluations about numerical modelling assumptions.

In particular, most of the research activities have been based on the BNZEB in Mediterranean climate; however, during a collaboration with a Belgian University, a short research activity was also carried out on another test facility designed and build, according to the Passivhaus standard, in a temperate climate (Ghent – East Flanders Belgium).

The first full-scale test facility is fully described in the chapter 3 of the Thesis. The results of experimental monitoring campaigns is described with the purpose to characterise the operational energy performance of an existing nZEB building during each season and to verify the effectiveness of chosen design and management solutions both for the whole building system and with reference to the installed devices. Moreover, in the same chapter, it is also shown also a numerical model of the case study building, suitable for performing transient energy simulations. Indeed, it is created and calibrated with the purpose to test in a simulation environment the system behaviour under different operation conditions. This model is used for comparing the BNZEB with other building; so it is evaluated the replicability of its design in others Mediterranean cities and several investigations about indoor comfort conditions have been performed in term of values and space distribution of some comfort indices and air temperature.

Furthermore, the chapter 4 concerns on the research activity performed during the short-mobility period, that has been focused on control and management strategies for achieving energy saving during the operation of HVAC system in an existing building. Indeed, this activity want to demonstrate how the overall performance of a heating system could be furtherly improved by changing its management and showing the importance role that the control strategy plays to ensure that nZEB building is operating as efficiently as possible. Moreover, it shows how analysis on real data, coming from in-field monitoring campaigns, allows to know how the energy is used, and it is fundamental as starting point to design and assess the improving of existing buildings and the behaviour change.

Finally, the chapter 5 is focused on the application of optimization methodologies for the design of the energy efficiency measures for existing buildings. In detail, it is discussed and applied an holistic approach, for educational buildings, based on the application of the Cost-Optimal methodology to evaluate the cost-optimal level of energy refurbishment with a macro-economic approach, taking into account, at the same time, energy, environmental and economic aspects. Indeed, the available studies generally take into consideration these aspects separately and do not start with a thorough understanding of the current situation. Then, using two existing university buildings as case study, the proposed methodological allow to understand the uncertainty of the use of numerical model and the real impacts due to the adoption of some energy efficiency technologies.

This allows stakeholders and designer to understand the importance of an accurate definition of building present performance, and, with reference to the scientific research, it shows how the adoption of simulation models is a good practice only if all variables are checked, monitored and suitably evaluated; finally, also the importance to use a dual approach will be demonstrated.

CHAPTER 1

FROM ENERGY REFURBISHMENT OF EXISTING BUILDINGS TO NEARLY ZERO-ENERGY ONES

This chapter introduces the important role played by the building sector in the context of climate change, energy shortage and environmental pollution challenges. Indeed, the ambitious long-term international targets cannot be achieved without a strong reduction of the energy needs in the building sector; this represents one of the most important contributors at global energy consumption and greenhouse gases emissions.

At world level, the energy used in the buildings sector, which includes residential and commercial structures, accounted for 20% of global delivered energy consumption in 2018 295[1]. Only the residential buildings are responsible of about 24% of global final energy consumption with an almost flat trend and small changes for different countries [2]. On the other hand, the most recent Eurostat data confirm that the buildings sector, that in EU-28 accounted 27.2% of final energy consumption during 2017 [3], has the highest potential in achieving energy savings. More in detail, it is important to take into account not only the current state of energy consumption of the buildings, but also its future trend scenarios and the international actions and regulations fielded by the countries for the transition towards a sustainable, competitive and decarbonized energy system. Indeed, the greenhouse gas emissions are closely related to population growth and urbanization, that is increasing with different rates in all world countries, but especially in low-income and lower-middle-income countries where an even more rapid urbanization is expected from now to 2050. Meanwhile, within the developed countries, there is a duality between new buildings, characterized by constructive criteria aimed to minimize environmental impact, and existing buildings stocks, for which the environmental impact has not been taken into account in the design process. For this reason, the international standard and legislation underline the importance to focus the scientific research not only on the optimization of the energy design of new buildings, but also for identifying energy retrofitting measures for the existing building especially by considering the very low renovation rate of the building stock (around 1-3%/year, before the pandemic of CoViD-19).

In this chapter, firstly it will be presented a global overview about climate changes and energy uses mainly focusing on the building sector. Then the international and national actions and regulations committed to increase the efficiency of the building sector will be introduced, with also the indication of settled targets. Finally, a review about the Nearly-Zero Energy Buildings (nZEBs) topic across Europe is proposed, as future buildings' energy target for both new and existing constructions. This analysis will be focused on Mediterranean climates, where the best trade-off between heating and cooling need has to be investigated more accurately.

1.1 OVERVIEW ON CLIMATE CHANGES AND BUILDING SECTOR IMPACT

According to the Intergovernmental Panel on Climate Change, IPCC [4], the human activities are the major responsible of the so called 'global warming'. Specifically, the global warming at a given point in time is defined as the global average of combined land surface air and sea surface temperatures for a 30-year period centred on that time, excluding the impact of natural climate fluctuations within that 30-year period and assuming any secular trend continues throughout that period, extrapolating into the future if necessary, expressed relative to the reference period 1850–1900, an approximation of pre-industrial levels [5]. So, the current level of global warming, in 2017, is estimated approximately 1.0±0.2°C, with an increasing of 0.2±0.1°C per decade. About it, in Figure 1, is reported the monthly global mean surface temperature, GMST, in the HadCRUT4, NOAAGlobalTemp, GISTEMP and Cowtan-Way datasets, expressed as departures from 1850–1900.

In many countries, a warming greater than the global annual average is found, with negative projections, and the evidences are also worse in the Arctic regions. With a high confidence level, the IPCC states that between 2030 and 2052 the global warming will reach 1.5°C if it continues to increase at the current rate. They also sustain that the global temperature rises to 2°C above pre-industrial levels would lead to devastating consequences: rising sea levels, desertification of many areas, loss of habitats and natural species and decrease in ice caps, which would have very serious repercussions on our health, livelihoods, human security and economic growth. So, actions to reduce the concentration of greenhouse gases in the atmosphere have to be taken in order to keep global warming below 1.5°C.

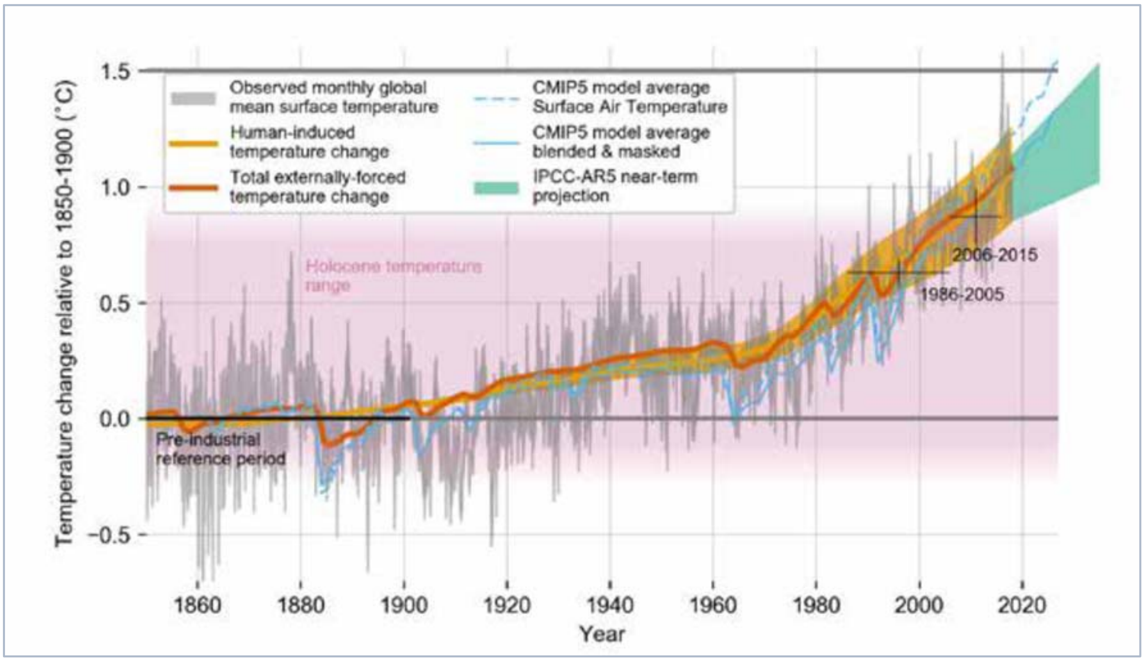


Figure 1: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Are shown: in grey colour the GMST in the HadCRUT4, NOAAGlobalTemp, GISTEMP and Cowtan-Way datasets; in yellow the Human induced contributions to GMST; in orange the total (human- and naturally-forced) contributions to GMST; in blue the modelled global mean surface air temperature (dashed) and blended surface air and sea surface temperature (solid) from the CMIP5 historical ensemble; in shading pink the range for temperature fluctuations over the Holocene; in light green plume the IPCC prediction in 2014 for average GMST over 2016–2035. Ref. [5]

The climate data monitored for Italy have been disclosed by the Italian national research council (CNR) and the Institute of Atmospheric Sciences and Climate (ISAC) coming from the historical Italian Meteorological Observatories, set up by Brunetti et al. [6]. Analysing the temperature deviation from the 1971-2000 results that the greater value has been reached in 2018 year (+1.58°C); and considering the whole trend, it has been highlighted that between the 30 warmest years, from 1800, 25 years occur after 1990. It is also found an increase of Italian rainfalls (cumulated value) in 2018 compared to the climatological cumulated values referred to 1971-2000 period. Moreover, as shown by Luterbacher et al [3], it is a recurring situation in Mediterranean countries during the winter.

The global warming induces climate changes with several impacts on natural and human systems. In particular: warming of extreme temperatures in many regions; increases in frequency, intensity, and/or amount of heavy precipitation in several regions; increase in intensity or frequency of droughts in some regions. The consequences on the land are the changing of biodiversity and ecosystems including species loss and extinction, and some of the services they provide to humans. The consequences on the sea are the increase in ocean acidity and decreases in ocean oxygen levels, with risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef. Moreover, the sea level will continue to rise, causing the increased saltwater intrusion, flooding, and damage to infrastructure to the small islands, low-lying coastal areas and deltas. So, according to [4], climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C. The most disadvantaged populations are vulnerable ones, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods. Moreover, any increase in global warming is projected to affect human health and mortality.

Anthropogenic emissions of many different climate forces affect the rate and magnitude of climate change, they will persist for centuries to millennia and they will cause further long-term changes [7]. In particular the climate forcers are divided into two broad categories in terms of their impact on global temperature [7]: long-lived greenhouse gasses (GHGs), such as carbon dioxide (CO_2) and nitrous oxide (N_2O), whose warming impact depends primarily on the total cumulative amount emitted over the past century or the entire industrial epoch; short-lived climate forcers (SLCFs), such as methane and black carbon, whose warming impact depends primarily on current and recent annual emission rates. The IPCC 2018 Report evidence that past emissions are unlikely to raise global average temperature to 1.5°C above pre-industrial levels, but they affect other changes, such as further sea level rise. It could be explained by means of Figure 2, in which all categories of 1.5°C pathways[1] (a) and associated annual rates of CO_2 emissions (b), assuming constant fractional contribution of non-CO_2 radiative forcing[2] to total

[1] The "1.5°C emission pathways" are defined, on the base of current knowledge of the climate response, as those that provide a one-in-two to two-in-three chance of warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot [5].
[2] The "non-CO2 emissions" are all anthropogenic emissions other than CO2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases [4].

human-induced warming, and cumulative emissions of CO_2 (c) are illustrated schematically.

It is shown the trend of an example of a 'time-integrated impact' (d) that continues to increase even after global mean surface temperature (GMST) has stabilised. So, the warming induced by human is proportional to the total cumulative CO_2 emissions. Reducing emissions to zero implies to stabilize cumulative CO_2 emissions and to fall concentrations of CO_2 in the atmosphere, and so stabilizing GMST, if non- CO_2 climate forces are constant and positive. Only reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales.

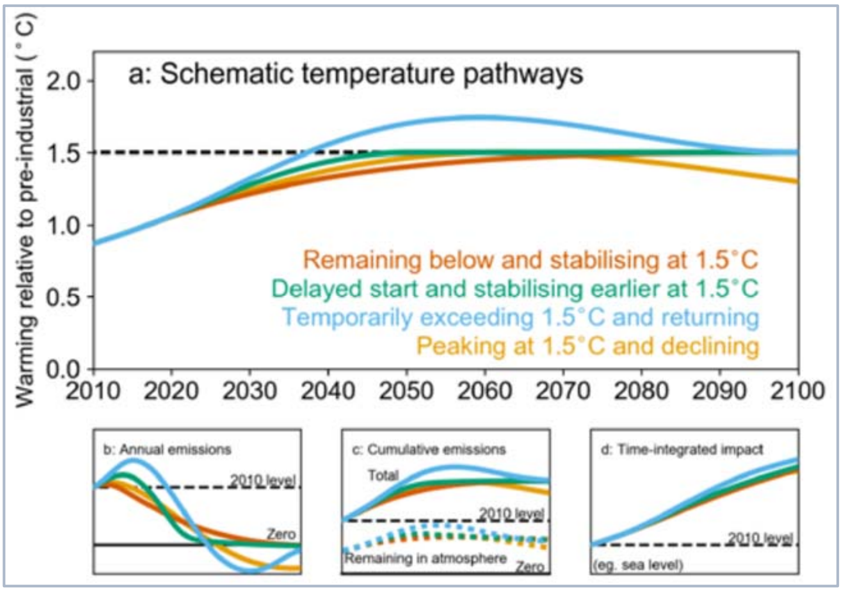


Figure 2: Schematic illustration of the relationship between (a) global mean surface temperature change; (b) annual rates of CO2 emissions; (c) total cumulative CO2 emissions (solid lines) and the fraction thereof remaining in the atmosphere (dashed lines; these also indicates changes in atmospheric CO2 concentrations); and (d) a time-integrated impact, such as sea level rise, that continues to increase even after GMST has stabilized. Ref. [5].

According to the data provided by annual report of BP Statistical Review of World Energy 2019 [8], in 2018 the total world primary energy consumption was 13864 Mtoe, of which OECD[3] shared 40.9% (5669 Mtoe), non-OECD the 59.1% (8195.9 Mtoe) and European Union 12.2% (1688.2 Mtoe). Primary energy consumption grew at a rate of

[3] The Organisation for Economic Co-operation and Development (OECD) is an intergovernmental economic organisation with 36 member countries, founded in 1961 to promote policies that will improve the economic and social well-being of people around the world (www.oecd.org).

2.9% last year, of which the share was 1.5%, 3.9% and -0.2 % respectively for OECD, non-OECD and European Union countries. The grew results almost double of 10-year, with an average of 1.5% per year, and it results the fastest growth since 2010. At same time, carbon emissions from energy use grew by 2.0%, again the fastest expansion for seven years, with emissions increasing by around 0.6 Gton. To a very large extent, the growth in carbon emission is simply a direct consequence of the increase in energy growth. The rapid growth in energy demand was largely driven by China, USA and India which together accounted for around two thirds of the growth. The strength in energy consumption was pretty much reflected across all the fuels, most of which grew more strongly than their historical averages. This acceleration was particularly pronounced in natural gas demand, accounting for almost 45% of the entire growth in global energy consumption. Digging into the data, it seems that much of the surprising strength in energy consumption in 2018 may be related to weather effects. In particular, there was an unusual large number of hot and cold days across many of the world's major demand centres last year, with the increased demand for cooling and heating services [8].

The elaboration made on by *BP p.l.c.* [9], indicates that the global energy demand grows in all the main sectors of the global economy, with buildings and non-combusted use increasing in importance. In particular, the industrial consumes around half of all global energy and feedstock fuels, while residential and commercial buildings accounting for 29%, and transport for 21%. It is interesting to analyse the annual trend of primary energy consumption by sectors shown in Figure 3 based on the data available from 1970 to 2020 and goes until 2040 with an "Evolving Transition" (ET) scenario, in which "government policies, technology and social preferences continue to evolve in a manner and speed seen over the recent past".

In particular, in the ET scenario the growth of energy consumption in all sectors slows as gains in energy efficiency quicken. The slowly in demand growth is most marked in the transport sector. Growth of energy demand used within industry is also slows but despite this, the non-combusted use of fuels within industry is the fastest growing source of incremental demand. Meanwhile, the energy used within buildings expands as growing prosperity in developing economies and leads to significant increases in power demand for space cooling, lighting, and electrical appliances. The growth, driven by developing economies thanks to the increase in prosperity and expanding middle class, involves in an improving wealth and living standards where people live and work in greater comfort. In the ET scenario, energy use in buildings grows of 1.5%, more strongly than industry and transport, with its share of overall energy consumption that could edging up to around a third by 2040. The majority growth in energy used of buildings is the electricity, reflecting the greater use of lighting and electrical appliances and the increasing demand for space cooling in much of the developing world (Asia, Africa and Middle East) as living standards increase; but there is also a small increase in gas consumption, which gains share from both coal and oil for space heating and cooking.

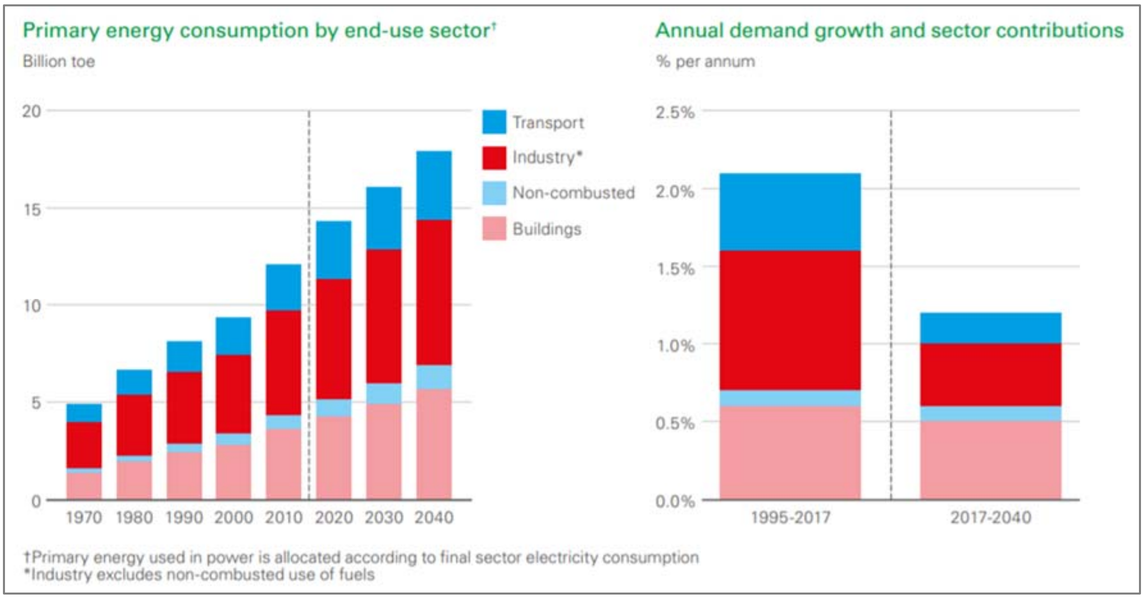


Figure 3: Primary energy consumption by end use sector (left); annual demand growth and sector contributions (right). Ref [9].

According to [10], buildings could play a major role in supporting the energy system decarbonisation. In 2014, the buildings sector accounted for 31% of global final energy use and 54% of final electricity demand. When upstream electricity generation is considered, buildings were responsible for 23% of global energy-related CO_2 emissions, with one third of those from direct fossil fuel consumption.

By analysing the most recent Eurostat data [3], the final energy consumption in EU-28 in 2017 was 1060 Mtoe, 1.3% higher than in 2016. Final energy consumption has increased slowly since 1994, reaching its highest value, 1123 Mtoe, in 2006. By 2017, the final energy consumption decreased from its peak level by 5.3%. As show in the Figure 4, analysing the end use of energy in the EU-28 in 2017 results that there are three dominant categories: transport with 30.8% of share, buildings with 27.2% and industry with 24.6% on total final energy use.

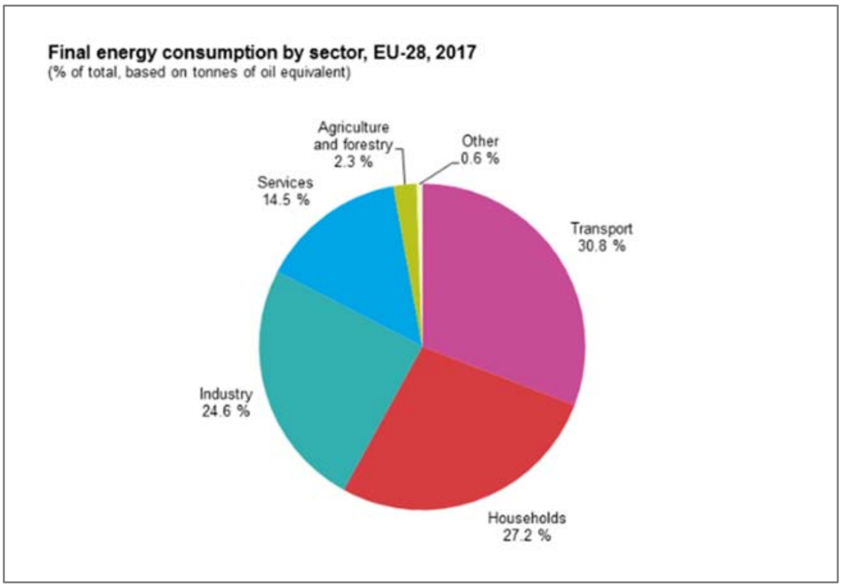


Figure 4: Final energy consumption by sectors, EU-28, 2017. Ref [3].

In order to go towards a competitive low-carbon economy and a sustainable future development, the communication of European Commission "A Roadmap for moving to a competitive low carbon economy in 2050", indicates that the EU countries should reduce their emissions around 80%, within the 2050 and compared to the 1990 level. In this direction, the EU States shared three main targets, that should be achieved within the 2030, in order to contrast the climate change: a 40% reduction in EU greenhouse gas emissions compared to the 1990 levels; raising at 27% the energy demand converted from renewable sources; improvement of 27% in energy efficiency.

At world level, the IPCC [4] has defined different emission pathways as modelled trajectories of global anthropogenic emissions over the 21st century. On the base of their temperature trajectory there are pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C and they are called "no overshoot"; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 and they are called "1.5°C limited-overshoot"; while those exceeding 1.6°C but still returning to 1.5°C by 2100 called "higher-overshoot". As regard the first two type of pathways ("no overshoot" or "1.5°C limited-overshoot") the global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030, reaching net zero[4] around 2050. If the global warming is limited to be below 2°C, all carbon dioxide emissions have to decline by about 25% by 2030 in most pathways and will reach net zero around 2070. The reduction of carbon dioxide, in both scenarios (that limiting global warming to 1.5°C or 2°C), can be achieved through several mitigation measures, which influence different balances such as the lowering energy and resource intensity, rate of decarbonisation, and the reliance on CO_2 removal. Different portfolios face different implementation challenges and potential synergies and trade-offs with sustainable development. The goal of sustainable development is to meet the needs of people living today without compromising the needs of future generations, while balancing social, economic and environmental considerations. Climate change affects the ability to achieve sustainable development goals and limiting warming to 1.5°C will help meet some sustainable development targets. The United Nation individuate a link between sustainable development and limiting global warming to 1.5°C by 17 Sustainable Development Goals (SDGs) [11], which include targets for eradicating poverty; ensuring health, energy and food security; reducing inequality; protecting ecosystems; pursuing sustainable cities and economies; and a goal for climate action.

Focusing on the building sector, as said, it is responsible of about a quarter of global energy-related CO_2 emissions, with one third of those from direct fossil fuel consumption. Kuramochi et al. [12] have estimated that the reaching of 1.5°C pathways requires that CO_2 emission in building have to be reduced by 80–90% by 2050. Hence new construction has to be fossil-free and near-zero energy by 2020, and an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD countries is needed. Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In the building sector, the CO_2 mitigation strategies, considering whole life cycle, are:

1. reduction of energy consumption by means of:
    a. decrease heating and cooling demand by improving the thermal characteristic of building envelope,
    b. use of more efficient HVAC system, equipment, lighting and appliances,

[4] Net zero CO_2 emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO2 removals over a specified period.

c. development of smart technology based on the Internet of Things (IoT), in order to optimize the building management,

2. electrification by replacing carbon-intensive fuels, like oil and coal [13];
3. installation of plants powered by renewable energy sources;
4. reducing the energy embodied in building materials [14], through increased use of bio-based materials.

1.2 INTERNATIONAL ACTIONS AND REGULATIONS

In order to promote the development of a sustainable, competitive and decarbonised energy system, some national and international actions have been put in place.

In 1988, it was created the *Intergovernmental Panel on Climate Change* (IPCC): a high-level scientific committee that studies reasons, impacts of climate change and possible solutions to the issue. Only in 1992, the *United Nations Framework Convention on Climate Change,* UNFCCC, was adopted with the aim to stabilize the concentration of greenhouse gases in the atmosphere at a level low enough to prevent anthropogenic interference harmful to the climate system. The most important UNFCCC implementation tool was adopted during the third session of the Conference of the Parties (COP3) held in Kyoto in Japan, in 1997. The Kyoto Protocol provides for quantitative limitations of greenhouse gas emissions for thirty-eight industrialized countries and the European Union compared to the ones in 1990 (baseline), in a different percentage from State to State, with the possibility of using flexible mechanisms, such as emissions trading. It entered into force in 2005, without the ratification of the United States. In 2008 the first commitment period of the Kyoto Protocol begins: thirty-seven industrialized countries and the European Union are committed to reduce their emissions by an average of five per cent compared to 1990 levels by 2012. In the same time, financial resources are needed for assisting developing countries in implementing mitigation and adaptation measures.

The last noteworthy conference of the parties was held on Paris in 2015: COP21. The *Paris Agreement* was negotiated, a global agreement on climate change reduction, the text of which represents a consensus of the representatives of the 195 participating parties. The overriding objective is to keep the temperature rise "well below 2°C", with the recommendation to do more (for a scenario below 1.5°C). One of the key provisions of the agreement is the creation of a review mechanism for the several countries' commitments: it will take place every five years, with a view to progressively increasing its ambition. After the COP21, the next Conference of Parties did not establish milestone agreements.

1.2.1 European regulations: strategies for improving energy performance of buildings

It was shown as the building sector can help to accelerate progress towards sustainable development through, for example, efficiency in the use of energy and more sustainable use of natural resources. The policies of the European Union have been directed towards the development of a diversified, competitive, sustainable energy system characterized by low energy consumption, and capable of facing the climate changes and global warming. Europe developed a strategic plan (SET Plan, 2007) to promote the development of low-carbon technologies and to deal with climate issues. In line with these objectives, in December 2008, the European Union has adopted an integrated strategy on the themes of energy and climate change, with the aim of developing, by 2020, a sustainable economy based on energy efficiency criteria. In particular, the Climate and Energy Package (20-20-20 Plan) has introduced a set of binding legislation to ensure the EU meets its climate and energy targets for the year 2020. The package sets three key targets:

- 20% cut in greenhouse gas emissions (from 1990 levels),
- meet 20% of Europe's energy needs with renewable energy,
- reduce energy consumption by 20% by increasing energy efficiency.

The Emissions Trading System (ETS) is the EU's main instrument for reducing greenhouse gas emissions from large energy, industrial and aviation plants and it affects around 45% of the EU's greenhouse gas emissions. For 2020, the objective is to reduce the emissions of these sectors by 21% compared to 2005. Moreover, there are national emission reduction targets: these objectives concern sectors that are not covered by the ETS and represent around 55% of total EU emissions: building; agriculture; trash; transport (excluding aviation). EU countries had to implement the annual binding emission reduction targets for these sectors by 2020 (compared to 2005), set by the *Effort sharing*. The objectives vary according to national income, from a 20% reduction for the richest countries to a maximum increase of 20% for the less wealthy ones (however, it was expected that efforts should have been made to limit emissions).

Subsequently, the 2030 climate and energy framework, adopted in October 2014, has extended the objectives of the 20-20-20 plan, setting:

- at least 40% cuts in greenhouse gas emissions (from 1990 levels); to reach this goal:
  - sectors affected by the EU Emissions Trading System (ETS) will have to reduce emissions by 43% (compared to 2005); for this purpose, the ETS will have to be reformed and strengthened,
  - sectors not affected by the ETS will have to reduce emissions by 30% (compared to 2005) and this will have to be translated into individual national binding targets for Member States,
- at least 27% share for renewable energy,
- at least 27% improvement in energy efficiency, the objective will be examined in 2020 starting from a target of 30%.

On 28th November 2018, the European Commission has presented its long-term strategic vision for a prosperous, modern, competitive, and climate-neutral economy by 2050. Following the calls made by the European Parliament and the European Council, the Commission's vision for a zero-impact future has affected almost all EU policies and it was in line with the aim of the Paris agreement to maintain the increase of the world temperature well below 2 °C and to continue efforts to maintain this value at 1.5 °C.

In this context, the EU has developed a series of Directives, aimed at achieving the targets set. In the present thesis only energy and environmental aspects related to the building sector are focused.

The first European Directive about the energy performance of buildings was 2002/91/EC [15], the *Energy Performance of Buildings Directive,* EPBD, which promoted the improvement of the energy performance of new and existing buildings, taking into account the external local and climatic conditions as well as the prescriptions related to the indoor climate and cost-effectiveness. It was aimed to create harmonized methodologies for the estimation of energy consumption and to release energy label.

This Directive was integrated and replaced by the 2010/31/EU [16], the *EPBD recast*, which widened the scope of the EPBD. It has imposed to Member States to set minimum requirements for the energy performance of buildings and building elements by introducing the idea of "*cost-optimal levels*" of energy performance in buildings, meaning the "energy performance which leads to the lowest cost during the estimated economic life cycle". It further extended certification to cover non-public buildings when they go on sale or rent and strengthened provisions on the inspection of heating and air-conditioning systems. The most important concept introduced is the one of *Nearly Zero Energy Building (nZEB)*: *a building that has a very high energy performance, which means 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*. Time constrains are imposed to Member States: starting by 31st December 2020, all new buildings have to be nearly zero-energy buildings. Moreover, starting from 31st December 2018, new buildings occupied and owned by public authorities have to be nearly zero-energy buildings. Member States shall draw up national plans for increasing the number of nearly zero-energy buildings. These national plans may include targets differentiated according to the category of building. It should be stressed the key role given to the public buildings, which must be virtuous examples on energy saving matter. The *Article 7* of this Directive is specifically dedicated to existing buildings: great emphasis is given to the importance of establishing requirements that lead to investments for interventions, which are optimal compared to energy savings achieved in the life cycle of buildings, highlighting the relevance of important restructuring, that is not single operations but global interventions referring to entire sectors.

On 9th July 2018, the *revised Energy Performance of Buildings Directive* (EU) 2018/844 [17] came into force. It includes measures that will accelerate the rate of building renovation towards more energy efficient systems and strengthen the energy performance of new buildings, making them smarter. The new Directive 2018/844/EU introduces targeted amendments to Directive 2010/31/EU with the vision of a decarbonized building stock by 2050 and the mobilization of investments. The revision also supports electro-mobility infrastructure deployment in buildings' car parks and introduces new provisions to enhance smart technologies and technical building systems, including automation. Member States have 20 months to transpose its provisions into national law.

In the context of energy efficiency, the Energy Efficiency Directive 2012/27/EU (EED) [18], amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, provides for energy redevelopment at least 3% of public buildings starting in 2014, applying increasingly restrictive minimum requirements, financing and technical support at national level. Furthermore, it established a common framework of measures for the promotion of energy efficiency in the Union in order to guarantee the achievement of the objectives outlined in the Climate and Energy 20-20-20 plan, and to introduce further improvements of the energy efficiency beyond that date. In particular, Member States had to promote energy saving strategies by setting national indicative energy efficiency targets. In addition, it also establishes an obligation of an energy audit for all highly energy-consuming companies, which is required every four years. This Directive was deleted because updated and included in the new Directive 844/2018.

Finally, the Directive 2009/28/EC on the promotion of the use of energy from renewable sources, that amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, establishes a common framework for the promotion of energy from renewable sources. Regarding the building sector, Member States are obliged to introduce in their building regulations and codes appropriate measures in order to increase the share of all kinds of energy from renewable sources in this sector. Furthermore, in establishing rules and obligations for minimum requirements for the use of energy from RES, both in new and in renovated buildings, Member States may take into account national measures relating to substantial increases in energy efficiency and relating to cogeneration and to passive, low or zero-energy buildings.

1.2.2 Italian legislation framework about energy performance of envelope/HVAC systems

With the publication in the Official Gazette of the Italian Decree n. 63 of the 4th June 2013 - coordinated with the conversion Law n. 90 of August 3rd 2013 and concerning "*Urgent provisions for the implementation of Directive 2010/31/EU of the European*

Parliament and of the Council of 19th May 2010 on the energy performance of buildings for the definition of infringement proceedings put in practice by the European Commission, as well as other provisions in the matter of social cohesion" – is one of the most important acts of the Italian legislative framework.

The Italian Ministerial Decree of 26/06/2015 (MD, in the following lines) on the "*Application of the energy performance calculation methods and establishment of prescriptions and minimum requirements of buildings*" [19] (MD) is entered into force in October 2015. It implements the national Law no. 90/2013, by modifying and integrating the legislative decree no. 192/2005. The MD sets the methodology for calculating the energy performance of buildings and establishes the minimum energy performance requirements of buildings and units. It introduces new prescriptions, both for new buildings and for the energy refurbishment and renovation of existing buildings. It also specifies the requirements of nearly zero-energy buildings (nZEBs) that will be applied to new buildings and major renovations from 1st January 2019 for the public buildings and from 1st January 2021 for the rest of the buildings.

As in the other States, the energy label of buildings and the regular inspection of boilers and of air-conditioning systems in buildings and also an assessment of the heating installation in which the boilers are more than 15 years old are mandatory. The MD gives the official scheme and rules to comply with these requirements.

In compliance with the Decree, during the design phase many parameters must be checked, ranging from the features of single components to energy performance (EP) indicators regarding the whole building. In the latter case, the building energy performance requirements are based on the comparison between the building and a reference (or target) building, which has the same location, function, size, but with parameters replaced by a reference value. A reference building has been defined for each case study variant. It is characterized by the same parameters of the design building except those specified in the MD for thermo-physical and performance parameters refer to different period, starting to 2015 and starting to 2019/2021.

According to the MD, the EP has to be calculated by means of the relevant standards of the UNI/TS 11300 series, which specifies a quasi-steady state calculation method based on EN ISO 13790 and EN 15316 series. The energy needs and the primary energy for space heating, space cooling, DHW and ventilation (residential building) and also for transport and lighting in other cases were determined on monthly basis. An asset energy rating was performed by applying standard building use and climate input data.

Based on the type of interventions, new building, refurbishment, restructuration, the Italian normative distinguishes several indicators that must be fulfilled. The value of energy performance index (global and thermal) is mandatory for new buildings.

However, the last official act of the Italian legislative procedure in matter of energy efficiency of the real estate, both public and private is the publication in the Official Gazette of the Italian Decree n. 48 of the 10th June 2020, concerning the "implementation of Directive (EU) 2018/844 of the European Parliament and of the Council of 30th May 2018, which amends Directive 2010/31/EU on energy performance in buildings and Directive 2012/27/EU on energy efficiency".

This Legislative Decree has not been considered, due to its late publication, in the PhD activity presented in this Thesis. It introduces important changes in the calculation methodologies to accelerate, as established by the corresponding European Directive, the economically efficient restructuring of existing buildings, to encourage the creation of zero-emission buildings until 2050. It promotes the use of information technology to ensure that the buildings operate as efficiently as possible, from boost to electric mobility, but above all it foresees the introduction of an indicator of "readiness" of the buildings for the use of smart technologies.

1.3 EXISTING BUILDINGS: RENOVATION TARGET AND RESULTS ACROSS EUROPE

At present, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient, moreover a very low percentage of building stock is renovated each year (around 0.4-1.2%) [20]. On the other side, for the existing buildings, there is a considerable potential in reducing energy consumption and carbon emissions [21]. It is estimated that the renovation of existing buildings can lead to significant energy savings, as it could reduce the EU's total energy consumption by 5-6% and lower CO_2 emissions by about 5% [22]. In this context, a full implementation and enforcement of existing energy legislation is considered one of the first priorities in establishing the

Energy Union. In detail, the EU has two complementary objectives: accelerating the renovation of existing buildings in the Union by 2050 and supporting the modernisation of all buildings with smart technologies and clearer link to clean mobility.

To boost energy performance of buildings, as previously cited, the European Union has established a legislative framework that includes the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU and the recent Directive 844/2018. These Directives promote policies that will help the achievement of a high energy efficient and decarbonised building stock by 2050, by creating a stable environment for investment decisions and enabling consumers and businesses to make more informed choices to save energy and money. The Energy Performance of Building Directive 2018/844/EU [17] introduced some new elements, sends a strong political signal on the EU's commitment to modernise the buildings sector in light of technological improvements and increase building renovations. In this way, the Commission want introduced a renovation wave of public and private buildings, and it aims to take further action and create the necessary conditions to scale up renovations and reap the significant saving potential of the building sector. Indeed, the amendments of the EPBD create a clear path towards achieving a low and zero-emission building stock in the Union by 2050, underpinned by national roadmaps and by progress indicators, and public and private financing and investment to ensure the renovation of existing buildings into highly energy efficient and decarbonised buildings by 2050, facilitating the cost-effective transformation of all existing buildings into nearly zero-energy buildings.

With the introduction of some new articles, the Directive 2018/844/EU required Member States to establish a long-term strategy for mobilising investment in the renovation of national building stocks. According to the EPBD's policies and supportive measures, to boost energy performance of buildings and improve the existing building stock the EU countries must:

- establish strong long-term renovation strategies, aiming at decarbonising the national building stock by 2050, with indicative milestones for 2030, 2040 and 2050;

- set cost-optimal minimum energy performance requirements for new buildings, for existing buildings undergoing major renovation, and for replacement or retrofit of building elements like heating and cooling systems, roofs and walls;
- establish that all new buildings must be nearly zero-energy (nZEB) from 31 December 2020;
- energy performance certificates must be issued when a building is sold or rented, and inspection schemes for heating and air conditioning systems must be established;
- support the electro-mobility by in introducing minimum requirements for car parks over a certain size and other minimum infrastructure for smaller buildings;
- create an optimal European scheme for rating the "smart readiness" of buildings;
- promote the smart technologies, through requirement concerning the installation of building automation and control systems and health and well-being of building users, for instance by taking into consideration air quality and ventilation;
- draw up a list of national financial measures to improve the energy efficiency of buildings.

Moreover, EU Countries must make energy efficient renovations to at least 3% of the total floor area of buildings owner and occupied by central governments; and all the measures to improve the building stock are support by a set of standards and accompanying technical reports that the Commission has established to support the EPBD. They are called the "Energy Performance of Buildings standards" (EPB standards) and are managed by the European Committee for Standardisation (CEN).

Moreover, within 20 months from of its publication in the GU, Member States should have to implement new rules with specific legislative measures, develop long-term national plans to support the efficient renovation of both public and private buildings. In this respect, Member States are required to establish a road map with measurable progress and indicators, with indicative milestones for 2030, 2040 and 2050, established at national level in view of the long-term objective for 2050, to reduce greenhouse gas emissions in the Union by 80-95% compared to 1990.

In this context, to accelerate energy efficiency investment, the European Commission has intensified its efforts, with specific calls to strengthen the existing financial framework, increase funding levels, diversity types of financial models and explore new supporting mechanisms. Various private and public financial and fiscal mechanisms for energy renovations in buildings are currently available in Europe and some good practices could be identified country-by-country [23]. A wide variety of policy options and efforts have helped to deliver considerable increase in energy retrofit of existing buildings, confirmed also by the variety of research study available in the literature [24][25] that shown an increasing interest in using multi-criteria approach for the energy performance optimization both in cold dominate climates [26] and in Mediterranean climate [27]. Other studies also show how the optimal design of distributed generation systems yields a positive synergy that nullifies the local pollution, drastically cuts the emission, and guarantees the economical sustainability of the investment in renewable energy sources without subsidiary mechanisms [28].

However, several studies proposing an overview of energy and economic feasibility for transformation of existing buildings into nZEB, highlight that a retrofit towards the nearly zero energy target is technically feasible in most of cases, but the costs are still too high if the aim is to make the process sufficiently attractive [29]. The real achievement of nZEB target for existing building seems to be more complicated than expected because in some cases, the nZEB retrofit produces energy and environmental payback times that are longer than the life cycle of the building [30]. Moreover, historically the market-based policies have been used to encourage retrofit investment by owner-occupiers based on a cost-effective-first basis [16], and as a result the most economically viable retrofit has been prioritised, due which often there are considerable unexploited remaining opportunities [31]. Often (this is the case of Italy), governmental Institutions support economically the energy renovation of buildings.

In general, as sustained by Nerr et Winkel [32], like other forms of public policy that seek to change behaviour, there can be no universal optimal position about the retrofit investment policy. Governments with different ideological background will have different orientations in terms of economic distribution and social equity, that affect energy policy more widely. Sure, truly effective retrofit policy making should involve simultaneous attention to occupiers and both to demand-side (householder) that supply-side actors (such as installer and designers) despite the tensions and trade-off involved.

Anyway, for the achievement of longer-term objectives, a key element of the EPBD, both with reference to new than existing buildings is the introduction of Nearly Zero-Energy Buildings (so called "nZEBs") as new constructive standard from 2020 onwards. Indeed, starting from the end of 2020, all new buildings or those receiving significant retrofit must show a very high energy performance [16] and be classifiable as Nearly Zero-Energy buildings.

1.4 NZEB DEFINITION AND CASE STUDY IN REPRESENTATIVE CLIMATES OF EUROPE

In northern European countries, standards and guidelines for designing and constructing passive houses and high energy efficient buildings started to be enacted already during the 90s. Their design had to meet detailed criteria about space energy demand and air tightness [33], with a strong attention to the building envelope, thermal losses through it and to the HVAC system to meet the comfort conditions inside the building and meantime minimizing the energy consumption. Only in last few years, the standard Passivhaus has been enlarged to include also buildings designed to be efficient in warm and mild climates, where different climatic condition must be faced. This also considering the new challenge in high performance buildings where are increasing even more the need for cooling and risk on overheating not only during the summer but all year around [34].

Today, the European Directive 2010/31/EU [16], recently amended by the 2018/844/EU [17] one, is the European Union's main legislative tool aiming to promote the improvement of the energy performance of buildings within the Community. The effects of the EPBD 2010/31/EU are very important for the next years, and this is why, even if amended by the 844/2018, still we consider this previous version. It defined the concept of the energy performance of buildings and requires Member States to introduce minimum requirements for them based on cost-optimal methodology. One of the most important elements introduced by the Directive 2010/31/2010 is the concept of Nearly Zero-Energy Buildings (nZEBs), as new energy performance target for all building's construction and renovation from 2020 onwards. This results into a new concept of high-performance building design, based on the energy balance between consumption and generation from renewable sources. Thus, over the building envelope and plant systems, the exploitation and integration of renewable systems assumes considerable importance. Although, the goal at the base still the same: occupants' high comfort conditions and respect for the environment towards a decarbonised energy system.

As defined in sub-section 1.2.1, the EPBD leaves to the Member States the task of defining the requirements and procedures though which a building can be defined as nZEB, in compliance with the country's policy targets and specific conditions [35]. Indeed, the EPBD didn't give minimum or maximum harmonized requirements neither detail of energy performance calculations, and it has been up to Member States to define what "*a very high energy performance*" and "*to a very significant extent by energy from renewable sources*" exactly constitute for them. This choice was necessary, also considered the heterogeneous situation characterizes Europe in relation to building and climate types [36], for which different cost-optimal level and energy efficiency solutions can be found and then due which there cannot be a single performance level for nZEBs across Europe. Indeed, there is a need of flexibility to account the impact of climatic conditions on heating and cooling needs and on the cost-effectiveness of packages of energy efficiency and renewable energy sources.

This context has led to significant differences across Member States about nZEB definition that remains not yet standardised [37], and the established requirements results different across the national legislations. The threshold value for the primary energy value, where is defined, change between 20 and 200 kWh/(m^2y) with the inclusion of different energy uses and only some countries specify the amount of RES, that result from 25% to 56%. The national regulations have implemented different numerical indicators and procedures for certifying the achievement of nZEB target that change for each country. Most Member States have adopted the yearly energy balance for the evaluation of these indexes [38] while the normalization procedure varies, and it could be the net conditioned area, the gross floor area or the net volume or floor area. Moreover, there are some regulations, e.g. the Italian one [19], that adopt technical standards based on the semi-stationary approach defined with the adoption of standardized boundary conditions for kind of uses and climate.

In this respect, D'Agostino e Mazzarella [38], by considering different source of information including Commission templates, the EPBD Concerted Action (CA), Energy

Efficiency Action Plans (NEEAP) and National Codes, have highlighted the main nZEBs definitions issues and status of implementation in European countries. As it can be verified, the EPBD, about the definition of nZEBs, has left Member States the freedom to define some aspect like building category, typology, physical boundary, type and period of balance, included energy uses, renewable energy sources, metric, normalization and conversion factors. Most Member States, but not all, have included some diversifications, concerning “new” and “retrofit”, and both “private” and “public” buildings in then ZEB definition. Most of them has indicated a yearly balance of primary/source energy (not including renewable) and delivered/site energy; and a few of them have referred to energy need or energy use and only one to equivalent carbon emissions. Also, normalization can vary a lot across Europe, and it can be the conditioned area, gross floor area, floor area and net floor area. A numeric indicator of energy performance expressed as primary energy use in kWh/m^{2}y has been largely used by European countries, but it results quite different across them. For example, in France, the building must be characterized by primary energy consumption lower than 60 kWh/(m^{2}year) for new residential edifices (including heating, domestic hot water, cooling, ventilation, lighting and auxiliary systems), lower than 110 kWh/(m^{2}year) for office buildings (by taking into account the same energy uses). In Austria, a building is a nZEB if the primary energy is lower than 160 kWh/(m^{2}year) for new houses and lower than 170 kWh/(m^{2}year) in non-residential edifices. For residential buildings, the energy demand of nZEB varies between 33 kWh/(m^{2}year) in Croatia to 95 kWh/(m^{2}year) in Latvia; otherwise, a threshold of about 45–50 kWh/(m^{2}year) is suggested. Few Member States have mentioned objectives that go beyond the nZEB standard; for instance, the Netherlands law proposes the targets of net zero-energy buildings (the word “net” refers to a balance, along the year, of the energy taken and supplied from and to the urban grid), moreover there are positive-energy buildings in Denmark and France, carbon neutral new buildings in Germany and zero-carbon standard in the UK [39].

Many scientific papers about the nZEB design are focused on new construction or on suggestion of economically efficient solutions. The literature suggests that the nZEB designing requires the adoption of optimization technique coupled with building performance simulation tools, and the goal could be the minimization of some design variants, among which, for instance, the thermal discomfort, energy consumption, life cycle. Another important role is played from the management of the active systems and the setting parameters that have a higher impact on the air conditioning energy demand for a nZEB compared to a traditional dwelling [40]. More in general, there are different strategies to achieve Nearly Zero-Energy goal. Surely the energy consumption can be reduced by evaluating different configurations at the design stage and implementing the most appropriate building envelope solutions, high-efficient HVAC systems and on-site renewable energy and considering the integration of advanced smart control logics for plants and windows as well as of building automation solutions. However, in some cases the achievement of nearly or net ZEB objectives seems still long, especially concerning the existing buildings that plays an important role in obtaining an energy neutral building stock. Indeed, although the retrofit towards the nearly zero energy target is technically feasible in most cases, the costs are still too high if the aim is to make the process sufficiently attractive [41]; and for someone some Southern European countries are poorly prepared for nZEB implementation, especially to the challenge of retrofitting of existing buildings [42]. There are different barriers towards the ZEBs renovation, that are mainly technical and financial, but also social, political and institutional. Existing structures limit the choose of the technical solutions that can be used, or existing solution are often expensive in addition to the financial challenge of having high investment in renovation projects. Apart from these barriers, communication of best practices and end-user behaviour are key aspects to be considered towards a wide nZEB retrofit implementation [43].

On other side, the analysis of research suggests that there are very sophisticated solutions for achieving the nearly zero energy goal. But what are the main diffused solutions adopted by designers in the existing nZEB? Usually the designers are oriented toward high thermal and airtightness performances of the building envelope, for minimizing the winter energy demand, and often seek to eliminate active cooling by using passive cooling design strategies, to achieve summer comfort conditions. Indeed, in one of the reports of ZEBRA2020 project [44], it was found that about 68% of existing nZEB buildings across Europe do not have system equipment for summer cooling.

In this context, pilot projects of nZEB or high-performance buildings are important in order to accelerate the progress towards achieving Nearly Zero-Energy buildings, as such projects provide relevant examples and practical experiences. This is important both for:

- users that want to learn how these types of buildings are possible, what they look like and what are the cost implications, the technologies used and user experience;
- industry organizations presenting their products can showcase their capabilities, test in real operation the chosen solutions and get feedback about real use operation and performance to identify advantage and possible further improvements.

Some reports contain a collection of examples of Nearly Zero-Energy Buildings around the world and in EU Member States [45][46] with the purpose to analyse the most common construction features and market trends [39]. Moreover, in the past recent years, several European projects dealt with the setup of building database, that although not are specifically focused on nZEBs, were aimed to class the building stock in representative typologies, identify general trends at country level and the effectiveness of energy related implemented policies [47][48][49]. Rehva, together with an Italian Aicarr teamwork, has developed a detailed database [50] about the high-performance buildings in Mediterranean climate to spread and engage the good practices to reach ZEB goals on a wide scale. While a Building Stock Observatory [51] was established in 2016 as a part of the "*clean energy for all European package*", and it contains a database, data mapper and information factsheets for monitoring its energy performance of buildings across Europe, with the purpose to be a useful instrument to policy-makers, investors, stakeholders, researchers and local and national authorities.

From an analysis of the existing nZEBs, it results that the building configuration is often based on designer's experience, but in this way, all involved decision variables are not taken properly into account. Analogously, this approach does not allow always to consider some interesting, innovative configurations or combinations of strategies that the research papers analyse. Very often, the designers tend to concentrate effort for reducing the energy needs for the space heating. This approach is certainly suitable for cold climates, but it cannot be applied to the South European cities, when, for example, the reduction of the transmittance value determines, on other side, the super-insulation of the building that might cause higher energy demand for space cooling and summer indoor overheating. Therefore, in Mediterranean climates, the reduction of the energy demand for cooling, by maintaining a good thermal comfort conditions, becomes the major target.

Considering that the Thesis is mainly focused on research activity performed on buildings in Mediterranean climate (South Italy), in the Table 1 the main characteristics of some existing nZEBs in European areas characterized by Mediterranean climates have been collected. In detail, the table specifies the building kind of use and if it is a new construction or a refurbishment intervention; the main data for building envelope (U indicates the thermal transmittance) and main plant systems features. In detail, are reported the kind of systems and nominal performance indications (η to indicate the efficiency of boilers, the coefficient of performance -COP- and the energy efficiency ratio -EER- for the heat pumps) or, when available, the seasonal coefficients of performance (indicated with SCOP and SEER) to give the realistic indication about the efficiency of the systems during the whole seasonal periods. Moreover, the adopted passive strategies and the consumptions with the renewable energy contribute are indicated (when available). About the energy performance, it is indicated if the values have been measured or estimated by means of calculations.

The analysis of case studies shows that the mostly used passive strategies consist in high insulated envelope and windows. Conversely, other solutions – like natural lighting, passive cooling, and more innovative technologies – are not so common, in practice. Concerning the active systems, heat pumps, mechanical ventilation with heat recovery systems are the most used technologies chosen during the design of the nZEBs, while condensing boilers are quite used for retrofitted existing buildings. Furthermore, the photovoltaic and solar thermal systems are the most used renewable energy technologies, while wind turbines are practically unused. A poor use concerns also biomass boilers, cogeneration, and district heating systems. Some of these facts are partly justified by the lack of availability of space, wind, and possibility of new heat and cold grids in dense urban areas, so that biomass, wind (sometimes also solar) and district technologies have limitations regarding source access or problems of local pollution.

Table 1: Examples of nZEBs made in areas with Mediterranean climate.

	Location/ climate	**Building type**	**Built or retrofitted**	**Year**	**Envelope**	**HVAC systems**	**Passive strategy**	**Energy performance**	**Monitoring**
[52]	Piedmont, Italy Named: CorTau-House	Single-family house	Retrofit	2015	Rock-wood insulation U-walls: 0.15 W/m^{2}K U-floor: 0.19 W/m^{2}K U-roof: 0.15 W/m^{2}K Windows aluminium frame, thermal break, low-e triple-plane with argon filler U: 0.96 W/m^{2}K	-Water-to-water heat pump (COP:4.78, ESEER:5.67) -Radiant floors -Mechanical ventilation with heat recovery -Condensing boiler (η:0.99) -PV system 7kWp		Heating: 17.2 kWh/m^{2}y Cooling: 19.7 kWh/m^{2}y Data from calculate	None
[53]	Mascalucia, (CA) Italy	Single family house of 144m^2	New	2015	-Structural concrete -Mineral wool insultation U-walls: 0.13 W/m^{2}K U-roof: 0.13 W/m^{2}K U-basement: 0.23 W/m^{2}K -Triple glazing windows U-factor: 0.90-1.10 W/m^{2}K	Earth to air heat exchanger (pre-heating or pre-cooling to the air) -Electrical heat pump -Thermal storage tank -Photovoltaic modules 8.14 kWp, -Solar thermal system 7 m^2	-Solar sharing -Adequate exploitation of natural ventilation)	All energy uses: 41.1 kWh/m^2 PV generation: 67.5 kWh/m^2	Detailed monitoring of energy and comfort performance
[54]	Koprinica, Croatia	Multi-family house of 1539m^2	New	2013	-Structural concrete -Stone wood insulation -XPS roof insulation	-Underfloor system -Heat pump COP:2.8 (90%)		Heating: 14.95kWh/m^{2}y Cooling: 15.65kWh/m^{2}y	None

					U-wall: 0.19 W/m²K (concrete)/ 0.22 W/m²K (brick) U-roof: 0.10 W/m²K U-ceiling: 0.21 W/m²K U-ground slab: 0.13 W/m²K -PVC frame triple low-e coated glazing with argon U-window: 0.99 W/m²K	-Boillers using natural gas (10%) -Ventilation system with energy recuperation -Solar thermal collector -DHW storage:4000l		renewable contribution: 22% calculated according to HRN EN ISO 13790/PHPP 2009	
[54]	Trino, Italy Named: ECOsil	Single-family house of 185m²	Retrofit	2012	-Autoclaved aerated concrete blocks -EPS insulation -Wooden roof U-wall: 0.18 W/m²K U-roof: 0.18 W/m²K U-ceiling: 0.21 W/m²K -Triple glazing wooden-aluminium frames U: 1W/m²K	-Gas condensing boiler (5-25kW) -Radiant wall panels -Solar thermal collector (9.32m²) -DHW storage (500l) -Mechanical ventilation system with heat recovery -PV System (2.94kWp)	The solar thermal system covers 96% of the needs for DHW	Heating: 25.81kWh/m²y Hot water: 2.05 kWh/m²y Cooling: 0 kWh/m²y Renewable contribution: 67%	Monitored in year 2012-2013
[54]	L'Aquila, Italy	Single-family	New	2013	-Wood-fibre walls -Insulation of liner fibre	-Reversible geothermal heat pump 10kW	Fixed and adjustable shades	Heating: 4.60kWh/m²y	Monitored during 2013

	Named: Maison Doisy	house of 175m^2			U-wall: 0.12 W/m^{2}K (upper)/ 0.126W/m^{2}K (lower) U-roof: 0.09 W/m^{2}K U-ceiling: 0.12 W/m^{2}K -Triple glazing	-Solar thermal -panel -Ventilarion system with heat recovery and integrated electrical heaters -PV system 8.5kWp		Hot water: 16.68 kWh/m^{2}y Cooling: 14.0 kWh/m^{2}y Total final energy use: 35.28 kWh/m^{2}y	
[54]	Malta Named: Mosta House of Character	Single-family house of 209m^2	Retrofit	Before 2014	-Stone masonry with air cavity Concrete slabs roof expanded polystyrene insulation U-wall: 1.57 W/m^{2}K U-roof: 0.25 W/m^{2}K U-ceiling: 1.97 W/m^{2}K -Double glazed with argon-filled U: 3.00 W/m^{2}K	-Inverter split-type air conditioning systems -Solar water collector (4m^2) Storage of 250l		Heating: 3.25 kWh/m^{2}y Hot water: 0 kWh/m^{2}y (100% renewable) Cooling: 5.62 kWh/m^{2}y according to EPRDM	None
[54]	Lisbon Portugal Named: SOLAR XXI	Office building 1200m^2	New	2011	-Brick external walls Expanded polystyrene insulation U-factor of wall: 0.54 W/m^{2}K U-factor of roof: 0.26 W/m^{2}K	-PV modules (50% of south oriented facede) -PV systems in car park -Solar thermal collector -Pre-cooled air by use of buried pipes	-South facade collecting direct solar energy, heat and natural light. -Adjustable venetian blinds -Natural ventilation due to	Heating 12 kWh/m^{2}y Cooling 0 kWh/m^{2}y Electrical appliances: 30 kWh/m^{2}y PV generation: -32 kWh/m^{2}y	Monitored during 2011 Final energy use are calculated by energy plus

					U-factor ceiling: 0.80 W/m^{2}K -Double glazing U-factor of wall: 4.5 W/m^{2}K		cross winds and stack effect via openings in facade and roof level	Electricity surplus: -2 kWh/m^{2}y Renewable energy contribution: 88%	
[55]	Laion BZ Italy	New building School building of 625m^2	New	2006	-Walls with mineral foam Roof insulated with wood fibres U-opaque envelope: 0.23 W/m^{2}K -argon triple coated panes with oak windows frames U-windows: 0.78 W/m^{2}K	-Radiant floors -Electric heat pump: 1.8kW electric, 8.3 kW thermal -Geothermal plant: 3ground probes of 50 -Solar thermal collector 18m^2 -Polycrystalline photovoltaic panel 17.7kWp	Large glazed surface facing maximized solar gains and natural ventilation	Demand: 5690 kWh/y Production: 16471 kWh/y Surplus: 10781 kWh/y Primary energy demand: 89 kWh/m^{2}y CO_2 emissions: 22.20 kg/m^{2}y	None
[56]	Zaragoza, Spain Named: Ciem Building	Office building of 2309m^2	New	2011	Thermal insulation by glass wool	-Geothermal heat pump -VAV (variable air flow system) -Radiant ceiling -floor cooling -ventilation system -PV system -micro wind system -biomass boiler		Air conditioning 25.79 kWh/m^{2}y Ventilation 11.77 kWh/m^{2}y Lighting 12.32 kWh/m^{2}y Renewable energy production: 70%	2012

[57]	Clusone (BG), Italy Named: Residenza Verdiana	Multi-family house		2011	Wooden structure U-walls 0.15 W/m^{2}K U-roof 0.064 W/m^{2}K U-ceiling 0.25 W/m^{2}K Windows with triple glass U-windows 0.91 W/m^{2}K	-Radiant ceiling -mechanical ventilation (0.45 vol/h) with heat recovery (85%) -geothermal heat pump (25kW COP 4.55) -PV system 10 kWp -DHW storage 500 l			None
[58]	Ancona Named: Leaf house	Multi-family house		2011		-Solar thermal collectors -photovoltaic system 20kWp -geothermal heat pump -fuel cells and hydrogen storage -mechanical ventilation with heat recovery		Heating and DHW: 16 kWh/m^{2}y Electric use: 7kWh/m^{2}y Cooling: 16kWh/m^{2}y Final consumption: 0 kWh/m^{2}y Emissions: 0kWh/m^{2}y	
[59]	Altamura (BA), Italy	Multy-family house	New	2016	Insulated walls U-factor: 0.17 W/m^{2}K Windows with triple glass low-e a wooden-frames U-factor: 1 W/m^{2}K	-Electrical heat pump -Solar thermal collector -PV system 16.5 kWp -mechanical ventilation system with heat recovery (85%) for single house		Renewable energy production: 77.2%	
[59]	Bisceglie (BAT), Italy	Multy-family house	New	2016	-Walls of tuff bricks and thermal plaster	-Radiant ceiling -Condensing boiler	-Passive solar greenhouses openable	Renewable energy production: 87%	

	Named: Casa di luce					-Reversible air-air heat pump -Solar thermal collector -Mechanical ventilation with heat recovery		
[59]	Gagliano del capo (LE), Italy Named: LiChiani	Single-family house	Retrofit	2017	-Walls of concrete bricks and external insulation U-walls: 0.155 W/m^2K U-roof: 0.123 W/m^2K Windows with PVC frames	-Solar thermal collectors -Compact electrical heat pump for heating, cooling, DHW and mechanical ventilation with heat recovery and filtration	Solar sharing	Renewable energy production: 100%
[60]	Caldaro (BZ), Italy Named: Casa Kato	Single-family house of 162 m^2	Retrofit	2015-2016	-wood structure -opaque envelope with recyclable materials U-new walls: 0.13 W/m^2K U-existing walls: 0.19 W/m^2K U-roof: 0.83 W/m^2K -Windows with triple gazed and pvc or aluminium frames Ug: 0.6 - 1.2 W/m^2K; g: 54%; LT: 74%	-Radiant ceiling -Solar thermal collectors -Mechanical ventilation system		Thermal index: 43 kWh/m^2y

CHAPTER 2

METHODOLOGICAL APPROACH FOR ENERGY INVESTIGATIONS ON HIGH-EFFICIENT BUILDINGS

The growing interest in sustainability, the intergovernmental energy policies and international Directives led to develop and investigate new systems, design solutions and management strategies for constructions, aimed to achieve energy efficiency and environmentally friendly buildings. However, what is the most appropriate approach to study these new technologies and solutions? To evaluate and answer to this question is the main purpose of the present chapter.

The first step of every possible investigation method is the definition of the control volume object of analysis, that could be a single building component or the whole HVAC/envelope system. Once this is defined, two different methodological approaches can be adopted, which are generally used in literature and current practice: a) the numerical approach (simulation/calculation), based on mathematical model implemented in most cases in a simulation environment; and b) the experimental approach in controlled or real environment. Obviously, it is also possible to follow both the methods in combination between themselves to perform a more detailed and advanced evaluation. In general, different study choices can be made, on the base of sustainable costs and available time as well as available experimental and computational resources.

It should be also considered that, from a physical point of view, a building is a complex system, influenced by a wide range of parameters. Indeed, it should be emphasized that often new technologies, can also influence other field (daylight, acoustic, etc.) compared to the purely energetic one. In this case, a multi-domain evaluation may be necessary, to have a complete characterization of the element under investigation. Finally, due to the technologic development, adaptive, dynamic, active, switchable building technologies can be realized. It requires studies under time domain, with frequent transient phenomena.

In the chapter, firstly a brief overview about the numerical methods for studying building's systems will be presented, focusing on Building Energy Simulation (BES) with nodal network model and Computational Fluid Dynamics (CFD) tools. Then, different experimental facilities to investigate the building energy performance will be introduced, focusing on the real-scale test building to evaluate the energy performance of systems and components in a "real use" environment. Moreover, a combination of experimental and numerical approach will be introduced as a method to evaluate the performances and energy retrofit possibilities for existing buildings. The evaluation methods that will be described are part of the broader methodological approach adopted for research activity object of the PhD Thesis. In particular, an overview on methodological framework will be presented in the last part of the chapter, together with the description of motivations and research's objectives.

2.1 NUMERICAL TOOLS FOR ENERGY ANALYSIS

In order to evaluate or replicate the HVAC-building system performance, two kinds of numerical approaches can be used. The first one is based on a set of algebraic equations that analyse the interaction between the building and the external environment under a macroscopic point of view. It can be defined as a simplified or even semi-stationary method. Instead, the second approach consists in the dynamic thermo-energetic simulation, that takes into account all those transitory phenomena that significantly affect the performance of the HVAC/envelope system (external weather conditions, lighting system, thermal inertia of the building envelope, performance of air conditioning systems at the part load conditions, regulation etc.). In this second case, there are two main approaches for the modelling: nodal network (or multi-zone) model and computational fluid dynamics [61].

In the first case, each building zone is considered a node with homogeneous distribution of temperature, pressure, concentration (zero-dimensional evaluation) [62]. This is a zero-dimensional study (with reference to a defined thermal zone), performed in the domain of the time. The building and its ventilation plants are treated as a collection of nodes representing rooms, equipment connection points, environment conditions etc. The inter-nodal connections are defined to represent components such as doors, windows, fans, ducts and pumps. Then, a model that gives its mass flow rate as a function of the prevailing pressure difference is assigned to each component. A lot of Building Energy Simulation programs, known with the acronym of BES, use the multi-zone modelling approach due to its easy implementation and reasonable computation time. On the other hand, the BES could not simulate the stratification of airflow with non-uniform temperature distributions and momentum forces. In this case, the local thermal comfort distribution of the occupant zone, which can be used to control the HVAC system, cannot predict as well as the air quality.

As regards the computational fluid dynamics (CFD) models, the building zone is decomposed into several control volumes in which a detailed description of the air flow can be provided by solving the Navier–Stokes equations. CFD method can predict detailed information of the airflow and the temperature distribution for various purposes. Thus, this analysis is performed in the domain of the space. On the other side, CFD method is characterized by a high demand in computational efforts and the results are sensitive to the boundary conditions. Current CFD programs usually do not have embedded or rigorously validated models to determine the dynamic boundary conditions in buildings. In most cases, the simulation is carried out by adopting fixed boundary conditions, such as fixed supply airflow rate and temperature, fixed wall temperature or heat flux through the envelopes.

In general, the objective of building performance simulation (BPS) is the quantification of aspects of building performance which are relevant to design, construction, operation and control of buildings as well as to predict the energy performance of a given building and thermal comfort for its occupants. Then, to overcome their own limitations, BES and CFD models can be coupled to provide the critical information mutually and achieve better results than standalone programs. BES could provide dynamic boundary conditions to CFD, which can provide the local airflow information to BES to study HVAC control and improve the thermal load calculation. This research field is nowadays under development.

Following a more depth analysis of two modelling approaches for the dynamic thermo-energetic simulation will be discussed: Building Energy Simulation (BES) with nodal network model and Computational Fluid Dynamics (CFD) tools.

2.1.1 BES for building-HVAC system

The simplified or semi-stationary calculation methodologies have several advantages compared to a dynamic simulation, including: the relatively small number of input data needed, easily understandable calculation rules, intuitive identification and easy correlation between inputs and outputs. However, this approach is considered insufficient to describe the behaviour the more complex HVAC/envelope system, for which therefore dynamic simulation tools are used.

The dynamic approach makes it possible to evaluate, in a transitory regime, and thus by evaluating the heat storage in buildings and HVAC equipment, the phenomena of thermal interaction between the building and the internal and external environment and to investigate the behaviour of innovative solutions, for which the simplified approach is not sufficient.

Dynamic thermo-energetic simulations have therefore several potentials and the main results that can be obtained with a dynamic simulation model, normally managed with a sub-hour time step are:

- cooling and heating loads calculation of different thermal zones for the design of air conditioning systems (design calculation);
- determination of energy requirements for heating and cooling to meet the performance values required by legislation and the performance values to be assigned within sustainability assessment protocols (calculation of consumptions);
- study of the hourly temperature and relative humidity of the indoor air in the absence of climate control (i.e., the free running evolution);
- evaluation of inside and outside surface temperature values of building envelope;
- analysis of thermal comfort conditions and air quality inside the rooms, in relation to the energy requirements;
- determination of the electrical demand for artificial lighting, which is linked to the characteristics of the building, to the daylight contributions and to the efficiency of the systems;
- determination of the polluting emissions produced by HVAC systems;
- analysis of the performance of the plants powered by renewable sources.

In advanced energy simulations, various BES codes and simulators are used, but most of these are organized on similar architectures. Indeed, usually, in a first section the creation of the model is required. It is necessary for the definition of the thermo-physical properties of the building, through the characterization of the opaque and transparent surfaces, the programming of endogenous loads (people, lights and equipment installed), HVAC systems and components, opening strategies and schedules, and simulation of specific parameters. In this same phase, the weather data are also loaded, which are generally climate files TRY, IWEC or TMY2. These are weather data representative of a "typical" year, obtained by statistical elaboration on locally recorded weather data for a proper number of years (typical 10 years).

The resolution algorithm most used in BES codes is often based on the conduction transfer functions (CTF), through which is possible the evaluation of thermal loads of the building, the energy required by the HVAC system and comfort conditions achievable inside. Some energy simulators make algorithms based on the finite difference method available by allowing two or more calculation options. The method of transfer functions, proposed for the first time by Mitalas in 1983, is based on Z-transforms, suitable for describing phenomena with a set of discrete data [63]. Mitalas showed that, for thermal systems, the coefficients used to describe the system tend to disappear quickly and allow to write a very simple function that simplifies the calculation using an iterative process. Substantially, therefore, the numerical codes of dynamic simulation, evaluate loads and needs by solving transfer functions, which describe physical phenomena such as the interrelation between input variables (causes) and output variables (effects).

The BES codes implement energy balances through a series of mathematical equations that can be divided into two main groups: the first one contains the resolution of algorithms related to the surfaces that delimit the building and the second one contains the resolution of algorithms related to indoor air conditions [64]. The solution of the first group of equations provides the temperatures of the internal surfaces and the quantification of the convective energy exchanges involving these latter, through which the average temperatures of the indoor air can be evaluated, as well as the total thermal load that must be balanced. Usually, convective heat transfer coefficient is not known and is estimated through empirical equations or assumed as a constant. Also for these reasons, a coupled analysis is useful, through dynamic energy building simulations and computational fluid dynamics (CFD) studies related to the internal environment.

Along with new systems, materials, components and construction techniques also energy simulation software tools of building have had developments over the years. Currently there are several energy simulation software tools with different levels of complexity and response to different variables. Among the most complete simulation software tools are the Energy Plus, the ESP-r (Energy Simulation Software tool), the IDA ICE (Indoor Climate Energy), IES-VE (Integrated Environmental Solutions - Virtual Environment) and TRNSYS.

In this PhD Thesis, to simulate the energy behaviour of the building/HVAC systems was used EnergyPlus [65] software for most of the considered case studies. More in detail, many studies have been performed by means of Design Builder v4.6/6.0 [66][67] a graphical interface software for the realization of the building model and to export the simulation results. EnergyPlus is one of the most accredited simulation engines based on the transfer functions method, able to integrate thermal, airflow, building services and daylight domains compared to the others available tools. It can be considered an effective tool for evaluating energy exchanges in a building system, since they linearly bind energy flows to current and previous temperature levels, and to thermal exchange phenomena, as well as to evaluate the overall behaviour of the building system also in term of internal loads, energy consumption of each active system and generation from renewable sources. Moreover, to study the indoor distribution of air velocity and temperature, and then evaluate in detail the environmental condition and overcome the limits of BES models, the DesignBuilder CFD module has been used too.

Another BES simulation tool used for energy evaluations on one case study building investigated in this PhD program - and thus object of the present PhD Thesis - has been Dymola (2020) [68], a simulation environment based on open Modelica modelling language [69]. In particular, considering that the control systems are becoming a more and more important part of buildings performance, to make an accurate prediction of the operation of buildings and them systems, BES programs need to include detailed control strategies to predict the behaviour of the HVAC system. However, most simulation programs simplify the dynamics of the heating, ventilation and air conditioning system and idealize especially the controllers used in the components' model [70]. In fact, many modern BES, including EnergyPlus, are not well-suited to evaluate advanced control sequences and are not well integrated with control applications and workflows in general, while the equation-based modelling language Modelica offers the possibility to implement in a BES models, created with it, detailed control system components.

Modelica is an object oriented equation based language, allowing a simple schematic modelling and generating code for both simulation and optimization [71]. It is a continuous time system simulation, contrary to widely used BES tools that calculates solutions at discrete time interval. Its definition is property of a no-profit institution (the Modelica Association), composed by tool vendors and users, that contribute to the development of the language and of a suite of standards model libraries. Some open source libraries have been developed to include building and HVAC components inside Modelica. One of the available libraries is "*IDEAS*", which integrate both building envelope that HVAC systems and electric system simulations [72][73][74]. Moreover, another important library that is developed, is "*BUILDINGS*" [75] which offers the ability to implement component and system models for building energy and control systems inside the Modelica building models.

2.1.2 CFD for building elements

Computational Fluid Dynamic (CFD), based on the Navier-Stokes equations to model the flow system or thermal system, is playing an increasingly important role in building design. In general, the information provided by CFD can be used to analyse the impact of building exhausts to environment, to predict smoke and fire risks in buildings, to qualify indoor environment quality, and to design natural ventilation systems.

The convection processes in fluids, described by partial differential equations, are derived from the general conservation principles formulated, usually, for open systems in fairly simplifying hypotheses. In particular, the temperature distribution, governed by the energy conservation equation, is based on the first principle of thermodynamics, while the velocity distribution, governed by continuity equation and the Navier-Stokes equations, are based, respectively, on the principle of conservation of mass and on principle of conservation of momentum. For the study of the thermal field, in the usual formulation of the energy equation, the variations of kinetic and potential energy, the work transferred and the conversion of chemical, electrical or nuclear energies into heat are neglected. The resulting differential expression includes only the terms of temporal variation, conductive and convection transport. The knowledge of the motion field is required for determining the thermal field, due to the presence of the velocity components as coefficients of the advective term.

The numerical solution of the equations of motion is difficult in the hypothesis of incompressibility because pressure does not appear as the main variable in the equation. The pressure plays an important role during the motion because instant by instant, it takes values that guarantee respect for continuity. So, the use of primitive variables, pressure and speed components, expects to transform the equation of continuity into an equation for pressure (found a pressure distribution which leads to a motion field that respects continuity if used in the Navier-Stokes equations). On the other hand, the respect for continuity, however, can also be achieved through alternative strategies such as, for example, the formulation of the equations of motion in terms of current function and vorticity.

Some alternative strategies such as, for example, the formulation of the equations of motion in terms of current function and vorticity, could lead to the respect for continuity, but their implementation in 3-D calculation codes is not possible [76]. The three-dimensional problems are generally solved in the context of primitive variables, that could be easily and efficiently implemented into the commercial codes.

The numerical solutions of convection equations by using primitive variables could be easily used in laminar flow regime, by estimating thermal diffusivity and kinematics. While, for turbulent flow fields, the direct solution requires domain dense meshes and/or very large number of temporal intervals, so difficult to support by commercial calculation codes. In order to overcome this problem, the equations mediated on fairly long intervals of time, or rather large portions of space are used instead the original differential equations. In this way, the motion variation in small time interval and limited space become negligible. With the mediated equations approach, specific turbulent stresses and heat flows have to be evaluated. For this aim, different models could be used, most of which are based on turbulent kinematics and thermal diffusivity. The most used turbulence model is the so-called k-ε model, based on turbulence kinetic energy (k) and the rate of dissipation of turbulence energy (ε) for describing the thermal diffusivity and turbulent kinematics.

Several are the commercial/open source software for solve CFD problems. The most accredited in the scientific community are COMSOL, OpenFOAM, Star-CCM+ and Fluent, which differ in a more or less thrust possibility of modification of the models that govern the calculation by the user.

As said, in this PhD thesis the DesignBuilder v. 6.0 CFD module has been used for solving the CFD calculation about the air airflow, temperature and the distribution of some comfort indices (Predicted Mean Vote and Percentage Person Dissatisfied) inside the building, with the adoptions of suitable boundary conditions derived from the building thermal energy simulation. In general, this CFD module can be used for both external and internal analyses, is based on the primitive variable method and k-ε turbulence model, and the boundary conditions may include the effects of climate internal heat gains and HVAC systems.

2.2 EXPERIMENTAL ANALYSIS

In general, Energy simulation tools support the understanding of how a given building operates according to certain criteria and enable comparison of different design alternative. Every energy simulation is based on thermodynamic equations, principles, and assumptions, but since thermal process in a building are complex, energy simulation programs approximate their predictions with qualified equations methods. Therefore, results can be arbitrarily incorrect, if certain assumptions are not satisfied in the simulation or matched in real life. Hence the importance to perform, when is possible, experimental investigation and analysis once the building or its systems are operating.

New developed envelope elements and plant components need to be tested under laboratory and in real dynamic weather conditions in order to characterise, and possibly to model, their behaviour and their effectiveness both in terms of energy saving and indoor environmental quality, and then tackle the challenging of experimentally characterising innovative elements. All this is possible through three main facilities categories: indoor laboratory facilities, outdoor test cells and outdoor real-scale facilities (whole buildings, possibly with occupants) [77].

In the first one, the measurements are carried out under controlled boundary parameters (such as air temperature, relative humidity, air velocity and so on). Steady state conditions or pre-defined sequences could be implemented. Moreover, accelerated tests could be carried out in order to study the aging of materials and theologies, that otherwise would take too long in real conditions. The possibility to recreate a boundary conditions if on one hand is a benefit for a full controlled and replicable test, on the other hand it does not allow to simulate some complex mechanisms (e.g. sky and the ground diffused radiation) and the purely random variability.

In the test cells, instead, the internal conditions are fully controlled while the outdoor ones are the real one. They could be characterized by the presence of occupants or not. So, these are a compromise between the indoor laboratory and outdoor full-scale facilities for evaluating the real energy performance of common or innovative building component and system, such as passive energy saving technologies.

Finally, the full-scale outdoor facilities are whole buildings with the possibility of being occupied. In these, the study of building elements results linked to the specific building characteristics (surface to volume ratio, window to wall ratio, exposition…); moreover, since the outdoor and indoor factors simultaneously act during the measurements it is difficult to isolate a single variable. However, only in this kind of test facility the analyses on building element and systems components could be carried out with real indoor and outdoor conditions. It is an advantage for the real characterization of the building elements and systems, resulting the compromise between test cell-facilities and real buildings.

In the following lines, a focus on the outdoor full-scale test facilities is firstly presented and then on in-situ performance evaluations, used to perform, respectively, research activities on building energy-efficiency solutions in a "real use" environment and in-field energy verification on real buildings after the construction phase.

2.2.1 Full scale test facilities

Full-scale test laboratories with different sizes and geometric shapes are placed in several countries with different climatic conditions. The choice of technologies to be tested and the types of assessment methods depend on the social context, the economic market, and the climate area, as well as on the scientific research or industrial market issues. But all of them are fully monitored with a large number of sensors and meters to characterize indoor and outdoor conditions, evaluate the energy requests and collect all information about thermal, acoustic and lighting performance like not real buildings.

The project report of International Energy Agency (*Annex 58*) [78] shows the interest in full scale testing from all over the world, with an increasing research taking place both on building components and on whole buildings (to characterise thermal performance and energy efficiency). So, numerical building component and building energy simulation models did not make full scale testing of building and its components redundant. On the contrary, together with increased application of numerical simulations, a renewed interest in full scale testing can be observed. This can be verified because dynamic full-scale testing showed to be of interest to study building (component) performance under different real conditions, and because quite often an important difference is observed between predicted and realised performance. Then, only basing on analysis of the measured dynamic data, the model of a component will be able to predict the thermal dynamic response of it; and then only in this is the way, it can be ensured that the behaviour of new advanced building components is integrated correctly in building energy simulation (BES) models. A similar approach of parameter identification based on dynamic measurements can be used to identify suitable models to describe the thermal dynamic of whole buildings including building system. Then, in combination with dynamic analysis and numerical simulation tools, full scale testing results of great importance in the ambitious targets on transforming the building stock into a highly energy efficient and low carbon system.

Moreover, the use of full-scale outdoor facilities is also fundamental to perform an experimental verification about the effectiveness of chosen designing solutions, in situ measurements on the energy performance of the building after the construction phase (and even more, during the use of the building by the occupants) and also experimental investigations of the influence of several operational conditions and control strategies on the energy performance of buildings in a “real use” environment. Indeed, these kind of analyses is necessary to verify if the forecasted performances (expected during the design phase) match with the real one, or, conversely, if it happens the so-called “performance gap” [79]; and to verify if a high performance designed building is really operating as efficiency as possible. In fact, several studies showed that the actual performance after construction of the building may deviate significantly from this theoretically designed performance. Frequently, it happens that the real consumption is higher than the predicted one and, sometimes, the difference between consumed and calculated energy requests could be larger than 100% [37]. In this context, knowledge-transfer and exchange of experiences with pilot programmes based on full-scale facilities may be crucial to avoid the mismatch and could be useful to bridge the gap between design expectation and actual energy performances and between research and commercially available products and their behaviour in real boundary conditions and interactions with other components. Full scale dynamic measurements are helpful to investigate the performance of building components and whole buildings as built in reality; this is why, currently, several in situ research testing activities should be performed.

Sources of derivations between the actual and expected performance can be attributed to occupants and operators, systems and building fabric. For the building fabric, building performance characterization based on full scale testing – testing of building components or whole buildings under realistic dynamic conditions – could help to bridge the gap between theoretically predicted and real life performance of buildings.

Janssens et al. [80], in the book about "Full Scale Test Facilities", present a collection of different test facilities built around Europe, by dividing them in two group: test facilities for outdoor testing of full-scale building components, and test buildings for energy use analysis at building level. Despite the difference in scope, they all have the objective in common to study the building and system performance under realistic dynamic conditions. To this purpose components, systems and buildings are tested in full scale and under varying interior and exterior climatic conditions. In most of cases, this is achieved by means of a well-controlled indoor environment and by exposing components to the real climate in the field, but there are also examples of test facilities in which user behaviour is not mimicked in order to obtain realistic conditions.

2.2.2 In-situ performance evaluation

As said before, although a building could be designed to be energy efficient, the energy performance predicted in the design phase rarely matches the measured performance, due to the phenomenon defined as "performance gap"; and the sources of derivations between the actual and expected performance can be attributed to the occupants and operators, the systems and the building fabric.

In this context, the quantification of the actual energy performance can only be effectively realised by in situ testing and dynamic data analysis. The in-situ monitoring evaluation has a great role for understanding the energy performance of a real building. A comprehensive analysis of the energy systems of the facility includes the use of instruments to measure energy use for the whole building and/or for some energy systems within the building (for instance, by end uses: lighting, office equipment, fans, chiller). The measurement should regard the variables needed to characterize the envelope and plants actual performance, the microclimate conditions inside the building and the energy request and uses of the whole building and its systems.

Envelope in-situ investigations

The actual performance of building envelope could be supported by in-situ no-intrusive diagnostic techniques, like in situ measurements of thermal transmittance, blower door test and infrared thermography.

In general, the operational performance of building envelope is different from the actual ones. From technical literature, it is found that generally the measured transmittance values are higher than those calculated, due to non-compliant implementation, degradation of insulation performance over time, or environmental conditions other than those of the project (for example humidity in the insulting layers). Then, when it is possible, the in-situ detection on envelope performances is needed.

For most European standards on energy conservation, a common indicator to define the thermal quality of the building envelope is the U-value of envelope’s components. It can be measured, according to ISO 9869 [81], by measuring the heat flow through the element and the temperatures difference across it.

Really, the thermal transmittance neglects the capability of materials to store and release heat over time. Then, in order to investigate the dynamic characteristic of building envelope, responsible for the “inertia effect”, some research studies in the literature have proposed a method to identify the dynamic response of envelope to external solicitations based on real monitored data [82][83][84]. In particular, they have defined some experimental equations for the decrement factor and the time-shift of the thermal wave, in terms of temperature response on the internal surface, and then calculable from monitored values of internal and external surface temperatures on object component.

On other side, to measure the airtightness of building envelope, a blower door test can be performed [85][86]. It can also be used to measure airflow between building zones, to test ductwork airtightness and to help physically locate air leakage sites in building envelope. This test is based on a combination of building-to-outside pressure and fan airflow measurements; it is largely used to assess the construction quality of building envelope, locate air leakage pathways, assess how much ventilation is supplied by the air leakage, assess the energy losses resulting from that air leakage, determine if the building is too tight or too loose, determine if the building needs mechanical ventilation and to assess compliance with building performance standards.

Often, the blower door test is combined with the use of a thermal imaging camera to pinpoints exactly where the energy losses are. Or the use of thermal imagine of building envelope can be useful to identify the proper position of sensors for the in-situ measurement of thermal transmittance by heat flow meter. However, in general the infrared thermography survey could be carried out to map the heat loos through envelope, identify thermal bridges due to defect of insulation material [87]. Moreover, it allows the detection of some criticalities like missing thermal insulation and vapour condensation, source air leaks, mould and badly insulated areas, water infiltrations and find faults in supply lines and district heating.

HVAC systems and indoor conditions

Concerning the HVAC performance characterization trough in-situ investigations, in buildings with mechanical ventilation, it would be wise to measure the air flows of the main ventilation or air-conditioning units as well as the temperature of the supply and exhaust air flow could be useful to evaluate how the systems works during the operation. Moreover, building heating system ventilation inspection and a duct blaster/air distribution system test could be performed to locates leaks within ducts that could cause inefficiencies during forced air heating and cooling. Duct leakage in home, indeed, typically wasted 20% to 40% of heating and/or cooling energy. Instead, in case of building with other kinds of HVAC systems, surface temperature measures with thermographic surveys could be useful to detect information about the system operation.

Meanwhile, for the characterization of indoor conditions, a room-by-room examination could be performed by the monitoring of air temperature, relative humidity, air speed, surface temperature and CO_2 concentrations, by means of stand-alone instrumentation suitable for evaluating the thermo-hygrometric conditions reached inside the building, and to understand if comfort conditions for occupants [88] are allowed. In the same way, in-situ measures about indoor lighting level and passive acoustic insulation could be performed to verify the respect of visual [89] and acoustic [90][91] requirements in the buildings. These systematic in-situ measurements will give a general view of real indoor conditions in a building and will give the possibility to evaluate the performance of envelope, plants and whole building system. Finally, also a thorough examination of past utility bills and in-situ measurements on heat and energy uses by meters could be useful to clarify and identify the actual energy use of building and its systems and then allow to evaluate if the operational energy performance of the building are the same one of those expected during the design phase.

2.3 ENERGY DIAGNOSIS AND COST-OPTIMAL APPROACH

In the context of methodological approaches for buildings performance evaluation, a methodological approach resulting from a strong combination of the experimental and numerical approach has been developed during the PhD activity and it is here explained. In particular, the overall method consists in the combination of in-situ measurements (experimental phase) for the performance evaluation of an existing building, and in the creation of a numerical model of the building system (numerical phase) for evaluating and comparing, in a simulation environment, different alternative strategies and retrofit measures to improve the overall performance of the existing building. In detail, as shown in the Figure 5, the experimental phase consists in the performing of an energy audit in order to have a comprehensive evaluation and analysis of a building's current energy use, as starting point to identify cost effective ways to save energy. Moreover, the numerical phase consists in the evaluation and comparison of alternative retrofit measures following the cost-optimal method.

The available papers generally take into consideration these aspects separately and do not start with a thorough understanding of the current situation. Here, the proposed method to define a proper Reference Building is shown in Figure 5, according to the more recent normative requirements in matter of energy diagnosis [92][93]. Briefly, data to collect can be divided into five categories: 1) architectural and historical investigations; 2) building envelope audit; 3) technical system and equipment characterization; 4) building uses and thermal zones definition; 5) historic energy needs.

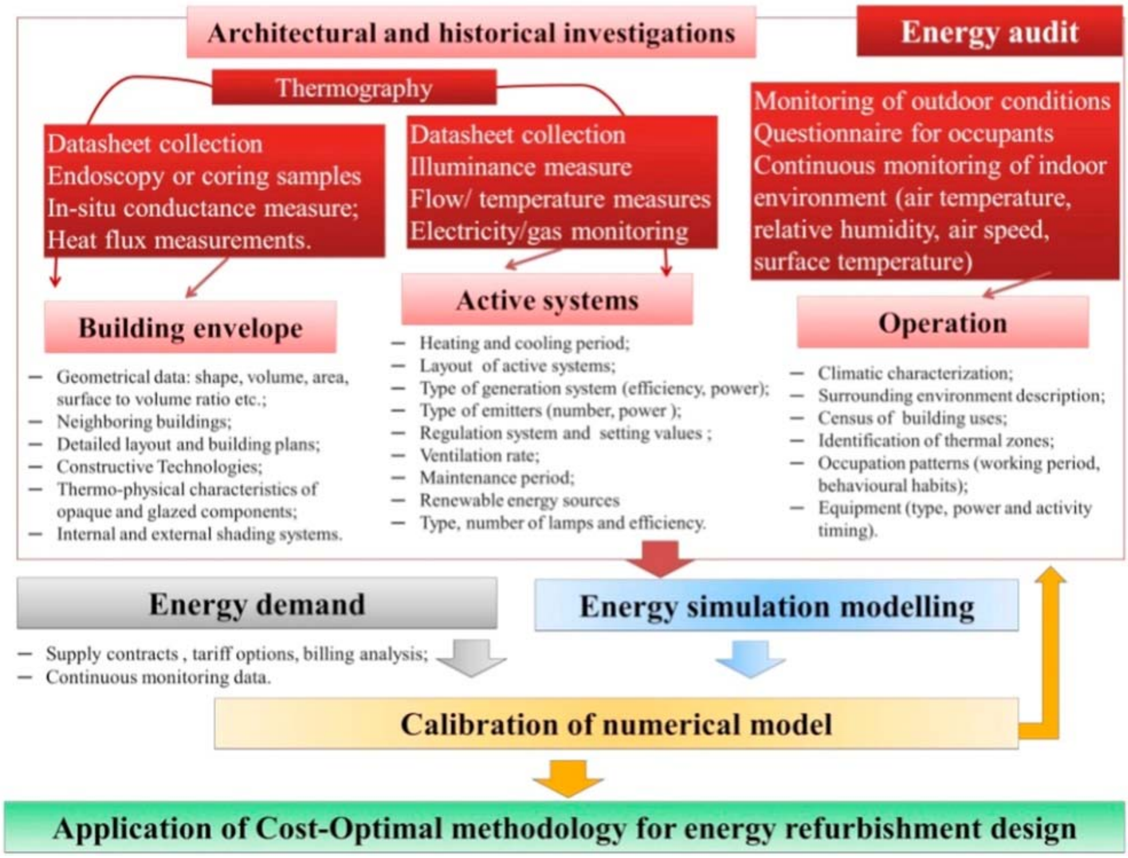


Figure 5: Proposed approach for energy retrofit of existing buildings

Then, the first step concerns the collection of historical data to know the year of construction, if the building is constrained by architectural prescriptions for the conservation, if it has undergone structural restructurings as well; then, there is the collection of geometrical data with characterization of the building envelope and active systems by means of in-field measurements. About this point, the characterization of the opaque and transparent components should be not only through available designs and technical sheets but also by means of in-situ conductance measurements, thermography or invasive test as endoscopic examinations and core samples. For HVAC and lighting system, datasheet and inspections can be used, but also measurements of flow or temperature of cooled or heated water, such as thermography for a qualitative evaluation of temperature uniformity of emitters and generation system.

Considering the available research, it is evident that the characterization of building uses (thermal zones) is usually simplified, through predefined schedules. Researchers as well as designers do not give adequate weight to this aspect that, instead, can influence greatly the reliability of diagnosis results. The energy audit requires a direct census, in each room (for which exposure and main dimensions have been taken), at least of the following information: number of occupants, number, type and power of installed equipment as well as of lighting sources, type of HVAC related to number and position of emitters. Occupation and utilization patterns for typical weekdays and weekends during a representative period of winter, summer, spring and autumn must be described in discrete schedules that should be detailed as much as possible.

Moreover, some measures should be done in significant rooms. The spatial distribution of the measurements can be established with a careful analysis of the building, by taking into account:

- subdivision into homogeneous zones for internal loads, external climatic solicitations (exposure), type of enclosure, type of HVAC system and lighting sources;
- choice of positioning of instrumentation within the reference rooms.

The measurement should regard the variables needed to characterize the comfort conditions and the performance of the plants, for instance: air temperature, mean radiant temperature, relative humidity and air speed as indicators of thermo-hygrometric conditions. However, the duration of monitoring depends on the required level of deepening, and from any criticisms evidenced by occupants. Also the monitoring of surface temperatures can be interesting not only for evaluation of comfort index, but also for the characterization of building components, and to evaluate if local discomfort conditions could be present. To evaluate how much the incident light illuminates the surface and the human brightness perception, the total luminous flux incident per unit area should be measured. Measurements should be done for different natural and artificial light scenes, in order to characterize working situations that are repeated in normal conditions. The most usual scenarios can be summarized as follows: open interior screens and artificial lighting off; semi-closed internal screens and artificial lighting off; closed screens and artificial lighting turned on. It is advisable a continuous monitoring for different periods during the working period by defining conventional day types for hosted activities and considering different external climatic conditions.

The monitoring of the energy requests has a great role to understand the present energy performances and thus design efficient actions for energy-oriented refurbishment. The historical energy consumptions must be analysed, by averaging the monthly billings of 3 or more years. When it is possible, punctual measurements or continuous monitoring of daily consumptions for selected usages are advisable.

Some other information can be found with occupant's interviews. The main questions could be: the description of a typical day inside the room, the judgment on the comfort (contextually with a measure of parameters), the interaction with air-conditioning system (e.g. modification of set-point temperature) and with windows or doors.

The proposed approach, that will be applied to the case studies in the chapter 5, assures the reliability of the building energy models that have to be calibrated before them usage. The availability of monthly, daily or hourly data to calibrate the numerical model is an essential requirement before to discuss the effectiveness of energy efficiency measures. Indeed, description of building envelope, HVAC system as well as occupant presence and behaviour are the major reasons for the performance gap between actual and expected energy consumption.

Literature analysis shows that the uncertainties due to the adoption of stochastic schedules have been evidenced mainly in case of residential sector; however, there are no studies about the evaluation of error committed during the retrofit stage in term of energy saving prediction as well as in term of costs if the building model does not comply the real building scenario. This problem is discussed for the case study basing on real data, by giving the magnitude of error in planning the benefits of energy requalification. This aspect is certainly not present in the current literature.

Then, all collected data are used to create a proper numerical model of the building and also to calibrate it by an iterative approach, in order to make a reliable prediction of energy performance of building and its systems in a simulation environment. Finally, the numerical model can be used to test and compare alternative measures following the cost-optimal method, and then identify the cost-optimal level of energy refurbishment with a macro-economic approach, taking into account, at same time, energy, environmental and economic aspects.

Energy audit of an existing building

In the various Energy Efficiency Directive (EED), energy audits are defined as "systematic procedures" used to identify, quantify and report existing energy consumption profiles and energy savings opportunities in buildings, industrial or commercial operations or installations, and private or public services. In building sector, its goal is a comprehensive evaluation and analyse of a building's current energy use to identify cost effective ways to save energy. Then an energy audit is based on an inspection survey and is aimed to analyse the energy flows for energy conservation. It may include a process or system to reduce the amount of energy input into the system without negatively affecting the output. Moreover, when the object of audit is a once occupied building, the reducing energy consumption while maintaining or improving human comfort, health and safety are of primary issue. Beyond simply identifying the sources of energy use, an energy audit seeks to prioritize the energy uses according to the greatest to least cost-effective opportunities for energy savings.

The European standard EN 16247-1 [93] describes the general requirements, common methodology and deliverables for energy audits, for all forms of establishments and organizations, all forms of energy and uses of energy excluding individual private dwellings. Specific energy audits requirements concerns special buildings, industrial process and transportation.

The purpose of the energy audit is to recognize types and energy performance of plants, building envelope and electrical equipment, as well as to recognize which are the methods of use of the technologies in order to reconstruct a balance of end uses (thermal and electrical) of the building, also proving for the energy, economic and environmental assessment of the possible saving measures to be performed on the building itself. By its own definition, the energy audit integrates data collected in field (following inspections) with calculation tools (elaboration of a mathematical model of the building/systems), through which to identify and analyse the building's energy possible retrofit, on the basis of the analysis of the real requirement. Therefore, it is possible to identify some stages necessary to carry out the analysis:

- inspection: an accurate inspection is required, because it allows you to identify the state of the building being analysed, by detecting the characteristics of the structures and parts that have a direct influence on heat losses;
- determination of historical consumption: it is necessary to know real consumption, generally as an average of those of previous years;
- determination of the envelope requirements: the characteristics of the building that were detected during the inspection constitute the basis of the mathematical model necessary for the determination of building needs;
- determination of the primary energy demand: the characteristics of the plants' components detected during the inspection or acquired through technical documentation are the basis for determining the primary energy demand of the building;
- simulation: the data determined by the final mathematical model of the building-plant system made congruent with historical consumption will be the basis of the simulations relating to possible energy requalification interventions.

Then, an energy audit should involve in a detection of various characteristics of the building envelope, like walls, floors, windows, with the purpose to quantify the building's overall thermal performance. Really, the audit should also assess the efficiency, physical conditions and programming of mechanical systems such as the heating, ventilation, air conditioning equipment and thermostats. Another common step is the detection of the quantity of electricity, natural gas, fuel oil, or other energy sources needed over a one or a two-years period. Finally, since a greatest effect on energy use is due to the user behaviour, climate and age of the building, an energy audit should therefore include an interview of occupants to understand their patterns of use over the time.

Generally, in order to have an accurate energy audit of a building, consultation of existing documentation, in-situ survey and in-field measures have to be performed to have all information for the characterization of: site and climate; opaque and transparent envelope; typology, use and regulation of systems; internal environmental comfort. The in-field measurements set out in the previous sections are generally required and, if necessary, also other more or less invasive measures can be performed to provide a complete characterization of the building and systems.

Cost-optimal method

The Energy Performance of Buildings Directive [16] requires Member States to introduce minimum energy performance requirements for buildings, building elements and technical building systems and set these requirements based on a cost-optimal methodology. In particular, according to the Directive, Member States must "assure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels". Then for the first time, this methodology introduces the prerequisite to consider the global lifetime costs of buildings to shape their future energy performance requirements.

The methodology to calculate cost-optimal levels of minimum energy performance for buildings and building elements was established in the Cost-Optimality Commission Delegated Regulation, while the Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 [95], supplementing the Directive 2010/31/EU, establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. Nevertheless, the EU regulation and guidelines leave a very large degree of flexibility for Member States, regarding the selection of input data for the calculation, the reference buildings selection, energy costs, etc.

The cost-optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle", and Member States will determine this by taking into account a range of costs including investments, maintenance, operating costs and energy savings. As indicated by [96], the complete process to assess the cost-optimal levels for building energy performance is extensively described in several studies [97][98] as well as in the guidelines document of the European Commission. However, in in the Figure 6 (BPIE, 2010) are reported the main necessary steps to be followed to implement cost-optimality at national level.

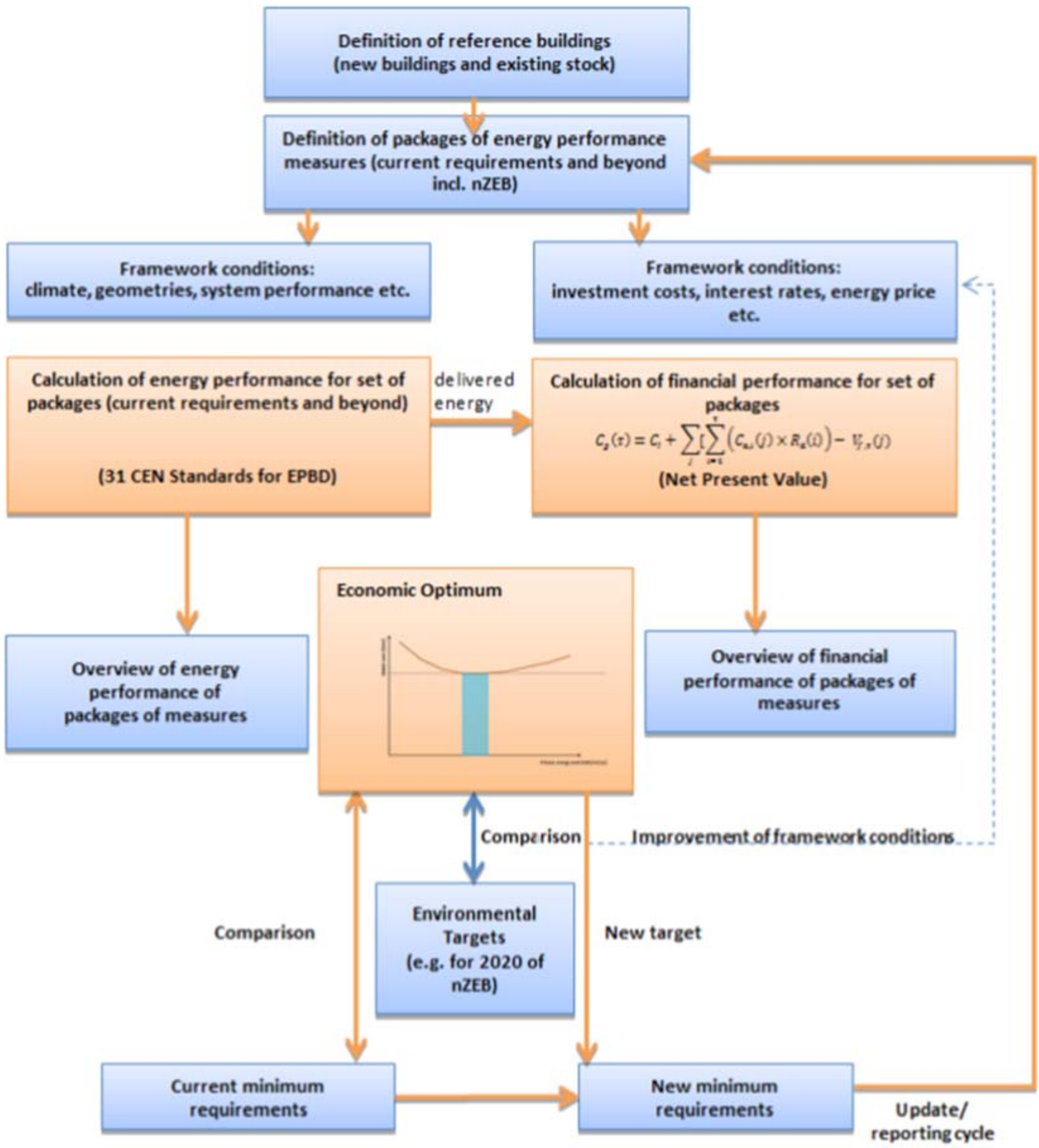


Figure 6: Implementation steps of cost-optimal methodology (Source: BPIE, 2010)

In detail, the comparative methodology framework, defined by the cost-optimal method, for the choice of energy retrofit measures could be divided into six steps:

- definition of reference buildings that are representative of the functionality and climate conditions of the existing buildings. The reference buildings must cover residential and non-residential buildings, both new and existing ones;

- definition of some variants energy efficiency measures that are assessed for the reference buildings. These may be measures for buildings as whole, for building elements or for a combination of building elements;
- assessment of the final and primary energy demand calculations of the reference buildings by calculating the impact of different packages of measures, and calculate the costs (i.e. net present value) of the energy efficiency measures during the expected economic life cycle applied to reference buildings, taking into account investment costs, maintenance and operating costs, as well as earning from produced energy;
- development of a sensitivity analysis including results of the macro-economic perspective, in order to check the reliability and stability of the baseline scenario results and analyses the impact of important framework conditions were tested, such as the discount rate or the energy price development.

At the end, as a matter of fact, the cost-optimum level is rarely found as a single package of measures applied to a reference building, but rather as a set of more or less equally valid cost-optimal solutions that can be considered as a cost-optimal range. In other words, for each building type there will be a set or even a “cloud” of curves, depending on the building features and on the combinations of cost-optimal variants used in the evaluation.

2.4 MOTIVATIONS, PURPOSE OF RESEARCH AND OVERALL METHODOLOGICAL APPROACH

As shown in the first chapter, in the context of climate change, energy shortage and environmental pollution challenges the improving of energy efficiency of the building sector could be one the effective solutions to address these issues. In this perspective, the worldwide International committees are aimed to reducing energy consumption, cost and environmental impact of buildings without compromising or even more improving occupants' comfort condition, achieving efficient and environmentally friendly buildings. Meanwhile, European directives identified the nZEB as a future building’s energy target. In this context, researches around the world are making many efforts to optimize the design and operation of buildings and their systems.

For what concerns the design process of a nZEB, several studies have been done for establishing the optimal designing configuration [99], mainly by considering the global cost, the life cycle and the investment once. Deng et al. (2014)[100] have underlined that in a nZEB design process, at least three focuses are required: (a) the analysis of local climate data, (b) the application of both active and passive solutions and (c) the integration of renewable energy systems. It is really important the optimization of each sub-system because even if the poor thermal behaviour of a building can be compensated by a large use of renewable energy sources, this represents both a waste of clean energy and, moreover, does not solve the issue of urban heat island (Ascione, 2017) [101]. Moreover, Ferrara et al. (2014) [102], with the aim of identifying the relationship between designing decisional variables, have underlined that the technical optimum for an nZEB is not the product of a simple sum of performances related to the optimal value of each parameter, but it is determined by the optimal interaction among the design parameters; therefore, it is necessary to use parametric analysis tools able to assess the trade-off between different design parameters in an integrated fashion.

Results of scientific literature suggest that the nearly zero energy design requires the adoption of optimization techniques coupled with building performance simulation tools. The goal could be the minimization of some design variants, among which, for instance, the thermal discomfort, the energy consumption, life cycle, as shown in Harkouss et al. (2018) [103] and by Buonomano et al. (2016) [104]. More in general, there are different strategies to achieve Nearly Zero-Energy goal. Surely the energy consumption can be reduced by evaluating different configurations at the design stage and implementing the most appropriate building envelope solutions, high-efficient HVAC systems and on-site renewable energy but also by considering the integration of advanced smart control logics for plants and windows as well as of building automation solutions. About it, Bano and Sehgal (2018) [105] have investigated the effect of factors such as the configuration, envelope materials, window-to-wall ratio and percentage of air-conditioned space on the thermal loads for office buildings in composite climate meanwhile, Ascione et al. have presented an analogous analysis for residential buildings in Mediterranean climates (Ascione et al., 2016 [106]) when different climate condition must be face. Indeed, as reported by Belussi et al. [107], the shape factor in cold region should be comprised between 0.16 m^{-1} and 0.47 m^{-1}. In warm climates, low insulation levels are recommended where thermal excursion between day and night is relevant, for exploiting the free cooling effect [108]. Considering the constructive solutions, according to Baglivo et al. [109], the best sequences of layers of wall are with high surface mass, for the internal side, followed by common insulating materials and eco-friendly insulating materials for the external layer. Ghosh and Neogi (2018) [110] have studied the effect of geometrical factors on the heating, cooling and lighting energy consumptions of a South facing building cell in warm and humid climate. Wu et al. [111] investigated the energy, comfort and economic performance of commercially available HVAC technologies for a residential nZEB, by adopting an experimentally validated model to measure the energy impacts of ventilation, dehumidification and heat pump options for the nZEBs, in mixed-humid climates. Ulpiani et al. (2019) [112] have highlighted the benefit of a mechanical ventilation with smart controller to optimize the air mix when a hyper-insulated envelope and a sunspace are coupled in the passive design. Furthermore, the importance of efficient appliances and lighting is highlighted by D'Agostino and Parker (2018) [113].

Another important role, to ensure that a building is really operating as efficiently as possible, is played by the controls strategies for the HVAC systems and installed devices. Guillén-Lambea et al. (2017) [40] have underlined that the comfort parameter setting has a higher impact on the air conditioning energy demand for a nZEB compared to a traditional dwelling. However, significant energy savings can be achieved with the adoption of extended comfort ranges, mainly in countries with temperate climates. Ding et al. [114], proposing a multi-objective optimization algorithm, show how without compromising the requirements of the thermal comfort of the building occupants, the energy system operating cost can be reduced of about 40% with an increase of system coefficient of performance compared with the current experience-based operation strategies. Sánchez-García et al. [115] found that the use of climate-based set point permits a better climate adaption, compared to the use of fixed set points. Aparicio-Ruiz et al. [116] seeking to find a relationship between occupants' comfort and energy efficiency, show that it is possible to improve the energy efficiency maintaining the occupants' comfort using the tools available in the Building Automation System of the building. While Yongchao et al. [117], through longitudinal field study, obtained insights into how occupants exercise adaptive control opportunities to meet their comfort needs without mechanical HVAC system. Papadopoulos et al. [118] have verified that, in regions with moderate climate, there is a potential to reduce HVAC-related loads up to 60% with a variation of set-point without compromising occupant thermal comfort levels, whereas, in regions where cooling loads are dominant, the energy saving potential is minimal. Surely, the control of all installed devices play a role in the building energy efficiency and have to be proper designed and implemented in a complex system like a building. For example, the paper of Yahiaoui (2018) [119] is focused on the control of shading devices, that can significantly improve the rational use of daylight in buildings and provide enhanced visual comfort for occupants while saving the electricity that would be used for artificial lighting.

However, by analysing the literature, we can identify some challenges that are still open on the achievement of "nZEB target". According to Belussi et al. [120], one of the greatest challenges is the filling of the existing gap between predicted energy performance of the buildings and the real measured one. Indeed, Magraner et al. [121], by comparing experimental results with respect to the predicted design value, have found that simulation results, tend to overestimate substantially the measured energy performance of an active systems. In this vein, de Wilde [122] sustains that it is necessary to provide "validation" and "verification" of energy prediction methods, in order to increase the adequacy of predictions.

It should be considered that most of the studies concerning the nearly or net zero energy buildings are based on numerical evaluations of designing configurations, and do not refer to operational data. Then, the major issue is that the literature shows quite few examples of real buildings, for which monitoring results in terms of consumptions or indoor air quality have been presented. The number of them is even lower with reference to the Mediterranean climate. Finally, the scientific diffusion of operational data is referred mostly to high performance buildings and Passivehaus located in cold or continental climate [123][124][125]. Simulation-based studies offer the obvious advantages of controllability, easy permutation to quickly cover and implement a variety of operational conditions, but do not reflect as-operated 'real world' conditions [126]. Then monitoring and verification of operational energy performances are fundamental in order to study and assess buildings' behaviour along their lifetime [127]. Analysis on real data, coming from in-field monitoring campaigns, may provide benchmarks for the existing and future building stocks, and thus could drive energy policies, by allowing better design of energy grids and services. In this perspective, Yu et al. [128] sustain that with the large diffusion of Building Automation Systems, a large amount of data on HVAC operations and installed devices are available and these could be leveraged to extract hidden knowledge and insights about operational signatures of these systems. Moreover, knowing how the energy is used, could help to improve building simulation and to enhance the construction of new ones [129]. The study of energy use over the operational stage might support the improving of existing building, the behaviour change [130] and it can support energy efficiency policies. Starting from monitored real data is generally fundamental to detect malfunctions, improve the control of the systems and to optimize the overall building performance, energy use and indoor comfort conditions. Carlon et al. [131], starting from one-year monitoring campaign, evidenced the importance of better managing the thermal inertia of the heating system and then tested improved control strategies in the simulation environment.

Surely, also to fully address the challenges with energy models, the quantity and quality of available data are crucial aspects [132]. Also for this reason, it is important the availability and the discussion about real monitoring data, for the main recurring operational conditions, in order to bridge the mismatching between the expected energy performance of the buildings and the operational energy consumption in real conditions [132].

Moreover, several models proposed for nZEBs evaluation or for the refurbishment of existing buildings consider the energy performance with theoretical behaviour, without taking into account, for example, the end-user contribution to the energy consumption, but considering the integrated systems like HVAC equipment and lighting. It is very important to focus on how different occupant behaviours and adaptation measures can influence the performance. Indeed, as said by Li et al. [133], the occupant behaviour is one of the main uncertainties in numerical or simulation studies and it is generally oversimplified as static schedules or predetermined inputs, which could cause a significant gap between simulated and measured performance. Moreover, Gunay et al. [134], by examining the operational parameters of HVAC that impact the performance gap in office buildings, show that habits of the occupants and default features of equipment could be improved to optimise the operation. Indeed, they also found that the AHU start and stop times and ventilation rate are the most critical parameters that affect energy and comfort performance for buildings and that one-hour change in AHU start or stop time is estimated to affect the HVAC energy performance by about 4% for the investigated buildings. Then, in general it is possible to conclude that the major sources of gaps between the actual and expected performance can be attributed to the occupants and operators, the systems control strategies and the building fabric.

Another important issue in matter of Nearly-Zero Energy Buildings concerns its energy balance, mostly rated on annual time scale. Indeed, although it aims is obtaining a balance between energy consumed and coverted close to zero, it should be considered that the most applicable and widely used renewable energy supply options cannot be perfectly programmed. So, the large-scale nZEBs diffusion into the existing power grid can affect their stability having a consequence on operation costs and environmental impacts. Indeed, there is a continuous, bi-directional exchange of energy and information between the buildings and the grid. A nZEB building can be labelled as ‘prosumer’ because it not only requires energy but itself converts, by increasing the complexity of the management of local power grid. For avoiding the infrastructure congestion, the planning and design of the future networks require a realistic representation of the future type of buildings performance [135].

In this matter, all the regulations, and when available, the research studies are focused on long-term energy balances (based on annual or monthly time step), without considering that the energy exchanges at shorter time scales (daily, hourly,) are most critical and do not evaluate the load match and grid interaction indicators. Some studies like the one of Tumminia *et al*. [136], by proposing a novel approach for developing of nZEBs, shows through some indicators, how install a PV system - merely able to cover the energy uses on a yearly net base - will have stress implications on the power grid.

In this perspective, the design of a nZEB should maximize the self-consumption because, with the spread of nZEBs that export energy, the management of the utility grid is becoming very complex. However, for its definition, a nZEB needs to be connected to one or more energy infrastructures. Then, in the most recent research, some studies begin to examine how the energy matching, grid impact and zero-energy level can be improved through the intelligent control system within the proposed nZEB system boundary [137]. Of course, the presence of thermal and electric storage systems will be very useful. It is spreading the association of the ‘energy flexibility’ to the buildings. More in detail, the International Energy Agency [138] has introduced, in the program “*Energy in Buildings and Communities*”, the concept of “*Energy Flexible Building”* that represents the capacity of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements. Similarly, the Directive [17] has introduced the concept of “*Smart Readiness Indicator*” that quantifies the capability of the building to adapt its operation in reaction to signals from the grid. Also in this case, not real data are now available. It is important to note that many post-occupancy analyses are not available and thus the real incidence of the energy consumption on operational energy balance and costs is not well arguable.

Starting from current literature and by considering the potentials and limitations of analysis methods described in the previous sections, according to a bottom-up approach, the work developed during the PhD has been focused on two main interconnected aspects:

- performance investigation of building energy performance in a real occupation mode;
- optimization of building/HVAC performance.

I) Performance investigation of building energy performance in a real occupation mode

Starting from the proposed literature review, it could be possible to say there is a limited availability of studies about real monitored data, and then concerning in-field monitoring campaigns about the operational behaviour and energy performance of building in a real occupation mode. On other hand, it should be considered that only the knowledge-transfer and exchange of experience, often resulting from pilot programs, could allow to avoid further mismatch between the expected energy performance and the real ones and to allow to export strategies of management, design logic and information about the operational energy performances of devices and systems in regions with comparable climate conditions. Moreover, the available studies are focused only on long-term energy balance, without considering the energy exchangers at smaller time scale.

In this perspective, the research activity has been also supported by full-scale facilities, to study building components’ performance or whole building system behaviour under different real conditions. In particular, most of the research activities were based on a real-scale test facility designed and built for a typical Mediterranean climate (in Benevento – South Italy); however, during a collaboration with a Belgian University, a short-term research activity was also carried out at another test facility, designed and built according to the Passivhaus standard, in a temperate climate (Ghent – East Flanders Belgium). The main characteristic of these real-scale test facilities is that these are, at same time, both an operational building and a "thermodynamic lab", in which real and comfortable "life" is allowed (as residential building and as lecture rooms), and contextually research activities can be performed to test how comfortable can be the "life" inside new high-efficient buildings and to verify if these are really operating as efficiency as possible. The nature of this kind of laboratory implies a presence of a number or sensors, meters, availability of monitoring of thermal, acoustic and lighting performance like no other buildings, as well as the availability and installation of monitoring of energy flows and systems operation. The real-scale test facilities are fully monitored and managed by means of an advanced Building Management Systems (BMS) with the purpose to test, in a real context, the chosen technologies for the envelope and plants systems as well as the whole performance of buildings like a complex system.

The elaboration of the real data, information and guidelines about the operational performance of a nZEB building in a real context is very useful in order to support the knowledge-transfer and exchange of experience resulting from pilot programs. On the other side, the use of data from in-field monitoring campaign in a real context could drive the develop of energy policies, the spread of zero-energy districts, the energy services design and it can be a reference to the export of management and design strategies in areas with similar boundary conditions, and thus climates, living styles and construction types.

In the following chapters, the real monitoring data will be used to evaluate the overall behaviour of case study buildings and the actual energy performance of installed system and devices, as well as the effectiveness of chosen managements strategies. Moreover, for the nZEB dwelling, the energy balance at shorter time scale will be evaluated during different seasons. Often the real monitoring data have been also used as starting point for the following topic, about the optimization of building/HVAC performances.

II) optimization of building/HVAC performance

The optimization of the whole building/HVAC system energy performance of the new and existing building stock is a key strategy to achieve tangible results for what concerns the reduction of worldwide energy consumption and, thus, polluting emissions. However, the path is very challenging. There are several purposes to be reached: increasing of the comfort conditions inside building, reduction of the energy request and then of the environmental impacts and so on.

Indeed, as mentioned above, the "performance gap" could be generally due to the different behaviour of occupants or the use of non-optimized control logic and HVAC's parameters, that will be investigated in the last two chapters. Moreover, sometimes although a building has high energy performance, these could often be furtherly improved by implementing more advanced control logic or by setting different operating parameters. Indeed, as it will be shown in the following chapters, changing the programming and control strategies of the active systems or implementing some retrofit measure on building envelope and HVAC system, could allow a significant increase of the performance of a building like a complex system, both in terms of improving the conditions of comfort, and decreasing of energy requests and therefore the environmental impact. Indeed, the knowledge of the system can support the design of strategies for optimizing the yearly energy performance of the buildings.

These aspects will be evaluated in the following chapters, through some analyses performed on real-scale test facilities, for evaluating the replicability of design measures and the feasibility of alternative control strategies for the installed devices; moreover, the same study is useful also when applied to existing educational buildings, for which a refurbishment design with cost-optimal approach will be shown.

Then, the methodological approach of the research activity is based on a close correlation and combination between the experimental approach and the numerical one. These will be combined with the following aims:

- to predict and evaluate the energy performance of a building and its systems;
- to evaluate the replicability of performed choices in other contexts or in different operating conditions, by testing them in a simulation environment well-

representative of the actual functioning of the system, because created and calibrated based on detailed monitoring data;

- to test possible alternative systems, devices, retrofit measures and control strategies for installed devices in a simulation environment before their implementation in a real building or in a full-scale test building for the evaluations in a real context. This can allow the improvement of their performances.

CHAPTER 3

A LIVING LAB LOOKING TO THE FUTURE: THE BNZEB

As it was introduced in the methodological section, the main part of PhD's research activity has been supported by the use of a real-scale test facility, designed and built in a middle-size city with typical Mediterranean climate, Benevento (south Italy) and thus named "BNZEB" (where the first "B" means Benevento).

The building is fully monitored with the purpose to test, in a real context, the chosen technologies for the envelope and plants' systems and for having a real building as starting point for future research study. This innovative prototype, besides being one of the first example of nZEB for Mediterranean climates, is a perfectly working "thermodynamic lab" where both "life" and "studies" are allowed. Indeed, this is a laboratory in which a real and comfortable life is allowed, and thus the innovative topic is that, contextually, "experiments" can test how comfortable can be the "life" inside new high-efficient buildings. The nature of the BNZEB as laboratory implies the presence of a large number of sensors and meters, to allow the monitoring of thermal, acoustic and lighting performances, probably like no other buildings in Italy. In detail, not merely the hourly balances of energy flows can be monitored, but also every criticality and event concerning each one of the multiple uses and conversions of thermal and electric energy. Indeed, the BNZEB was designed and equipped to be a living laboratory built for monitoring and measuring residential energy demand, renewable energy production, indoor environmental quality and other aspects of performance, as well as to test different technologies and their integration to evaluate energy conservation measures, control strategies and energy performance in a real context. This full-scale living lab allow numerous investigations aimed at reducing the energy needs of the building, as much as possible, by controlling and improving the indoor liveability in terms of comfort.

In this chapter, first a global description of the BNZEB building and its systems will be shown in detail (section 3.1). Moreover, the creation and calibration of numerical model of the building, suitable for dynamic simulation will be described (section 3.2). Then, the research investigations resulting both from simulation studies and from experimental testing in different operational conditions, control strategies, different set up of HVAC and devices and their influence on the final performance of the building will be detailed. It wants to be remarked that the set-up of the laboratory has been the first activity followed during the PhD and it has required several tests and configuration adjustments before to do it fully operative.

In particular, the results of all monitoring campaigns will be shown with the purpose to characterise the energy performance of this building during each season and to verify the effectiveness of chosen design and management solutions. For this reason, the energy balance at lower time scale (hourly or daily) will be proposed with the aim to evidence the impact of PV production and electric storage on building energy consumptions. This is one of the innovative aspects of the studies done during the doctorate, by considering that the monitored energy balance based on daily or hourly time step is not available for other existing studies, because, in general, research and regulation are focused on long-term energy balance (based on annual or monthly time steps), without considering the energy exchanges at a short-time. Really, for improving load matching and for reducing grid interaction and energy bills it is important a balanced design. The nZEBs design should maximize the self-consumptions, because, with the increment of buildings that export energy, the management of the utility grid is becoming very complex being a continuous, bi-directional exchange of energy and information between buildings and grid.

In general, it is really important the presentation and discussion about the monitoring results because, very often, the real performance does not coincide with the expected ones and thus further optimizations are needed. Moreover, by considering also the limited availability in the literature of studies about real monitored data, studies on building energy performance in a "real use" environment are fundamental to support the knowledge transfer and exchange of experience, to export strategies of management, design logic and information about the operational performance of devices and systems in regions with comparable climate conditions, as explained in the section 2.4. On the other side, as said, a numerical model of the case study building, suitable for performing transient energy simulations, will be used to compare the BNZEB with other buildings, to evaluate the replicability of its design in other Mediterranean cities and to perform investigations about indoor comfort conditions in term of values and space distribution of some comfort indices and air temperature.

3.1 DESIGN OF A NEARLY ZERO-ENERGY LIVING LAB IN MEDITERRANEAN CLIMATE

This section describes the design criteria and the technical features of the BNZEB, shows in the Figure 7. The single-family building is the outcome of an Italian project named “SMARTCASE”, promoted under the umbrella of the European Regional Development Fund. The building has been designed for being a best existing practice of a new way of living, by reducing, as much as possible, the needs of active energy systems and by covering the entire energy needs with all on-site available renewables sources. Indeed, the design aim is close to zero the annual energy balance by maximizing the self-consumption through the electric storage and thus avoid the need to export on the electric grid a great amount of energy.

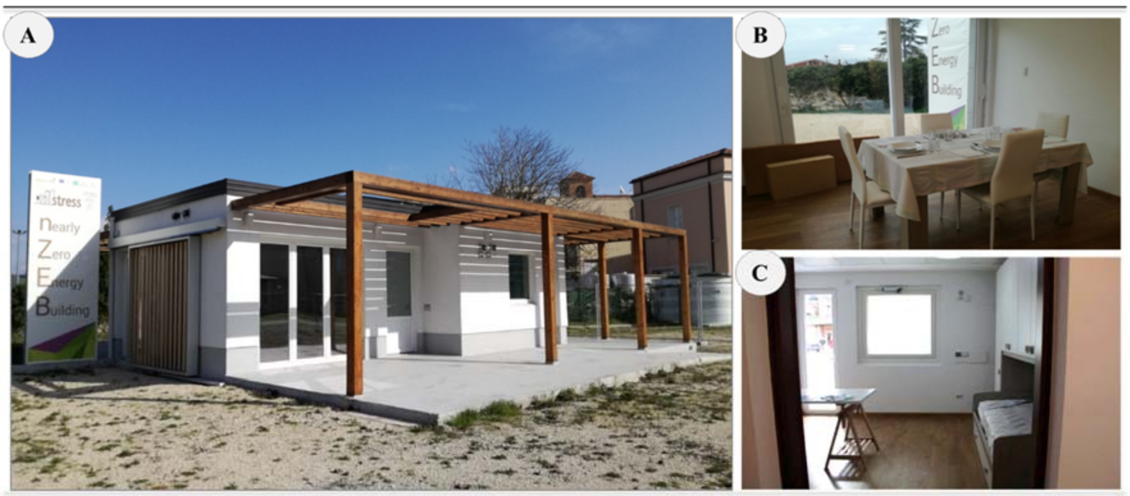


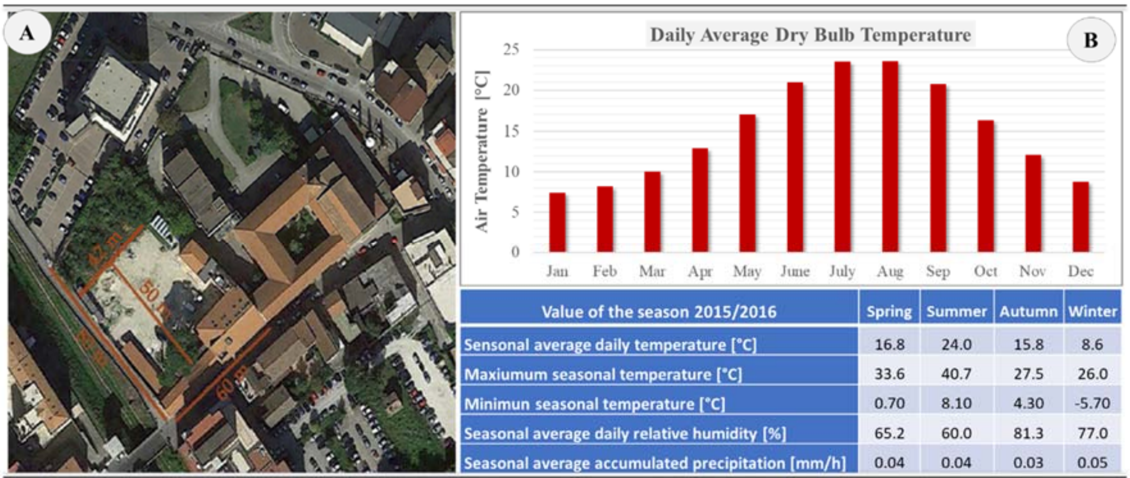
Figure 7: BNZEB: (a) external view, (b) and (c) some internal rooms.

During the design phase, an optimization technique coupled with building energy performance simulation tools, has been used. According to the aim of finding the best design for human comfort and load reduction, a multi-objective optimization problem has been performed to investigate the best trade-off between passive and active technologies.

The adopted methodological approach is shown, in detail, in previous studies [139] of the research group who tutored me in this PhD. The tested parameters, which have been modified during the optimization analysis, include several early-design phase decisions, such as window-wall ratios, glazing components, shading systems, spectral characterization of last layer of roof slab and opaque envelope constructions by varying technology, thickness and type of insulation material. The final selected configuration is described in the following sections.

3.1.1 Climatic analysis

The BNZEB was built on 2017 in a west-facing area of University of Sannio, in Benevento (Figure 8). This is a middle-size city located in south Italy and characterized by a Mediterranean climate with warm to hot, dry summers and mild to cool, wet winters. It is in a climatic zone Csa according to the Köppen-Geiger classification [140] and it results inside the Italian climatic zone "C", characterized by 1315 Heating Degrees-Days (HHD baseline 20°C). The main climate statistics data are provided in Figure 8: a typical temperature profile during the year and the seasonal value or air temperature, relative humidity and precipitation.



Value of the season 2015/2016	Spring	Summer	Autumn	Winter
Sensonal average daily temperature [°C]	16.8	24.0	15.8	8.6
Maxiumum seasonal temperature [°C]	33.6	40.7	27.5	26.0
Minimun seasonal temperature [°C]	0.70	8.10	4.30	-5.70
Seasonal average daily relative humidity [%]	65.2	60.0	81.3	77.0
Seasonal average accumulated precipitation [mm/h]	0.04	0.04	0.03	0.05

Figure 8: (a) area of construction and (b) climatic data of the city.

However, according to the most recent monitoring data, the summer 2019 has been characterized by temperature higher than 35°C (August), with average daily value very often upper to 28°C. January and February are usually the coldest months and during the last autumn, the mean temperature was around 9.0 - 12°C.

3.1.2 Geometrical features

During the early-stage design, different architectural configurations have been analysed, in which the plan floor was - more or less - a square. Also, location, type and size of windows have been widely studied. Indeed, in a mixed-humid climate, solar gains through the south-facing windows can reduce the heating energy need during the winter, but also these can increase the cooling energy need during the summer. For this reason, the shading system of the south façade has been created through a deep study to obtain a geometry that allows to exploit the solar gains during the winter season (when the sunrays are sub-horizontal) and to maximize the shading effect during the summer (when the sun is apparently high on the horizon).

The chosen solution has the main entrance close to the living room, that has a large window facing on southwest exposure, appropriately shaded, a kitchen with openings to the north-west and south-west exposures and two bedrooms with openings facing south and south-east. The south-facing windows, along the main section of the house, are fully shaded, in order to control solar radiation in the warm season. Moreover, since all windows are openable, the use of natural ventilation is possible, and if the indoor doors are open, natural ventilation involves the entire house when the weather conditions make it suitable. Regarding the main geometrical parameters, the building net surface is $70m^2$, the window-wall ratio is 22.5% and the gross volume is around $300m^3$. This value is the one typical of villas, and more detailed information can be found in the Table 2.

Table 2: Geometrical features of the building.

Occupied building area	82 m^2	Net conditioned building area	70 m^2
Gross building volume	323 m^3	Gross building height	3.2 m
Occupied building volume	220 m^3	Net conditioned building volume	188 m^3
Window/wall ratio	22.5 %	Surface to volume ratio S/V	1.03 m^{-1}

3.1.3 Building envelope

The structural technology adopted for the building is a wooden-based structure (cross-laminated panel: X-Lam). The X-Lam structures can be assembled remarkably quickly and it allows higher net utilization of the building's surface. Moreover, the solid timber

frame enables building structures to avoid thermal bridges. In detail, the wall configuration, shown in Figure 9, is made of two layers of fibre-wood insulation, with an overall thickness of 19 cm. The insulating panel on the indoor side of the external wall is a flexible panel of wood fibres, with a thickness of 5 cm. On the outer side of external walls, the same thermal insulation technology is used, with a panel of 14 cm, in wooden fibre with a different density. For what concerns the roof, different configurations have been tested and considered, and finally also to avoid the thermal bridges effects, a wooden-based construction has been chosen. All details about elements of the opaque envelope of the building are reported in Figure 9. Herein, the design values of thermal transmittance calculated according to standard methods UNI EN ISO 6946 [141] are also indicated.
Also regarding windows and frames, different types of windows have been considered during the design. At the end, the installed solution is a double-glazing system, with argon-filled cavities and low emission film. The thermal transmittance of the double-glazing (U_g) is equal to 1.1 W/m^2K, the solar factor (g) is equal to 0.58 and the light transmission is 0.79. The windows frames are made of PVC, with a value of thermal transmittance (U_f) equal to 1.17 W/m^2K. An automated movable shading system is installed on the window (west exposure) in the living area. Its frame is made of extruded anodized aluminium profiles and it has wooden slats. Both the sliding of the structure and the rotation of the slats are commanded by an electric control with a linear action; it is connected with a sensor of solar radiation located on the vertical surface near the screen. The automation allows to change, rapidly, the configuration of the shading, thus solving the risk of indoor overheating during the summer. Moreover, when the shading is closed (e.g. winter night time), it helps to increase the thermal resistance of the window.

For one window, exposed to the south, it was decided to test an electrochromic surface layer that is activated after the overpassing of a threshold of solar irradiance measured on the external glass. More in detail, the innovative window is composed by a vacuum glass with high thermal performance (8.2 mm), an air gap of 16 mm and low-emissive glass (5.0 mm) with a smart film adhesive (0.4 mm). In this case, the value of thermal transmittance is 0.53 W/m^2K and the solar factor is equal to 0.79 if clear and of 0.06 if the film is activated. This window has a wooden frame with a thermal transmittance equal to 1.15 W/m^{2}K: the thermal transmittance U_w of the whole window is equal to 0.85 W/m^{2}K.

	s [m]	λ [W/(mK)]	ρ [kg/m³]	c [J/(kgK)]
External walls s_{tot} = 0.337 m				
Internal plaster	0.01	0.91	1200	1960
Clay panel	0.022	0.353	1600	1100
Wood fiber thermal insulation	0.05	0.038	55	2100
X-Lam	0.095	0.13	500	1600
Wood fiber thermal insulation	0.14	0.04	130	2100
External plaster	0.02	0.90	1000	1800
Thermal transmittance = 0.172 W/m²K				
Internal walls s_{tot} = 0.259 m				
Internal plaster	0.01	0.91	1200	1960
Clay panel	0.022	0.353	1600	1100
Air	0.05	R = 0.11 (m²K) /W		
X-Lam	0.095	0.13	500	1600
Air	0.05	R = 0.11 (m²K) /W		
Clay panel	0.022	0.353	1600	1100
Internal plaster	0.01	0.91	1200	1960
Thermal transmittance = 0.789 W/m²K				
Roof covering s_{tot} = 0.498 m				
Bituminous membrane	0.008	0.13	800	2100
Leveling screen	0.06	0.129	380	1000
Insulating layer	0.10	0.041	2100	145
Vapor barrier	0.0001	0.400	427	1800
X-Lam	0.12	0.130	500	1800
Internal plaster	0.01	0.91	1200	1960
Air	0.19	R = 0.17 (m²K) /W		
Plasterboard	0.01	0.072	480	1380
Thermal transmittance = 0.229 W/m²K				
Floor s_{tot} = 1.35 m				
Parquet	0.02	0.10	450	1700
Leveling screen	0.05	0.12	400	1000
Insulating XPS	0.08	0.035	30	920
Screed	0.05	1.6	2400	1000
Air igloo	0.55	R = 0.46 (m²K) /W		
Concrete platform	0.30	1.91	2400	1000
Concrete	0.30	1.4	2000	1000
Thermal transmittance = 0.252 W/m²K				

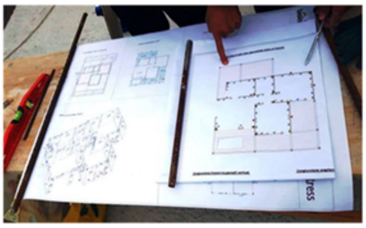


Figure 9: thermo-physical characteristics of the building envelope of BNZEB.

3.1.4 HVAC system and renewable sources

The building has been designed as an “all-electric net zero-energy house” where no fossil fuels are used, nor for the space heating nor for other energy uses. Indeed, for what concerns the indoor microclimatic control, both for heating and cooling needs, an aerothermal heat pump and a backup DX multi-split are installed.
More in detail, the air-to-air heat pump provides mechanical ventilation, with warm air in winter and cold air in summer. The same system also provides dehumidification in the summer and it is equipped with an internal filter to purify the air before supplying it into the internal rooms. The system is equipped with an active thermo-dynamic heat recovery and it means that, in order to increase the coefficient of performance of the system, part of the exhaust air interacts with the outdoor heat exchanger (evaporator in winter, condenser in summer), so that the thermal level of the ambient air is more suitable to discharge or supply energy. Another part of return air is recirculated, mixed to primary (outdoor) air, filtered again and handled in the package heat pump before the new supply into the rooms. The same compact system provides also the domestic hot water, indeed this is equipped with two thermal storage tanks for a total volume of 180 litres. Some technical features regarding the heat pump are shown in Figure 10. This compact system has a maximum heat capacity of 3.18 kW and maximum cooling capacity of 2.14 kW. These capabilities, clearly, are quite low, so that the system is essentially developed for small nZEB and high-efficient single-family buildings. Then, in order to have a backup plant and to have a higher thermal power capability in critical outdoor conditions (in winter) or high occupancy (in summer), an additional heating/cooling system is installed, based on the direct expansion technology (DX multi-split system). This technology is composed by one outdoor unit and two indoor terminals, hidden in channels, dedicated to living room and kitchen (one unit) and to the bedrooms (the second one). The overall DX system has a heating capacity of 9.6 kW and a cooling capacity of 8.0 kW.

In order to improve the overall HVAC performance, the commercial layout of the system has been modified by adding a pre-treatment section of the outdoor ventilation air. In detail, an additional heat exchanger may pre-cool the ventilation air during the summer period and pre-heat it during the winter, before the intervention of the aerothermal heat pump. The ventilation air is taken from the external environment and, after a first handling in an active electrostatic filter, it crosses a water-to-air heat exchanger linked alternately to solar collectors or to the horizontal ground-to-water heat exchanger. An overall scheme of the HVAC systems is reported in the Figure 11. The geothermal heat exchangers (water pipes) are positioned at a depth of 2 m, with a total linear length of 100 m. Conversely, the solar collector has an area equal to 2.16 m^2 and it is deputed to both preheat the ventilation air in winter and to produce domestic hot water (DHW), also by means a thermal storage tank with a net volumetric capacity of 196 l.

Regarding the artificial lighting, the building is equipped with fully dimmable LED lamps, with a specific electric absorbed power ranging from 1 to 39 W/lamp, a lighting efficiency in the range 40 – 82 lumen/watt, and with variable colour temperature. These systems are designed to recreate multiple lighting scenes of the indoor environment, and in order to adapt the artificial light scenes to the external natural lighting conditions. Moreover, these are equipped with a presence sensor for automatic switching on and off. Some features, both for internal and external lighting systems, are shown in Figure 10.
Finally, the types of domestic appliances are typical for a new house of this size with the highest energy label. Electric energy is used also for the kitchen (induction burners and an electric oven).

In addition to the geothermal sources and to solar thermal system, the building is equipped with a photovoltaic system, composed of 16 monocrystalline silicon panels with an area about 1.63 m^2/each and a peak power of 330 Wp each one. The PV modules are oriented to the south (i.e., azimuth angle of 0°), with a tilt angle of 5° to achieve the best trade-off among installable number and power, minimization of mutual shadows, energy production and visual impact. The modules are divided into three strings, one from 6 panels and two from 5 panels, the last two are then connected in parallel so that two strings arrive at the inverter. Moreover, there is a lithium battery for the electricity storage, so that, when converted and not directly used by the house, it can be stored for the next hours. In general, the building can supply, when the batteries are full, the surplus energy to other edifices of the universities, so that all energy converted will be used in buildings of the same administration, without a connection to the public suppliers. This maximize the PV profitability.
Then the building is equipped with different energy conversion systems from renewable sources, all those achievable on-site, and thus solar thermal, solar photovoltaics,

aerothermal and geothermal. Only hydropower and wind are not exploited, being not available nor suitable in that place. Some technical data about the components of the HVAC system, renewable energy systems and lighting system are shown in Figure 10.

Device type	Manufacturer	Model	Main characteristics	
Aerothermal Heat Pump	CLIVET	Elfopack	Maximun heat capacity = 3.18 kW Maximun cooling capacity = 2.14 kW 2 DHW tank. total volume = 180 l electrolytic filter	
Multiplit	DAIKIN	4MDXM80 and two of FDXMF35	External: heating capacity = 9.6 kW cooling capacity = 8.0 kW internal: power = 3.5 kW	
Solar thermal collector	SUNERG	HV12	U-pipe tecnology Vacum collector Net surface area = 2.2 m^2	
DHW tank	SUNERG	HB200	Net volume = 196 l two heating coils	
geothermal heat exchanger	REHAU	multilayer pipes	Total lenght of coils = 100 m Depth of coils = 2m	
Active carbon filter	ASPRA S INDUCT	AIRQM VFA	Power = 14W Efficiency = 99%	
Photovoltaic collectors	BENQ	SunForte PM096B00	Nominal power = 330W Efficiency = 20.3% 96 cells	
Battery	LG	RESU6.5	Litium type Total energy = 6.5 kWh Usable energy = 5.9 kWh Max power = 4.2 W	
Inverter	SOLAX	SK-TL(SU)5000	Max power in input = 5000W Max. efficiency = 97.6%	
External light	Disano	1576 Square	LED 32 W dir. 2650lm - 4000K; ind. 270lm– 4000K	
		1210 BOX LED	Power = 1W 4000K; 45 lm	
Internal light	Philips	Fair Hue White ambiance	39 W 3000 lm adjustable intensity 25000 h	
		Gainsbro applique whit LED lamp Hue white and color ambiance kit E27	10W 25000 ore 345-550 lm – 2000/6500 K 80lm/W a 4000K	

Figure 10: Main features of installed device in the BNZE building.

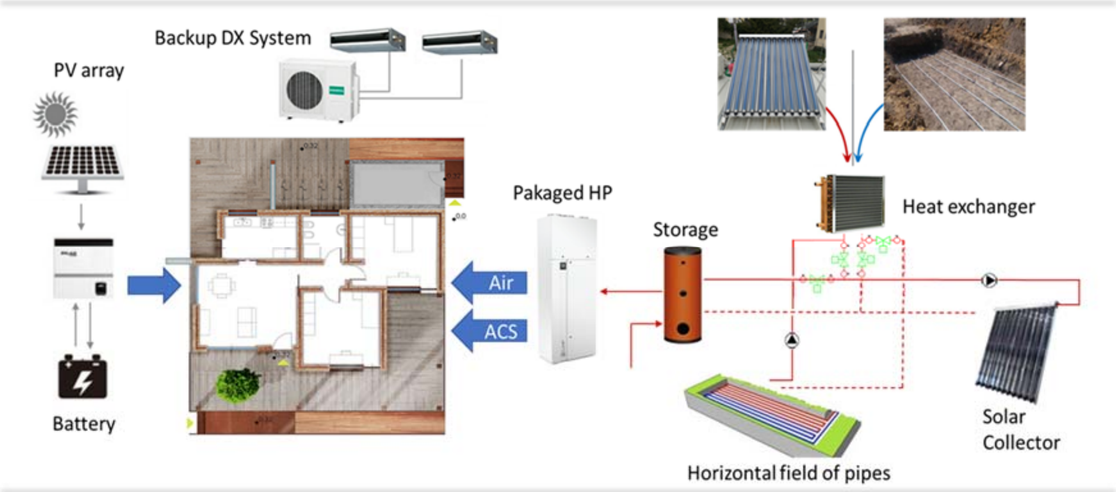


Figure 11: Overall scheme of plan systems.

3.1.5 Smart home automation

The building has been designed to be a high energy efficiency house with a high level of automation and controls but also to be a research laboratory suitable for testing residential energy demands, conversion of energy from renewable sources, quality of indoor environmental and other issues of sustainable performances, measured according to a realistic and real life. According to these objectives, the house has been equipped with many tools, sensors, and actuators, both fixed and stand-alone equipment, as:

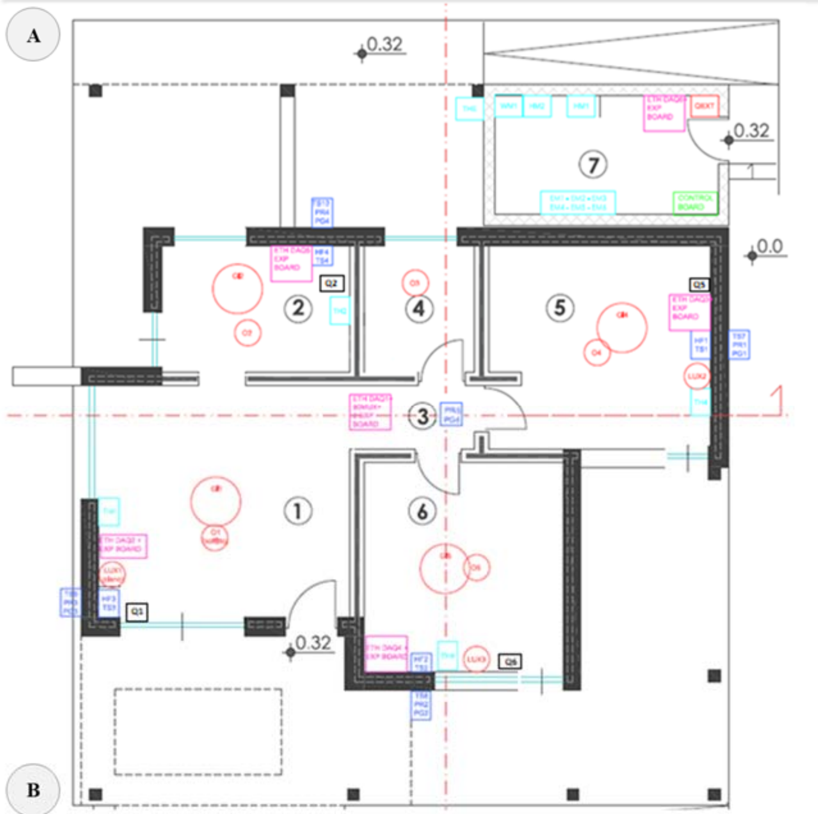
- meters for electric energy (general, lighting, plugs, technical room, HVAC systems and equipment, pumps and fans, electricity generation form PV system);
- thermal energy from solar collectors and thermal energy recovered (from) or supplied (into) by means of geothermal boreholes;
- indoor air quality, in terms of CO_2 and VOC concentration in each room;
- thermo-hygrometric indoor conditions in terms of air temperature and relative humidity in each room;
- surface temperature for one wall for each exposition (i.e., north, south, east and west) on the inner and outer sides;
- lighting level in each room and sensors of presence of each room;
- volume and mass flow rate of domestic hot water and cold water from the city pipes;

- outdoor climate variables, and thus wind speed and direction, air temperature and relative humidity, precipitations, outdoor air quality, longwave (infrared) radiation and solar radiation on horizontal plate and on vertical one for each exposition.

As aforementioned, there is installed a window that can both varies its optical characteristics in relation to the incident solar radiation, and can open automatically to allow natural ventilation, if external conditions make it convenient; this operating mode is based on monitored parameters of the air quality (mainly CO_2 and VOC concentration inside and outside the building). The sensor and electrical controls that allow the automated operation of this component are installed inside the frame. Moreover, also a few stand-alone sensors were installed, among which a sensor for wet bulb temperature, some heat flow meters (one for each orientation to be applied easily to walls), measurement of mean radiant temperature and operative one.

The structure of the monitoring system consists of two macro-sections defined: *BMS*, consisting of the entire network of sensors and actuators for monitoring and control of the entire building; and *Lab-Home*, consisting of high-resolution monitoring instrumentation, used mostly for study/research purposes. At implementation level, the subsystems are managed by a central system through an Ethernet interface. Then, the data measured are transmitted to a unique remote analysis system, placed inside the technical room, which can be also accessed from remote control. In addition, different levels of system access have been established, based on the type of user: system administrators, researchers, occupants, other authorized users. Moreover, through a tablet app, it is also possible to have a smart and remote heating and cooling management, as well as the possibility to act on artificial lighting and remotely control the energy parameters of the house. In addition, a smartphone app is available for connecting, according to the different kind of allowed authorizations, to the real-time data and to manage the building.

The technical specifications of all devices installed into the house (both embedded that stand alone) are summarized in Figure 12, together with indications of their position with respect to the dwelling. Moreover, during the in-situ investigations about the building envelope features (section 3.3.1), also an IR-thermography FLIR p660 and a wireless Optivelox Thermozig heat flow meter has been used, respectively for the IR-images recorder and for the in-situ measures of thermal transmittance.



n°	Instruments	Type	Model
6	Meters for electric energy	Energy meter EM	Schneider electric A9MEM3250
2	Meters from solar collectors and from geothermal source	Thermal energy meters HM	Multical 403+Modbus RTU module
1	Domestic hot water volume and energy demand	Consumption meter WM	Itron Echodis
1	External temperature	Temperature sensor Pt1000 THE	Thermasgard ATM2 (s+s regeltechnik)
1	-Wind speed and direction -temperature -relative humidity -barometric pressure -global solar radiation	-Ultrasound sensor -Pt100 for air temperature -Capacitive for humidity -Piezoresistive for pressure -Thermopile for radiation	Delta ohm HD 52.3DP147
1	Rain gauge	Cylindrical body of 400 cm^3	Delta ohm HD2013UA
1	External concentration of CO_2 and VOC (air ducts)	Infrared absorption measurement (NDIR) QEXT	Siemens QPM2102
4	External light	Photodiode Si LUX	Delta ohm HD2021T
5	Air temperature and relative humidity	RHR room humidity and temperature sensors TH	Syxthsense RHR-MOD
5	Presence and light level	Monition and light sensor O	Stelix domat dip2000
4	Concentration of CO_2 and VOC	Infrared absorption measurement (NDIR) Q	Siemens QPA2002
10	Surface temperature	Thermistor sensor TS	Omega SA2F-TH-44033-80
5	Solar radiation	Pyranometer PR	Delta ohm LP PYRA 3 AV
5	Longwave infrared radiation and sky and equivalent ground temperature	Pyrgeometer Temperature sensor Pt100 PG	Hukseflux IR20
4	Heat flux sensor	Thermopile HF	Hukseflux HFP01
1	Globe thermometer	Pt100 GT	Delta ohm TP876.1
4	Air temperature and relative humidity	hygrometric and NTC sensors	Test 177-H1

Figure 12: Technical specification of installed instruments and location of the indoor sensors.

3.1.6 Performance according to the Italian law

The nZEB standard according to Italian legislation [19] can be assigned when the building reach the best possible labelling for its energy performance and if simultaneously the energy needs for domestic hot water is covered for at least 50% by in-situ renewable energetic sources and, analogously, renewable sources cover at least the 50% of the sum of the building energy needs (heating, cooling, dhw).
The energy performance is calculated by means of “non-renewable primary energy need index” ($EP_{gl,nren}$) that quantifies the amount of energy actually consumed or estimated to meet the different needs associated with a standardized use of the building, which may include, inter alias, heating, hot water heating, cooling and ventilation (for residential building). The energy label classifies the energy demands on a scale from A4 to G, defined starting by a specific Reference Building [19] defined according to the procedure of the European Delegated Regulation n° 244/2012 [95]. More in deep, the reference building is an ideal version of building, geometrically identical to the original one, placed in the same geographical coordinates and with the same orientation. But the reference building’s energy needs are calculated by applying standard boundary conditions and defined characteristics for the building, according to the climate zone of the project, comprehensive of structural and geometrical thermal bridges. This procedure is in agreement with the European Standard 15217 [142] and EN ISO 52003-1 [143].
For the case study, this analysis has been performed by means of a software accredited by the Italian Thermo Technical Committee and thus TERMUS [144]. The main outcomes are reported in Figure 13.
The admitted maximum value of the $EP_{gl,nren}$, for the reference buildings (that is representative of the real building use and geographic location), is equal to 162.4 kWh/(m^2 year) that means Class B tending to A1. Actually, the building has an $EP_{gl,nren}$ ≈ 9.37 kWh/(m^2 year), with a consequent achieved energy Class “A4”.

Moreover, by considering the heating performance index $EP_{H,nd}$ (energy need, that takes into account only the energy behavior of the building envelope), the value for the building is 29.3 kWh/(m^2 year), and thus lower compared with the reference. Regarding the summer performances, the global periodic thermal transmittance is 0.0235 W/m^2K and the equivalent solar area A_{sol}/A_{sup} is equal to 0.02, therefore also these parameters are abundantly better than the reference building parameters. The results show that the technologies adopted for the opaque and transparent envelopes allow high performance both in winter and summer seasons (as indicated in the left side of the Figure 13 with two smiling faces.

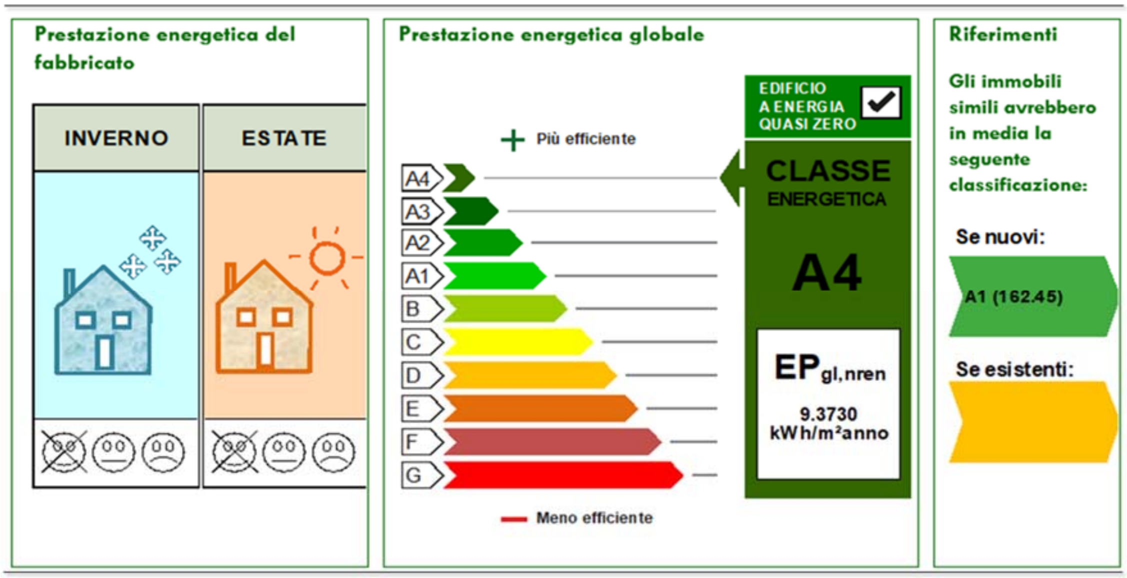


Figure 13: Energy classification of the BNZEB building according to the Italian law.

Moreover, as benchmark, the values imposed by Italian normative [19] for typical Mediterranean zone (Italian Climatic Zone "C") can be considered. As regards, the reference insulation level for new buildings, the thermal transmittance of the wall must be lower than 0.34 W/m^{2}K, for the roof and the slab on the ground the values are respectively 0.33 W/m^{2}K and 0.38 W/m^{2}K otherwise for the windows the thermal transmittance has to be lower than 2.2 W/m^{2}K. Globally the thermal characteristics of the building envelope are much better than the thresholds established by the Italian laws. In any case, during research studies, temperature sensors (already installed almost everywhere) and measurement of thermal flows will confirm, during the building life, the effect of aging and weather phenomena on the values of thermal transmittance for each building element.

According to the standard ISO 13786 [145], the parameters related to the dynamic thermal behavior of a building components can be calculated. These are the *decrement factor* (f) that qualifies the reduction of thermal wave amplitude from outside to inside building; the *time-shift of decrement factor* (Δt_f) thus the period of time between the maximum amplitude of external temperature (cause) end the maximum amplitude of inner heat flux (effect); the internal *areal heat capacity* (κ) that indicates the capacity of store thermal energy on an internal building element and the *periodic thermal transmittance* (Y_{IE}) that is a complex quantity which characterizes a building component incorporating the concept of thermal transmittance, time shift and decrement factor. More in detail, for the walls Y_{IE} is 0.01 W/m^{2}K with surface mass (M_s) of 136 kg/m^2 and κ equals to 50 kJ/m^2 K instead for the roof Y_{IE} is 0.04 W/m^{2}K, M_s is 300 kg/m^2 and κ is 31 kJ/m^2 K.

Considering the Italian benchmark in matter of thermal inertia [145], for the vertical opaque envelope, on all sides except north, north-east and north-west, M_s has to be higher than 230 kg/m^2 and/or Y_{IE} must be lower than 0.10 W/m^{2}K. Moreover, for horizontal envelope, Y_{IE} must be lower than 0.18 W/m^{2}K. It is clear that the use of wood and high-density thermal insulation allows optimal values of periodic thermal transmittance. Indeed, also with a lightweight structure, a very low decrement factor (0.06 for wall and 0.15 for roof) and a long time-lag effect (around 17 hours for wall and 14 hours for roof) are achieved, and these allow a high liveability and comfort in the warm season. Indeed, low values of the decrement factor combined with high values of internal areal heat capacity, and high values in the time shift, designate an optimal envelope configuration that can decrease the effects of external thermal loads during summertime.

3.2 BUILDING SIMULATION MODEL

By using all information about building's geometry, envelope, plant system features, and some results from in-field monitoring, the numerical model of the building has been created and calibrated, according to the methodology proposed by M&G guidelines [146].

DesignBuilder [67] was used as primary modelling tool. It offers a rapid model building OpenGL interface combined with a "full-featured user interface to EnergyPlus HVAC". A key feature of DesignBuilder is its integration with the EnergyPlus [65] calculation engine; it also offers an integrated CFD package. Moreover, DesignBuilder allows the modeler to use the same building also for the CFD study, and thus a coupled investigation (BES and CFD) can be performed. The software automatically generates a finite volume mesh to fit the objects within the selected study domain based on user-preferred grid spacing.

In particular, the numerical model of the BNZEB building, suitable for performing dynamic simulation, is used to predict detailed information of the airflow and temperature distribution inside the building as well as the distribution of some comfort indices (by CFD model). Moreover, it is used also for comparing the BNZEB to other buildings, in order to discover how much its energy performance are better compared to standard building and to evaluate the replicability of the BNZEB design in several cities across Europe (by BES model).

3.2.1 Simulation set up

The model has been developed in detail both from the points of views of the architectural and technical systems. Indeed, all information about building's geometry, envelope and plant system features have been included in the numerical model. Also particularized information concerning thermal envelope and windows, lighting systems and air conditioning system, have been included, by including all features of fans and pumps too. Moreover, renewable energy source systems have been also appropriately modelled, as well as the detailed operational schedules of devices. Figure 14 shows the external view of the building model created with DesignBuilder.

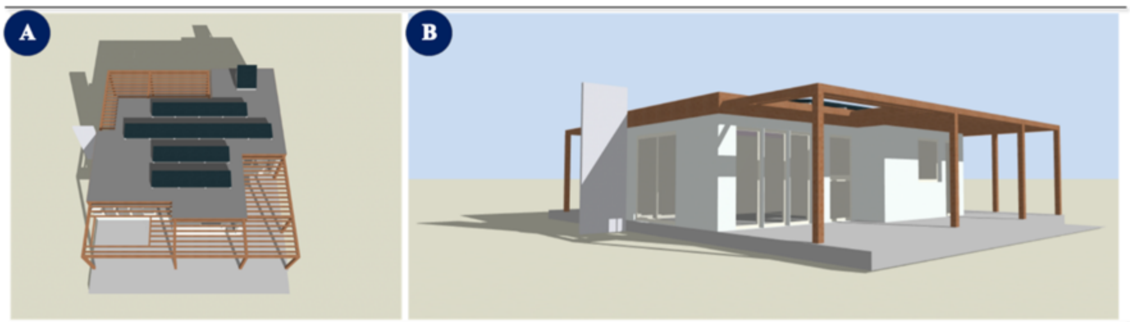


Figure 14: Rendering of simulation model: (a) view from above; (b) south-west view.

EnergyPlus allows to use customized weather data, so that when the model has been simulated, the climatic data of the city of Benevento, gathered from another University test building [147] placed at less than 1 km away from the BNZEB building, have been implemented. In particular, a dedicated ".*EPW*" weather file has been created and imported into the EP launch of EnergyPlus. Finally, starting from real monitored data, collected during the monitoring campaigns performed in a "real use" context, detailed schedules about the real operation and uses of plant systems and installed devices have been created and implemented into the numerical model.

In the first part of PhD activity, the numerical model of the building was created by DesignBuilder v 4.6, and this first version of BNZEB building's model didn't include the aeraulic heat pump, but only the DX multi-split was included as HVAC system. Following the model has been updated, using DesignBuilder interface v 6.0, to including also the aeraulic heat pump and the air pre-treatment section. Obviously, shielding devices, renewable source systems, the weather file based on real monitored data, and the operational schedules have been always included into the model from its first version.

In detail, while the weather data are constantly monitored by the weather station the outside temperature is constantly measured also at the inlet of the air system and it has been used as input for the HVAC system. Following the technical datasheets and them properties, each installed device has been modelled starting from a component derived from the DesignBuilder library. The DX-system has been modelled as a "VRF system", composed by one outdoor unit and two indoor units; it includes a variable speed compression system and a load-based control. In the same way the aeraulic heat pump has been modelled as an "unitary air to air heat pump", with a heat recovery system, extract fan and a pre-heat and pre-cool coils to model the interaction with geothermal probe (air pre-treatment section). In the main HVAC sections the measured values of air flows and temperatures have been included in the numerical model. However, due to the impossibility to model the internal hot storage of the air-to-air heat pump in DesignBuilder, only the contribution of the solar thermal system has been modelled to satisfy the domestic hot water needs.

Finally, as shown in the following sub-sections, the model has been always calibrated basing on detailed hourly monitored data and according to the specific analysis purposes.

On other side, concerned the CFD simulations, the well-known k- ε turbulence model has been adopted in combination with the upwind discretization scheme. This model involves replacing the instantaneous velocity in the Navier-Stokes and energy equations with a mean and fluctuating component; and the calculation process involves replacing the defining set of partial differential equation with a set of finite difference equations. Moreover, the discretization approach will be used is the finite volume method: the set of partial differential equations (PDEs) are converted into a set of simultaneous algebraic equations and the space domain is divided into a set of non-overlapping adjoining. The grid lines, which divided the space domain under investigation in the finite volume grid, are parallel to the major axes with a spacing of 0.3m. Moreover, to avoid the creation of cells with a high aspect ratio that can lead to instability in the equation solver, a grid line merge tolerance of 0.03 m has been included into the CFD model. In this way the grid lines that are very close together can be merged.

3.2.2 Model calibration process

The calibration process is an iterative process of comparison between the outputs of a simulation and those derived from measured data, determining the deviation of the results and the degree of uncertainty. Generally, in the scientific literature, this process starts from the setup of the numerical model, created as accurately as possible by assigning all the information about geometry, thermal properties of the construction, real weather data, properties and control logic of the HVAC and electrical systems of the building and by setting activity and schedules for equipment and occupation. Then, the baseline model is adopted in a trial-and-error approach to manually adapt the variables which results not have a satisfactory correspondence between the simulated results and the real measured ones. In this way, possible modelling errors are evidenced, as well as precautions to be put in place to obtain a model that represents as well as possible the actual behaviour of the real system.

Then, after a comparison between the results of simulation and the monitoring ones, an accurate calibration of the building model is allowed and, in this way, it is understandable how the model well-represents the behaviour of the real building. There are several sources for correct calibration of the models, through coded procedures and protocols. In particular, for this study, the calibration of the simulation model is performed according to the M&V Guidelines [146]. Here, the comparison requires the verification of some statistical indices such as the Mean Bias Error (MBE), given in Equation 1, and the Coefficient of Variation of Root Mean Square Error (CvRMSE) as shown in Equation 2-4.

$$MBE = \frac{\sum_p (S - M)_{daily}}{\sum_p M_{daily}} \tag{1}$$

$$RMSE = \sqrt{\sum \frac{{(S-M)_{daily}}^2}{N_{interval}}} \tag{2}$$

$$A_{hourly} = \frac{\sum_p M_{interval}}{N_{interval}} \tag{3}$$

$$CvRMSE\ (\%) = \frac{RMSE_{period}}{A_{period}} * 100 \tag{4}$$

where S is simulated data, M is measured data and N is the number or sampling.

Obviously, the more the value of these indicators are close to zero, the better is the quality and the predictive capacity of the numerical model. In particular, according to the M&V Guidelines, models can be considered calibrated, and then well-representing the current energy demands of the real buildings, if these produce MBE ≤ 10% and CvRMSE ≤ 30% when the hourly data are considered; for monthly data, the requirement are respectively ≤ 5% and ≤ 10%. The same indices, in our study, have been used for both energy meters and microclimatic parameters.

The first version of BNZEB numerical model was calibrated on the basis of monitored data collected from 20th to 30th July 2018, when the air conditioning system was turned on in cooling mode. More in detail, the multi-split system runs, while the aeraulic package heat pump for ventilation was turned off. Indeed, during the first performed analysis (reported in the section 3.6), the test would verify the indoor conditions and loads and not the HVAC system operations. Moreover, it should be noted that, inside the building, at this stage, there are no loads nor occupants.

Table 4 shows the hourly-based evaluated indices for the electricity demand for building microclimatic control (E_el), the generation from PV system (E_gen) and finally the air temperature (T_1) and relative humidity (HR_1) monitored in the living room (room 1 in Figure12), in the bedroom with south orientation (T_6 and HR_6 for room 6 in Figure 12) and in the bedroom with north orientation (T_5 and HR_5 for room 5 in Figure 12). As it can be inferred by Table 3, the results are always within the admitted tolerances, and thus the energy model can be considered well-calibrated and well-representative of the real building behaviour.

Table 3: Evaluation of calibration indexes.

	E_el	E_gen	T_1	HR_1	T_5	HR_5	T_6	HR_6
MBE %	-2.03	-3.60	0.65	-1.69	4.21	3.11	2.31	-0.78
CV(RMSE) %	29.6	29.5	1.58	8.34	9.81	11.2	2.56	6.77

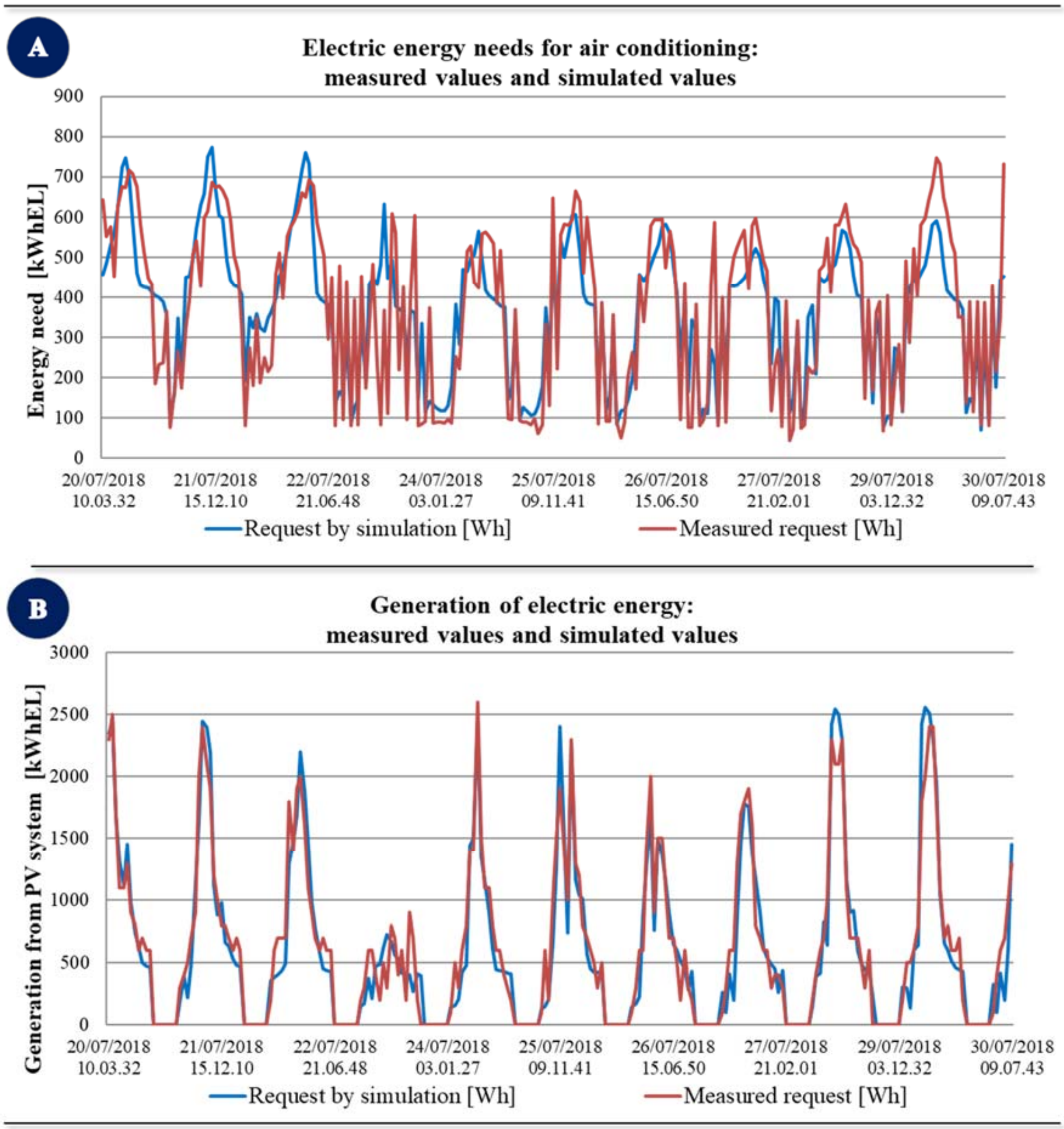


Figure 15: Comparison between measured values and simulated values: (a) energy demand for building's climatization and (b) energy generation from PV system.

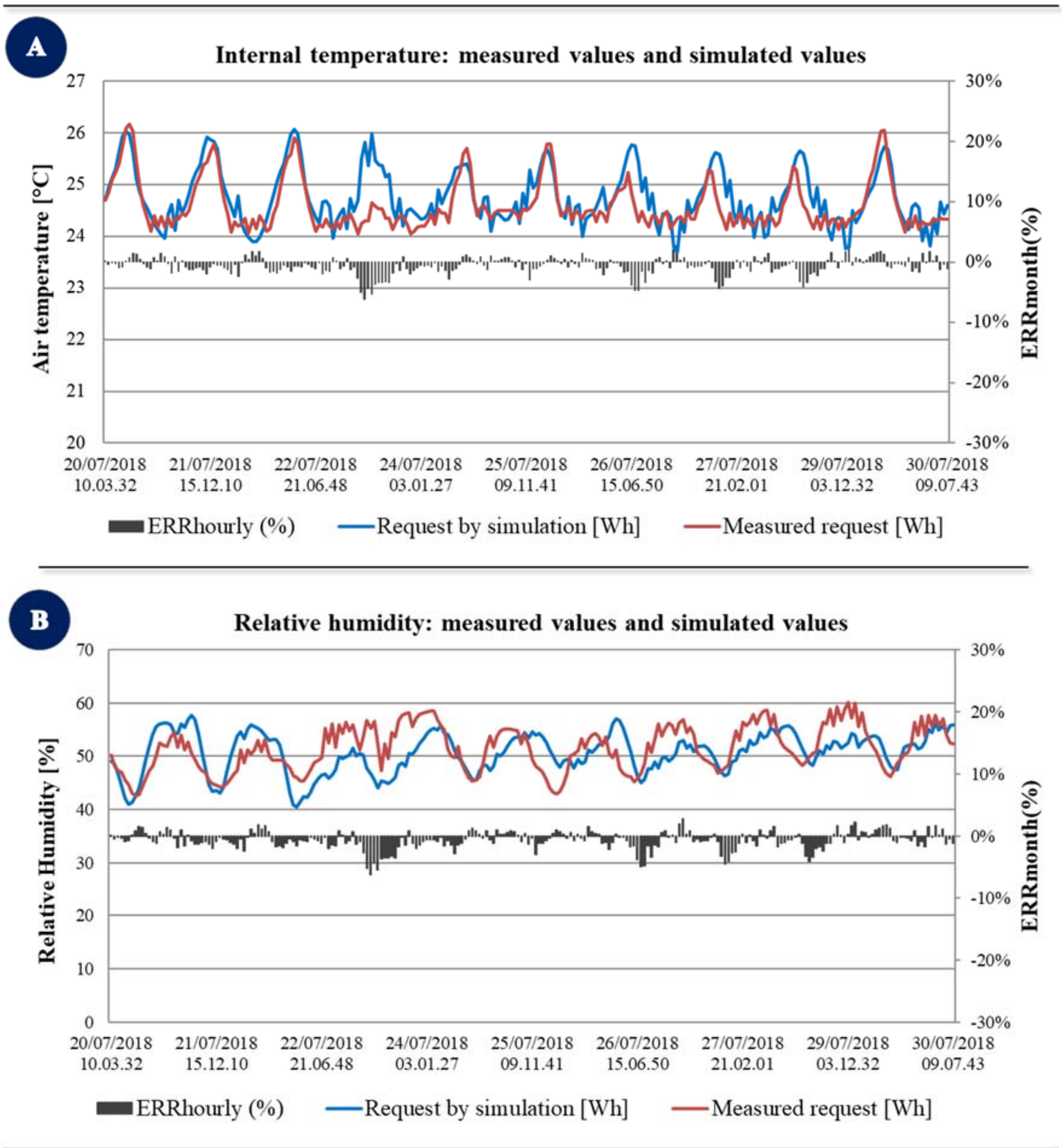


Figure 16: Comparison between measured values and simulated values: (a) air temperature inside the living room and (b) relative humidity inside the living room.

Moreover, in Figure 15, the trend of measured and simulated values of energy request for building's cooling and generation from PV system are compared during the period from 20th to 30th July 2018. Figure 16 shows, during the same period, the comparison of the simulated and measured values for indoor air temperature and relative humidity with also the indication of the error in the hourly values (ERR_{hourly}) in the living room. It is representative of the domestic space and it is also the most critical in the summer because the room is south oriented, and it has the highest glazed surface.

According to proposed results, the energy model can be considered well-calibrated and then it well-represents the behaviour of real building in terms of energy demand and in terms of energy conversion from PV system and also regarding the indoor air conditions. In general, once a model has been calibrated, it can be used to determine energy performance of the building, through a numerical simulation, also under different conditions of use or climate. Here, the model just calibrated has been used to compare the energy performance of BNZEB with other buildings and to evaluate the replicability of its design in Mediterranean cities, as it will be shown in the section 3.6.

Furthermore, in order to improve the reliability of the adopted model and to evaluate, by the DesignBuilder v.6.0 CFD tool, the indoor space distribution of air temperature and some comfort indices inside the building during the spring (section 3.4.3) and summer period (section 3.5.3), and then the overall HVAC system operations, the numerical model of the building has been updated to include all the installed systems and thus the modelling of all possible air conditioning configurations has been performed. In this second step, the comparison between measured values and simulated ones and then the calibration indices evaluation concerned only the indoor air temperature and relative humidity inside the building. In other words, the model's calibration has been verified only for the variables that will be used and evaluated during the CFD investigations, according to the purpose of the analysis. In particular, the CFD analysis has been performed during the spring and summer periods because, due to the high heat gain through highest glazed surfaces of the building, these two seasons could be the most critical in terms of indoor comfort conditions and air temperature difference in the indoor space.

In particular, in the Figure 17, the comparison between the monitored hourly indoor air temperature (in the living room) and the one given by the simulated model is reported, with also indication of hourly gap. The data shown refer to the period from 11^{th} to 18^{th} May 2019 during which the HVAC system is set in ventilation mode (springtime). In particular, the multi-split system is turned off and the aeraulic heat pump is set in mere ventilation mode, while the air pre-treatment heat exchanger interacts with the earth-water exchanger. Then, also in this case, it is found that the simulated and measured values are comparable, and that the CV(RMSE) index is 4.05% while the MDB is -0.14%. The numerical model can be still considered well calibrated concerning the indoor thermo-hygrometric variables and then it is still strongly in agreement with the behaviour of the real building also for the springtime.

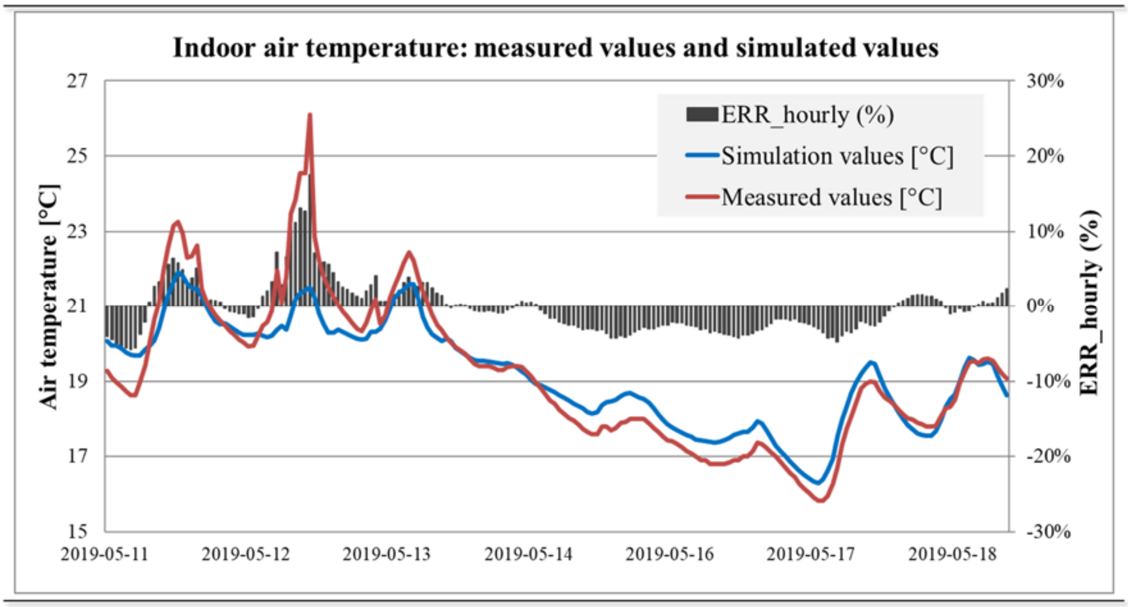


Figure 17: Calibration model results: indoor air temperature.

Finally, also for a summertime analysis (July 2019), it has been verified if the BNZEB building's model can be considered calibrated for different HVAC possible configurations. Indeed, the calibration verification was performed on the basis of a summertime monitoring campaign, during which four different configuration of HVAC system were tested in the real-scale BNZEB. These are based on the use of the aeraulic heat pump or the DX multi-split system (alternatively) to provide the cooling needs and with or without the availability of pre-cooling system, as reported in the Table 4, with also indication of periods of tests. These have been implemented in the numerical model of the building, and the energy simulation performed in all different considered configurations gave back the indoor air temperature and relative humidity data in all rooms of the building. Here, the outcomes for one bedroom were analysed (room 5 in Figure 12) and these data were compared to the measured ones. Table 4 shows also the evaluated indices for air temperature and relative humidity monitored in the bedroom 5, and the results are always within the admitted tolerances. Thus, the energy model can be considered well-calibrated and well-representative of the real thermo-hygrometric conditions inside the building in all possible HVAC configurations.

Table 4: HVAC system configurations and corresponding calibration indices for one building room.

	HVAC system		MBE (%)	CvRMSE (%)	MBE (%)	CvRMSE (%)	Evaluation period
	Cooling system	Pre-cooling activation	Air temperature		Relative humidity		
C1	Heat pump	Off	-1,55	3,11	5,94	11,56	8th – 12th July
C2	Heat pump	On	1,86	-1,91	-7,79	10,74	15th – 18th July
C3	DX system	On	-3,66	-1,87	-6,38	8,95	22nd - 25th July
C4	DX system	Off	3,04	3,08	0,23	5,91	27th – 30th July

3.3 WINTER PERFORMANCE: BUILDING ENVELOPE INVESTIGATION AND NEARLY ZERO ENERGY TARGET IN COLD DAYS

This chapter is aimed to discuss the real energy performance of the BNZEB during the winter period, that could be critical due the greater uncertainty of renewable sources availability. In detail, both the building envelope characteristics and the overall energy consumption have been verified under a real use environment, when the building is also occupied by some students. Moreover, it has been evaluated if the comfort conditions inside the building are guaranteed together with the achievement of the "nearly zero energy" target; and how the changing of HVAC setting parameters affect the indoor conditions and the building energy requests.

First of all, in order to verify the envelope characteristics of the test building, some in situ measurements (i.e., infrared thermography and measures of thermal transmittance) have been performed to compare the current envelope performances with the expected one derived from standard calculation procedures (sub-section 3.3.1).

Then, the results of an experimental campaign about energy consumption for heating, ventilation, lighting, electric loads, water use will be discussed, as well as the monitored microclimate variable under real operational conditions. The energy balance with hourly time step will be proposed to verify the effectiveness of selected solution to reach the "nearly zero energy" objective during the winter, and to evaluate the incidence of photovoltaic production. In particular, the discussion about the load matching and interaction of the building with the electric grid will be performed to evaluate the feasibility of sharing the not self-consumed energy to the close buildings (in a perspective of sharing of resources and small energy community).

With this purpose, specific indices based on monitored data at hourly time step will be introduced and evaluated in order to quantify the energy produced and not self-consumed with the perspective of maximize the self-consumption (sub-section 3.3.2.2). Meanwhile, in order to proceed to the assessment of indoor comfort conditions in terms of air temperature and relative humidity, as well as for what concerns the air CO_2 concentration, the recommended limits proposed by the EN 15251 standard [88] have been considered (sub-section 3.2.2.1).

Finally, the applicability of adaptive comfort approach for the management of the heating system, in order to reduce the building energy requirements, will be investigated, and its effect on building energy performance will be evaluated (sub-section 3.2.3).

3.3.1 Results concerning the building envelope analysis

Thermal transmittance and thermal inertia are practically the most important factors that affect the building envelope behaviour, especially during the winter and summer period respectively. The first parameter determines the building energy losses while the thermal inertia affects the way in which the building reacts to changes in external and internal conditions and thus it characterizes the dynamic performance of the whole building.

In order to identify any criticality and to evaluate the performance of the envelope, during the winters 2017-2018 and 2018-2019, some in-situ measurements have been performed. In detail, some IR-thermographs on external walls have been performed according to EN 13187 [145], while in-situ measurements of thermal transmittance have been performed according to EN ISO 9869 [81] for some external walls of the building and for one window.

More in detail, the IR-thermography allows to evaluate presence of wrong installation or damaged thermal insulation in walls and roof, and the eventual presence of thermal bridges or air leakages, but it is used also to identify a proper position of the sensors for the in-situ measurements of thermal transmittance. Figure 18 shows some recent IR-images recorded on 16th February 2019, by means of an infrared camera: FLIR p660 with a nominal accuracy of ±2%.

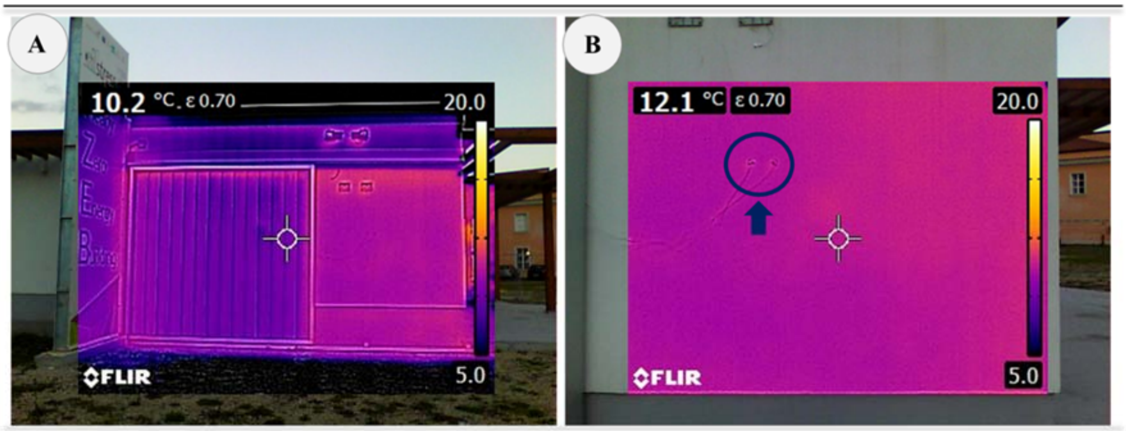


Figure 18: Outdoor thermography on west exposition: (a) whole west-wall of living room and (b) indication about proper sensors position.

The pictures show that the outside surface temperature of building walls is substantially uniform, and it is possible to see that there are not issues due to thermal bridges. This is a good outcome because it confirms the validity of the adopted design solution. Furthermore, also the inspection around the windows' frame has not evidenced air leakages or infiltration phenomena.

Meanwhile, to measure the thermal transmittance, a wireless Optivelox Thermozig heat flow meter has been used. This is made by a heat sensor with an operative range between ±300 W/m^2 and accuracy of ±5% (to 20°C), while the surface temperature has a measurement range between -50 and 125°C, and an accuracy of ± (0.10+0.0017|t|)°C. The measures of thermal transmittance have involved all walls and one window (north-exposure). During the monitoring periods, the heating system has been switched on, with a set-point temperature of 20°C, and the temperature difference between indoor and outdoor was always higher than 10°C (suitable threshold conditions for a fast convergence of the measurements). Figure 19 shows the trends of measured thermal transmittance of the window and of one examined wall (west-exposure).

In particular, the measured value of thermal transmittance results equal to 0.19 W/m^{2}K for a wall on the east side (measured performed from 11th to 18th December 2018) and for west wall (performed from 17th to 22nd January 2019). While a measured value equal to 0.17 W/m^{2}K is obtained for the wall with north exposure (from 5th to 11th December 2018). Thus, in general, the difference between the measured values of thermal transmittance and the calculated one (equal to 0.17 W/m^{2}K) is lower than 10%. This means that the operational performance of building envelope is satisfactory and there are characteristics adequate to those expected in the design phase. Similar results have been obtained during the previous winter period, with a measured value of thermal transmittance of 0.18 W/m^{2}K with reference to one wall exposes on the north-east side, during the period between 22nd February to 13th March 2018.

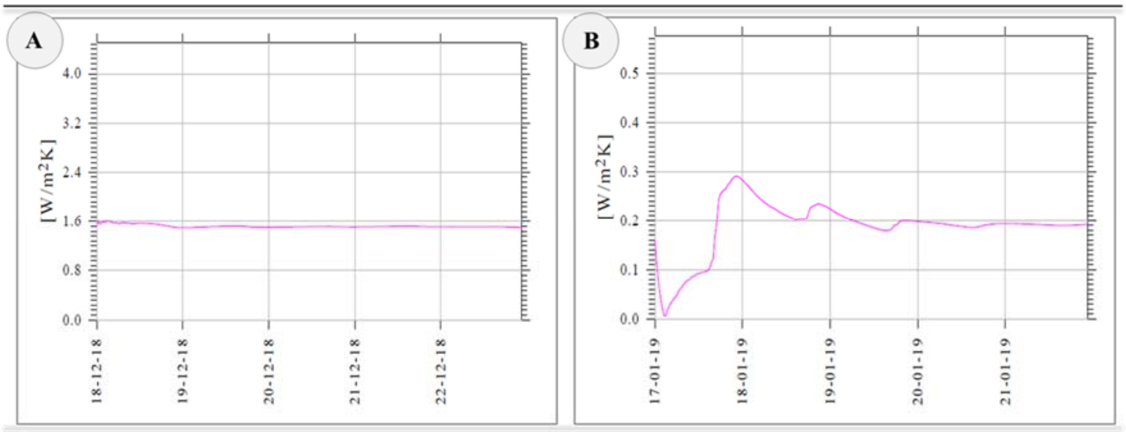


Figure 19: Measurement of thermal transmittance: (a) west wall and (b) north window.

The Figure 19 shows also the result of a measure performed on the window (from 18th to 23rd December 2018) that provides a measured U-value equal to 1.5 W/m^{2}K. It is a good result since the glass transmittance, according to technical datasheet is 1.1 W/ m^{2}K and the U_f is equal to 1.17 W/m^{2}K.

The above reported results, about the envelope performance investigations, have been previously published in two papers. In particular the paper about the test-building set-up [IV] include the envelope investigations for the wintertime 2017-2018; while in the paper about the winter performance assessment [V] are reported the results of the monitoring campaign performed in the wintertime 2018-19.

3.3.2 Daily monitoring results during the winter season

Concerning the energy performance of the entire building system, both the comfort conditions of the internal environment and the hourly energy balance have been examined. Some of the following results (sub-section 3.3.2.1 and 3.3.2.2) have been published in a conference paper about the overall performance assessment of the BNZEB building during the winter period [V].

These evaluations will be presented for two days representative of the winter season, during February 2019. Indeed, February is one typical winter month in Benevento (Mediterranean climate). Considering data monitored in 2019, the mean monthly temperature has been 7.9°C, with peak value of 19.5°C (recorded on 2nd at 13:40) and minimum value of -3.5°C (recorded on 26th at 6:20). The relative humidity during the day is ranged between 21% to 70% and, during the sunny hours, the global solar radiation measured on the roof surface is varied between 450 to 620 W/m^2 with peak value of 670 W/m^2 during the late morning of 23rd and 26th February. There were only five rainy days (in the beginning of February), with maximum intensity of 2.6 mm/h.

The 27th and 28th February have been selected as representative days since in both days the mean daily temperature is resulted 8.1°C with peak values respectively of 15.2°C and 18.1°C. The maximum solar radiation has been 650 W/m^2 on 27th and 616 W/m^2 on 28th, meanwhile the average relative humidity has been 57.4% and 63.3%. However, the same kind of analysis has been performed for 14th February [148], characterized by and average daily temperature of 10°C with a peak value of 15.5°C, a maximum value of solar radiation of 568 W/m^2 and an average value of relative humidity of 49.1%.

Since the BNZEB is located within the university residential complex, during the monitoring phase, two students have occupied the building and they replicated the typical daily actions. The patterns of occupation and usage of common electrical devices (like oven, cooker, fridge, hoover, computers, and so on) have been freely chosen by the users based on their needs as well as also the use of domestic hot water.

Moreover, during the monitoring campaign, several variables have been monitored with a sample time of 15 minutes and in detail: the electricity consumptions for different lines (lights, plugs, air conditioning systems); the electricity generation due to PV-system; the values of air temperature, relative humidity and CO_2 concentration inside and outside the building.

3.3.2.1 Indoor thermal comfort and air quality

The assessment of indoor conditions in terms of thermo-hygrometric comfort and air quality has been performed according to EN 15251 Standard [88]. In particular, for moderate environment, without considerable asymmetry of mean radiant temperature, the winter comfort range for the indoor air temperature has been assumed 19-23.5°C (a little bit higher than the EN 15251 prescriptions but comfortable according to common practice) and the same range has been considered for the operative temperature, by taking into account the comfort category II of residential buildings. A suitable comfort range of 30-60% has been considered for the relative humidity values and finally, for CO_2 concentration, the upper limit of 500 ppm above the outdoor concentration has been assumed; also in this case, the reference was the category II.

This analysis is aimed to verify if the settings of the HVAC system provide satisfactory conditions for the occupant, during the winter, when the system provides heating and ventilation service with set-point temperature of 20°C.

The analysis of monitored comfort parameters highlights that optimal conditions are guaranteed inside the dwelling. The questions to answer concerns the indoor satisfaction of the occupants. In particular, the Figure 20 shows the variation of indoor and outdoor air temperature and relative humidity inside the BNZEB, with also the indication of recommended range established by EN 15251. In Figure 21, the trend of CO_2 concentration has been reported with also indication of recommended limit values [88]. For these days, the bedroom on the north side and the living room have been chosen since these can be considered the most critical rooms. Indeed, the bedroom is characterized by lower solar gains during the wintertime, instead the living room has the greater glazed surface of the dwelling because there are two large windows: the first (5.8 m^2), on south exposure, is permanently shaded by the wooden porch that has a depth 3.2 m and it is made of horizontal *brise-soleil* spaced with a variable distance from (15 -20 cm). On the internal side there is a dark curtain that is usually opened. The second window (5.3 m^2) on the west exposure has got an external shading system made of vertical wooden slats that can be automatically moved by means of a temporal program or on the basis of an irradiance value lecture. In particular, it has been opened during the day and closed during the night. These windows allow to maximize the solar gains during the day, but during the night these surfaces are characterized by lower thermal resistance and thus highest losses.

Nevertheless, according to Figure 20a, during both days, the temperature inside the living-room results in the range of 19-23.5°C for 70% of the time while for the 28% of the time results below 19°C; meanwhile during the same days, for 99% of the time the temperature inside the bedroom results between 19°C and 23.5°C. Concerning the relative humidity, the values of this variable inside the living-room results for 81% of the time in the range of 30-60%, while for the bedroom it is in the recommended range for 70% of the time.

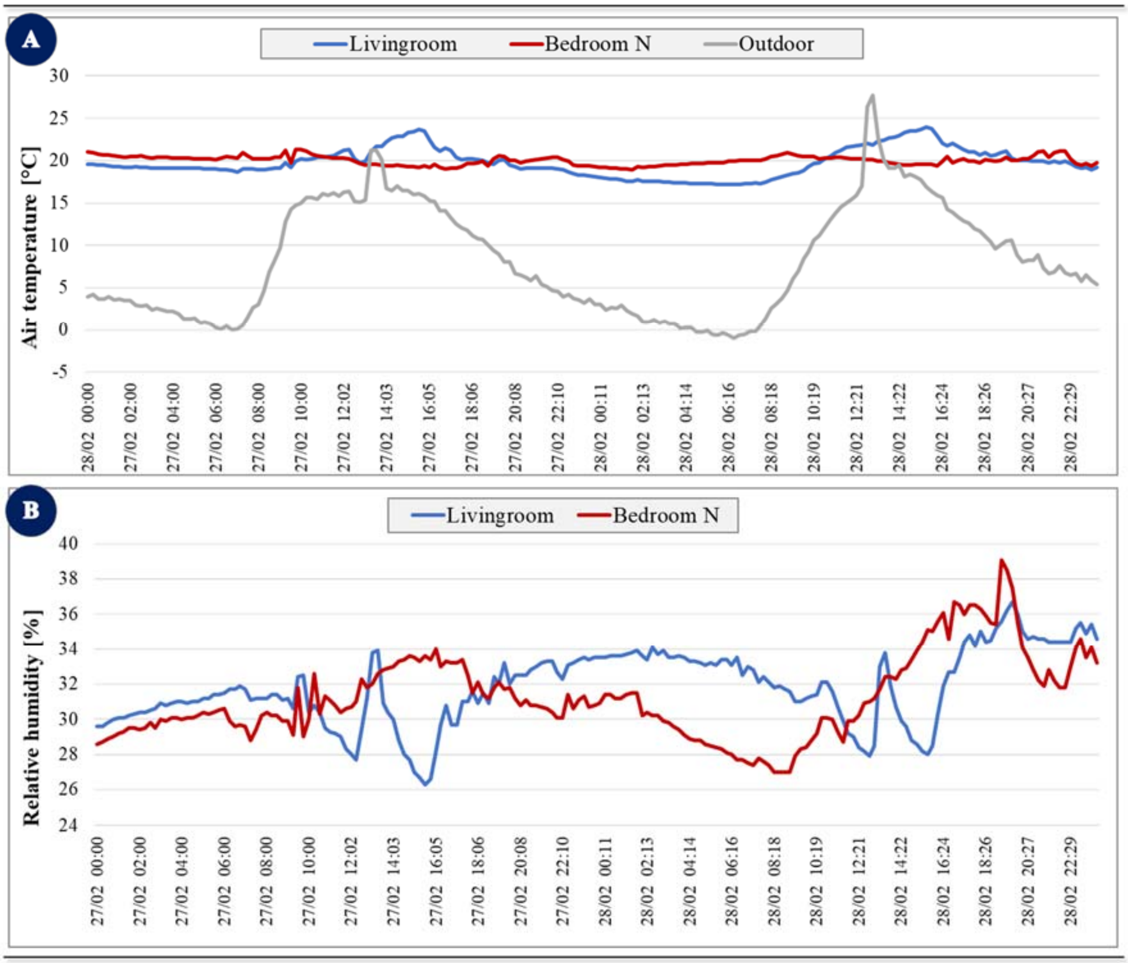


Figure 20: (a) indoor and outdoor air temperature; (b9 indoor relative humidity – 27th and 28th February.

Globally, it could be considered that inside the building acceptable comfort conditions are guaranteed during the winter period, and it is easy to conclude, according to Figure 21, that also a good air quality condition can be guaranteed. The same conclusions can be made for the day 14th February, during which the air temperature in the bedroom results always in the comfort range, while in the living room it is resulted in the range for 84% of the time. This because during the early hours of the day the temperature is lower presumably due to the energy losses through the glazed components, while during the afternoon the temperature rises above the recommended threshold due to the solar gains. Moreover, regarding the humidity values, it must be considered that the air conditioning system does not operate on this variable for which reason, on 14th February, the relative humidity inside the rooms is highly variable during the day and it remains within the established comfort range only for 53% of the hours in the living room and for 71% in the bedroom; while the CO_2 concentration results always lower the admitted threshold.

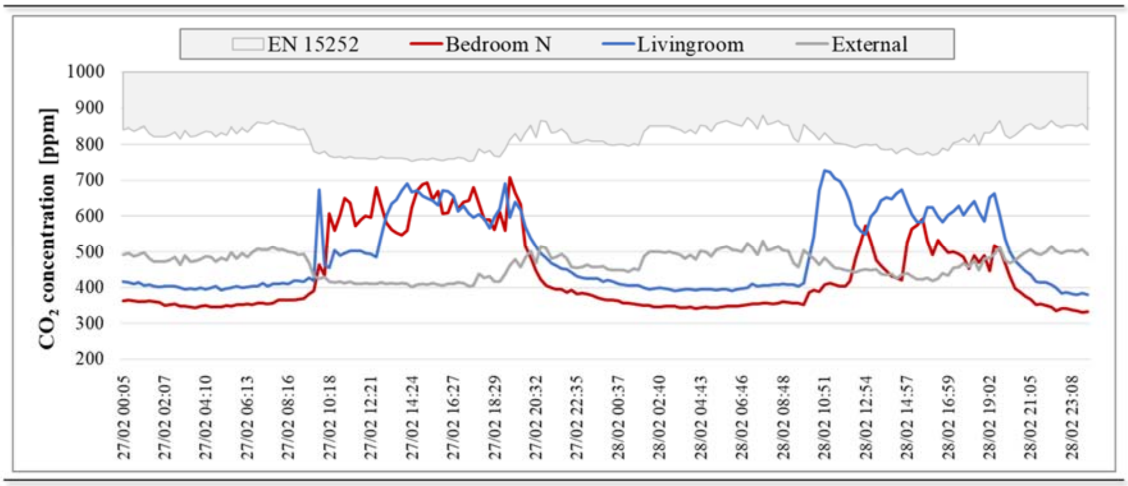


Figure 21: Co_2 concentration inside and outside the building – 27th and 28th February.

3.3.2.2 Hourly energy balance

Concerning the energy balance, the temporal correspondence between building load and PV-generation is evaluated, in order to quantify the energy produced and not self-consumed through specific indices, with the perspective to maximize the self-consumption. In particular, the real monitored energy consumption and PV generation have been compared at hourly time step.

With this purpose, some indices will be evaluated starting from monitored data, the firsts two are named “RenEl” and “PVin”. These indices are, respectively, the ratio between the amount of electricity from renewable source used to satisfy the request and the total daily consumption of the building, and the ratio between generation from PV system and the daily consumption. Moreover, a further used index is the Load Match index [149][150] defined as shown in Equation 5. It can be used to quantify the building ability to temporal match a building’s load and its energy generation and then it quantifies the ability to work beneficially with respect to the needs of the grid infrastructure.

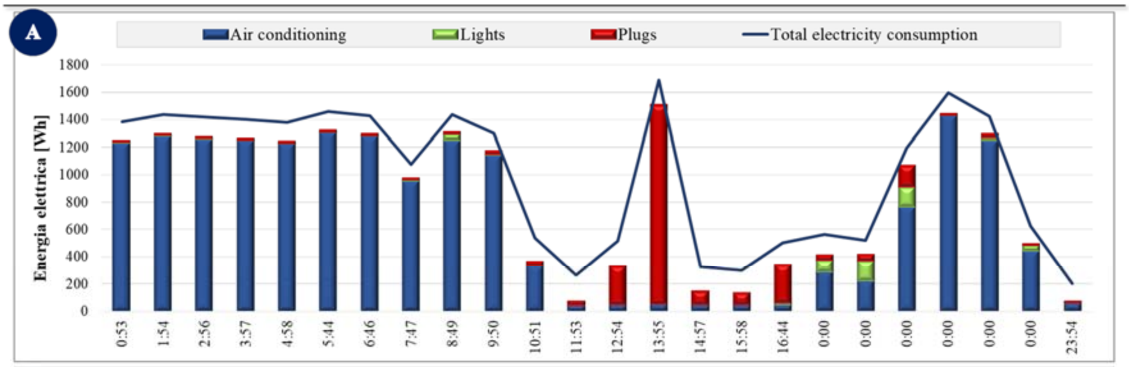
In the Equation 5, g is the on-site electricity generation, l is the electric load, t is the time interval used (e.g. hour, day or month), p is the evaluation period and N is the number of data samples (i.e. if p is equal to 1 year, this value is 12 for monthly time interval and 8760 for hourly time interval respectively).

$$F_{load\ match} = \frac{1}{N} * \sum_{p} \min\left[1, \frac{g(t)}{l(t)}\right] \quad (5)$$

In other words, this index represents the percentage of electrical request covered by on-site electric generation, and higher is the index, better is the coincidence between the load and generation. In this way, the researchers want highlight the criticalities that can occur when the energy balance of the building is not solved at small time scale. Indeed, even if at the monthly or yearly level the balance is closed to zero or positive, the daily performance could be not optimal.

As said before, two students have occupied the building to recreate a real use profile of installed systems and their main performed activities during the two investigated days are reported in Figure 22b and in Figure 23b respectively. Globally, the total energy consumption of the building is equal to 24.0 kWh and 18.4 kWh respectively for 27th and 28th February; the incidence of each type of energy request (heating, ventilation, cooking devices, computers, lighting) can be seen in Figure 22a and 23a, in which are reported the hourly energy consumption for the selected days.

During the monitoring period, the HVAC system is turned in heating mode with a set point temperature equal to 20°C. The monitored results show that, with this setting, the request for air conditioning accounts for about 72% and 62% of the overall energy consumption of the building, respectively during 27th and 28th February. Artificial lighting accounts for about 2% and the electric devices for about 12% in both days.

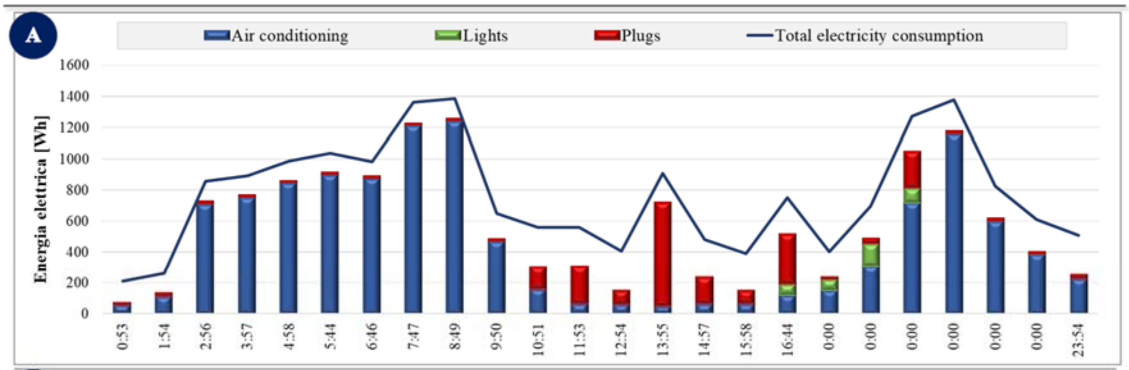


B

Use of devices during the time (minutes of use for each hour)

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
living room lights											10min	1h	30min	5min			
room N lights	30min									40min	1h	1h	30min		30min		
room S lights	30min												30min		30min		
kitchen lights																	
bathroom lights											2min	20min	10min				
burners							20min										
oven							10min	30min									
hood							30min	30min									
fridge	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h
hoover										15min							
computer n.1		30min	1h	1h	1h	1h	1h	1h	1h	1h	1h						
computer n.2						10min	1h	1h	1h	20min							
mobile phone n.1						10min	1h			45min							
mobile phone n.2									25min	1h	20min	30min					
television						30min	1h	1h									
hair dryer												10min	5min				
open window																	
set point 20°C	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h
toilet flush				1			1		1		1	1	1				
toilet sink				1min			1min		1min		1min	1min					
shower stall												15min	10min				
kitchen sink							1min										

Figure 22: 27th February: (a) Hourly energy consumption; (b) activity performed during the day by occupants.



B

Use of devices during the time (minutes of use for each hour)

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
living room lights												40min	15min				
room N lights	30min									20min	1h	10min					
room S lights	30min										20min	10min					
kitchen lights																	
bathroom lights												12min	10min				
burners							15min										
oven																	
hood																	
fridge	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h
hoover																	
computer n.1			20min	1h	1h	1h	1h	1h	1h	1h	1h	1h					
computer n.2						30min	1h	1h	1h	10min							
mobile phone n.1						5min	1h	25min				30min	15min				
mobile phone n.2						50min						20min	5min				
television				50min	50min		40min	12min									
hair dryer												5min	5min				
open window																	
set point 20°C	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h
toilet flush				1		1	1					1	1				
toilet sink				1min			1min		1min			1min					
shower stall												15min	5min				
kitchen sink							1min										

Figure 23: 28th February: (a) Hourly energy consumption; (b) activity performed during the day by occupants.

Finally, the Figure 24 shows the hourly energy balance; more in detail, the electric energy consumption, the PV-system production and the electricity available in the battery have been shown. The results confirm that also during the winter days, thanks to the low energy needs due to high performance building envelope, the generation from solar source (when is available) allows to cover most of energy demand. In the early morning, the battery is discharged, and the energy request is satisfied by the national grid (building needs to import energy); meanwhile, starting from middle day, the PV production covers the whole request and it also charges the battery. Indeed, during the evening, the stored energy allows to cover the needs of the building until 21:00.

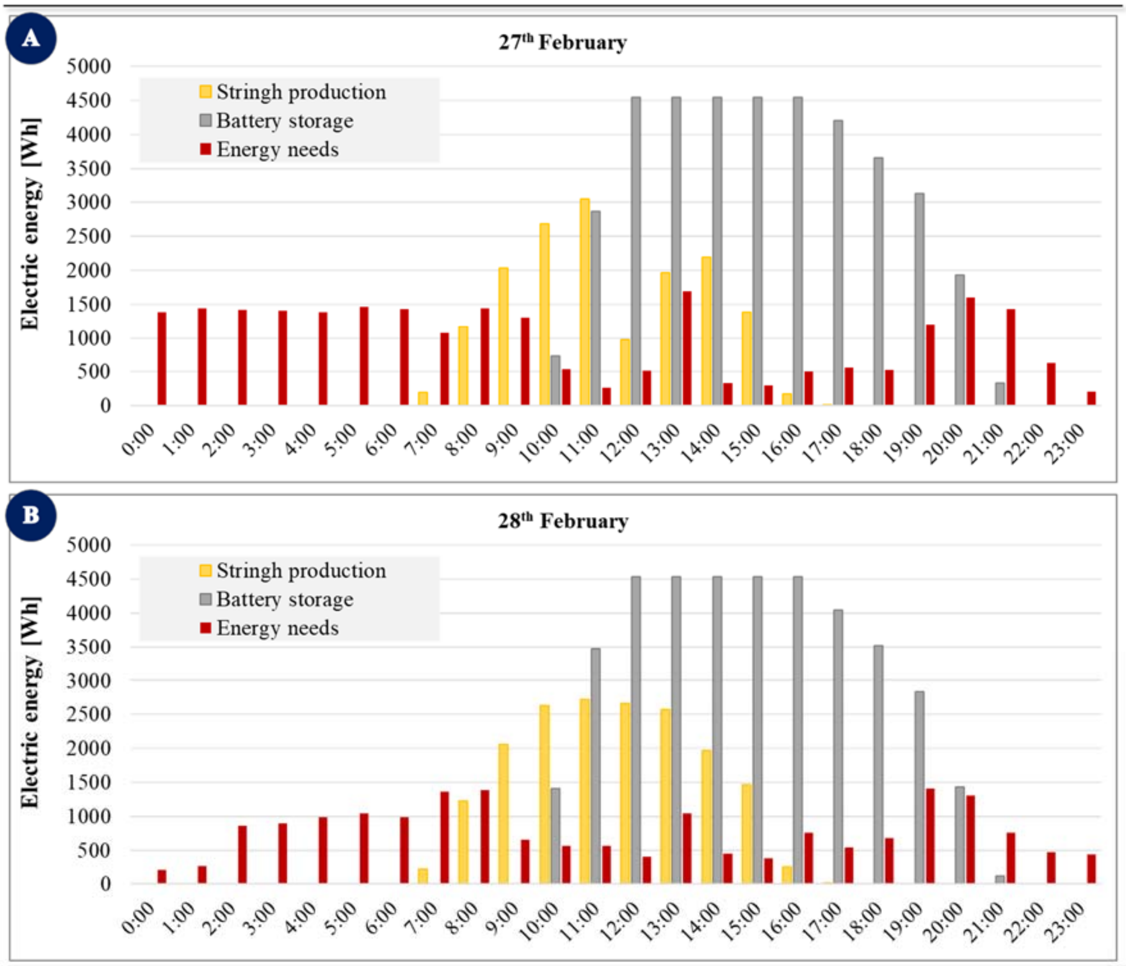


Figure 24: Hourly energy balance: (a) 27th February; (b) 28th February.

Based on monitored data, RenEl and PVin are respectively equal to 51.8% and 65.9% on 27th February; meanwhile on 28th February these indices are 60.2% and 96.9%. This means that a large amount of the energy consumptions can be satisfied by energy production from the photovoltaic system, due to the battery use too. Moreover, the Load Match index results equal to 60.6% and 59.6% respectively for 27th and 28th February. Thus, there is a satisfactory matching between building load and PV generation during the winter period and it is an optimum result for the achievement of nearly or net zero energy. The same conclusion can be made for the day 14th February, for which the RenEl and PVin indices results respectively 79% and 96%.

Considering the daily energy balance of the whole month of February, reported in the Figure 25, the trend suggests that also in the winter period, with favourable external climatic conditions, a large amount of the energy consumption can be satisfied by energy production from PV system. Globally, during February, about the 56% of the total energy needs are covered by photovoltaic generation and the PVin varies between 7.89% on 4th February (rainy day) to 100% on the 26th February. Furthermore, the coupling with the storage system maximizes the self-consumption, by minimizing the impact of the surplus energy produced and not use for self-consumption.

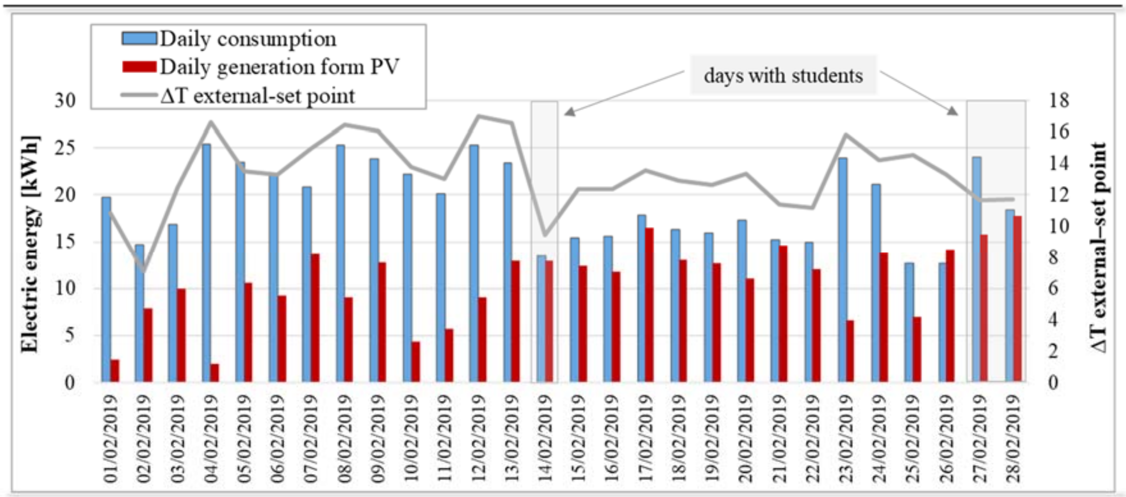


Figure 25: Daily energy balance and difference between external and internal set point temperature.

The monitoring results demonstrate the effectiveness of the design choices and control strategies. Indeed, also during winter days, the great part of the energy consumption can be satisfied by energy production from the photovoltaic system. About 72% of consumption is due to air conditioning, and more than 50% of the energy requirement is covered by renewable source even with a discrete correspondence (Load Match Index is around 60%) between the load and the generation, mainly thanks to the storage battery.

Finally, it can be remarked that, in a perspective of energy performance assessment, both of single building than urban context, it is fundamental the knowledge-transfer and exchange of experiences resulting from pilot programmes to avoid further mismatch between the expected and the real performance and to export design login and information about operational performance in a real use context. Indeed, until real data will be not available, the improvement of cities sustainability will have significant uncertainties and it will be not quantifiable the contribute that buildings must pay in matter of an active role within the context of an intelligent energy system. Finally, monitoring besides simulations are needed.

3.3.3 Effect of different management strategies for the indoor temperature set point

In the scientific research on Nearly Zero Energy Building, the applicability of adaptive management strategies to reduce the energy requirements and, meanwhile, allowing adequate internal comfort conditions for occupants is not adequately investigated.

Indeed, several studies have focused on the adoption of adaptive comfort principles for the heating and cooling system management while, in some cases, it has shown how the occupants comfort temperature changes with the outdoor climate. About this matter, van der Linden *et al*. [151] have proposed, for different buildings and climates, limits for the operative indoor temperature as a function of the running mean outdoor temperature. Honjo *et al*. [152] have proposed adaptative models to predict and control the indoor comfort temperature by using the relationship between indoors and outdoors ones. Meanwhile Sánchez-García *et al*. [153] have found that the use of climate-based set point, guarantees a major adaption compared to the use of fixed set points. They have also quantified the energy demand and consumption, by using daily set point temperature based on the adaptive thermal comfort approach. Studies like the one of Ming *et al*. [154] show how the use of flexible energy operation based on thermal comfort demand can achieve energy saving compared with fixed temperature set point. Aparicio-Ruiz *et al*. [155], with the aim to find a relationship between occupant comfort and energy efficiency, have underlined that is possible to improve the energy efficiency using tools available in the Building Automation System of the building. Moreover, Yongchao *et al*. [156] have studied how occupants exercise adaptive control opportunities to meet their comfort needs without an active system. More in general, the concept of adaptive thermal comfort has been validated in numerous in-field studies. Wider acceptable temperature ranges based on adaptive models have been included in international standards and the adaptive approach to thermal comfort can give a significant contribution in achieving low energy building operation. However, the overall understanding of how translate the adaptive principles into design practise and concepts for operating building is still limited, mainly with reference to the winter period. Moreover, there is a gap between the scientific outcomes and the real applications [157], mainly for the Nearly Zero-Energy Buildings. However, some studies have highlighted that occupants adapt to a much larger temperature range compared to the prediction of the O. Fanger model [158]. Then, the adaptative theory could represent a valuable alternative in an energy-constrained world by simultaneously increasing occupant satisfaction and reducing building energy intensity.

Basing on these considerations, this sub-section is focused on the evaluation of the applicability of adaptive theory for establishing, during the winter period, the set point value for the air temperature in the BNZEB. In particular, it wants to evaluate the effect on comfort conditions and on energy consumption due to setting a temperature set point value upper or lower than 20°C, by taking into consideration the occupant's judgement. Indeed, the starting point is the threshold value of 20°C indicated by the Italian current legislation [159] as recommended HVAC temperature set point.

According to this purpose, a monitoring campaign has been performed from November 2019 to January 2020, under real operational conditions, from 9 a.m. to 6 p.m.; during the campaign, the set point temperature (T_{set}) was fixed according to the empirical relation (to be validated) reported in the Equation 6, that, starting from the Italian legislative reference, allows the identification of different level of regulation based on the mean outdoor temperature (T_{ext}):

$$T_{set} = 20 \pm a * T_{ext} \quad (6)$$

In question 6, a is a coefficient that range arbitrarily between 0 and 0.15 and T_{ext} is the average value of the external temperature recorded during the seven days preceding the once to be heated. It wants to be remarked that this relation has not been found in the literature or normative and it is not validated. It is the first attempt to verify the effectiveness to change the set-point temperature in a building designed to be very efficient. After the analysis of the data resulted from the empirical tests, a deeper work will be done to formalize a validate equation, also considering different type of occupations, and by considering also a wide questionnaires' campaign. However, this activity is still ongoing and then it is not shown in this PhD Thesis.

As in the previous section, the monitoring campaign was performed in real operational conditions, during which the building has been occupied by two students and all information about the energy consumption, the generation from renewable sources and the indoor microclimate conditions, like air temperature and relative humidity, have been collected with a time step of 15 minutes. The results obtained in the tested configurations are shown in the following sub-sections. In particular, the first one will be based on the results about the indoor microclimate conditions, while, in the second one, the corresponded results about monitored energy consumption and the energy balance will be discussed. Moreover, the following results have been already reported in a conference paper named "Effect of renewable energy integration in the hourly energy balance of a nZEb in Mediterranean climate during the wintertime" [VIII].

3.3.3.1 Indoor microclimate conditions

For the characterization of thermo-hygrometric conditions inside the building, the collected data about the air temperature and relative humidity are shown respectively in the Figure 26 and Figure 27. The data are referred to the outdoor environment, the living room and one bedroom that have been chosen as the most representative thermal zones of the building. Moreover, Figure 26 also shows the set point value settled for each day.

During the week December 9th -13th, the external temperature varies in the range between 4°C to 14°C. The temperature monitored in the bedroom is usually more uniform, it is some tenths higher than the living room temperature and it is closer to the set-point, due to the higher percentage of glazed surface in the living room. Even by using a set point lower than 20°C, the temperature inside the building results within between 17.5°C and 19.5°C. Only in some conditions, when the solar radiation gives an important contribution, the air temperature gives up the set point value. For instance, during December 11th, the set-point is 18.7°C but inside the living room during the afternoon the sensor has recorded 22°C as maximum value. In general, the occupant perception is not positive for this management strategy indeed they have described the indoor condition as "slightly cold" for all the days.

During the week January 9th - 15th, the set point has been increased meanwhile the outdoor temperature is varied between 0 °C and 14 °C. For all days, the value of air temperature is usually lower than the set point except during the afternoon when in the living room the temperature rises up 20 °C with a maximum value of 28 °C during 15th January that is characterized by a solar radiation (monitored on the roof) of around 400 W/m^2 during the whole afternoon.

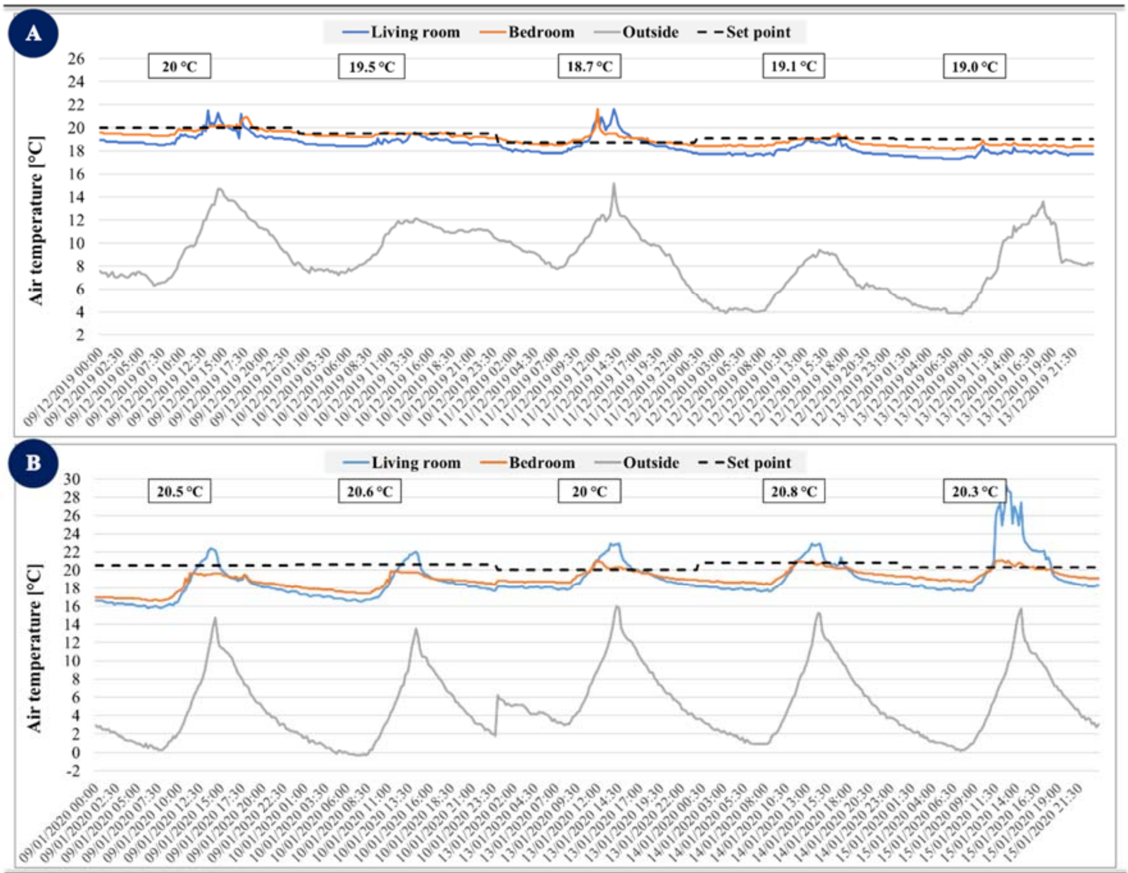


Figure 26: Temperature inside the building with set point (a) lower that 20°C and (b) upper that 20°C.

It is interesting to note that when the outside temperature decreases during the night the temperature inside the building drops by about two degrees even if the set point is settled at a temperature above 20°C. However, for these days, the occupants have affirmed to be in comfort conditions. This is a notable conclusion that underlines how the occupants are influenced by the knowledge of the test to which they are subjected and how the comfort has a significant psychological component. Indeed, it can be observed objectively that the trends of the two periods are comparable.

The relative humidity, shown in the Figure 27, results always within between 30% and 60%. Finally, the changes in the set point value do not determine considerable variation in the humidity value inside the rooms.

Based on the results obtained, we can conclude that surely the external temperature leads to the need to use a suitable set point to maintain comfortable internal conditions. Furthermore, the external conditions mainly in terms of solar radiation, influence the occupant perception. Indeed, the second week is characterized by average value of solar radiation higher than the considered week in December and the sky has been usually clear compared with December. Probably, this condition has led the occupants to consider more comfortable the rooms also if the indoor temperatures are comparable.

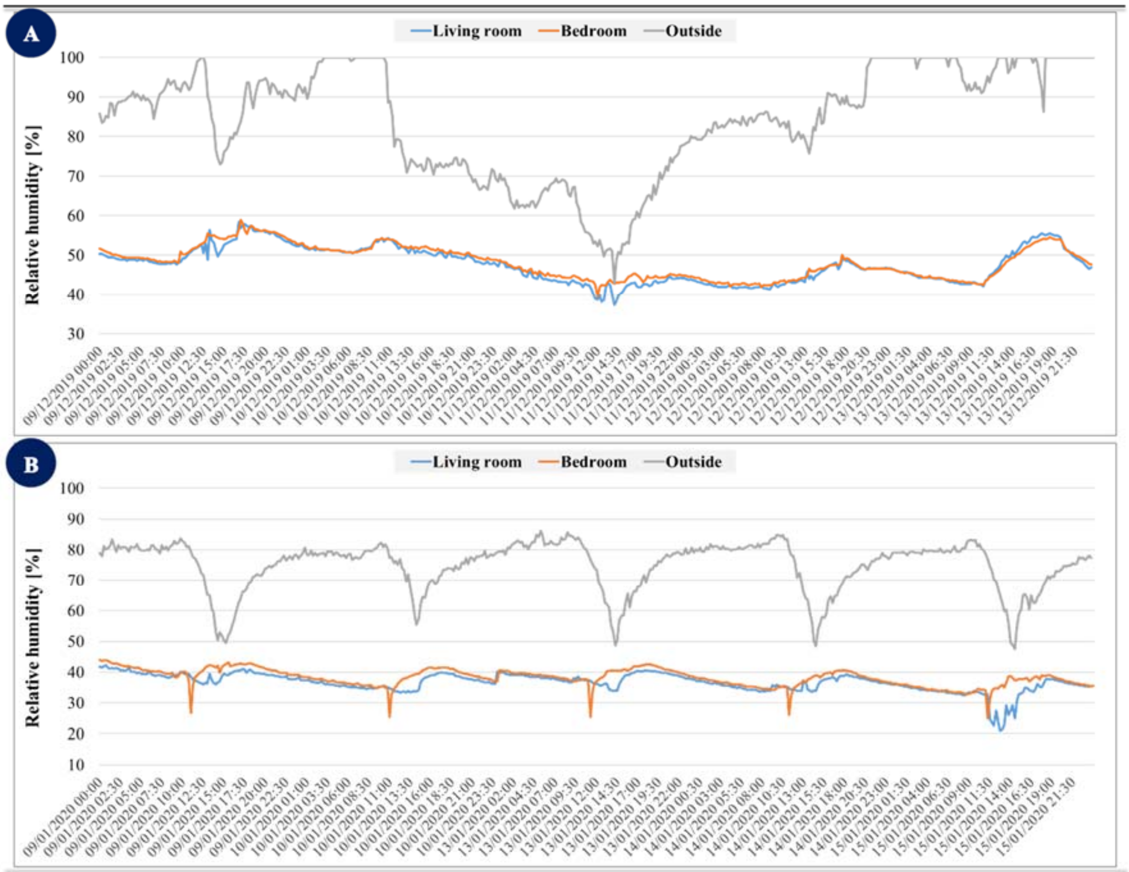


Figure 27: Relative humidity inside the building with set point (a) lower that 20°C and (b) upper that 20°C.

3.3.3.2 Energy consumption and energy balance

In order to evaluate how varying the temperature set point affects the HVAC energy consumption with the purpose to evaluate if it could be possible to obtain a further reduction in energy request also guaranteed indoor comfort conditions for occupants, in the Figure 28, the monitored energy consumption are reported, for both weeks, with also the indication of the set point settled for each day.

In detail, both the overall energy consumption than the indication of the main loads (HVAC – Heating, Ventilation and Air Conditions system, lights, and plugs) are plotted.

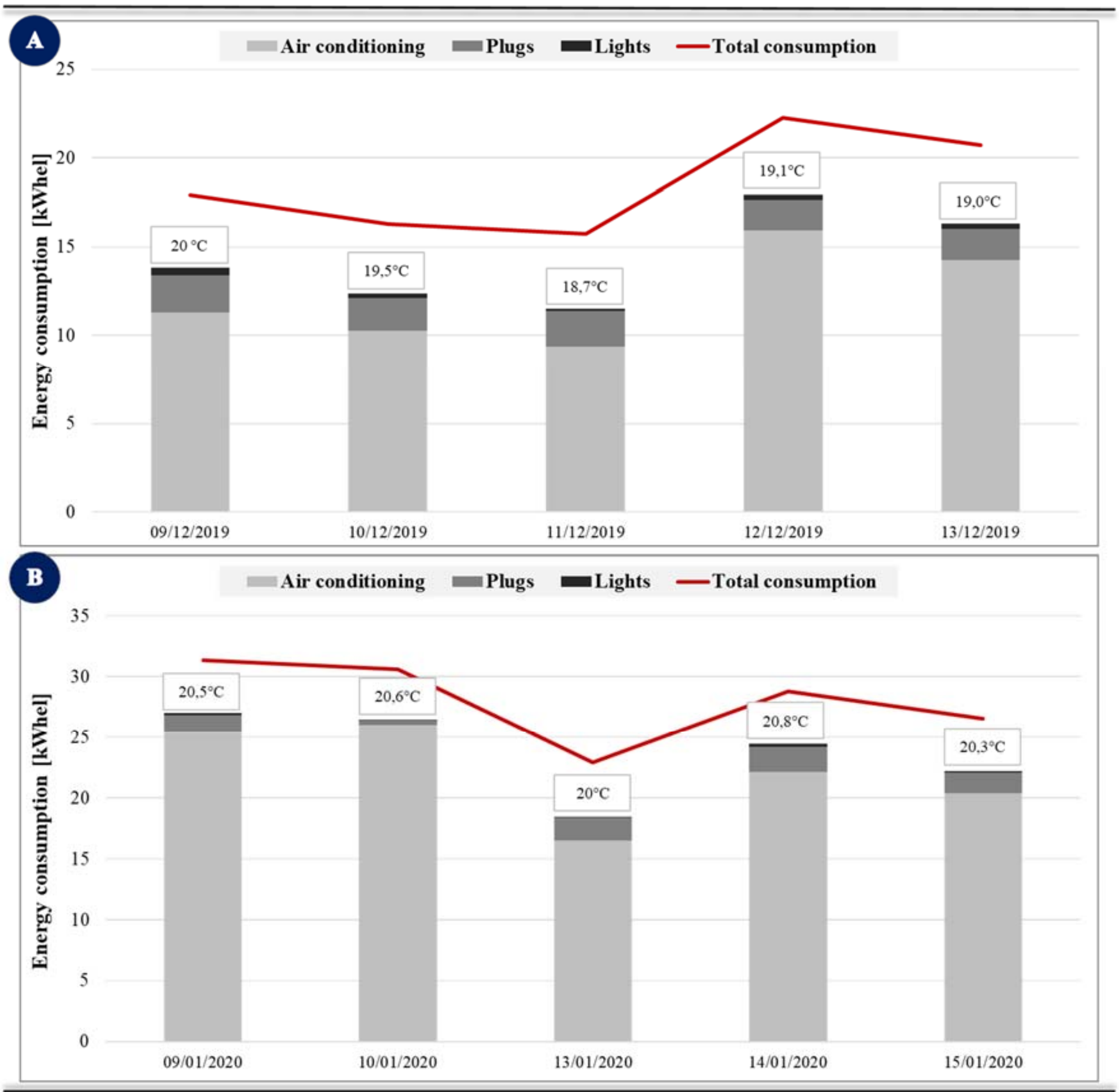


Figure 28: Energy consumption trend: (a) set point lower that 20°C and (b) upper that 20°C.

The results show that energy consumption of the HVAC system covers around 63-72% and 72-85% of the total energy consumption of the building, respectively for the first and second considered weeks. The artificial lighting accounts for around 2% of overall energy consumption. It can be noted that the set point of 20.5°C determines an increase of the heating consumptions of 54% compared with 13th January; instead with a set point of 18.7°C, the heating consumption is reduced of around 21% compared with the 9th December. These data, based not on simulation results but on monitored values, confirm that the management strategy of the heating system has a great influence on the building energy balance.

Figure 29 shows the hourly energy balance in terms of electric energy consumptions, generation from PV-system and the electricity available in the battery, while Table 5 reports the calculation of the introduced indexes for evaluating the incidence of production from photovoltaic system.

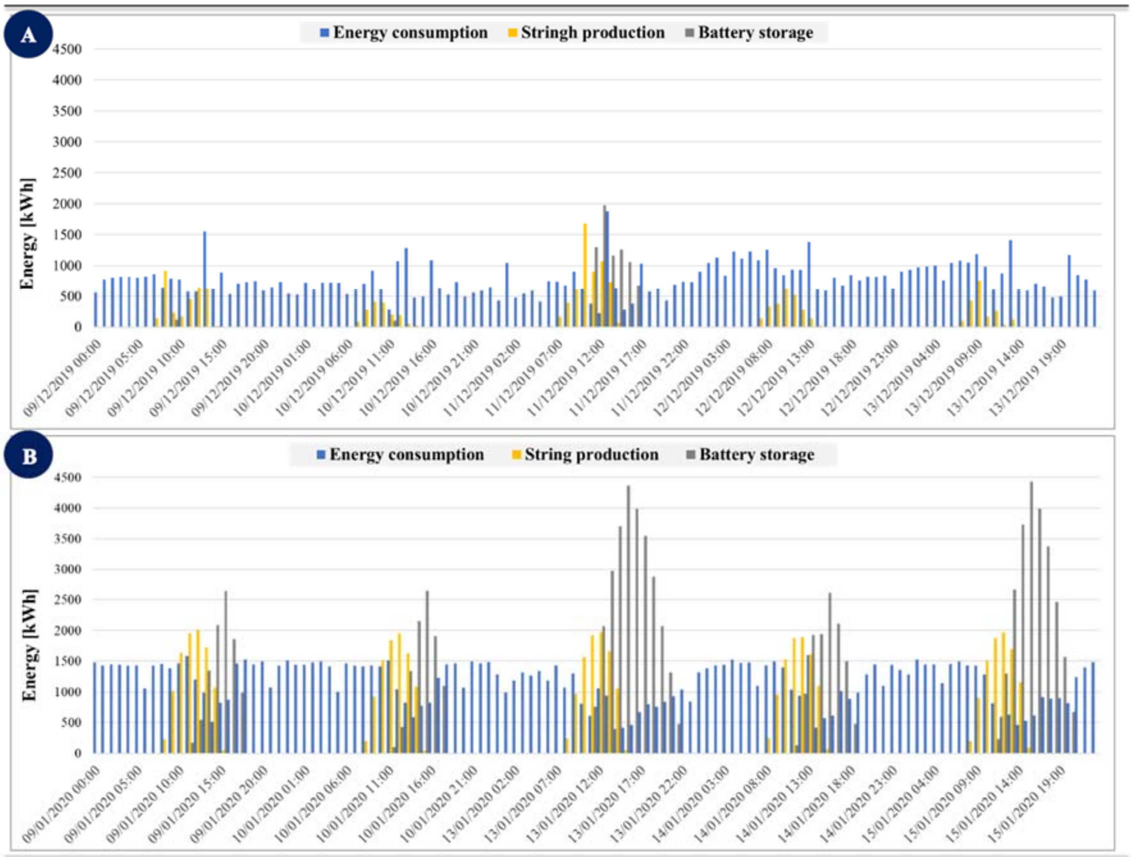


Figure 29: Total energy consumption and global electricity available in PV-system (a) first week and (b) second week of monitoring campaign.

Table 5: Assessment indices about energy balance.

	RenEl	PVin	f.load
12/09/2019	17.8 %	17.8 %	17.4 %
12/10/2019	10.1 %	10.7 %	11.21 %
12/11/2019	35.8 %	35.8 %	34.8 %
12/12/2019	12.0 %	11.0 %	10.9 %
12/13/2019	9.28 %	9.28 %	8.73 %
01/09/2020	35.6 %	30.9 %	39.8 %
01/10/2020	34.1 %	30.1 %	9.5 %
01/13/2020	45.2 %	41.2 %	56.0 %
01/14/2020	35.2 %	32.3 %	43.0 %
01/15/2020	38.5 %	35.4 %	51.3 %

It is clear that, during the winter period, the electric renewable generation is not always enough to satisfy the energy need of the building. The RenEl indicates that the renewable energy used for covering the electric request cannot reach the 50% during the analysed days. The 11th December, day with the lowest set point, is characterized by the higher percentage of integration during the first selected week and the 13th January during the second one. With reference to this day, the renewable production was sufficient to satisfy the 45.2% of the consumptions. Finally, the Load Match Index ($F_{load\ match}$) results within 11% and 56%, and thus the percentage of electrical demand covered by on-site generation at hourly level is very low; really, it is due to the very limited production from PV system.

The results shown that, although energy savings are achieved by lowering set point with respect to that established by Italian legislation, it is not always possible to guarantee comfort conditions inside the building. However, the achievement of the comfort conditions seems closely related to the external conditions mainly in terms of clearness of the sky but also by the awareness of the testing conditions. Indeed, it seems that occupant can accept lower internal temperatures when the external temperature is rather rigid.

The decrease of set point value always determines a reduction of the heating consumptions, but the hourly energy balance between renewable production and consumption seems to be not influenced by the decision of set point. Indeed, the index related to the load match and to the coverage from renewable sources is usually lower than 50%. In general, the setting of HVAC set point values according to external conditions seems to be a promising strategy to contain energy consumption without penalizing the comfort conditions for the occupants.

3.4 ANALYSIS OF BUILDING BEHAVIOUR DURING SPRING AND AUTUMN SEASONS

The aim of this section is to evaluate, during the intermediate seasons (spring and the autumn), the energy performances of the BNZEB. Moreover, the indoor microclimate is analysed, by taking into account the behaviour of occupants and their perceptions with respect to visual and thermo-hygrometric conditions and air quality.

For the climatic zone of Benevento, according to the Italian legislation [160], the heating systems have to be turned off from 31st of March to 14th November. For what concerns the cooling period, it has to be calculated according to the procedure explained by UNI TS 11300 – PART 1 [161] and thus it depends by the building characteristics. For the nZEB under investigation, it is from 15th May to 30th September. Indeed, in Italy, there is not a law that prescribes the operating period for the space cooling.

The spring season (from 20th March to 21st of June in the boreal hemisphere) has been chosen for the investigation, because it could be really critical in term of indoor comfort in Mediterranean climate. Indeed, also due to climate changes, the spring months can be colder or significantly hotter than people expectations, but the heating and cooling systems are usually turned off, also according to legislative prescriptions (with the exception of the weeks stating from the second half of May). In this way, the internal conditions could not be in comfort zone. Really, indoor conditions are also influenced by building envelope insulation and thermal inertia, and by control strategies for blinds and ventilation. Thus, the aim of this section is to propose a method to analyse, by means of physical measurements combined with occupants' opinions, if the design choices are adequate to answer to the external conditions in an intelligent manner through an optimal interaction between inertial properties of building envelope, management of shading systems and activation of free cooling mode for a real case study. In other words, during the springtime monitoring campaign, different configurations of shading devices will be tested, and also the dynamic response of building envelope will be evaluated in operational conditions.

Meanwhile, the autumn period (from 22nd September to 20th December) was chosen because also it could be critical for the greater uncertainty of renewable sources contribute to the energy balance, and for the great variability of external conditions both in terms of temperature and solar radiation, while the heating system is conventionally turned off (with the exception of the weeks after the half of November). In particular, as during the springtime, the HVAC system is settled in ventilation mode, considering that mechanical ventilation systems are essential for ensuring the indoor quality of air in nZEB with a high level of airtightness [162]. Moreover, this section is not only aimed to evaluate the real performance of the BNZEB during the autumn period, but the in-field monitoring campaign is also aimed to evaluate the contribute of geothermal source for the pre-treatment of ventilation air flow when the HVAC system is set merely in ventilation mode.

Contextually, for both the two seasons, the discussion about indoor environment conditions and the hourly energy balance will be considered to verify the effectiveness of selected solution and for the evaluation of the occupant behaviour or management strategies can influence the achievement of the "nearly zero" objective and to evaluate the incidence of PV-production. In particular, as performed for the winter analysis, the electric energy balance will be presented, comparing with an hourly time step the photovoltaic production and battery storage with the building energy need. Some indices have been introduced as explained in section 3.3.2.2, to evaluate the daily balance.

Then, the experimental analysis is aimed at the evaluation of the dynamic building envelope dynamic parameters (sub-section 3.4.1) and the effect of shading devices during the spring season (sub-section 3.4.2), and at evaluating the effectiveness of the free-heating of external air by evaluation of the contribute of geothermal source and of heat recovery during the autumn period (sub-section 3.4.3). Moreover, a CFD investigation will be performed (sub-section 3.4.2.3) to evaluate the comfort conditions achieved inside the dwelling in the different shading configurations tested in the springtime monitoring campaign. For both two periods, the energy consumption, the hourly energy balance and the indoor microclimate variables will be evaluated for all the tested configurations under a real use context. Indeed, also during the monitoring periods, that will be shown in the following sub-sections, two students have occupied the building, and they have used, according to their needs, common electrical devices like oven, cooker hood, fridge, computers, hairdryer, television (without a prescribed schedule) to replicate the typical profiles of use of a real dwelling.

Moreover most of the results reported in the following are included in a journal paper entitle “Nearly zero energy target and indoor comfort in Mediterranean climate: Discussion based on monitoring data for a real case study” [VII].

3.4.1 Dynamic behaviour of the opaque walls

The dynamic response of the building envelope to external solicitations, mainly with extremely variable weather forcing, influences both the comfort perception that the energy consumptions, and its importance is universally recognized. However, national legislations are more focused on stationary parameters that neglects the ability of materials to store and release heat over time, and research papers usually cannot evidence if there is any discrepancy between the design value of dynamic parameters (e.g. periodic thermal transmittance, time lag, etc.) and the real monitored performance. In order to investigate the dynamic characteristic of building envelope, some research studies have proposed a method to identify the dynamic response of envelope to external solicitations based on real monitored data [82][83][84]. More in detail, they have defined some experimental formulations for the thermal wave decrement factor and the time-shift of decrement factor in terms of temperature response on the internal surface, and then calculable from monitored values of internal and external surface temperatures of the building component.

Then, to evaluate the dynamic behaviour on BNZEB’s walls, the indoor and outdoor surface temperatures are monitored on the south wall and on the west wall of the living room. During the monitoring, the HVAC system is turned off because the aim is to estimate only the envelope behaviour. The values are elaborated to assess an experimental decrement factor (f) and the time-shift of decrement factor (Δt_f), and these values are compared with the nominal ones that have been calculated during the design phase.

The decrement factor is the decreasing amplitude of the thermal wave during its propagation process from outside to inside, while the time lag is the time it takes for a heat wave to propagate from the outer surface to inner surface (minimum or maximum temperature peak on external side and internal side of the structure). Both parameters can be experimentally calculated in terms of the temperature response on the internal surface. However, in real simplifications of the periodic analysis on both sides is not acceptable. For this reason, the alternative form of the decrement factor can be used. It is defined as the ratio of the amplitude of the internal surface temperature trend to the amplitude of the external sun–air temperature [82][83], as in the following equation (Equation 8):

$$\Delta t_f = \frac{T_{s,i,max} - T_{s,i,min}}{T_{sun-air,max} - T_{sun-air,min}} \quad (8)$$

where $T_{s,i}$ is the internal surface temperature and $T_{sun\text{-}air}$ is the outdoor sun–air temperature. For the calculation of $T_{sun\text{-}air}$ the irradiance value on vertical surface monitored on each side has been used and the value of external temperature monitored by the sensors near the walls.

Meanwhile, the thermal delay can be calculated as the temporal distance between the maximum T sol-air temperature, with reference to the specific exposure, and the maximum internal surface temperature [82][83] and thus it is the difference between the time instant when the maximum temperature is reached on internal surface and for the sun air temperature. Another point must be underlined: the living wall have two windows and two occupants; thus, other phenomena influence the indoor surface temperature. For this reason, also a modified attenuation capacity indicator introduced by Ferrari e Zanotto [84] is calculated. They have defined the amplitude transmission coefficient (ΔT) as reported in the Equation 9, where $T_{a,i}$ is the indoor air temperature.

$$AT = \frac{\Delta t_f}{T_{a,i,max} - T_{a,i,min}} \quad (9)$$

Also for the time lag effect, Ferrari e Zanotto [84] have proposed an adjusted formulation reported in the Equation 10:

$$TL = t_{(T_{s,i} - T_{a,i})max} - t_{T_{sol-air,max}} \quad (10)$$

As explained in the section 3.1.6, the BNZEB wall type has period thermal transmittance of 0.01 W/m^2K with surface mass (M_s) equal to 136 kg/m^2, and according to the calculation method proposed in the international standard [163] the decrement factor is 0.06 and the time-lag effect is around 17 hours. Considering the Italian benchmark in matter of thermal inertia [145], for the vertical opaque envelope, on all sides except north,

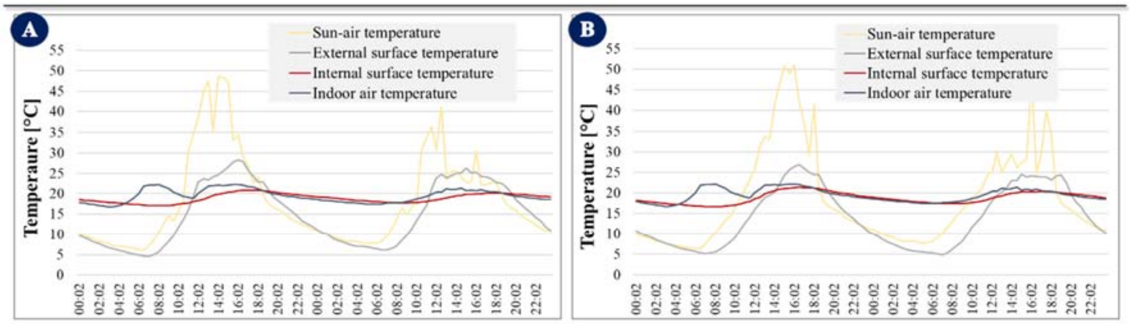
north-east and north-west, M_s has to be higher than 230 kg/m^2 and /or Y_{IE} must be lower than 0.10 W/m^{2}K. This means that the designed wall has good behavior according to conventional adopted approach.

However, the experimental values have been calculated according to definition proposed in this section in four different days: 18th and 19th April with HVAC system settled to ventilation mode and two students inside the room only during the first day; 11th and 12th May with HVAC system turned off and without occupants in the living room for nullify the internal influences. These days are comparable in terms of external temperature and solar radiation; for instance, the maximum value of external air temperature has been around 26°C and the mean daily value has been around 14-15°C.

Figure 30 shows the trend of sun-air temperature, indoor air temperature, internal and external surface temperature on south and west wall of the living room for selected days in April and the calculated values of experimental parameters. Analogously Figure 31 shows the same information for the selected days in May.

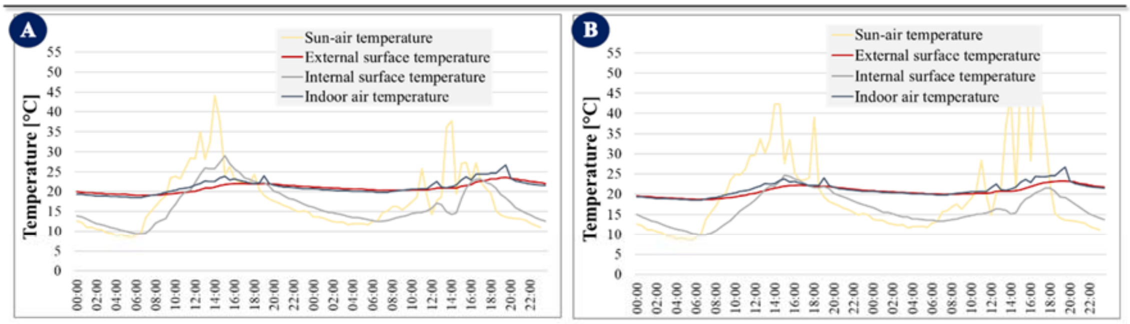
Firstly, it can be noted that the decrement factor (according to Equation 8) is not comparable among different exposures and days. More in detail, comparing its values for each exposure, it can be concluded that there is not a clear influence of occupants and mechanical ventilation, and these aspects seem to not contribute significantly to change the considered parameter. The values calculated in the same day with data acquired on different exposure are comparable and these are also comparable (same magnitude) with the nominal value calculated according to [145]. The experimental values are representative of the real envelope behaviour that, according to the proposed index, results to be really good. Indeed, the value of surface temperature on inner side is almost constant near 20°C for all considered days meanwhile the peak of sun air temperature varies between 45-49°C. The attenuation of the heat wave oscillation determines a lower peak load that means a smaller size of the HVAC system and lesser variability of the internal temperature that positively influences the indoor conditions and therefore it reduces eventual on/off cycle of HVAC system. The modified attenuation capacity indicator has quite the same values for all analyzed periods; it considers the normalization respect to the other forcing. When also the effect on the indoor air temperature is considered, the value of decrement factor is lower than nominal one for both exposures.

On the other hand, the value of time lag, also if the modified formulation is considered, is very far from the calculated one. Also in this case, the influence of inner gains and ventilation system cannot be explained easily. The only possible conclusion is that, for the analysed conditions, it is difficult to evidence the time shifting because the indoor surface temperature does not vary greatly (±2°C respect to the mean daily value) and there is not an increase of indoor surface temperature comparable with external forcing trend.



	South wall				West wall			
		ΔT	f [h]	T_L [h]		ΔT	f [h]	T_L [h]
18/04/2019	0.09	0.02	02:00	08:30	0.11	0.02	00:30	05:00
19/04/2019	0.05	0.01	05:00	06:00	0.09	0.02	01:00	04:00

Figure 30: 18th – 19th April: outdoor and indoor parameters, experimental decrement factor and time lag.



	South wall				West wall			
		ΔT	f [h]	T_L [h]		ΔT	f [h]	T_L [h]
11/05/2019	0.08	0.01	02:00	11:00	0.01	0.02	02:00	09:15
12/05/2019	0.12	0.01	05:45	06:15	0.09	0.01	03:00	09:45

Figure 31: 11th – 12th: outdoor and indoor parameters, experimental decrement factor and time lag.

More in general, on the basis of the monitoring during the spring season, the solution selected for the building envelope seems to be adequate to reduce the overheating risk during the summer period, by assuring, at the same time, an optimal insulation level.

3.4.2 Adoption of different management strategies for shading systems

As aforementioned, the purpose of this section is to investigate the management of shading devices to find the optimal control strategy of the internal and external shadings and ventilation system, basing on energy requests assessment and on the occupants' perception in terms of thermo-hygrometric and visual comfort as well as indoor air quality. Moreover, it is discussed how seasonal/daily variations can influence the efficiency of the whole building-HVAC system and the reaching of high level of indoor comfort and air quality also if the building achieves a positive nearly zero long-term energy balance.

In this perspective, during the monitoring phase, different configurations for installed shading devices were tested in the living room in order to assess their effect on thermal and visual comfort inside the building and identify the best management of shading devices. The analysis of indoor parameters is focused on the living room (22 m^2) because it is the most critical room due to the presence of two large windows. The first (5.8 m^2), on south exposure, is permanently shaded by the wooden porch that has a depth 3.2 m and it is made of horizontal brisoleil spaced with a variable distance from (15 -20 cm). On the internal side there is a dark curtain that is usually opened. The second window (5.3 m^2) on the west exposure has an external shading system made of vertical wooden slats that can be automatically moved by means of a temporal program or of an irradiance value lecture. Two simple shielding strategies are considered: one control strategy with closed shading devices on south and west sides and one other with closed shading only on west side (as shown in Table 6).

Meanwhile, the operation of the artificial lighting system (from 9:00 a.m. to 7:00 p.m.), is automatically controlled by value of the illuminance measured by the sensor placed on the table (at 75 cm height) in the centre of the room. When the value goes below 300 lux, the lamps are turned on. This value is chosen for visual comfort according to the Standard EN 12464-1 [164] that prescribes a lighting level of at least 300-500 lux for reading and writing activities. The evaluation of glare has been based on the simplified procedure presented by Karlsenet *et al*. [165]. They found that the 1700 lux vertical eye illuminance at the occupant position and 1900-2100 lux horizontal at the desk are the thresholds to avoid excessive glare conditions.

For the assessment of indoor comfort conditions, in the springtime, there are not specific indications given by the standard UNI EN ISO 7730 [166]. Indeed, it reports that, for lighting activity, the operative temperature has to be between 20°C and 24°C during the heating mode and between 23-26°C during the cooling period, while the relative humidity should not be lower than 30% or higher than 60% in both seasons. These values are used as reference for the examination of monitored values. Moreover, according to [88], the indoor air quality requires that the CO_2 concentration is not 350 ppm above the outdoor concentration.

To improve the readability of monitored data, in the following sections, the hourly values of all indoor parameters and the energy balance will be shown for some representative days. All selected days are not rainy, but only in June, there are some days with perfectly clear sky for all the time. Table 6 shows a global description of the weather conditions, the operational mode of the HVAC system and the management of shading devices for the selected days. In these days, with the exception of 19th and 11th April and 12th May, the students have been in the living room or kitchen starting from the morning (8:30, breakfast) until the late evening (20:30, dinner).

Table 6: Monitoring boundary conditions.

Day	External conditions			HVAC mode	Shading device	
	T_a [°C]	UR [%]	sky		west	south
4th April	16.6	59.8	cloudy	Ventilation	open	Open
9th April	15.9	64.5	cloudy	Ventilation	close	Open
18th April	15.0	56.8	clear	Ventilation	mobile	Open
19th April	14.4	59.9	variable	Ventilation	close	Open
30th April	18.1	50.0	variable	Ventilation	open	Open
8th May	15.6	60.9	variable	Ventilation	close	Open
11th May	15.2	80.5	clear	Off	open	Open
12th May	14.0	81.9	clear	Off	open	Open
11th June	26.1	57.7	variable	Cool+ Vent	open	Close
12th June	26.8	56.7	clear	Cool+ Vent	close	Close
13th June	27.2	57.6	clear	Cool+ Vent	close	Open

As said, also in this case the monitoring campaign was performed under real operational conditions during which all information about the energy consumption, the generation from renewable sources and the indoor microclimate conditions have been collected with a time step of 15 minutes. The results obtained in the tested configurations will be shown in the following sub-sections. In particular, in the first one, it will be shown the experimental results from monitoring about the indoor microclimate conditions (sub-section 3.4.2.1), while in the second one the corresponded results about monitored energy consumption and the hourly energy balance will be discussed (sub-section 3.4.2.2). Finally, in the last sub-section (3.4.2.3), it will presented the CFD investigation results about the thermo-hygrometric comfort conditions reached inside the building in the tested configurations.

3.4.2.1 Indoor thermal comfort and air quality

To evaluate the ability of passive solutions to meet the comfort conditions, the period of this analysis started on 1st April and finished on 15th June when the HVAC system should be turned off. The evaluation of indoor conditions is based on the monitoring of several indoor parameters: air temperature and relative humidity; CO_2 concentration; illuminance values on working planes. But also all external climatic parameters are collected, like the vertical solar radiation on the west wall and the CO_2 concentration.

In particular, in April, the outdoor temperature varied between a minimum value of 2.6°C and a maximum of 31°C; the mean value has been 13°C the highest percentage of values (62%) is inside the range 10-20°C. The sky has been very often cloudy with 12 days of rain with a maximum precipitation phenomenon of 3.4 mm/h. During May, the weather has been colder than usual. Indeed, the minimum temperature has reached 4.3°C while the maximum one has been 26°C. Around 78% of monitored values is contained in the range 10-20°C and the mean monthly value has been 14°C. The number of rainy days (17) has been high with a maximum precipitation accumulation of 9.0 mm/h and the wind velocity has reached also 13.4 m/s. Finally, June has been hottest than yearly mean conditions. The air temperature risen up 30°C very often (22%) with a maximum recorded value of 39°C on 14th June, however, it was usual between 20-30°C (45%) with a mean value of 24°C.

The trends of CO_2 concentration inside the living room and outside the building are shown in Figure 32 for the selected days of the monitoring period when the students are inside the living rooms. Here, there is also the indication of the limit values calculated according to the Standard EN 15251 [88]. The trends shown that, in all conditions, the limit values are far from being reached. The students stay in the living room from the morning (breakfast) until the early evening (dinner); this is evident because the CO2 emissions increase, but the ventilation is enough to assure the respect of the limit value.

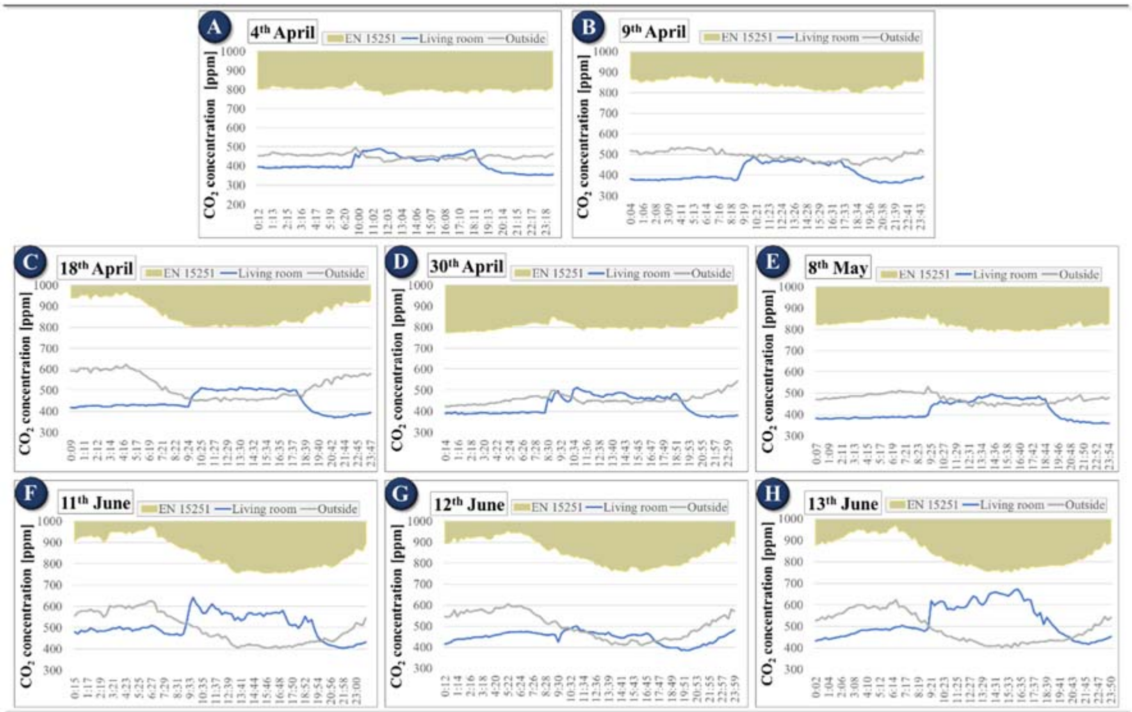


Figure 32: CO_2 concentration: (a) 4th April; (b) 9th April; (c) 18th April; (d) 30th April; (e) 8th May; (f) 11th June; (g) 12th June; (h) 13th June.

Meanwhile the trends of air temperature and relative humidity inside the living room and outside the house are shown in Figure 33 during two selected days of April characterized by an overcast sky.

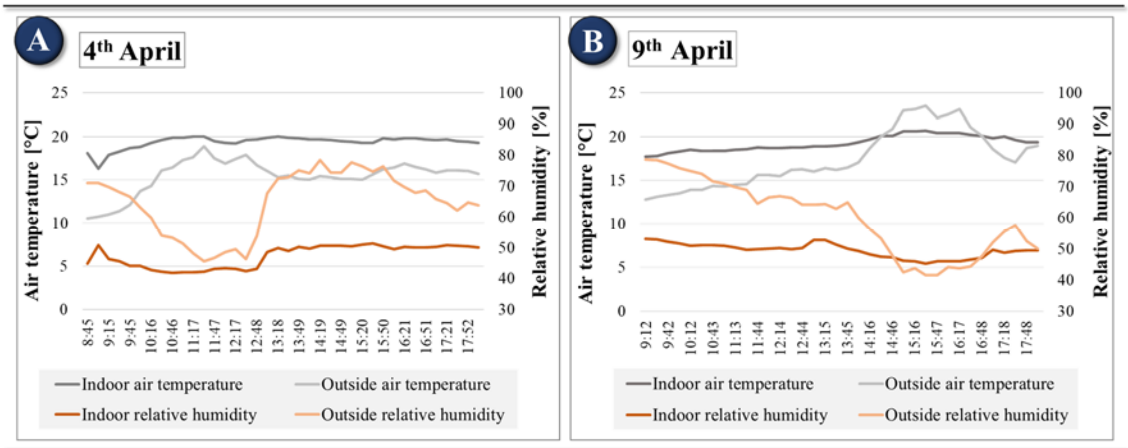


Figure 33: Indoor and outdoor air temperature and relative humidity: (a) 4th April; (b) 9th April.

Instead Figure 34 shows, for the same days, the trend of the illuminance on the working surface inside the living room and the values of vertical global solar radiation measured on the wall with west exposure where there is the mobile external shading system.

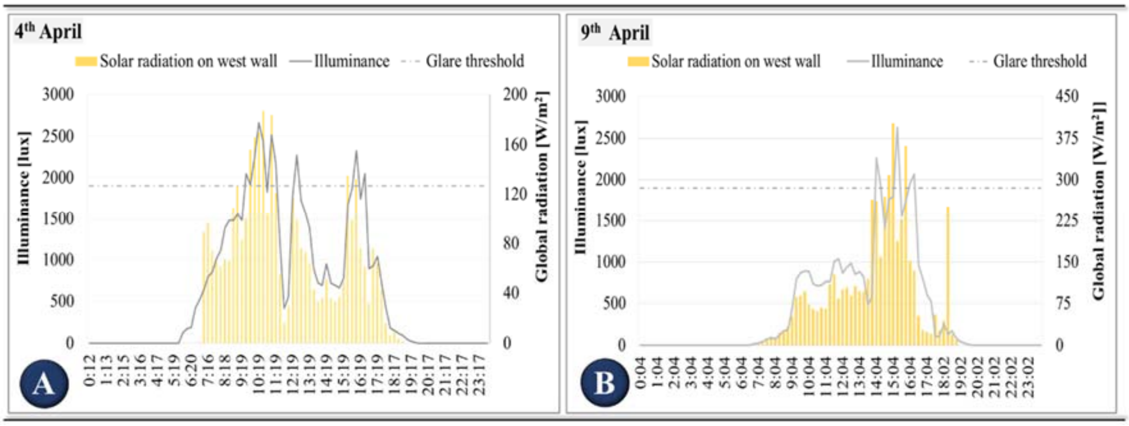


Figure 34: Lighting level and solar radiation on the west side: (a) 4th April; (b) 9th April.

During the 4th April, the air temperature is varied between 10°C and 19°C with a mean value of relative humidity of 60%. It is a typical not sunny day of Mediterranean spring season during which the mean value, between the 6:00 and the 16:00, of the solar radiation on the roof has been 232 W/m^2 with a maximum of 800 W/m^2 at 9:00. The shades of the living room are opened, and the incoming solar radiation contributes to heat the room. Indeed, the indoor air temperature reached 20°C (Figure 33a) at 10:46 and the comfort threshold value is maintained until round the 17:00. At midnight, the temperature is 18°C. The relative humidity varies only slightly inside the comfort range [88] although the heating system is turned off.

The 9th April is slightly warmer, since the air temperature varies between 12-23°C and the solar radiation on the roof is characterized by a mean value of 207 W/m^2 and a maximum one of 834 W/m^2 at 13:30. The west window is completely shaded, but the trend of air temperature does not change compared with the 4th April. It ranges between 17.5°C and 20.7°C; more in detail, the comfort threshold values are reached only from 14:00 to 17:30 meanwhile during the late evening and the night, the temperature decreases of around 2.0°C and also in this case it is around 18.0°C at midnight. This simple comparison allows to understand the importance of solar gains and it suggests that the appropriate use of the shading system is more important than the heat recovery for the exanimated external conditions.

The trend of the lighting level (Figure 34a) measured on the table in the room centre, shows how in the case of low solar radiation (4th April), the completely opening of shading devices allows to reach an illuminance level that ensure conditions of visual comfort. The occupants have also confirmed this. In few cases the illuminance exceeds 1900 lux. This happens when the value of solar radiation on the west wall goes up 110-120 W/m^2. However, being for short periods and since it is not a direct radiation due to the overcast sky, the occupants have declared that there was not visual discomfort or glare problems.

During 9th April (Figure 34b), the value of solar radiation monitored on the west side is higher, with peak values of 402 W/m^2 at 12:40. The occupants have decided to close the west exposure starting from the 10:00 in the morning; indeed, although it is a cloudy day, the incoming radiation causes discomfort for studying activities. Nevertheless, the lighting level exceeds the value of 1900 lux; according to occupants, it is due to the position of the sun between the clouds, that, when it is uncovered, is filtered only by the slats of the porch. Moreover, since the west window is shaded, the natural lighting is not enough many times, thus the artificial lighting systems has been turned on also during the morning.

Figure 35 shows the indoor and outdoor monitored variables for three typical spring days with variable weather condition and three different situations for window on the west side. The days 18th April and 8th May are characterized by almost clear sky conditions but with frequent and brief cloudiness and with very variable conditions in term of air temperature. More in particular, during the 18th April, the air temperature in the afternoon rises up 26°C with peak value of 30.9°C instead during the early morning (4:00 – 6:00 am) is lower than 10°C with a minimum value of 5.9°C. A comparable trend has been recorded during the 8th May when the temperature is the early morning is lower than the common values for this period, with minimum value of 7.1°C; then, during the afternoon, it reaches 29.4°C, as maximum value. Despite this variability, in both days the variability of indoor air temperature in the living room is quite limited. In the first case, starting from the 10:00 in the morning and until the 21:00, the indoor air temperature changes in the range 19-22°C and the shading system has been closed around at 14:00 when the monitored value of solar irrandiance on the west wall was greater than 250 W/m^2, the threshold value indicated in the literature [167]. Instead, with the window shaded starting from the early morning, the indoor temperature changes in the range 18-21°C in the same hours of 8th May. The comparison between these days can be performed considering three time intervals. From 10:00 to 14:00, in both days, the students are in the living room, the solar radiation penetrates inside the room but the shading system on west exposure is opened during the 18th April. With closed system, during the 8th May, the air temperature increases in this interval of around 3.0°C, until 12:00 it is higher than the external one for a maximum of 4.7°C and then it is lower than external one with a difference of -4.7°C at 13:00. Instead during the 18th April, the indoor value increases of around 4°C until 14:00 and it becomes lower than the external value at 12:30. Due to the positive contribute of solar gains at 10:00, the difference is 6.9°C and thus it is higher than in the previous case. At 14:00 the shading device on west side it is closed and until the 18:30, the radiation can be considered directly incoming. The temperature trend is in balance near the value of 22°C until 17:30 with a maximum difference of -9.3°C (at 15:15) with the external one. Due to the action of the shading system, during the morning of 8th May, the temperature increases slowly and from 14:00 until 19:00 it varies between 20-21°C with a maximum difference respect the outdoor value of -7.9°C. It can be concluded that the envelope characteristics allow to stabilize the temperature meanwhile the adoption of a shading system on the bigger window of the room decreases the indoor temperature of more than 1.0°C. Starting from available type of measures, and considering all possible variables, it is difficult to establish the contribute of ventilation in terms of temperature. However, it can be remarked that it allows the balancing of the latent load also if there is not an active humidifier; indeed the trend of relative humidity suggests that for both periods the comfort range established by EN 15251 (30-60%) is respected. Some other qualitative indications can be obtained considering the time intervals when the students do not stay in the living room and there is not solar radiation, for instance until the 5:00 in the morning. The 18th April, with the shade system opened, from 1.00 to 5:00 the external temperature ranges from 8.0°C to 10°C but the heat exchanges with the water of geothermal probes allows to maintain the indoor temperature (without other inner gains) in the range 17.9°C (00:00) – 16.9°C (5:00). During the 8th May (the shading device was been closed in the evening before), by considering the same hours, the external air temperature is ranged from 6.1°C to 8.9°C meanwhile the indoor temperature is varied between 17.2°C and 16.5°C. Globally, it can be noted that the geothermal heat recovery allows to keep the indoor conditions higher than the outdoor in a range of -6.1°C to -10.4°C; it can be also noted that when the shading panel is closed, the temperature decreases slowly, since it contributes to reduce the nocturnal radiative cooling and thus the heat losses.

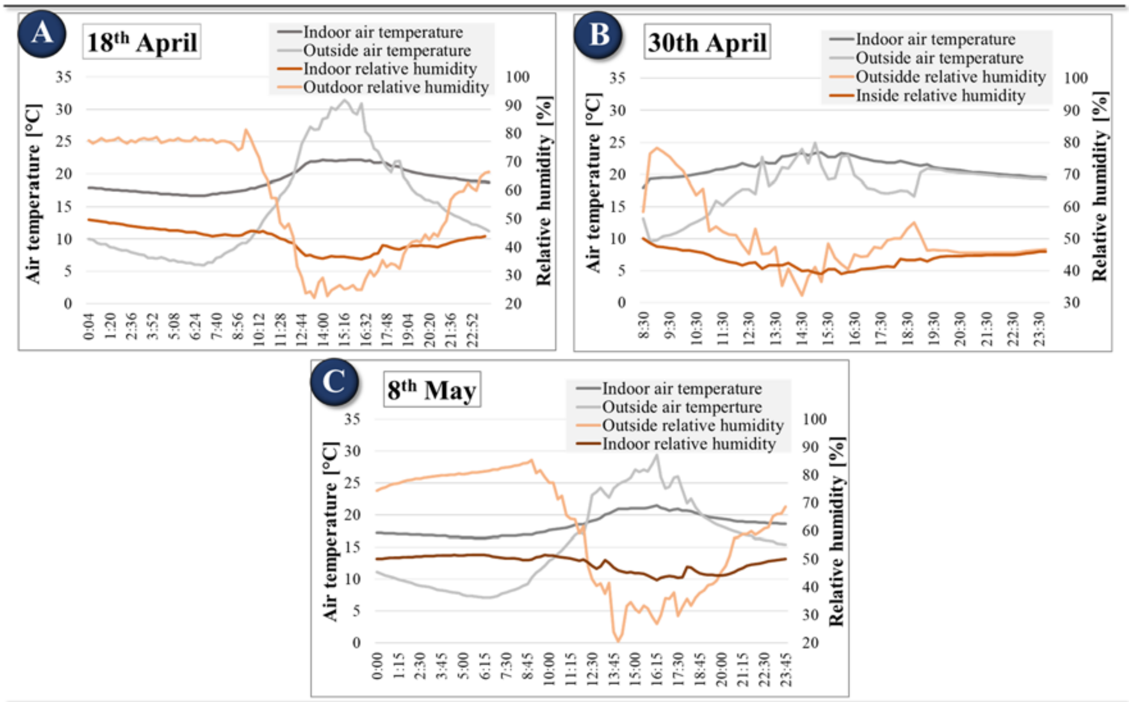


Figure 35: Indoor and outdoor air temperature and relative humidity: (a) 18th April; (b) 30th April; (c) 8th May.

Comparing the lighting level monitored in the room for these three days (Figure 36), the contribution of the external screen on the west side is clear. Indeed, while on 18th April, the illumination trend grows starting from the morning and it exceeds 2100 lux starting from 11:15 with maximum value of 4530 lux; then it falls sharply when the shading device is activated. However, it goes down the threshold value starting from 16:30 also if the radiation monitored on the west side is more than 500 W/m^2, with peak value of 625 W/m^2 at 16:20.

The visual conditions is better during the 8th May since the shading closing allows to contain the lighting level below 1900 lux during the whole day. It is a good result also in consideration of monitored radiance on west wall that reaches 720 W/m^2 in the afternoon as peak value. In both days, it is clear the great contribution of radiation through the south window in the morning, despite there are not clear sky conditions.

The overcast sky characterizes the 30th April, and, also in this case, the temperature is variable but with lower peak value since it ranges between 4.2°C (at 3:50) and 25°C (at 15:00). The windows are not shaded, and the occupants have declared to be satisfied with regard the thermal conditions. The living room is colder than in the other considered days, indeed the air temperature is 19.7°C at 10:00 and it becomes 21.4°C at 19:00 but reaches 23.3°C in the afternoon due to indirect solar gains.

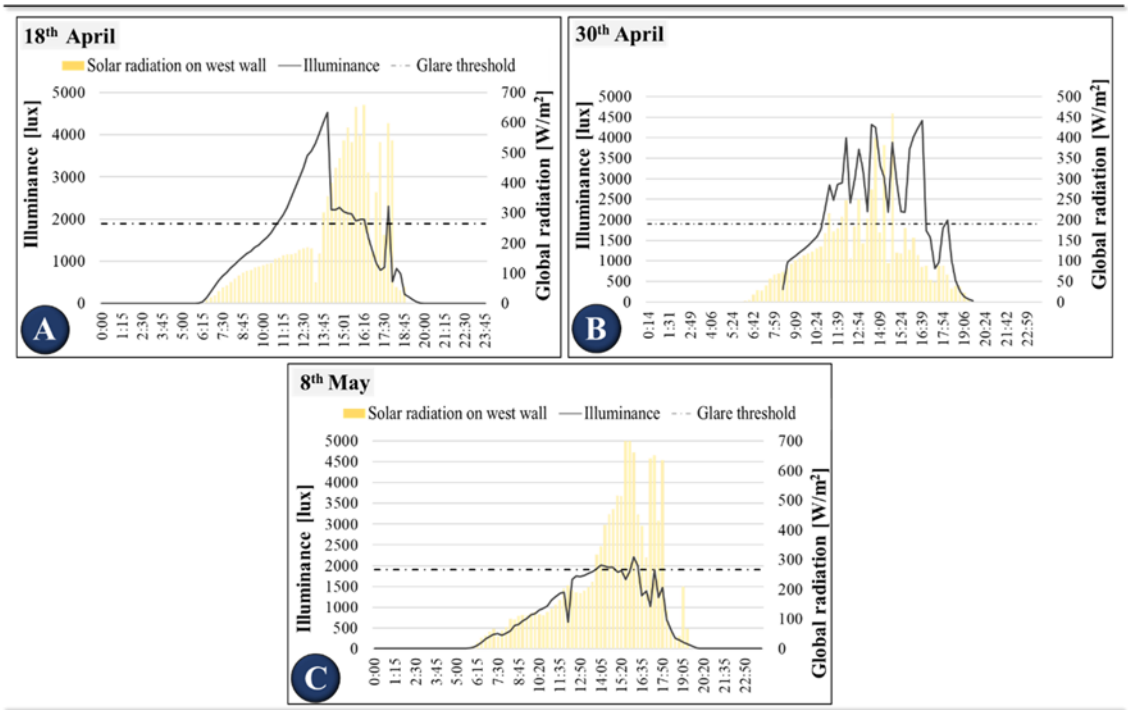


Figure 36: Lighting level and solar radiation on the west side: (a) 18th April; (b) 30th April; (c) 8th May.

Instead, referring to the conditions of visual comfort, it is clear in the Figure 36b that the lighting level on the work surface is above the 1900 lux threshold for most of the time, detecting visual discomfort for the occupants. It can be easily concluded that in the case of clear sky, if the shading systems is not adopted, the visual comfort for the occupants is not assured. Otherwise, the room is colder but in reference to the thermal conditions the occupants have declared acceptable conditions for all three days.

The last selected three days are characterized by very warm conditions for the spring season. According to the perceptions of the occupants of some days before, there has been the need to turn on the air conditioning system. The selected set-point value is 26°C. Moreover, since the amount of solar radiation incoming from the south window during clear sky conditions, the use of the blackout blind on the internal side of the window has been also considered. The monitoring results for these days remark the strategic role of the shading systems mainly on the external blind on the west side. Indeed during the 11th June (Figure 37a), in the early morning, the indoor air temperature is around 28.5-29°C and the students have decided to turn on the heat pump at 9:00 when the external temperature was around 24°C and the relative humidity of 60%. The outdoor temperature rises greatly, until 37.4°C at 14:30 and the solar radiation starts to penetrate directly in the living room from the west side at 13:00 when the monitored value by the sensor on the west wall is 1204 W/m^2; it reaches the peak value of 2772 W/m^2 at 15:00 (Figure 38 a). In this condition, the heat pump (set on, in cooling mode, given the very warm period) is not able to guarantee the comfort conditions inside the living room. The indoor temperature increases until 29.5°C between 14:30 – 15:30 meanwhile the relative humidity is always in the comfort range. The indoor temperature starts to decrease during the sunset (19:30) when the incident radiation becomes lower than 1000 W/m^2. The problem is the solar gain and this strategy for the shading system cannot allow the comfort condition inside the living room. This is confirmed by the value monitored, for instance, in the bedroom (15 m^2) south facing (next to the living room).

In the living room, that has two windows on south exposure for an overall area of around (3.9 m^2), the problem of solar radiation is solvable thanks to the use of the dark curtain in addition to the shading due to the porch. The effect of blind panel on west exposure is most evident looking to the Figure 37b. The outdoor conditions are comparable to the day before, since during the afternoon the outdoor temperature rises up to 37°C, with a maximum of 37.6°C at 15:30 and until the 19:00 it does not go down. The solar radiation exceeded 2000 W/m^2 from the early afternoon with a peak value of 4067 W/m^2 (Figure 38b). However, this time, the air-conditioning system is able to assure the comfort condition and the indoor temperature is always near the set-point value.

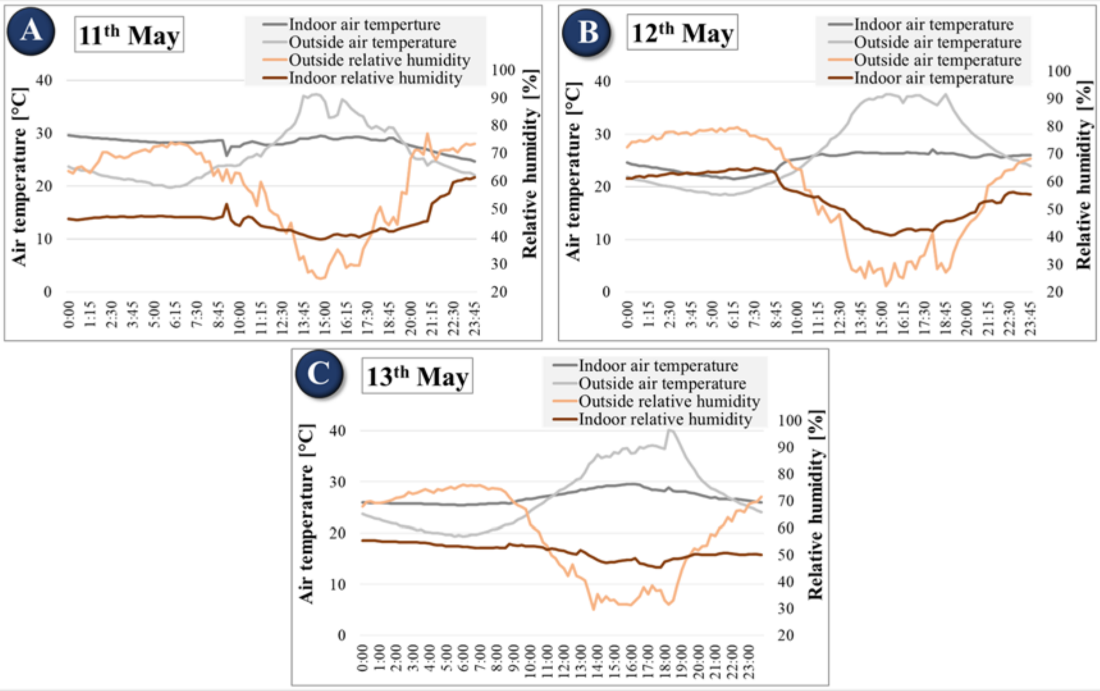


Figure 37: Indoor and outdoor air temperature and relative humidity: (a) 11th June; (b) 12th June; (c) 13th June.

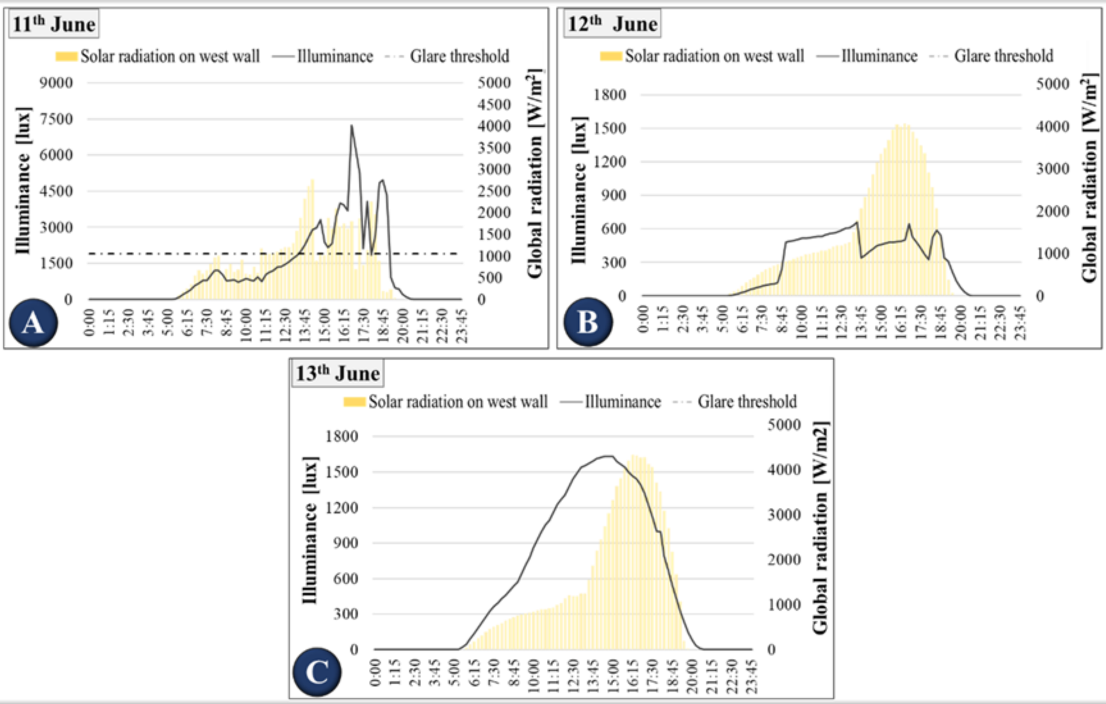


Figure 38: Lighting level and solar radiation on the west side: (a) 11th June; (b) 12th June; (c) 13th June.

By taking into consideration the visual aspect, (Figure 38a, 38b), the presence of the blind on the inner side limits the lighting level during the morning, then it rises sharply and exceeds 1900 lux during the afternoon when the sun is on the west side of the dwelling.

Nevertheless, the artificial lighting is not necessary also if the external conditions have been variable and the sky has been sometimes cloudy during the afternoon.

On 12th June, instead, due to shading devices, the lighting level on the working desk is less than 300 lux, for this reason it is necessary to use the artificial lighting system from 8:50 to about 1:45 and from 16:20 to 19:00. The glare threshold is always far to be reached in this case.

The indoor thermo-hygrometric conditions are comparable with the 12th of June during the day after, when the west blind is active, and the porch is the only shading system on south exposure (Figure 37c). In this case, the indoor temperature varies between 25.4°C and 26.8°C meanwhile during the afternoon the outdoor temperature increases continuously with peak value of 40.2°C at 18:00. Moreover, it can be observed that for the case study building, the use of external shading device on west side is enough to guarantee an adequate level of illumination (Figure 38c) and at the same time the 1900 lux threshold is not exceeded.

It can be concluded that the designed porch positively affects the reduction of solar gains during the spring but only if the shading system is active on west side the heat pump can balance the cooling load. The interpretation of visual conditions is more difficult. The first consideration is that the use of the shading device on west exposure seems fundamental for avoiding the glare threshold within the living room.

However, the occupants have expressed discordant opinions about the perception of visual discomfort within the same area; their indecision is mainly length to the permanent shielding of the window on the south exposure. But, on other side, the adoption of both blinds entails the need to use artificial lighting to guarantee a level of lighting suitable for the performance of the visual task on the work surface.

Considering the thermal and visual aspects, starting from the monitoring results, it can be considered appropriate during the spring season, the following control strategy in order to avoid the direct solar radiation into the room:

- closing the internal blind on the south from 10:30 am to 3:00 pm;
- activation of the west external shielding starting from 2:00 pm.

In this way it is possible to exploit natural lighting as much as possible and therefore limit the use of artificial lighting but at the same time avoid glare conditions for the occupants. More in general, according to the perception of comfort for the occupants, the limit beyond which there is the need to use the shading systems corresponds to the moment in which the solar radiation enters directly on the desk. Thus, it could say that the using vertical solar radiation as the set point for the control of shading systems is not always the best choice because, although it is the most widely used strategy in the literature, it does not prevent the experimental discomfort glare and does not solve the overheating problem during the intermediate season. Then, the optimization of both thermal and visual comfort requires the adoption of control strategy for shades not based only on a static range of the outside solar radiation. Moreover, the shading of windows with west exposure seems fundamental to guarantee the fulfilment of the indoor comfort without the activation of HVAC system but also to help the active system to reach the set-point value when the size of the generation system is very small. External directionally selective blinds could be the solution otherwise mobile device controlled with a simple timer that should be set, for each exposure, to close the shading device when the direct solar radiation start to enter in the room.

3.4.2.2 Hourly energy balance

The optimization of the hourly operational performance of the nearly zero energy building is a crucial in-coming objective for researcher and designers. Indeed, load matching and grid interaction are key aspects to be analyzed for the diffusion of Nearly Zero-Energy Buildings together with the fulfillment of the yearly energy balance and of the comfort requirement.

The analysis of hourly energy balance for the selected days is proposed in this section. First of all, it can be observed that in all days, the greatest consumption is due to the ventilation and air conditioning system. More in detail, when only the ventilation is turned on, it requires from 23% (4th April) to 42% (30th April) of total electricity needs. While during the days when the system is settled up in cooling and ventilation mode, its energy consumption varies from 40% (13th June) to 70% (11th June) of total electricity consumption of dwelling.

In order to evaluate if the nearly zero target is achieved, it is really interesting the analysis of the hourly energy balance of the building-HVAC system. The hourly trend of energy consumption, PV-system generation and the energy storage are shown in the following figures. Moreover, Table 7 reports the indexes introduced before (section 3.3.2.2 and 3.4) to evaluate the effectiveness of integration of renewable sources in real operational mode.

The analysis of Figure 39 indicates that when the system operates only for the mechanical ventilation, the electric request is fully covered by renewable production. Indeed, except for the 9th April, the RenEl index is equal to 100% as well as the $F_{loadmach}$; this means that the combination of production and storage can assure to cover the whole daily electric request with perfect matching between request and production. It is also clear that during the intermediate season, when the outdoor conditions are particularly favourable in term of solar irradiance, the installed capacity determines very high production.

The comparison between 4th and 9th April highlights the different behaviour during the cloudy days, basing on the ability to intercept the solar radiation and on energy consumptions. In both days, the electric energy given by the battery allows to cover the energy requests during the early morning. Instead, since during the morning of 9th April (until 11:00), the whole sky looks like a snowstorm, the PV-production is very low compared with 4th April, respectively 568Wh and 1058Wh at 10:00. This means that during the morning a part of the produced electricity charges the battery during the 4th April and it is available in the following hours so the requirement of the building can be completely satisfied (RenEl 100%) also in terms of hourly matching between load and generation ($F_{load\ match}$ 100%). During the late morning and afternoon, the situation is reversed. At 14:00, the PV-production is 1976 Wh during the 9th April and 455 Wh during the 4th April. The production during the afternoon helps to close with positive results also the balance in the second day since RenEl is 99% but the ratio between the production and the consumption is the lowest (74%) with reference to all considered days.

During the days with the system settled up in cooling and ventilation mode, the building energy consumption is not completely satisfied by the electricity from photovoltaic system.

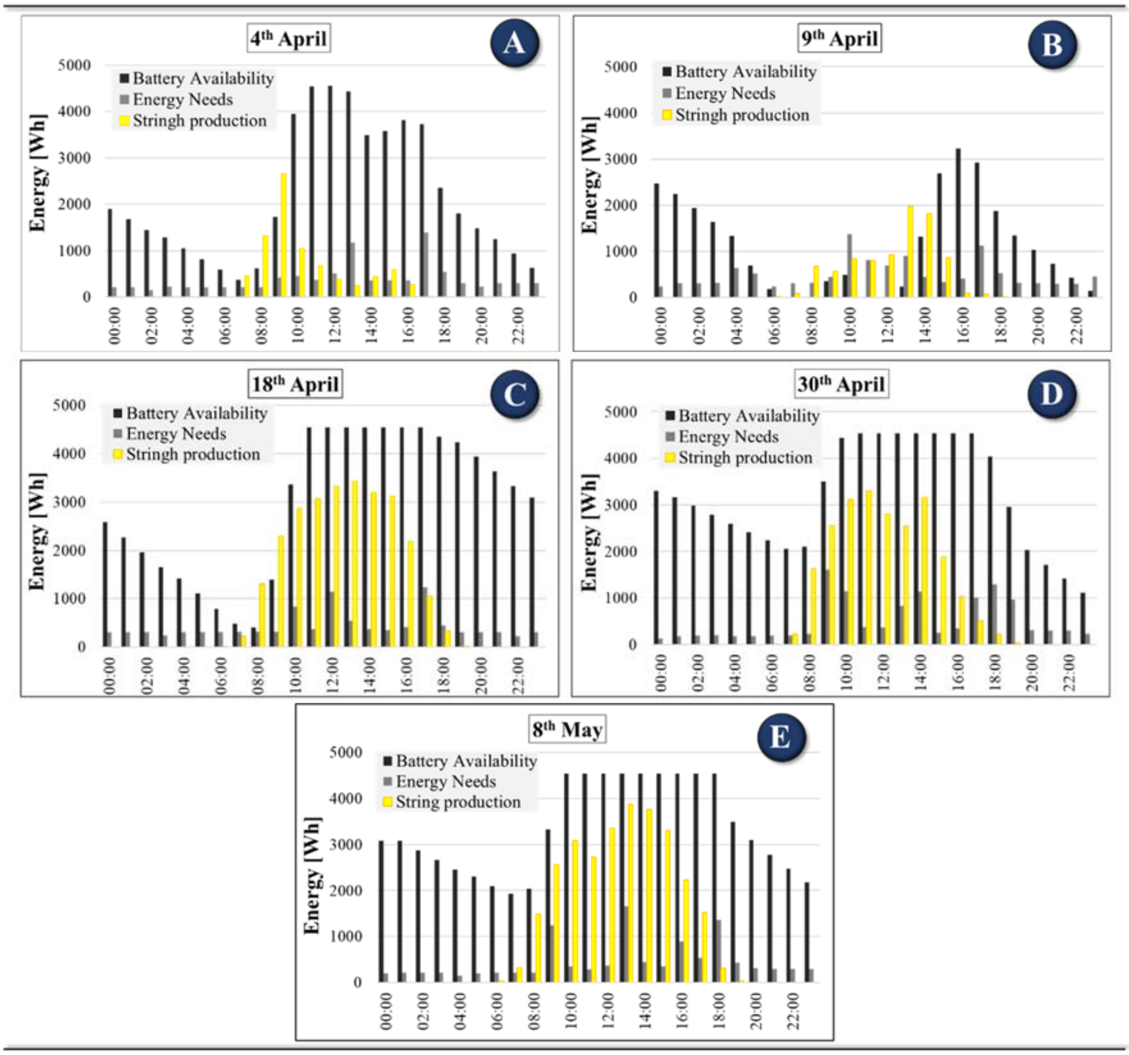


Figure 39: Hourly energy balance: (a) 4th April; (b) 9th April; (c) 18th April; (d) 30th April; (e) 8th May.

Table 7: Load match index, renewable electricity index and photovoltaic index.

	4th April	9th April	18th April	30th April	8th May	11th June	12th June	13th June
$F_{loadmatc}$	100 %	95 %	100 %	100 %	100 %	85 %	67 %	57 %
RenEl	100 %	99 %	100 %	100 %	100 %	98 %	87 %	62 %
PV	89 %	74 %	258 %	182 %	251 %	86 %	131 %	141 %

Figure 40 describes two different situations; during the day before the 11th the air-conditioning system is turned off, thus the surplus of renewable electricity is available in the battery. This covers the building request until the morning; at 9:00 the students turned on the heat pump but the simultaneous production (peak value 3411Wh at 11:00) and for some hours the battery satisfies the requests (RenEl 98%). Starting from the 20:00, the consumptions are covered by imported electricity from the grid.

The last two days are characterized by an increased interaction with the national grid. Instead, in both cases, during the night, the battery is discharged, and the electricity must be supplied from the external grid. Starting from the 7:00, the PV-production allows to cover the request and also the battery starts to charge. At 13:00 the production reaches the maximum value of 3400Wh during the 12th June and the same value is reached at 12:00 during the following day. Two considerations can be done; first of all, the energy storage assure the contribution of renewable source until 20:00 or 21:00, for this reason the RenEl index is higher than 60%. The hourly consumption can be less matched compared to the other days, indeed the $F_{load\ match}$ is lower than 70%.

Secondly, the daily generation from the panels exceeds the sum of the energy consumption and the storage availability; indeed, the PV index is higher than 100%. The amount of surplus energy is exported to the grid during the hours of highest production from the PV system. It can therefore be stated that to further increase the coverage of the consumptions from the on-site generation, a battery with greater storage capacity seems the solution.

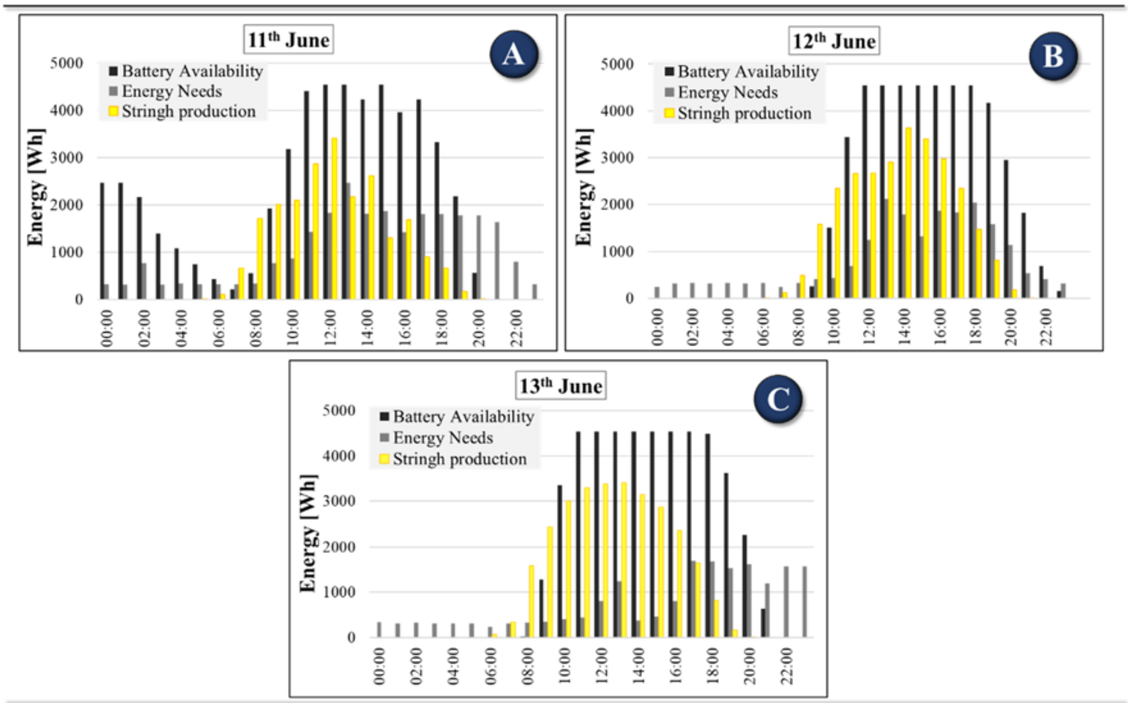


Figure 40: Hourly energy balance: (a) 11th June; (b) 12th June; (c) 13th June.

The comparison between non-cooled and conditioned days underlines a criticality of the new designing objectives. Considering the BNZEB, during the 18th April the PV index is 258% since the production is around 26.4 kWh instead the consumption is around 10 kWh. Mainly in Mediterranean climate, when the designer tries to match the load and source for the summer period, the system configuration often ends up with excess generation in the intermediate period due to lower consumptions. The result is that surplus renewable electricity needs to be curtailed to balance the system. This can be treated primarily as a technology problem during the designing. It is needed an adequate energy storage to convert the excess at one time of day into necessary power system supply at another. However, it could be not enough, as in the case of BNZEB. This means that the featuring designers and researchers cannot look only to the single building, but they should consider the design in a broader perspective of high efficient smart grids. Especially smarter distribution systems will be better able to manage increasing shares of renewables as well to install and charge their battery powered devices when there is excess production. And finally, the growth of EVs (i.e., electric vehicles, currently driving global battery demand) represents a huge potential source of storage and demand-side flexibility as well.

The results of energy balance underline that it is really important the time interval with which the design and the real operational mode are evaluated. The goal of featuring design is to assure that the three indexes introduced could be near the 100% not only during the summer but also to the intermediate season. This assure that the positive yearly balance has not been achieved by oversizing the PV-system but with the optimal designing of building envelope, renewable active system, storage capacity and management strategy.

In general, the results from this springtime assessment might give indications of how blinds should be treated in nZEB design in hot climates for maximizing the visual and thermal comfort. Moreover, experimental data could help designers in the evaluation of the usefulness of mechanical ventilation with heat recovery to reduce the discomfort during periods without active heating or cooling. Since the energy balance with daily or hourly time step is not available for other existing buildings, the presentation of some new and already used indexes to evaluate the impact of renewable production on short time step allows a discussion on the possible load matching and grid interaction; the positive effect of the electric storage is also considered. These are the main problems that designers will have to face in the near future when the nZEBs will become not only a research topic but a normative definitely prescription, with many examples and real buildings in real operation.

3.4.2.3 CFD assessment during the spring season

The calibrated numerical model of the building (sub-section 3.2.2) was used to study the air temperature distribution inside the building as well as the distribution of global comfort indices by the Computational Fluid Dynamic (CFD) tool of DesignBuilider.

As it is well known, the thermal comfort is the condition of mind that expresses satisfaction with reference to the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55) [168]. Maintaining a standard of thermal comfort for occupants of a building is one of the main goals of HVAC systems and passive design solutions. Most people will feel comfortable a room temperature, but this may vary greatly between individuals, and this is depending also on factors such as activity level, clothing, and humidity. A condition of thermal neutrality is obtained when the heat generated by human metabolism is balanced, thus maintaining thermal equilibrium with the surroundings. Moreover, psychological parameters, such as individual expectations, also affect thermal comfort. When discussing thermal comfort, both static model (PMV/PPD, according to Ole Fanger) can be used, as well as adaptive approaches. In recent years, these are recommended for naturally ventilated buildings. Conversely, with reference to the case study here discussed, given that the indoor environment is fully air conditioned, the traditional PMV and PPD indexes have been considered.

The PMV/PPD model by P.O Fanger was developed in order to define thermal comfort by solving heat balance equations and empirical studies about skin temperature. PMV stands for "Predicted Mean Value" and it is useful to estimate the average thermal sensation vote on a standard scale for a huge number of people. The PMV index predicts the mean response of a large group of people according the ASHRAE thermal sense scale: +3 hot; +2 warm; +1 slightly warm; 0 neutral; -1 slightly cool; -2 cool; -3 cold. While the PPD is an index that predicts the percentage of thermally dissatisfied people who feel too warm or too cool and is calculated from the predicted mean vote. In particular, at the neutral temperature as defined by the PMV index equal to 0, PPD indicated that 5% of occupant will still be dissatisfied with the thermal environment.

The analysis was focused on living room of the building, characterized by largest windows surface with also mobile shading devices; it was also focused on analysis of distribution of Predicted Mean Vote Index (PMV) and Predicted Percent Dissatisfied Index (PPD).

Unlike an energy simulation that gives results in which the investigated variables assume different values over time (i.e. hourly results), before running a CFD simulation, a precise time instant must be fixed. The calculation method requires that the geometric space across which the analysis has to be conducted is first divided into a number of non-overlapping adjoining cells, which are collectively known as the finite volume grid (or mesh). The analysis of PMV distribution (as well as temperature or other variables) requires the adoption of proper boundary conditions. These are fixed and equal to value at 1:00 p.m. given by simulations, for the days investigated. Moreover, in order to evaluate the comfort conditions by means of CFD simulation, also the indication of the metabolic rate and the thermal resistance of clothing are required. In detail the metabolic rate is set equal to 1.2 met (equivalent to 70 W/m2) corresponding to sedentary activity for home or school; the thermal resistances of clothing are set equal to 1 clo for the first three days, 0.8 clo for the fourth and fifth days examined and 0.6 clo for the last two days, according to the real characteristics of occupants' clothing.

The results of CFD analysis confirm the consideration already shown concerning the in-field monitoring investigation reported in the sub-section 3.4.2.1. In particular, during the 4^{th} April, the air temperature varied between 10°C and 19°C, the shades of the living room are opened, and the incoming solar radiation contributes to heat the room. Indeed, the indoor air temperature becomes 20°C and the comfort threshold value is maintained until round the 17:00. The 9^{th} April is slightly warmer, since the air temperature varies between 12-23°C while the west window is completely shaded. But, in general, the trend of air temperature does not change compared with the 4^{th} April. The CFD analysis confirms that comfort conditions inside the living room are guaranteed during both two days. Indeed, looking the Figure 41, the PMV results within the range ± 0.5 with a regular space distribution too, and the PPD results lower that ± 10%.

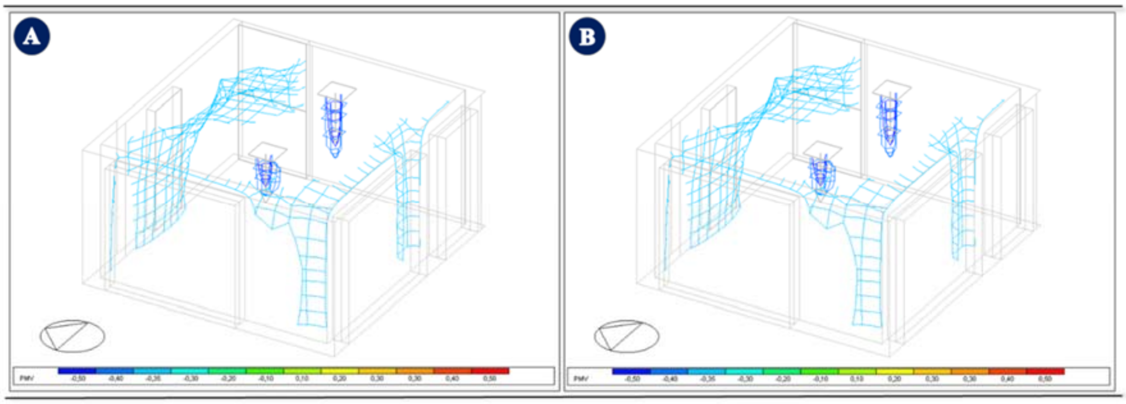


Figure 41: PMV evaluated at 1 p.m. on: (a) 4th April and (b) 9th April.

Meanwhile, the days 18th April and 8th May are characterized by almost clear sky conditions but with frequent and brief cloudiness and with very variable conditions in terms of air temperature. Despite this variability, in both days the variability of indoor air temperature in the living room is quite limited. In the first case, the indoor air temperature changes in the range 19-22°C and the shading system has been closed around at 14:00. Instead, on 8th May, with the window shaded starting from the early morning, the indoor temperature changes in the range 18-21°C in the same hours. Due to the action of the shading system, during the morning of 8th May, the temperature increases slowly and from 14:00 until 19:00 it varies between 20-21°C, with a maximum difference respect the outdoor value of -7.9°C. In general, it can be concluded that, in these conditions, the envelope characteristics allow to stabilize the indoor temperature and the adoption of a shading system on the bigger window of the room, allows to decrease the indoor temperature of more than 1.0°C. Indeed, also in these cases, comfort conditions are guaranteed inside the living room with a value of PMV within ± 0.5 and PPD lower that ± 10%.

Meanwhile, due to the overcast sky during the 30th April, with a peak value of outdoor air temperature of 25°C (at 15:00), the living room is colder than in the other considered days, indeed the air temperature is within 19.7°C - 21.4°C. By the evaluation of PMV and PPD results that, inside the living room, there is a condition of "slightly cold" for the occupants. However, the occupants have declared to be satisfied with regard to the thermal conditions until 1:00 p.m., probably because the windows not shared influenced the perception of occupants and in the afternoon due to the sole gain the air temperature reach 23°C.

The last selected three days are characterized by really warm condition for the spring season, during which despite the activation of air conditioning system, inside the living room there are discomfort condition for occupants. The problem is the solar gain and the adopted strategies for the shading system cannot allow the comfort condition, that meanwhile are guaranteed inside the bedrooms. Indeed, for the living room, the PMV index result always higher than 0.5, with a corresponding PPD index of about 50%.

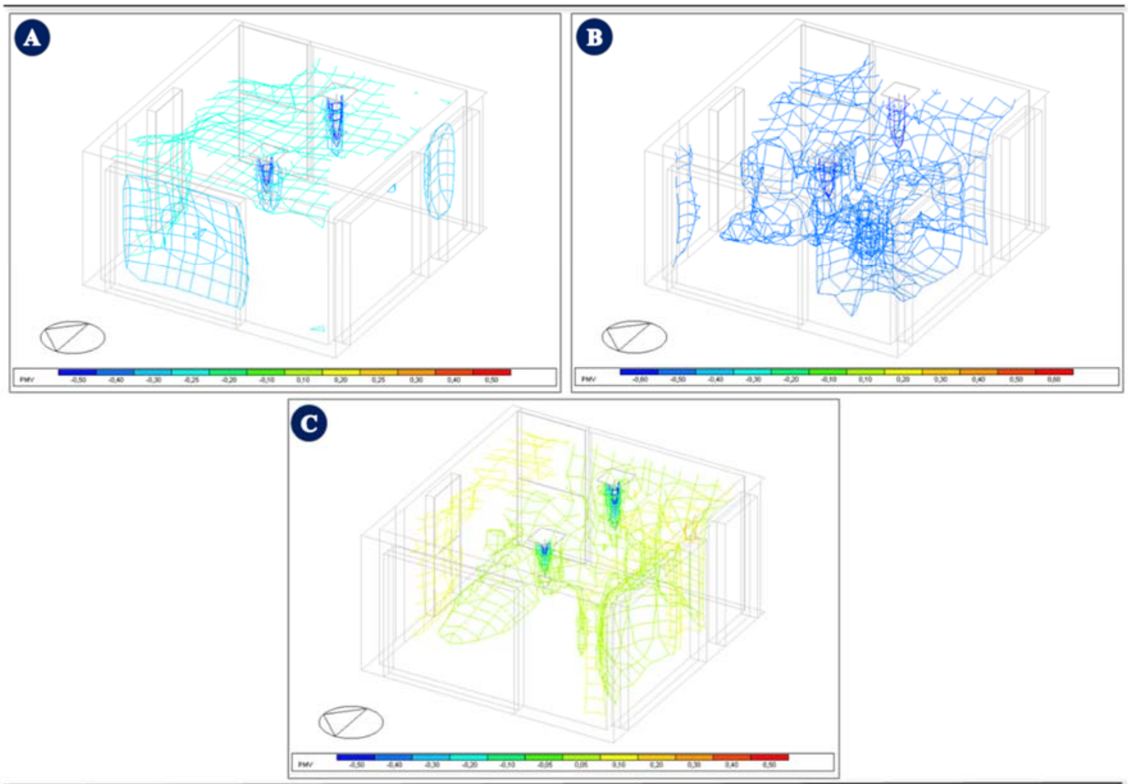


Figure 42: PMV evaluated at 1 p.m. on: (a) 18th April; (b) 30th April and (c) 8th May.

However, by considering that the outdoor conditions of these three days are more or less comparable (with an outdoor air temperature of 26.1°C, 26.8°C and 27.2°C respectively), looking the Figure 43 it is possible to notice the positive effect of the shading device on the indoor conditions. Indeed, the worst values and space distribution of PMV index are obtained on the days 11th and 13th May during which only one of the shading devices is active, respectively the one with south and west exposition. Meanwhile on 12th both the shading devices, on west that south exposition, are activated, by resulting in a more regular space distribution of comfort indices and in a lower value of PMV compared to the results obtained for the close days.

In general, the results of CFD analysis shown for the first fourth days of monitoring campaign a PMW index close to neutrality, because it is between ±0.5 with a PPD almost equal to 8% or 10%. The same cannot be said for the last three days of monitoring campaign, where the PMV index results between 1.8 and 1.3, and then the indoor environment has been considered a "warm environment" with a PPD between 50-70% during 11th and 13th June and equal to 50 % during 12th June. Finally, during 8th May the PMV was exactly equal to -0.5 and thus PPD result equal to 10%. These is in agreement with the occupants' impressions and the analysis of the indoor environmental parameters reported in section 3.4.2.1.

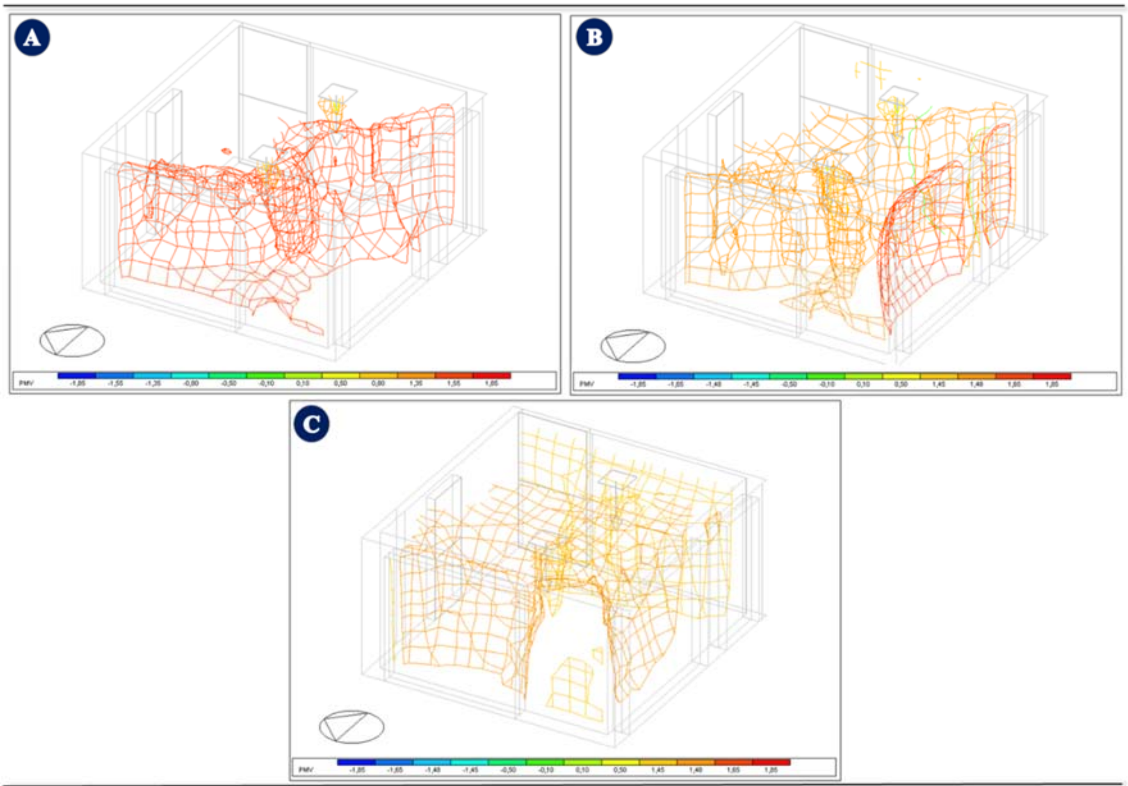


Figure 43: PMV evaluated at 1 p.m. on: (a) 11th May; (b) 12th May and (c) 13th May.

The performed CFD analysis allowed to verify the conditions reached inside the building and the effect of shading management on the indoor comfort conditions; resulting an important instrument to predict the indoor conditions under different HVAC configurations and management of installed device during the year.

3.4.3 Effectiveness of pre-handling system based on earth-water heat exchanger

As mentioned before, the monitoring campaign during the autumn period, further than to evaluate and discuss the real performance of an existing nZEB and its energy balance at hourly time scale, is aimed at evaluating the contribute of geothermal source for the pre-treatment of ventilation air flow during the intermediate season. Then, when the heating system is turned off and there is a great variability of external conditions both in terms of temperature and solar radiation, that could be balanced only by a high effectiveness and proper designed of air pre-treatment section.

Recently, in order to achieve the zero-energy balance goal, different strategies for the supply of ventilation pure air into zero energy buildings were investigated, as shown in the review of Liu *et al*. [169]. In general, in the literature, the mostly used technology to pre-cool/heat the fresh air consists in the exploitation of geothermal source, often also combined with heat recovery units [170]. Indeed, thanks to the property of the earth at a certain depth, the low-enthalpy geothermal energy is one of the renewable energy sources with an easier access and low impact on the environment [171]. In this perspective, Eicker *et al*. [172][173] studied the influence of soil parameters and inlet temperatures to the ground heat exchangers. In the same vein, Lyu *et al*. [173] simulated the energy saving potential of geothermal fresh air pre-handling system in different climate of China, shallowing that geothermal energy could be quite effective in various climatic zones. Furthermore, Ascione *et al*. [174], even by means of numerical simulations, evaluated the benefits of the use of an earth-to-air heat exchanger in a nZEB in an Italian city with a typical Mediterranean climate. However it is important to consider that the study of the recent literature reveals that the ground-to-water heat exchangers are often integrated with building envelopes and used in ground source heat pumps, while the earth-to-air heat exchangers are already commonly adopted to pre-cool or pre-heat the ventilation air before supplying this into buildings [175]. Only some studies [176][177] established more attention to the ground-coupled heat exchanger systems based on water instead of air, but this strategy can be considered an interesting alternative also to pre-cool and pre-heat the ventilation air in low-energy houses, especially due to the high heat capacity of liquid water. Moreover, this kind of system allows to avoid the requirement of large surface area below the ground, necessary in case of earth to air heat exchangers, characterized by large tubes installed underground. Obviously, in earth-to-water systems, the ventilation air will be indirectly cooled or heated with the water flow in an intermediate water-to-air heat exchanger in the inlet ventilation channel, whose design, consequently, will affect the overall performance of the system. Moreover, with the exception of few numerical studies like the one performed by Chel *et al*. [178], there are not experimental in-field investigations that evaluate feasibility and energy performance of earth-to-water exchangers, aimed at the pre-cooling and pre-heating of ventilation air, in order to contribute in achieving low-energy buildings. Then, starting from the proposed literature review, it is clear that there is a need of experimental studies concerning the evaluation of energy performance of systems in which an earth-to-water heat exchangers are coupled to water-to-air heat exchanger, and so evaluating if the whole system could be capable in pre-cooling and pre-heating the ambient air, necessary for air-change purposes and indoor air quality.

In this perspective, the analysis proposed in this section is aimed to verify if the setting of pre-handling system, composed by a EWHE system coupled with a recirculation of the exhaust air from internal environment, provide satisfactory conditions for the occupant during the autumn period. In particular, the EWHE consists of a ground-to-water heat exchanger which is coupled with a water-to-air exchanger for pre-cooling or pre-heating the outdoor air before its entering in a commercial aeraulic heat pump. Moreover, the contribution of the internal air recirculation inside the aeraulic heat pump and the contribution of the EWHE system will be evaluated in terms of monitored air temperature in each section of the pre-treatment system and in terms of heating capacity of the earth-water-heat exchanger calculated through monitored data. Obviously, as said, the hourly energy balance in a "real use" context and the thermo-hygrometric conditions inside the building will be evaluated too.

With this purpose, several variables have been monitored with a sample time of 15 minutes and in detail: the electricity consumptions for different lines (lights, plugs, air conditioning systems); the electricity generation due to PV-system; the values of some microclimate variables inside and outside the BNZEB building; the air temperature at the inlet of the recirculation section and in the section before it is released into the rooms; the air temperatures upstream and downstream of the pre-treatment heat exchanger and the flow and temperatures of the water-glycol mixture at the inlet and outlet of the earth-water exchanger.

The obtained results will be shown in the following sections. In particular, the performance assessment concerned the energy balance on the building (sub-section 3.4.3.2) and the occupants' satisfaction with respect to thermo-hygrometric comfort and air quality (sub-section 3.4.3.1) will be shown in the first two sections; while in the last one, the effectiveness of EWHW system will be shown (sub-section 3.4.3.3).

3.4.3.1 Indoor thermal comfort and air quality

The evaluation of indoor conditions is based on the monitoring of several indoor parameters: air temperature, relative humidity and CO_2 concentration. Really, some external climatic parameters are also collected with the same time step, and thus the air temperature, relative humidity and the CO_2 concentration.

October is the typical autumnal month for Mediterranean cities during which the heating and cooling system are turned off. During the 2019, considering the data monitored by weather station on the roof of the building, the mean monthly temperature has been 17.2°C with peak value of 31.6°C during the hottest day (23th October at 16:10) and minimum value of 5.6°C in the coldest day (28th October at 6:30). There were only two rainy days (7th and 16th) with maximum intensity of 4.0 mm/h, meanwhile the global solar radiation in the late morning usually ranges between 400-650 W/m^2. The results of monitoring during this period is shown for two days, the 14th and 15th October that can be considered representative of the external and internal conditions. As regard the external variables, the mean temperature has been respectively 17.3°C and 17.6°C and maximum temperature in both cases around 27.5-28°C with the relative humidity that during the sunny hours is ranged between 46% and 70%. The maximum intensity of global solar radiation measured on the roof has been 601 W/m^2 during the 14th and 577 W/m^2 during the 15th.

As regard the indoor conditions, Figure 44a shows the trend of the indoor and outdoor air temperature and Figure 44b refers to the relative humidity. Instead, Figure 45 reports the trend of CO_2 concentration with the indication of the limit values according to EN 15251

[88]. In both cases the bedrooms (with north and south exposure) are the rooms where the occupants stayed for the most of hours during the day.

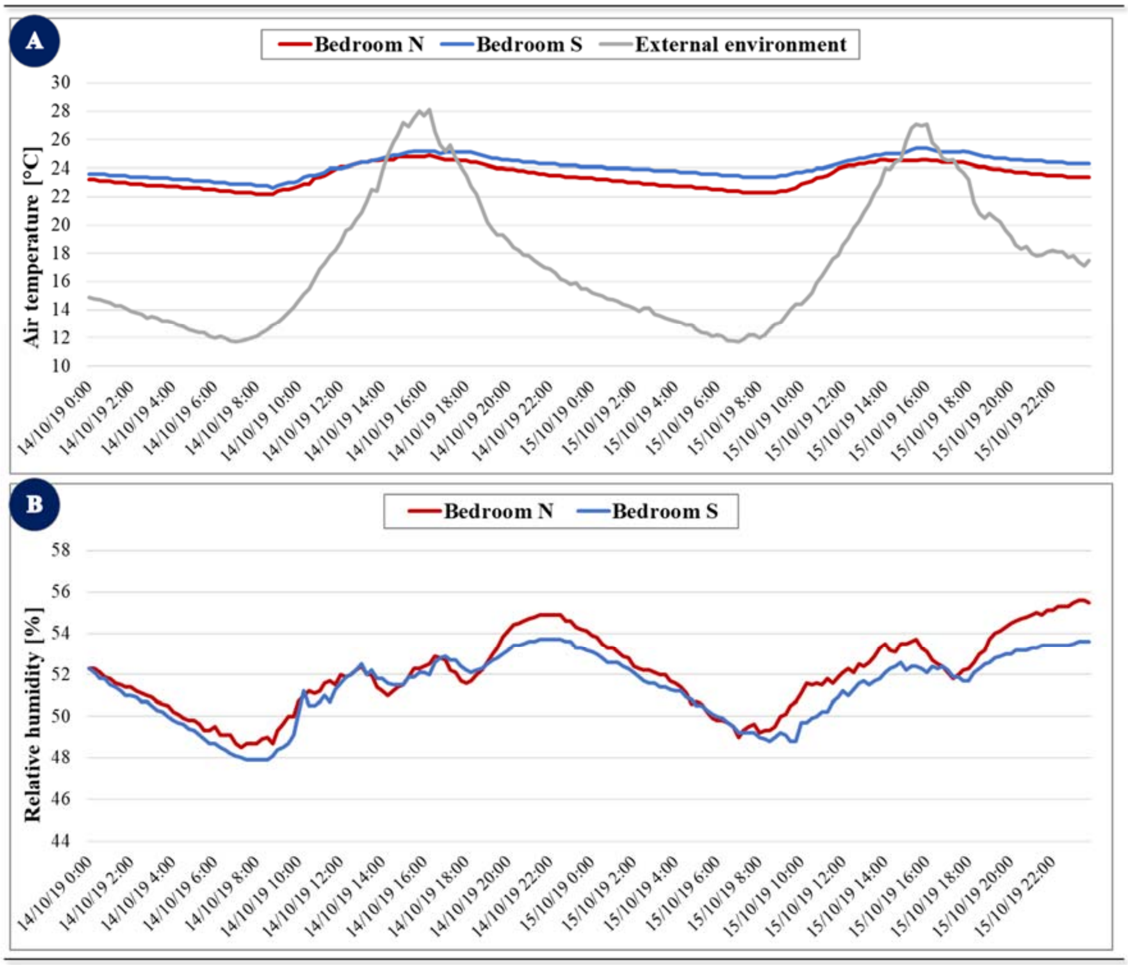


Figure 44: (a) Indoor and outdoor air temperature; (b) indoor relative humidity – 14th and 15th October 2019.

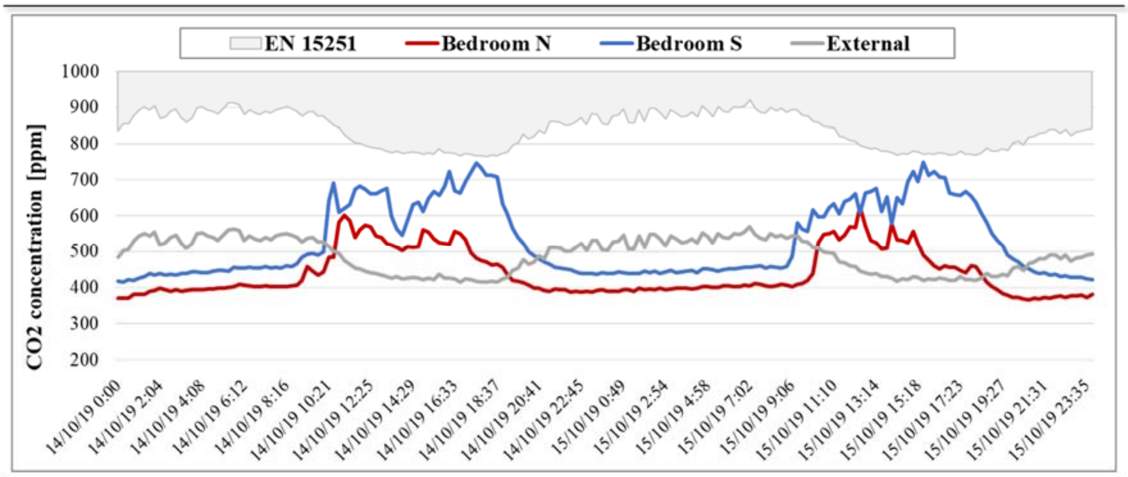


Figure 45: CO_2 concentration inside and outside the building – 14th and 15th October 2019.

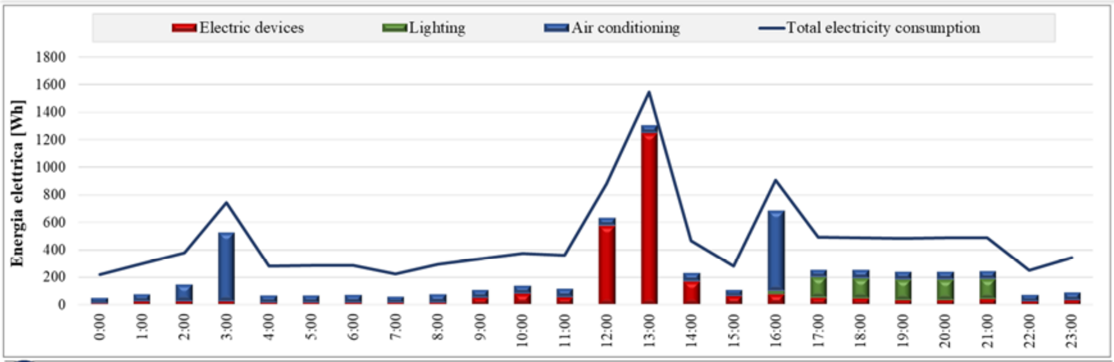
The monitoring campaign indicates that the temperature inside the building varies between 22°C and 25°C while the external temperature fluctuates between 11°C and 28°C (Figure 44), while the relative humidity varies in the ranges of 48 ÷ 56%. The international standards do not indicate reference range for establishing the acceptability of indoor conditions. Considering as reference the range for the winter period, it can be said that inside the building comfort conditions are guaranteed. Indeed, the occupants have expressed satisfaction with regard the thermo-hygrometric conditions. Therefore, it is possible conclude than inside the BNZEB building even during the autumn period, when the HVAC system is only in ventilation mode, comfort conditions are guaranteed for the occupants both in terms of values of acceptable indoor temperature and relative humidity, that in terms of uniformity of conditions over time. Moreover, even good air quality conditions were guaranteed, since the CO_2 concentration (Figure 45) inside the building has been always below the limits.

Then, the results show that during the autumn period, although the HVAC system is settled in only ventilation mode, satisfactory comfort conditions for the occupant are guaranteed inside the building, confirming the effectiveness of design chosen. This are assured by the presence of fresh air pre-treatment system (EWHE) and the internal recirculation of the heat pump. The first provides the pre-heating of outdoor air before the heat pump; instead thanks to the recirculation system integrated in the heat pump the air introduced into the rooms is, under favourable conditions, a mixture of extracted air and fresh one and therefore part of the energy is recovered.

3.4.3.2 Hourly energy balance

As already explained, during some representative days two students have occupied the BNZEB, replicating some typical actions using common electrical devices for a dwelling in order to use the building as in “real use” conditions. During these days, the HVAC system has been set in ventilation mode, and the fresh renovation external air is firstly pre-heat or cool by means of the water-glycol mixture at outlet of the earth-water exchanger, and then it is mixed with part of extracted air from the indoor environment.

Figure 46 and Figure 47 show the hourly energy consumption of the building, respectively during 14th and for 15th October.

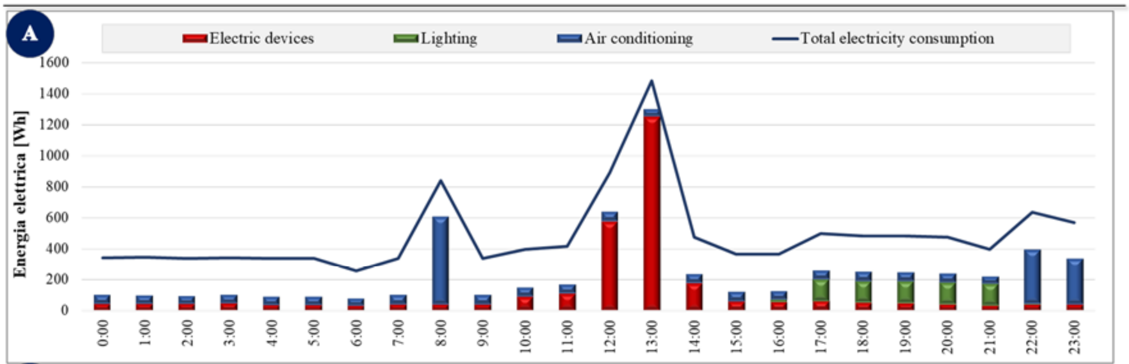


B

Use of devices during the time (minutes of use for each hour)

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
living room lights																	
room N lights										10min	1h	40 min					
room S lights										15min	1h	40 min					
kitchen lights																	
bathroom lights																	
burners						20min	10min										
oven							40 min										
hood						20min	10min										
fridge	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h
computer n.1			15 min	1h	1h	1h	1h	1h	1h	1h							
computer n.2				1h		1h		30min	30min								
mobile phone n.1								30min		50min							
mobile phone n.2							1h										
television							30min	30min									
hair dryer																	
open window																	
toilet flush		1			1			1		1			1				
toilet sink		1min					2min										
shower stall												20min	20min				
kitchen sink							10min										

Figure 46: 14th October: (a) hourly energy consumptions; (b) activity performed during the day by occupants.



B

Use of devices during the time (minutes of use for each hour)

	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
living room lights																	
room N lights										15 min	1h	5 min					
room S lights											1h	5 min					
kitchen lights																	
bathroom lights																	
burners						20min	10min										
oven							40 min										
hood						20min	10min										
fridge	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h	1h
computer n.1					1h	1h		1h									
computer n.2				1h				1h									
mobile phone n.1					1h												
mobile phone n.2				1h			1h										
television							30min	30min									
hair dryer																	
open window																	
toilet flush		1			1			1		1			1				
toilet sink		2min					2min										
shower stall												20min	20min				
kitchen sink							10min										

Figure 47: 15th October: a) Hourly energy consumptions; b) activity performed during the day by occupants.

In detail, both the overall consumption that the amount of energy required for lights, plugs and HVAC are reported. In these figures the activities performed by the occupants are also reported. Globally, the total energy consumption is equal to 11.1 kWh during the 14th October and 11.8 kWh during the 15th October.

Synthetically, the energy consumption for ventilation is about 15% - 18% of the total request, respectively for 14th and 15th October. The artificial lighting affects for, respectively, the 7% and 6% the daily balance. The main consumption is due to the monitoring system and other technical device that occurs for 50% and 49% on total daily consumption of the BNZEB during14th and 15th October respectively.

Finally, Figure 48 shows the hourly energy balance during the chosen days. In detail the electric energy consumptions, the generation from PV-system and the electricity available in the battery are reported for each hour.

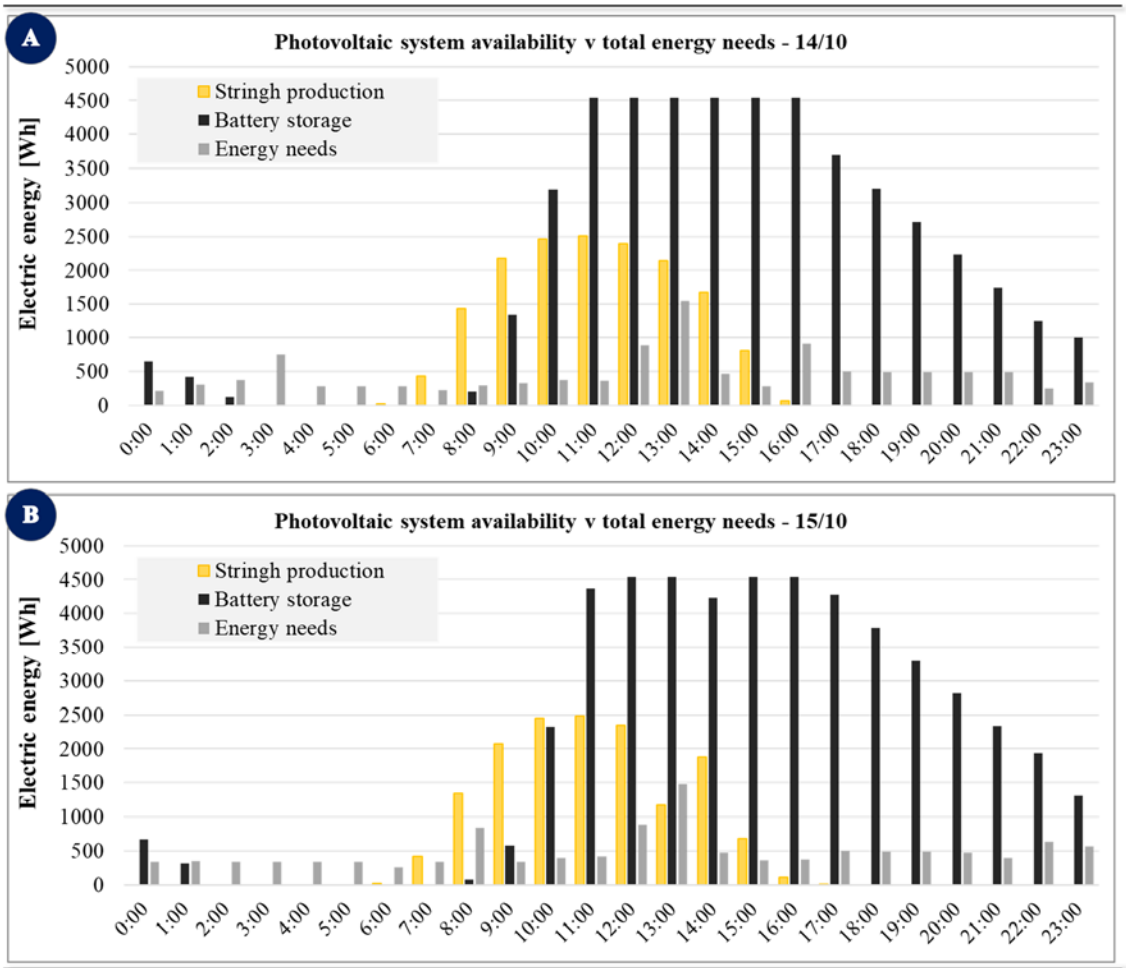


Figure 48: Hourly energy balance: (a) 14th October; (b) 15th October.

These balances testify that during the autumn, thanks to the lower energy needs, the electric storage allows to cover the whole energy demand during the evening hours and up to the first hours after midnight. In the early morning, when the battery is discharged, the energy request is satisfied by the electric grid. Based on monitored data, the RenEl and PVin are respectively equal to 93.4% and 155.0% during 14^{th} October; while on 15^{th} October these indices result equal to 92.3% and 131.7% respectively. This means that the daily generation from solar source is greater than the total energy request thus, during the late morning and afternoon, it covers, entirely, the consumptions and it also charge the battery up to the maximum capacity. A small amount of electric energy is exported to the national grid. Globally, considering the battery contribute, the building is almost net zero energy since only after midnight it imports very low amount from the national power grid.

The Load Match index, that represents the percentage of electrical demand covered by on-site generation at hourly level, results equal to 89.9% and 88.3% respectively on 14^{th} and 15^{th} October. This index indicates that there is an acceptable coincidence between the building needs and the photovoltaic generation. The monitoring results demonstrate the effectiveness of the design choices and control strategies. Indeed, results that during the autumn the great part of the energy consumption can be satisfied by energy production from the photovoltaic system. Globally, the production from the photovoltaic plant is higher than the energy demands of the building; about 90% of the consumptions are satisfied by the in-situ generation with a time correspondence just under 90%.

Research studies concerned on monitoring campaign on existing building are focused only on overall and any case long-term energy balance without considering the energy exchangers at smaller time scale. However, in a perspective of energy performance assessment both of single building than urban context, it is crucial the knowledge-transfer and exchange of experiences resulting from pilot programmes to avoid further mismatch between the expected and the real performance. Indeed until real data will be not available, the improvement of cities sustainability will be only a research topic and it will be not quantifiable the contribute due to the fact that buildings must pay an active role within the context of an intelligent energy system.

3.4.3.3 Evaluation of the potential of ground heating of ventilation air

As aforementioned, adequate comfort conditions inside the building are assured by the presence of fresh air pre-treatment system (EWHE) and the internal recirculation of the heat pump. The first provides to pre-heat the external air before the heat pump; instead thanks to the recirculation system integrated in the heat pump the air introduced into the rooms is, under favourable conditions, a mixture of extracted air and fresh one and therefore part of the energy is recovered.

In order to evaluate the potential of these treatments, some experimental data collected from October 14th to 20th are shown. Figure 49 shows the air temperature on entry and exit of the intermediate air-water heat exchanger (T_air.in.EWHE and T_air.out.EWHE), the temperature of air extracted from the rooms (T_air.back) and the one after the mixing section (T_air.supply).

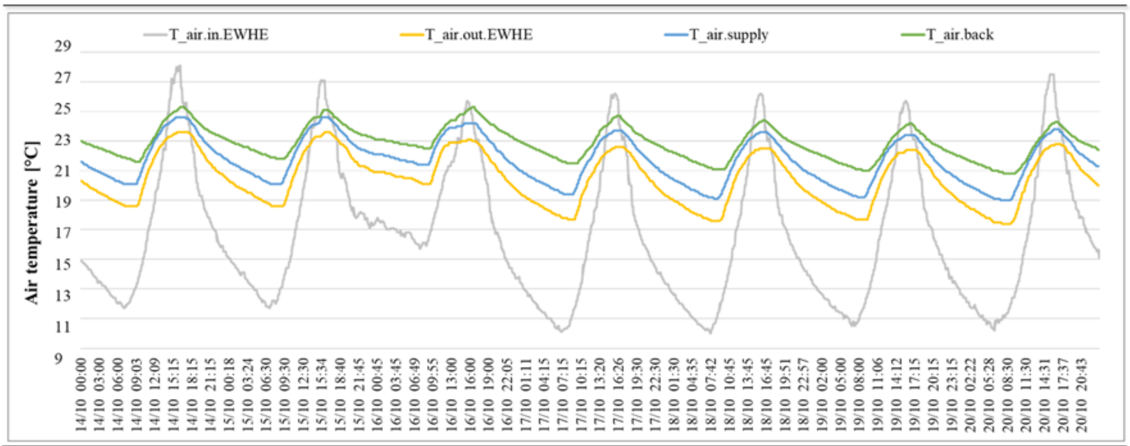


Figure 49: Temperature trend on the pre-treatment system.

The effectiveness of EWHE system is based on the more stable temperature of the soil, indeed thanks to itself inertia, the soil is characterized by lower temperature than the outdoor air during the late morning and afternoon (when overheating problem could occur) and by higher temperature during the evening and night. This means that the fresh air is heated when the outdoor air temperature goes down until 8-10°C while it is cooled when the outside environment is characterized by temperatures up to 28°C. Indeed, if the fresh air is entered directly inside the building would result much cold during the night and too hot during the central part of the day. In both, the simple ventilation would lead to thermal discomfort for the occupants due to the large variation of internal conditions during the day.

More in detail for the examined period, by taking into account only the contribute of geothermal heat-exchanger, the higher increase (10.5°C) for the temperature of ventilation air has been obtained at 8:30 of 20th October; in the same day it has been recorded also the maximum decrease (-6.8°C) at 16:00. During the 14th October, the temperature difference between T_air.out.EWHE and T_air.in.EWHE is varied between -4.50°C (16:48) and +6.90°C (7:14) with the lower potentiality of heat recovery during the early afternoon. During the 15th October, it varied between -3.70°C (17:22) and +6.90°C (8:04).

Considering the recirculation section, the temperature can be increased from 0.7°C to 1.9°C respect to T_air.out.EWHE; these extreme values has been respectively obtained at 17:00 of 20th October and at 9:00 of 17th October. By summing (i.e., overlapped effect) these two effects, globally, the temperature of the air supplied into the environment results always between 19°C and 24.6°C.

To evaluate the effectiveness of EWHE system, an important parameter for the performance assessment is the heating /cooling capacity. This parameter can be evaluated using the monitored data through the following equation (Equation 10).

$$Q_{-h} = \dot{m}c_p(\mathrm{T\_mix.out} - \mathrm{T\_mix.in}) \qquad (10)$$

Where $Q_{\_h}$ is the capacity of earth-water heat exchanger (W), $\dot{m}$ it the mass flow rate (kg/s), c_p and ρ are the specific heat at constant pressure and the density of water-glycol mixture (with 25% of glycol concentration) and are, respectively, equal to 3.84 kJ/kgK and 1038 kg/m^3. Finally, T_mix.out and T_mix.in are the temperature of water-glycol mixture in and out the earth-water heat exchanger.

The capacity calculated based on experimental data varies between 666 W (free-heating), reached at 8:30 a.m 14th October, and -413 W(free-cooling), reached at 4:02 p.m of the same day. As shown in Figure 50, the calculated capacity has opposite variation trend with the external air temperature, and this assures promising potential for the handling of ventilation air during the intermediate season. Indeed, it allows to avoid that the external thermal variations are reflected in wide variations of the internal conditions thanks to the positive trend to bring the ventilation flow towards intermediate conditions damping the external peaks.

Data monitoring have also demonstrated that the application of ground-to-water heat exchanger has a great potential to achieve nZEBs target, surely with reference to the energy required for the space heating. It is recommended that the earth-to-water heat exchanger will be controlled on the basis of the real effective heating potential. Indeed, this must be turned off when the outdoor air temperature is lower than the one of the ground pipes. In fact, when this condition occurs, the pre-treatment system goes to cool the incoming ventilation air instead of heating it, and this induces an increase of heating load, with a negative effect on the indoor comfort conditions for occupants, of course. Therefore, the continuous operation of the water pump could lead in a negative effect on indoor conditions in the long period, but a proper control for the water pump of the ground-to-water heat exchangers is recommended.

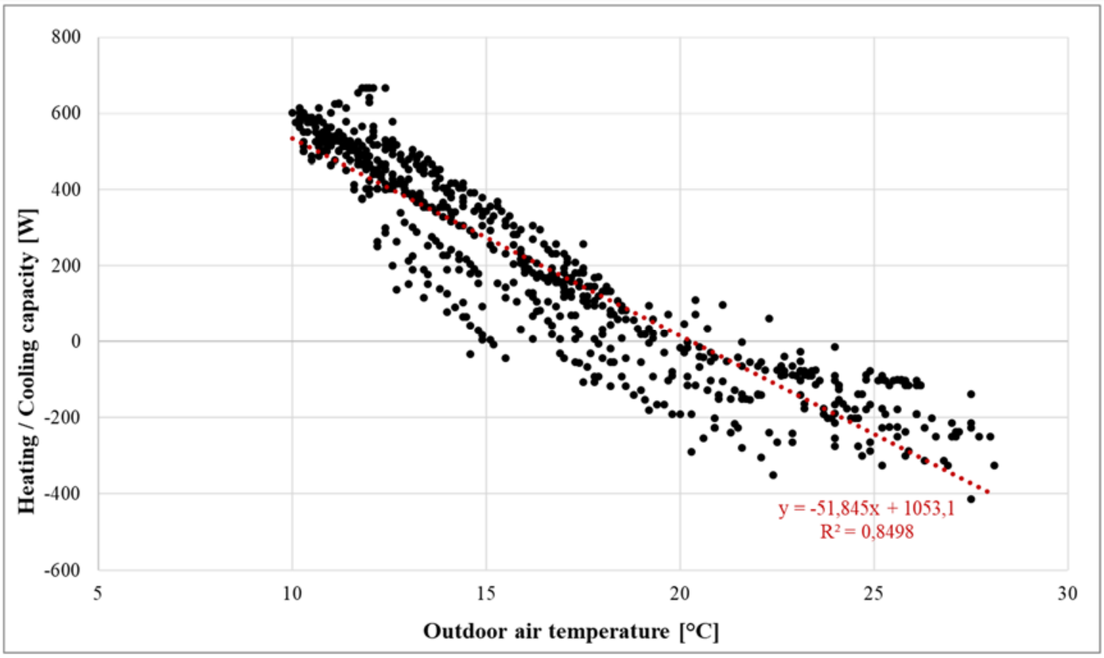


Figure 50: Heating / Cooling capacity of EWHE.

Indeed, an important result of the autumntime analysis is that although the HVAC system is set in only ventilation mode, satisfactory comfort conditions for the occupant are guaranteed inside the building. The study shown the potential of the integration of an earth-water exchanger to pre-treat ventilation air before it goes into the aeraulic heat pump. The feasibility and potential of this kind of pre-handling system are not sufficiently verified in the literature, but this study shows that it could have a great contribution to achieve nZEB target and could play a significant role to improving the comfort condition inside the building even more during the intermediate seasons. Indeed, the earth-water pre-treatment system allows to avoid that the external variations are reflected on the internal conditions thanks to its capability to bring the fresh air flow towards intermediate conditions damping the external peaks.

3.5 OPERATIONAL ENERGY PERFORMANCE DURING THE SUMMER PERIOD

The purposes of this section are: to assess the operational energy performance of BNZEB building during the summer period, and to perform a comparison between different HVAC possible configurations, in order to evaluate, based on experimental data, the potential of a pre-cooling ventilation air section. In particular, the installed air pre-treatment section is based on a ground-to-water heat exchanger, coupled with an intermediate water-to-air exchanger that pre-heat/cool the fresh air before it goes into the aeraulic heat pump (as discussed in the previous sub-section).

According to these purposes, measurements of several performance parameters in four different HVAC possible configurations will be shown, as well as monitoring of energy uses and indoor microclimatic conditions, in order to verify if comfort conditions inside the building are guaranteed together with the achievement of ‘nearly zero energy target’ (sub-section 3.5.2). Indeed, as for the analysis about the winter and intermediate periods, the electric energy balance will be presented by comparing, with an hourly time step, the photovoltaic production and battery storage with the building energy need. Moreover, as always, some indices have been introduced to evaluate the energy balance and they are evaluated starting from monitored data. The first one, named RenEl, is the ratio between the “electricity from renewable source used to satisfy the requests” and the “total daily request of building”; the second one, named PVin, is the ratio between the “PV generation” and the “daily electric consumption”. These indexes have been already presented in the previous pages.

Finally a further used index is the Load Match Index [149] defined by the Equation 5 in the section 3.3.2.2, and thus capable of quantifying the building ability to temporal match a building's load and its energy generation and then work beneficially with respect to the needs of the grid infrastructure, indeed higher the index is, better the coincidence between the load and onsite generation.

Meanwhile, in order to proceed to the assessment of indoor comfort conditions in terms of air temperature and relative humidity, as well as for what concerns the air CO_2 concentration, the recommended limits proposed by the EN 15251 standard [88] have been considered. In particular, it has been considered the comfort range of 23-26°C for the indoor air temperature and the range 30-60% about the relative humidity, by considering the category II of comfort in residential buildings. Finally, with reference to the CO_2 concentration, it has been considered an upper limit of 500 ppm above outdoor concentration, by taking into consideration, also in this case, the category II of comfort in residential buildings.

In particular, the monitoring campaign was performed during July 2019, a typical summer month for Benevento city (Mediterranean climate) during which, considering the monitored data, the outside temperature often reached peaks of over 40°C, with an average temperature during the 24 hours of the day just below 30°C and minimum values usually above 15°C. Moreover, global solar radiation on horizontal plane has reached almost every day maximum values above 600 W/m^2.

The results of summer experimental campaign on energy consumption for heating, ventilation, lighting, electric loads, water use will be discussed for each HVAC configurations in the following sections, as well as the monitored microclimate variable in real operational conditions (section 3.5.1). Indeed, also in this case, the monitoring campaign was carried out when the building was occupied by some students, that lived the building during weekdays, from 9 a.m. to 6 p.m., and they replicated a typical day use of the house, such as the operation of common electrical device (e.g., oven, cooker hood, fridge, computers, television, hairdryer, consumption of domestic hot water), which operation was freely chosen by the user, like for the artificial lighting, on the basis of their needs, in order to apply a real operational condition of the building. Moreover, in the last part of the investigation (sub-section 3.5.2), a simple economic comparison is proposed, that consists in the evaluation of the operating costs of solar-based system for highlighting the incidence of photovoltaic production and of battery. Finally, a CFD investigation will be performed in a simulation environment to evaluate the thermal conditions reached inside the dwelling in the different HVAC configurations investigated (sub-section 3.5.3). Also in this case, with the exception of the CFD analysis (sub-section 3.5.3), all of the results examined in the following have been also reported in a journal paper named "Hourly operational assessment of HVAC system in Mediterranean Nearly Zero-Energy Buildings: Experimental evaluation of the potential of ground cooling of ventilation air" [VI].

3.5.1 Presentation of four different HVAC possible configurations

With reference to the air-conditioning systems installed in the BNZEB, described in the section 3.1.4, four different HVAC configurations were tested and monitored during July 2019.

Table 8: Information about tested HVAC configurations.

Conf.	Monitoring Period	Inside people presence and thermal load	Ventilation System	Pre-cooling activation	Cooling System	Indoor Set point
C1	8 – 11 July	Yes	Packaged Heat Pump	Off	Packaged Heat Pump	25 °C
	12 July	No				
C2	15 – 18 July	Yes	Packaged Heat Pump	On	Packaged Heat Pump	25 °C
C3	22 - 25 July	Yes	Packaged Heat Pump	On	Direct Expansion Heat Pump	25 °C
C4	27 - 28 July	No	Packaged Heat Pump	Off	Direct Expansion Heat Pump	25 °C
	29 - 30 July	Yes				

Some information about the configurations are reported in Table 8 and shortly below described:

1. C1: the aeraulic heat pump, with set point equal to 25°C, provides the ventilation and air conditioning services, but the outdoor air is not pre-cooled by the geothermal heat exchanger and thus it is only cooled by the heat pump.

2. C2: it is similar to the first one, but in addition the geothermal heat exchanger provides to pre-cool the outdoor ventilation air before it enters into the heat pump, which performs then the thermodynamic processes for assuring the suitable conditions of supplying into the indoor environment.
3. C3: the direct expansion system, with a set point of 25°C, provides the indoor air cooling and then it balances the thermal loads. In addition, the packaged heat pump system is activated merely in ventilation mode and then satisfies the ventilation needs together with a partial recirculation of the indoor air, filtered and mixed with the outdoor flow. In this configuration, the geothermal heat exchanger, coupled to the air-to-water heat exchanger, allows a pre-cooling of the ventilation air.
4. C4: it is the same of the third one, except for the pre-cooling of the external ventilation air, which is deactivated by switching off the pump of the ground-to-water heat exchanger and thus the pre-handling coil.

With reference to the described configurations, a deep monitoring campaign has been performed, in order to evaluate the energy consumption and the indoor microclimate conditions (e.g., the values of air temperature, relative humidity and CO_2 concentration). All data were collected using a time step of 15 minutes. Even the information about operational conditions of the HVAC system were collected, for instance the values of air temperatures outside the building, upstream and downstream of the air-to-water heat exchangers, and of the air introduced inside the building. The sensors and meters used during the monitoring campaign and their location within the building are shown in Figure 12 (subsection 3.1.5).

In the following four sub-sections, the main results of monitoring campaign, in terms of energy consumption for air conditioning system and indoor microclimate conditions, are shown for each configuration. Then, it follows a section (sub-section 3.2.5) of comparison and discussion between configurations investigated and the overall building's energy balance and the chosen evaluation indices are proposed, these are calculated by using monitored data for total energy consumption of the building and generation from PV system. Finally, the CFD investigation about the indoor comfort conditions reached in corresponding to the different HVAC configurations will be described (sub-section 3.2.6).

3.5.1.1 C1 configuration of AC system: thermal, environmental and energy performances

C1 configuration has been tested for five consecutive days, and during the first four days the building was occupied alternately by one or two students while on the last day the persons left the dwelling and only the HVAC system was in operation.

Figure 51 concerns the monitoring results and shows the indoor microclimate parameters collected in order to characterize the indoor conditions in terms of thermo-hygrometric comfort and air quality, also providing the indications of recommended limits proposed by the EN 15251 Standard [88], as a grey area. The trends reported in the figure shown that the temperature inside the bedrooms were around the set point value, while the same does not happen for the temperature inside the living room, where due to the large windows, the solar radiation enter inside the room implying the increase of air temperature that in the central hours of the day reaches also 28-29°C.

Indeed, during monitoring period, for the window with south exposition has never been activated the shielding system and when there are very severe external conditions the configuration C1 would seem to fail to satisfy the load.

In detail, it results that the air temperature is in the comfort range for the 69% of the hours for the living-room and 93% and 83% for the bedroom 5 and 6 (see Figure 12 for the nomenclature), respectively. The relative humidity is in the comfort range for the 98% of the hours in the living room, for 86% of the hours for the bedroom 5 and for 99% of the hours for the bedroom 6. Finally, the CO_2 concentration is always below to the recommended limit in each room.

In order to evaluate the operational performance of the configuration C1, in the Figure 52 the hourly energy demands for air conditioning are shown, throughout the reference period together with indications of operating temperatures. In particular, in Figure 52 there are also reported the outside temperatures, the air temperatures inside the building (with also the average values between the main three rooms), the temperature difference between inside and outside the building and finally the temperature of outdoor air before that it enters into the heat pump.

In Figure 52, it is quite evident that this configuration, in which there is not the pre-treatment of the external ventilation air, the temperature of air entering into the heat pump is comparable or equal to the external one, and the slight difference is mainly due to the passage through channel and fan.

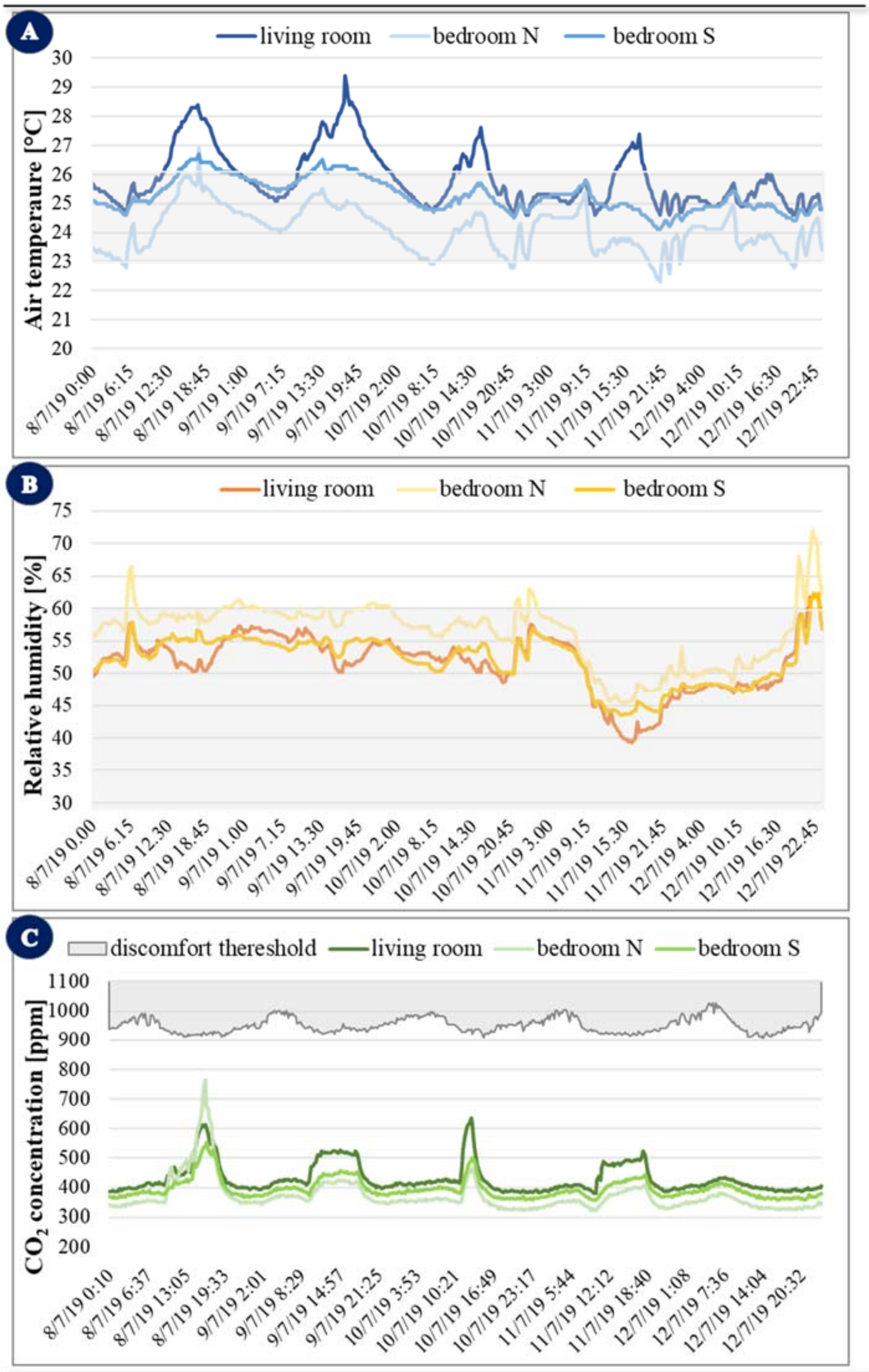


Figure 51: Configuration C1: (a) air temperature; (b) relative humidity and (c) CO_2 concentration.

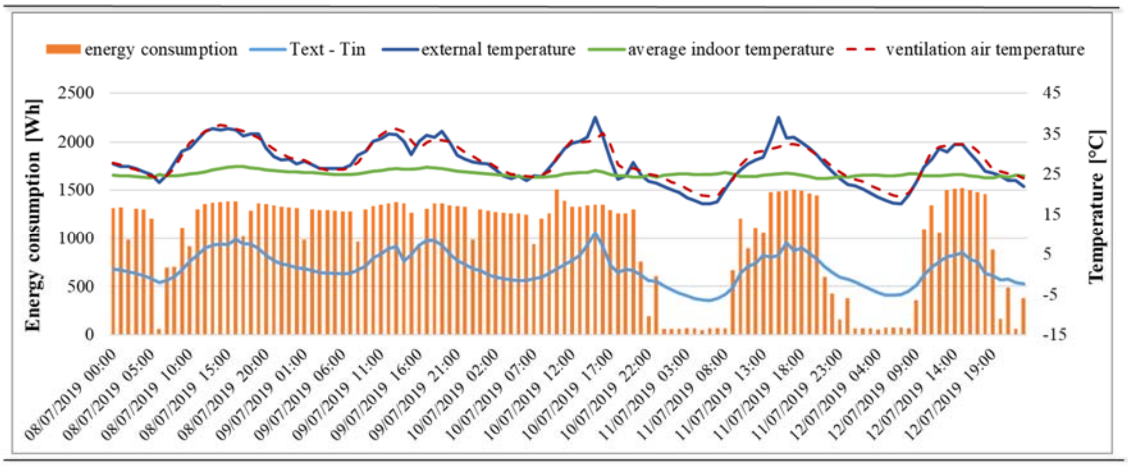


Figure 52: Energy consumption for air conditioning in the configuration C1.

Moreover, it results that, even when the external temperature exceeds 35°C, the HVAC system maintains the temperatures inside the building around 25°C. Globally, this configuration requires, for the air conditioning, from a maximum of 1.5kWh per hour to a minimum of about 50Wh per hour, in terms of electricity need. At daily level, the electric energy consumption ranges from 17.0kWh and 15.7kWh during 11th and 12th July (when, thanks to favourable external conditions, the system works in free-cooling during the night), up to a maximum of 30.3kWh during 8th July.

3.5.1.2 C2 configuration of AC system: thermal, environmental and energy performances

The second HVAC configuration tested is identified with the code C2 (see Table 8). Compared to the previous configuration, the system here analysed provides a pre-cooling of the outdoor air aimed at the needs of ventilation. This configuration was tested for four days, from 15th to 18th July, in which the building was occupied by two students. Figure 53 shows the indoor microclimate parameters collected during the period, in order to characterize the indoor conditions in terms of thermo-hygrometric comfort and air quality. Moreover, the figure also shows, with the grey area, the indications of recommended limits proposed by the Standard EN 15251 [88].

More in details, the results show that the air temperature and relative humidity in the living room are in the comfort range for 100% and 89% of the hours, respectively. Moreover, the air temperature inside the bedroom 5 results in the comfort range for 78%

of the hours; the same parameter, for the bedroom 6, results in the recommended range for 100% of the time. The relative humidity results in the recommended ranges for 100% of the hours with references to both the bedrooms. Finally, concerning the CO_2 concentration, it results below the recommended threshold for all the considered hours and for each room of the building.

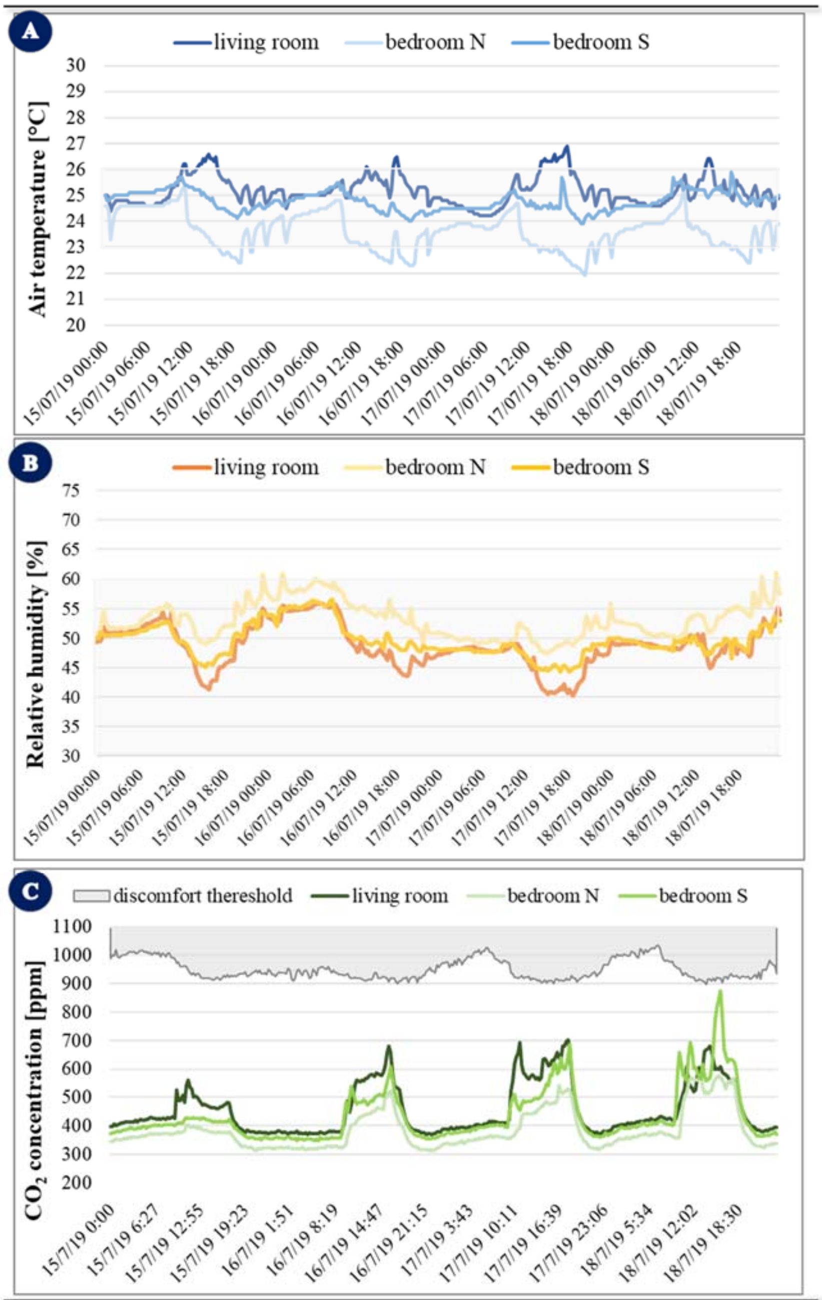


Figure 53: Configuration C2: (a) air temperature; (b) relative humidity and (c) CO_2 concentrations.

Information about the operational performance of configuration C2 is reported in the Figure 54. In this figure, hourly consumptions for air conditioning are shown, as well as the outside temperatures, the average temperatures inside the BNZEB, the indication of difference between inside and outside temperatures and the temperature of ventilation air before that it will enter into the heat pump. In this way, the authors want to correlate the operational energy consumption of HVAC system to the operative conditions of the system and then it will allow a comparison between the different tested configurations.

Figure 54 indicates that, due to the pre-treatment of the outdoor ventilation air, its temperature at the entrance of the heat pump is less oscillating compared to the external temperature and it is up to 10°C lower than the outside temperature in the peak hours.

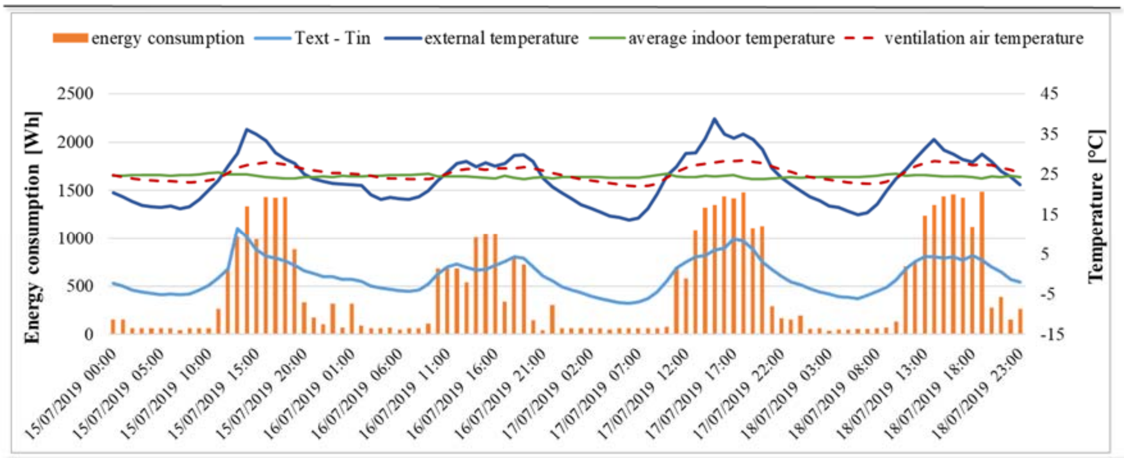


Figure 54: Energy consumption for air conditioning in the configuration C2.

The results show that, even for the C2 configuration, although the outside temperature exceeds 30°C, the HVAC system maintains the temperature inside the building at values close to the set point temperature. In addition, generally lower temperatures are maintained inside the building compared to the previous configuration (without the pre-treatment of the ventilation air) and also lower energy consumptions are evident. In detail, this HVAC configuration implies an energy demand for air-conditioning ranging from a maximum of 1.49kWh per hour to a minimum of 40Wh per hour. However, in this configuration, the whole system operates much more frequently in free-cooling mode and, for this reason, at daily level, the electric consumptions range from 9.1kWh on 16th July to 12.9kWh on 17th and 18th July. This is due to slightly more favourable weather conditions (average lower outdoor temperatures during the reporting period) and mainly due to the lower temperature of air at the entering of heat pump, thanks to the pre-treatment of the incoming outdoor air.

3.5.1.3 C3 configuration of AC system: thermal, environmental and energy performances

According to the information indicated in the section two, the third tested configuration is identified with the code C3.

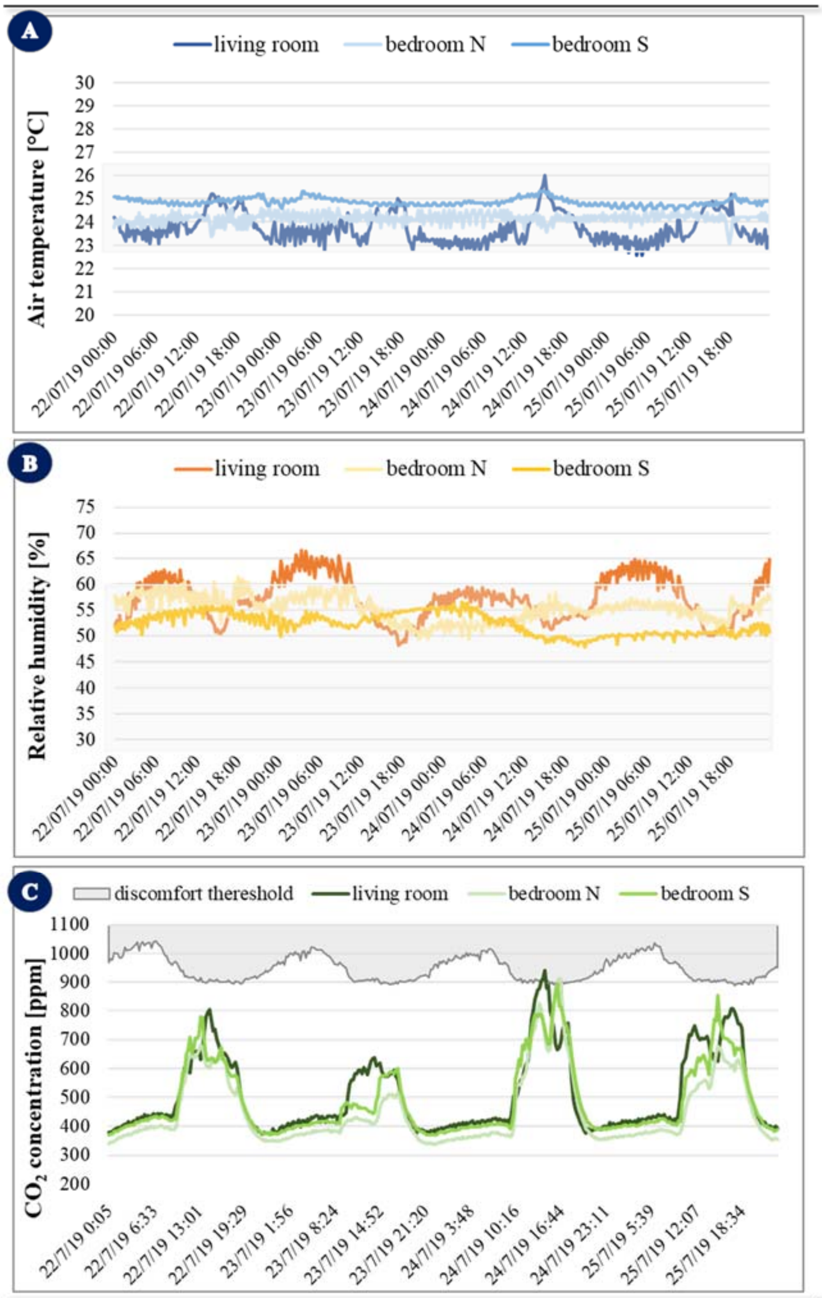


Figure 55: Configuration C3: (a) air temperature; (b) relative humidity and (c) CO_2 concentration.

Moreover, during the testing of this configuration, from 22nd to 25th July, the building was occupied by two or three university students. As for the previous cases, Figure 55 shows some indoor microclimate variables, collected during the testing period, in order to characterize the thermo-hygrometric comfort conditions and indoor air quality. Furthermore, also the indication of recommended limits proposed by the Standard EN 15251 [88] are reported. The results of Figure 55 shows that the air temperature and relative humidity in the living room are in the comfort range for 99% and 70% of the hours, respectively. Air temperature and relative humidity of the bedrooms are within the recommended range for 100% of the hours. Instead, concerning the CO_2 concentration, it results always below to the recommended threshold, with the exception of the afternoon of 24th July, when from three to four students were inside the building and thus the concentration of carbon dioxide raised. However, the CO_2 concentration has always remained below 1000 ppm. Also in this case, some information about the operational performance of the configuration C3 are reported in Figure 56. Herein, hourly consumptions for air conditioning, outside temperature, average temperatures inside BNZEB, differences between inside and outside temperatures and the temperatures of outdoor air before it enters into the heat pump are shown. The investigation aim was to correlate the operational energy consumption of the HVAC system to its operative conditions, in order to allow comparisons among the different configurations.

Figure 56 clearly shows that, thanks to the pre-handling by means of the ground heat exchanger, the air temperature at the entrance of the cooling section is much more stable compared to the its thermal conditions before the treatment. Moreover, the air temperature at the exit of the pre-treatment coil is also up to a maximum of 8°C lower than the ambient air temperature. In general, the results show that, although the outside temperature reaches 40°C, the temperature inside the BNZEB remains the same as the set point temperature. In this configuration, the hourly electric energy consumption for air conditioning ranges from 189Wh to 1.0kWh. At daily level, for the considered period, the energy consumption ranges from 11.9kWh (23rd July) to 14.4kWh (22nd July).

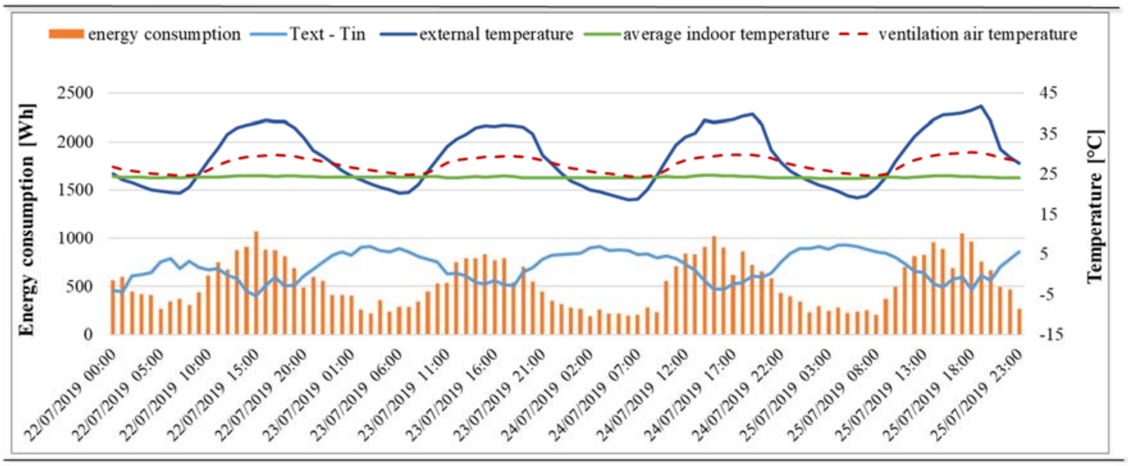


Figure 56: Energy consumption for air conditioning o the configuration C3.

3.5.1.4 C4 configuration of AC system: thermal, environmental and energy performances

Differently from the previously analysed configurations, C4 does not include the pre-treatment of outdoor ventilation air though geothermal source. During the testing period (from 27th to 30th July), the building was occupied by two or three students during only the last two days.

In Figure 57, the indoor microclimate variables, collected in order to characterize the thermo-hygrometric comfort conditions, and air quality are depicted, with also indications of recommended comfort limits by the Standard EN 15251 [88].
The results show that, during the testing period, the air temperature in the living room is inside the recommended comfort range for the 95% of the hours. Conversely, the relative humidity is within the range only for the 18% of the time. Concerning the bedrooms, it results that the air temperature is always in the comfort range (100% of the hours) for both rooms; conversely, the relative humidity is inside the suitable ranges for the 20% of hours in the bedroom 5, 100% of the time in the bedroom 6.

In Figure 58, hourly consumptions for air conditioning, outside temperatures, average temperatures inside the building, differences between inside and outside temperatures and conditions of the outdoor air before its entering into the heat pumps are shown. Given the lack of geothermal pre-treatment, the temperature of the air at the entering into HVAC system follows the external temperature (see Figure 58).

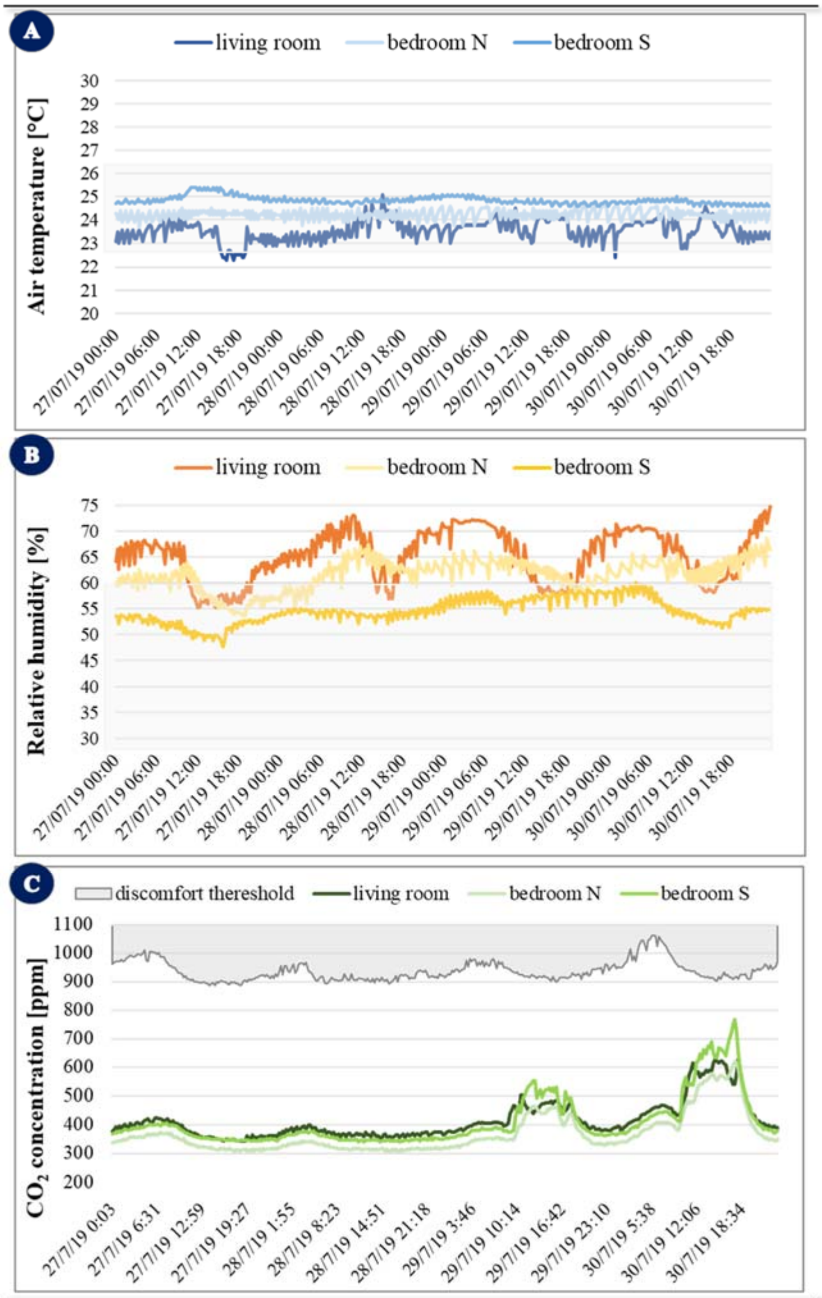


Figure 57: Configuration C4: (a) air temperature; (b) relative humidity and (c) CO_2 concentration.

However, the energy consumption for air conditioning is comparable with the previous configuration. This occurs because, in this last configuration, the outdoor ambient conditions, in terms of external temperatures, were less critical. In general, in the C4 configuration, the hourly energy consumption for air conditioning ranges from 100Wh to 1.1kWh. At daily level, the energy consumption ranges from a minimum of 7kWh during 28th July to 10.8kWh on 27th July.

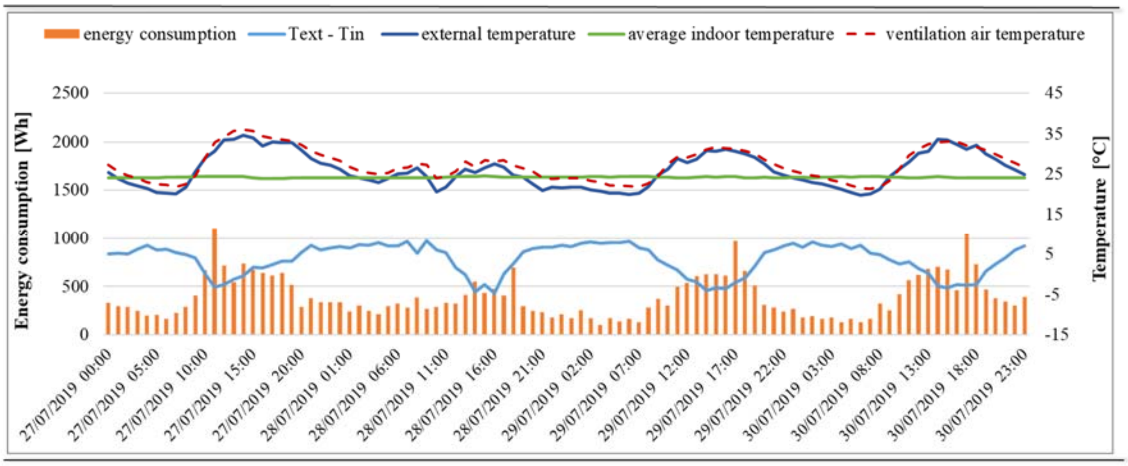


Figure 58: Energy consumption for air conditioning of the configuration C4.

3.5.2 Discussion about the experimental results and energy balance

In order to evaluate the effects of the air pre-treatment system on energy consumption for air conditioning, similar days in terms of external temperature and global solar radiation have been selected, with the aim to compare configurations with and without the pre-treatment system, under analogous external conditions. In particular, two main comparisons have been performed. In the first one, a comparison has been made between the first two HVAC configurations (C1 and C2); in both configurations, the aeraulic heat pump provides cooling, dehumidification and ventilation needs together with the recirculation of internal air, but only in the second one it is activated a geothermal horizontal heat exchanger that, coupled with a water-to-air coil, provides the pre-treated of the ventilation air. The second comparison has concerned the last two configurations (C3 and C4), in which a direct expansion system balances the thermal loads, while the aeraulic heat pump satisfies only the ventilation. Obviously, also in this case, the pre-treatment system is activated only in the configuration C3.

Then, to make the first comparison, the day July 12th has been chosen for the C1 configuration and July 18th for the configuration C2. These days are characterized by an average external air temperature of 24.4°C and 23.8°C respectively and by a peak value of temperatures equal to 32.0°C and 33.5°C. While concerning the solar radiation, both the days are characterized by an average value of 288W/m^2 and peak values of 617W/m^2 and 638W/m^2 respectively for 12th and 18th July.

For the comparison between the other two configurations, it was chosen July 23rd for the configuration C3 and July 27th for the C4. In this case, the chosen days are characterized by an average external temperature of 28.9°C and 27°C, with peak values of 37.1°C and 34.4°C respectively. Moreover, for what concerned the global solar radiation, the 23rd July is characterized by an average value of 260W/m^2 and peak value of 641W/m^2 while 27th July has values of 286W/m^2 and 632W/m^2 for the average and maximum values, respectively.

In Figure 59, with reference to the first two chosen days, the trends of relevant variables are shown, and thus energy consumption and operational temperatures, in order to compare the configurations C1 and C2. The results show that, during July 12th (conf. C1), the energy consumption for air conditioning was 15.7kWh while, on July 18th (conf. C2), this was equal to 12.9kWh, and thus about 18% lower.

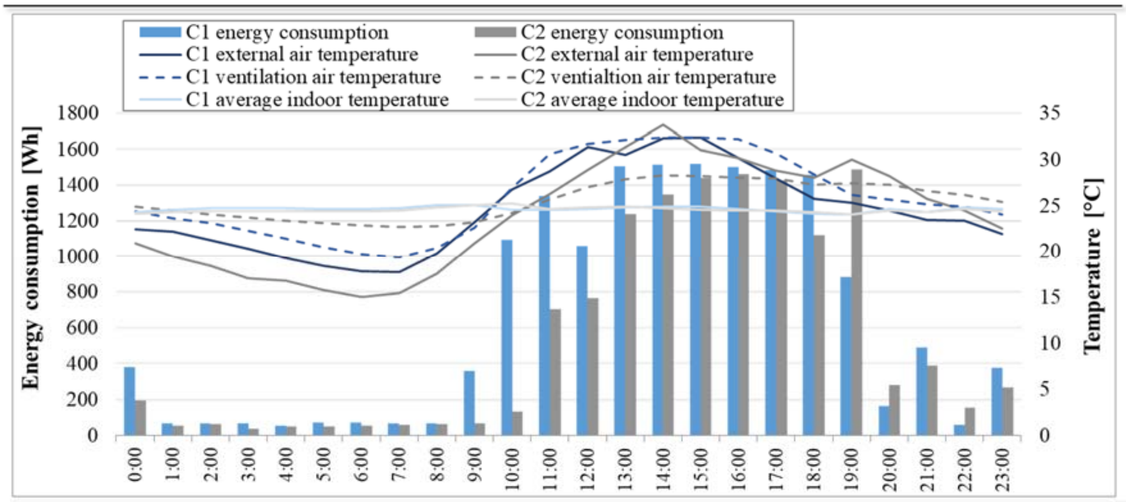


Figure 59: Comparison between configuration C1 and C2 during 12th July and 18th July, respectively.

Thus, in a warmer day, the energy consumption for cooling associated with the configuration C2 is lower than that of the C1, except in the early evening hours. Thanks to the pre-treatment of the ventilation air, during the central hours of 12th July, the temperature at the heat pump inlet is up to 5°C lower than the corresponding outdoor temperature during 18th July. This free cooling, due to the ground heat exchanger, explains obviously the lower consumption of the configuration C2. Moreover, between 7.00 pm and 8.00 pm (see Figure 59), the outside temperature of 18 July is about 4°C higher than the one of 12 July at same hour, and thus, in this case, the pre-cooling is not sufficient in lowering the temperature at the entering of the heat pump at a value correspondent to the inlet temperature of configuration C1: thus, in these minutes, the energy consumption associated to C2 is higher than the one of configuration C1. The same results, due to a different phenomenon, are obtained in the evening and during the night: indeed, looking the trend of temperatures, it is clear that, due to its thermal inertia, the ground remains at a higher temperature than that of the outdoor air. Therefore, the pre-cooling system provides a pre-heating effect of the ventilation air and it induces an increase of the cooling load, and then it has a negative effect on the energy consumption. This negative aspect could be easily avoided bypassing the pre-treatment system during the hours when the ground has a thermal level penalizing compared to the ambient air.

In general, based on the experimental data, it is shown that the investigated geothermal pre-cooling system has a considerable potential to cool the ventilation air in Mediterranean climates, during the summer periods. Indeed, in Figure 60 (referred to the whole testing period), it is evident the contribution of the proposed system in terms of outdoor air temperature decreasing at the inlet of the heat pump. This decreasing can even reach about 10°C.

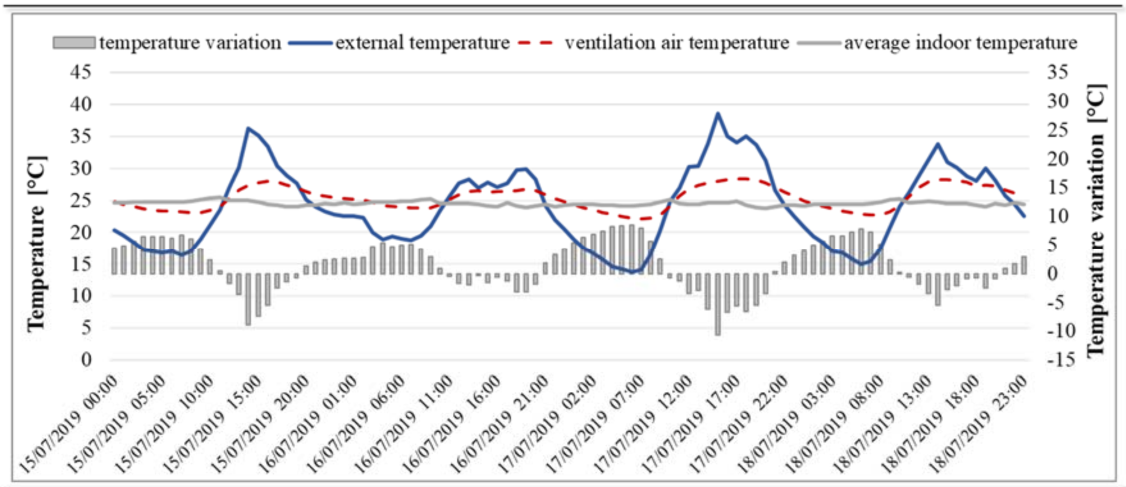


Figure 60: Temperature variation due to pre-treatment system for the configuration C2.

Really a further improvement of the overall potential of this pre-treatment system is possible, by trying to avoid the additional heating that occurs during the night. Indeed, when the external conditions, due to the day-night excursions, are particularly advantageous, as it occurs in some nights, it is not advisable to use the proposed system that can increase the ambient air temperature of also 8°C compared to the outdoor conditions. In this perspective, it could be useful the development of an optimized management system, based on thermal conditions, which induces a bypass of the air pre-treatment system when adverse effects can happen. In this direction goes the investigation of Chel *et al*. [178] which nevertheless based such conclusions on data obtained by numerical models. For instance, an on/off control for the water pump of the earth-to-water coil could be recommended.

The same analysis was performed for the configuration C3 and C4 (Figure 61). In detail, the trends of energy consumption and operational temperatures during the 23rd and 27th July are shown, in order to compare the configurations C3 and C4. It results that a little bit higher daily consumption is correlated to the C3 configuration compared to the C4, and then the configuration provided with the pre-treatment does not show a reduction of energy demand for cooling. More in detail, C3 has an energy demand of 1.19kWh for July 23rd, while C4 has an energy requirement of 1.08kWh for July 27th.

However, it must be considered that the 23rd of July has been characterized by more heavy external weather conditions than the day 27th of the same month. This can be seen in the Figure 61, where the external air temperature during the central hours of 23rd July (grey curve) is from 2°C to 4°C higher than the outdoor temperature of 27th July (red curve), with peaks reaching 37°C and 34°C, respectively. Finally, the outcomes of this comparison are not definitive.

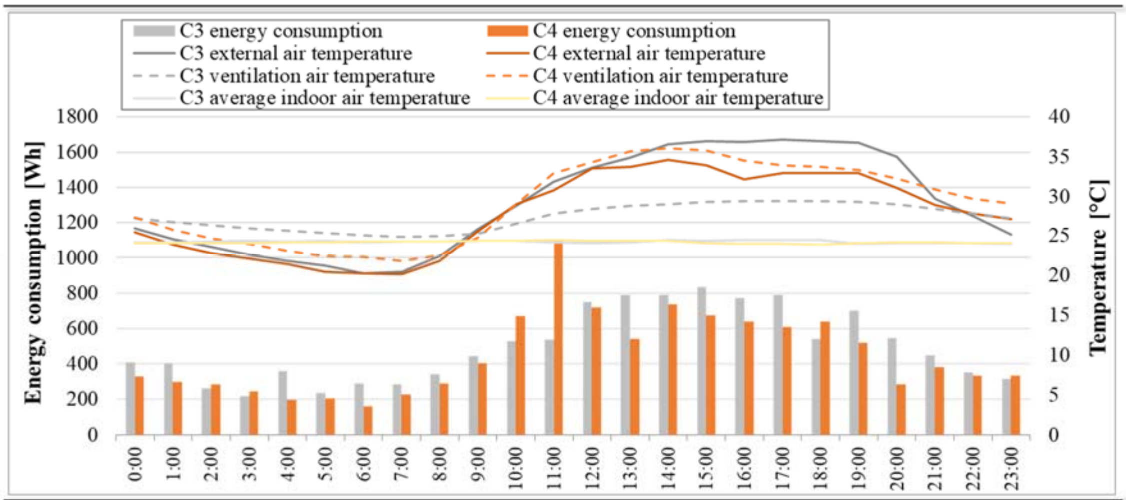


Figure 61: Comparison between configuration C3 and C4 during 23rd July and 27th July, respectively.

Furthermore, by seeing the first part of the graph, it is possible to infer how, even in this case, the contribution given by the pre-treatment is disadvantageous during the night. The situation during these hours is the same of the configuration C2. In the evening and night, since the ground remains at a higher temperature than that of the outside air, the pre-treatment system goes to heat the incoming external air instead to cool it. This effect turns into an additional load and thus it has a negative effect on the energy consumptions which are greater than those that could be. Therefore, also in this case, this adverse effect must be avoided, by bypassing the pre-treatment system when the external conditions are more convenient (i.e., cooler) compared to the ground. Finally, it would be advisable, during these hours, to not exploit the geothermal source, which is useful instead in the central hours of the day, when it is capable in cooling the ventilation air.

In Figure 62, the trends of air temperature, upstream and downstream the pre-treatment system, are shown, with also the indication of temperature variation through the investigated system. Here it is evident the contribution of the proposed pre-treatment system in reducing the air temperature at the inlet section of the heat pump (which always provides only the ventilation). In some cases, mainly when the outdoor temperature is very high, this temperature decreases (and thus the free cooling effects) can be also very significant, with a cooling of 10°C. In this way, based on experimental data, the potential of the proposed pre-treatment system, under severe external conditions, has been demonstrated.

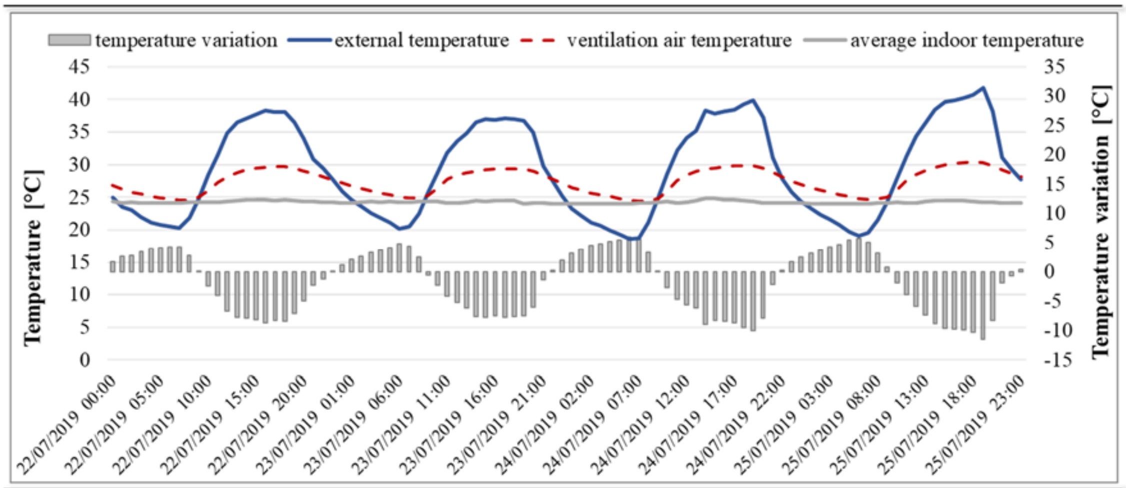


Figure 62: Temperature variation due to pre-treatment system for the configuration C3.

It should be said that despite in this second comparison the overall daily energy balance does not show completely the convenience of the pre-treatment system investigated, this is due to external conditions different and thus some results are altered. Surely, the whole analyses and trends have demonstrated a high potentiality of the ground-to-water and then water-to-air coils for pre-handling the ventilation air. A further improvement of the overall efficiency of this pre-treatment system can be achieved by avoiding the additional heating that occurs during the night. Under this aim, for example, an on/off control for the water pump of the earth-to-water system will be implemented, when the external conditions are more suitable (lower temperature) compared to the ground source. This will avoid the increases of outdoor air temperature shown in Figure 62 and in the Figure 60.

As said before, during the testing periods, some students (i.e., two or three) occupied the building, with the aim of replicating the typical daily use of a dwelling. In these real conditions, the generation of electricity from the PV system and the energy consumption have been continually monitored. In detail, for the four tested configurations, both the total consumption and the single energy demands from plugs, lights and air conditioning systems have been collected, and the results show that the greatest consumption is linked to the air conditioning system. Indeed, its energy request cover from 59% of total energy demand during the testing of configuration C4, up to 80% for the configuration C1.

Moreover, in order to evaluate the energy performance of the overall building system, the balance between total energy demand and energy generation from PV systems was performed. In particular, in Figure 63, the electric energy made available from PV system is shown together with indication of the total energy demand of the building, with reference to each one of tested periods. The energy offered by the PV panels and the one stored in the battery are reported, separately, in Figure 63 together with indication of the overall energy consumption of the building. Finally, in Table 9, the indexes defined in the methodology section are reported, with reference to each investigated day.

Figure 63 shows the trends of availability from the photovoltaic system and the overall energy consumption of the building and it appears that the PV system is able to satisfy the entire energy demands of the building. Indeed, at the monthly level, the electricity generation from the photovoltaic system exceeds the total energy consumption of the month of July, with a generation approximately of 714 kWh, which satisfies the 102% of the building consumption, which is around 697 kWh.

Table 9: Indexes concerning the energy balance on the building.

	RenEl [%]	PV [%]	$F_{load\ match}$ [%]
8 July	64.0	73.8	61.0
9 July	63.0	62.5	60.9
10 July	57.0	53.3	50.4
11 July	85.7	111.8	61.8
12 July	80.4	82.60	54.2
15 July	81.9	96.3	60.5
16 July	86.4	97.8	73.6
17 July	95.5	114.8	90.8
18 July	80.4	103.0	56.8
22 July	80.9	101.3	72.2
23 July	81.6	139.8	72.4
24 July	89.2	135.2	81.1
25 July	85.3	126.3	75.0
27 July	87.2	145.0	79.5
28 July	85.8	126.3	84.2
29 July	95.4	156.6	91.8
30 July	95.7	134.8	92.1

Moreover, in Table 9, it emerges that, for most of the days, the PV index was quite high and, starting from July 17th, it was always higher than 100%, meaning that the daily electric demand of the building is almost completely covered by the generation from the PV system. The same outcome cannot be seen about the effective daily coverage of energy demand from the PV system, represented through the RenEl index, which varies between 56% to 97%. Furthermore, by evaluating the values of the last index calculated ($f_{load\ match}$), it emerged that, for the analysed days, the hourly correspondence between load and generation was quite satisfactory, being between 50% and 92%, but it has never reached the value of 100%. This demonstrates how, although at monthly level the balance appears to be net positive, it does not happen at the lowest level (daily and hourly), despite the use of an electric storage system.

Therefore, although the current practice adopts an annual or monthly reference as reference period, it should be useful consider what happens at lower scales of time (daily or hourly), and this evaluation, because of the quote different values of energy purchased or sold, must be performed during the design phase and during the assessment of the operating performance of a Nearly Zero-Energy Building, in order to always maximize the self-consumption and to work beneficially with respect to the needs of the local grid infrastructure.

Finally, for the proposed economic comparison, that consists in the evaluation of the operating costs of solar-based system for highlighting the incidence of photovoltaic production and of battery, for the four configurations the operating costs are calculated considering a unitary price for the electricity in case of residential use of 0.204 €/kWh [179]. The calculation is done for three cases: a) the electricity is entirely derived by the national grid (NoPV); b) the real configuration with photovoltaic panels and battery storage (PV+BAT); c) the battery is not available (PV) and thus the building can use only the electricity produced simultaneously with the request. This evaluation will allow understanding the importance of maximize the self-consumption also under the economic point of view. For the last two configurations, it is assumed, as in the real case, that the surplus energy is given to another building owned by the same university rather than being sold on the national grid.

Figure 64 reports the operational costs for the periods with the four configurations analysed. Assuming as the base case NoPV (building without photovoltaic system) it can be seen that the reduction of costs varies between 68% (C1) and 91% (C4) in case of the present configuration with the battery associated with the PV system. If the battery had not been inserted in the plant configuration, the contemporaneity between load and production would have ensured saving in the energy costs variables from 39% (C1) and 78% (C4).

Since the energy balance with daily or hourly time step is not available for other existing nZEB, the presentation of these indexes to evaluate the impact of renewable production on short time step also under the economic point of view, allows to understand the importance of load matching and the positive effect of the electric storage. These are the main problems that designers will have to face in the near future when the nZEB will become not only a research topic but a normative definitely prescription.

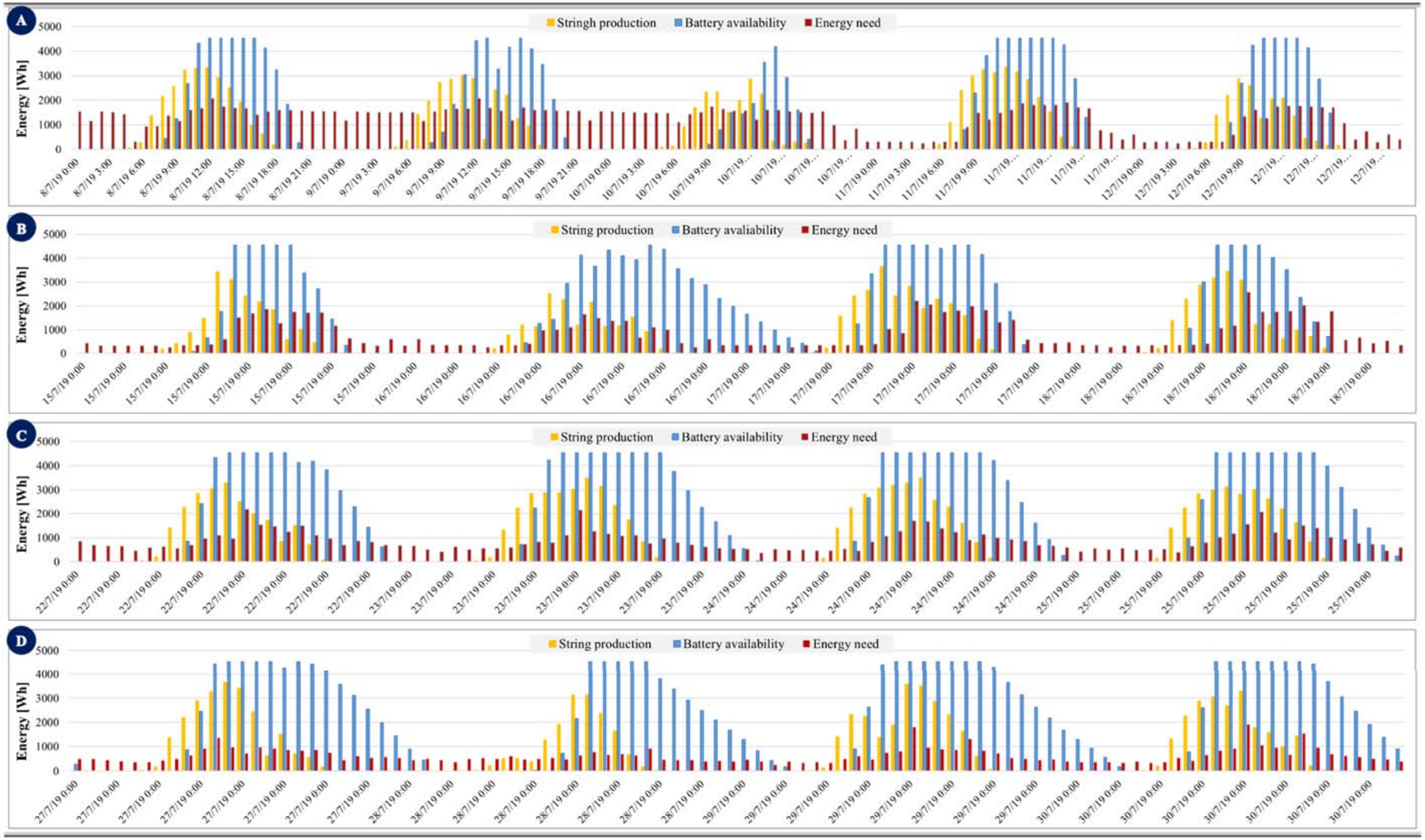


Figure 63: Availability from PV system and total energy consumption: (a) C1; (b) C2; (c) C3 and (d) C4.

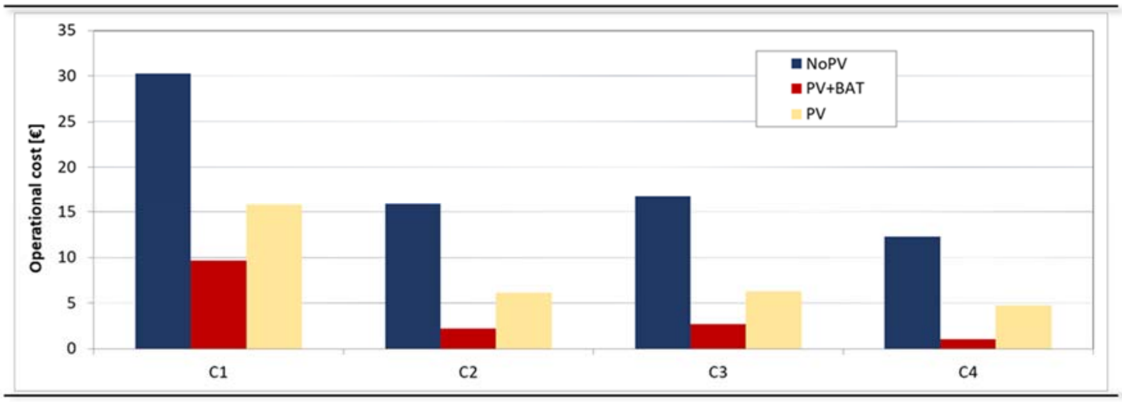


Figure 64: Operational cost and incidence of PV production and battery storage.

In general, this summer study investigated the potential of the ground capability in pre-cooling the ventilation air, by means of two heat exchangers (ground-to-water and water-to-air) and it is quantified the reduction of the energy demands for cooling. Different HVAC configurations, with and without the availability of pre-cooling system, were tested and monitored for a real nearly zero energy building, and experimental measures have provided a considerable amount of information about the system performance. The results of this summertime analysis allowed to draw the following conclusions about the operation of this kind of pre-treatment systems.

- On the basis of experimental data, it is demonstrated that the investigated system had sufficient potential to pre-cool the outdoor air in Mediterranean climate, and the positive effects are very significant under severe external conditions. Indeed, the results show that the pre-cooling geothermal system is able to reduce the temperature of outdoor ventilation air up to over 10°C compared to the outdoor temperature. The maximum temperature difference, between inlet and outlet of the water-to-air heat exchanger, reached 10.7°C and 11.5 °C, when a packaged heat pump with thermodynamic heat recovery (C2) or a traditional high-efficient DX system (C3) are used, respectively.
- It is recommended that the water pump of the earth-to-water heat exchanger will be controlled on the basis of the real effective cooling potential. Indeed, this must be turned off when the outdoor air temperature is lower than the one of the ground pipes. In fact, when this condition occurs, the pre-treatment system goes to heat the incoming ventilation air instead of cooling it, and this induces an increase of

cooling load, with a negative effect on the energy consumption, of course. Therefore, the continuous operation of the water pump could lead in raising the overall cooling consumption of the present house in the long period, and then the control for the water pump of the ground-to-water heat exchangers is recommended.

Data have also demonstrated that the application of ground-to-water heat exchanger has a great potential to achieve nZEBs target, surely with reference to the energy required for the space cooling. Indeed, considering the interaction with the photovoltaic system and the battery, the great part of the energy consumption can be satisfied by renewable electric production. Globally, the percentage of coverage of consumptions with in-situ generation ranges from 57% to 97% 90 with a time correspondence variable between 50% and 90%. Meanwhile the evaluation of the operation costs underlines the importance to maximize the self-consumption of energy, in order to achieve an economic profitability. In the most favorable day, the operational costs are reduced of 91% compared with the same building without the PV system and of around 78% compared with a solution without the electric storage.

In general, these assessments on BNZEB want to remark that the use of data from in-field monitoring campaigns and post-occupancy evaluations in a real context, could drive energy policies, smart grid and service designs, and thus such investigations allow useful guidelines for the building and systems designs in areas with similar boundary conditions, and thus climates, living styles and construction types.

3.5.3 CFD assessment during the cooling season

The calibrated numerical model of the building (subsection 3.2.2) has been used with the purpose to investigate the air temperature and the distribution of global comfort indices by the Computational Fluid Dynamic (CFD) tool of DesignBuilider, when different configurations of the air conditioning system were activated (Table 8 of sub-section 3.5.1). As introduced in the sub-section 3.4.2.3, thermal comfort is the condition of mind that expresses satisfaction with reference to the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55) [168]. However, also in this case, given that the indoor environment is fully air conditioned, the static model of thermal comfort (according to Ole Fanger) has been used, and then the traditional PMV and PPD indexes have been evaluated. The analysis was focused on living room of the building, characterized by largest windows surface with also mobile shading devices.

The CFD analysis is a space-variant analysis and it requires the adoption of proper boundary conditions. Unlike an energy simulation that gives results in which the investigated variables assume different values over time (i.e. hourly results), before running a CFD simulation, a precise time instant must be fixed. The calculation method requires that the geometric space across which the calculations are to be conducted is first divided into a number of non-overlapping adjoining cells, which are collectively known as the finite volume grid (or mesh). Moreover, in order to evaluate the comfort conditions by means of CFD simulation, also the indication of the metabolic rate and the thermal resistance of clothing are required. In detail, the metabolic rate is set equal to 1 met, corresponding to sedentary activity for home or school; while the thermal resistance of clothing is set equal to 0.5clo (a typical summer value).

In this analysis, CFD simulations were carried out for four days in July 2019, each day belonging to a different HVAC configuration (see Table 10). During these days, the set point temperature inside the building was 25°C and the simulations where carried out in three different hours of the day, i.e. 10 a.m., 2 p.m. and 6 p.m. Table 10 shows also the values of external temperature and the average indoor temperature for each hour of the investigated days.

Table 10: Investigated hours: outdoor temperature and average indoor temperature.

HVAC configuration and investigated day	Investigated hour	Outdoor temperature [°C]	Average indoor temperature [°C]
C1 - 12th July	10 a.m.	27.9	24.5
	2 p.m.	31.9	24.9
	6 p.m.	24.2	24.1
C2 - 17th July	10 a.m.	26.6	25.1
	2 p.m.	38.7	24.6
	6 p.m.	33.6	24.3
C3 - 24th July	10 a.m.	31.3	24.3
	2 p.m.	37.9	24.8
	6 p.m.	39.5	24.5
C4 - 30th July	10 a.m.	27.6	24.2
	2 p.m.	33.6	24.4
	6 p.m.	30.7	24.1

The results of the different simulations, shown in the following the 2D distribution of indoor air temperature, and the 3D distributions of PPD and PMV inside the building due to the performed comfort calculations.

CFD results on 12th July: configuration C1

In Figure 65, 2D distribution of air temperature and 3D distributions of PMV and PPD inside the BNZEB are shown. These values are the results of a CFD simulation ran on 12th July at 10 a.m., when the HVAC configurations C1 guaranteed the indoor cooling by means of the aeraulic heat pump. As shown in the figure, the distribution of indoor air temperature oscillates around the real average indoor value indicated in Table 10. In particular, north and south rooms are the zones characterized by a temperature value lower than the living room, where, due to the large windows the solar radiation entered inside the room and implied an increasing of the air temperature, despite the presence of two vents. The kitchen is characterized by a higher level of temperature, due to the absence of cooling vents that also causes a stratification of the air due to the absence of significant convective flows and air speed.

As regards the PMV and PPD indicators, in Figure 65 a more complex 3D distribution is shown, but in order to make a feasible analysis of their values, they can be calculated in three significative areas of the house (Table 11):

- the coldest room;
- the warmest room;
- the living room, as an average representative value of the entire house.

In order to calculate the values of PMV and PPD, as reported above, a value of 0.5clo for the clothing thermal resistance, a value of 1met for the metabolic rate, a value of about 50% for the relative humidity and a value of 0.15 m/s for the air speed were considered. The only two parameters that change for each calculation are the air temperature and the mean radiant temperature and they are reported in Table 11 as an "operative temperature".

Table 11: PMV and PPD values calculated on 12th July at 10 a.m.

12th July – 10 a.m.	Coldest room	Hottest room	Living room
Operative temperature	24	26.4	25.2
PMV [%]	-0.83	0.05	-0.39
PPD [%]	20	5	8

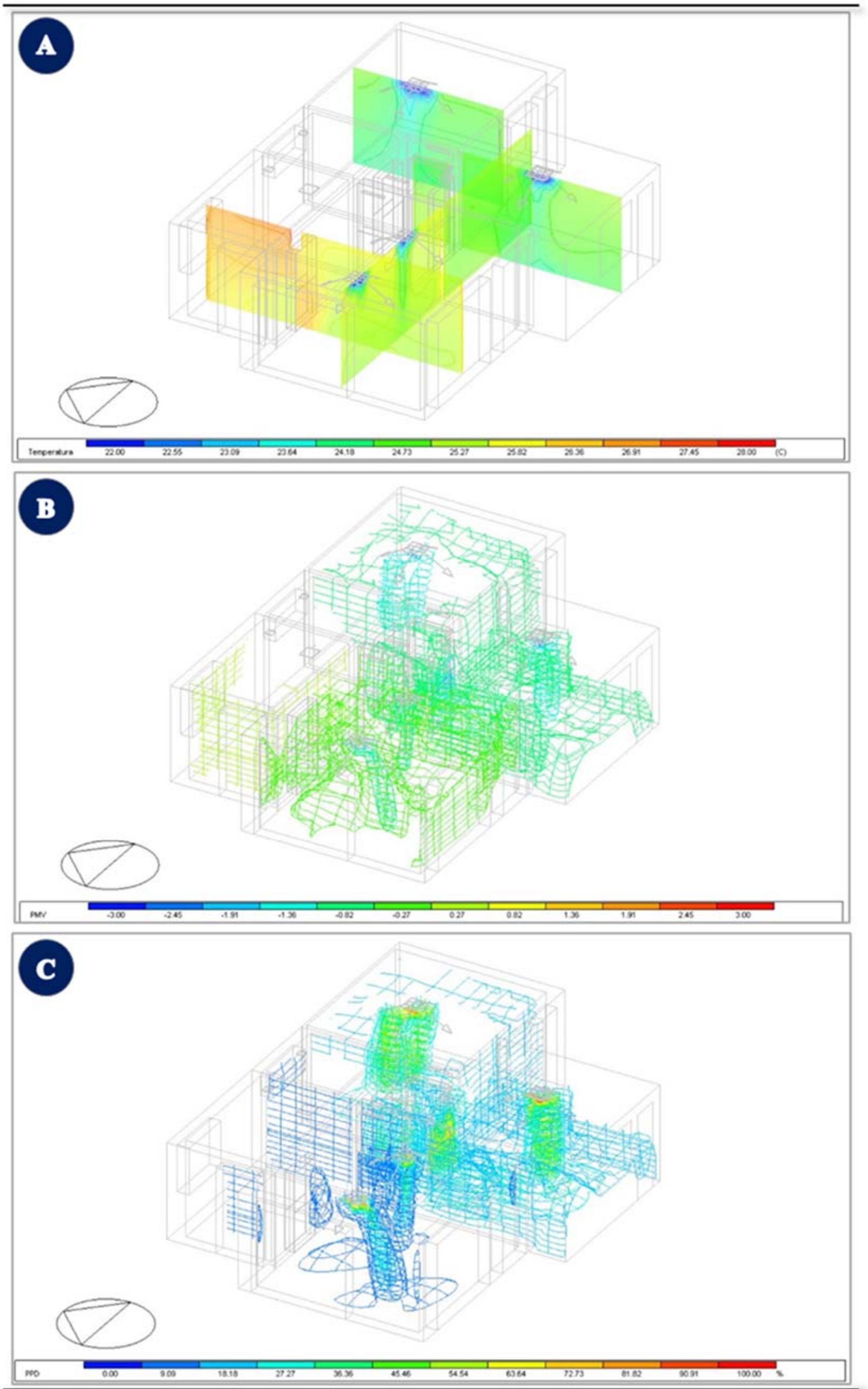


Figure 65: CFD results on 12th July at 10 a.m.: (a) air temperature 2D distribution; (b) PMV and (c) PPD 3D distribution.

As regards the PMV value, for the coldest room (the north bedroom), it does not comply with the ASHRAE Standard 55-2017 [168] (-0.5 < PMV < +0.5) and it means that the temperature of the supply air is not suitable for that room.

Figure 66 shows the 2D distribution of air temperature inside the BNZEB, resulted from two CFD simulations concerned 12th July at 2 and 6 p.m., when the HVAC configurations guaranteed the indoor cooling by means of the aeraulic heat pump and the outside mean temperature was 31.9°C and 24.2°C respectively.

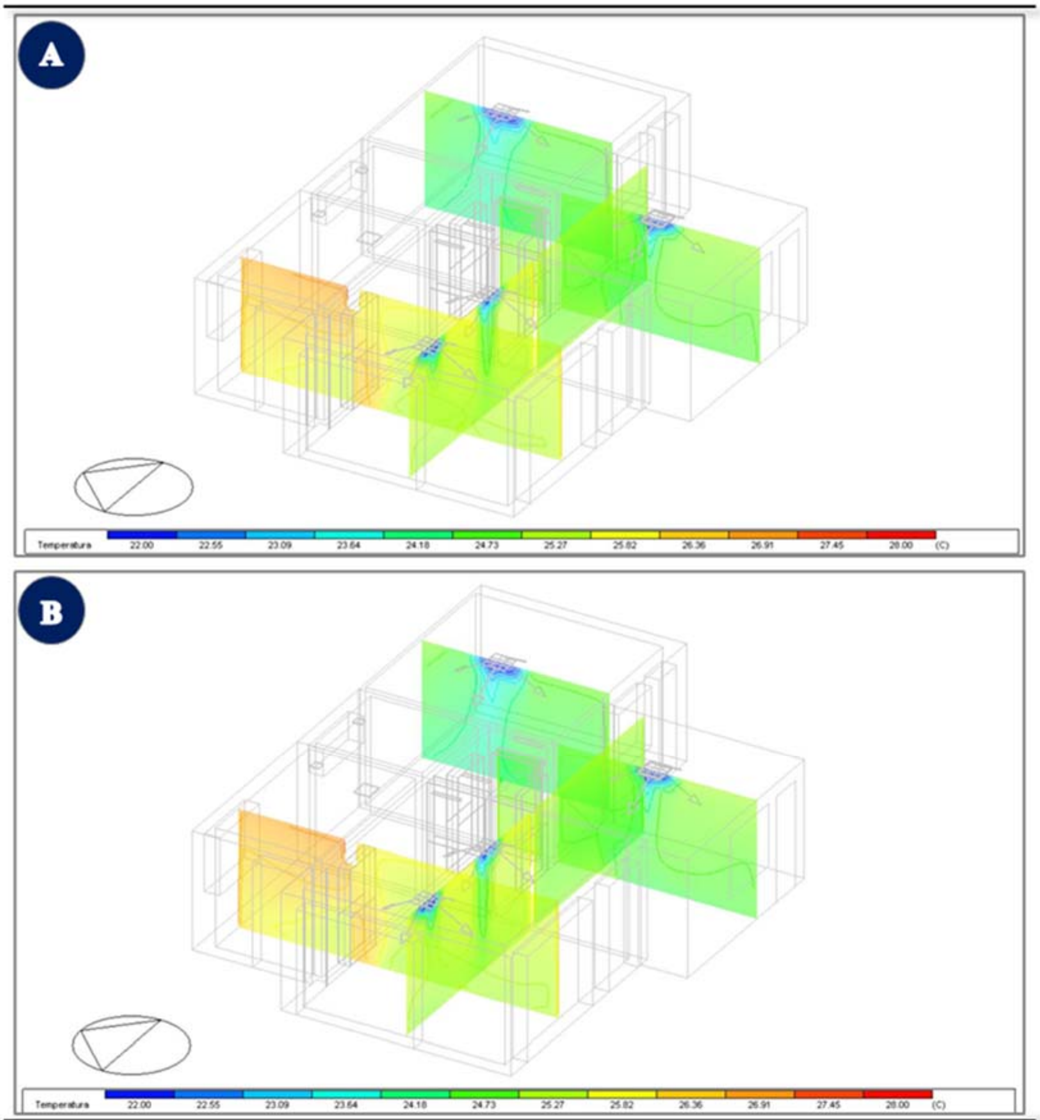


Figure 66: 2D distribution of air temperature on 12th July: (a) at 2p.m. and (b) 6 p.m.

As shown in figure, also in these cases, the distribution of indoor air temperature oscillates around the real average indoor value indicated in Table 10. More in detail, in both cases, north and south rooms are the zones characterized by the lower values of temperature. The solar radiation, due to the two south-facing windows in the south room and in the living room, entered inside the room and implied an increasing of the air temperature. In the living room, the temperature is even higher than the south room, despite the presence of two vents that provide cooled air. The kitchen is characterized by a higher level of temperature and it is the hottest room of the dwelling, due to the absence of cooling vents that also causes a stratification of the air. In Table 12 and 13, the values of PPD and PMV are shown for the coldest and the hottest room and for the living room at 2 p.m. and at 6 p.m. respectively. Also, in these cases, the PMV values, for the coldest room, do not comply with the ASHRAE Standard 55-2017 [168]. This suggest that the supply conditions (flow rates or temperature) must be differentiated between the two identical rooms. Indeed, the cooling load of the north room is obviously lower, so that, because of the air-conditioning, cold conditions can be experienced.

Table 12: PMV and PPD values calculated on 12th July at 2 p.m.

12th July – 2 p.m.	Coldest room	Hottest room	Living room
Operative temperature	23.7	26.2	25.5
PMV	-0.94	-0.03	-0.28
PPD [%]	24	5	7

Table 13: PMV and PPD values calculated on 12th July at 6 p.m.

12th July – 6 p.m.	Coldest room	Hottest room	Living room
Operative temperature	23.6	26.3	25.3
PMV	-0.98	0.01	-0.36
PPD [%]	25	5	8

CFD results on 17th July: configuration C2

In Figure 67 2D distributions of air temperature inside the BNZEB are shown during 17th July at 10 a.m., 2 p.m. and 6 p.m. These values are the results of CFD simulations run considering that, in these cases, the HVAC configuration was C2, thus the heat pump worked to provide cooled air and the ventilation air was pre-cooled by crossing the water-to-air heat exchanger. These three hours were carachterized by an external temperature of 26.6°C, 38.7°C and 33.6°C respectively.

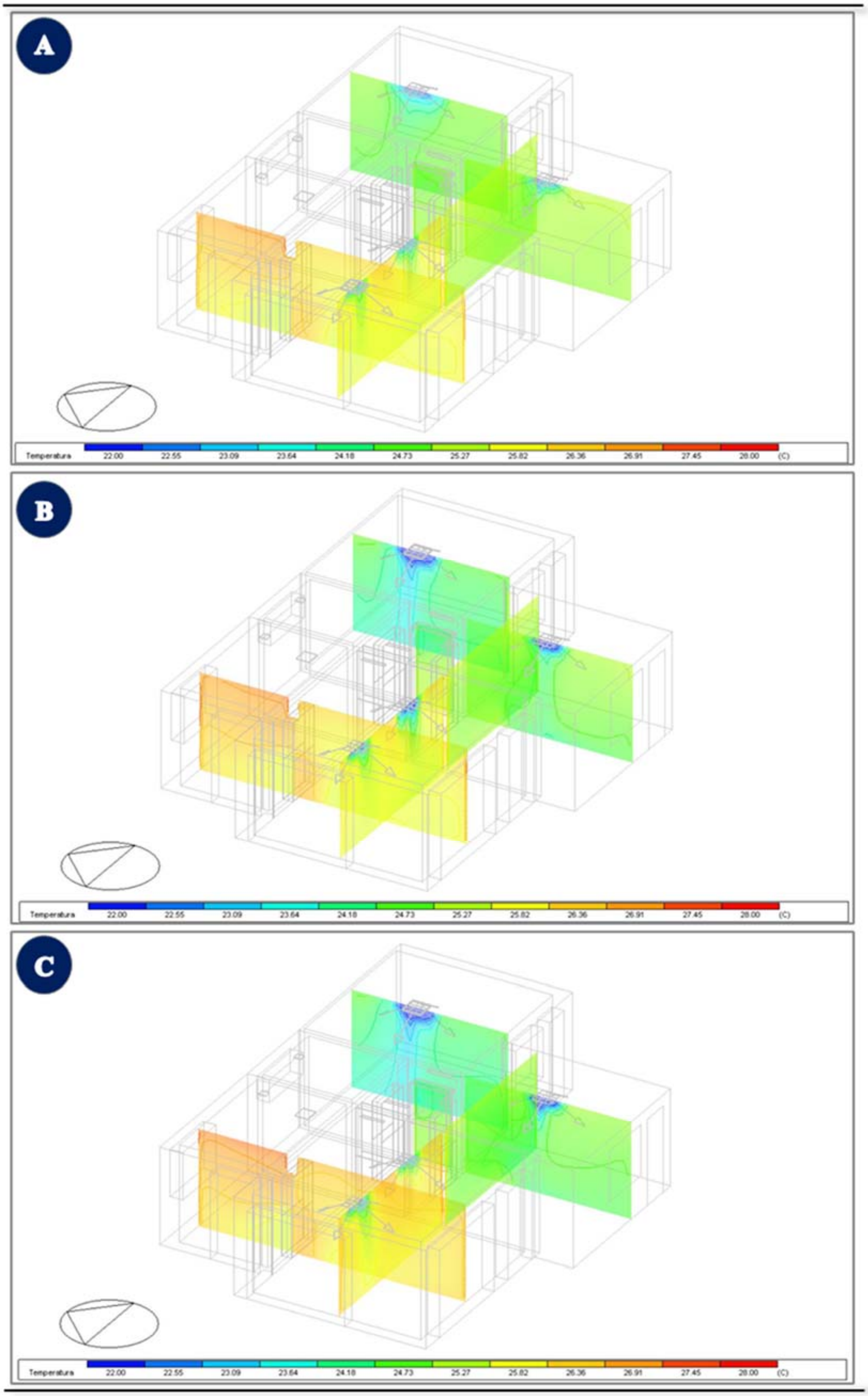


Figure 67: 2D distribution of air temperature on 17th July at (a) 10 a.m.; (b) 2 p.m. and (c) 6 p.m.

More in detail, also in this case, the north room is the one characterized by the lower values of temperature. It is possible to notice that, in comparison with configuration C1, the living room presents higher values of temperature, due to a consistent difference of external temperatures. As for the kitchen, during these three hours, it is characterized by a higher level of temperature compared to the 12th July, due both to the absence of cooling ceiling diffusers and the adjacency to the living room. Even in these cases, a stratification of the air in the kitchen happens.

In general, it can be noticed that the pre-handling of the ventilation air does not make significative differences in terms of indoor comfort but also in terms of energy consumption (as shown in the previous sub-section 3.5.2).

In Table 14, 15 and 16, the values of PPD and PMV are provided for the coldest and the hottest room (i.e. the north room and the kitchen) and for the living room. Also, in these cases, the PMV values for the coldest room do not comply with the ASHRAE Standard 55-2017 [168].

Table 14: PMV and PPD values calculated on 17th July at 10 a.m.

17th July – 10 a.m.	Coldest room	Hottest room	Living room
Operative temperature	24.3	26.4	26
PMV [%]	-0.72	0.05	-0.1
PPD [%]	16	5	7

Table 15: PMV and PPD values calculated on 17th July at 2 p.m.

17th July – 2 p.m.	Coldest room	Hottest room	Living room
Operative temperature	24	26.7	26.3
PMV [%]	-0.83	0.16	0.01
PPD [%]	20	6	5

Table 16: PMV and PPD values calculated on 17th July at 6 p.m.

17th July – 6 p.m.	Coldest room	Hottest room	Living room
Operative temperature	24.1	26,8	26.4
PMV [%]	-0.80	0.19	0.05
PPD [%]	18	6	5

CFD results on 24th July: configuration C3

In Figure 68, 2D distributions of air temperature inside the BNZEB are shown during 24th July at 10 am, 2 pm and 6 pm.

These values are the results of CFD simulations ran considering that, in these cases, the HVAC configuration was C3, thus the heat pump worked only to provide ventilation while the backup DX multi-split system worked to supply cooled air and the outdoor air was pre-cooled by crossing the water-to-air heat exchanger. These three hours were carachterized by an external temperature of 31.3°C, 37.9°C and 39.5°C respectively.

During this day, it is possible to notice that the average indoor temperature is lower compared to the previous days, despite the values of external temperature that are the highest of the four configurations.

More in detail, the living room is the coldest room in the morning (10 a.m.): it happened because, in this HVAC configuration, the air-cooling diffuser in the kitchen worked and provided a cooling effect also for the living room. The south room, in this case, is the hottest room. At 2 and 6 p.m., the coldest room is the north room, while in the living room, due to the south-facing window, the air temperature is increased. The hottest room, in these cases, is the kitchen where, due to the cooling vent, there is no stratification of the air.

In Table 17, 18 and 19, the values of PPD and PMV are shown for the coldest room (i.e. the living room at 10 a.m. and the north room at 2 and 6 p.m.) and the hottest room (i.e. the south room at 10 a.m. and the kitchen at 2 and 6 p.m.) and for the living room.

In these cases, the PMV does not comply with the ASHRAE Standard 55-2017 in the coldest room, the room north, but also in the living room at 2 p.m.. The perceived sensation would be slightly cool, and this means that the cooling system provided too cooled air or too high mass flow rate.

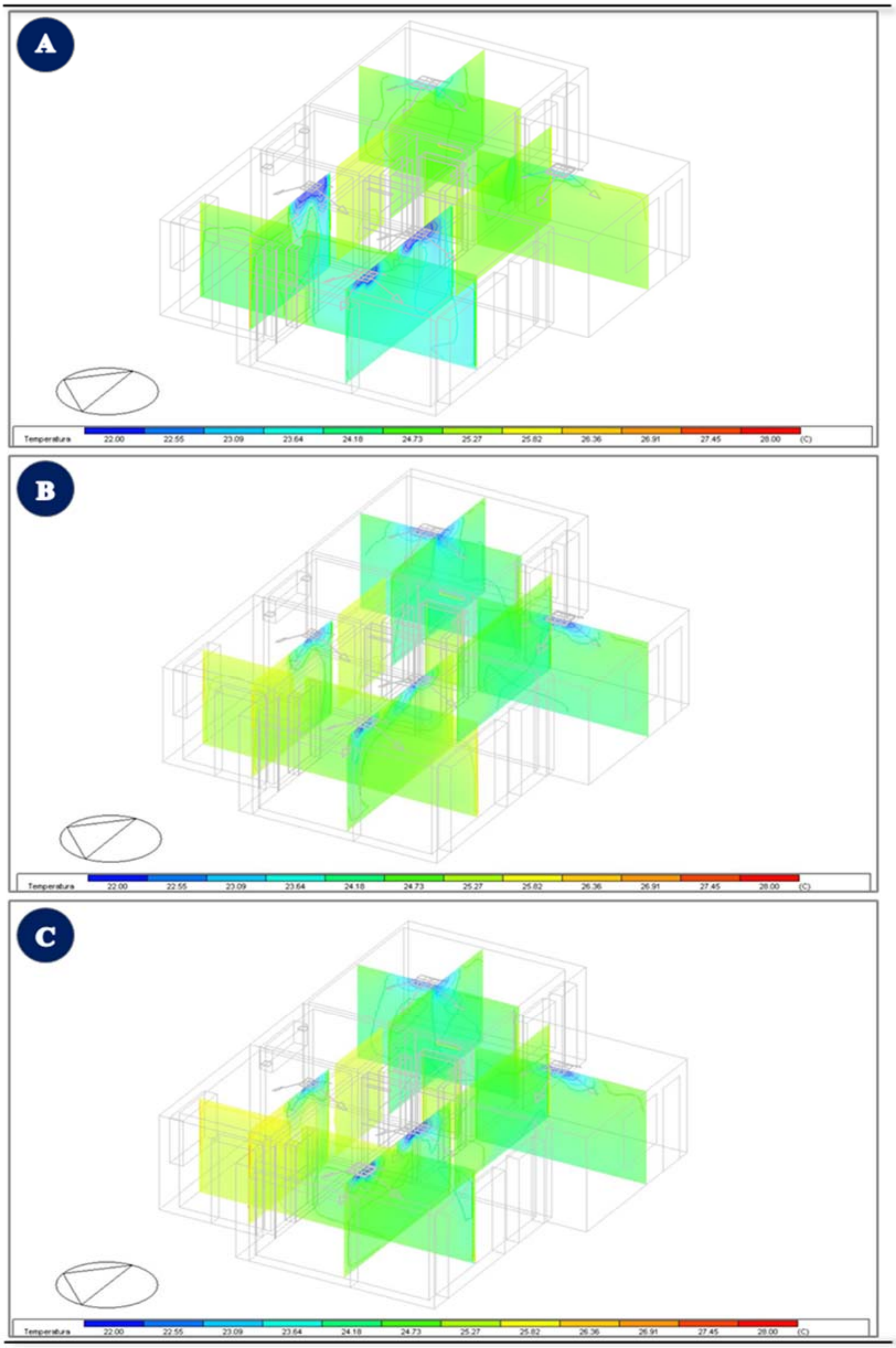


Figure 68: 2D distribution of air temperature on 24th at 10 a.m. at: (a) 10 a.m.; (b) 2 p.m. and (c) 6 p.m.

Table 17: PMV and PPD values calculated on 24th July at 10 a.m.

24th July – 10 a.m.	Coldest room	Hottest room	Living room
Operative temperature	23.6	25.2	23.6
PMV	-0.98	-0.39	-0.98
PPD [%]	25	8	25

Table 18: PMV and PPD values calculated on 24th July at 2 p.m.

24th July – 2 p.m.	Coldest room	Hottest room	Living room
Operative temperature	24.1	25.4	24.8
PMV	-0.80	-0.32	-0.54
PPD [%]	18	7	11

Table 19: PMV and PPD values calculated on 24th July at 6 p.m.

24th July – 6 p.m.	Coldest room	Hottest room	Living room
Operative temperature	24.3	25.7	25
PMV	-0.72	-0.21	-0.47
PPD [%]	16	6	10

CFD results on 30th July: configuration C4

In Figures 69 2D distributions of air temperature inside the BNZEB are shown during 30th July at 10 a.m., 2 p.m. and 6 p.m.. These values are the results of CFD simulations ran considering that, in these cases, the HVAC configuration was the C4, thus the heat pump worked only to provide ventilation while the backup DX multi-split system worked to supply cooled air. In these three simulations, the external temperature was 27.6°C, 33.6°C and 30.7°C respectively, according to the 3 considered hours of the day.

Also, during this day, it is possible to notice that the average indoor temperature is lower compared to the previous days (12th and 17th July). More in detail, the living room is the coldest room: it happened because in this HVAC configuration, the kitchen is cooled by the vent and provided a cooling effect also for the living room. The hottest room, in these cases, is the kitchen where, due to the cooling vent, there is no stratification of the air. Really, the indoor conditions are quite uniform in the whole building.

In Tables 20, 21 and 22, the values of PPD and PMV are shown for the coldest room and the hottest room (i.e. the kitchen). As for the living room, it coincided with the coldest room.

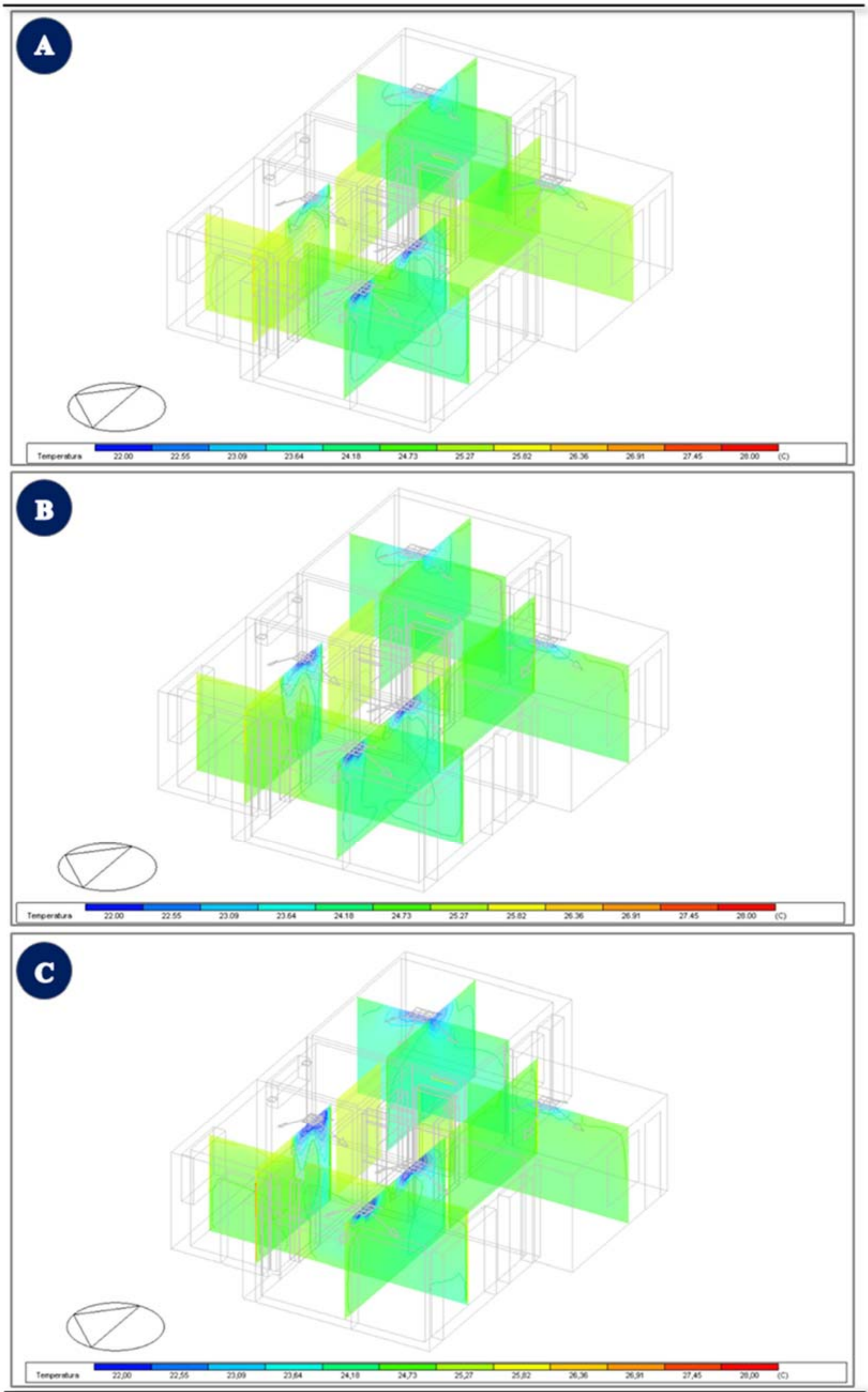


Figure 69: 2D distribution of air temperature on 30th July at: (a) 10 a.m.; (b) 2 p.m. and (c) 6 p.m.

Table 20: PMV and PPD values calculated on 30th July at 10 a.m.

30th July – 10 a.m.	Coldest room	Hottest room	Living room
Operative temperature	24	25.4	24
PMV	-0.83	-0.32	-0.83
PPD [%]	20	7	20

Table 21: PMV and PPD values calculated on 30th July at 2 p.m.

30th July – 2 p.m.	Coldest room	Hottest room	Living room
Operative temperature	24.2	25.2	24.2
PMV	-0.76	-0.39	-0.76
PPD [%]	17	8	17

Table 22: PMV and PPD values calculated on 30th July at 6 p.m.

30th July – 6 p.m.	Coldest room	Hottest room	Living room
Operative temperature	24	25.3	24
PMV	-0.83	-0.36	-0.83
PPD [%]	20	8	20

In these cases, the PMV does not comply with the ASHRAE Standard 55-2017 in the coldest room, that is the living room. The perceived sensation would be slightly cool, and this means that the cooling system provided too cooled air.

In general, the CFD analysis performed according to the four different configurations allowed to verify that the pre-handling has no effect on the indoor comfort: indeed, it only guarantees a lower temperature of the air supplied to the heat pump, and therefore a saving of the energy demand and costs, but the supply temperature, operated by the A/C vents, does not change. The CFD analysis could be an important instrument to predict the indoor comfort conditions under different HVAC configurations, during the year.

3.6 Replicability of BNZEB design

In general, the discussion about monitoring activities, but also simulation results are useful to identify general guidelines for a correct design of a Nearly Zero-Energy Buildings in comparable climate conditions. The purpose of this section is indeed, compare the energy performance of the BNZEB with standard buildings and evaluate the replicability of its design chosen in several areas characterized by a Mediterranean climate.

As said in the section 3.2, a numerical model of the BNZEB building, suitable for performing a proper dynamic simulation, was created and calibrated basing on detailed monitoring data. In this section it is used to compare, in a simulation environment, the BNZEB with other buildings in order to discover how much its energy performance are better that standard buildings for what concerns the summer season. In detail, it is compared with two types of buildings, one representative of the constructive standard established by Italian law, another representative of construction stock of Benevento (city when the BNZEB is placed). Finally, in the last sub-section, the energy performance of the building is simulated in several cities across the Europe (Lisbon, Montpellier, Madrid, Seville and Athens) in order to evaluate the replicability of the chosen designing in other Mediterranean areas. Also in this case all the results reported in the following sub-section have been already published in a journal paper. In this case they are included in a paper named “A framework for NZEB design in Mediterranean climate: Design, building and set-up monitoring of a lab-small villa” [IV].

3.6.1 Comparison of the energy performance with the reference building stock

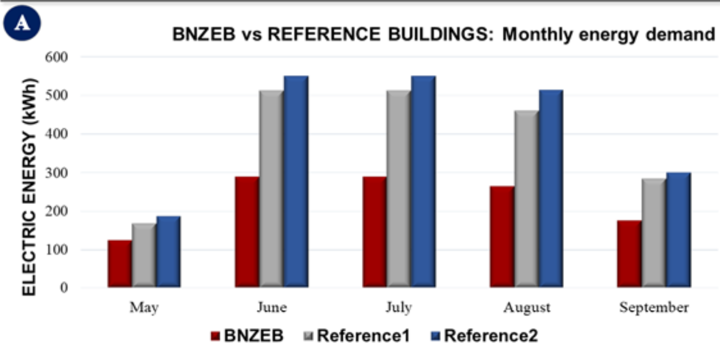
The calibrated numerical model of the BNZEB (*Real Building*) is used for a comparison, under the same operational conditions, with two kind of building configurations in order to evaluate how much its energy performance are better than standard designs, mainly during the cooling season.

In detail, the first configuration is representative of the constructive standard established by the Italian law (*Reference1*) for new buildings that should not be nZEB until 2021. More in detail, the *Reference1* has been obtained by considering the characteristics of the envelope (opaque and transparent) and the features of air-conditioning systems and renewable energy plants, set by the cited DM 26/06/2015 [19]. More in deep, Benevento is within the Italian climatic zone C, and the values of thermal transmittance should be not higher than 0.34 W/m^2K for the external walls, 0.33 W/m^2K for the roofing slab, 0.38 W/m^2K for the floor slab. For the windows, the cited law prescribes a total thermal transmittance equal to 2.2 W/m^2K. Finally, regarding the technical systems, the same decree establishes the energy efficiency ratio of cooling system (i.e., SEER – Seasonal Energy Efficiency Ratio, at least equal to 2.5) and of energy systems from renewables.

The second reference building (*Reference2*) is representative of the common construction stock of Benevento. The envelope features have been identified by considering the most common technologies of construction, on the basis of statistical information [180]; about it, it should be considered that the city centre of Benevento is quite ancient, with many buildings built with masonry and stones. In detail, a tuff masonry structure was considered for the external walls, with a thermal transmittance of 0.751 W/m^2K. Conversely, for horizontal ceilings and roof, a reinforced concrete structure with beams, joists and hollow clay blocks has been considered, with a value of thermal transmittance equal to 1.036 W/m^2K. Finally, for the windows, it emerged that only 20% of the buildings have been renewed in the last decades, so that a thermal transmittance value of the windows of 5.0 W/m^2K has been considered (single glass and wood frame). Obviously, in order to represent the real building stock of the city, renewable energy systems for the *Reference2* were not considered. Conversely, regarding the cooling system, always based on statistical data, the most widespread system for summer air conditioning is the direct expansion technology, and thus common split systems with an energy efficiency ratio equal to 2.82. This value has been chosen by considering that, in Italy, the year in which the highest number of A/C systems for residential buildings were installed was the 2004 [181].

The results of the comparison are shown in Figure 70, where the electric energy demands are reported. Also, a monthly comparison between building's electric demands and energy conversion from PV system is proposed.

The comparison shown the better performance of the proposed design. Indeed, the results show that the BNZEB has an energy requirement for summer air conditioning of about 40% lower than the building representative of the construction standard (*Reference1*) and 45% lower than the building stock (*Reference2*). Moreover, by considering also the generation from PV systems, it is evident that the BNZEB provides an on-site energy conversion from renewables higher that the used one. Indeed, although between the BNZEB and the *Reference1* the difference in terms of in-situ generation is less than 1%, in the first case the energy generation from PV system is higher than the building’s consumption (around 34%) while, for the *Reference*1, the in-situ generation is able to satisfy around 86% of the total energy requests.



	BNZEB		Reference1		Reference2
	Electric demand (kWh)	On-site PV conversion (kWh)	Electric demand (kWh)	On-site PV conversion (kWh)	Electric demand (kWh)
May	125.27	-312.03	168.82	-314.65	188.54
June	290.16	-386.54	512.81	-386.11	551.36
July	290.16	-386.54	512.81	-386.11	551.36
August	265.04	-331.56	461.19	-333.74	515.28
September	176.87	-253.96	28528	-252.29	301.70
Total	1147.50	-1670.64	1940.91	-1672.89	2108.24
ΔEtot			40.9%		45.6%

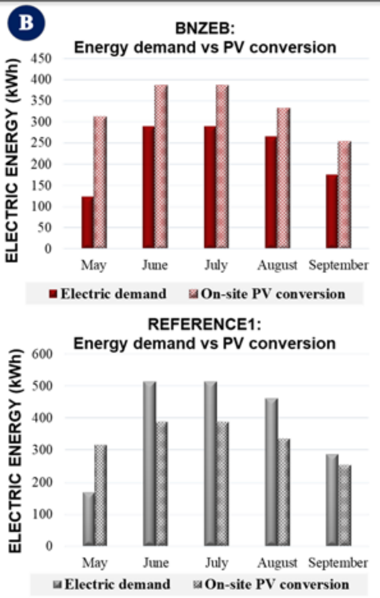


Figure 70: Comparison of BNZEB with Reference buildings: (a) electric energy demand for summer cooling; (b) building's electric demands and energy conversion from PV system.

3.6.2 Replicability of BNZEB designing in Mediterranean countries

In this section, in order to investigate the effectiveness of the performed design choices and their replicability in other Mediterranean countries, the building energy performances have been evaluated in several European cities: Lisbon (Portugal), Montpellier (France), Madrid and Seville (Spain), Athens (Greece). The chosen cities, such as the city of Benevento, belong to the Csa class of the Köppen classification: it means temperate climate with hot summers [140]. On the other hand, these cities are characterized by quite different climatic conditions, so that these well-represent the variability of Mediterranean climate across the European Countries.

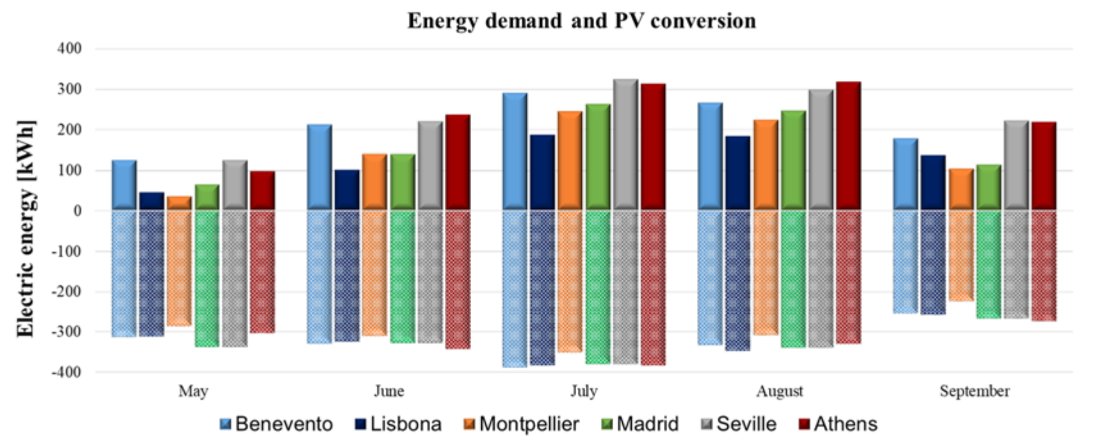
The climatic conditions of the different cities have been simulated by using a specific hourly weather file available in EnergyPlus, obtained starting from hourly weather data originally archived at the U.S. National Climatic Data Center [182]. It should be noted that, for the climatic conditions of the city of Benevento, a specific file was created by using the climatic data collected during 2018, while, for the other cities, a typical year obtained from data collected by considering a certain number of years (average values) has been used. Taking into the mind this difference, the results are nevertheless consistent, and these are shown in the Figure 71 in terms of monthly electricity demands of the building and the generation of energy from renewable sources.

By considering that the summer air conditioning system is in operation from May to September, it results that the total electricity consumption for summer air conditioning throughout the period goes from 655 kWh (i.e., 9.1 kWh/m^2) for the city of Lisbon to 1188 kWh (i.e., 16.5 kWh/m^2) for Seville. However, the requests are completely covered by the production from PV system, in all the cities considered; this allows to conclude that the adopted solution is surely replicable in all considered Mediterranean cities.

More in detail, the requests for the summer air conditioning are averagely higher in cities such as Athens (+10%) and Seville (+11%) and thus characterized by both higher average summer temperatures and higher solar radiation compared to the characteristic values of the city of Benevento. Indeed, usually, Athens in summer is the hottest capital of Europe since the temperature quite easily reaches 35/36 °C and sometimes it goes up to 40 °C. For instance, August is characterized by energy request higher than Benevento of around 19% while the renewable production is slightly lower (-1.0%). In Seville, the summer is hot, dry and sunny, with frequent episodes in which the temperature rises to around 45°C. Even September is a summer month, especially in the first half, when highs usually exceed 30 °C, indeed the comparison shows that the electric demand for air-conditioning is higher than Benevento of around 25.3% and, at the same time, the solar production is increased (+5.0%). However, in both cities, the selected configuration determines a positive energy balance along the summer period with around 450 kWh of surplus-energy and thus the envelope configuration has good potentialities for reducing the summer overheating as well as the adopted plants and renewable sources could configure the building as plus-energy house.

On the other hand, much lower summer air conditioning requests can be seen for cities like Lisbon, Montpellier and Madrid, characterized by both lower average temperatures and global solar radiation. Indeed, taking into consideration Madrid, it has weather conditions of transition between the Mediterranean climate and the cold semi-arid climate, with diurnal summer temperatures of around 31-32 °C and overnight temperatures of around 19 °C. The adoption of wood-structure and highly efficient electric plants is satisfactory since the energy need is lower than Benevento between -

7.0% in August and -47% in May while the PV-generation is always comparable. This means that the summer energy balance is positive with around 750 kWh of surplus-production and thus, in real context a lower size for the PV-system could be chosen.



ENERGY DEMAND (kWh)						
	Benevento	*Montpellier*	*Madrid*	*Athens*	*Lisbon*	*Seville*
May	125.27	3621	65.87	97.33	46.95	125.49
June	211.36	140.52	141.00	235.16	101.26	220.27
July	290.16	244.78	261.34	312.47	185.91	323.37
August	265.04	223.11	245.51	316.69	183.00	297.36
September	176.87	104.77	113.66	217.35	137.46	221.63
Total	1068.70	749.39	827.38	1179.0	654.58	1188.12

CONVERSION FROM PV SYSTEM (kWh)						
	Benevento	*Montpellier*	*Madrid*	*Athens*	*Lisbon*	*Seville*
May	-312.03	-284.90	-304.15	-302.09	-310.42	-336.64
June	-328.81	-308.61	-336.49	-341.67	-323.16	-326.85
July	-386.54	-349.51	-380.66	-381.55	-381.78	-378.01
August	-331.56	-308.00	-323.93	-328.32	-346.76	-338.98
September	-253.96	-223.08	-233.07	-27367	-25686	-266.53
Total	-1612.90	-1474.09	-1578.31	-1627.31	-1618.98	-1647.01

Figure 71: Monthly energy demand and generation from PV system for cities considered across Europe.

Lisbon, from June to mid-September, is warm and sunny but normally the temperatures are pleasant, in fact high temperatures do not reach 30 °C and the low ones are below 20 °C. In this case, the electric demand is much lower than all other cities (-39% compared with Benevento and -45% compared with Seville) with solar renewable production comparable (from -1.0% to +5.0%) with Benevento and thus also in this case the design configuration is optimal and the installed photovoltaic power could be reduced for avoiding the problems connected to the stabilization of national electricity grid due to put the excess energy produced in each building. The same happens, similarly, for Montpellier, where the mean summer temperature in the hottest month is 23.4 C. Indeed, in this case, the energy demand in May (-71%) and September (-41%) is extremely reduced compared to Benevento and considering the whole summer period the surplus energy is around 724 kWh.

This comparison shows that the design solution proposed and experimented in Benevento is suitable solution to be implemented in other cities with similar boundary conditions.

CHAPTER 4

ANALYSIS AND OPTIMIZATION OF HVAC SYSTEM OPERATION IN A NZEB EDUCATIONAL BUILDING

During the PhD period, a short-term mobility has been carried out at a foreign, authoritative, research group, from early February until 17^{th} May 2020. A research collaboration with a foreign University was performed, supported by the use of a full-scale test facility, located at Technology Campus Ghent of KU Leuven (Belgium).

The case study is an nZEB educational building designed with the aim of fulfilling the passive house standard, and with the purpose to have a school building that, at same time, can be used as lecture rooms and a test facility for scientific research in the matter of building energy-efficiency, in a "real use" environment [183].

In this chapter, after a briefly description of the case study building (section 4.1), motivations, purpose and results of performed activity are shown, focused on control and management strategies for achieving energy saving during the operation of HVAC system during the winter season. Indeed the aim of the study is to demonstrate how the overall performance of a heating system could be furtherly improved by changing its management and it will show the importance of the control strategy for ensuring that nZEB operates as efficiently as possible. Then, a deep analysis, starting from an in-field monitoring campaign (section 4.3), will be carried out during the winter period, in order to assess the actual operation and the energy use of building system under real conditions, and as starting point to identify proper alternative control strategies. Then, an energy model of the building, created and calibrated against real monitoring data (sub-sections 4.4.1 and 4.4.2), has been used to test several control strategies (sub-section 4.4.3) and to compare these mutually and with the current configuration in a simulation environment (section 4.5). It is important highlight that the purposes, the methodology and all the results of the study reported in this chapter are included in the journal paper "*Evaluation and optimization of the performance of the heating system in a nZEB educational building by monitoring and simulation*", written in collaboration with the "Sustainable buildings" research group of the above mentioned host University **Errore. L'origine riferimento non è stata trovata.**.

4.1 PRESENTATION OF CASE STUDY BUILDING

The nZEB school building is placed in Ghent, a city characterized by a temperate climate. It is located in East-Flanders of Belgium, in climatic zone Cfb according to the Köppen-Geiger classification [140] and whose main climate statistics are provided in Figure 72.

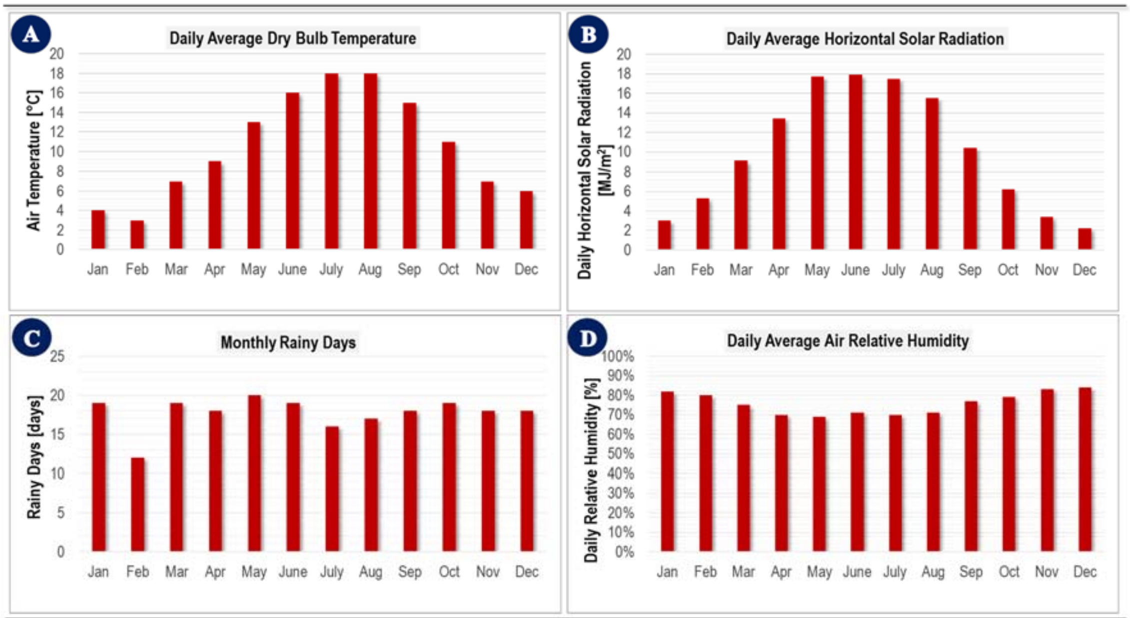


Figure 72: Climate of Ghent (Belgium): monthly profiles of air temperature (a), solar radiation (b), rainy days (c) and air relative humidity (d); [184].

The building was realized on the top of an existing university edifice and it contains two lecture rooms (1-2 in Figure 73) with a floor area of 140 m^2 and a heated volume of 380 m^3 each, a staircase (3) and a technical room (4). The whole construction is shown in Figure 73. The lecture rooms have identical geometrical features but different thermal mass. In particular, both the rooms have a concrete slab floor, with different vertical opaque envelopes, indeed: the lecture room on the first floor has a brick external wall with exterior insulation, while the one at the second floor has a lightweight timber frame external wall.

In both cases, the overall thermal transmittance is quite the same, around 0.15 W/m^2K. The window-to-wall ratio is 26.5% on both facades and the window-to-floor ratio is 13%.

Windows have triple glazing with g-value of 0.52 and these are equipped with internal and external solar shadings, offering both the possibility of manual and automatic operability. Moreover, also the external shading systems, on the southwest façade, can be both automatically and manually activated.

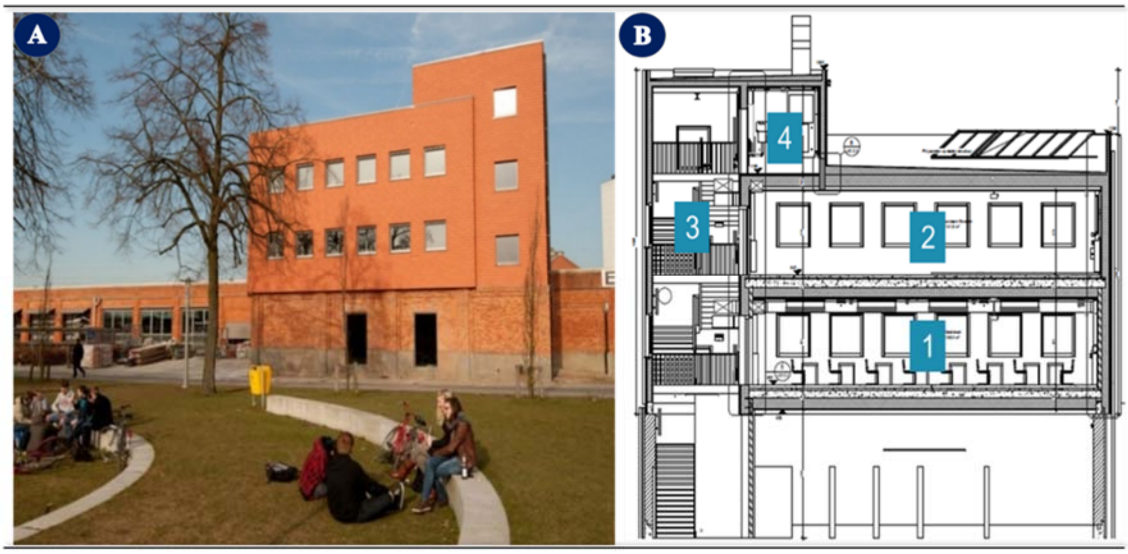


Figure 73: (a) outside view of test lecture rooms and (b) section of test building.

The heating and cooling needs are satisfied by means of an all-air system, with a balanced mechanical ventilation, with a total supply airflow of 4400m^3/h. Each classroom is a single zone, with a supply and return VAV (i.e., Variable Air Volume) boxes regulated by the AHU, by means of a request signal to control the airflow, based on CO_2 concentration and operative temperature inside the classrooms. Thus, it is an application of Demand Control Ventilation. For the space cooling needs, when necessary, the AHU cools the supply air by controlling the modular bypass of the heat recovery section and by using an indirect evaporative cooling (IEC). Conversely, to satisfy the space heating needs, the primary air is both preheated by an air-to-air heat recovery with modular bypass and, after, the active heating is achieved by the passing through a water heating coil of 7.9 kW, integrated in the supply ducts of each classroom. The heating generator is a condensing wood pellet boiler, with a nominal thermal capability of 7.8 kW, equipped with an internal water storage tank with a volume of 0.6 m^3.

During the winter season, the set-point values for CO_2 and indoor temperature are settled at 1000 ppm and 22°C respectively, while during the night the HVAC system operates in standby mode, with the heating set back decreased to 15°C. The lecture rooms, with a maximum occupancy of 80 persons, are usually used from Monday to Friday, between 8:15 and 18:00. In general, the academic year counts 124 days of activity, with university courses (September-December and February-May) and 63 days of exams (in January, June, and August-September).

Finally, with reference to the systems and equipment for the managing and monitoring, the building is fully monitored through a set of sensors installed in order to collect all variables necessary to characterize the indoor and outdoor conditions. Moreover, the building is provided with a dedicated weather station that monitors the main outdoor parameters, and thus solar radiation, outdoor temperature, humidity, wind speed and direction. For what concerns the indoor conditions, the air temperature, relative humidity, and CO_2 concentrations are continuously monitored with a time step of 1 minute, while the occupancy level is measured by a motion sensor and a high definition camera, with face recognition. The operation of the HVAC system is fully monitored too, by means temperature and mass flow sensors located in the main sections of the system. All these recorded data are collected in an accessible database, so that these are available for further elaborations.

4.2 OPTIMIZATION OF THE HEATING SYSTEM IN NZEB BUILDING: MOTIVATION AND ADOPTED APPROACH

As said in the first chapters, in non-domestic buildings - but often also in these ones - the energy consumption of the HVAC system is the main end energy use, with a weight close to 50% of the overall energy demand at European level [185]. Hence, it is evidenced the importance to optimize the operation of buildings and HVAC systems, that result very sensitive to control strategies and management and to a different level and consciousness of user interactions. In this regard, Gunay *et al*. [186], by examining the operational parameters of the HVAC that impacts on the performance gap in office buildings, show that habits of the occupants and default features of equipment could be improved for bettering the system operation. They have also found that the start and stop times of the Air Handling Unit (AHU, in the following lines) and the ventilation rate are the most critical parameters that affect energy and comfort performance in buildings. More in deep, one-hour change in AHU start or stop time is estimated to affect the HVAC energy performance by about 4% for the investigated buildings. Really, the topic of the role of occupant behavior is very actual, having a great impact on buildings' energy demands.

Moreover, especially with reference to non-residential buildings, the time-dependent nature of their heating loads gives the possibility, by studying the heating load variation, of improving the efficiency of energy systems and to reduce the energy consumption and system operating costs. Ding *et al*. [187] have proposed a multi-objective optimization algorithm, by showing that, without compromising the requirements of the thermal comfort of building occupants, the energy system operating cost can be reduced of about 40%, with an increase of system coefficient of performance compared to the current experience-based operation strategies.

Obviously, there is a need to know and understand how the real system actually works, as starting point to test and improve the management of a building like a complex system. In general, monitoring and verification of operational energy performance are fundamental to study and assess building's behavior along their lifetime. Furthermore, the knowledge of how the energy is used and the real boundary conditions could help to improve both the reliability and usefulness of building simulation models, that can be then used for enhancing the construction of new ones [188]. The study of energy demands, in a real operational context, might support the improvement of the energy performance of existing buildings, the behavior change [189] and can support energy efficiency policies. Finally, analysis on real data, coming from in-field monitoring campaign, allow to knowing how the energy is used, and it is fundamental to design and assess the improving of existing buildings, improve the control of the systems and to optimize the overall building performance and energy use. Then, starting from monitored real data, it is in general fundamental to detect malfunctions, to improve the control of the systems and to optimize the overall building performance, energy use and indoor comfort conditions. In this regard, Carlon *et al*. [190] started from a one-year monitoring campaign of a building and evidenced the importance of a better management of the thermal inertia of the heating system; then, these authors tested improved control strategies by means of suitable simulations.

The optimization of HVAC control in high-efficient buildings, is worth investigating. The most recent paper of Bechtelet al. [191] have shown that in single family houses, a model predictive controller determines the cost-optimal operating cycles of the heat pump in combination with thermal energy storage. Liu et al. [192] have evaluated as control strategies of a heating and cooling system: adjustment of set-points for heating and cooling and adjustment of set-points together with a rule-based weather predictive control strategy. The paper of Guillen-Lambea et al. [193] is focused on the control strategies for the energy recovery ventilators. The optimum strategy during winter is a control based only on the sensible energy. The optimal strategy found for the summer season is based on the enthalpy control. Georgiou et al. [194] have introduced a novel approach able to adapt to a given PV generation and load demand and individually control the battery and the net grid energy. Aranguren et al. [195], by means of a numerical model, have proposed the adoption of a thermoelectric cooler-heat pump. Taking into consideration the lowered heating and cooling load of high efficient buildings, the adoption of a natural heat transfer air-conditioning terminal device has been investigated by Shu et al. [196]. Finally, Huang et al. [197] have underlined another important aspect: a proper control of the nZEB cluster is essential for improving load matching, reducing grid interaction and reducing energy bills.

Briefly, most of the recent papers about the nearly zero energy building are focused on the optimization of solution design, on the global energy balance or thermal comfort. Few papers give suggestions on the management approach for optimizing the activation of HVAC system and there is a poorness of experimental data for validating the operation in real conditions. The availability of real monitored data is limited, because few studies in the matter of in-field monitoring campaigns and about operational behavior and energy performance of building in a “real use” condition are available, at today.

More in general, without considering the case of nZEB, in the recent scientific literature, the most investigated HVAC control strategies are based on the model predictive control (a very up-to-date frontier) or these are rule-based strategies. In particular, the first logic is implemented both to improve the real-time management of storage tanks [198], boilers [199], district heating systems [200][201]. For instance, in [202][202], with reference to the heating and cooling systems of office buildings, the model predictive control is applied to improve the indoor microclimate control. On the other hand, with reference to the rule-based and association rules, there are a number of control strategies, like the occupancy-based heating control proposed by Shin *et al*. [203][203] for the optimal start and stop control of radiant heating systems to improve the energy saving and the thermal comfort, or control strategies based on weather compensation, for which the supply water temperature is related to the outside air temperature according to specific heating curves [204] or mathematical correlations. In this matter, Péan *et al*. [205], in a huge review about existing controls aimed at improving the energy flexibility of building systems, provided a clear difference in terms of concept and complexity of predictive and rule-based controls. A self-tuned HVAC controller that provides customized thermal conditions to satisfy occupant preferences while minimizing energy consumption, and its implementation in a real occupied office has been proposed by Lee [206]. Most advanced strategies are also proposed basing on simulation tools. For instance, Shunian et al. [207] have proposed a stochastic optimized chiller operation strategy based on multi-objective optimization and measurement uncertainty. Gue tel al. [208] by employing four wise metaheuristic algorithms, have studied a control for residential buildings through predicting heating and cooling loads. Ganesh et al. [209] have solved an optimization problem for calculating the ventilation rate that minimizes the total energy consumption, while maintaining the indoor pollutant concentrations below to acceptable thresholds. The proposed techniques are really innovative but the effectiveness on the management of real HVAC has not been proven.

Here, the aim of the activity shown in this chapter is to investigate the actual operation and energy use of an existing educational nZEB, as the starting point to identify alternative control strategies for the heating system and then to demonstrate how the overall performance could be improved by managing differently the same installed equipment. The novelty of this study, under both the point of views of methods and application, is the improvement of the management of energy system, in an existing nZEB by evidencing that energy demand can be reduced and also indoor thermal comfort conditions can be improved, at the same time. One of the main findings is that, as also sustained in [210], buildings designed to be high energy efficient require a deeper investigation of the management of air conditioning systems compared to a traditional building. A building designed to have a high passive control of internal conditions could allow the use of control strategies and optimized managements able to further decrease the energy consumption, still maintaining indoor comfort conditions for the occupants. Indeed, usually the management of air conditioning systems are based on a “fixed point” using a constant set-point temperature in each room or in the most representative ones. Moreover, sometimes, thermal storages are maintained at a constant temperature to avoid the effect of time lag (due to the inertia) at the start up. Furthermore, the supply temperature, of water or air, often is chosen based on conventional values, without considering that it could cause an overheating effect, during the heating season, compared to the optimal comfort conditions, with further negative effects, and thus the increase of thermal losses and of the energy demands for the heating service. Thus, the present study provides a deepening about the management of the heating system in an existing building designed for being a nearly zero-energy educational building, in order to understand how the energy efficiency of a nZEB is sensitive to controls strategies and the important role played by the control systems: really, the control strategy is fundamental to ensure that the building operates as efficiently as possible, in terms of energy demands and thermal comfort.

4.2.1 Methodological approach

As said, the test lecture rooms on KU Leuven Ghent Technology Campus have been chosen as case study building for the present research activity. Then, starting from a current HVAC system configuration, and thus by monitoring data then implemented in a validated numerical model, different control strategies are proposed and tested, all based on heating curves for the control of water supply temperature and the water storage tank temperatures dependent from the outdoor one, on the shifting back of AHU's switching on, and also by proposing the introduction of a set-back value for the water temperature inside the storage tank. The investigated control strategies will be described in the following, then these will be tested in a simulation environment based on the Modelica open language [211], and the results are then compared to the baseline scenario and each other, in terms of both achievable thermal comfort and required primary energy demands for the space heating service. In particular, the methodological approach consists in two parts that will be described in the following: the experimental one and the simulation one.

In field monitoring

The starting period of the winter academic season 2019-2020 has been chosen for the campaign, and thus from the beginning of October until the end of December 2019. During the monitoring phase, the two test lecture rooms were occupied by the students of the university courses, and thus this allowed the evaluations of the actual operation and energy use of the building and facility, under a real condition of use. More in deep, the results are specifically shown for the month of November 2019 and the parameters that have been analyzed are environmental, thermal, energy and configuration parameters, and thus: a) air temperature (zone and supply), b) VAV damper position (in order to evaluate the actual supply airflow), c) the CO_2 concentration in rooms, d) the outdoor conditions from the weather station, e) the supply water temperature and f) water mass flow from the boiler, g) the thermal power at the AHU heating coils. Moreover, further variables, and thus doors and windows opening, occupancy level and HVAC operation time, have been used to evaluate the reliability of achieved results.

Properties of the main sensors used for the measurements are listed in Table 23. The time interval used for the measurements is 1 minute.

Table 23: Properties of sensors.

Parameter	Type sensor	Accuracy
Room temperature	SE CSTHR PT100	± 0.1 °C
Air temperature	Omega PT100	± 0.10 °C
Supply temperature	SE CSTHK HX	± 0.4 °C
Water temperature	AMTRON SONIC D	± (0.30 + 0.005 * reading)
Water flow	AMTRON SONIC D	± 0.2 % reading
AHU outdoor temperature	SE PT100	± 0.10 °C
Occupancy	Acurity Crosscan Camera	± 5 %
CO_2 concentration	Vaisala GMW83	± 30 ppm + 3% reading
Outdoor temperature	Vaisala HMS82	± 0.3 °C at 20 °C
Wind velocity	Ultrasonic 2D Anemometer	± 0.1 m/s (0-5 m/s)
Wind direction	Ultrasonic 2D Anemometer	± 1°
Solar radiation	SPLite2Silicon Pyranometer	4.5 % reading

The monitoring data have been used both to assess the actual operation and energy use of the case study building and to understand the possibility to have a better management of the hot water supply, by identifying some possible alternative control strategies, that will be described in the following.

Numerical modeling and simulation

The simulation analysis is carried out to demonstrate how the overall performance of the heating system could be improved, by using a better control strategy and then how improving the choice for the management of energy systems in existing buildings can affect their energy consumption and the indoor comfort conditions for the occupants.

Dynamic building simulation is an essential tool for the designing of appropriate system solutions and to test different control strategies in existing buildings too. In this study, the dynamic simulation environment Dymola and the equation-based Modelica [211] language were chosen for the modeling of the complex systems, and thus building and equipment. Obviously, the dynamic simulation model of an existing building must be correctly settled-up and calibrated, to ensure that the model is representative of the real behavior of the building under analysis. There are several standards to follow for the correct calibration of the models, through codified procedures and protocols and, in this study, the model validation has been performed by taking into account the ASHRAE Guideline 14 (2014) [212], based on detailed monitoring data of building and HVAC systems, as shown in the validation process sub-section (4.4.2, in the following of the chapter).

Then, the alternative control strategies have been implemented in the calibrated numerical model of the building in order to have different scenarios to test and the results are compared to the baseline model and each other, in terms of primary energy consumption and comfort condition inside one of the two lecture rooms during the time of students' occupation.

4.3 OPERATION OF THE HVAC SYSTEM BASED ON MONITORING DATA

In this section, the HVAC system response to the heating and hot water demand is experimentally investigated. Furthermore, the real operation of the AHU and of the combustion pellet boiler in the considered system configuration are characterized, to implement, in a sequent phase, this operational peculiarity into a suitable energy simulation model.

Moreover, analysis on real data, coming from in-field monitoring campaigns, allow to have a deep knowing of how the energy is used, and it is fundamental to design and assess the improving of existing buildings and the behavior change. Indeed, start from monitored real data is in generally fundamental to detect malfunctions, improve the control of the systems and to optimize the overall building performance, energy use and indoor comfort conditions.

The Figure 74 gives a general picture of the operational asset of the overall system. The pellet boiler is always available to provide hot water for the space heating needs of both rooms, separately. The AHU is turned on from 7:30 a.m. to 6:00 p.m. and, according to the heating needs, such unit sends a request signal to the supply pump of the hot water supply.

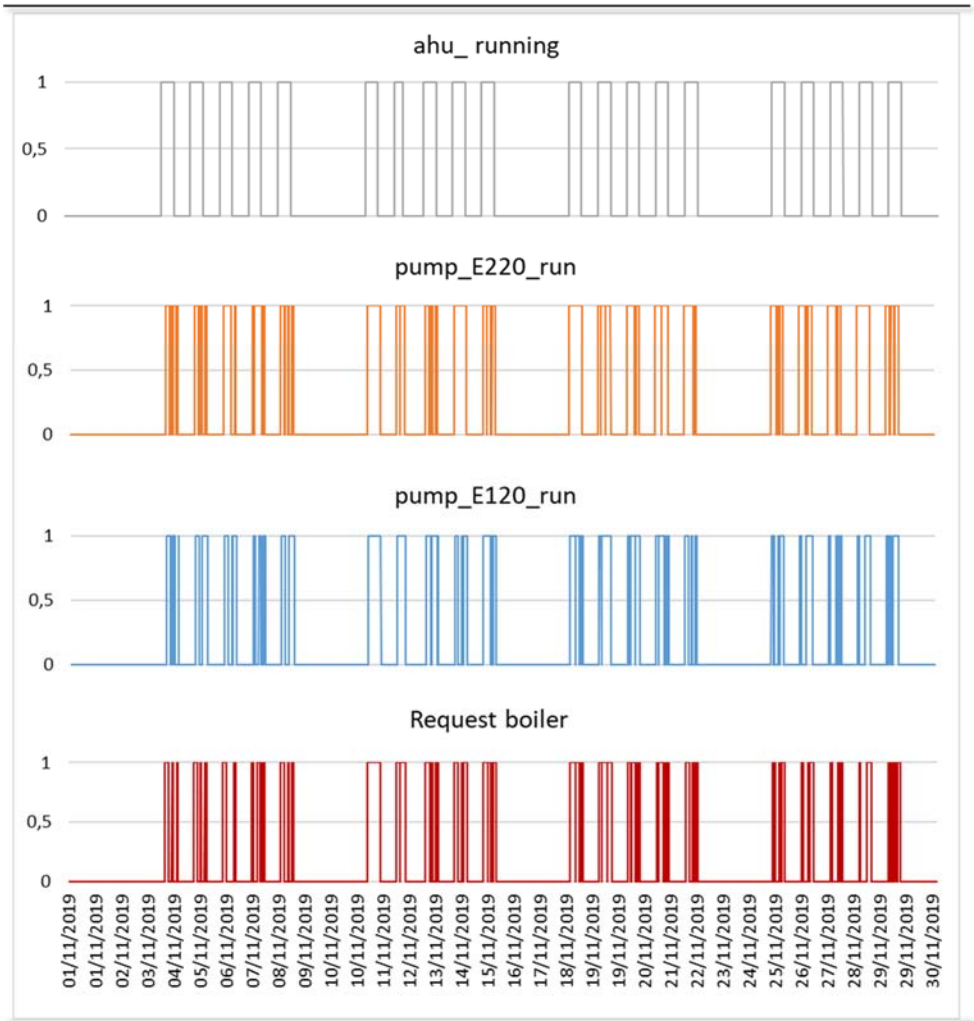


Figure 74: General operational of HVAC system (November 2019).

In Figure 75, for the classrooms E120 (first floor) and E220 (upper floor), the supply airflow rate, the room temperature and CO_2 concentration are shown, with reference to

November 2019. During the AHU operation hours, the airflow in the classrooms increases as result of the low room temperature and high CO_2 concentration. During the start-up of the AHU, because of a low room temperature in the morning, the supply airflow increases, by exceeding 2000m^3/h, in order to allow the set-point temperature inside the rooms. Conversely, when the zone temperature exceeds the set-point, the airflow decreases.

Moreover, after the end of a lecture, the system still operates at a certain airflow rate, in order to reduce the CO_2 concentration in the rooms. Moreover, during the low or no occupancy periods, the airflow decreases to a minimum, to reduce the energy demands for fans. In general, the air system works as it is designed and according to the expectations, on the base of the planned scheme of demand control ventilation.

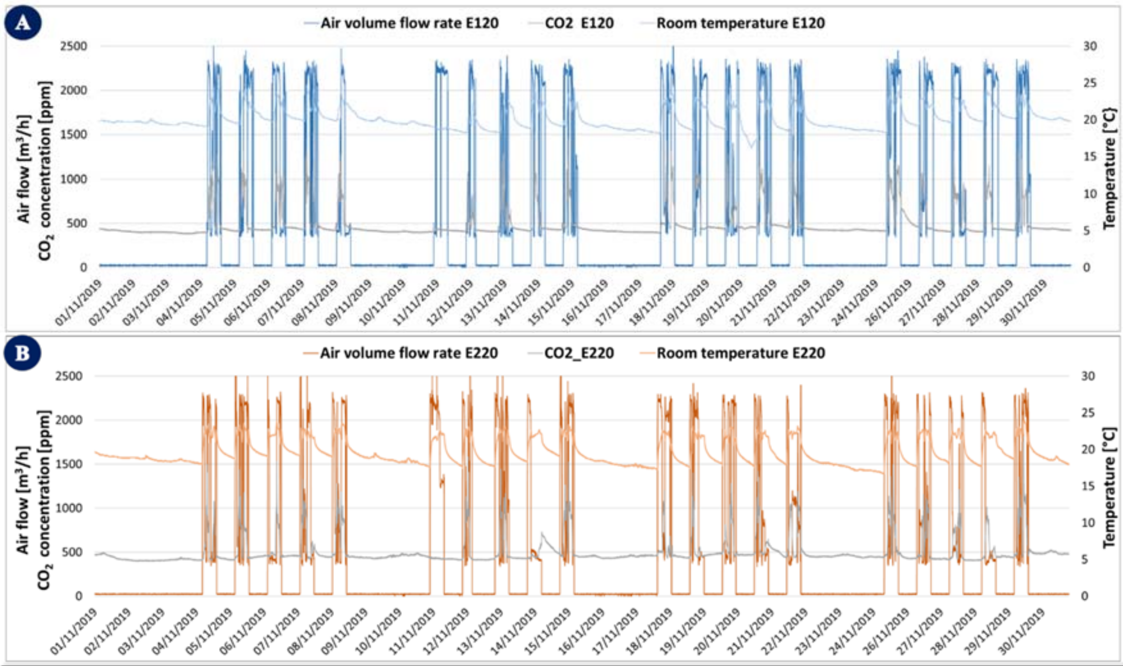


Figure 75: Supply Airflow, air temperatures and CO_2 concentrations in the classrooms (November 2019).

In Figure 76, the supply water temperature from the boiler, the air temperature at the AHU's heating coil, the temperature inside the rooms and the indication (with grey areas) of the time during which the system requests hot water from the boiler are provided, still with reference to the month of November 2019. The results show that, during the AHU start-up, the boiler immediately provides water at a temperature also above 60°C, in order to heat the supply air which temperature increases from 16°C up to 30°C to meet the heating set-point in the classrooms. Indeed, even if slowly, also the temperature inside the rooms increases, by reaching the set-point temperature after about one hour from the AHU's start-up.

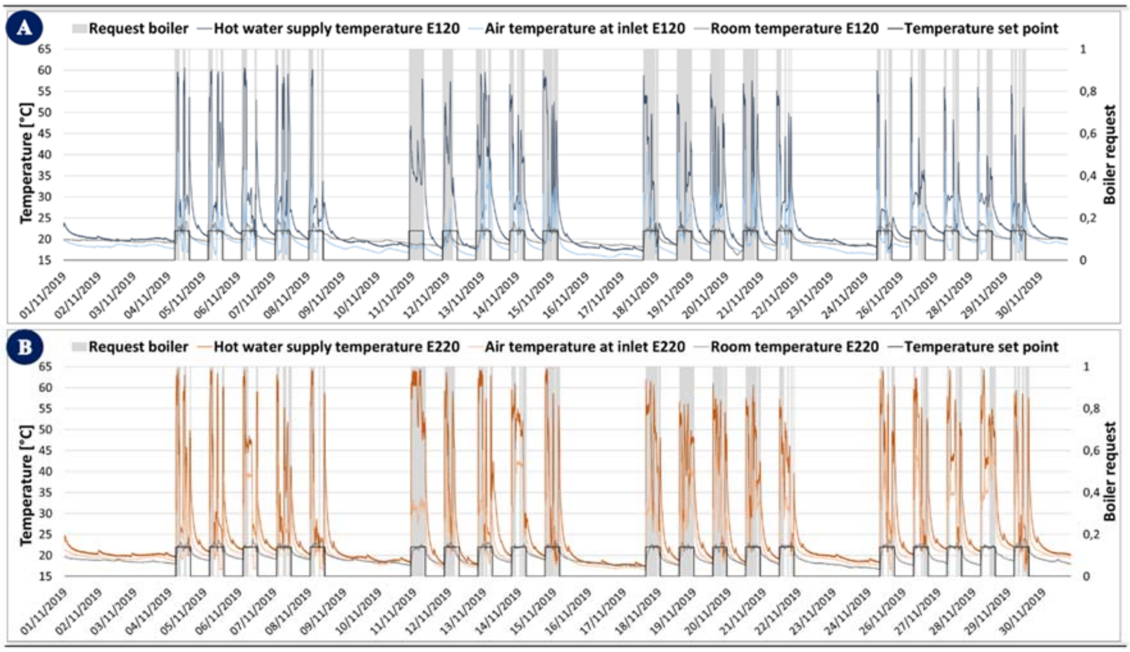


Figure 76: Boiler activation and operative temperatures (water, indoor air, AHU supply and set-points) in the classrooms (November 2019)

Finally, in Figure 77, the daily energy demands for the fans and the thermal energy provided from the boiler to the AHU's heating coils, with reference to both the classrooms, are reported. Furthermore, here it is also reported the indication, for each day of the month, of the parameters that affect the energy demands, and thus the operating hours of the pump for the water supply for each room, the mean outside temperature, the daily occupancy inside the rooms (in terms of the mean number of people and number of hours of occupancy) and the supply water temperature at the heating coils.

By analyzing Figure 77, it is possible to see that the AHU consumption changes according to the occupancy. On 11th November, for instance, there are no people inside the lecture rooms, and thus a high energy request is recorded, with reference to both fans and thermal need, because the system works to meet the set-point temperature without the thermal contribution due to the occupancy (i.e., the heat endogenous gain). Surely, the occupancy is an internal load that positively affects the overall heating load, by reducing the thermal energy need, but, on the other side (in this configuration of HVAC system) also increases the ventilation requested to reduce the CO_2 concentration inside the lecture rooms.

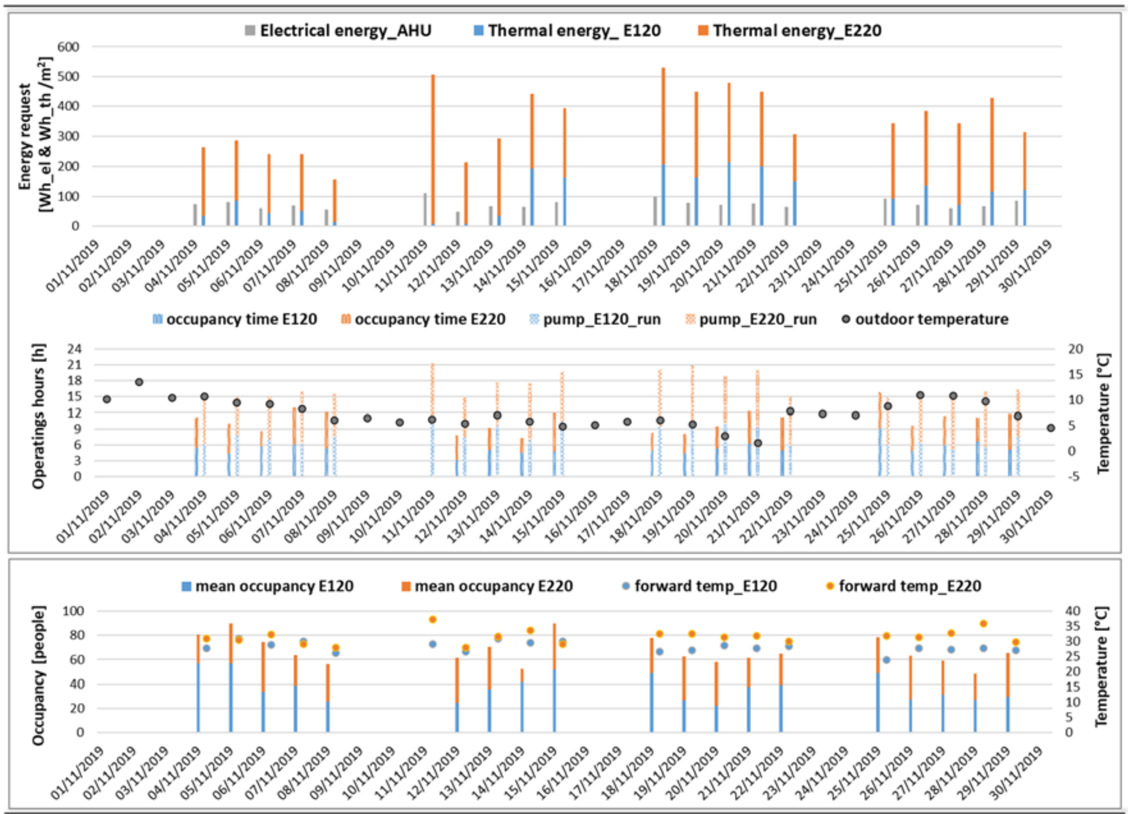


Figure 77: Current energy demands and main influent parameters (November 2019).

As shown, during the last three days of the month, the mean outdoor temperature progressively decreases and the fans energy consumption increases. Moreover, the thermal energy needs are clearly affected by occupancy and outdoor temperature, in both cases with an opposite correlation (i.e., the heat demand rises when occupancy and/or outdoor temperature decrease). More in deep, the occupation hours are comparable, but on 28th there is the highest thermal need with an intermediate outdoor temperature and a lower occupancy inside the rooms, while, on 29th, there is the lowest thermal need despite the lower outdoor temperature. During the 27th November, the outdoor temperature is the highest, but the thermal demand is intermediate, giving that the occupancy is lower compared to the 29th November.

The monthly lowest outdoor temperature is measured during the 21st November (of course, with reference to this month), when the energy consumption is relatively high but not the maximum value of the month because of the positive occupancy effect. Indeed, a high energy consumption occurs during the 11th and 18th of November. For the first day, the thermal need is high, because there aren't people inside the lecture rooms and thus there is a lack of the positive contribution of the internal load to meet the set-point temperature. Conversely, during the 18th November, the higher energy consumption is due to the opening of the door of the room E220. In general, the lower thermal demands are recorded for the room E120, that is the most used, in terms of time and mean number of occupants.

As expected, there is a relation between the supply water temperature and the internal needs. This temperature is higher when the outside temperature is lower and, moreover, this is affected also by the occupancy rate, as above already justified.

In general, the monitoring results show how the system suitable response to the outdoor and indoor conditions and optimizes the behavior to minimize the energy demands and to meet comfort conditions inside the building. On the other side, there is a possibility of improving the management of hot water generation and storage: indeed, according to the current control logic, the pellet boiler keeps the hot water inside the integrated tank at a quite high and constant value of temperature, over the time, without considering the time-varying nature of the heating loads of a university building. Then, the possibility of improvements will be investigated testing (in the section 4.5) proper alternative control strategies based on the time-varying values of water temperatures, according to the monitored and then actual trend of building's uses and according to the actual heating load of the building following the outdoor conditions.

4.4 BUILDING SIMULATION SET UP

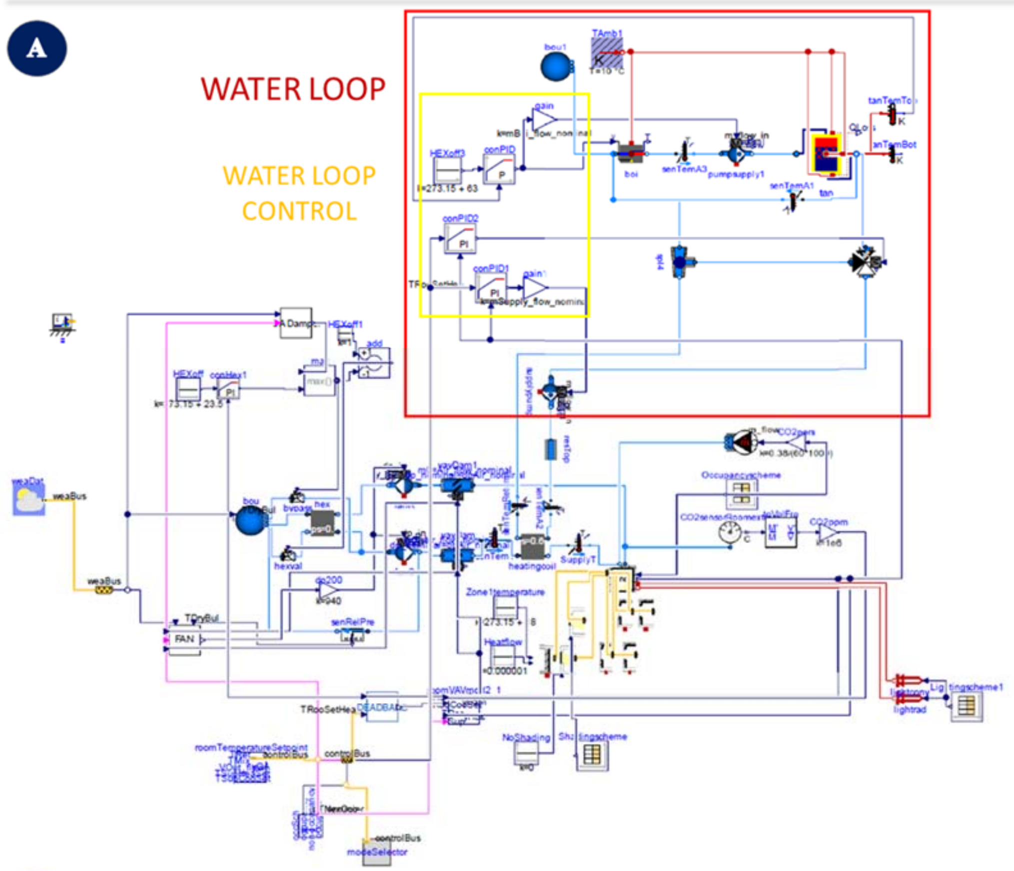
According to the purpose and adopted methodology of the present research activity, in this section, first the creation of simulation model of the building will be shown (sub-section 4.4.1). Then, to make a reliable prediction of the operation for the building system and its system in a simulation environment, the model calibration process, based on detailed monitored data, will be described (sub-section 4.4.2). Finally, in the last part (sub-section 4.4.3) some alternative control strategies will be selected and described according to the main considerations derived from the monitoring evaluations.

4.4.1 Building simulation model

The building simulation model of the case study building has been already created in Modelica (Dymola, 2018) and calibrated according to the ASHRAE Guideline 14 (2002) [213]. A detailed description of this model and related calibration against real measurements is inferred in Merema et al. [214][214]. In additions, according to the purposes of the present study, the model has been updated, by using a new version of the same tool (i.e., Dymola 2020) in order to implement the hot water generation section in the previous model (i.e., the pellet boiler, the tank and the water pumps with related controls). In particular, the added components are derived from the so-called *Building* open-source library [215] and are reported in Figure 78 together with an overview of all used simulation models and connections.

The hot water generation from the boiler is controlled by a proportional control with a gain factor of 0.7. The thermal generation from the pellet boiler keeps the water temperature inside the tank at 60 - 65°C. Furthermore, two PI controls have been used to manage the hot water supply from the water storage tank to the AHU heating coil. In particular, the chosen gain factors are 0.01 for the PI pump control and 0.08 for the three-way valve control, with an integration time of 180s in both cases. The control logic is conceived for obtaining the set-point temperature inside the room, measured by a temperature sensor with radiative fraction settled to 0.15. In addition, a dead band equal to 1 °C on the heating set-point of 22°C is included to avoid the oscillating of the damper in the air section of the system.

The outside temperature is constantly measured by the weather station and used as input for the HVAC system control. As input air temperature for the ventilation system, the outside temperature measured inside the AHU is used. Finally, with reference to the shading devices, artificial lighting and occupancy, the measured data from the building monitoring system (BMS) have been included inside the simulation model, with reference to each day of the simulation period, by using detailed schedules.



B

Component	Simulation model
Boiler	Building.Fluid.Boilers.BoilerPolynomial
Tank	Building.Fluid.Storage.Stratified
Pumps	Building.Fluid.Movers.FlowControlled.mflow
Valve	Building.Fluid.Actuators.Valves.ThreeWayEqualPercentageLinear

Figure 78: (a) Modelica model of the case study building and (b) simulation models used for the update of the building model.

4.4.2 Model calibration process

As said in the section 3.2, the calibration process of a building model is an iterative process of comparison among the output of a simulation and those derived from measured data, by determining the deviation of the results and the degree of uncertainty. Then, starting from a baseline model, created as accurately as possible, and whose outcome are deeply analysed and compared to the monitored data, a trial-and-error approach is adopted to manually adapt the variables which results not have a satisfactory correspondence among the simulated outcomes and the real measured data. This is the “calibration phase”, in which input data, boundary conditions and possible modelling errors are corrected. The goal is to achieve a numerical model that properly represents and reproduces the real base scenario, so that it can be expected that design alternatives implemented in the model can offer reliable results for what concerns their application in the real facility. Finally, the availability of a validated and calibrated numerical model of a real building energy performance is a powerful tool for designing design alternatives and understanding their feasibility, in terms of technical, economic, environmental usefulness.

There are several sources for a correct calibration of energy models, through coded procedures and protocols. For this case study building the calibration of the simulation model has been performed according to the ASHRAE Guideline 14 (2014) [212], that defines the same statistical indices and admitted threshold of M&G Guidelines [146][213] used in the chapter 3 for the calibration of BNZEB building model. In particular, the statistical indices defined by the guidelines are the Mean Bias Error (MBE), given in Equation 1, and the Coefficient of Variation of Root Mean Square Error (CvRMSE) as shown in Equations 2-4.

$$MBE = \frac{\sum_p (S-M)_{daily}}{\sum_p M_{daily}} \tag{1}$$

$$RMSE = \sqrt{\sum \frac{{(S-M)_{daily}}^2}{N_{interval}}} \tag{2}$$

$$A_{hourly} = \frac{\sum_p M_{interval}}{N_{interval}} \tag{3}$$

$$CvRMSE\ (\%) = \frac{RMSE_{period}}{A_{period}} * 100 \tag{4}$$

In the equations above reported, S are data resulting from simulation, M those measured, and N is the number of sampling. Obviously, lower is the value of these indicators, better is the quality and the predictive capacity of the numerical model. In particular, the ASHRAE Guidelines requires for the MBE a value ≤ 10% and for the CvRMSE ≤ 30%, when the validation is performed on the basis of hourly data; for monthly data, the requirements are respectively ≤ 5% and ≤ 10%. Since for daily data there are not requirements specified by the Guidelines, then the same requirements as for the hourly data have been used in this research. Surely, this is a conservative approach. It should be noted that both indices (MBE and CvRMSE) must be calculated, indeed the first one offers the mean gap and the second one provides information about compensation errors.

To validate the model, the monitored data (i.e., the one-minute time interval registrations) available from the building monitoring system (BMS) are used, and the calibration indices were calculated daily. The simulation results are calibrated with reference to the heating demand. Really, in order to verify, in the main section of the system, if the model behaved like the real system, also the following variables are analysed and checked during the validation process: air temperature and CO_2 concentration inside the room, operation of the ventilation system (in terms of temperature and mass flow of air streams), operation of water circuit (i.e., temperatures and mass flow of supply and return water from the boiler storage tank) and the thermal power of the heating coil. In detail, to evaluate if the results of these variables were comparable with the measurement results, with reference to each validation steps, the simulation outputs are compared with the measured trends and the calibration indices MBE and CvRMSE have been evaluated. The resulted indices, at the last step of the calibration process, are shown in the Figure 79, together with the heating power that was compared against the measurement results of a test period of two-weeks, by showing an overall good agreement in term of magnitude and trends.

A

	Troom	Tw.in	Tw.out	Ta.in	Ta.out	Wflow	Aflow	CO_2	Qheat.coil
MBE [%]	0.31	4.32	2.90	-7.24	-9.93	1.22	3.58	3.19	1.43
CvRMSE [%]	2.41	7.81	5.70	7.70	12.27	11.06	25.04	5.97	25.93

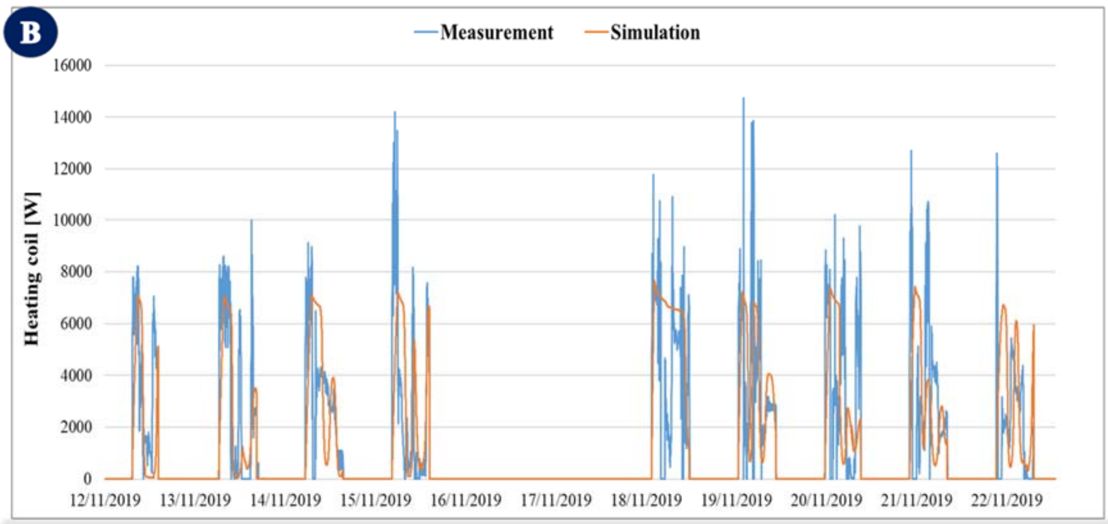


Figure 79: Results of model calibration: (a) MBE and CvRMSE for the calibration period; (b) heating power transfer by the heating coil.

The calibration indices indicate that there is a good agreement between the simulation model and the monitored results for all the considered parameters. This is an important result, because when data with a short time step (minute, hour, day) are compared, it is really difficult to reach the calibration convergence. Indeed, due to the simplification and to the implicit limits of the calculations tool, also when the global parameters (monthly or annually based) are comparable, the behavior, at short time step, could be very different. Figure 79 shows the comparison for a test period of two-weeks. At daily level, the calibration indices proposed, indicate that the threshold values are respected. However, the analysis of this figure indicates that, when the comparison is done with short time step (minutes in this case) a large difference between the two values is noticed on for instance November 15th. For a few minutes the monitored demand is double the simulated one. This can be explained by a peak absorption during the on/off cycle, or by some instabilities of the battery power supply network, or by a transient water flow. These phenomena are not controllable by the simulation program and cannot be replicated. However, the overall performance and the trend of heating power is comparable.

As a final step, in order to evaluate if the results of the room temperature are in agreement with the measured values, it has been verified if the simulation results are within the magnitude of ±0.5°C compared to the measurements.

Normally, there is a difference between the simulated and measured values of indoor air temperature also due to the thermal stratification inside the zone that is due to the natural convection (all the air heating systems, obviously, has convective terminals) and this spatial effect is not implemented in Modelica. Indeed, to have a suitable analysis also in the domain of the space, besides that time-variable, the coupling of BPS (Building Performance Simulation) and CFD (Computational Fluid Dynamic) is necessary.

Moreover, in this case, the typical difference between simulated and measured values is increased due to the different inertial behavior of the simulated building, that is simplified compared to the real one. Indeed, as it can be seen in the Figure 80, the greater difference between simulated and measured values occurs during the night and during the weekend, when the HVAC system is turned off and then the indoor temperature is influenced only by the thermal behavior of the edifice, and specifically by the thermal inertia (and thus time lag effects and decrement factors) of the building components. This phenomenon is evident especially during the weekend, where the temperature in the room is even 2°C less compared to the measured value and this also reflects in a different reaching of the temperature in the following morning.

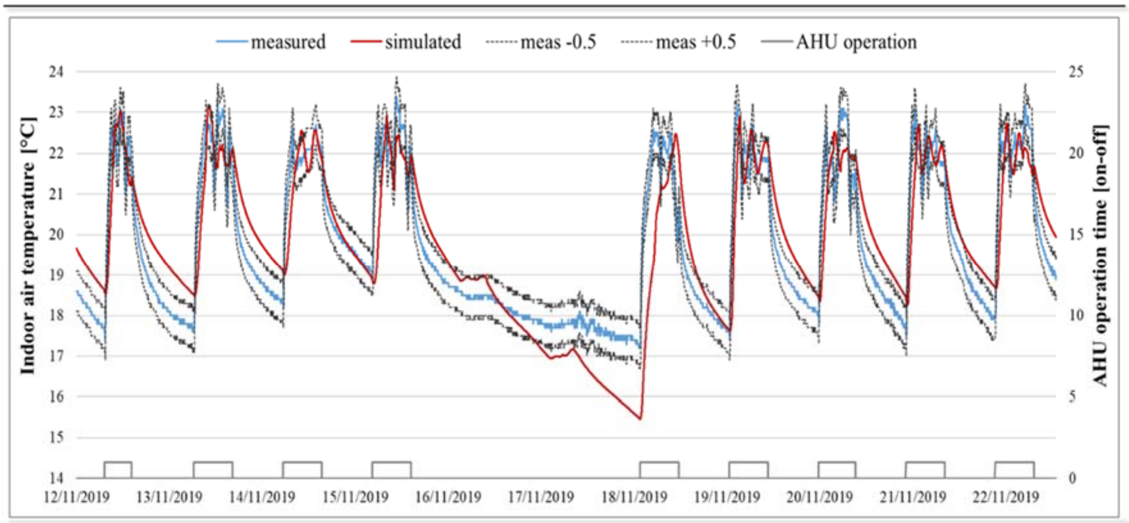


Figure 80: Results of model calibration relatively to the indoor air temperature.

In order to calibrate the model, the following parameters were adjusted during the calibration process: the parameters of pump and three-way valve PI controls, the value of air tightness and the boundary temperature used by the model in order to evaluate the heat exchange between the lecture room and the other thermal zones not included into the building model.

Regarding the PI control parameters, by supposing some common values for the gain factor and the integration time, these were ranged until obtaining the same behavior of the real components. In other words, they were adjusted until the simulated trends and values of the supply and return water temperatures, mass flow and power exchanged in the heating coil, resulted comparable to the measured values. Meanwhile, some adjusted actions were also taken about air tightness. In particular, starting from the values obtained from a blower door test, performed a few months before, and considering that during the validation period the windows are not locked, the starting value was increased until obtaining the minimum value of the validation indices and then the best agreement between the predictive capacity of the model and the actual behavior of the real system. Finally, compared with the previously validated model, the value of room boundary temperature has been lowered by 2°C (from 22°C to 20°C), obtaining an improvement in the agreement between the simulated room temperature and the measured one. Finally, it supports the correctness of the adjustment.

4.4.3 Alternative configuration for microclimatic control and system operation

In the baseline model, the Air Handling Unit (AHU) regulates the VAV dampers by sending a request signal to control the airflow based on operative temperature and CO_2 concentration sensors, placed in the lecture rooms. The boiler operation control ensures to keeps the water temperature inside the tank constantly at 65°C during the weekdays and at 60°C during the weekends. There is, therefore, a constant availability of hot water which, according to the heating needs, is supplied to the heating coils of the Air Handling Units.

As previously said, in order to improve the management of heating system in the existing building and to try to not generate more energy than the amount currently demanded, some alternative control strategies for the hot water circuit have been identified, in order to minimize the energy consumption without affecting, negatively, the indoor comfort needs. Indeed, starting from in-field monitoring campaign (section 4.3), results the possibility to improve the management of hot water generation and storage: indeed, according to the current control logic, the pellet boiler keeps the hot water inside the integrated tank at a quite high and constant value of temperature over the time, without considering the time-varying nature of the heating load in a university building. Then, the possibility of improvements has been investigated testing proper alternative control strategies based on the time-varying values of water temperatures, according to the monitored and then actual trend of building's uses and according to the actual heating load of the building following the outdoor conditions. Then, several control scenarios are defined:

- supply": some heating curves (Figure 80) are defined for the control of the supplied water temperature according to the value of outside air temperature;

- "tank": the heating curves are applied for the boiler control, in order to have a temperature inside the storage tank adjusted with a climatic control as a function of the outdoor temperature;
- Time: a set-back temperature value of 65°C is assigned for the water tank from 6:30 a.m. to 6:00 p.m as described in Figure 82;
- AHU: the availability of air handling unit is fixed from 6:30 a.m. to 6:00 p.m as reported in Figure 82, thus an hour earlier compared to the current timetable of activation.

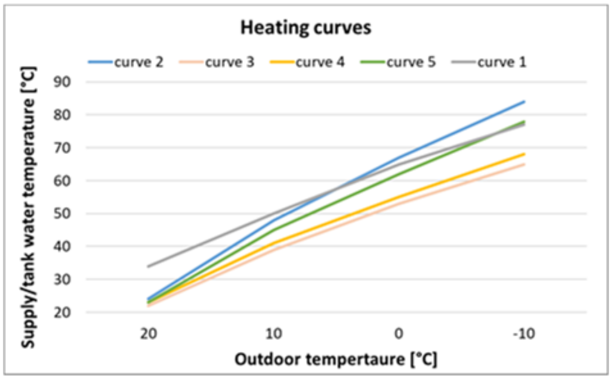


Figure 81: Heating curves for control strategies based on climatic corrections.

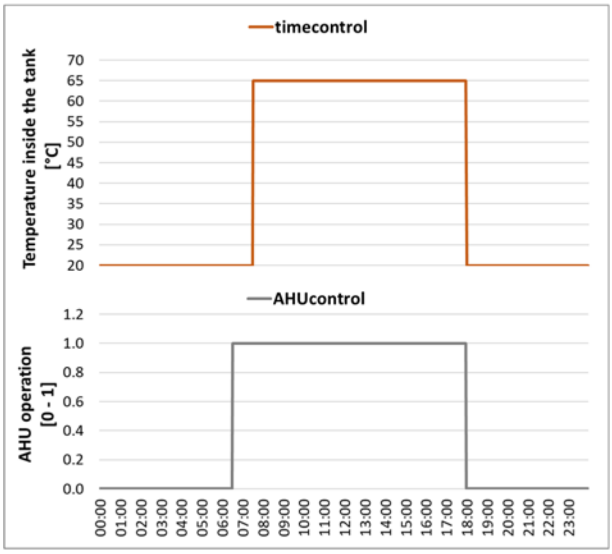


Figure 82: Time schedules for selected control strategies.

More in deep the scenarios "supply" and "tank" are obtained implementing the heating curves proposed in Figure 81 (from 1 to 5) to adjust the position of the three-way valve that mix the hot water from the tank with the water flow returning from the AHU heating coil. For this reason, five scenarios in case of “supply” control are proposed (e.g. supply1, supply2, etc) and five different scenarios for “tank” (e.g. tank1, tank2, etc..).

The selected curves, shown in Figure 81, are typical heating curves used by boiler manufactures with embedded weather control logic. The considered ones are those that allow to obtain a level of internal comfort comparable to the one obtained with the current control strategy have been considered.

Finally, to obtain better comfort conditions and energy saving, some scenarios are combined; more in detail, as explained in the following section, according to the obtained results in case of single application, the “tank” and “time” controls are combined; the “supply” is combined with “tank”; the “tank” is added to the “AHU” control.

4.5 SIMULATION RESULTS: VARIATION OF ENERGY DEMAND AND INDOOR CONDITIONS

In this section, validated and reliable energy model of the building, calibrated on real monitored performances and thus properly representing the real working conditions, will be used to compare the new several design control strategies, to the baseline scenario and each other. Indeed, herein the alternatives were simulated and tested to optimize the behavior for what concerns the minimization of energy demands and the achievement of improved comfort conditions inside the building.

The proposed control strategies have been simulated during a period of about 75 days, from October 5th to December 20th. The simulation results have been analyzed in terms of thermal comfort and primary energy demands, as shown in Figure 83, in which, with reference to the whole period, the percentage of discomfort hours and the total primary energy demand, for all control strategies and combination of them, have been reported. In Figure 84, for each configuration, the primary energy for the working of fans with respect to the overall primary energy demands is depicted. Finally, in Table 24, the main numerical values of the obtained points in the graphs are inferred.

In particular, with reference to the indoor thermal conditions, the compliance with the comfort conditions was assessed according the EN 15251 standard [88], which defines the range 20-24°C as the comfort interval for operative temperature in lecture rooms, but it is possible to assume the same thermal range also for the air temperature in a moderate environment. For the calculation of the primary energy, the value equal to 2.5 kWh/kWh_{el} was used as conversion factor from electric energy to primary energy, in accordance with [216]. Moreover, the value 4700 kWh/t was used as fuel calorific value according to the current used pellet in the system hot water boiler.

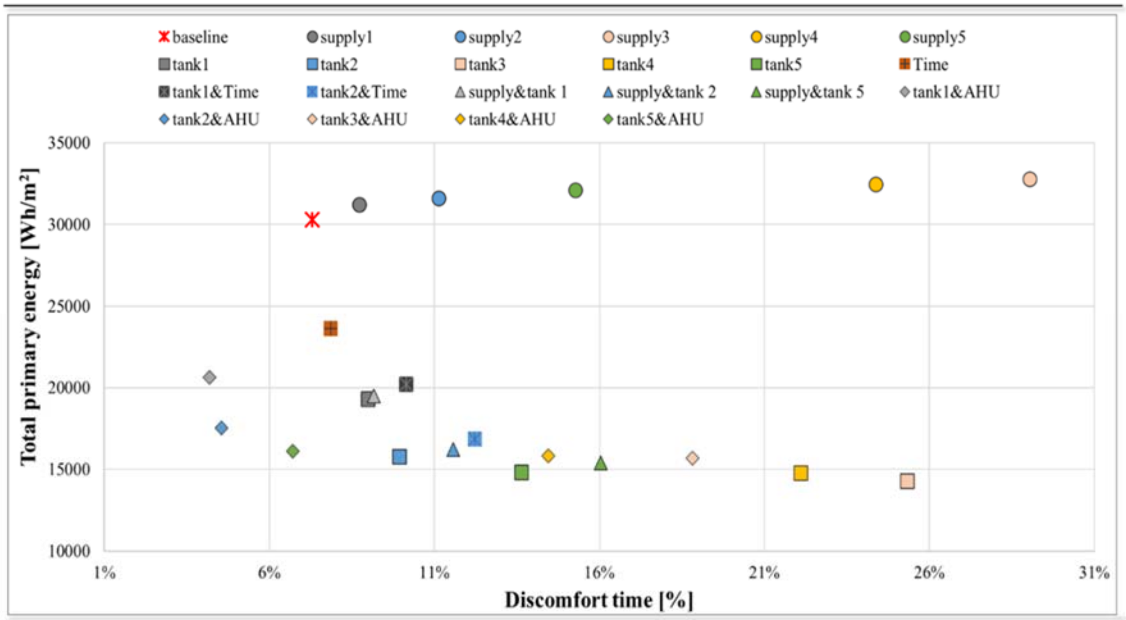


Figure 83: Comparison of results, total primary energy demand and the indoor discomfort time.

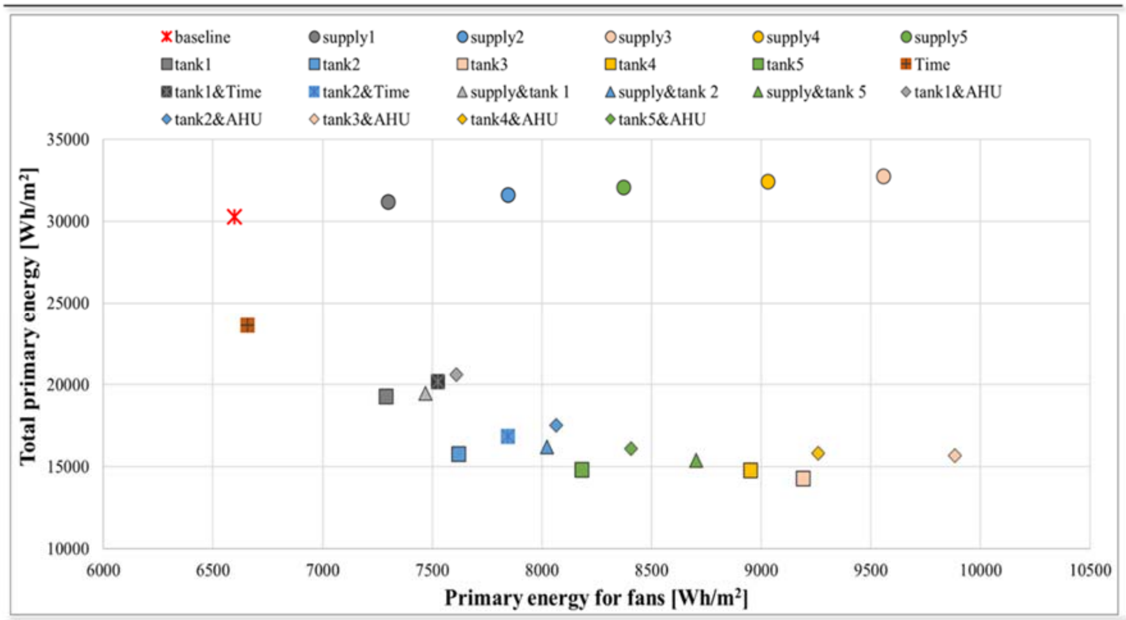


Figure 84: Comparison of results, total primary energy and primary energy for the AHU fans.

Table 24: Comparison results – numerical values.

	Primary energy tot [Wh/ m^2]	Primary energy of fans [Wh/ m^2]	Discomfort time [%]	
			cold	warm
Baseline	30245	6597	6.76	0.54
Supplycontrol1	31135	7230	8.27	0.48
Supplycontrol2	31549	7846	11.10	0.04
Supplycontrol3	32699	9558	29.05	0.0
Supplycontrol4	32386	9031	24.40	0.0
Supplycontrol5	32031	8374	15.29	0.01
Tankcontrol1	19231	7290	8.50	0.50
Tankcontrol2	15714	7622	9.51	0.44
Tankcontrol3	14227	9192	25.21	0.14
Tankcontrol4	14723	8954	21.93	0.19
Tankcontrol5	14755	8183	13.24	0.40
Controltime	23584	6657	7.32	0.54
Tankcontrol1&time	20143	7526	9.68	0.47
Tankcontrol2&time	16822	7846	11.99	0.24
Supply&tankcontrol1	19461	7470	8.68	0.48
Supply&tankcontrol2	16193	8023	11.55	0.03
Supply&tankcontrol5	15358	8702	16.03	0.01
Tankcontrol1&AHU	20598	7611	3.47	0.72
Tankcontrol2&AHU	17480	8065	4.01	0.53
Tankcontrol3&AHU	15635	9882	18.50	0.33
Tankcontrol4&AHU	15783	9260	14.03	0.42
Tankcontrol5&AHU	16086	8405	6.23	0.49

In Figure 83, it is shown that all the alternative tested control strategies are characterized by an increase of energy consumption for the fans, because these operate with a lower supply water temperature and then of supply air, to meet the temperature setpoint inside the room. This means that the system work with a higher supply mass flow of water and air and this turns in a higher operation and energy consumption of the fans.

This happens especially when the outdoor temperature is relatively high (higher than 10°C) and then the supply water temperature is also 10-15°C lower compared with the baseline scenario, and then the mass flow rate has to increase, for achieving the maximum value can be processed by the supply pump, depending on the particular considered scenario. On the other hand, when the outdoor temperature is relatively low (lower than 10°C) the supply water temperature is more or less comparable with the one of the baseline scenario and thus the supply flow rate increases, surely, but not too much.

Moreover, from Figure 84, it can be seen that the use of different slopes for the heating curves doesn't have a great effect on the total primary energy demand, but, on the other hand, it has a great effect on the energy demanded by the fans. As expected for a winter period, the higher primary energy consumption is due to the thermal needs that has an impact of 78% on the overall primary energy consumption in the simulated baseline scenario. In particular, the weight of thermal primary energy consumption on the overall once change implementing the investigated control strategies. It varies from 77% with the configuration "supplycontrol1" to 35% with the strategy "tankcontrol3", with which it could be possible obtain the minimum value of overall primary energy consumption and the maximum increase of fans energy consumption among the considered strategies. Then the weight of thermal (and fans) primary energy on the overall one decrease (increase) both due to a decrease of pellet consumption that for an increase of fans consumption and then as expected the weight of thermal primary energy is higher in the baseline configuration.

Returning to Figure 83, it is evident that the control strategies could be divided in three groups:

- the first one is characterized both by an increase of primary energy consumption and an increase of discomfort time compared with the baseline scenario.
- the second one is characterized by a decrease of primary energy consumption, but there is an increase of time in which a thermal discomfort occurs;
- the last one is characterized by a decrease of primary energy consumption and an increase of comfortable time.

As recently confirmed by an authoritative study [217], environmental conditions in a school building are very important for both improving the learning process and the students' wellness. About the control strategy that operates on the three-way valve (i.e., the "supplycontrol"), the results show that the overall primary energy consumptions increase of 2-7% compared to the baseline scenario, due to the increase of the fan energy demand. Moreover, basing on the considered heating curve, there is an increase of discomfort time too, from 1% to 23%, as it is shown in Figure 83.

Considering the same heating curves, but implemented for the temperature control in the storage tank ("tankcontrol"), more or less the same variation in terms of supply temperature and mass flow rate compared to the previous scenarios ("supplycontrol") can be seen. Really, this allows a greater energy saving because the water is directly produced at lower temperature and then the thermal energy saving is higher than the increase of fan electric consumptions. Indeed, while for the previous kind of control, the hot water temperature inside the tank was almost constant around 65°C, in this control strategies it changes during the time, by following the outdoor air temperature. Depending from the used heating curve, at this group of scenarios it corresponds a decrease of the overall primary energy, from the 38% of “tankcontrol1” to the 56% of the “tankcontrol3”, with an increase of discomfort time of about 2% and 19%, respectively, compared to the baseline scenario.

In the scenario "timecontrol", the temperature trends of supply water and air are the same of the baseline scenario, because, during the AHU operation time, the two systems work in the same way. However, there is an important overall energy saving, due to the fact that, during the hours of AHU inactivity, to meet the low set-back value of temperature, the boiler doesn't work and then there is not fuel consumption. Indeed, it results that the temperature inside the storage tank is almost constant around 65°C during the operation time, while during the nights it drops, but with levels never lower than 50°C during the weekends and therefore the boiler activation (with the following primary energy demand) is not required. Finally, through the implementation of this control strategy, it is possible to obtain, using a set-back temperature from 45°C to 20°C, an overall primary energy saving of 23% and an increase of discomfort time of 0.6%.

With the combination of "timecontrol" and “tankcontrol” (“tankcontrol&time”), it is possible to see a quite decrease in comfortable time. Indeed, by working at lower temperatures during the night, the system needs more time to reach the requested indoor conditions during the day. In particular, the results shown a decrease in the overall primary energy of about 35% and 46% with the control strategy “tankcontro1&time” and “tankcontrol2&time” respectively, with a corresponding decrease of indoor comfortable time of 3% and 5% respectively compared to the baseline scenario.

By implementing the combination “tank&supply”, meanwhile, it is verified an expected decrease of primary energy demands compared to the case “supply”, but it shown also an increase of energy demands compared to the scenarios “tank”, because - in this second comparison, due to a quite lower supply water temperature - there is an increase of the air mass flow and then an increase of primary energy consumption for fans.

For the same reason, after the weekend operation breaks, the lower supply temperature is not enough to increase the room temperature until the meeting of the setpoint temperature inside the building, with a consequent decrease of comfortable time during the whole period.

Finally, with the combination of "tank" control with an early switching on of the AHU ("tank&AHU"), it could be obtained an improvement on the comfort conditions inside the building together with a reduction of energy consumption compared to the baseline scenario. In particular, by turning on the AHU at 6:30 a.m. (and thus one hour earlier than the current time), there is an increase of about 3.9% of total primary energy but also an increase of comfort conditions time of 4.3% with reference to the whole period, due to the better achievement of comfort conditions inside the classroom before the beginning of lessons. On the other side, by working with a lower water temperature inside the water storage tank of 600 l, compared to the baseline scenario, there is both an increase in the energy consumption for the fans and a strong reduction for what concerns the pellet consumption. Finally, with these kinds of control strategies, it is possible to obtain a reduction of the primary energy demands from 32% to 46%, with a correspondent increase of comfort time in the period from 0.6% to 3.4% compared to the baseline scenario, depending to the relationship between the external temperature and water temperature inside the water storage tank.

With the control strategy "tank2&AHU", it is possible to obtain the best trade-off between energy saving and improvement of comfort conditions, with a reduction of overall primary energy of 42.2% and an increase of comfortable time of about 3%. With the configuration "tank1&AHU", it is possible to obtain the maximum improvement of comfortable time (3.4%), with an energy saving of 31.9% in terms of overall primary energy demand.

In general, if it would be admitted a discomfort time of maximum 10% of the occupancy period (9.9% for the strategy "tankcontrol2"), it is possible to obtain an energy saving of about 48%, with an increase of 2.85% of discomfort time compared with the baseline scenario. However, almost the same energy saving (47%) can be achieved with the combination "tankcontrol5&AHU", that allows almost the same comfort condition compared with the baseline scenario (+0.63%). Moreover, it would be possible even to obtain a discomfort condition lower than 5%, with an energy saving around 30% compared to the baseline scenario (current condition). This is the leftmost point of Figure 83.

In general, the simulation results show that the improvement of the management of the heating system can furtherly reduce the overall energy demands and increase the comfortable time and thus the occupant thermal satisfaction (and this is very important also under the point of view of the learning process in an education building).

More in detail, the simulation results show that there are some alternative control strategies characterized both by an increase of the primary energy consumption and of the discomfort time compared to the baseline scenario. On the other hand, it has been verified that also a contemporary decrease of primary energy demand for heating and ventilation and of discomfort time can be achieved. Obviously, also strategies that improve only one of these two conflicting targets (i.e., reduction of energy consumption and limiting of not comfortable time in the building) have been found. In general, by changing the control strategy, it could be possible to obtain both a great variation of the comfortable time, that can vary from -23% ("supplycontrol3") to + 3.4% ("tank1&AHU") compared to the baseline scenario, and a reduction of the overall primary energy consumption, despite the increase of the energy demands for fans. In particular, the greater energy saving could be about 56% that, on the other hand, causes also a huge increase of discomfort time of 19%, compared to the baseline scenario, and it means a number of not comfortable hours of around the 25% of the occupancy period.

Obviously, these results are only referred to the chosen case study building and, in general, also more advanced control strategies could be evaluated and tested starting from more detailed monitoring data concerning boiler, tank and AHU operations. Really, this study could be considered a starting point for an optimization process about the control and management of high-efficient buildings, in which the HVAC suitable management can be a further opportunity for energy saving. Finally, this study demonstrates how the overall performance of a building could be improved using better control strategies, by underlining how the energy efficiency is sensitive to the control strategies and thus the role played by the management of the HVAC system becomes essential for having a high-performing building, really operating as efficiently as possible. At the same time, continuous monitoring remains the main activity for evidencing a suitable operation and, thus, for avoiding criticalities and adjusting, promptly, possible malfunctioning.

CHAPTER 5

SELECTION OF ENERGY EFFICIENCY MEASURES FOR THE PERFORMANCE OPTIMIZATION OF EXISTING BUILDINGS

This chapter is focused on the application of optimization methodologies for the selection of energy efficiency measures for existing buildings. In detail, it will be discussed and applied a new holistic approach, for university buildings, based on the application of the Cost-Optimal methodology for evaluating the cost-optimal level of energy refurbishment with a macro-economic view, taking into account, at the same time, energy, environmental and economic aspects. Indeed, the available studies generally take into consideration these aspects separately and these do not start with a thorough understanding of the current situation. Moreover, herein, the method to define a proper *Reference Building* according to the more recent normative requirements in matter of energy diagnosis is proposed.

The recurrent use of university buildings as case studies lies in the fact that the literature review has shown that not many works are available for university buildings though these are an important example of public buildings to be refurbished. Moreover, educational buildings are considered as community centres of activities and learning by local authorities, as such there is an emphasis to make schools exemplar buildings within the community and demonstrate best practice with regards to high energy performance. It must be considered that these have particular yearly energy balance since typical uses and occupation patterns are intermediate between schools and offices. This aspect requires a deepening both as regard the methodological approach than guidelines for refurbishment with the purpose of providing useful information to designers and for future research topics.

By using two existing university buildings as case study, the proposed methodological approach for designing energy refurbishment measures of buildings, allows to understand the uncertainty of using numerical modelling and the real impacts due of adoption some energy efficiency technologies.

In particular, the performed analysis has been reported in a journal paper named "University building: Energy diagnosis and refurbishment design with cost-optimal approach. Discussion about the effect of numerical modelling assumptions" [I] for the first case study building, and in the papers "Energy refurbishment of a University building in cold Italian backcountry" [II][III] divided in part1 and part2 for the second case study building.

Then in the following sections, firstly the motivation and adopted approach will be introduced (section 5.1), then the presentation of chosen case study buildings (section 5.2) and the obtained results will be discussed (section 5.3 and 5.4).

5.1 Energy refurbishment of University building: motivation and adopted approach

As explained in the first chapter, the refurbishment of public buildings is one of key factor of energy efficiency policy of European States, and the recent literature has focused mostly on the economic viability of the energy retrofit in buildings [218]. The trend of energy use in European non-residential buildings is roughly in line with their share of floor area. The highest total energy use is within shops (28%), offices (26%) and educational (12%) edifices. Educational buildings account for the largest share of the oldest buildings, since around 75% were constructed before 1980 [219]; this allows to evidence that the great challenge, also in this sector, is not in fabricating new nZEB, but in retrofitting existing buildings towards nZEB through cost-optimal approach [220].

It is also simple to understand the high potential for energy savings in the Mediterranean area, where, in spite of having mild temperatures, there is high energy consumption in winter due to the low energy performance of existing building stock [221]. Moreover, educational buildings are seen as community centres of activities and learning by local authorities, as such there is an emphasis to make schools exemplar buildings within the community and demonstrate best practice with regards to high performance and zero-carbon design [222].

Optimizing energy consumption of buildings during operation can significantly reduce their impact on the global environment [223]. On this matter, Sesana *et al*. [224] have presented an overview on retrofitting approaches, in particular for the university communities, highlighting the importance to promote green building initiative on campuses. Moreover, the study proposed by Salvalai [225] based on the classification and analysis of 38 school buildings in Lecco municipality, want provide replicable guidelines useful to the Public Administration in planning of energy retrofit interventions, in defining the total investment amounts and the consequent raising of necessary investments. Moreover, Irulegi *et al*. [226] have proposed a method to define and assess strategies to achieve nZEB target in university buildings based on student comfort analysis under real conditions. For the University of the Basque Country, their results show a potential energy saving of up to 58%. Munoz *et al*. [227][227], using a school case study, have demonstrated that for ranking nZEB standard, LCEA approach should be taken into account. Indeed, their results have shown that, despite the building shows a low thermal transmittance of enclosures and it also incorporates renewable energies, it cannot be considered as nZEB because the PEC varies from 91.2 to 161.4kWh/m^{2}y. Bernardo *et al*. [228][228] have proposed an energy and indoor climate integrated approach to assess eight representative school buildings throughout the Portuguese mainland territory. A methodology involving dynamic building simulation and inside temperature measurements has been successfully applied to evaluate the energy performance of Villa Mondragone, property of the University of Rome Tor Vergata [229]. Moreover, the study of Katafygiotou and Serghides [230], basing on monitoring and questionnaires in a secondary school in Cyprus, has confirmed that the indoor climatic conditions are in many cases unsatisfactory for the occupants. About it, in case of educational buildings with large transparent surfaces on the facades, a proper choose of workplace location, can determine important cooling energy savings without invasive measures as shown by Kalmar [231][231]. Pritoni *et al*. [232][232] have described a software tool that solicits thermal feedback from students and analyses its impact on energy use and energy management procedures.

Semprini *et al*. [233]have developed diagnosis and energy audits for the School of Engineering in Bologna. Results of the microclimate monitoring campaign in different classrooms show how the lack of thermal control, together with poorly insulated envelopes' components, determine high energy consumption. Allab *et al*. [234] have presented an audit protocol including simultaneously energy efficiency and indoor climate quality issues using as case study a French university campus. Ascione *et al*. [235]

have proposed a multi-objective optimization process for the energy refurbishment of a building of University of Sannio. In this case, the most profitable configurations of energy retrofit include installation of an air-source heat pump for the space heating and of a full-roof PV system. Ferrari and Beccali [236] have explored some retrofit options for an existing office building for a university department of Milan. The results demonstrated that the retrofit solutions that do not include improvements on the building envelope are generally the most cost-effective options.

Instead, Niemelä *et al*. [237], for typical educational buildings in Lappeenranta University of Technology, with cold climate, have shown that the cost-effective solutions include renovation of the original ventilation system, a ground source heat pump system, new energy efficient windows and a relatively large area of PV-panels. Tadeu *et al*. [238] have assessed the relevance of applying the real options theory and return on investment criteria to the cost optimality of energy efficiency measures in the retrofit of buildings. Instead, Bras *et al*. [239] have observed that reaching better levels of energy performance might be very difficult or not cost-effective in some Portuguese cities. Finally, it can be underlined that there are also several European projects conducted in the Mediterranean Zone [240][240][241][242] to improve the sustainability of educational buildings.

In this context, the present study discusses the critical issue of dealing the energy refurbishment of a University building in South Italy, in order to select efficiency measures that allow the improvement of comfort condition, the reduction of polluting emissions during the operation phase of building and the global cost. About this point, to select the Cost-Optimal configurations, the Energy Performance of Buildings Directive [16] with the Delegated Regulation 244/2012 (EC, 2012) has been followed [95]. The results could be useful to implement refurbishment strategy for buildings in similar climatic conditions.

Accurate information and modelling are important aspects for reliable energy simulation. If input parameters are not carefully provided to the building modelling software, final outcomes of the simulation can be far from reality. For instance, Salehi *et al*. [243][243] have found that in a LEED Platinum-certified university building, the overall measured energy consumption is 60% higher than the energy modelling result. Thus, often researchers underline the need for a reliable energy simulation model to predict buildings energy consumption [244]. Several papers have evidenced that building occupancy and usage schedules are a key factor for accurate prediction of building energy use and energy saving potential. Stazi *et al*. [245] illustrating the results of a literature review on occupants' behaviours, have concluded that there is no general agreement about the reasons people interact with building systems or the driving factors that trigger their decisions. By applying homogeneous Hidden Markov Models on frequent measurements of electricity consumption from smart metering data, Liisberg *et al*. [246][246] have classified the obtained states in accordance with occupant behaviour by global decoding for fourteen apartments. Ahn *et al*. [247][247] have presented evidence that occupant presence in some rooms and buildings follows a ‘‘random walk” pattern. In other words, occupant presence in certain types of buildings cannot be predicted stochastically. Pino and de Herde [248] have tried to implement models of occupant behaviour profiles in combination with meteorological information as input data in simulations to make calculations of energy performance of dwellings more accurate, reliable and representative. Ramallo-Gonazles *et al*. [249] have presented a first step to more elaborated optimisation mechanisms that will provide building designers with solutions that are robust against the many parameters which are in truth unknown or ill-defined during the design stage, may vary during value engineering or construction, or dependent on the behaviour of occupants. Sun and Hong [250][250] have shown that the impact of occupant behaviours on energy savings varies with the type of efficiency interventions. For measures with strong occupant interaction, such as the use of zone control variable refrigerant flow system and natural ventilation, the relative savings can differ by up to 20%. Moreover, in another paper [251][251] they have evidenced that the occupant behaviour measures can achieve overall site energy savings as high as 22.9% for individual measures in office buildings and up to 41.0% for integrated measures.

In general, main critical issues concerning the building energy modelling are: a) adoption of old or standardized weather data; b) building envelope is described without a deep investigation on materials; c) nominal values for HVAC performance parameters; d) occupancy schedules, internal loads and interaction of the occupants with components like windows or plant systems are described with deterministic schedules. Data about occupant behaviour represent some of the largest variables during the energy modelling. This problem is surely difficult to examine and to solve. Indeed, a probabilistic approach should be used to describe these variables since deterministic methods are not representative of human behaviour. Moreover, today, the great part of commercial tools provides to designers a library of possible schedules that allow description of thermal zones. But in most cases, users do not pay close attention to diversify thermal zones and to modify or to adapt predefined profiles, and results of designing are affected positively or negatively without any alarm about it.

In this context, the proposed investigation is aimed at introducing a methodological approach to select energy refurbishment measures for university buildings, by means of accurate energy diagnosis that allows the characterizations of building /HVAC system and the indoor conditions (mainly related to thermo-hygrometric and lighting comfort). Indeed, high performance and economical effective refurbishments can be obtained only if in the early design stage, designers have appropriate building information. Instead, very often, building configuration is selected basing on their experiences through adoption of simplified or approximated models.

For the case studies, the validity of energy simulation results is examined by means of the comparison with the real data (monthly but also hourly). Briefly, by varying the models used to described inner loads and occupant behaviour, it is evaluated the error committed in the estimation of energy performance and the uncertainties on the estimation of potential energy and economic savings.

Indeed, according to this aim, two aspects will be exhaustively examined by using a case study:

- the importance to use validated models to estimate the present building performance (topic already discussed in the previous chapters 3 and 4);
- the environmental benefits and the economic implications of a deep energy refurbishment of university building in cold climates.

The proposed investigation wants to suggest original guidelines for select traditional efficiency measures for building designed as the case study with common criticalities in Italian university building. Indeed, designers should usually consider a high number of designs possibilities and solve a multidisciplinary problem with contrasting objectives (e.g. minimization of costs and energy demand, maximization of indoor comfort). Results of case studies can give some general indications for retrofit that lead to lowest global cost during the estimated economic life-cycle, taking into account not only the investment cost but also the operational costs, linked to energy consumption and polluting emissions.

Methodological approach

A proper design approach requires building simulations, but this method is time-intensive and involves complex processes. The study introduces and explains, in all aspects, a new holistic approach based on the application of the Cost-Optimal methodology [95][16] to evaluate the cost-optimal level of energy refurbishment with a macro-economic approach, taking into account, at the same time energy, environmental and economic aspects. The available papers generally take into consideration these aspects separately and do not start with a thorough understanding of the current situation.

The proposed method to define a proper Reference Building has been already shown in the sub-section 2.3, according to the more recent normative requirements in matter of energy diagnosis [92][93]. Briefly, data to collect can be divided into five categories: 1) architectural and historical investigations; 2) building envelope audit; 3) technical system and equipment characterization; 4) building uses and thermal zones definition; 5) historic energy needs. As explained in the methodological section 2.4, in order to simulate reliable energy performances, the Reference Building has been defined as the model with the energy performances deriving from the present building envelope and active systems configuration, and it has been characterized by data acquired according to procedure. In other words, in the first part of the study, all information acquired by means in-situ surveys, interview with occupants, in-field measurements, allowed the complete characterizations of building, HVAC system, indoor conditions; all information and data acquired during the audit phase have been used to define the Reference Building as numerical model. After the assignment of input data into the numerical model simulated with EnergyPlus [65] through the DesignBuilder interface [66], the output of simulations have been compared with measured energy data, by determining the deviation and the relevant uncertainty. The 'Whole Building Level Calibration with Monthly Data' approach proposed by M&V Guideline [146] can be used. Here, the adopted statistical indexes are the error in the monthly energy consumption (ERR_{month}), the mean value for the whole year ($ERR_{average\ year}$), the coefficient of variation of the root mean squared error CV(RMSE) and the mean bias errors (MBE). Typically, models are declared to be calibrated if these produce, with monthly data, ERR_{month} within ±15%, $ERR_{average\ year}$ within ±10%, CV(RMSE) within ±10% and MBE within ±5% (as shown in the sub-section 3.2 too). Then, in the second part of the study, the calibrated dynamic simulation model, has been used both to evaluate the energy performance of several refurbishment scenarios, and to make a sensitivity analysis to evaluate the incidence of modelling assumption on the estimation of present and potential performance of simulated buildings.

In detail, the considered energy efficiency measures include renewable sources integrations, HVAC systems and envelope technologies. They have been selected according to the main criticalities evidenced during the audit phase, occupant's requirements about indoor comfort, and administrative needs of reducing operational costs have been considered too. According to the macroeconomic perspective, for each considered energy efficiency measures, the global cost is calculated, as shown in the following lines, considering the initial investment (C_I), the sum of the annual costs and the final value, all with reference to the starting year (2017) of the calculation period and by excluding the VAT, according to the following Equation 11:

$$C_g(\tau) = C_I + \sum_j[\sum_{i=1}^{\tau}\left(C_{a,i}(j) * R_d(i) + C_{c,i}(j)\right) - V_{f,\tau}(j)] \quad (11)$$

where τ is the calculation period (20 years); $C_g(\tau)$ is the global cost referred to starting year; C_I is the initial investment costs; $C_{a,i}$ is the annual cost during year i for measure or set of measure j, and $C_{c,i}$ is the annual cost of polluting emissions; while R_d discount factor for year and $V_{f,\tau}$ is the residual value of measure or set of measures at the end of the calculation period.

The discount rate multiplies the periodic cost (as replacement costs) and it is calculated according Equation 12, in which R_r is the real interest rate and p the lifespan.

$$R_d(i) = \left(\frac{1}{1+R_r}\right)^p \quad (12)$$

For the annual costs, the discount factor becomes, more properly, a present value factor (f_{pv}), calculated as in Equation 13, where "n" is the number of years considered for costs.

$$R_d(i) \rightarrow f_{pv} = \frac{1-(1+R_r)^{-n}}{R_r} \quad (13)$$

The cost of greenhouse gas emissions is calculated using as prices 20 €/t$CO_{2,eq}$ until 2025, 35 €/t$CO_{2,eq}$ until 2030 and 50 €/t$CO_{2,eq}$ after the 2030 [95]. While the adopted economic parameters are shown in Table 25 according to the national indications [252]; moreover, natural gas and electricity tariffs, that include regional and national taxes, comply the energy billings.

Finally, the emissions of equivalent carbon dioxide have been calculated adopting the Italian emission factors, considered for the combustion of natural gas, equal to 0.205 t$CO_{2,eq}$/MWh and 0.563 t$CO_{2,eq}$/MWh_{el} for electricity [253].

Table 25: Economic parameters for global cost evaluation.

R_i	0.3%
R_r	3.0%
R_d	0.74 (10 years)
	0.55 (20 years)
f_{pv}	14.9
Electricy cost	0.160 €/kWh
Natural gas cost	0.0616 €/kWh

The packages of energy efficiency measures are compared with the reference building in term of primary energy saving (ΔEP), reduction of the global cost (ΔC_g) and evaluating the avoided polluting emissions ($\Delta CO_{2,eq}$).

Finally, as said before, sensitivity analysis is performed with the aim to evaluate the incidence of modelling assumptions on the estimation of present and potential performances of simulated buildings. More in detail, it is evaluated the error due to adoption of standardized schedules system to describe occupation, equipment usage, lighting system turning on, air-conditioning operating mode (by varying the schedules with which are described into the model). The calibration indexes are evaluated again, comparing energy billings and different scenarios with a proper discussion. Moreover, the incidence on energy saving and global cost is investigated for the first considered case study. Moreover, for the second case study building, the sensitivity analysis has been made other than on occupation patterns, internal load and lighting, also on the envelope characteristics (by varying the value of thermal transmittance of the walls).

5.2 PRESENTATION OF CASE STUDIES

Two university buildings are chosen as case study of proposed investigation. These were built in the early '90s and are named *I Edificio Polifunzionale* and *II Edificio Polifunzionale*. They host, respectively, administrative offices and classrooms of the Department of Law and of the Department of Economy of University of Molise. The case study buildings are in Campobasso, one of the coldest cities of central/south Italy. According to the Köppen climate classification, Campobasso has an oceanic climate that is borderline with subtropical. During the winter, snowfalls are frequent, and, with reference to January 2017, the mean daily temperature is varied between 1°C and 5°C while in March between 3°C to 10°C. The months May, June, September and October have nice weather with a good average temperature; for instance, the mean daily temperature in July 2017 has been 24-25°C with peak values of 29°C. The most important climatic characteristics, according to the standard UNI 10349-1 [94], are given in the Table 26.

Table 26: Campobasso site information and project weather data.

Site: CAMPOBASSO (Italy)			
Latitude	41° 33' 36''	HDD (baseline 20°C)	2346
Longitude	14° 39' 37''	Heating period	15/10 – 15/04
Elevation (m)	701	Climatic zone	E
Project winter data		Project summer data	
T_{ext} (°C)	-4	T_{ext} (°C)	29
φ_{ext} (%)	48.8	φ_{ext} (%)	50.0
V (m/s)	4.3	ΔT_d (°C)	9

These buildings have been selected because they have typical reinforced concrete structure of edifices built in Italy and Europe in last 30 years, without particular attention to insulation level and it has a typical HVAC system for tertiary building designed without local or zonal regulation system. Finally, these are public buildings that should have an exemplary role for other projects in the same region.

5.2.1 *I Edificio Polifunzionale* as Reference building: energy audit and model calibration process

As said, the first case study building is named *I Edificio Polifunzionale* and hosts the administrative offices and classrooms of the Department of law of University of Molise. Figure 85 shows the main entrance on the north-west exposure and the building geographic locations.

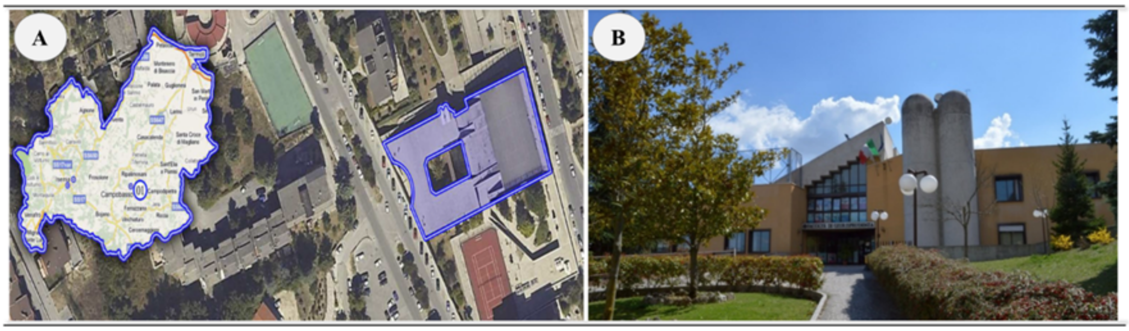


Figure 85: I Edificio Polifunzionale: (a) location and (b) external view.

5.2.1.1 Energy audit and numerical model set up

This section describes all collected information for the evaluation of the present state of the building following the approach proposed, and the creation and proper calibration of the numerical model suitable for dynamic simulations.

Geometrical features

The building has a hollow rectangular shape with four usable floors; one of them is not conditioned, since it is used as a car park. There is also a football field on the external side. The building is conceived symmetrically respect to an inner courtyard dominated by a sloped glazed wall with offices, lecture rooms and others space on the outer perimeter and a central area dedicated to the connections. The most important geometrical characteristics are summarized in Table 27.

Table 27: Building geometrical characteristic.

Building total floor area	7935 m^2		Gross Volume		7940 m^3
Net conditioned floor area	4834 m^2		Surface to volume ratio		0.43 m^{-1}
Geometry	**Total**	**North**	**East**	**South**	**West**

Gross wall area [m^2]	3605	1039	794	959	814
Window opening Area [m^2]	533	181	110	184	57.5
Window-Wall ratio [%]	14.8	17.5	13.9	19.2	7.06

Figures 86a and 86b compare the model built in simulation environment and the real building, while Figure 86c shows the particular of the glazed wall and the overall layout of building on lateral side.

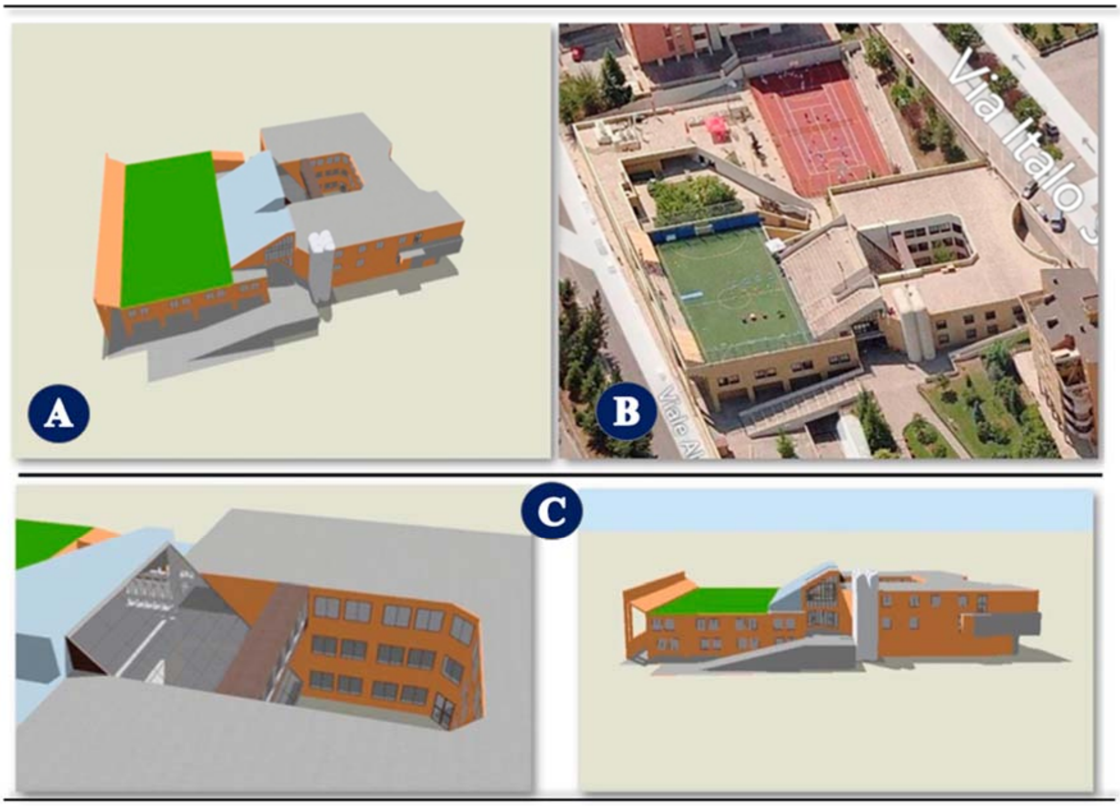


Figure 86: (a) rendering of simulation model; (b) imagine of real building and (c) geometrical model details.

Building envelope audit

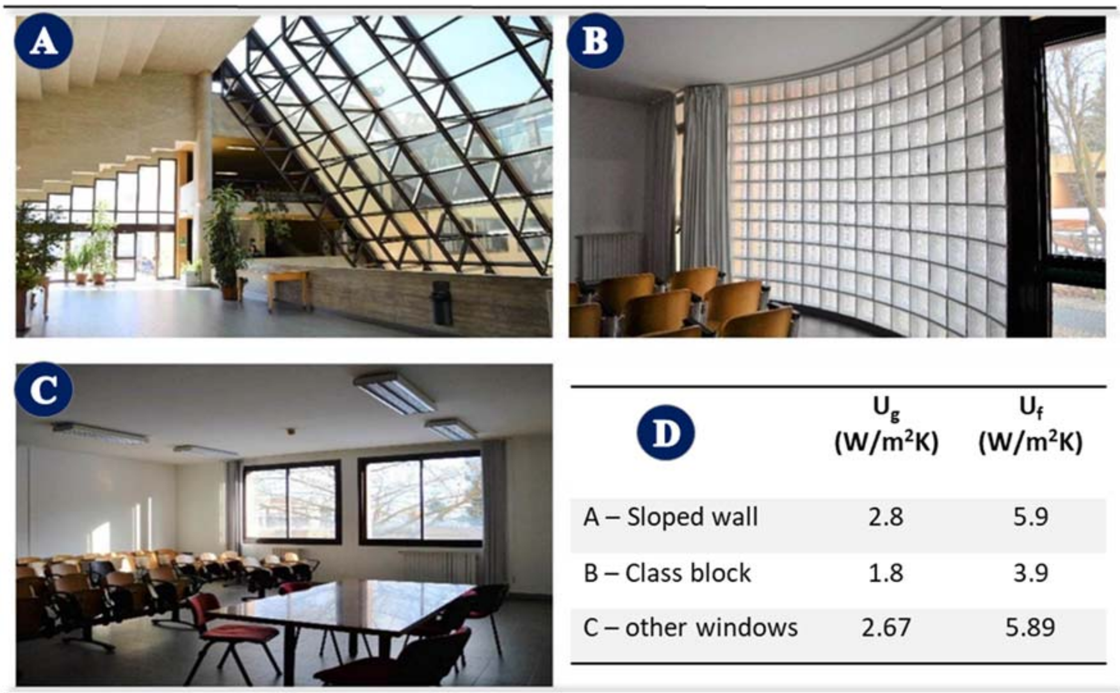
The envelope audit has been supported by a no-intrusively diagnostic technique, like infrared thermography and by in-situ measurements of thermal transmittance. Moreover, technical office of University has made available some results of previous studies aimed at the energy labelling. From this documentation, some general data have been found. More in detail, the building has external walls of hollow brick, air cavity and concrete panels. The walls have different thicknesses and only some exposures have insulating material (glass fibre). Also ceiling, basement and roofs structures differ for materials and thickness. Briefly, the floor on the ground is made of 24-cm-long parallel elements, for the slab of the first floor, on which the football field is located (sport slab in the following), there are also a layer of polystyrene and a thin layer of cement for a total thickness of around 72 cm. The nominal value of thickness (t), stationary thermal transmittance (U) and periodic thermal transmittance (Y_{IE}) of the main elements are reported in Table 28; these have been calculated in according to the standards [254][254][141][145] starting from available technical sheets.

Table 28: Building envelope: walls, ceiling, and floors.

	t (m)	U (W/m²K)	Y_{IE} (W/m²K)
North-west external wall	0.48	0.329	0.05
North-east external wall	0.30	0.839	0.43
South- west external wall on courtyard	0.36	0.559	0.16
Underground wall	0.32	0.570	0.24
Internal wall	0.10	2.510	2.39
Internal ceiling	0.52	0.478	0.17
External ceiling (covered)	0.52	0.478	0.02
Underground floor	0.61	0.392	0.01
Roof slab with tiles	1.46	0.300	0.02
Sport slab	0.72	0.318	0.02
Roof slab	0.72	0.376	0.01

In order to quantify the insulation level, it can be considered that if the building was subjected to a refurbishment, according to Italian normative [19] the value of the thermal transmittance should be less than or equal to 0.30 W/(m^2 K) (from 2015, according to the Italian DM 26/06/2015) for vertical elements and less than 0.26 W/(m^2 K) (from 2015) for horizontal structures. Thus, in the present state, the building has a very low level of insulation; this results in high losses for winter transmission and it has a negative impact on both the heating needs as well as on the comfort conditions for occupants. Normative requirements about the periodic thermal transmittance are not satisfied. For instance, the value for vertical walls is usually higher than 0.10 W/(m^2 K) [19]. Thus, the building envelope does not prevent overheating of indoor environments during the summer period.

There are three types of window elements. The first type concerns only the sloping glass wall (Figure 87a). It is a double-glazed system with aluminium frame and dividers. There is not a shading system.



	U_g (W/m²K)	U_f (W/m²K)
A – Sloped wall	2.8	5.9
B – Class block	1.8	3.9
C – other windows	2.67	5.89

Figure 87: (a) Slope glazing wall; (b) glass block made window; (c) other window types; (d) thermal transmittance values.

The second type involves some rooms at ground floor (south-east exposure) with glass blocks (Figure 87b) and a clear glassed chassis. White curtains are installed on the inner side. All other windows (Figure 87c) are provided with an aluminium frame and double clear glazing (6 mm glass/12 mm argon/6 mm glass) with white or grey vertical lamellas. In Figure 87d the value of thermal transmittance is reported for window frame and glazed element. In this case both the insulation level that the type of shading systems is not adequate mainly respect to visual and thermal comfort of occupants as some interviews have relived.

The infrared thermography surveys were carried out in the winter season, when the sky was overcast, and the measurement conditions have been considered almost optimal. Figure 88 shows some outdoor thermographs where it is in evidence the poor behaviour of glazed systems and thermal bridge due to defect of insulation for the walls. First, this analysis has allowed the detection of some criticalities that must be considered during the refurbishment process, like missing thermal insulation, thermal bridges, vapour condensation. Moreover, this survey has been used to support in-situ measurements of thermal transmittances for proper positioning of sensors. For instance, the result of measurement for wall with north-west exposure is presented. It consists of lightweight alveolar bricks (dimensions 25x25x20 cm), an air gap (10 cm) with fiberglass insulating material (5 cm) and a lightweight reinforced concrete panel (10 cm); on inner side it is finished with lime plaster, while externally with cement mortar. The overall thickness is 48cm.

Figure 88: Outdoor thermography: (a) walls with noth-west exposure; (c) inner courtyard wall.

Figure 89a shows the thermography on the external side evidencing the position of temperature sensor (red circle) and Figure 89b has the heat flux sensor on the inner side. The measurements have been carried out from 22 to 28 of February 2017, with heating system turned on. The selected sampling time-step has been 600s and the value of thermal transmittance is consisted of the average calculation of 802 measure.

Following the methodology of the ISO 9869 [81], the value is resulted 0.370 W/(m2 K) as shown in Figure 89c. Measured value has been compared to those derived from analytical calculation, according to the standard ISO 6946 [141], that provided a thermal transmittance value equal to 0.329 W/(m2 K). Therefore, a difference between the value of the measured thermal transmittance and the value derived by analytic calculation, is around 12%. This means that satisfactory convergence was found. Indeed, in the technical literature experiences this difference was also around ±20%. Some other comparisons have been done to describe accurately the opaque envelope. The measurement campaign has been finished at the beginning of April.

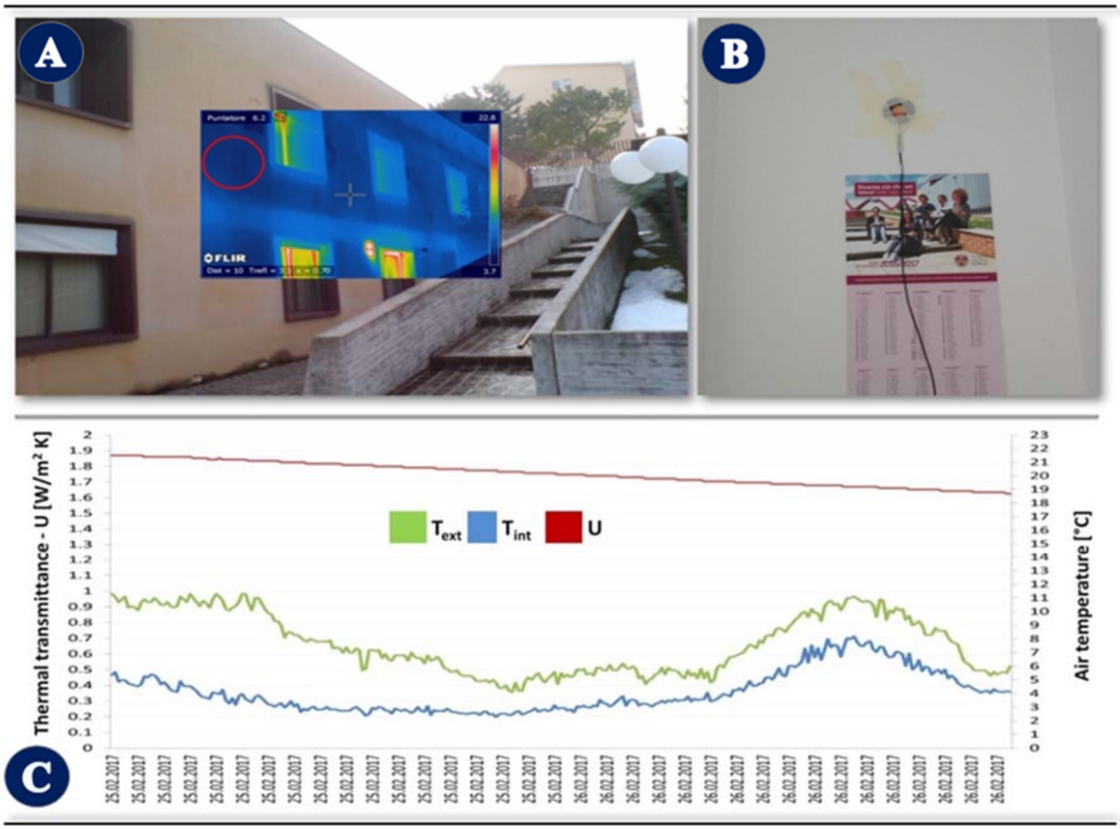


Figure 89: In situ measurement of thermal conductance: (a) infrared thermography; (b) heat flux meter; (c) measure results.

Audit of technical system and equipment

All offices, small classrooms, lecture rooms, bar and circulation zones have a mixed air/water system with radiators (or fan coil) and air handling units only for ventilation requirements, not equipped with heat recovery systems. Toilettes and one classroom at second floor have only a heating water system. The three biggest classrooms and the auditorium have an air HVAC system which provides heating, cooling, and ventilation needs.

The "hot water" heat transfer fluid is produced by a thermal plant located in the dedicated technical room adjacent to the structure. The "cold water" heat transfer fluid is produced by the refrigeration unit located outside, in an area annexed to the building. The air handling units and the storage tank for domestic hot water production and storage are in a room dedicated to them adjacent to the building in question. Figure 90 shows the positions of the aforementioned systems with respect to the building.

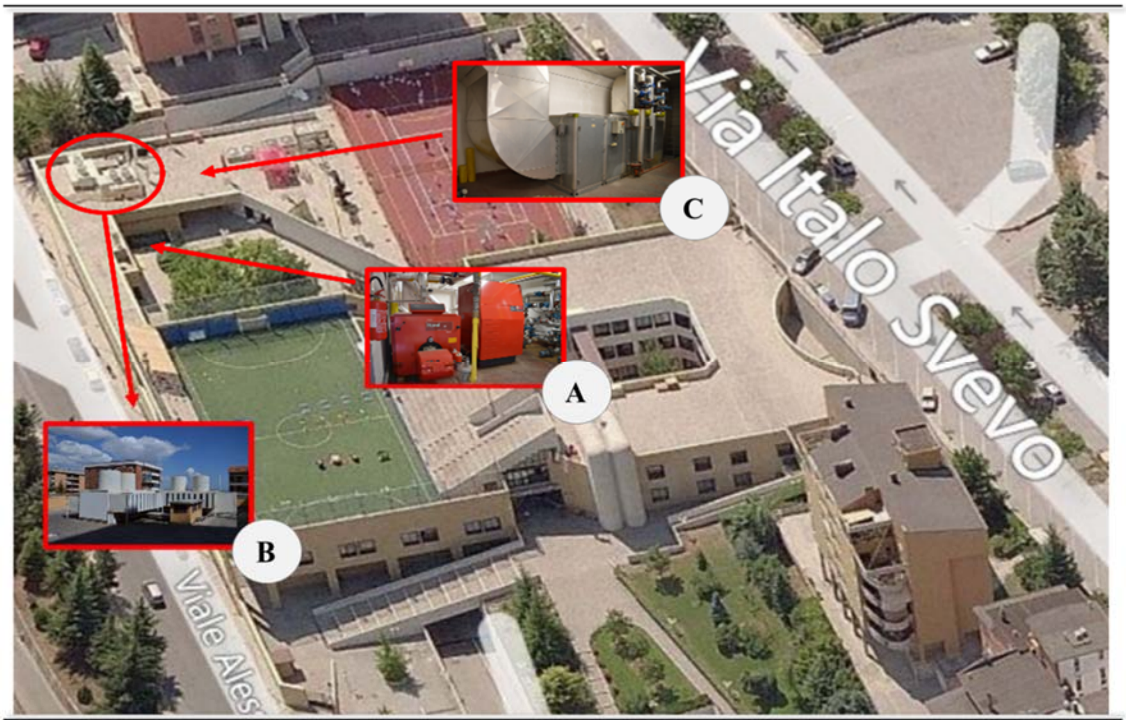


Figure 90: Placing of the machines serving the building: (a) thermal plant; (b) refrigeration unit and (c) AHU.

The hot water also for sanitary uses is produced by a condensing boiler with nominal power of 400 kW and efficiency ratio at full load equal to 98.3% and by a traditional boiler with nominal power 420 kW and efficiency ratio at full load equal to 85.8%. Instead the cool water is supplied by two electric air chillers with nominal power of 167 kW. There are also four air handling units, one of this satisfies merely the ventilation needs. Finally, there is one hot water storage with a capacity of 1’000 l.

Each one of the air handling units provides for the conditioning requests of a specific area of competence; in particular:

- “AHU classroom 300 seats” provides, with an air flow rate of 13’800 m3/h, the air conditioning of the main hall that develops between the ground floor and the first floor;
- “AHU classroom 8” and “AHU classroom 7” they are two equal treatment units, each of which treats an air flow of 4’300 m3/h. In fact, they satisfy the air-conditioning requests of two classrooms that are identical in size, characteristics, and terminal facilities: room 8 and room 7, located in the central area of the ground floor;

- "AHU classroom 180 seats" serves the Kesnel classroom with 180 seats; for it, however, but it was not possible to find information about the processed scope;
- "AHU primary air" with an air flow rate of 17'900 m^3/h, it provides air treatment (for the sole purpose of guaranteeing the quality and the right air changes) of classrooms, offices, study rooms, circulation areas and dining areas.

The first 4 AHUs listed are equipped with a heating and a cooling coils, while the one called primary, only with a pre-heating and a post-heating coils. These coils are powered by the heat and cooling systems. All the AHUs are also equipped with an evaporating pack humidifier, which however does not appear to be in operation.

Some infrared thermographs of generation equipment and emitters have been done as well as the measurement of temperature and air speed for air emitters. These indicated the uniformity of hot water distribution for radiators while as regard air emitters, the speed is always in comfort zone, but temperature is too much height. About this point, two aspects can be underlined: air does not balance only latent load but also sensible one; there is no regulation system for temperature of hot water that supplies radiators, fan coils or heat exchangers of air handling unit. From interviews to occupants, frequent discomfort conditions have been arisen. Indeed, there is not a regulation system, not thermostat in offices neither in classrooms and only the temperature of the water supply by the thermal power plants is controlled.

The artificial lighting systems consists mostly of fluorescent lamps with two sources of 58W or single source of 32 W. Only in the auditorium, there are also 7 halogen spotlights.

In the simulation model, in order to model as well as possible the overall artificial lighting system, fluorescent lamps type and a normalized power density of 15 W/m^2 has been chosen and settled for the whole building. The HVAC system has been created according to surveyed details. In addition, the boiler and chiller supply water temperatures have been settled equal to 80°C and 6°C respectively; instead, the supply domestic hot water temperature, from the hot water storage, is chosen equal to 45°C. Concerning the AHUs, the above-mentioned air flow rates have been included in the numerical model. Moreover, the supply air temperature of the "AHU primary air" is equal to 30.5°C during the wintertime, 16°C during the summertime, and equal to 24°C for the other periods. The other AHUs provide air temperature at 30°C during the wintertime, 16°C during the summertime and at 24°C during the intermediate periods.

A schematic visualization is shown in Figure 91, created by "Detailed HVAC" model of DesignBuilder software. It is a graphical interface provided for the assembly of component-based HVAC systems which may be combined with building models for energy simulation using EnergyPlus.

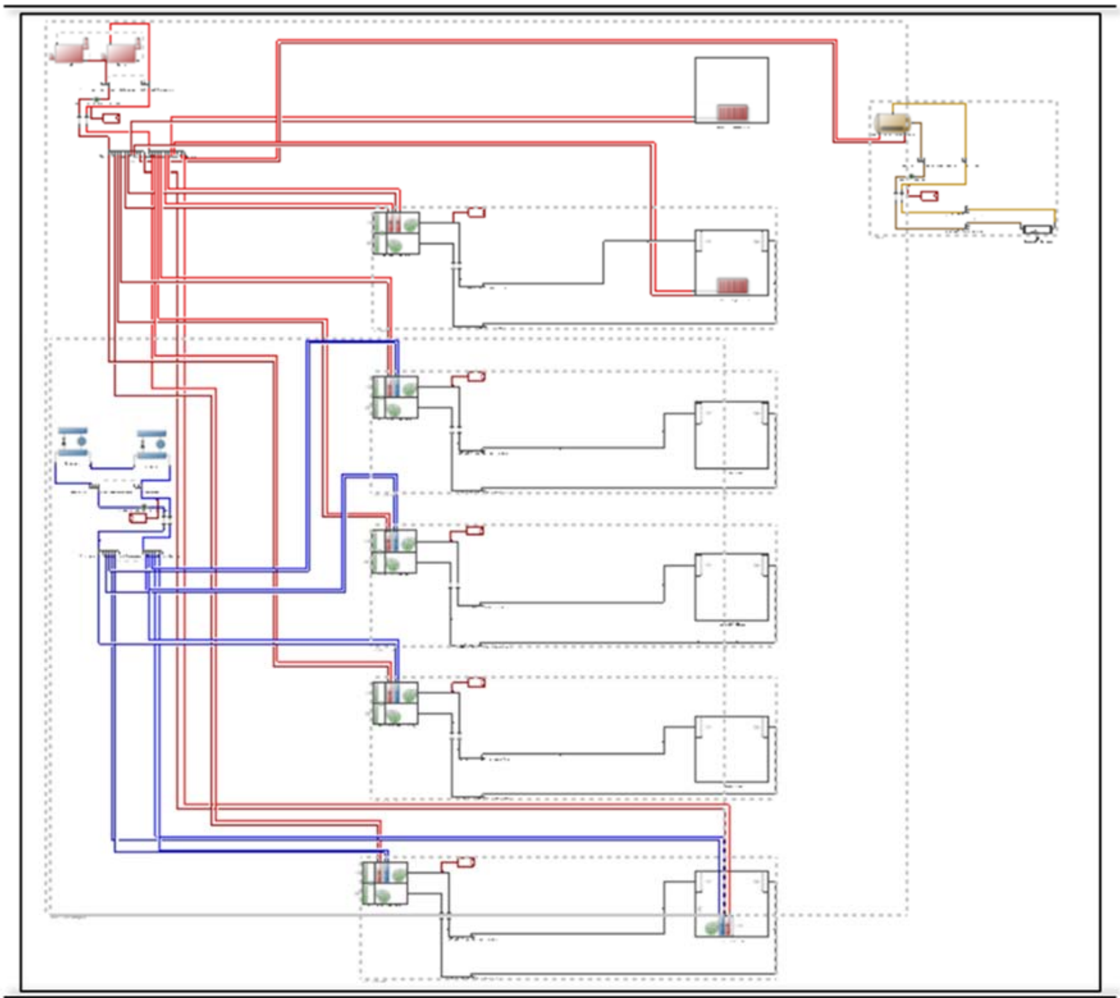


Figure 91: Schematic visualization of the thermal systems.

The operation schedules have been created according to manager and occupant information. Thus, the heating period starts on 15th of October and it finishes on 15th of April considering the hours between 6:30 and 18:00; the cooling period is 15th June – 31st August from 10:00–15:00, while the ventilation is always turned on from 7:00–18:00.

During the weekends and holiday periods, all the systems have been considered turned off; however as in the real situation, a control has been considered to avoid frozen phenomenon during the coldest period. No heating and cooling set-point temperatures have been fixed, but as in present building, only the temperature of hot/cold water has been controlled.

Characterization of building uses and definition of thermal zones

The building hosts around 966 students (data for 2017), with age between 18 and 35 years, around 40 professors and 20 technical-administrative operators. The building is open from 8:00–20:00 every weekday, from 7th January until 31st July and from 21st August until 20th December.

Through an accurate inspection, the kind of use of each room has been verified. At the ground floor, there are classrooms, information point, and a copy shop. The first-floor hosts classrooms, lecture rooms, bar, and administrative offices. The auditorium is located between ground and first floor. Finally, at the second floor there are all the offices of professors and only one classroom. Systems and equipment have been collected and, with reference to each office, averagely, two personal computers and printers are associated, with an overall normalized power density of 6 W/m^2. It is law faculty with oral lessons and equipment are not been considered for classroom but only for lecture rooms.

Data for characterized thermal zones have not been derived from a large-scale questionnaire, but some questions have been done to office occupants and students contextually to the survey for verify thermal zones distribution. More in detail, in each occupied office, the following questions have been done:

- How long do you spend in the building during the day?
- How long do you spend working at a computer?
- How would you describe the indoor conditions in winter and summer?
- What are the main criticalities according to you?

As regards classrooms, the official lessons hours in each period for 2017 and the students have answered to the following questions:

- How would you describe the indoor conditions in winter and summer?
- What are the main criticalities according to you?

Taking into account their answers, for modelling phase (as shown later in Figure 99), the holiday periods have been considered, while the occupation rate has been considered according to the most common behaviour, and for instance in the office between 9:00 and 19:00 as well as the equipment schedule. For lighting usage, a differentiated schedule is used, assuming that is always turned on during the winter, only 4 h during spring and summer (here with reduced power), all day in autumn with reduced power until the afternoon.

The monitoring of the mean air temperature, relative humidity, air speed and lighting level has been done in significant rooms, selected according to kind of use and internal loads, exposure, envelope resistance, type of HVAC system and lighting source, indications of occupants. More in detail, nine rooms have been selected and their main characteristics are shown in Figure 92. The measured values allowed to know the actual thermal and visual indoor conditions.

Use	Floor	Positioning	Surface	Window	Terminal unit	Photo
Office 8	II	North-west	48 m²	1	1 Radiator 1 Diffuser	
Classroom 5	0	South-east	63 m²	1 Wall	1 Radiator 2 Diffuser	
Classroom 8	0	-	128 m²	0	2 Diffuser	
Office RA	I	North-west	37 m²	1	1 Radiator 1 Diffuser	
Lecture-room	0	South-east	307 m²	Sloping wall	6 Radiator	
Classroom 10	II	North-west	30 m²	1 ext. wall 1 int. wall	1 Fan coil	

Figure 92: Main characteristic of rooms selected for monitoring.

Figure 93: classroom 5: (a) sensors for temperatures and relative humidity; (b) light level measure.

For brevity, in this analysis, monitoring results are discussed only for classroom 5, for which students have evidenced local discomfort phenomenon due to glazed wall; it has 50 seats and is located at ground floor.

Air temperature, relative humidity and surface temperature have been recorded with a time step of 5 min. Figure 93a shows installed sensors for classroom 5, during the monitoring period from 22nd of February to 1st March.

The recorded values for air temperature are shown in Figure 94a; here it is also evidenced the reference value of comfort range (19–23°C) and the calculated mean value ($T_{a,mean}$), the maximum ($T_{a,max}$) and the minimum one ($T_{a,min}$). During the weekdays, temperature is always up to 21°C with peak values around 25°C. During the weekend, the temperature decreases but it does not go down 19°C. The contribute of solar gain is clear; if a local regulation system would be available, the heating system could be turned off and more comfortable conditions could be reached. Indeed, students, interviewed after two hours of lesson, have judged the room too hot. Analogously, the relative humidity, the comfort range and the extreme calculated values are reported in Figure 94b. Briefly, the humidity value is usually very low, and it is always below the optimum threshold value of 50%. The air system does not allow the balance of latent load actually. Figure 94c shows the value of the surface temperature on the glazed wall, considered one of the most critical elements of the building. It is clear that heat gains contribute to increase the surface temperature more than air temperature with peak value of 28°C. During the night, the temperature is reduced by about 6°C compared with daily value; however, also when the heating system is turned off and the building is not occupied, the value does not go below 17°C.

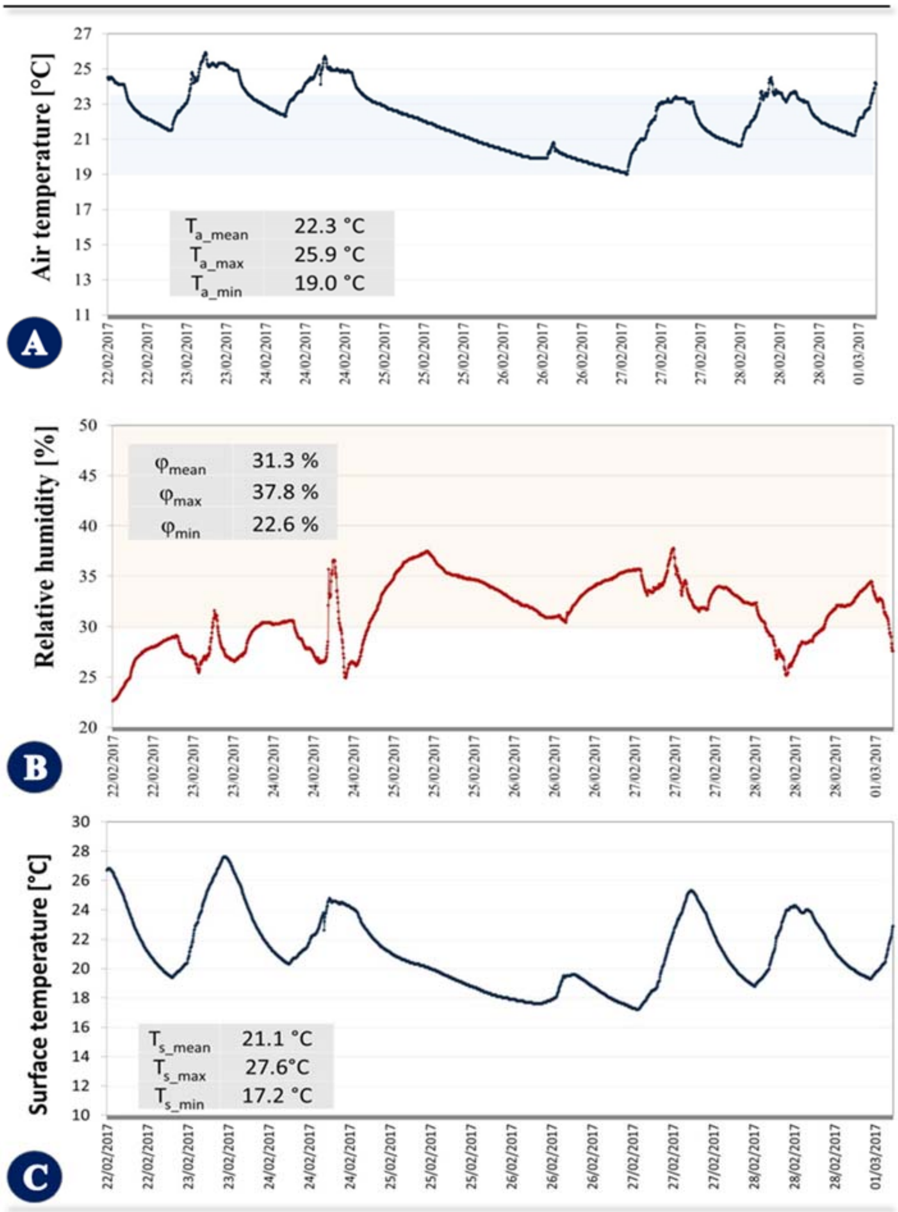


Figure 94: Classroom 5: (a) trend of air temperature; (b) monitoring of relative humidity; (c) surface temperature monitoring.

For air speed and lighting level, some punctual measurements have been performed considering different natural and artificial scenarios with a sampling time of 10 min. These measures have been compared with illuminance values indicated by the standard UNI EN 12464-1 [164], that suggest 300/500 lx for classroom/office. For classroom 5, two scenarios for the measure on a desk of the first (Figure 93b) row have been selected, taking into account the external condition (25th January, sunny day, clear sky) and lighting system (consisting of 6 lamps 2×58 W). These are: (desk_1) opened drapes and lighting system turned off; (desk_2) closed drapes and lamps turned on. Table 29 shows results of measurements considering 10 min of continuous acquisition. It is clear that electric system provides light level according to the standard meanwhile the natural scenario is strongly discorded with [164].

Table 29: In-field measured of lighting level.

Illuminance	Max [Lux]	Min [Lux]	Mean [Lux]
Desk_1	77	39	43
Desk_2	482	260	479

These results have been confirmed also in the other rooms selected; however, it has to be underlined that often, when drapes or shading systems are not used, people have visual discomfort. As suggested by Bellia *et al.* [255], for Italian educational building, the analysis of lighting quality should not only focus on the respect of the EN 12464-1 requirements, but also on the analysis of light's characteristics at the users' eye level in order to apply models to evaluate non-visual effects of light. For this reason, other future analyses should support the implementation of refurbishment project.

For having a building model suitable to predict reliable thermal loads, several typologies of thermal zones have been created and they were detailed according to the specific use of zones. Table 30 shows the main information in terms of occupancy and installed power, obtained from in-site inspections.

The air change provided by mechanical ventilation system has been fixed to 2 l/s person. This value is an average one, assumed for the calibration of the model, by taking into account the 7 l/s per person when the systems is activated and lower or zero values when the system is turned off. An additional air change equal to 0.3 vol/h has been considered in order to take into account the infiltration due to opening of windows and doors.

Table 30: Main thermal zone data.

Thermal zone	Activity [W/person]	Occupation [person/m^2]	Plug/process [W/m^2]	Water [l/m^{2}day]	Lighting [W/ m^2]
Office	123	0.2	6	-	8.0
Classroom	127	0.4	0	-	8.0
Lecture room	115	0.2	0	-	8.0
Circulation zone	140	0.2	0	-	8.0
Bar	110	0.2	4	0.4	8.0
Toilet	140	0.1	0	0.2	8.0
Copy point	180	0.2	6	-	8.0

Occupancy schedules and installed equipment, lighting and operation of shielding systems have been created according to surveyed characteristics. The main area of the building is referred to Office and Classroom thermal zone type; for them, the schedules are reported in Table 31.

Energy building data

The last step of energy audit has been an accurate analysis of the historical energy requests, by collecting data about the last available billings (2014–2016). With regard the electricity, the building has a contract for a power of 420 kW and the annual average consumption is over 176’929 kWh; the monthly request is quite constant. The gas request is around 410’451 kWh, by considering the calorific values reported by the billings.

Detailed monthly trends will be shown in the next section, during the calibration of the numerical model.

Table 31: Description of schedules for equipment, occupation and lamps of classroom and office thermal zones.

Classroom			Office		
Occupation	**Equipment**	**Lights**	**Occupation**	**Equipment**	**Lights**
Through: 07 Jan, For: AllDays, Until: 24:00, 0, Through: 31 Jul, For: Weekdays, Until: 09:00, 0, Until: 14:00, 0.75, Until: 18:00, 1, Until: 20:00, 0.1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 30 Sep, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 14:00, 0.75, Until: 18:00, 1, Until: 20:00, 0.1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 07 Jan, For: AllDays, Until: 24:00, 0, Through: 31 Jul, For: Weekdays, Until: 09:00, 0, Until: 14:00, 0.75, Until: 18:00, 1, Until: 20:00, 0.1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 30 Sep, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 14:00, 0.75, Until: 18:00, 1, Until: 20:00, 0.1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 07 Jan, For: AllDays, Until: 24:00, 0, Through: 30 Apr, For:Weekdays, Until: 09:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 May, For:Weekdays, Until: 16:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Jul, For:Weekdays, Until: 16:00, 0, Until: 20:00, 0.5, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 30 Sep, For: AllDays, Until: 24:00, 0, Through: 31 Oct, For:Weekdays, Until: 09:00, 0, Until: 15:00, 0.4, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Dec, For:Weekdays, Until: 09:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 07 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For:Weekdays, Until: 09:00, 0, Until: 18:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For:Weekdays, Until: 09:00, 0, Until: 18:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 07 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For:Weekdays, Until: 09:00, 0, Until: 18:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For:Weekdays, Until: 09:00, 0, Until: 18:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 07 Jan, For: AllDays, Until: 24:00, 0, Through: 30 Apr, For:Weekdays, Until: 09:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 May, For:Weekdays, Until: 16:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 1 Aug, For:Weekdays, Until: 16:00, 0, Until: 20:00, 0.5, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 31 Oct, For:Weekdays, Until: 09:00, 0, Until: 15:00, 0.4, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Dec, For:Weekdays, Until: 09:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;

5.2.1.2 Calibration of numerical model

All information and data acquired during the audit procedure have been used to define and calibrate the numerical energy model of the building. Here, proper geomorphological data for Campobasso have been used and the available weather year (IWEC data files) to consider high probability conditions [182].

Table 32 shows the evaluated indexes and tolerance range (in the last line) separately for the natural gas (E_G) and the electric energy demand for all building uses (E_{el}).

Table 32: Calibration indices evaluation.

% $ERR_{average\ year}$		%MBE		CV(RMSE)	
E_G	E_{el}	E_G	E_{el}	E_G	E_{el}
4.1%	3.9%	4.4%	4%	6.7%	7.2%
± 10%		± 5%		± 15%	

The results are always within the tolerance range; thus, the energy model can be considered well-calibrated to well-represent the present energy demands. In detail, Figure 95a infers the comparison between the gas request of real building and that of simulated model, with also the indication of monthly error; Figure 95b shows the same analysis for electricity request. Finally, Figure 95c shows, for classroom 5, a comparison of the indoor air temperature measured during around 7 days and the profile of air temperature provided by the simulated model; note that both occupied and not occupied days are included. Simulated and measured trends are comparable, and the hourly error is always less than 30% (limit value for hourly data [146]). The difference is very low during the not-occupied days (weekend), this assures that building/HVAC system is well modelled. Major difference (10–12%) is during the occupied hours and it is related to occupant behaviour and interaction with their equipment or shading system.

In conclusion, the numerical model seems to be strongly in agree with real building usage.

In order to calibrate the model, the following parameters were adjusted during the calibration process: occupancy times and equipments operation, as well as the occupancy density. Starting from the configuration obtained considering the survey's results, they were adjusted until the simulation trends and values of energy consumption and indoor air temperature resulted compared to the measured values. In particular, the adjustments were made considering the default schedules and values suggested by DesignBuilder for the corresponding thermal zones, and therefore bringing the values chosen at the beginning closet to those suggested. This strategy seemed to be the best one given the large building size, the amount of different thermal zones and the complexity of occupants' behaviour.

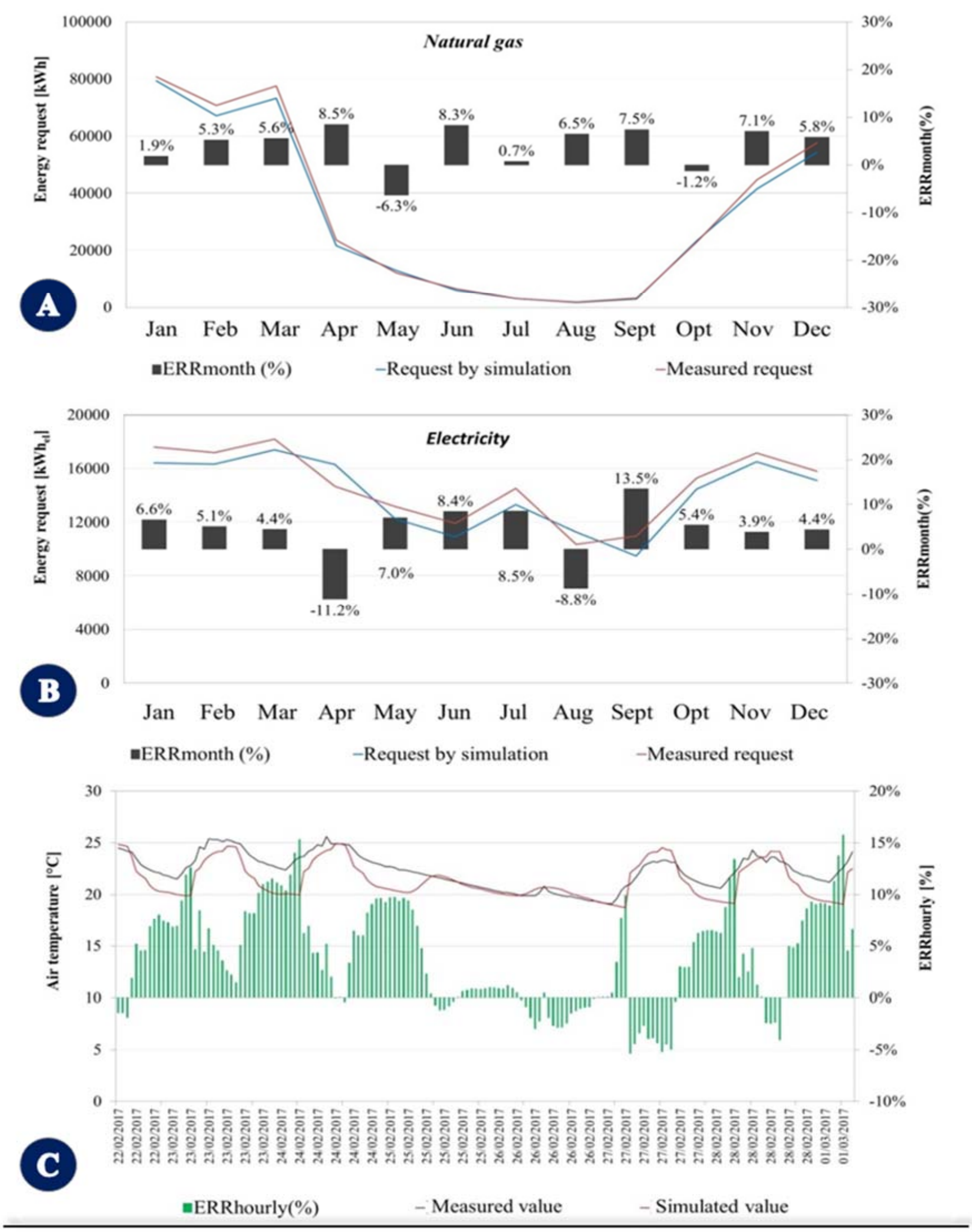


Figure 95: Calibration: (a) natural gas request; (b) electricity energy request; (c) air temperature classroom 5.

5.2.2 *II Edificio Polifunzionale* as Reference building: energy audit and model calibration process

The second case study building is named *II Edificio Polifunzionale*, it hosts the administrative offices and classrooms of the Department of Economy of University of Molise. Figure 96 shows the main entrance on the north-east exposure and the building geographic locations.

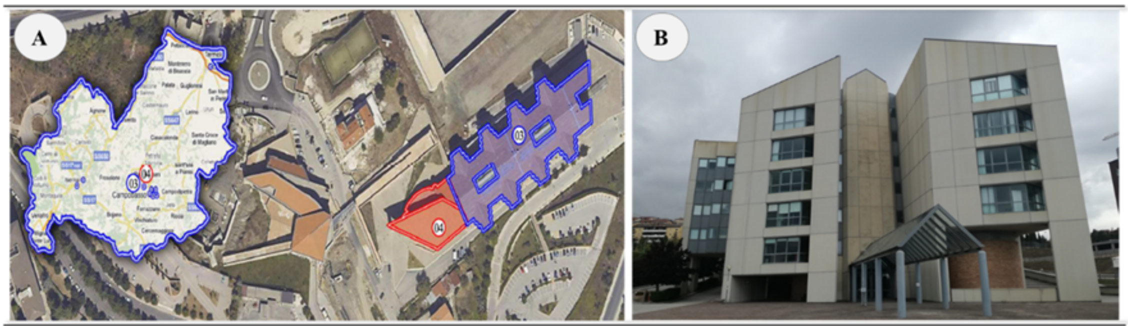


Figure 96: *II Edificio Polifunzionale*: (a) location and (b) external view.

The analysis performed for the first case study building has been performed also for the one herein presented. Then, the following sections describe, in more synthetically way, all collected information for the evaluation of the present state of the building, and the creation and calibration of numerical model of the building and its systems.

5.2.2.1 Energy audit and modelling set up

The building has an almost rectangular shape, with 6 usable floors; one of them is not conditioned, since it is used as car park. The most important characteristic of building and thermo-physical properties of the envelope are summarized in Table 33. In addition, Figure 97a and 97b compare the model built in simulation environment and the real building.

For what concerns the building energy performance, the envelope audit has been supported with no-intrusively diagnostic techniques, like infrared thermography and by in-situ measurements of thermal transmittance. It presents different types of external walls, mostly made of hollow brick, air cavity, insulation material and full-block or aluminium layer as outer layer. At the present state, the analysed building has not a good value of thermal transmittance and the periodic thermal transmittance (see Table 33), compared to the values established of Italian legislation for new or refurbished buildings. This causes high heat losses transmission and, moreover, also a negative impact on heating needs and on the comfort conditions for occupants. Conversely, during the summer period, the building envelope does not prevent overheating of indoor environments.

Table 33: Site and building features

Building Geometry					
Total building floor area (m^2)	21314.16	Total volume (m^3)			66520.38
Net conditioned floor area (m^2)	12280.21	Conditioned total volume (m^3)			34468.83
	Total	North	East	South	West
Gross wall area (m^2)	11092	3589.18	2080.60	3408.89	2013.66
Window opening area (m^2)	1705.12	2108.09	2038.03	3170.17	1854.83
Net window-wall ratio (%)	16.76	16.62	20.02	14.19	17.84
Building envelope	t (m)	U (W/m^{2}K)		t (m)	U (W/m^{2}K)
Wall with external block	0.615	0.308	Auditorium roof	0.275	0.337
Wall with external brick	0.310	0.428	Transparent envelope	U_f (W/m^{2}K)	U_f (W/m^{2}K)
Internal wall	0.580	0.427	Skylights	5.88	2.67
Floor	0.466	0.529	Glass walls	5.88	3.09
Sloped roof	0.390	0.963	All other windows	5.88	2.69

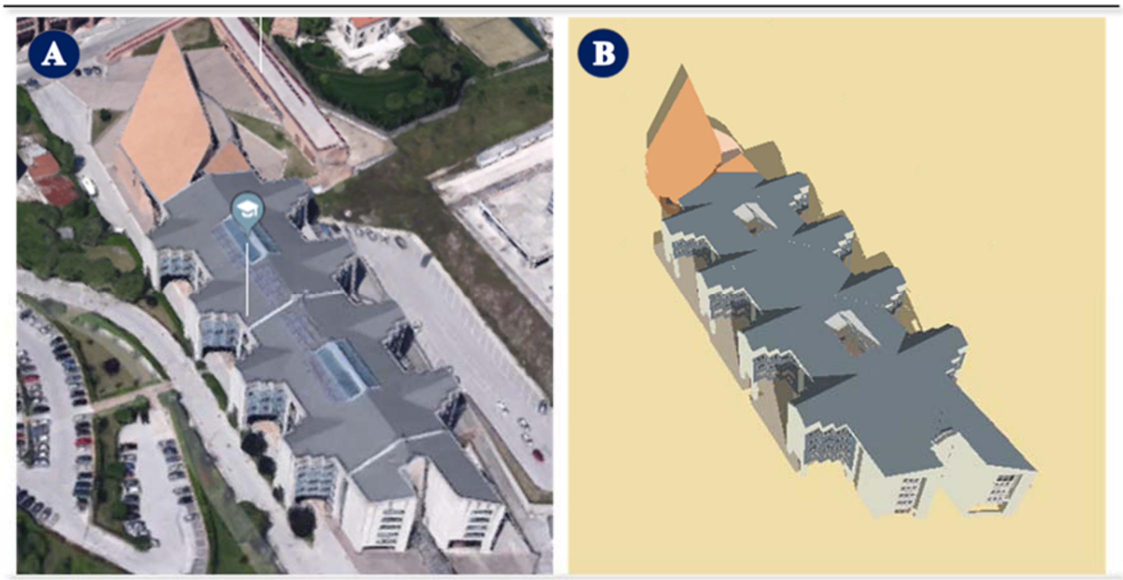


Figure 97: (a) Imagine of real building and (b) rendering of simulation model.

The building has four types of window elements. The first type is glass blocks, used in the entrance at ground floor and for the hallway at the first floor (north-west exposure). The second type is a double clear glazing, which composes the skylights of the roof. Only the glass walls at the entrance are made of single clear glass, with an aluminium frame. For these types of windows, there are not shading systems. Finally, all other windows are realized with an aluminium frame and double clear glazing (6mm glass/12mm air/6mm glass). Most of these types of windows have an inner shading system, made by white vertical lamellas.

Infrared thermography surveys (Figure 98) were carried out during winter period, in optimal measurement conditions such as an overcast sky. Moreover, this surveys have been used to identify a proper positioning of the sensors for the measurements of thermal transmittance, according to the standard ISO 9869 [81]. The difference between the values of the measured thermal transmittance and the value derived by analytic calculation is around 35%.

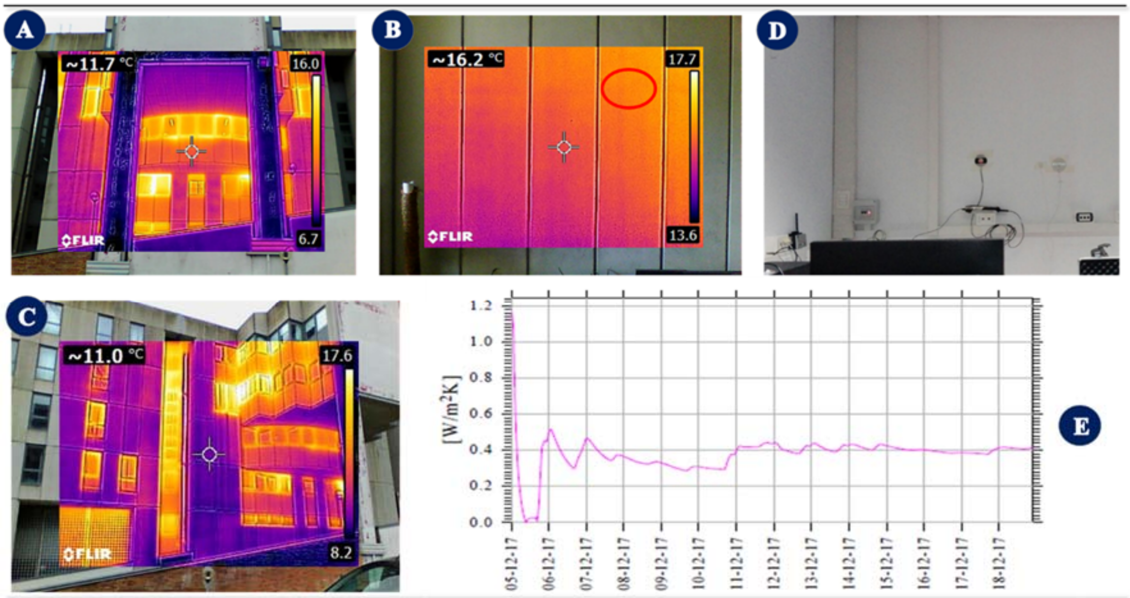


Figure 98: (a), (b) and (c) infrared thermography; (d) and (e) measures with heat flow meters.

About the technical plants, all offices, lecture rooms, bar, circulation zones, and most classrooms have a mixed air/water system, given by combination of fan-coil and air handling units. This system provides heating, cooling, and ventilation requests. Only toilettes have a heating and cooling water system. The six biggest classrooms, which are placed in the central part of the structure, have an all air system, which provides both heating, cooling, and ventilation needs. The hot water, also for sanitary uses, is produced by two traditional boilers with nominal power of 1100 kW. The chilled water is supplied by two electric air chillers with nominal power of 840 kW. There are also five air handing units, two of these provide only ventilation. Finally, there is one hot water storage with a volume of 1500 litres. Also, in this case, thermographic studies, coupled with other instruments, were performed also for generation equipment and emitters, as well as these have been performed for supporting measurement of air speed and temperature. These indicated that the speed is always in comfort zone, while the temperature is higher than conventional values for mixed air-water HVAC. About it, it should be specified that the only one regulation criterion is a climatic compensation of temperature of supply water. For this reason, the temperature inside the building is often too high and this causes high consumption of the building and a negative impact on the comfort conditions for occupants. For what concerns other equipment, on the building roof there is a photovoltaic system of about 19 kWp. Moreover, the lighting systems consist of fluorescent lamps of 36 W, with an average installed lighting power of 6 W/m^2.

In the simulation model, the HVAC system has been created according to the aforementioned surveyed details. In the simulation model, the boiler supply water temperature has been controlled by a weather compensation control strategy, following which its value come from 80°C to 60°C depending on the measured external air temperature. Instead, the chiller supply water is constant and settled equal to 11°C, while the supply domestic hot water temperature, from the hot water storage, is chosen equal to 55°C. All AHUs provide air flows at 31°C during the wintertime, 16°C during the summertime, and at 26°C during the intermediate periods. The operation schedules have been created according to manager and occupant information. Thus, the heating period starts on 15th of October and it finishes on 15th of April, the cooling period is 25th June – 5th September, while the ventilation is always turned on. The operational hours are in the period 7:00 - 18:00, with possibility to turn on the heating system when the external temperature is too low during the night. During the weekends and holiday periods, all systems have been considered turned off.

Moreover, through an accurate inspection, the use of each room has been verified. At the ground floor, there are the entrance and information point. At the first floor there are classrooms, bar, and copy shop. Also, the second and third floor host classrooms and some administrative offices. At the fourth and fifth floors there are mostly professor's offices. Finally, the auditorium is in an adjacent structure, outside the building. Finally, to describe, as accurately as possible, the real conditions inside the building, some questions were asked to office occupants and students, contextually to a survey for verifying the thermal zone distribution. More in detail, as for the first case study building, the questions concerned: a) the time spent daily in the building, b) how many hours are spent by working at a computer, c) conditions of comfort or discomfort for what concerns the indoor microclimate and d) the list of the most important criticalities of the building.

In this way occupation rates, equipment schedules and lighting systems usages have been described into the numerical model of the building, by considering the achieved answers. Moreover, for some significant rooms, also monitoring of air temperature, relative humidity and lighting levels have been performed, with the aim to describe the actual thermal and visual indoor conditions. More in detail, the significant rooms have been selected according to kind of use and internal loads, exposure, envelope resistance, type of HVAC system, lighting source and indication of occupants.

In this study, for brevity, analyses of monitoring results are discussed only for one administrative office (Office 2). In detail, during the monitoring period, from 8th to 21st of November 2017, air temperature and relative humidity have been recorded with a time step of 5 minutes, and the recorded values for air temperature are shown in Figure 99a. In the figure, it is also evidenced the reference value of comfort range (19-23°C) and calculated mean value ($T_{a,mean}$), maximum ($T_{a,max}$) and minimum ones ($T_{a,min}$). Analogously, for the relative humidity, the comfort range and the mean, minimum and maximum values monitored in the Office 2 are reported in Figure 99b. Briefly, the humidity values are usually very low, and always below the optimum design value of 50%. Indeed, the air system does not balance the latent load and, moreover, the air temperature are too high. Similar trends have been recorded for the other selected areas and these confirm that often the air temperature and relative humidity are outside the range of comfort recommended by current standards [88]. Indeed, from interviews to occupants, frequent discomfort conditions have been arisen.

For what concerns the luminance level, some punctual measurements have been done in correspondence of working surfaces (around 90 cm of height) and by considering different natural and artificial scenarios with a sampling time of 10 minutes. These measures have been compared with illuminance values indicated by the standard UNI EN 12464-1 [164], that suggests 300/500 lux for classrooms/office. Always referring to

Office 2, the measurement was carried out on the two work-surfaces (at the centre of desks) as shown in Figure 100. Different scenarios have been considered, by taking into account the external conditions and lighting system consisting of 6 lamps (36W). In detail, the following conditions were considered: scenario 1) opened drapes and lighting system turned on, without sunlight (evening); scenario 2) opened drapes and lamps turned off, whit covered sky; scenario3) closed drapes and lamps turned on, with covered sky.

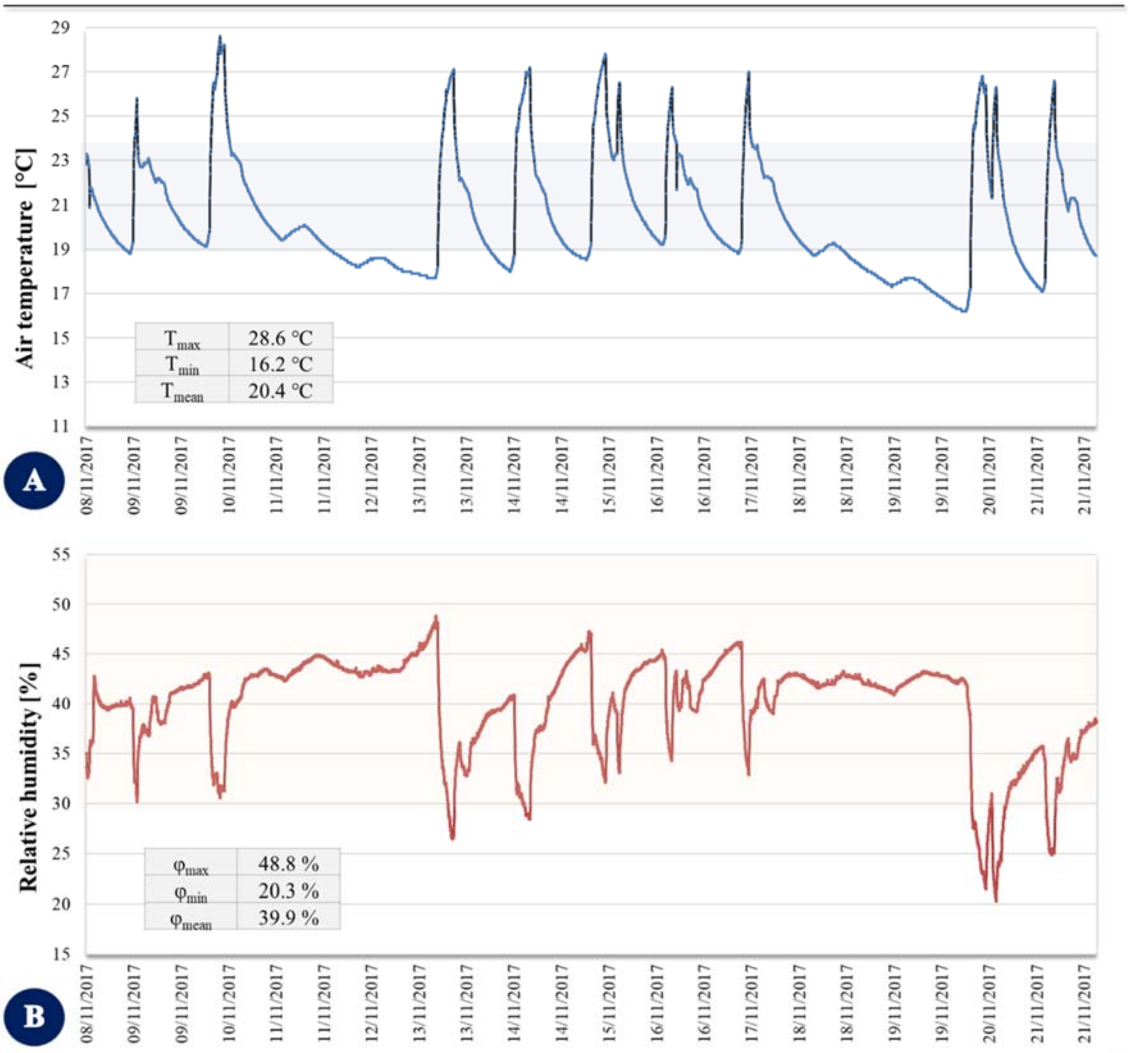


Figure 99: Office 2: (a) trend of air temperature; (b) monitoring of relative humidity.

Table 34 shows the results of measurements, and it is shown that, both artificial lighting system and natural scenario provided lighting levels discorded to the standard [164]. In general, this result has been confirmed also in some other selected rooms, and it means that people have visual discomfort. In the building model, to define reliable thermal loads, several typologies of thermal zones have been created and they were detailed according to the specific use of zones, in terms of occupancy and installed power. In detail, occupancy schedules, installed equipment and lighting have been created according to surveyed characteristics. An overall normalized power density of 6 W/m^2 has been chosen to model as realistic as possible the artificial lighting system. Instead for the equipments, a normalized power density equal to 22 W/m^2 and 10 W/m^2 have been chosen respectively for offices and classrooms. Moreover, additional air change equal to 0.35 vol/h has been considered to take into account infiltration due to opening of windows and doors.

The last step of energy audit has been an accurate analysis of the historical energy requests, by collecting data about the last three years (i.e., the available bills) of the electricity and natural gas demands, that is fundamental for the next step of the method: the calibration of the numerical model.

Figure 100: Installed sensor for light level measure: (a) desk1 and (b) dek2.

Table 34: in field measure of lighting level.

Illuminance		I_M	I_m	I_{Mm}
Desk1				
Scenario 1	08/11/2017 17:04	306	284	304
Scenario 2	15/11/2017 15:08	65	38	51
Scenario 3	15/11/2017 15:23	384	363	381
Desk2				
Scenario 1	08/11/2017 17:10	306	302	304
Scenario 2	15/11/2017 15:15	134	80	131
Scenario 3	15/11/2017 15:27	347	334	336

5.2.2.2 Calibration of numerical model

All information and acquired boundary conditions about the building uses have been adopted to define and calibrate the numerical energy model of this building too. Table 35 shows the evaluated calibration indexes and tolerance ranges (in the last line) for natural gas (E_G) and electric demand (E_{el}) for all building uses. The results are always within the tolerances; thus, the energy model can be considered well-calibrated and well-representing of the present energy demands.

Moreover, in Figure 101, the comparison between the electricity request of the real building and that resulting from simulated model is reported, with also the indication of monthly gaps. The same analysis for gas request has been performed too. According to the M&V Guidelines, the MBE (Mean Bias Error) and the CV(RMS) (Coefficient of variation of the root mean squared error) have been calculated and these resulted lower than the maximum admitted values. All told, the numerical model is enough in agree with the real building usage. This means that the simulation model describes, as accurate as possible, the real building performances. Indeed, it is important to underline that, in this study, also the behaviour of the occupants and the use of the equipment, which are often not considered, have been adequately modelled as aforementioned.

Table 35: Evaluation of indices of calibration.

%MBE		CV(RMSE)	
E_G	E_{el}	E_G	E_{el}
3.4%	2.5%	13.1%	6.9%
± 5%		± 15%	

Then, collected data, together with a comparison with energy bills, allowed a proper calibration of numerical models simulated by EnergyPlus: it has been used in the following sections as reference scenario. Indeed, as it was said in the methodology section (section 5.1), starting from a calibrated model of the case study buildings, some retrofit measures have been implemented to evaluate the environmental benefits and economic implication of a deep energy refurbishment (section 5.3) and to evaluate the importance of using validated models to simulate the present performance of building systems (section 5.4).

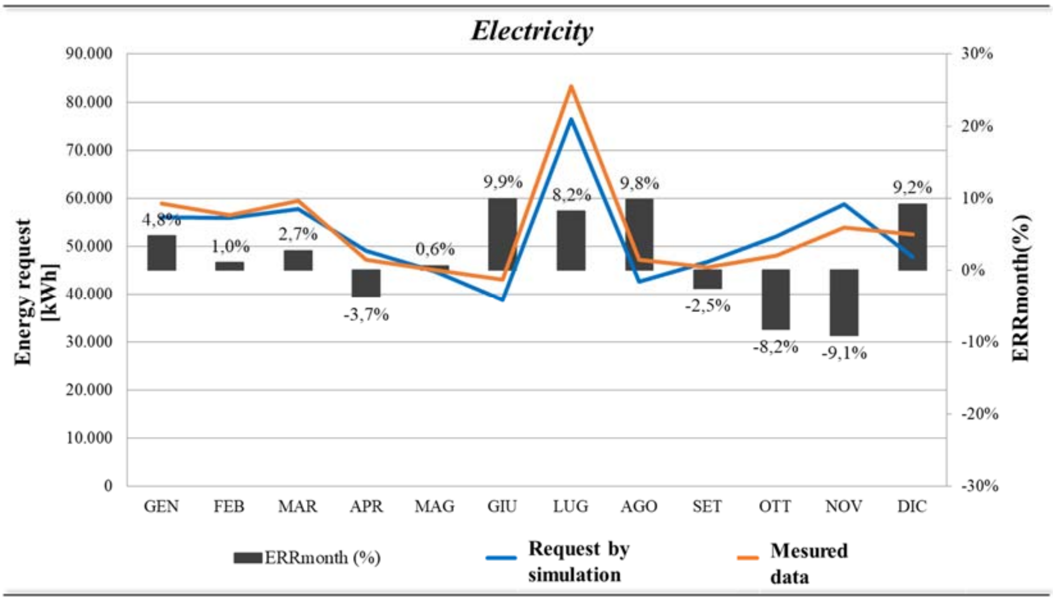


Figure 101: Calibration electricity energy request.

5.3 Energy efficiency measures evaluation

For both the two case study buildings, the surveys and some interviews to occupants and technical operators have evidenced some important criticalities and according to these, the energy efficiency measures have been chosen and investigated in a simulation environment. In this section, these will be compared in a simulation environment through the cost optimal approach.

5.3.1 Energy efficiency measures evaluation for *I Edificio Polifunzionale*

In this sub-section, the chosen retrofit measures for the first case study building will be first described and then they have been compared each other and also in combination of them through the cost optimal approach.

5.3.1.1 Description of energy efficiency measures

The retrofit scenarios concerned intervention both on the building envelope and on plant and active energy systems.

Thermal insulation of building envelope

By considering the not-uniformity of building envelope due to the absence of insulation material in some opaque components and the poor conditions of glazed envelope, thermal insulation has been considered for reducing thermal dispersions.

- Thermal insulation of vertical walls and external ceiling

The refurbishment design considers the application of 12 cm of insulating material both on walls and external ceiling. Two materials have been considered: the expanded polystyrene (ep12 in the following analysis), with a thermal conductivity of 0.040 W/(mK) and density of 30 kg/m^3; a rock wool layer (rw12), with a thermal conductivity of 0.033 W/(mK) and density equals to 75 kg/m^3. The adoption of two different materials has been considered to evaluate the improvement of thermal inertia by means of more massive insulation.

- Thermal insulation and spectral peculiarities of roof

For the roof, two different retrofit solutions have been explored. In the first configuration only the application of 12 cm of expanded polystyrene has been considered (measure code r_ep12). In the second one, in addition, the roof finishing layer is made of paint with a value of solar reflectivity of 0.56 (measure code r_ep12al) while presently it is 0.30.

- Replacement of windows and shading systems

The installations of low-emissive glazing system (leW), selective windows (sW) and electrochromic ones have been evaluated. For all of these, an argon-filled cavity and an aluminium frames with thermal transmittance equal to 2.39 W/(m^2 K) have been considered. About the shading systems, the adoption of two fixed external systems are explored: projection Louvre of 0.5m (pL) and horizontal overhang shades of 0.5m (Ho); moreover the scenario with only existing internal shading (IV) has been considered.

Table 36 summarizes the symbols that will be used in the following analysis and the investment cost (C_I) of each alternative, calculated according to official price list of the Molise region. The wall insulation is considered on the outer side of building; thus, the C_I includes not only the insulation material but also the preparation of wall, the scaffolding, the labour costs and the final painting with water paint for outdoor. For roof's interventions, besides materials (waterproofing, paint and insulation), it has been considered the cost of removing and of waste disposal of the external cladding layer and waterproof covering and the labour cost.

Moreover, Table 36 indicates also the variation of thermal transmittance U; for instance, for the north-east wall the U-value is reduced of around -71% and the Y_{IE} becomes 0.077 W/(m^{2}K) with ep12 while for rw12 case, the thermal transmittance is reduced of around -75% and the Y_{IE} becomes 0.060 W/(m^{2}K).

Furthermore, Table 36 shows the glass system' s thermal transmittance and the solar factor (g). The installation of low-emissive glazing system that allow the reduction of U of around 37% while selective glazed windows (ΔU ≈-50%) with reduction of solar factor of around -40%. Also in this case, as well as for external shading, the investment cost includes the labour, the dismantling and disposal of the old components plus all ancillary works. Finally, the lifespan (p) is also indicated for each measure.

Table 36: summery of insulation measures.

Code	Description	C_I [€/m^2]	U [W/m^2 K]	g	p [years]
ep12	Wall insulation with expanded polystyrene	79.2	0.155-0.229		50
rw12	Wall insulation with rock wool layer	88.2	0.141-0.209		50
r_ep12	Roof insulation with expanded polystyrene	107.3	0.163-0.175		50
r_ep12al	Roof insulation and aluminium membrane	106.3	0.163-0.175		50
leW	Installation of low-emissive glazing system	300	1.689	0.64	35
sW	Installation of selective glazed windows	320	1.338	0.42	35
ecW	Installation of electrochromic windows	748	3.437	0.71	35
Ho	Adoption of horizontal overhang shades of 0.5 m	64.9			50
pL	Adoption of projection Louvre of 0.5 m	100			35

Energy efficiency measures on plants

- Installation of regulation system for HVAC

In-situ survey and in-field measurement have evidenced two important criticalities: air temperature tends to be higher than standard value (20 ± 2°C) because there isn't a suitable regulation system; the latent load is not balanced, so the value of humidity is too low compared to the optimal working conditions. For these reasons, it has been considered the installation (indicated with REG) of 100 thermostatic valves (one for each radiator), 12 room thermostats and one control system for the air handling units.

- Replacement of lighting systems

The replacement of present system with LED lamps has been assumed according to both energy efficiency aims and visual comfort. In detail, a lamp type with lifetime of 30’000 h and efficiency equal to 100 lm/W has been selected.

In another configuration, also the installation of automated control for lighting system has been considered, based on occupancy sensors and daylight availability.

- Installation of heat recovery systems in the air handling units

The last retrofit measure is the installation of the heat recovery system in the air handling units. In detail, crossflow air exchangers have been considered with mean efficiency of 0.54. Nomenclature, investment cost (including installation and disposal values) the lifespan for each adopted component (p) and the annual rate of maintenance cost (M) rate are indicated in Table 37.

Table 37: Summary of measures on plant systems.

Code	Description	C_I [€/unit]	p (years)	M (%)
LED	LED installation	19.7	15	-
LEDC	Installation of LED and controller	25.0	15	-
REG	Addition of sensor to air handling units	100	15	4
	Thermostats application	30	15	4
	Thermostatic valves installation	40	15	4
REC	3 Heat recovery systems installation	6’551.4 5’050.8	20	2

5.3.1.2 Cost-optimal level and economic sensitivity analysis

The reference building consists of the edifice with its actual performance. Briefly, according to simulation model, the building primary energy demand (EP) is equal to 166 kWh/(m^{2}y), the total carbon dioxide equivalent emissions are about 181 tCO_{2eq} and the global cost is about 183 €/m^2. The primary energy demand includes all building uses and thus, air-conditioning, lighting, equipment and so on.

To identify the cost-optimal level of energy performance building, the selected efficiency measures and a combination of these measures have been considered.

Energy efficiency measures' analysis

Figure 102 shows the results of simulations for base case with R_r =3%. Here, the position of reference building has been evidenced; it is characterized by highest energy demand. Really, only one configuration determines an increment of primary energy demand and this happens with the installation of electrochromic windows. This solution is not suitable for the considered climate.

This analysis allows to conclude that single measures on the building envelope are not cost effective. For instance, the measures ep12 and rw12 allows respectively a reduction of primary energy of around −1.51% and −1.61% with ΔC_g ≈+17%. Considering the energy measures on the roof, the insulation (r_ep12) determines a ΔEP ≈−2.33% while adding also the reflective paint it is −4.66%; in both cases, an increment of global cost of around 25% is achieved.

The interventions on the glazed components, coupled with external shading, allow an energy saving not higher than 2% with the increment of global cost (ΔCg ≈ +11–15%). Instead, the best package on the envelope, that consist in the realization of both the thermal insulation of walls and roof of the building and the windows replacement (r_ep+r_ep12al +sW) with existing internal shading allows an energy saving of 10% with a global cost of 279 €/m^2.

However, the same energy saving can be reached with the replacement of the lighting system, with a reduction of global cost of around −8.55% and ΔCO2 ≈−11.1%. Adding the control system, the energy saving becomes−13% with global cost of 163 €/m^2. Briefly, the measures on plants (HVAC and lighting system) allows both energy and environmental savings that costs reduction. For instance, the installation of heat recovery systems determines ΔEP ≈−14% and ΔCg ≈−11%.

Obviously, the packages of envelope and plant system allow a great reduction of primary energy demand and polluting emissions. Indeed, the energy optimal configuration considers insulation of wall with expanded polystyrene, application of reflective paint on insulated roof, installation of selective windows with existing internal shading, adoption of heat recovery systems, microclimatic control devices and LED lamps with an automated control. The energy primary demand is 95 kWh/m^2 with reduction of polluting emissions of −42% and global cost of around 191 €/m^2.

Finally, the cost optimal level of energy performance is the minimum of the ideal curve that starts from the RB point in the Figure 102; it is represented by installation of heat recovery systems, microclimatic control devices and the adoption of LED lamps with an automated control. For this point, the primary energy demand is around 111 kWh/m^2 and the reduction of polluting emissions accounts for about 33%. The global cost is the lowest one and it is around 137 €/m^2.

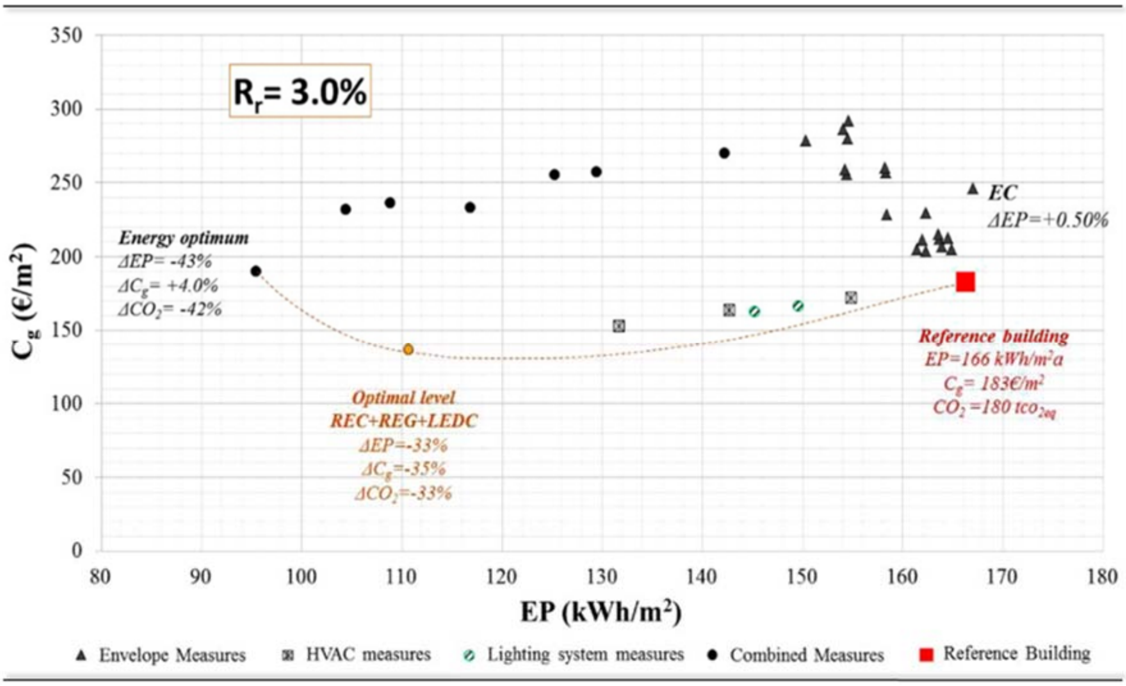


Figure 102: Cost-Optimal diagram for Rr = 3.0%.

Sensitivity analysis

In this section, the sensitivity analysis has been performed for different real interest rate, as indicated in the normative [19]**Errore. L'origine riferimento non è stata trovata.**. More in detail, the global cost has been calculated by using real interest rate of 0.5% (very low inflation rate) and 5.0% (very high value). A lower interest rate results in an increased discount rate (Rd is equal to 0.95 for lifespan of 10 years and 0.91 for 20 years) as well as in increased incidence of annual cost because the present value factor is higher (19).

In this case (looking Figure 103**Errore. L'origine riferimento non è stata trovata.**), the reference building is characterized by a global cost equal of 207 €/m^2 while the optimal point, that is always REC+REG+LEDC, has global cost of around 153 €/m^2. The optimum from the energy point of view (the same that in previous case, obviously), has global cost of around 190 €/m^2; thus, in this scenario, minimization of energy demand can be reached with also economic profitability.

Figure 104 shows the results achieved for a real interest rate of 5.0% for which the present value factor is 12.5 and the values of Rd become 0.61 (p=10 years) or 0.38 (p=20 years). In this case, the annual costs incidence is reduced and the global cost for the real building becomes 157 €/m^2. The cost-optimal point is not changed with a global cost of 120 €/m^2.

The Cg value is increased in all configurations; in this case, the energetic optimum determines a global cost of around 192 €/m^2 and it is not convenient.

The sensitivity analysis confirms results of basic scenario (Figure 102). More in general, interventions relating to HVAC system and lighting sources should be considered to reach good results in term of energetic, environmental and economic indicators. The optimal solution is the same for all considered economic scenarios.

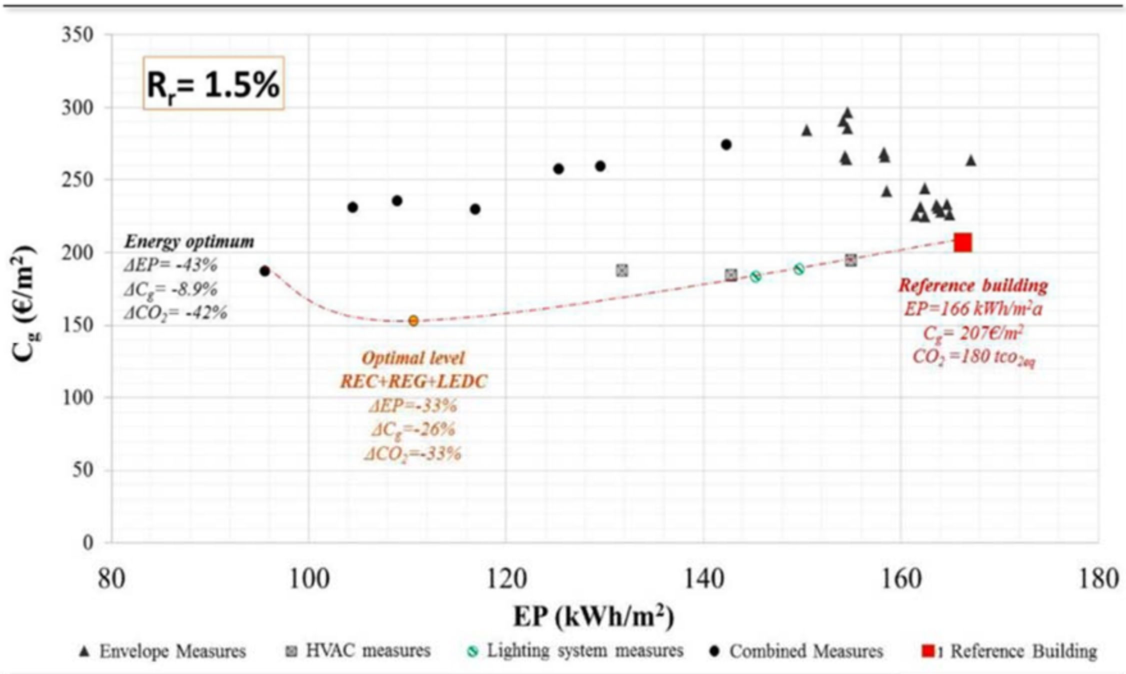


Figure 103: Cost-optimal diagram for Rs = 1.5%.

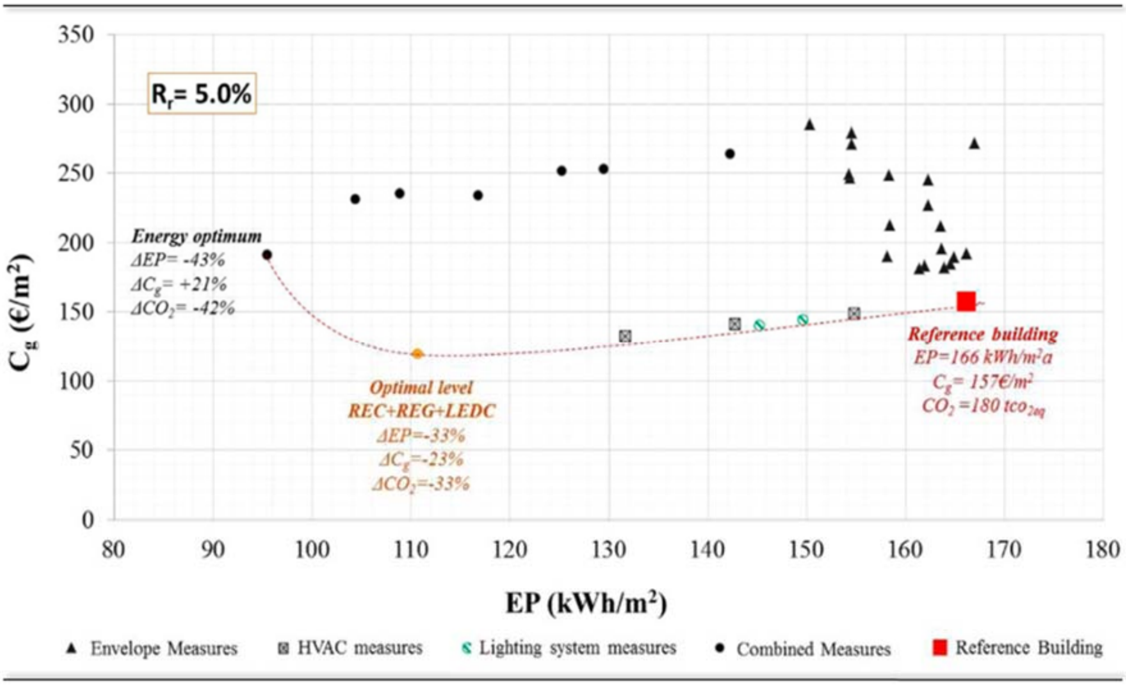


Figure 104: Cost-optimal diagram for Rr = 5%.

5.3.2 Energy efficiency measures evaluation for *II Edificio Polifunzionale*

The same analysis in terms of energy efficiency measures selection and evaluation has been made for the second case study building, named *II Edificio Polifunzionale*, and the most important aspect and conclusions will be shown in this sub-section.

According to some important criticalities identified during the audit phase, some energy efficiency measures have been investigated and described in the following bulleted list:

- Envelope insulation: insufflations with cork for walls with air cavity (INS) or application of thermal plaster, 3 cm, on all inner walls (TI);
- WD: replacement of windows, with the installation of triple low-emissive glazing system, with argon-filled cavity and an aluminium frame with thermal break;
- SS: installation of fixed shading systems, which consists in external horizontal louvre systems;
- BL+CH: replacement of HVAC generation system, with more efficient boiler and electric heat pump/chillers;
- REG: installation of regulation system for HVAC system;
- LED: replacement of lighting systems with LED lamps;

- LEDC: replacement of lighting systems with LED lamps and automated controls;
- PV: replacement of photovoltaic system and installation of photovoltaic glasses in place of the current roof skylights.

More than 20 measures and combination (i.e., packages) of energy efficiency measures have been simulated and the energy saving, carbon dioxide emissions, investment and exercise costs have been determined. Figure 105 shows the net present value (NPV) for a lifetime of 20 years, by considering 3% as discounting rate, and the primary energy saving (ΔEP) for each energy retrofit measure.

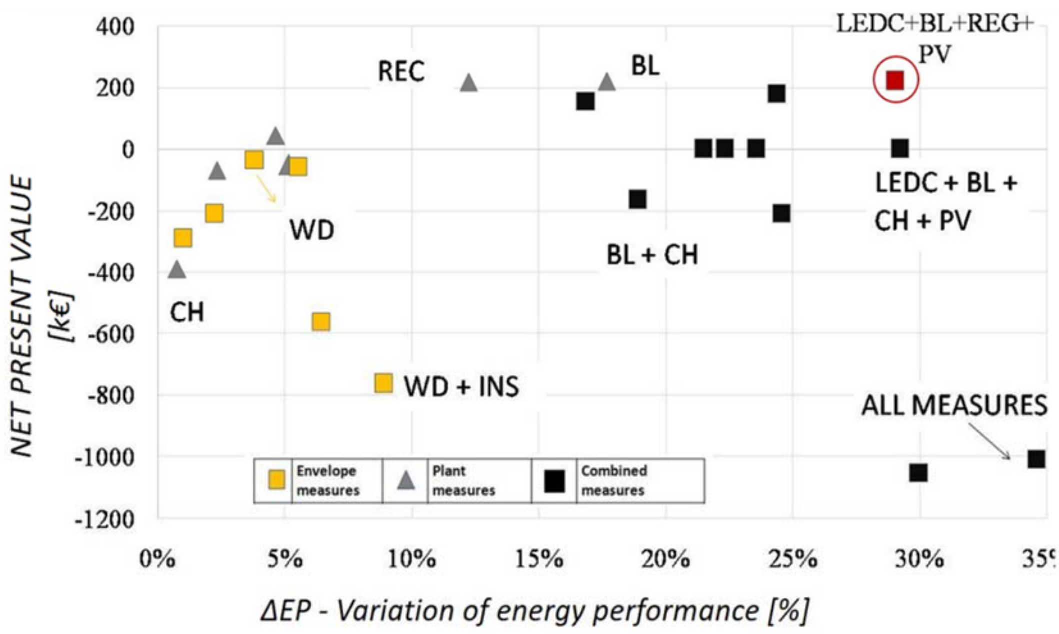


Figure 105: Economic evaluation: comparison of the different retrofit solutions.

Several packages are characterized by discounted payback period of around 19-21 years and, when the NPV is positive, these refer to interventions concerning plant systems. For instance, the replacement of boiler and of the current PV panels, allows ΔEP ≈ 22% and NPV≈ 1561 €. On the other hand, the replacement of windows determines ΔEP ≈ 3.8% and NPV≈ -36000 €. More in general, the measures only on building envelope (squared yellow points) are usually not profitable with negative NPV; the best one in terms of energy saving (ΔEP ≈ 6.45%) has a NPV≈ -562 k€, and it involves the replacement of windows and insufflate insulation. Conversely, refurbishment measures on plant systems and the combination of them are very often profitable; for instance, the installation of devices for indoor temperature regulation provides a ΔEP ≈ 12.3%, with a NPV≈ +218 k€.

According to energy saving results, the best package is characterized by applications of all measures (ΔEP ≈ 34.6%), but it has not evaluable discounted payback periods and the NPV is around -1000 k€. Indeed, the most interesting retrofit measures package, that is a compromise between energy and economic performances (red circled point), consists in:

a) installation of two condensing boilers,
b) installation of regulation system for HVAC system at room level (single-room thermostats),
c) replacement of lighting systems with LED lamps with automated controls,
d) replacement of photovoltaic system with installation of more efficient panels and photovoltaic glasses in place of the current roof skylights.

By adopting all energy efficiency measures - from a) to d) - the discounted payback is 12 years, with energy saving of around 29%. This could be considered the best retrofit package for the second case study building (LEDC+BL+REG+PV).

In general, for both case study buildings, it results that energy efficiency measures focused on the HVAC equipment and lighting system have the greatest potentiality in terms of energy saving and environmental benefits. Indeed, these allow always a good economic profitability and the improvement of the indoor thermal condition.

5.4 INFLUENCE OF MODELLING ASSUMPTIONS ON REFURBISHMENT DESIGN

In this section, the importance to use validated models is examined exhaustively by proposing a sensitivity analysis on uncertainties due to modelling assumptions mainly referring to the adoption of stochastic schedules for occupant behaviour and equipment or lighting usage, but also concerned assumption about the building envelope modelling.

5.4.1 Assumption of energy modelling: *I Edificio Polifunzionale*

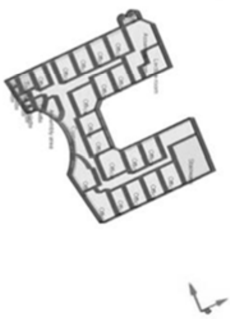
As said, data such as occupancy schedules, internal loads and the interaction between people and windows or plant systems, are some of the largest variables during the energy modelling and to understand calibration results. This is mainly due to the adoption of discrete standardized and conventional schedules with important consequences on the prevision of the energy consumptions. The problem is surely difficult to examine and to solve. In this part of study, a sensitivity analysis is presented, to understand which is the order of magnitude of the error achieved by varying the deterministic schedules used for occupation, internal load and lighting system. This could be a typical uncertainty for a case study as the presented one, where there is not a regulation system for the HVAC system, thus the occupant cannot interact with it.

More in detail, starting from adopted schedules that allowed a good calibration of energy simulation model, several different scenarios are tested. Two type of analysis are presented: the electricity and natural gas scenario for the reference building is compared with these scenarios. Then, for the more interesting cases, all aliquots of consumption are compared, and the values of calibration indexes are analysed. Moreover, the same simulations are done for the optimal refurbishment solution; indeed, authors want study the variation on the prevision of energy saving and global cost reduction. This parametric analysis is aimed at underlining the effect on performance indexes evaluation of the modelling assumptions for the description of thermal zones. Thus, in a first stage, only the thermal zones assigned to office use have been modified in the simulation model. These represent the 26% of the building conditioned area.

The schedules adopted for reference case are shown in Figure 106. The results obtained in the reference scenario have been compared with those achievable using default values of UK's National Calculation Method for Non Domestic Buildings, available in *DesignBuilder*; as shown in Figure 106, fraction values are used considering the lamps and the equipment turned on until the night (19:00 or 20:00), while the occupation rate is variable with peak values in intervals 9:00–12:00 and 14:00–17:00. Then, all thermal zones have been modified simultaneously, by considering 5 scenarios, randomly generated; these have been applied to all three usage categories and to all kind of thermal zones. More in detail, scenarios II, III and IV consider the most likely period of work, as the holidays, according to the university calendar, have been excluded. Instead, the schedules have been varied both in term of hours per day than and for percentage of occupation /usage. Scenarios V and VI assume the building opened all days during the year, excluding the weekend. These differ for operating hours, continuous in scenario VI.

Figure 107a shows electricity and gas demand for all building uses. Considering the first scenario exclusively for offices in building model (I_off), in this case, electric energy for equipment increases up to 90%, cooling demand of around 11% and gas request of 4.4% respect to RB. Considering the overall energy demand, E_G becomes 406 kWh while E_{el} is around 206 kWh. This means that calibration indexes for natural gas gives very satisfying results, however, for electricity $ERR_{average\ year}$ becomes −18.7%, CV(RMSE) is 20.2% and MBE ≈−16.3%. Finally, the variation of schedules for a little part of conditioned area causes very inadequate results. To understand the implications of this modification on building level, scenario I in Figure 107 describes results of savings reaches −41% while ΔCg ≈−36%. Very close results are obtained in the other scenario for instance in the last one (VI) for which in term of primary energy demand (−40%) while ΔC_g ≈−32%.

Reference building			II scenario	III Scenario	IV Scenario	V Scenario	VI Scenario
Office_OCC_RB	Office_EQ_RB	Office_Lig_RB					
Through: 06 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For: Weekdays, Until: 09:00, 0, Until: 19:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 19:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 06 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For: Weekdays, Until: 09:00, 0, Until: 19:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 19:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 06 Jan, For: AllDays, Until: 24:00, 0, Through: 30 Apr, For: Weekdays, Until: 09:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 May, For: Weekdays, Until: 16:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 1 Aug, For: Weekdays, Until: 16:00, 0, Until: 20:00, 0.5, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 31 Oct, For: Weekdays, Until: 09:00, 0, Until: 15:00, 0.4, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 20:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 06 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For: Weekdays, Until: 07:00, 0, Until: 08:00, 0.25, Until: 09:00, 0.5, Until: 12:00, 1, Until: 14:00, 0.75, Until: 17:00, 1, Until: 18:00, 0.5, Until: 19:00, 0.25, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 07:00, 0, Until: 08:00, 0.25, Until: 09:00, 0.5, Until: 12:00, 1, Until: 14:00, 0.75, Until: 17:00, 1, Until: 18:00, 0.5, Until: 19:00, 0.25, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 06 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For: Weekdays, Until: 09:00, 0, Until: 12:00, 1, Until: 14:00, 0.75, Until: 17:00, 1, Until: 19:00, 0.75, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 12:00, 1, Until: 14:00, 0.75, Until: 17:00, 1, Until: 19:00, 0.75, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 06 Jan, For: AllDays, Until: 24:00, 0, Through: 1 Aug, For: Weekdays, Until: 09:00, 0, Until: 14:00, 1, Until: 18:00, 0.5, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 20 Aug, For: AllDays, Until: 24:00, 0, Through: 20 Dec, For: Weekdays, Until: 09:00, 0, Until: 14:00, 1, Until: 18:00, 0.5, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 24:00, 0;	Through: 31 Dec, For: AllDays, For: Weekdays, Until: 09:00, 0, Until: 12:00, 1, Until: 14:00, 0.5, Until: 17:00, 1, Until: 18:00, 0.5, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0;	Through: 31 Dec, For: Weekdays , Until: 09:00, 0, Until: 17:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0;



I scenario (UK's National Calculation Method)		
Office_OCC_I	Office_EQ_I	Office_Lig_I
Through: 31 Dec, For: Weekdays , Until: 07:00, 0, Until: 08:00, 0.25, Until: 09:00, 0.5, Until: 12:00, 1, Until: 14:00, 0.75, Until: 17:00, 1, Until: 18:00, 0.5, Until: 19:00, 0.25, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0;	Through: 31 Dec, For: Weekdays, Until: 07:00, 0.05394, Until: 20:00, 1, Until: 24:00, 0.05394, For: Weekends, Until: 24:00, 0.05394, For: Holidays, Until: 24:00, 0.05394, For: AllOtherDays, Until: 24:00, 0;	Through: 31 Dec, For: Weekdays, Until: 07:00, 0, Until: 19:00, 1, Until: 24:00, 0, For: AllOtherDays, Until: 24:00, 0;

Figure 106: Description of schedules for equipment, occupation, and lamps.

Figure 107b shows the points that represent the primary energy and the global cost each configuration. Obviously, this kind of analysis could be improved by adding more and more scenarios of simulation. However, the conclusion appears to be clear. There is an evident correlation between results produced by casual schedules. Conversely, the only point (red one) far from the linear pendency is the reference building. This indicates that there is not a correlation between the estimation of realistic post-retrofit performances and designing studies done starting to default schedules or profiles derived without considering the mean real attitude of occupants.

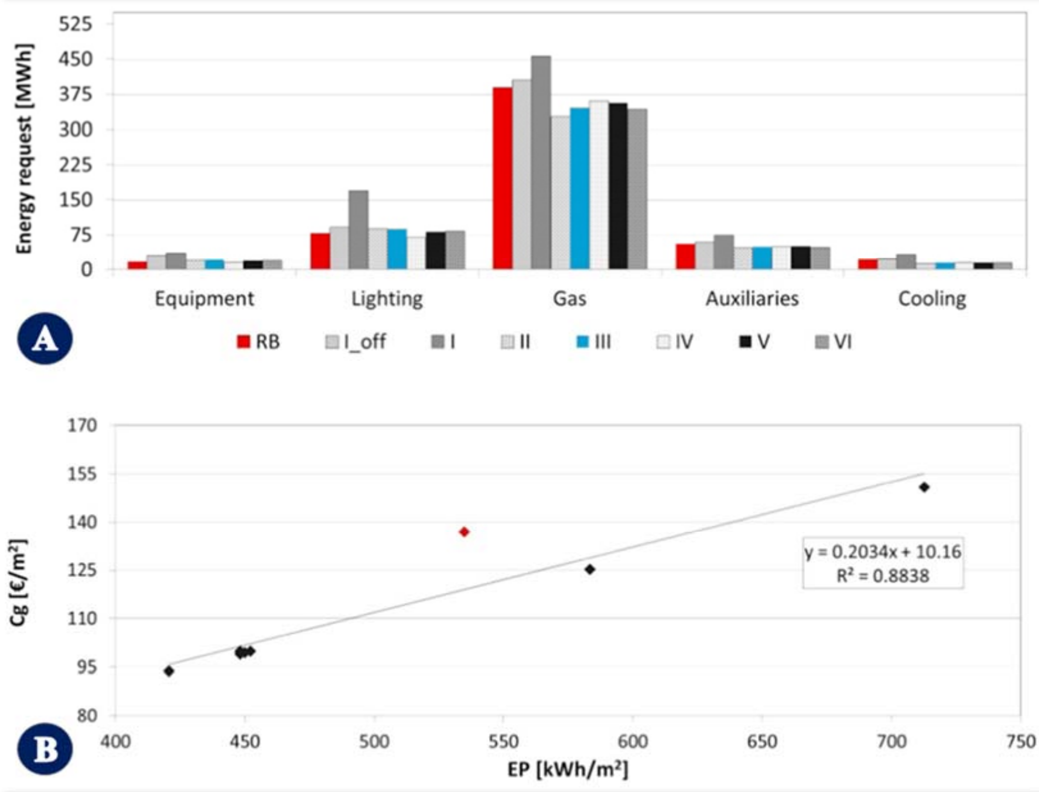


Figure 107: (a) affect of modelling assumptions regards occupant, equipment and lamps; (b) primary energy and global cos for refurbishment design.

5.4.2 Assumption of energy modelling: *II Edificio Polifunzionale*

Also for the second case study building, starting from the reference scenario (RB) discussed in the sub-section 5.2.2.2, a sensitivity analysis is presented in order to understand which is the error due to wrong characterization of the envelope or to assumptions about the behaviour of occupants.

More in detail, starting from the calibrated model, in which the measured value of thermal transmittance is equal to 0.415 W/m^2K, two different scenarios are tested, by varying the value of thermal transmittance of the most recurrent stratigraphy. For the first scenario (U1), the value of the transmittance calculated in according to ISO 9869 has been used, by knowing the materials and the structure of the wall. For the second scenario (U2), by supposing that the materials and the type of wall are unknown, the value of thermal transmittance that refers to the most recurring type of construction in the period of this building has been used; it is equal to 0.59 W/m^2 K [256].

For what concerns the occupant's behaviours, starting from adopted schedules, determined on the basis the available information and documents gathered during the audit phase and that allowed a good calibration of the energy model, ten different scenarios are tested. For all of these, the operating schedules of the heating and cooling systems of the reference building have been maintained. The first seven scenarios have been obtained by changing only the programs for occupation rate and operation of the equipment and lighting system. In the last three scenarios, all thermal zones have been modified simultaneously, and therefore, for some zones, also the value of internal loads has been changed. In particular, the first scenario (S1) has been obtained by considering the schedules of UK's National Calculation Method for a University building, available in DesignBuilder [66]. Always starting from the reference building case, the second, third and fourth scenarios have been created like respectively the medium-intensity-use scenario (S2), low-intensity-use scenario (S3), and the high-intensity-use scenario (S4), respectively. For the fifth (S5), sixth (S6) and seventh (S7) scenarios, the schedules have been randomly generated. Moreover, in the eighth scenario (S8), the schedules defined for the offices' reference building have been used for all thermal zones. Finally, for the last two scenarios, the default values available in DesignBuilder for office zones (S9) and for classrooms zones (S10) have been used, respectively.

In Table 38, the gas (E_G) and the primary energy for electricity (E_{el}) requests have been reported, as well as the equivalent carbon dioxide emissions (CO_2), the operating costs (CE) and the values of calibration indexes for natural gas (MBE_g and CV_g) and electricity (MBE_{el} and CV_{el}) for the reference building and all simulated scenarios applied to the baseline model.

These results suggest that inaccuracies for the envelope description produce very limited errors. About it, it should be noted that the variation on total energy primary request is -1.9% with U1 scenario and +1.5% for scenario U2. Also, the validation indexes are quite satisfactory, and the models could be considered validated. The only problem is the value of indexes for gas request in the U1 scenario.

Table 38: Effect of modelling assumption regarding occupation, equipment and lamps.

	E_G (MWh/y)	E_{el} (MWh/y)	CO_2 (t/y)	CE (€/y)	MBE_G (%)	CV_G (%)	MBE_{el} (%)	CV_{el} (%)
RB	1010	1000	584	166196	3.4	13	2.1	6.9
U1	977	994	575	163592	6.4	16	3.1	7.2
U2	1040	1000	590	168043	0.6	12	2.1	6.8
S1	990	1862	920	254564	5.2	15	-97	87
S2	1020	831	521	149212	2.0	12	21	20
S3	1220	508	430	127928	-17	27	58	53
S4	1040	1262	689	195243	0.4	11	-27	25
S5	1180	989	603	173464	13	21	6.1	11
S6	962	988	570	162041	7.8	18	3.8	12
S7	735	994	529	148578	30	44	3.2	12
S8	1120	1400	762	214570	-7.8	17	-43	40
S9	960	1708	854	236717	8.5	15	-79	71
S10	924	1037	582	164706	11	18	-1.7	12

Moreover, the results underline that a greater error could be made when the description of thermal zones does not consider a realistic profile of use. More in detail, when conventional profiles are used (S1), the primary energy need increases of +41% mainly for what concerns the electricity prevision; in this case, the exercise cost is higher (+53%) compared with RB and all calibration indexes are out of range. For the low-usage profile (S2), it can be noted that the reduction of equipment and lighting uses determine an increase of heating request, but the primary energy need is lower than RB (-14%), as well as the polluting emissions (-26%) and the exercise costs (-23%). Finally, when the thermal zones are not differentiated, and the same schedule is assigned indistinctly, the error is higher, with variation of +33% for S9 with increment of +42% of operational costs.

Then, a sensitivity analysis has been then performed by considering only the best refurbishment scenario (named "LEDC+BL+REG+PV" in section 5.3.2). More in detail, the previous indexes have been calculated by considering the different input data described in this section (assumption of energy modelling). Indeed, the aim is to underline the effect of the modelling assumptions for the description of thermal zones on economic profitability and energy saving evaluation. Figure 108 proposes simulation results where, for each scenario, the reference one is shown in Table 38. The red circular point is the best configuration for building model already proposed in Figure 105. It is evident that, by using simplified model, the refurbishment design can appear more or less profitable than the case with well-calibrated model.

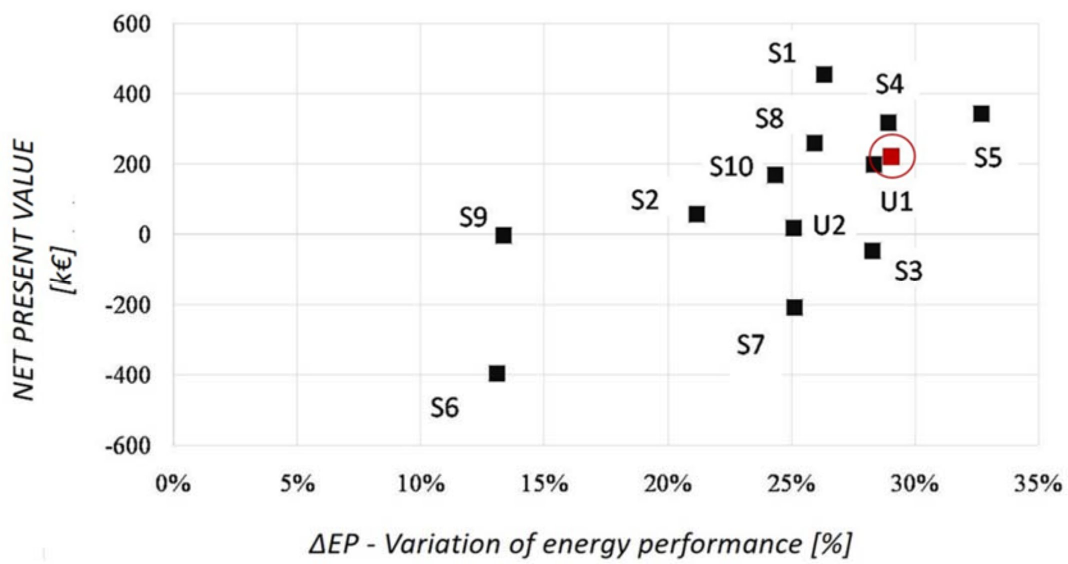


Figure 108: Effect of modelling assumption, simulation error using different scenarios.

More in details, the simulation scenario S1 determines the most profitable prevision since the energy saving reaches +26%, with discounted payback of 9 years and NPV equal to 454 k€.

Also, for scenarios S4 (ΔEP ≈ 28%, DPB ≈ 10 years and NPV ≈ 317 k€), S5 (ΔEP ≈ 28%, DPB ≈ 10 years and NPV ≈ 342 k€) and S8 (ΔEP ≈ 26%, DPB ≈ 12 years and NPV ≈ 259k€), the prevision of refurbishment results is more advantageous compared to the calibrated model. The scenario U1 is comparable with the real one, since the discounted payback is 13 years and NPV is around 197 k€. Conversely, in case of U2, a greater difference in the economic profitability is evident, with NPV of 18 k€ and discount payback of 19 years and energy saving equal to 25%.

Then, for all other scenarios, the refurbishment does not allow to obtain good economic results. Indeed, the NPV is negative and thus the discounted payback is higher than 20 years. A bad case is S7, which NPV ≈ -209 k€ and ΔEP ≈25%, while the worst one is S6 for the which NPV of -397 k€ and energy saving equal to 13%.

Globally, the results show that the occupant behaviour, more than approximation on the envelope, can distort the energy performance of the building system and the refurbishment design can appear more or less profitable. In this way, this part of work shows that an incorrect characterization of the envelope and even more the adoption of default schedules brings to results for the energy performance very far from real performance. Moreover, the adoption of simulation models is a good practice, but only if all variables are checked, monitored, and suitably evaluated as shown in the first part of work.

In general, the proposed investigation gives indications for the stakeholders involved in the design process to understand the uncertainty to use numerical modelling and the real environmental and economic impacts of adopting some energy efficiency technologies. At research level, it is important to point out that the sensitivity analysis on modelling assumptions has evidenced that there is a relation between results produced by casual schedules while there is not a correlation between the estimation of realistic post-retrofit performances and designing studies done starting to profiles derived without considering, during the diagnosis, a direct census of occupants' behaviours.

At the designer level, the outcomes of the case study allow to point out that, at least for educational buildings in medium cold climate, energy efficiency measures focused on the HVAC equipment and lighting system have the greatest potentiality in terms of energy saving and environmental benefits. Indeed, these allow always a good economic profitability and the improvement of the indoor thermal condition. Results could be usefully considered by designers because these allow to know the effect of traditional technologies and systems on tertiary building where heating requests are higher than cooling needs. Well-known technologies are combined for building envelope, by varying singularly and simultaneously, transparent components, type of insulation material and spectral characteristics of roof for commercially available products. Moreover, selected interventions for plants are adequate for this type of systems and can be implemented in many office/university building in south Italy, very often designed with the same approach, without any regulation devices and with old lamps without luminance or presence sensors.

Thus, the cost-energy curves could represent a pre-elaborated material, ready to be used for selecting the more suitable technologies for refurbishment design, when these four fundamental aspects are considered together: minimization of global cost, energy saving, reduction of polluting emissions and improvement of indoor comfort. Indeed, the position of energy optimum and cost-optimal points can be considered when no invasive measures must be promoted.

CONCLUSIONS

The research activity carried out during these years of PhD has led to the work presented in this Thesis entitled: “From energy refurbishment of existing buildings to Nearly Zero-Energy ones: set-up, experimental measures, performance gap and numerical modelling”.

Mitigating and adapting to climate change are key challenges of the 21st century. At the core of these challenges is the questions of energy – more precisely, our overall energy consumption and our dependence on fossil fuels. To succeed in limiting global warming, the world urgently needs to use energy efficiently while embracing clean energy sources to make things move, heat up and cool down. These aspects, fully investigated in the first chapter of the thesis, are the main motivation and the starting point of research activities on energy efficiency of the building sector, which represents today one of the most important contributors to the globally energy consumption and greenhouse gases emissions. Indeed, national, and international regulations on energy saving are undergoing to a progressive and radical transformation, due to the increasing needs of high-performance materials, technologies, design strategies and controls to optimize the energy performance of the whole building/HVAC system.

For this reason, the research activity carried out during the PhD, by means of numerical and experimental approach, has been aimed at the evaluations the energy performance of nearly zero energy buildings (as new construction energy target from 2020 onwards) during the operational phase. Moreover, the research activity has been focused on the optimization of the building/HVAC system, by means of the introduction of holistic methodological approach, that starting from the energy diagnosis allows to design the refurbishment of existing buildings.

The conclusions reported in the following, summarize the main aspects of the work carried out during the PhD years, according to the two research levels detailly described in the chapter 2: i) performance investigation on building energy performance in real operational mode; ii) methodological approach for the optimization of building/HVAC performance. It is clear that the two topics are strongly interconnected.

In particular, the monitoring campaigns that involved the BNZEB building has allowed to characterize its performance during the different seasons both in terms of envelope behaviour than in terms of energy balance at shorter time scale. This is one of the innovative aspects of the research activity, indeed the monitored energy balance based on daily or hourly time step is not available for other existing studies, because in general, research and regulation are focused on long-term energy balance (based on annual or monthly time step), without considering the energy exchanges at short time. However, to improve load matching and to reduce grid interaction and energy bills is important a balanced design. In general, the nZEBs design should maximize the self-consumptions, because, with the increment of buildings that exploit renewable sources, that are known as "prosumers", the management of the utility grid is becoming very complex being a continuous, bi-directional exchange of energy and information between buildings and grid.

Concerned the BNZEB envelope, thermal transmittance and thermal inertia are practically the most important factors that affect the envelope behaviour. The investigations' results show that the insulation level and the dynamic behaviour of selected solution for building envelope allow to reduce the cooling and heating demands and to minimize the overheating risk during the summer. In particular, the main conclusions for the case study building are:

- during the winter period, from the in-situ measurement of thermal transmittance results that, in general, the difference between the measured values and the calculated one is lower than 10% (measured value is equal to 0.19 W/m^2K for most of the walls analysed), confirming that the operational performance of building envelope are satisfactory and are adequate to those expected in the project phase;
- during the spring period, the experimental evaluation of decrement factor and the time shift of decrement factor (respectively equal to 0.02 and 7 h on average), show that the dynamic response of envelope seems adequate or reduce the overheating risk during the summer period assuming at the same time the optimal insulation level. Indeed, the values of surface temperature on inner side is almost constant near to 20°C for all considered days meanwhile the peak of sun air temperature varies between 45-49°C.

With reference to the building energy balance, during the winter period, when HVAC system is turned on in heating mode with a set point temperature of 20°C, the air conditioning system accounts for about 60-70% of the overall energy consumption of building. The energy balance at hourly time step shows that, with favourable external climatic conditions, a large amount of the energy requests can be satisfied by energy production from PV system. Indeed, in February, the 56% of total energy needs are covered by photovoltaic generation, but with a daily variation between 7% (rainy day) to 100% (sunny day). Then, in general, the storage system allows to maximize the self-consumption, by minimizing the impact of the surplus energy produced and not self-used. Of course, it is clear that, during the winter period, the electric renewable generation is not always enough to satisfy the energy need of the building and sometime the daily renewable energy used for covering the electric request cannot reach the 50%, due to le low availability of sun source. Meanwhile, as expected, during the summer period, the great part of energy consumption can be satisfied by renewable electric production thanks to the great availability of solar radiation, and this is true with all HVAC configurations tested during the PhD activity. Globally in the monitored summer period, the percentage of coverage consumption with in-situ generation ranges from 57% to 97% with a time correspondence variable between 50% to 90%.

During the spring season, that could be colder or hotter compared to the people expectations, thus it could be a critical period in term of indoor comfort, it is resulted that, when only the ventilation is turned on, it accounts within 20% to 40% of electricity needs, while, during the days when the system is settled up in cooling and ventilation mode, its energy needs varies from 40% to 70% of total electricity consumption of the dwelling. Concerning the energy balance, it results that, also due to the lower energy needs of the intermediate period, the ratio between the PV generation and the daily energy consumption varies from 70% to 250%, with a time correspondence that varies between 60% and 100%. The same happens during the autumn period, that could be also critical due to the not constantly availability of solar source, however the energy needs for ventilation results very low and it accounts for about 20% of the total request. Also in this case, from energy balance at hourly time step, it results that the ratio between PV generation and daily energy consumption is higher than 100% (thus, a net supply of energy toward close buildings happens), when there is availability of solar source.

In general, the results of energy balance underline that it is important the time interval with which the design and the real operational mode are evaluated. The goal of featuring design is to assure that the evaluation indexes introduced could be near the 100% not only during the summer but also to the intermediate season. This would assure that the positive yearly balance has not been achieved by oversizing the PV-system but with the optimal designing of building envelope, renewable active system, storage capacity and management strategy. Since the energy balance with daily or hourly time step is not available for other existing buildings, the presentation of some new and already used indexes to evaluate the impact of renewable production on short time step allows a discussion on the possible load matching and grid interaction; the positive effect of the electric storage is also considered. These are the main problems that designers will have to face in the near future when the nZEBs will be not only a research topic but a consolidated standard for building construction.

Moreover, the comparison between “unconditioned” and “conditioned” days (definitively, availability of the indoor microclimatic control) underlines a criticality of the new designing objectives. Considering the BNZEB, sometimes during the spring or summer periods, PV production can be also more double than consumption. Mainly in Mediterranean climate, when the designer tries to match the load and source for the summer period, the system configuration often ends up with excess generation in the intermediate period due to lower consumptions. The result is that the surplus renewable electricity needs to be curtailed to balance the system. This can be treated primarily as a technology problem during the design phase. It is needed an adequate energy storage to convert the excess at one time of day into necessary power system supply at another. However, it could be not enough, as in the case of BNZEB. This means that the featuring designers and researchers cannot focus merely only to the single building, but they should consider the design in a broader perspective of highly efficient smart grid. Especially smart energy distribution systems will be a suitable strategy to able to manage properly the increasing shares of renewables as well to install and charge single or shared battery powered devices when there is excess production. And finally, the growth of EVs (currently driving global battery demand) represents a huge potential source of storage and demand-side flexibility as well.

In general, the monitoring results demonstrate the effectiveness of BNZEB design choices and its control strategies; indeed, also concerning the indoor microclimate conditions inside the building, it results that - in most of cases - comfort conditions for occupants are guaranteed. The investigation results of springtime assessments might give indications of how blinds should be treated in nZEB design in hot climates to maximize the visual and thermal comfort. About this point, experimental data could help designers in the evaluation of the usefulness of mechanical ventilation with heat recovery and pre-treatment section based on EWHE, for reducing the discomfort during periods without active space heating or cooling. Indeed, by the monitoring campaigns performed during the summer and intermediate periods, also the following results have been identified:

- the importance of solar gains and the appropriate use of the shading system on overall building performance. In the BNZEB, the designed porch positively affects the reduction of solar gains during the spring but only if the shading system is active on west side, the heat pump can balance the cooling load. The interpretation of visual conditions resulted more difficult, but in general, by considering the thermal and visual aspects, for the installed shading devices it can be considered appropriate the following control strategy, in order to avoid the direct solar radiation into the room: the internal blind should remain closed on the south from 10:30 to 15:00 and the west external shielding must be activated starting from 14:00. In this way, it is possible to exploit natural lighting as much as possible and therefore to limit the use of artificial lighting but at the same time avoiding glare conditions for the occupants. Moreover, the optimization of both thermal and visual comfort requires the adoption of control strategy for the shades not based only on a static range of the outside solar radiation. In addtion, the shading of windows, with west exposure, seems fundamental to guarantee the fulfilment of the indoor comfort without the activation of HVAC system but also to help the active system to reach the set-point value when the size of the generation system is very low.
- concerning the investigations about the installed pre-treatment section, based on a EWHE, the continuous operation of its water pump could lead in a negative effect on indoor conditions in the long period, but a proper control for the water pump of the ground-to-water heat exchangers is recommended. Indeed, an

important result of the analysis during the autumn is that, although the HVAC system is settled in only ventilation mode, satisfactory comfort conditions for the occupants are guaranteed inside the building. The study shown the potential of the integration of an earth-water exchanger for pre-handling the ventilation air before its entering into the aeraulic heat pump. Indeed, the feasibility and potential of this kind of pre-handling system are not sufficiently verified in the literature, but the developed research shows that it could have a great contribution to achieve nZEB target and it could play a significant role to improve the comfort condition inside the building even more during the intermediate seasons. Indeed, the earth-water pre-treatment system allows to avoid that the external variations are reflected on the internal conditions due to its capability to bring the fresh air flow towards intermediate conditions, damping the external peaks. Indeed, from monitoring campaign performed during October 2019, it results that, thanks to the geothermal heat exchanger combined with the recirculation section of aeraulic heat pump, the air temperature introduced into the environment results always between 19°C and 24°C, also if the outdoor temperature change within the range from 10°C to 28°C.

- Based on experimental data, it is also demonstrated that the investigated system has sufficient potential to pre-cool the outdoor air in Mediterranean climate, and the positive effects are very significant under severe external summer conditions. Indeed, the results show that the pre-cooling geothermal system can reduce the temperature of outdoor ventilation air up to over 10°C if compared with the outdoor temperature. The maximum temperature difference, between inlet and outlet of the water-to-air heat exchanger, reached 10.7°C and 11.5 °C, when a packaged heat pump with thermodynamic heat recovery or a traditional high-efficient DX system are used, respectively. But it is recommended that the water pump of the earth-to-water heat exchanger will be controlled based on the real effective cooling potential. Indeed, this must be turned off when the outdoor air temperature is lower than the one of the ground pipes. In fact, when this condition occurs, the pre-treatment system goes to heat the incoming ventilation air instead to cool it, and this induces an increase of cooling load, with a negative effect on the energy consumption, of course. Therefore, the continuous operation of the water pump could lead in raising the overall cooling consumption of the present house in the long period, and then the control for the water pump of the ground-to-water heat exchangers is recommended.

Moreover, the simulations studies on BNZEB have also demonstrated the effectiveness of the design choices and implemented control strategies. The CFD analysis allowed to verify the conditions achieved inside the building and the effect of shading management on the indoor comfort conditions. Finally, CFD resulted an important method to predict the indoor conditions under different HVAC configurations and management of installed device during the year. More in particular, the dynamic thermal simulations have demonstrated the better performance of BNZEB proposed design compared to the existing building stock, and the replicability of proposed design solution in other cities with similar boundary conditions. Indeed, the comparisons show that the BNZEB has an energy requirement for summer air conditioning of 40% lower compared to buildings representative of the construction standard and 45% lower than the building stock. Moreover, the proposed design solution, according to the experiments performed in the city of Benevento, seems suitable for being successfully implemented in other cities with Mediterranean climate.

The conclusions above reported are referred on a particular case study (the building named BNZEB), however starting from them, some wider lessons could be learned. For example, the importance of evaluating the energy balance at smaller time scale is well-founded in any case where there is an in-situ generation from renewable sources. The elements of energy balance and their aid will obviously be different according to the specific weather characteristics, building type and end uses, but the importance of evaluating strategies aimed at maximizing self-consumption are always valid, also evaluating different climate contest, types of buildings and final uses. This even more in a perspective of district or city scale energy management. Indeed, in this perspective it is essential to know and analyse energy loads and energy availability at short time interval, in a view to sharing the resources.

On other side, it is important highlight that energy uses in buildings depends on a combination of good architecture and energy systems design and on effective operations and maintenance once the building is occupied. It should be understood that different climates and different building type probably require different designs and equipment, and that the performance and value of any component technology depends on the system in which it is embedded, and the control strategies must be adapted to the needs of each individual building and climatic context. However, the effectiveness of some devices and strategies above reported, such as the air pre-treatment section interacting with a geothermal system, the heat recovery integration, and the control of the shielding systems, as they have been found effective for a Mediterranean climate, they could also be well-funded in different climates. For example, in a warmer climate, the control of solar gains through the window will be even more important to guarantee the fulfilment of the indoor comfort supporting the active systems. On the other hand, in a colder climate, an appropriate combination of shielding systems control, and pre-treatment section could be adequate to satisfy the summer cooling needs, which is the new challenge must be faced in high performance buildings in northern European country where there are an increase of cooling needs and the risk on overheating. In general, to quantify the energy performance of tested devices in different climate conditions or identify the best combinations of solutions and control strategies, could be useful the use of dynamic simulation models in which all energy components are included in a model under expected operating conditions and based on operational information acquired from the real case study building, as has been performed in the evaluation of overall BNZEB performance in different Mediterranean cities.

Instead, concerning the optimization of building performance, a study on the management of HVAC system has been performed on BNZEB building, by changing the set point temperature value during the winter period. In general, the adaptive approach to thermal comfort can give a significant contributor in achieving low energy building operation, but the overall understanding of how translate the adaptive principles into design practices and concepts for operating building is still limited mainly with reference to the winter period. The results have shown that, although energy saving can be achieved by lowering set point with respect to that recommended one by Italian legislation, it is not always possible to guarantee comfort conditions inside the building. A notable conclusion is that the occupants are influenced by the knowledge of the test to which they are subjected and how the comfort has a significant psychological component. It is possible to conclude that surely the external temperature leads to the need to use a suitable set point to maintain comfortable internal conditions. Furthermore, the external conditions mainly in terms of solar radiation, influence the occupant perception. Indeed, the second week of the wide monitoring campaign is characterized by average value of solar radiation higher and the sky has been usually clearer compared to the first week, and probably this condition led the occupants to consider more comfortable the rooms despite the indoor temperatures are comparable. A role can be played also by the radiant effect. Indeed, the corresponding monitoring data show that objectively the air temperature trends of the two investigation periods are comparable but the occupants declared to be in comfort conditions only during the second one.

Concerning the optimization of HVAC system operations, the activity performed on the nZEB test school building of Ghent has shown that the improvement of the management of the heating system can furtherly reduce the overall energy demands and increase the comfortable time and thus the occupant thermal satisfaction. More in detail, the calibrated simulation results indicated that it is possible to obtain some alternative control strategies characterized both by an increase of the primary energy consumption and of the discomfort time, compared to the baseline scenario. On the other hand, it has been verified that also a contemporary decrease of primary energy demand for heating and ventilation and of discomfort time can be achieved. Obviously, also strategies that improve only one of these two conflicting targets (i.e., reduction of energy consumption and limiting of not comfortable time in the building) have been found. However, the results depend from the considered alternative control strategies, and the research demonstrates how the energy efficiency is sensitive to the control strategies and thus the role played by the management of the HVAC system becomes essential to have a high-performing building, really operating as efficiently as possible. Indeed, for the considered case study building, moving from a standard control logic based on the use of constant temperatures to control logics based on the real thermal load and external conditions, it could be possible obtain also a great variation of the comfortable time, that can vary from -23% to +3.4% and a reduction of the overall primary energy consumption also to 56%. At the same time, the performed investigation showed how continuous monitoring remains the main activity for bringing a suitable operation and, thus, to avoid criticalities, by adjusting, promptly, possible malfunctioning. Indeed only starting from in-field monitoring campaign, it is possible know how the system actually works and how the energy is used and then is fundamental as starting point to identify a possible design and proper improvement of energy performance of whole building system.

Finally, the methodological approach proposed in the last chapter for two cases study (existing buildings) is useful for the stakeholders for understanding the uncertainty to use numerical modelling and the real environmental and economic impacts of adopting some energy efficiency technologies on existing buildings. Results could be usefully considered by designers because these allow to know the effect of traditional technologies and systems on tertiary building, where heating requests are higher than cooling needs. On other side, a sensitivity analysis has shown how some modelling assumptions on envelope characterization, and even more the adoption of default schedules proposed by simulation tools, brings to results for the energy performance also very far from real performance and the refurbishment design can appear more or less profitable. Then, it is possible conclude that the modelling of the occupant behaviour has an impact deeper than some envelope design parameters. Thus, the adoption of simulation models is a good practice only if all variables are checked, monitored and suitably evaluated; then, also the importance to use a dual approach has been demonstrated.

In conclusion, the research activity developed during the PhD program, at UniBG and UniNA - with long time spent also at UniSannio and Uni Ghent - could be useful as guidelines for designers and stakeholders of the building sector, with reference to the next years, in which nZEB and NZEB will become the standard. The use of data from in-field monitoring campaign and post-occupancy evaluations, in a real context, could drive energy policies, smart grid and service designs, and thus such investigations allow useful guidelines for the building and system design, in areas with similar boundary conditions, and thus climates, living styles and constructions types. The information about the real operational performance are also useful for occupants that want to learn how these types of buildings are possible, what they look like and what are the cost implications, technologies used and user experience. Moreover, for industry organizations, these results can be useful for presenting their products, showing capabilities, tested in real operation. Moreover, some emerged limits can be useful for possible further improvements.

Moreover, the proposed approach, that combines experimental and numerical approach, could be implemented as methodologies for the evaluation of other innovative solutions for building and for the optimization of building envelope/HVAC system performance towards nZEB target, with reference to both new and existing buildings.

Further steps

Energy use in buildings depends on a combination of good architecture and energy systems design and on effective operations and maintenance once the building is occupied. It should also be understood that different climates and different building type probably require different designs and equipment, and that the performance and value of any component technology depends on the system in which it is embedded.

The conclusions reached in this study are obviously site-specific and case-study based, because they are strongly dependent of in-situ and experimental investigations, but these could be considered a starting point to achieving a wider impact on the research. Indeed, a deep and detail knowledge of systems behaviour on real operational mode is fundamental to really understand their actual performance. After, these knowledges could be used to identify wider general rules and may provide general guidelines about the systems performance also in different context and climate or considering different type of building and final uses by occupants, or with respect other possible parameters and factors which are not included in the PhD dissertation. The assessments performed in the dissertation could be extended through numerical studies in which first all energy components are well included in a model under expected operating conditions and then use the simulation environment to test the devices' performance, combination of them and control strategies in different context. This always starting from the lessons learned during the experimental investigations, because the main problem of numerical studies is that at the beginning it is not possibly know the gap between expectations and actual performance, and it is unknown the actual occupants' behaviour that is usually modelled as fixed time schedules, as well as it is not possible to known they judgment on building-system and reached indoor conditions.

In a further perspective, it could be also possible use the collected data, from experimental analysis, in the development of building energy prediction techniques that have been developed over the last years, or in the development of solutions for building energy benchmarking handle by data mining techniques combining building data characteristics, and which take sensitivity analysis as a feature selection problem, and building grouping as a clustering problem, being different from traditional statistical or simulation models.

Moreover, in the perspective of a bottom-up approach, focused on the buildings' specific context, if the model is accurate the method could also be used to identify improvement opportunities in energy efficiency, for building diagnostics, or used to establish a baseline for energy performance targets. Indeed, through the bottom-up methods benchmark a building against its own theoretical performance and could be invaluable for system diagnostics and performance improvement, and it could be used to establish new benchmarks for energy performance.

NOMENCLATURE

A_{hourly}	Mean of the measured data	%
A_{sol}/A_{sup}	Equivalent solar area	-
BL	Replacement of boiler	--
C_a	Annual costs	€ or €/m^2
C_c	Annual cost of greenhouse gas emissions	€ or €/m^2
C_g	Global cost referred to starting year	€ or €/m^2
CH	Replacement of chillers	--
C_I	Investment cost	€/unit or €/m^2
$CO_{2,eq}$	Carbon dioxide equivalent emissions	kg or t
c_p	specific het at constant pressure	KJ/kgK
CvRMSE	Coefficient of variation of the root mean squared error	%
ecW	Adoption of electrochromic glass	--
E_{el}	Electricity request	kW
E_G	Energy request for natural gas	kW
EP	Primary energy demand	kWh or kWh·m^{-2}
ep12	Insulation of wall and external ceiling with the expanded polystyrene	--
$EP_{gl,nren}$	Non-renewable primary energy need index	(kWh/m^{2}year)
$ERR_{average\ year}$	Mean error in the annual energy consumption, %	%
ERR_{hourly}	Error in the hourly consumption	%
ERR_{month}	Error in the monthly consumption, %	%
f	Decrement factor	-
$F_{load\ match}$	Load match index	%
f_{pv}	Present value factor	%
g	Solar factor	-
HDD	Heating Degree Days	°C
Ho	Horizontal overhang shades of 0.5 m	--
INS	Insufflations with cork for walls with cavity	--
LED	Installation of LED lamps	--
LEDC	Installation of LED lamps and control system	--
leW	Installation of low-emissive glazed windows	--
M	Annual maintenance operation and repair and service factor	%
$\dot{m}$	mass flowrate	kg/s
MBE	Mean Bias Error	%
M_s	surface mass	kg/m^2
n	Number of years considered for the cost	--
p	Lifespan of building elements and systems	--
pL	Projection Louvre of 0.5 m	--
PV	Replacement of photovoltaic system	--
PVin	PV generation / total daily request	%
Q_h	capacity of earth-water heat exchanger	W
r_ep12	Insulation of roof slab with the expanded polystyrene	--
r_ep12al	Insulation of roof slab and application of reflective paint	--
RB	Reference Building	--
R_d	Discount factor (or rate)	%
REC	Installation of the heat recovery system	--
REG	Installation of regulation systems	--
RenEl	Used PV generation / total daily request	%
R_i	Inflation rate	%
RMSE	Root mean square error	%
R_r	Real interest rate	%
rw12	Insulation of wall and external ceiling with rock wool	--
sW	Installation of selective glazed windows	--
t	thickness	m

T_air.back	temperature of air extracted from the rooms	°C
T_air.in	temperature on entry	°C
T_air.out	temperature on exit	°C
T_air.supply	temperature of air entered in the rooms	°C
$T_{a,i}$	Indoor air temperature	°C
T_{ext}	Outdoor recorded temperature	°C
TI	Application of thermal plaster	--
T_L	Adjusted formulation of time shift coefficient	hours
Tmin_in	temperature of water-glycol mixture out the earth-water exchanger	°C
Tmix_out	temperature of water-glycol mixture in the earth-water exchanger	°C
$T_{s,i}$	Internal surface temperature	°C
T_{set}	T set point	°C
$T_{sun-air}$	Outdoor sun-air temperature	°C
U	Thermal transmittance	W/m^2K
U_f	Thermal transmittance of window's frame	W/m^2K
U_g	Thermal transmittance of window's glass	W/m^2K
v	outdoor wind speed	m/s
V_f	Residual value at the end of the calculation period	€ or $€·m^{-2}$
WD	Replacement of windows	--
Y_{IE}	Periodic thermal transmittance	W/m^2K
ΔT_d	Temperature variation day-night	°C
Δt_f	Time shift of decrement factor	hours
Greek symbols		
κ	areal heat capacity	kJ/m^2 K
Δ	difference	-
ρ	density	(kg/m^3)
φ_{ext}	outdoor relative humidity	%
τ	Calculation period	number of years
Subscripts		
a	Referred to air	--
mean	Mean value	--
max	Maximum value	--
min	Minimum value	--
el	Referred to electricity	--
G	Referred to natural gas	--
Acronyms		
PV	Photovoltaic system	--
HVAC	Heating, Ventilation and Air Conditioning system	--
nZEB	Nearly Zero-Energy Building	--
DHW	Domestic hot water	--
EWHE	Earth to water heat exchanger	--

LIST OF PAPERS

In the following section, the list of the scientific papers written within my research group, during the three-years PhD School.

[I] L. Bellia, M. Borrelli, R.F. De Masi, D. Ruggiero, G.P. Vanoli, University building: Energy diagnosis and refurbishment design with cost-optimal approach. Discussion about the effect of numerical modelling assumptions. Journal of Building Engineering, 2018, 18, 1-18.

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[III] F. Ascione, M. Borrelli, R.F. De Masi, F. de Rossi, G.P. Vanoli, Energy refurbishment of a University building in cold Italian backcountry. Part 2: Sensitivity studies and optimization. Energy Procedia, 2019, 159, 10-15.

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[VI] F. Ascione, M. Borrelli, R.F. De Masi, G.P. Vanoli, Hourly operational assessment of HVAC system in Mediterranean Nearly Zero-Energy Buildings: Experimental evaluation of the potential of ground cooling of ventilation air. Renewable Energy, 2020, 155, 950-968.

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[IX] M. Borrelli, B. Merema, F. Ascione, R.F. De Masi, G.P. Vanoli, H. Breesch. Evaluation and optimization of the performance of the heating system in a nZEB educational building by monitoring and simulation. Energy and Building Journal, 2021, 231, 110616.

**All authors, including the candidate, have contributed equally to all stages of each above reported articles: definition of aims, designed the experiments and/or simulations, performed the experiments and/or simulations, analysed the data and results, and finally wrote the papers. The candidate Martina Borrelli has collected all the results and research purposes in this monography. The published material (list of papers) is cited appropriately in the thesis.*

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