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Energy Efficiency and Climate-Resilient Strategies towards Zero-Emission Buildings

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ABSTRACT

The purpose of this thesis is to investigate the application of energy efficiency and climate resilient strategies on an existing building in Turin, taken as a case study, within a wider renovation project managed by AI Studio, where I conducted my thesis work. The aim is to assess their influence on building energy consumption and their impact in the long-term, taking in to account the challenges related to climate change and the possible implications for energy performance.

The method of investigation used in this analysis follows an iterative approach, whereby the model is improved upon time after time in order to achieve the best possible combination of solutions. The study is based on dynamic energy simulations, conducted using the IESve software, to assess building's energy consumption under different weather scenarios. Starting from the basic building model, three climate conditions referring to the years 2020, 2050 and 2080 were simulated using the relevant weather files. After obtaining the results of the baseline model, targeted modifications were made to optimize building's energy performance, starting with the envelope enhancement. Subsequently, strategies such as the cool roof and the ventilative cooling were integrated in order to reduce energy consumption in the long term and improve the building's resilience in relation to expected rise in temperatures.

Once energy consumption results were obtained for the improved model, a detailed analysis of the primary energy usage was carried out by categorizing energy types based on their end uses, comparing the values achieved with those of the building's starting condition. This comparison made it possible to assess the proportion of the building's energy demand that could be covered by renewable energy sources, and to examinate possible solutions to increase this proportion.

In the end, results show that although the need for cooling increases over time, it is maintained low thanks to the strategies applied in this study; in particular, the integration of automated shading devices and the use of ventilative cooling proves to be fundamental in limiting the increase of energy consumption. In spite of this, the overall energy use values remain very high due mainly to the lighting contribution.

These outcomes suggest that, over the next 50 years, the application of climate-resilient strategies is able to contribute significantly to reducing the building’s energy consumption and that an integrated design that goes hand with energy analysis will become increasingly essential for the achievement of Zero Emission Buildings.

Overall, this thesis provides valuable insights for professional practice by offering practical recommendations on integrating energy-efficient and climate-resilient strategies, thus contributing to the advancement of sustainable building design and enhancing the industry's ability to address the challenges of climate change.

1. INTRODUCTION

Over the last few decades, climate change has had substantial impacts on urban environments and built structures. Rising average temperatures, more extreme weather events and seasonal variability have intensified the energy needs of buildings, highlighting a growing demand for more sustainable and resilient solutions. The construction sector, which accounts for a significant percentage of global energy consumption, must be designed and adapted to reduce consumption, both to mitigate environmental impacts and to meet the challenges of climate change.

Energy consumption in buildings is strongly influenced by climate change: rising global temperatures have increased the demand for cooling, while extreme phenomena such as heat waves and colder winters put a strain on heating and air conditioning systems. In addition, increasing urbanization and the deterioration of existing infrastructure make it even more difficult to contain environmental impacts and reduce energy consumption, creating pressure on energy resources and increasing greenhouse gas emissions.

The aim of this study is to analyze the relationship between climate change and energy consumption in buildings, with a focus on energy-efficient and climate-resilient solutions that can contribute to a reduction in energy demand while ensuring living comfort. The impact of climate change on energy consumption and the adaptation strategies that different types of buildings can adopt to become more energy efficient will be explored.

In order to answer the above questions, the research is based on dynamic energy simulation models, comparing different climate scenarios: current, medium-term and long-term. The analysis of energy consumption data leads to an assessment of the impact that the application of these strategies has on the building's energy performance.

In this first chapter of the thesis, an in-depth overview of climate change issues and their impact on the building sector is provided, with a focus on the EPBD Recast 2024, which represents a key step towards energy efficiency in buildings in the European Union.

The following three chapters introduce the building taken as a case study, which is part of a wider renovation project (managed by AI Studio), an explanation of the investigation method followed in the work and an introduction to the IESve software, used to carry out simulations, with an in-depth look at the generation of the climate files used to analyze future scenarios. Then, Chapter 6 provides a detailed description of the energy modelling and simulations carried out with the different variants of the baseline building. Finally, in the last part of the thesis, discussion and comparison of the outputs of different simulations and the main results emerging from the work are reported in order to highlight, in the last section, the answers arrived at through this study.

This study aims to contribute to the understanding of the dynamics between climate change and energy consumption in buildings, providing practical and theorical solutions to improve energy efficiency and promote building sustainability. The work offers useful insights for professionals to promote the design of more resilient and environmentally friendly buildings.

1.1. Climate change

Nowadays, it has become evident a people's awareness about environmental themes and climatic change. In fact, the most important challenge per human being today regards the global warming phenomena which is leading to irreversible global warming, which will create dangerous effects for human life.

The rate of global warming is reported to be rapidly increasing, with global temperature in 2020 over 1°C above pre-industrial levels and the last years being the warmest on record.

European Environmental Agency research has highlighted that the mean global temperature has increased of about 0.8 °C in the last 150 years and every decade it is recorded the warmest weather ever and this is worrying fact for the human being.

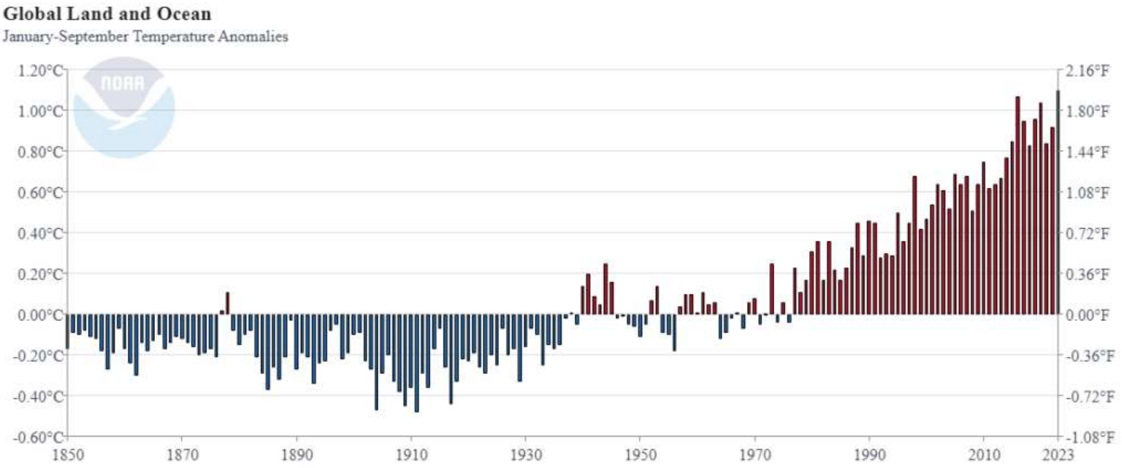


Figure 1 Climate Monitoring Data, 2021 – National Centers for Environmental Information, National Oceanic and Atmosphere Administration of USA

Many scientific communities' studies show that humans and their activities are responsible for all these changes from the second half of the XX century.

Moreover, the increasing of global population is strictly connected to the increased demand for food, wood and energy: this means more land and water used for agriculture, more industrial production and so a higher GHG emissions rate.

The greenhouse effect fundamentally is an essential and natural phenomena required for having life on Earth. The problem comes when the production of GHGs rises exponentially, due to human activities: this overproduction of gases lets the sunrays enter in the atmosphere and traps them, causing global warming.

So, the main causes of this phenomena are:

- Fossil fuel combustion that produces CO_2 and N_2O;
- Deforestation, because of the decreasing number of trees, it is reduced also their role of absorbing the CO_2; moreover, when they are cut, they released all the CO_2 stored, increasing the greenhouse effects;
- Intensive farming: the digestion of sheep and cows produces methane.
- Fluorinated gases inside some products used by humans

Effects of this rising of temperatures are now tangible and scientifically recognized: natural climate-change related disasters such as droughts, extreme rainfall, wildfires and hurricanes are becoming more severe and frequent, reportedly today more than a disaster a week on average, with increasing risks striking tropical regions above all. It is estimated that the worldwide economic losses from natural disasters could reach 10% of gross domestic product by 2100 in the United States alone.

Moreover, the indirect costs in terms of human losses and endangering of animal and plant species are by far greater than the economic costs. One of the best-known risks is sea level rise due to the melting of polar glaciers that is estimated at about 30 cm by 2050 and, in the worst scenario, up to 2m by the end of the century. This means that, in this scenario, not only one billion people living in lands less than 10 m above current sea level are in danger, but also that the ice-cap melt could cause major changes in the oceanic streams, further increasing the ecosystem disorders and the pattern of severe weather conditions.

To avoid catastrophic economic, social and environmental consequences, climate scientists advise that the temperature rise must be limited to 1.5°C, which implies a remaining carbon budget of less than 10 more years of emissions at their current level, about 420 Gt of CO_2.

In case population won't take any actions to contrast these effects, the global temperature will increase, causing irreversible changes with dangerous consequences for future human life on Earth.

Role of construction industry

Construction sector is one of the most relevant for the economy of each Nation in the world thanks to the big supply chain, but also the sector responsible for the highest carbon dioxide emissions and a high energy consumption.

In fact, the building sector contributes significantly to global climate change, accounting for about 21% of global greenhouse gas emissions. In 2022, buildings were responsible for 34% global energy demand and 37% of energy and process-related carbon dioxide emissions, with 10 Gt of CO_2 emitted by buildings operations and material production: taking into account:

- Direct emissions: emitted by material production processes
- Indirect emissions: derived from heating and electric power generation

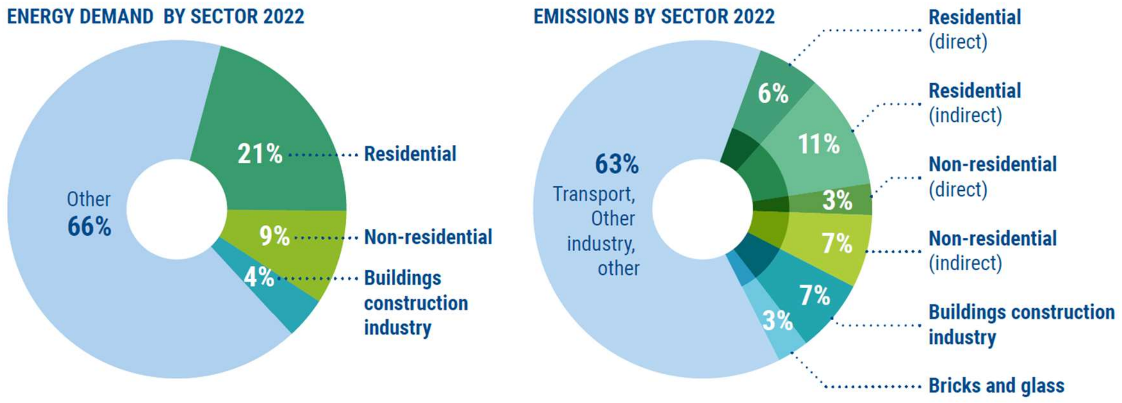


Figure 2 Buildings and construction's share of global energy and energy-related CO_2 emissions, 2022 - Source: Global status report for buildings and constructions 2023

Regarding direct emissions, the only concrete production is responsible for 9% of total greenhouse gas emissions in the world.

Actually, despite common belief, concrete can be considered more sustainable per kilo compared to other construction materials (such as steel, glass, timber and brick), basing the evaluation on its embodied energy.

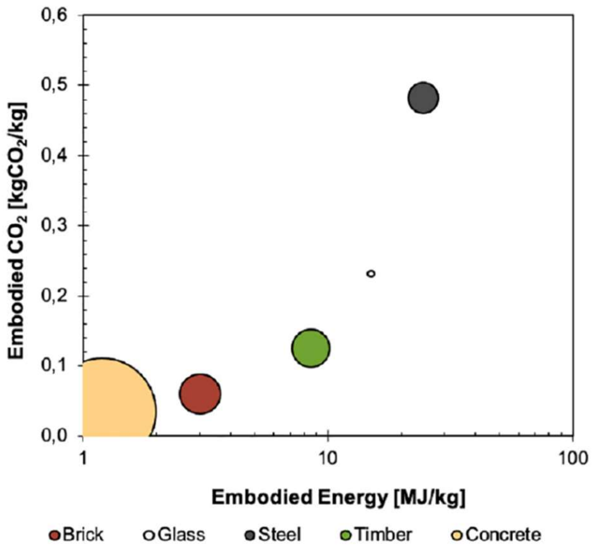


Figure 3 U.S. Geological Survey, Mineral Commodity Summaries 2020, U.S. Department of Interior, 2020

However, its overall environmental impact is very high, due to its huge volume of use, estimated at over 10 billion cubic meters per year worldwide.

To reduce the CO_2 impact of this material, the process of its production should be implemented with the use of renewable energy, avoiding fossil fuel combustion.

Over the past few years, several innovative technologies have been developed that aim to reduce the environmental impact of this production process. One of the most promising solutions is the Carbon Capture, Utilization and Storage (CCUS) technology, which use captured CO_2 in a feedstock mix for producing value-added materials and chemicals for construction.

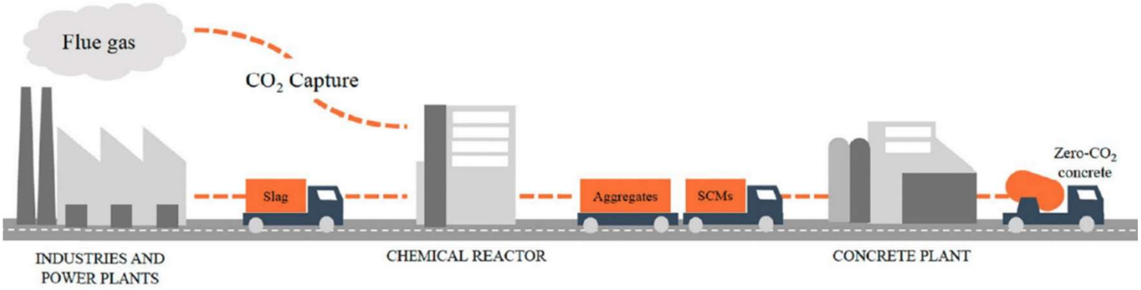


Figure 4 CCUS Process – Source: Pathways towards sustainable concrete (ELSEVIER)

On the other hand, with regard to indirect emissions, the energy consumption for space cooling has more than tripled since 1990, leading to increased pressure on electricity grids, higher GHG emissions and the exacerbation of urban heat islands.

A significant share of global population struggles with limited access to affordable and sustainable cooling, exacerbating risks such as heat stress, reduced thermal comfort, decreased labor productivity, and negative health impacts. The growing demand for cooling is primarily driven by evolving thermal comfort expectations, especially in countries here heat exposure and maladapted buildings are resulting in conditions where cooling is being sought.

Since 2000 energy demand for space cooling has grown at an average rate of four per cent per year, doubling the rate for water heating and in 2022, the number of residential cooling units in operation touched over 1.5 billion, a threefold increase since 2000.

This rise in energy consumption for space cooling leads to peak electricity demand, especially during hot days, increasing the risk of power outages. Addressing this challenge, requires a rapid shift to best-practice adaptive designs and the use of nature-based solutions with the adoption of high-performance cooling products that are affordable and accessible in regions with rapidly growing cooling needs, such as India and Sub-Saharan Africa.

Without this shift, electricity demand for space cooling is estimated to rise by up to 40 per cent globally by 2030.

So, in a scenario where the human population on the planet is expected to grow exponentially, reaching 9.7 billion in 2050, less developed regions will be characterized by a strong rate of urbanization, rising from 50% to 65% over the next three decades. Therefore, the construction industry will be called to respond to two apparently incompatible human needs: to preserve the environment and to support the growth of population by providing housing and infrastructures.

Responses to climate change

In this potentially dangerous scenario, there are two components which are fundamental to take into account in building sector, in order to counteract climate change:

a. Political choices that can address the market toward a green transition
b. Sustainability certificates for new construction and renovations, such as BREEAM, LEED, Passivhaus, Green Star.

a. Political choices

The first fundamental aspect of this transition is the role of governments, which are the only ones who have the power to lead people toward rapid and immediate change.

A significant step forward has been represented by the Agenda 2030 for Sustainable Developments: a global action plan adopted in September 2015 by 193 countries members of United Nations. The focus of this document is the “Sustainable Development Goals”, 17 targets related to different themes in the environment, social and economic sectors. The aim of this action plan is to promote sustainable development at global level by 2030, addressing worldwide challenges such as poverty, inequality, climate change and environmental protection.

In the image below, the 17 goals are presented.

Figure 5 Development Goals by Agenda 2030

All the 193 members of the United Nation are trying, year by year, to create political measures to get the goals, with the possibility of presenting a voluntary annual national report on the goal progresses. It therefore follows that this growing interest in sustainability issues allows Nations to direct their measures toward solutions that drive the market into a green transition.

A positive effect of the 2030 Agenda can be seen in the dissemination of building energy codes worldwide: in fact, taking a look at the global situation, increasingly more countries are adopting building codes in order to regulate construction and imposing high performance standard.

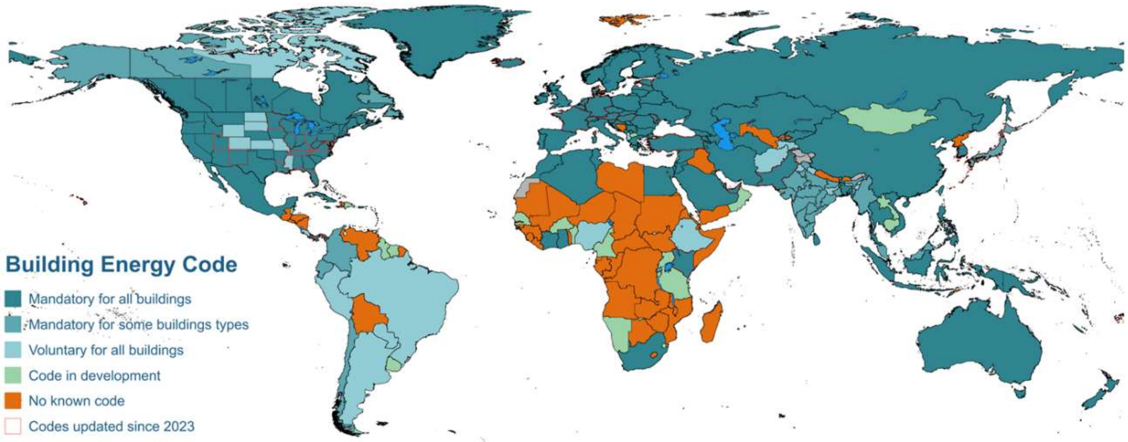


Figure 6 World plan about diffusion of green certifications - Source: Global status report for buildings and constructions 2023

As of 2023, there are now 81 and 77 national buildings adopted codes for the residential and non-residential buildings respectively, of which 80 per cent are mandatory. Twenty of these codes have been updated and adopted since 2021, and 17 adopted codes developed or revised in 2023 alone.

Another significant step in the role of governments in the green transition is the Energy Performance of Buildings Directive (EPBD). This European legislation aims to improve the energy efficiency of buildings by reducing their environmental impact through requirements for design, construction and operation. The EPBD also promotes the renovation of existing buildings by encouraging solutions that favor the use of renewable energy and the reduction of consumption. In the following Subchapter 1.2, the aspects and objectives of this specific directive will be analyzed in detail.

b. Sustainability certificates

Green certifications represent the efficiency of a building, but they can also be a means through which owners and investors distinguish their structure on the market. They are mainly focused on nearly zero emissions parameters, with a particular attention on energy consumption.

They promote sustainable building practices which have positive impacts on different aspects: they reduce the environmental impact of buildings, improve the quality of life and respond to the increasing demands of energy efficiency and social responsibilities.

The most important ones are:

- *BREEAM* (Building Establishment Environmental Assessment Method): environmental sustainability assessment methodology, developed in 1988 by the Building Research Establishment (BRE);
- *LEED* (Leadership in Energy and Environmental Design): the most widely used green building rating system, developed by the U.S. Green Building Council (USGBC) in 1993;
- *Passivhaus*: a certification for building, components and professionals developed in 1991 by a group of German researchers;
- *Green Star*: a certification rating system developed by the Green Building Council of Australia in 2003;

1.2. EPBD Recast

An important role in the decarbonization process of the building sector is played by the European Union, which has always been focused on implementing regulations that could bring about a significant change in this industry. One of the most important steps in this field is the issuing of the Energy Performance of Building Directive.

The EPBD Directive was born in the first 2000 as an answer to the increasing worries related to climate change and for the high energy consumption in the building sector, which in Europe represents almost 40% of the entire energy consumption and more than one third the GHG emissions. The first version of the Directive, the 2002/91/CE, had the aim of improving buildings energy efficiency in the EU, introducing the first standards of building energy efficiency, representing a starting point in the EU strategy of reducing the environmental impact of the building stock.

The growing awareness of issues related to climate change and the importance of reducing Greenhouse gasses emissions have led the EU to review and update this normative. Over the course of the years, the directive has been revised several times to meet the emerging challenges and guarantee that buildings contribute in a significant way to the climatic goals of the EU. In 2010 the Directive has been updated with the 2010/31/EU, which introduced the concept of Nearly Zero Energy Building (NZEB), defining more ambitious standard per new constructions.

The Directive stated that a Nearly Zero Energy Building is a building that has a very high energy performance, meaning that the amount of energy required for its operation is extremely low. The little energy that is needed should come primarily from renewable sources, preferably generated on-site or nearby.

The obligation of building NZEB building for the public sector within 2018 and for all the new building by 2021 gave a fundamental contribution to promoting the use of technologies and materials which are sustainable and renewable sources.

In 2018 the Directive has been updated again, this time to encourage the adoption of smart building and to promote a higher efficiency of the consumptions; the latest version, the EPBD Recast 2024, published in the official journal of the EU the 8th of May and entered into force the 28th of May 2024, comes about in a context of growing political ambition and of the European Green Deal implementation. This new approach is not only aimed at guaranteeing more efficient buildings from the energetic point of view, but it also wants to promote the transition towards an energetic sustainable system, in line with the objectives of climatic neutrality of the EU by 2050. In this framework the EPBD Directive represents a fundamental tool to guide member States to the adoption of practical and measurable actions, underlining the increasing commitment for long-term sustainability in which the energy efficiency of buildings plays a crucial role.

Main objectives of the directive

The EPBD Recast 2024 Directive aims to achieve several key objectives, designed to improve energy efficiency in Europe and reduce CO_2 emissions, leading to a transformation of building sector in a sustainable way, with benefits not just in environmental terms, but also in relation to economic and social aspects. Below the main objectives are listed:

a. Reduction of energy consumption and CO_2 emissions of buildings

One of the main goals of the Directive is the minimization of total buildings energy consumption through the implementation of higher energy performance minimum standards and requirements of requalification for existing buildings. In fact, the directive aims to give a contribution in the reduction of GHG emissions, due to the fact that most of them come from building sector, in line with the European goals of decarbonization.

b. Promoting the use of renewable energy

The EPBD Recast 2024 encourages also the integration of renewable energy in the building for new construction and renovation. The Directive gives specific incentives for the use of technologies such as solar panels, heat pumps and storage systems, with the aim of making economically advantageous the transition towards clean energy.

c. Promoting energy requalification of building stock

Moreover, the Directive promotes the renovation of existing buildings, encouraging energy requalification interventions. This is particularly relevant for the huge European building stock, which is often characterized by poor energy performance, which doesn’t respect the latest energy standards. At this purpose, the directive requires the establishment of funding mechanisms to facilitate citizens and companies in the regulatory adaptation path.

d. Reducing energy poverty

With around 35 million European citizens who live in energy poverty conditions, the Directive established measures to make renovations more accessible, with the aim of decreasing bills up to 30% for most vulnerable families. These interventions, also designed to increase the living comfort, should shoot down building energy consumption, improving at the same time the quality of life and promoting greater social equity.

e. Promoting smart buildings

The EPBD Recast 2024 introduces the Smart Readiness Indicator (SRI) which aims at stimulating the adoption of smart technologies in at least 30% of buildings within 2030. This indicator will measure the building capacity of monitoring, optimizing and managing efficiently its own energy consumption, adapting itself to occupants needs and interacting with the power grid. The Directive also includes the automation and control systems, which can potentially decrease building energy consumption up to 20%. This objective aims to make buildings more resilient, efficient and able to respond to future challenges.

Through these objectives, the EPBD Recast 2024 Directive intends to provide a clear and coherent regulatory framework which can lead member States through the building sector decarbonization within the 2050.

In summary the EPBD Recast 2024 plays a key role in the transition to a greener and more sustainable EU.

Principal innovations

The EPBD Recast 2024 represents a fundamental revision of the European directive regarding building energy efficiency, with the aim of reducing CO_2 emissions of the building sector and speed up the transition toward a more sustainable building stock. It is essential to underline which are the main innovations introduced in the Directive, with special attention to minimum standards of energy performance, requirements for existing building renovation and incentives for the use of renewable energy.

- Minimum standards of energy performance

One of the most relevant aspects of the EPBD Recast 2024 regards the strengthening of minimum standards of energy performance. The Directive establishes stricter limits in terms of building energy efficiency, requiring that all the buildings (residential and not) achieve a minimum energy class within certain deadlines. Through the implementation of these higher minimum standards, the directive aims to guarantee that all new buildings are designed to be at zero emissions within 2030, while existing buildings must achieve a minimum energy class within certain deadlines. Regarding existing residential buildings, objectives are particularly ambitious cause the intent is to lead most of them to the energy class E by 2030, and class D by 2033.

In particular, the objective to improve the energy efficiency of existing buildings is central. It is estimated that about 75% of EU buildings don't satisfy the minimum energy requirements, and that the building sector is responsible for more than 40% of the total energy consumption and around one third of CO_2 total emissions in Europe. In order to reduce the environmental impact, the Directive aims to decarbonize the construction sector through the imposition of stricter energy limits. These changes will not apply just to new buildings but also to existing ones which need energy renovation.

- Requirements for existing building renovation

The EPBD Recast 2024 underlines the need for renovation of the existing building stock to reduce the total energy consumption. at this purpose, the Directive establishes objectives of energy requalification, mostly regarding buildings with low energy efficiency, in order to guarantee that they will achieve progressively higher standards. Numerically speaking, it aims to double the energy requalification rate in the EU, going from the current 1% to an ambitious 2% a year by 2030. It is estimated that this energy requalification can decrease existing building energy consumption to 60% and reduce the CO_2 emissions of building sector of over 150 million tons each year by 2030.

However, it should be specified that the energy refurbishment previously mentioned doesn't regard just the thermal insulation of buildings, but it concerns also the update on HVAC systems and replacement of outdated systems with low emissions technologies. In particular, energy requalification should include the installation of renewable energies such as solar panels or heat pumps, in order to make buildings not just more efficient but also less dependent on traditional energy sources.

Concerning renewable energy, the goal is to cover at least 49% of building energy demand by 2030, with the objective of achieve the 100% for fall the new constructions within the 2050. The measures envisage include mandatory installation of Photovoltaic System over commercial and public buildings by 2027 and over all the new residential buildings by 2030. This integration of renewable energy sources in the buildings contributes to the diversification of the energy sources and to the reduction of the dependency on fossil fuels.

Implementation tools

Funding mechanisms

One of the biggest challenges related to this Directive is the economic accessibility of renovation interventions. In fact, the EU knows that without appropriate financial support, many owners may not be able to meet the initial costs of energy upgrading interventions. For this reason, it requires the establishment of funding mechanisms and incentives, such as European funds and tax credits, to support citizens and companies in the regulatory adaptation path.

From EPBD Recast 2024 it is possible to identify 3 different types of funding mechanisms, at different levels. They are:

a. EU funds

European funds, like the European Regional Development Fund (ERDF) and the Just Transition Fund (JTF) are intended to finance energy renovation projects and environmental performance improvements of buildings. These funds are accessible from member States to support national and local initiatives, encouraging the use of green technologies and the reduction of emissions. Moreover, the NextGenerationEU gives economical resources to sustain the post-pandemic recovery, paying special attention to the ecological transition. All these funds aim to reduce economic disparities and to promote energy transformation in the most disadvantaged regions.

b. National funding mechanisms

Besides European funds, many members of EU establish national funding mechanisms in order to incentive energy requalification at local level, with the aim of achieving ambitious objectives of decarbonization and improvement of energy efficiency.

All these programs include:

- Bonus and specific facilitations for energy efficiency
- Direct subsidies to vulnerable households and businesses
- Training program for building sector professionals, with the aim of increase competences regards energy technologies and sustainable construction techniques

These funding mechanisms are thought to guarantee that the passage towards a low-emissions building sector will be achievable for all the social groups, boosting the inclusiveness of the process and lowering inequalities regard the access to benefits of the energy transition. Some of the most important initiatives are the Superbonus 110% (Italy), the MaPrimeRénov (France) and the BEG Bundesförderung für effiziente Gebäude (Germany).

c. Local funding mechanisms

At local level, regional and municipal authorities are fundamental for the financing and the actuation of these energy renovations policies. Many regions and European cities have developed specific initiatives to incentivize energy efficiency and building infrastructure improvement, creating a financing framework for citizens, companies and local institutions. Regarding this type of programs, in Spain many cities have introduced the Municipal Green Energy Programs to finance energy interventions on public and residential buildings. Moreover, Scotland, with the program Low Carbon Economy, promotes the energy efficiency at municipal level, allowing local authorities to access to the funds. These initiatives are particularly crucial in urban contexts, where the adoption of sustainable solutions can significantly reduce carbon emissions, improving the quality of life, also with a positive impact on people’s health and the environment.

Energy performance monitoring

The energy performance monitoring is an essential element for the success of the EPBD Recast 2024 Directive, since it allows to evaluate in a precise manner buildings energy efficiency and the effectiveness of the renovation interventions. In fact, the Directive underlines the importance of monitoring, not just as a verification tool, but also as an incentive for energy management which is aware and sustainable.

The tracking of energy performance uses a series of systems and technologies which enables a detailed evaluation of building energy consumption. Among the most common technologies used, there are:

- Smart meters: meters able to register in real time power, gas and water consumption, giving detailed data which allows people to understand the energy behavior of the building. These devices can identify also potential inefficiencies and energy losses, offering a database to optimize the consumptions;
- Building Management Systems (BMS): integrated management platforms which enable monitoring and control of the different energy systems of the building (heating, cooling, ventilation and lighting). By the BMS it is possible to optimize the energy use, lowering consumption based on real needs and adjusting performance of various systems in order to maximize efficiency;
- IoT sensors: they allow to collect data regarding several environmental parameters (as temperature, humidity and quality of air) and to monitor in real time the energy performance. The collection and analysis of these data permit to realize predictive models, which are very useful to improve building energy management.

Implication for various stakeholders

The EPBD Recast 2024 implementation will have significant implications for different groups of stakeholders involved in the building sector and in the energetic transition. New laws impact both professionals (as builders and renovators) and owners and tenants of buildings, but also in society in general.

a. Impacts on builders

The introduction of minimum standard of energy performance and the renovation obligation for existing building means operational and strategic changes for construction companies. Builders and renovators will be called upon to adopt new technologies, respect energy efficiency parameters and invest in specialized skills.

On a practical level, the main consequences are listed below:

- Updating of professional skills: the directive requires an in-depth knowledge of green technologies (as the use of materials at high energy efficiency, thermal insulation and mechanical ventilation systems). Therefore, companies are forced to invest in training to update the staff and align themselves to new standards;
- Construction costs rise: the adoption of advanced materials and technologies will undoubtedly increase construction costs, affecting profit margins. However, the availability of financial incentives and the greater demand for efficient building could offset some of the costs;
- Competitiveness: companies which quickly invest in sustainable technologies and training can obtain a competitive advantage on the market, attracting customers and projects interested in sustainability;
- Resources management: builders and renovators will have to coordinate more sustainable resources management, limiting waste and implementing an efficient design.

b. Impacts on owners and tenants

For owners and tenants of buildings, the EPBD Recast 2024 represents a challenge but also an opportunity for improving the living comfort, reducing energy bills and enhancing the property. However, new regulations require a significant change in the way buildings are lived and maintained.

Practically speaking, the main consequences will be:

- Grater investments for the owners: owners will have to bear costs for the building’s adjustment to new standards for energy efficiency. Although financing incentives are available, there could be significant initial costs, especially for outdated buildings;

- Energy bills reduction: interventions of energy requalification contribute in reducing energy consumption and, as a consequence, in decreasing also costs for heating, cooling and lighting. In the long term, this represents a significant economic benefit, both for owners and tenants;
- Rise of the value of the property: buildings which respect new energy standards are intended to increase their value on the real estate market. This fact can encourage owners, who could benefit from a higher return on investment in case of sale or rent of the property;
- Impact on rental contracts: from the tenants' point of view, the rising energy efficiency can represent an advantage in terms of energy bills reduction. However, owners could move part of renovation costs to tenants, requiring a revision of contractual politics and a greater transparency on shared costs.

a. Involvement of civil society

Society plays a key role in supporting and monitoring the energy transition. The EPBD Recast 2024 aims to diffuse a greater awareness between citizens and to incentive more sustainable behaviors, with the objective of reducing the environmental impact of building sector.

As a consequence, it could be found:

- Change of habits: the society is called upon to modify its habits to lower energy consumptions. Awareness campaigns and educational programs are crucial to promote the environmental consciousness and the adoption of sustainable behaviors;
- Public participation: the directive encourages citizens' involvement by community initiatives, such as co-financing programs and participatory projects;
- Role of non-governmental organizations (ONG): the ONG are fundamental to sustain the directive, providing information to citizens and monitoring the respect of energy standard. Some ONG could offer services of free consulting to help owners understand better the requirements of the directive and financing options which are available.

Challenges and criticalities

The implementation of the Directive EPBD Recast 2024 represents a significant step towards the decarbonization of building sector in Europe. However, this process faces many challenges and criticalities which make its application complex on a large scale. These obstacles regard financial, technical, social and States coordination aspects. In this specific paragraph the main difficulties which can hinder Directive efficiency are discussed in detail, with an analysis of the barriers that the stakeholders could deal with in the long term.

Implementation difficulties

The practical implementation of the Directive implies considerable operational difficulties, especially for existing buildings, which represent the largest part of the European building stock. The requalification of these buildings requires complex interventions, which involve structural, technological and plant aspects. The principal difficulties regard:

- Technical limitations in historic buildings: in many European cities, most of the buildings are historic and therefore bound to specific conservation regulations. This makes it difficult, or better impossible, to carry out energy upgrades without compromising the architectural heritage. So, intervention on this type of building often requires customized solutions and specific materials, involving higher costs;
- Accessibility of incentives: although the Directive provides funds and incentives to sustain the requalification, the accessibility of them could represent a problem. Low-income families and small businesses can find complex access to financing and subsidized credit to carry out renovation work, because these procedures often demand complex requirements and burdensome bureaucratic documentation;
- Lack of trained professionals: the increasing demand of energy requalification has underlined the lack of skilled manpower and professionals in the green building sector. The training and professional updating are necessary to guarantee that renovations will be made according to standards, but these training programs require time and resources.

Change resistance

The energy transition often encounters cultural, economic and social resistances which slow the adoption of new regulations, such as the EPBD Recast 2024. These resistances can come from historic and outdated buildings' owners, who are reluctant to adopt expensive interventions, seeing the cost as a burden without any immediate and certain benefits.

Moreover, the limited awareness concerning long term benefits of energy requalification and the lack of clear and comprehensive information on environmental advantages restrains many people from undertaking these initiatives, and in this way the adoption of energy efficiency measures is likely to remain confined.

Finally, the current incentives could not be sufficient to cover the initial costs of the interventions for low-income segments of the population.

States coordination

Being a European directive, the EPBD Recast 2024 must be implemented at national level by each single member State, which generates challenges related to coordination and harmonization.

First of all, member States have different national regulations regarding building and energy efficiency. Harmonizing these policies in order to them aligned with the objective of the EPBD Directive requires a complex reform which may encounter resistance at local level. Another aspect to consider is the economic disparity between member states: in fact, some countries, as those in eastern Europe, could have more difficulties in sustaining energy requalification costs due to lower availability of financial resources and supporting infrastructure. This factor could lead to delays in the large-scale implementation of the Directive.

Furthermore, each Nation has the autonomy of adopting different approaches to implement the directive, and this could lead to a policy fragmentation, making difficult an evaluation of obtained results in different countries and consequently slowing down the overall effect of the Directive, at community level.

The challenges and critical issues of the EPBD Recast 2024 highlight the complexity path of the decarbonization of the European building sector. It is essential that European institutions and member states work together to reduce barriers to implementation by simplifying access to funds and incentives, increasing professional training and promoting greater public awareness, cause without a coordinated approach, the directive's ambitious goals are unlikely to be achieved on time.

Future prospectives

The EPBD Recast 2024 represents one of the most ambitious initiatives of the EU to face climate change through the building sector transformation. Looking ahead to the future, the directive is intended to influence in a significant way the energy policies, the housing market and the stakeholder's approach toward sustainable construction. Future prospectives of this directive depend on different factors, such as the speed and the effectiveness of the implementation, the availability of financing resources, the innovative technologies and the public and political support. One of the long-term goals of the Directive is the achievement of the climatic neutrality of the European building stock by 2050: this objective practically means that, during the next decades, all buildings will undergo requalification interventions.

From the economical point of view, the EPBD Recast 2024, in the future, could also incentive the development of "green jobs", namely new professional figures involved in sustainable construction, giving a great impulse to train specialized professionals, with a positive effect both on the job market and on the economy.

Additionally, the Directive also sets the stage for increasing digitalization of the building sector: the introduction of energy performance monitoring and smart building management will lead to an increasing use, year by year, of technologies like the Internet of things (IoT) and Artificial Intelligence (AI). These kinds of innovations will pave the way for a future in which buildings will be not just sustainable but also smart, capable of adapting themselves in real time to external and internal changes, in order to maximize energy saving and improving the living comfort.

Finally, the future prospective of the Directive depends on the capacity of the EU to overcome current challenges of lack of funds and difficult accessibility to incentives and on how much effort will be put into promoting a sustainable culture, sensibilizing citizens and stakeholders regarding the benefits and opportunities of energy requalification.

Then, with appropriate policies, targeted investment and increasing awareness, Europe can bring about a future in which sustainable construction will not be just a goal, but a concrete and tangible reality.

2. CASE STUDY

In this section, the case study on which it is applied the dynamic energy study of this thesis is introduced. In particular, the project concerns the renovation, and the functional reuse of a hospital located in the North of Italy, more precisely in Turin, proposing an interesting opportunity of "Adaptive Reuse" of an existing construction, converting the complex of buildings into a student residence with housing facilities and disability assistance.

Therefore, the project aims to assign a new identity to a hospital which was an important healthcare and social facility of the territory in the urban history of the XX century.

Overall, the intervention has a clear focus on the renovation and protection of the bonded historic volume and on general conservation with punctual additions of completion of portions realized in the second half of the Nineteen.

It is chosen this specific case study because it highlights the importance of the renovation of the existing building stock in Italy, by the Adaptive Reuse: a contemporary modality of the traditional restoration more and more diffuse in Europe since it provides the possibility of giving a new life to outdated buildings. These constructions are not in use by a society in continuous development that changes over the years interests and needs, also in relation to the urban context modifications.

This new approach allows to transform a dated building stock, which doesn't meet current minimum requirements, into innovative constructions that add value to the urban context in which they are embedded.

This is done by customized strategies of interventions, namely tailor-made solutions and design choices able to maximize results of each single renovation in relation to the conversion of building functions, with a special attention to the energy efficiency which is a central topic in the current European regulatory scene.

2.1. Existing context

The hospital, located in Turin, taken as case study, was built at the end of the XIX century, in the vicinity of a watercourse. Because of the proximity to a river, the complex of buildings was subjected to repeated floods that led to the decision to raise the existing buildings above grade.

From the early 1900s through the early 2000s the structure underwent numerous expansions which made the complex into a collection of buildings belonging to different historical periods, built in different ways with a variety of materials. Precisely for this reason, in the early 2000s the hospital was defined inadequately with respect to the structural standards required for the various healthcare facilities at that time and it permanently closed, leaving in disuse a structure of significant size.

In fact, the existing complex occupies almost an entire city block, with a rectangular amount of 800 m^2. As previously mentioned, the current configuration of the hospital is the result of successive renovations and expansions in different periods throughout the 20th century.

Volumetrically, 6 building bodies are recognizable in the lot, with various construction characteristics and heights, all connected internally and facing internal courtyards. Since it was a hospital, the main uses of the spaces are outpatient clinics, operating rooms, impatient wards and so on. Depending on the era of construction, the load-bearing structure is done in masonry, for the historic part of the building, and in brick-concrete structure in the rest of the building, with pitched or flat roofs.

In general, the heterogeneity of the building, which grew up in different times and with different goals, without any formal control, imposes in the project a rearrangement of the composition, renewing the identity of the place.

Constraints and regulations

In the hospital under study, object of renovation, the 2 volumes of nineteenth century origin are subject to a monumental constraint as the cultural interest of the building is recognized.

The protection of these buildings represents a challenge for the restoration of the entire complex because it involves the presents of parts of the envelope for which design choices are limited by current regulations. Therefore, the goal of energy efficiency is more articulated to achieve, having to find non-invasive intervention strategies that still contribute with good performances to the overall result of the project.

2.2. Overall project

The transformation project proposes a multifaceted renovation and reuse of the existing complex with the goal of realizing a university residence hall, with about 400 beds, with a gross floor area of about 15000 m^2.

The project aims to create an urban micro pole through a complex of resilient buildings that, after years of disuse, rediscover new functions by changing their features. The intervention pursues sustainability criteria and choices in the entire process, respecting a high-quality profile of sustainability principles considering a nonconsumption of land in the entire existing complex. Thus, the project addresses the issue of the new identity of the structure as a whole: including that of plant engineering and performance issues from an energy perspective.

Interventions strategies

The project under study plans several types of intervention strategies, taking into account that the current condition of the hospital is good from a structural and material point of view, while as far as the present technological installations are concerned, systems are considered non-recoverable.

More specifically, the basis of the project is the intention to work on the existing envelope (excluding buildings under protection), which is the subject of an articulated energy efficiency intervention starting with the installation of an external thermal insulation and the replacement of external fenestration with higher performance ones, with the aim of reducing dispersion in order to minimize energy consumption.

The design choices regarding the systems also have energy conservation and the exploitation of renewable sources as their focus.

2.3. Building under analysis

Among the 8 buildings which are included in the ex-hospital, the subject of this intervention, the energy modelling it is performed for just one building, the Building C which represents the volume that must comply with monumental constraints, due to its historical value (highlighted in a red rectangle in Figure 7).

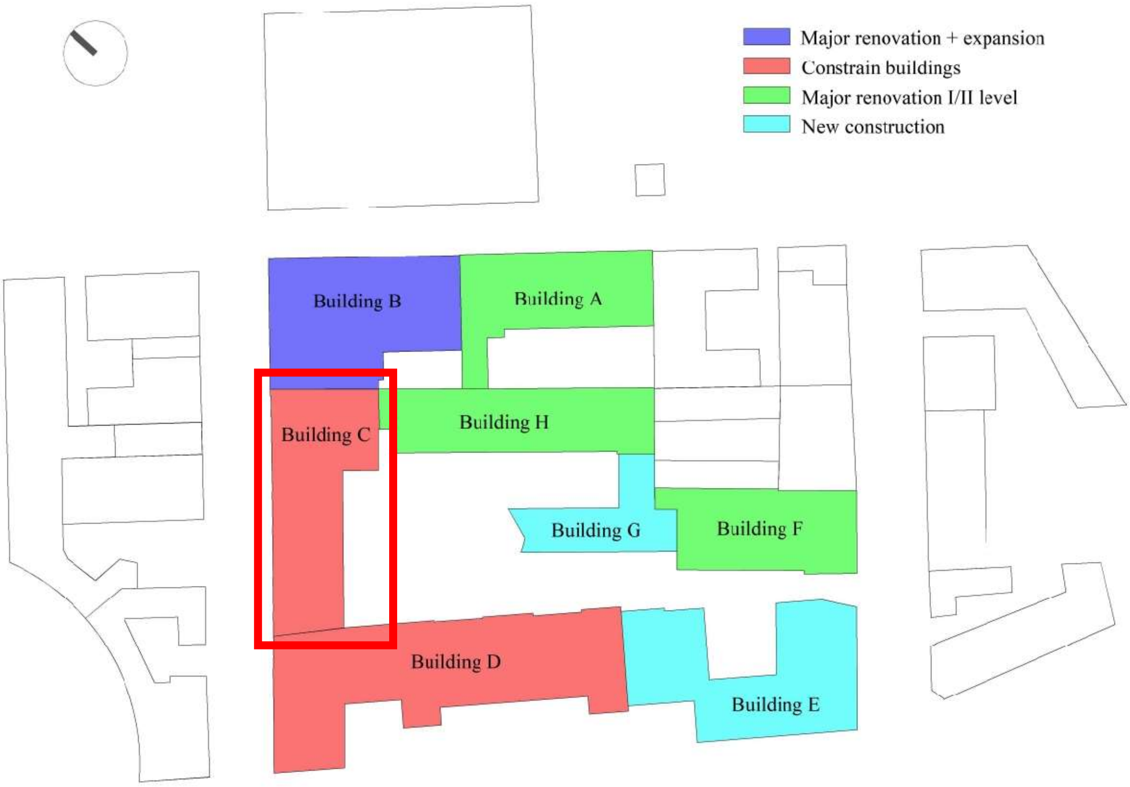


Figure 7 Outline of the buildings in the complex and the relative type of intervention

The building under study has three levels, including a non-conditioned basement and two-above ground floors. Specifically, the longitudinal structure of the building has just two floors, giving the main part of the building a compact and linear appearance. In the northern part of the construction, on the other hand, the volume takes on a square plan and extends with a third floor, creating a volumetric variation with respect to the main body.

All the above-ground floors consist of the modular repetition of distribution schemes containing a bedroom and a bathroom. The rooms can have different sizes depending on whether they are used for single or double occupancy.

These modules are all connected by a single longitudinal corridor on both the ground and first floors. In addition, there is a staircase block and a lift in the northern part of the building that allow the vertical connection of the different levels and extends up to the third floor.

3. METHOD OF INVESTIGATION

The present study aims to establish an iterative methodology for analyzing and evaluating the performance of buildings while considering the potential impacts and challenges posed by future climate changes.

This thesis considers three different climate data, which encompasses information about present conditions as well as projections for the years 2050 and 2080. Through the application of an iterative analysis approach, it investigates the ways in which various parameters of building physics can be adjusted, optimized, or redefined. The primary objective of this approach is to explore potential modifications that could lead to significant improvements in building performance, ensuring that these structures are better equipped to adapt to and perform efficiently under the challenges posed by the projected future climate scenarios.

Therefore, starting from the baseline building design, the purpose is to research solutions and changes inspired by the output of the previous simulations, implementing time-by-time the precedent version of it in relation to the energy demand of the building for heating, cooling, DHW, lighting and equipment, considering that over the analyzed range of time, there will be less and less need for heating and more need for cooling due to rising temperatures.

The entire workflow can be outlined as it could be seen in the scheme below, represented in Figure 8. The concept behind the realization of this scheme is that each version of the building model corresponds to a unique block, defined with a specific color and a sequence code name which goes from A0 to A4. Furthermore, each single block of the workflow stands for a series of simulations, clustered in groups of three different weather scenarios, and able to provide useful results for the definition of subsequent changes to be made. Indeed, the progression of these blocks involves an iterative implementation of the building model with solutions suitable for the specific case study, according to the outputs of preceding simulations.

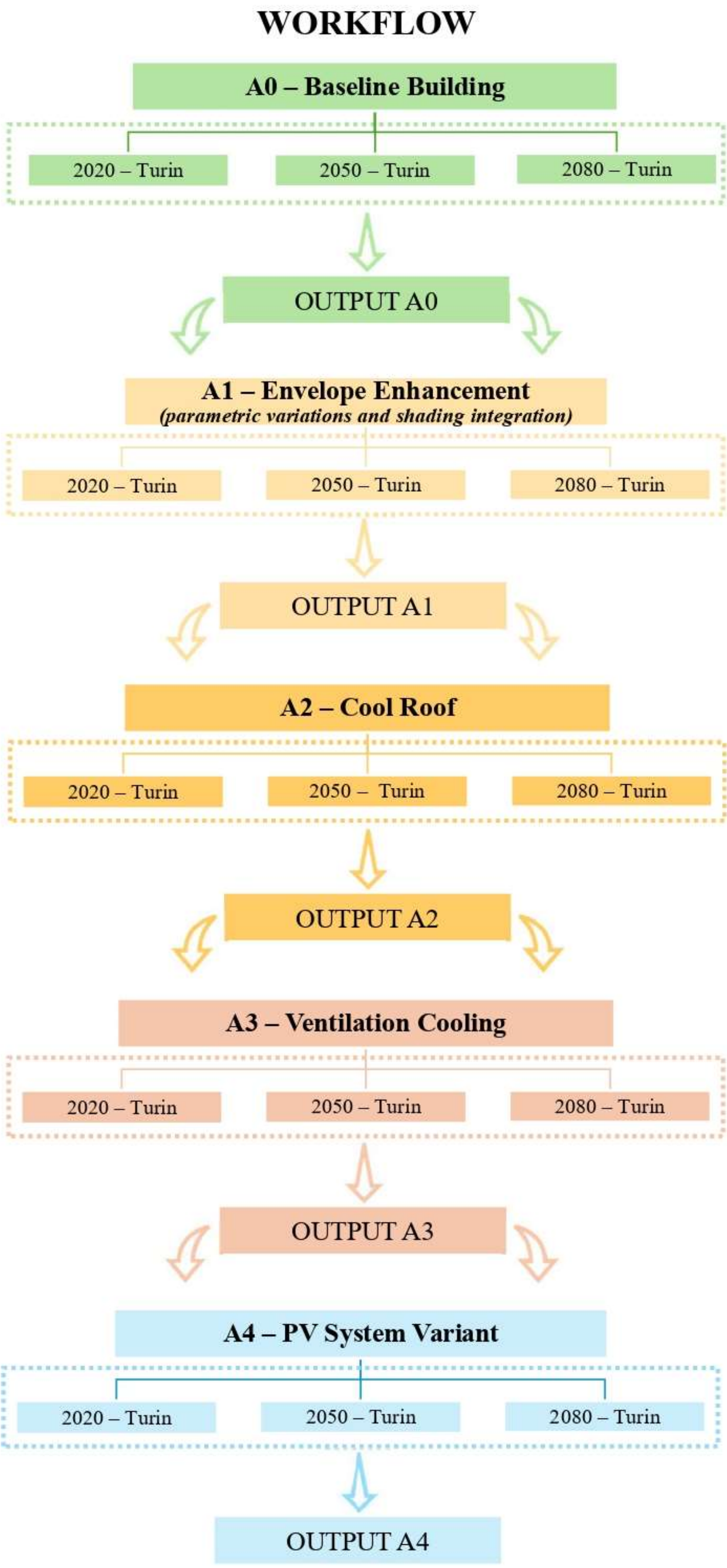


Figure 8 Workflow block diagram

Then the first block, the green one, consists in simulations of the baseline model, having the characteristics of the project at the origin, without any changes: the only variation is about the selected weather file. This first step is essential for the development of the study because it provides the possibility of highlighting where it is necessary to focus the attention; in fact, it allows, by a critical examination, the identification of the weaknesses of the design concerning energy consumption, in relation to the predicted increasement of temperatures over the next 60 years.

From this initial investigation it is possible to extract fundamental information as outputs which will lead to the definition of improvement strategies for the project to maintain comfort in the building and to limit the energy of consumption of it.

The second step of the analysis is represented by simulations of the A1 block, described in Sub-chapter 6.2: this variant of the model performs the envelope enhancement by traditional approach. This choice comes to the will to start the survey from the basic modifications of the stratigraphy of the building under study, in order to understand in more depth which are the effects obtained in the outputs simulating the same building, with the same technical solutions but an optimization of layers thicknesses involved in the construction packages of building elements. In particular, the variants of this model involve the thermal insulation thickness and the shading integration: various series of simulations are carried out to define the more suitable combination of these two adjustments in relation to analysis outcomes.

After parametric variations, the following blocks of simulations are each the consequence of the outputs of the previous one. So, they consist in variations of the precedent simulated model, always with the aim of optimizes as much as possible the results. Therefore, the iterative critical analysis of the outputs, obtained from each block, enables the selection of the most suitable technical solution for the next step.

Basically, the intent is preferring climate-resilient solutions in order to solve problems related to the rising of temperature without enhancing the energy load of the building. The other strategies selected for this specific case study are the cool roof (block A2) and the free cooling (block A3), which are respectively described in more details in Subchapter 6.3 and 6.4.

At the end of all these simulations, the second-to-last improved version of the model (block A3), potentially represents the maximization of the climate resilient solutions benefits that the building can obtain from its own composition.

At this stage of the study, the current version of the model undergoes a final modification (block A4), described in Subchapter 6.5, focusing on the increasement of the renewable energy percentage available on site. Specifically, a larger size of the photovoltaic system means a higher electricity producibility, which is traduced in a reduction of energy demand to the power grid (which is the main objective of the NZEB).

This step aims to evaluate the electrical consumption of the building in detail, following the maximization of the envelope's performance. By addressing this additional aspect, the study seeks to provide a more comprehensive understanding of the building's overall energy efficiency and operational sustainability.

4. IESVE SOFTWARE

4.1. Energy assessment

Energy calculation in general could be carrying out in two different regimes, following semi-steady conditions or dynamic conditions.

The semi-steady calculation allows to investigate just partially the real building performances because it assumes that the periodic variation of temperature and of the solar radiation contribution could be neglected; precisely for this reason, in this type of calculation it is possible to use monthly or annual average climate data.

The dynamic energy calculation permits to investigate the real thermo-energy behaviour of the building using a simulation on hourly basis. This kind of analysis enables a very precise evaluation of consumption and dispersions hour by hour. In particular, allowing a more realistic and complete study, it is assessed in detail the response of the building envelope in inertial terms, taking into account external temperature, solar radiation, natural ventilation, occupants behaviour and air-conditioning system.

This analysis uses hourly data of temperature and humidity for the calculation of energy needs, ensuring that investigations are carried out for the 8760 hours per year and making the calculation more computationally burdensome but also more precise in relation to the results obtained as outputs.

The advantages that come from the use of dynamic calculation are mainly two: first of all, this evaluation enables a more precise idea regarding the building's expected consumption, secondly the high accuracy with which loads are determined, permits a better dimensioning of plant systems, avoiding oversizing and so an increasement of installation, management and maintenance costs.

4.2. Virtual Environment

The use of a certified energy simulation software, for the dynamic modelling finalized also at the obtainment of the "Optimize Energy Performance" credit in LEED

Certification, besides being a requisite of the standard ASHRAE 90.1-2010, it is also a fundamental element for the achievement of consumption results as realistic as possible. Among all the software available in the market, validated for the energy simulation, in this thesis project it is chosen the IES Virtual Environment software.

IESve applications

This specific software is characterized by a set of applications, distinct in modules, with a common user interface in which they can interact with each other.

First of all, the program provides different modules, which are grouped in the following categories:

- *Model Builder* (Model IT, Component), for creating or importing the geometric model 3D and for characterizing the thermal-physic properties of the envelope components;
- *Solar* (SunCast), for shading analysis, whose data are used for energy calculation. This module calculates, each hour of the 15th day of each month, the shading factor of all the surfaces which are exposed to direct solar radiation;
- *Energy* (Apache, Apache HVAC, MacroFlo, Vista Pro), for thermal-energy simulation in dynamic regime; specifically:
- *Apache* analyses heat transfer processes, for convection, conduction and radiation between inside and outside the building;
- *Apache HVAC* permits the single components analysis of thermal refrigeration system;
- *MacroFlo* is a specific tool which allows the analysis of the humid air masses transfer phenomena;
- *Vista Pro* constitutes the graphic interface for the visualization of simulation results;
- *Lighting* (Flucs, LightPro, RadianceIES), for daylight simulation and design options;
- *Cost and value* (CostPlan, LifeCycle, Deft), for economic evaluation;
- *Egress* (Lisi, Simulex);
- *Mechanical* (IndusPro, PiscesPro)

- *CFD* (MicroFlo), for fluid-dynamic computational analyses, both internal and external;

One of the points of strength of the software is the ease by which different modules are able to communicate with each other.

Procedure for thermal-energy simulation

The framework for performing a thermal-energy simulation of a buildings using the software IES Virtual Environment includes the following steps:

a. Creation of the 3D geometric model in the module ModelIT

The 3D model defined in ModelIT could be created, starting from a DXF base, through the editing commands of the programme or it could be imported from other 3D modelling software such as Revit, but this option sometimes includes problems reading the model. In this first step all the envelope elements (windows, walls, ceilings, roofs, …) have no thickness: in fact, it will be subsequently assigned, directly during the stratigraphies' definition.

So, at this initial point, the level of detail in the modelling is still very low, based on just the definition of simple blocks, where each space in which the building is subdivided is called "Room". In function of the required precision of the simulation, it is possible to perform a thermal block modelling or a more detailed one focused on each single room. Moreover, the software is able to understand if a surface represents a wall, a roof or a floor thanks to the automatically identification of boundaries of each face of the blocks. Once created the opaque elements of the vertical and horizontal envelope, it is possible to add them holes, windows and doors, whose energy characteristics will be set out later, as for the opaque elements, inside the Apache module, during the stratigraphies definition.

b. Weather file attribution

Climate will play a key role in the performance of any buildings; therefore, it is important to use the appropriate location settings for any analysis. So, the second essential step is the definition of the simulation weather file which will be used for Apache dynamic simulations in IESve. These files contain data for variables including dry bulb and wet bulb temperature, wind speed and direction, solar altitude and azimuth, cloud cover etc. for each hour of the year.

c. Creation of envelope stratigraphies

Since the complete geometric block model has been determined, all rooms drawn at this point of the modelling are going to transformed from blocks to “real” rooms, by the creation of an inner volume. This step initially assigned in an automatic way standard stratigraphies to all elements of the envelope, in order to represent the thickness of walls, ceilings, roofs. Once all the inner volumes are obtained, the specific stratigraphies creation is needed to assign at each element its own design layers. The stratigraphies database is subdivided in the following sections:

- External Wall
- Internal Partition
- Roof
- Ground/Exposed Floor
- Internal Ceilings/Floor
- Door
- Glazed elements.

Inside each section generic stratigraphies od the programme could be chosen, or they could be created in accordance with design specifications, selecting materials from the software archive or creating new ones. For each element, it allows to define thermal-energy characteristics such as transmittance and solar factor for transparent part.

d. Profiles definition

Once having determined the envelope in detail, the following step is the determination of usage profiles, namely those profiles which describes the variation in time of parameters, such as implants functioning, the number of people present in a room, the power of lights and other internal loads. For each profile it is necessary to define the variation throughout the day, so the daily profile and subsequently, at each day of the week it should be assigned a daily profile (weekly profile). In case there is a variation during the year, weekly profiles are assigned to different periods of the year (yearly profile). There are two types of profiles:

- *Absolute*: equal to the absolute value of the variable in its unit of measure (used for example in case of temperature set points variation in time);
- *Modulating*: it is defined the percentual variation in time with values between 0 and 1 (used for example to regulate the windows opening, shadings activation or to define the internal loads variation).

Both the profiles could be defined in function of variables, by formulas (formula profile).

e. Template creation and assignment to rooms

A template is a set of characteristics of the room to which they are assigned. They are divided into:

- Room attributes
- Constructions
- MacroFlo Opening Types
- Thermal conditions
- Electric lighting
- Radiance Surface Properties

In the following part, the "Thermal conditions" section is described: for the other sections, please refer to the software guide, cited in the bibliography. In thermal templates, implants characteristics are specified in terms of:

- Functioning profiles
- Set points
- Seasonal efficiency of generators
- Humidity control
- Air changes

Moreover, all the internal loads are defined for each single room, indicating:

- Number of people
- Power absorbed by equipment
- Power absorbed by lights
- Generic internal loads

For each single internal load, it is necessary to define the maximum sensible and/or latent heat and their modulating profiles of variation in time inside the room.

f. Definition of dynamic simulation settings and its outputs

This step consists in the definition of the simulation characteristics, such as the model links, the time of the year which should be investigated (in case it is not required a simulation of the entire year), the simulation timestep and the reporting interval.

A simulation can be referred to a period of time which can vary from a day to a year, with a timestep between 6 minutes to 1 hour. As a consequence, increasing the time analysed and decreasing the timestep, there is an exponential rise of the calculation time. Moreover, it is necessary to set the detailed outputs of all the building and of the single rooms that should be visualize in the result.

g. Apache simulation

One set all the options in function of the interest of the study, the simulation can be performed. The time needed for the simulation varies depending on the number of rooms modelled, the type of implant assigned and the complexity of the geometry.

h. Results visualization

The module Vista Pro allows the visualization of all the results as charts of different types. The representation possibilities are multiple, and the variables of the graphs can be chosen from the parameters available in the outputs (previously set). In case various simulations are performed, the module permits also the overlapping of results of different simulations, expanding the potential for data analysis.

IESve Apache – Calculation method

The module *Apache* permits to carry out a detailed analysis of building, envelope and implants performance.

In general, Apache Simulation is a dynamic thermal simulation program based on first-principles mathematical modelling of the heat transfer processes occurring within and around a building. Through these investigations it can be hypothesis an optimization of

the entire project evaluating the representative parameters of the internal comfort and the energy consumption.
Conduction, convection and radiation heat transfer processes for each element of the building fabric are individually modelled and integrated with models of room heat gains, air exchanges and plant. The simulation is driven by real weather data and may cover any period from a day to a year. The time-evolution of the building's thermal conditions is traced at intervals as small as one minute.

With the aim of obtain the wanted results, it is necessary providing to the Apache section the following input data:

- *Site location* (Latitude and Longitude) and *Weather Data*, namely data hour by hour of: temperature (dry-bulb and wet-bulb), radiation (direct, diffuse and global), winds, cloud cover and humidity. In general, these data are available directly in the database inside the software (for most areas).
- *Building geometry*, defined in ModelIT;
- *Obstructions* which cause self-shading phenomena, computed by the SunCast module;
- *Envelope components* which include materials and stratigraphies of all the elements (walls, roofs, windows, ...)
- *Shading* (internal, external, fixed or movable)
- *Internal loads* due to the generation of sensible heat (transmitted for radiation or convection) and latent heat caused by the presence of people, lighting and equipment;
- *Ventilation rates* (mechanical and natural);
- *Infiltrations and air exchanges:* it is necessary to underline that in the air exchanges the software takes into account the simplifying hypothesis of air perfect mixed in the room, so the air change takes place at the average room temperature;
- *Implants* for domestic hot water, heating, cooling. Humidification and dehumidification of the air: in particular, it is important to specify the set-points, the radiant fraction of terminals and the on/off profiles for thermal calculations. For the energy calculation, it should also be pointed out the efficiency and the nominal power of generators, the type of fuels and the eventual use of renewable sources:

- *Time profiles* (concerning a day, a week or a year) of input variables: these data are essential for the simulation of the internal gains' variation in function of time and they can be assigned to occupancy, the lighting switch on, the heating/cooling set points, the ventilation rates and the shading activation.

From this analysis it is possible to derive comfort indexes, energy consumptions and temperature data (separated into air temperature, mean radiant temperature and dry resultant, which represents the average between the first two), humidity, implants load, internal loads, air exchanges of each single room for each time-step of calculation.

Room and Building Heat Balance

The *Apache* module uses a stirred tank model of the air in a room. This means that, to summarize, the principal assumptions on which it is based this calculation method are:

- Bulk air temperature and humidity uniform within the room (perfect mix);
- Uniform temperature on each surface;
- Long-wave radiant heat transmission uniform on the surfaces;
- Short-wave solar radiation uniform on the surfaces;
- Mono-dimensional heat transmission for conduction;
- Air cavity (both for opaque and transparent components)

In case it is required a finer spatial resolution of these variables, it can be achieved by subdividing the room, or through the use of computational fluid dynamics (for example through the module *MicroFlo*). The determination of thermal conditions throughout the building is achieved through the balancing of sensible and latent heat flows entering and leaving each air mass and building surface.

Sensible heat balance

For the sensible heat flow balance, three equations have to be solved.

1° Equation: Node equation

For the resolution of this first equation, the air volume inside the room is discretized in a finite number of nodes and is calculated the solution for each single node. So, the balancing of heat flows for the air in each room involved the following components:

- Thermal storage in the air and the furniture;
- Convection from the room surfaces;
- Heat transfer by air movement;
- The convective portion of casual gains;
- The convective portion of any plant input;

The derived equation consists in the sum of these terms equalised to zero, for each node of each room.

2° Equation: Internal surface equation

The second equation concerns the resolution of the balance for each internal surface of rooms and the sum, equalled to zero, of:

- Heat conduction out of the building element;
- Convection to the surface form the room air;
- Thermal radiation exchanged with the radiant temperature node;
- Solar gain absorbed by the surface;
- The surface's share of the radiant portion of casual gains;
- The surface's share of radiant plant input;

3° Equation: External surface equation

The third equation is solved for each exterior surface of the building, in contact with the outside and it consists in the balance of the following factors:

- Heat conduction out of the building element;
- Convection to the surface from the outside air;
- Thermal radiation exchanged with the external environment;
- Solar gain absorbed by the surface;

The heat balance equations, mentioned above, are solved using non-linear algebra techniques. Because some of the equations are nonlinear, iteration is used to converge on a global solution.

Latent heat balance

As regards the latent heat balance, a balance of water vapour flows is established for the air in each room, involving:

- Water vapour transfer by air movement;
- The latent portion of casual gains;
- The dynamics of water vapour storage in the air;
- Any plant humidification of dehumidification;

Heat exchanges

During the simulation by the *Apache* module different types of heat exchanges are involved; they are listed below:

- Heat conduction and storage
- Convection heat transfer
- Heat transfer by air movement
- Long-wave radiation heat transfer

In the following part, these heat exchanges are described in more details.

a. Heat exchange and storage

The time-evolution of the spatial temperature distribution in a solid without internal heat sources is governed by the following partial differential equations:

$$(1)\ W = -\lambda \nabla T$$

$$(2)\ \nabla W = -\frac{\rho c \partial T}{\partial t}$$

Where:

- $T(x, y, z, t)$ is the temperature (ºC) in the solid at position (x,y,z) and time t;
- $W(x, y, z, t)$ is the heat flux vector (W/m^2) at position (x,y,z) and time t;
- λ is the conductivity of the solid (W/m^2 K);
- ρ is the density of the solid (kg/m^3);
- c is the specific heat capacity of the solid (J/kgK);

Equations (1) and (2) are expressions of the principles of conduction heat transfer and heat storage, respectively. The heat diffusion equation (in its most general form in which λ , ρ , and c may vary with position) then follows:

$$\nabla(\lambda\nabla T) = \rho c\partial T$$

It is also necessary to consider heat storage in air masses contained within the building. The model of this process is:

$$Q = \frac{c_p\rho_a V dT_a}{dt}$$

Where:

- Q is the net heat flow into the air mass (W)
- c_p is the specific heat capacity of air at constant pressure (J/kg*K)
- ρ_a is the air density (kg/m^3)
- V is the air volume (m^3)
- T_a is the air temperature (ºC)

b. Convection heat transfer

Convection is defined as the transfer of heat (and, in general, other physical quantities) resulting from the flow of a fluid over a surface. For the purpose of this discussion, the fluid is air, and the surface is an element of a building. If the convective airflow is driven by external forces (e.g. wind or mechanical ventilation), it is referred to as forced convection. Convection arising from buoyancy is known as natural convection.

Experimental findings have demonstrated that convective heat transfer can be accurately described by equations of the following form:

$$W = K(T_a - T_s)^n$$

Where:

- W is the heat flux (W/m^2) from the air to the surface;
- T_a is the bulk air temperature (ºC);

- T_s is the mean surface temperature (ºC);
- K, n are coefficients;

For forced convection at sufficiently high air velocities it is found that, to a good approximation $n = 1$, and the process is thus linear. For natural convection, although n is usually somewhat greater than 1, its value is often sufficiently close to 1 for the approximation:

$$W = h_c(T_a - T_s)$$

Where h_c is the convective heat transfer coefficient;

c. Heat transfer by air movement

The types of air movement that could be modelled with the *Apache* simulation are the following ones:

- Pre-specified air exchanges: classified as infiltration, natural ventilation or mechanical ventilation. These air exchanges may be sourced from outside air, outside air modified by a temperature offset, air at a (possibly varying) temperature defined by an absolute profile or air from another room. The rate of air flow is specified before the simulation but may be made to vary with time by means of a profile. If the profile is a formula profile, the air flow rate may also vary with simulation variables such as room air temperature;
- Air flows calculated by MacroFlo: this module calculates natural ventilation air flows arising from wind and stack pressure (buoyancy). It also takes account of flow imbalances generated by HVAC systems. MacroFlo runs in tandem with ApacheSim and the calculations of the two programs are interdependent;
- Air flows specified or calculated by ApacheHVAC: this module is fully integrated with ApacheSim and its ducted mechanical ventilation rates are superimposed on other air flows dealt with by ApacheSim;

The rate of heat transfer associated with a stream of air entering a space is:

$$Q = mc_p(T_i - T_a)$$

Where:

- m is the air mass flow rate (kg/s);
- c_p is the specific heat capacity of air at constant pressure (J/kg/K);
- T_i is the supply temperature of the air (ºC);
- T_a is the room mean air temperature of the air (ºC);

As regards the water vapour gain associated with the air supply, which plays a part in the room's latent balance, is:

$$w = m(g_i - g)$$

Where:

- m is the water vapour gain (kg/s)
- g_i is the humidity ratio of the supply air (kg/kg)
- g is the humidity ratio of the room air (kg/kg)

d. Long-wave radiation heat transfer

Building surfaces emit thermal radiation by virtue of their absolute temperature. For small surface element (dA) of a Lambertian emitter the radiation flux emitted into a small solid angle (dω) lying in a direction making an angle θ to the surface normal is:

$$dW = \frac{1}{\pi}\varepsilon\sigma\Theta^4 cos\theta d\omega dA$$

Where:

- dW is the radiation flux (W/m^2);
- ε is the surface emissivity (W/m^2);
- σ is the Stefan-Boltzmann constant (= 5.6697x10 $^{-8}$ W/m^2 K^4);
- Θ is the absolute temperature of the surface (K);
- θ is the direction angle measured from the surface normal;
- $d\omega$ is an element of solid angle;
- dA is an element of surface area (m^2);

Integrated over solid angle, the total radiation (W) emitted by a plane surface of area A is:

$$W = \varepsilon A \sigma \Theta^4$$

Surfaces also absorb a proportion of the radiation they intercept. By Kirchhoff's law the fraction of incident radiation that is absorbed by a surface is equal to its emissivity (ε). The results presented here in represent an idealisation of the physics of radiation emission and absorption. They assume Lambertian angular characteristics and do not enter into the detail of wavelength dependence (the grey body assumption). However, they provide a sound basis for modelling radiation exchange in buildings.

5. FUTURE WEATHER FILE

In this thesis study the weather file definition represents an essential step for the analysis carried out with the software IESve.

In fact, due to the intent of investigate the response of the building over the years, to the now inevitable climate change, climate data used in the simulation are the focal point of the research. For the current climatic condition, the software IESve makes available in its own archive the relative weather file, each one specific to a particular area.

With reference to the future climatic conditions, inside the program no data are provided so they have to be obtained from external sources, which generally are online platforms with generator tools capable of originating predictive climate files. It must be noted that, since the information under discussion pertains future, they would not be certain data, but predictions obtained from various studies over the years.

In this specific thesis project, weather data relative to future scenario come from the *CCWorldWeatherGen*, a weather file generator which is explained in more details in the following paragraph.

CCWorldWeatherGen tool

The climate change world weather file generator (*CCWorldWeatherGen*) allows the generation of climate change weather files for world-wide locations ready for use in building performance simulation programs. It uses Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report model summary data of the HadCM3 A2 experiment ensemble which is available from the IPCC Data Distribution Centre (IPCC DDC).

The tool is Microsoft Excel based and transforms ‘present-day’ EPW weather files into climate change EPW or TMY2 weather files which are compatible with the majority of building performance simulation programs, such as EnergyPlus and IESve.

The underlying weather file generation routines of this tool are based on the so-called ‘morphing’ methodology for climate change transformation of weather data, which was developed by Belcher, Hacker and Powell. It builds on previous work by the Sustainable Energy Research Group on climate change transformation of UK weather data.

The *CCWorldWeatherGen* tool permits the generation of climate change weather files with few simple steps. It is possible to produce ‘morphed’ EPW and TMY2 files as well as present-day TMY2 files from the original EPW format files.

Climatic file selection

For this study, three weather files are selected for carrying out simulations with the software. The first one is the file related to the current climatic situation with the aim of having the reference of the present scenario. These data are already available in the software, so the selection is immediate. While the second and the third files are referred to the climatic conditions of 2050 and 2080. This choice comes from the will to investigate the behaviour of the building in two different periods approximately 30 years apart one from the other.

Comparison of selected weather files

In this section it is reported a general overview of the selected scenario and a comparison between these three different series of data. So, in the following charts, results of these three weather files are shown, in order to have an outline of the main parameters' variation over time.

In detail, the Figure 9 represents the average monthly temperature which undergoes a significant increment with the passing years. Although the graph simplifies scenarios taking into account just average data, it can be noticed an upward trend over the years.

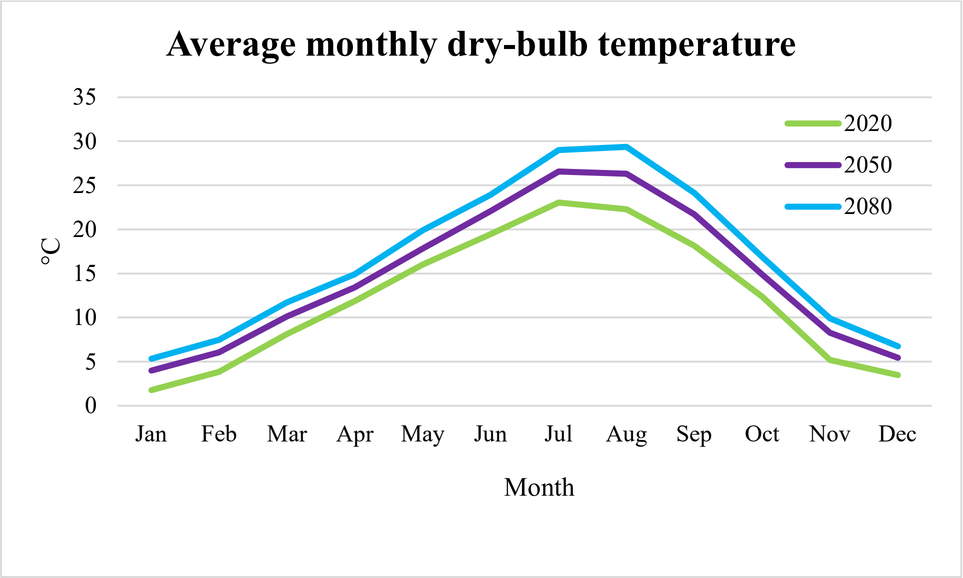


Figure 9 Average monthly dry-bulb temperature of different weather scenarios

More specifically it is evident an increase in temperature, from the current condition of around 3°C in the 2050 and of 5°C in the 2080, with a pronounced variation in summer months.

Whereas, speaking of maximum temperatures, in all the series they are reported in the month of August. In detail, from the chart shown in the Figure 10 the current scenario registered a peak value of 32.20°C while the predictive data suppose in the 2050 a highest temperature of 37.20°C and in 2080 of 41.20°C.

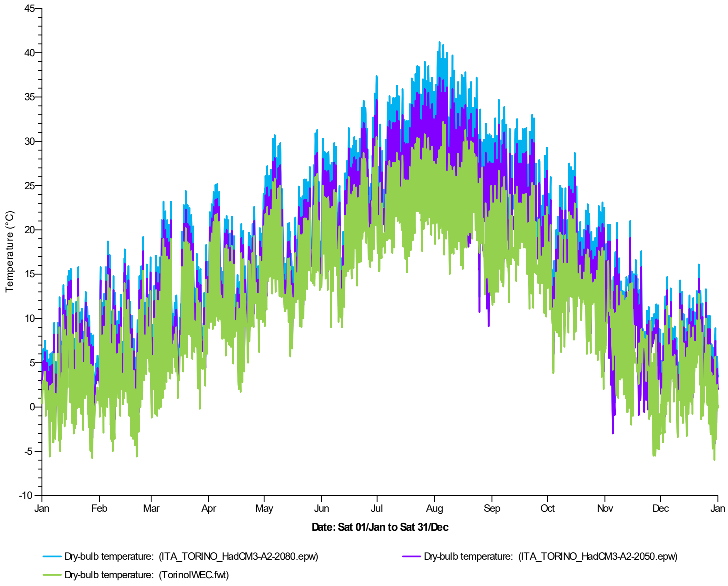


Figure 10 Dry-bulb temperature of different weather scenarios

While, in the bar chart represented below, it can be seen the variation of the monthly global radiation, during a year, in the three different scenarios taken into account.

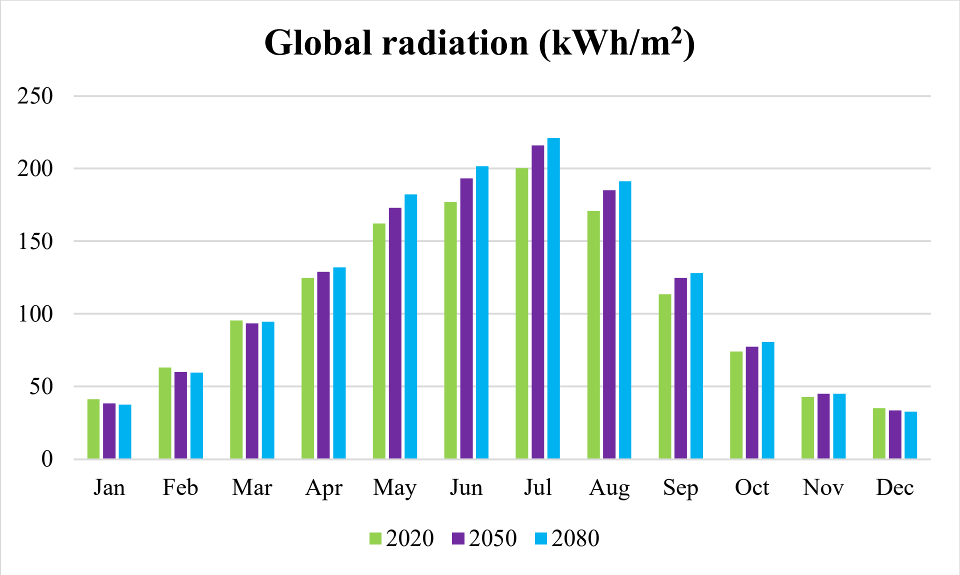


Figure 11 Monthly global radiation of different weather scenarios

It can be observed that, also this parameter follows the behaviour of the temperature respect the incremental rising over years, with a remarkable variation especially in summer months. Despite these similarities, the highest supply of radiation is recorded during the month of July.

6. ENERGY MODELLING AND RESULTS

In this section of the thesis work, all steps necessary for the energy simulations are reported and described in detail, starting from the building modelling in IESve and continuing with the execution of simulations.

Building geometric model

The initial step for the energy analysis of this case study consists in the realization of the geometric model of the building. This is a time-consuming process which starts with the creation of a *dxf.file* from the available dwg: this phase is essential to speed up geometric modelling in IES, allowing a simplification of design layouts, keeping only the wheelbase lines of all the internal partitions, the external boundaries of the building and the windows positions. Another useful piece of information to keep in the *dxf.file* is the function of each single room assigning a symbol to each destination of use, in order to facilitate the identification in the other software. So, once the above-mentioned information needed to build the model for energy simulations has been gathered, for each floor a *dxf.file* is obtained, as the one shown below:

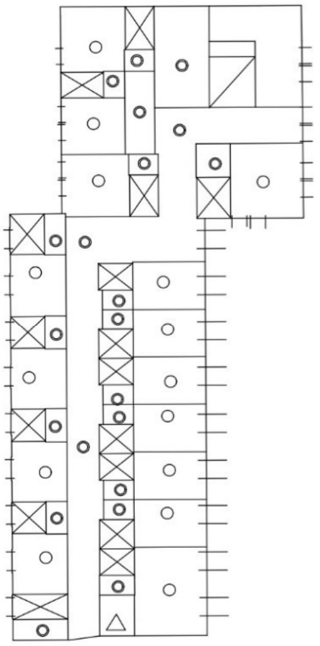
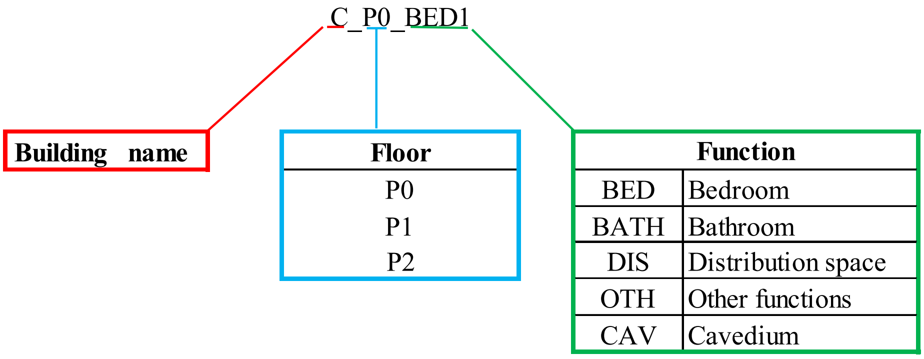


Figure 12 Example of dxf.file of first floor

The following step involved the importation of the *dxf.file* in IESve software and the realization of the rooms, drawing the shape over the reference lines of the dxf, defining the placement by setting the Plane (m) and the Height (m) of the space and assigning a name.

To facilitate rooms' identification a nomenclature was defined, referring to the following coding:



C_P0_BED1

Building name

Floor
P0
P1
P2

Function	
BED	Bedroom
BATH	Bathroom
DIS	Distribution space
OTH	Other functions
CAV	Cavedium

Figure 13 Explanatory scheme of the room nomenclature

Another useful function in the program is the possibility of creating classifications in order to turn the display of spaces on and off quickly and thus facilitate modelling. In this specific case, rooms are classified in function of level and the destination of use.

At the end of 129 rooms modelling, and the openings addition, the building obtained is shown in Figure 14 and Figure 15:

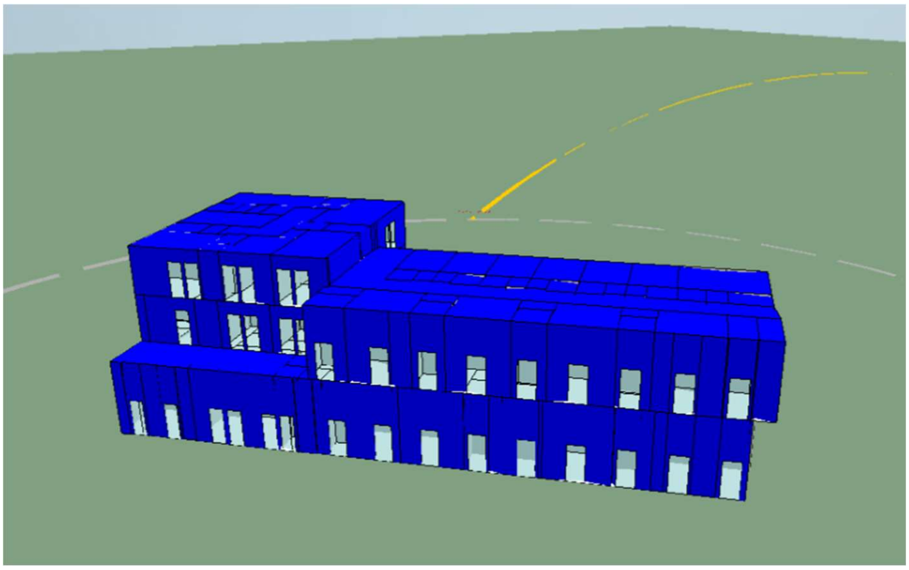


Figure 14 Three-dimensional view of building model, West side

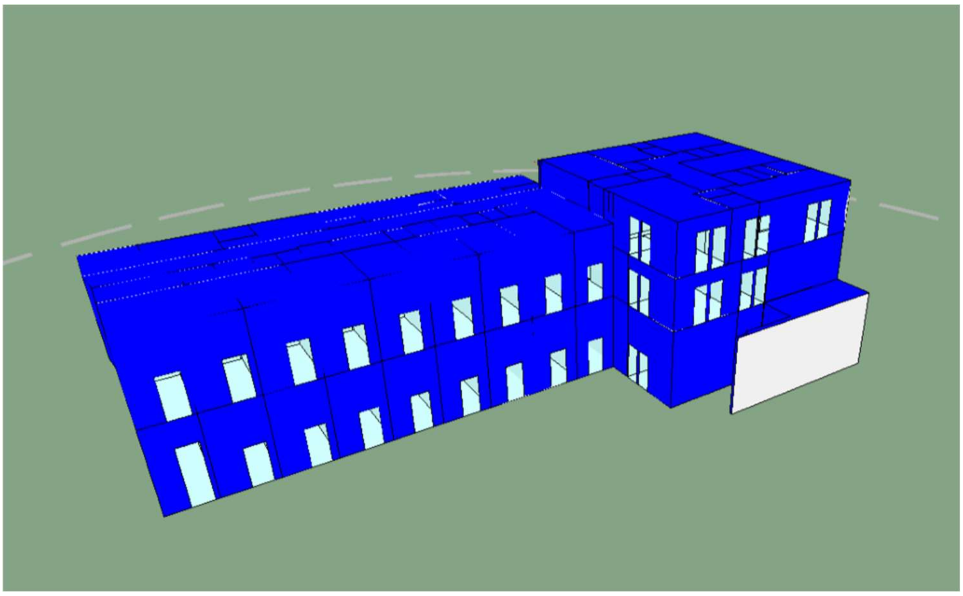


Figure 15 Three-dimensional view of building model, East side

In the same way that the building was modelled, it is also necessary to represent the adjacent buildings as simple masses, which are the key elements for an accurate analysis of the shading during simulations.

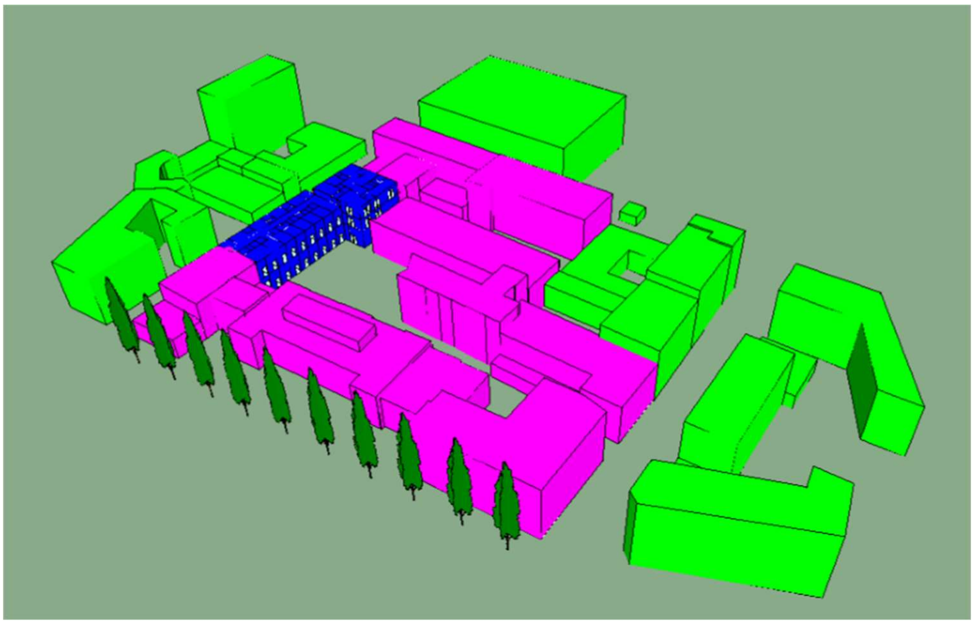


Figure 16 Three-dimensional view of the urban context

At this point in the modelling, all rooms belonging to the building are selected to create inner volumes. As a default setting, software will automatically assign default stratigraphies, which are already present in the archive, to the construction elements.

Therefore, to obtain an accurate representation of the model, it is necessary to create specific stratigraphies of the case study in the archive of IESve, so that they can be assigned to the respective walls, floors and openings. When the correct layers are assigned to building elements, the thicknesses are also automatically updated in the geometric model.

The next step consists in the "Space-by-Space method": this classification allows to assign a specific category of destination of use to each single modeled room. The following table shows the categories used in the building taken as case study.

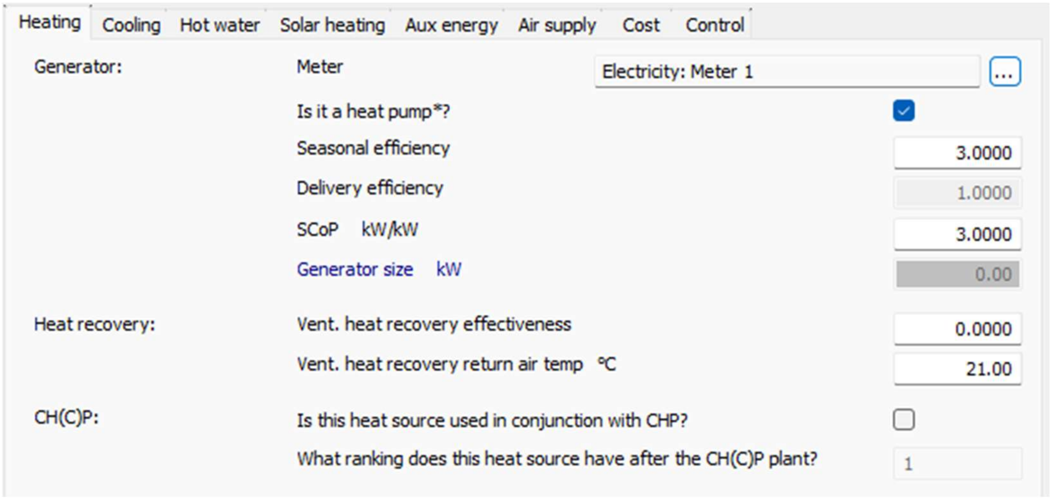
SPACE BY SPACE METHOD
SPACE: Corridor/Transition
SPACE: Dormitory – Living quarters
SPACE: Elevators - Equipment
SPACE: Office - Enclosed
SPACE: Restrooms
SPACE: Stairway
SPACE: Storage

Table 1 Space-by-space method assignment

Thanks to this assignment, the respective templates are automatically attributed to rooms with default values of internal gains which are modified following design conditions.

Systems modelling

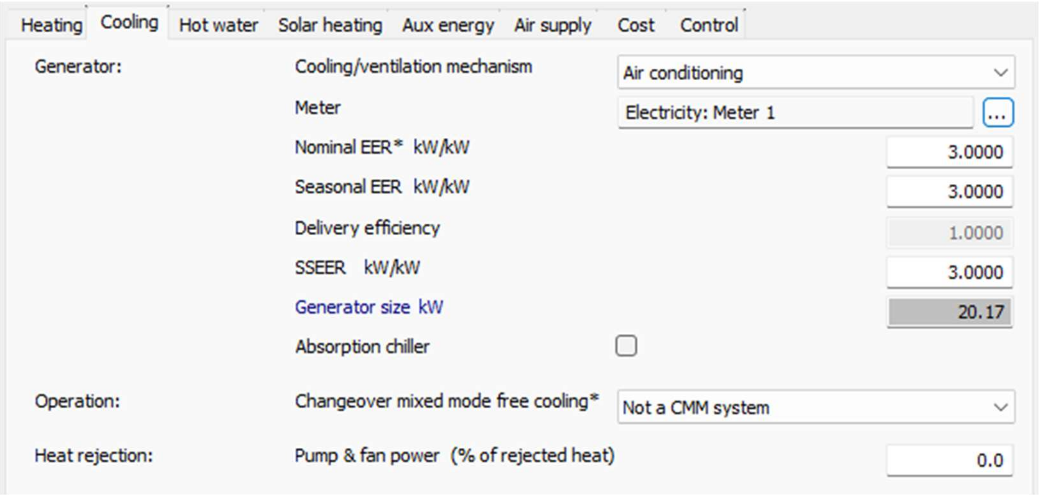
Regards to systems modelling, the process starts from the definition of a new system in the archive of the software, called "Prototype system". It is designed to satisfy heating, cooling and domestic hot water needs (DHW). The generator of the system is a heat pump, powered exclusively by electricity, which guarantees efficient and sustainable operation. In the following images, its technical and operational features are illustrated in detail.



Generator:
Meter: Electricity: Meter 1 ...
Is it a heat pump*? ☑
Seasonal efficiency 3.0000
Delivery efficiency 1.0000
SCoP kW/kW 3.0000
Generator size kW 0.00

Heat recovery:
Vent. heat recovery effectiveness 0.0000
Vent. heat recovery return air temp °C 21.00

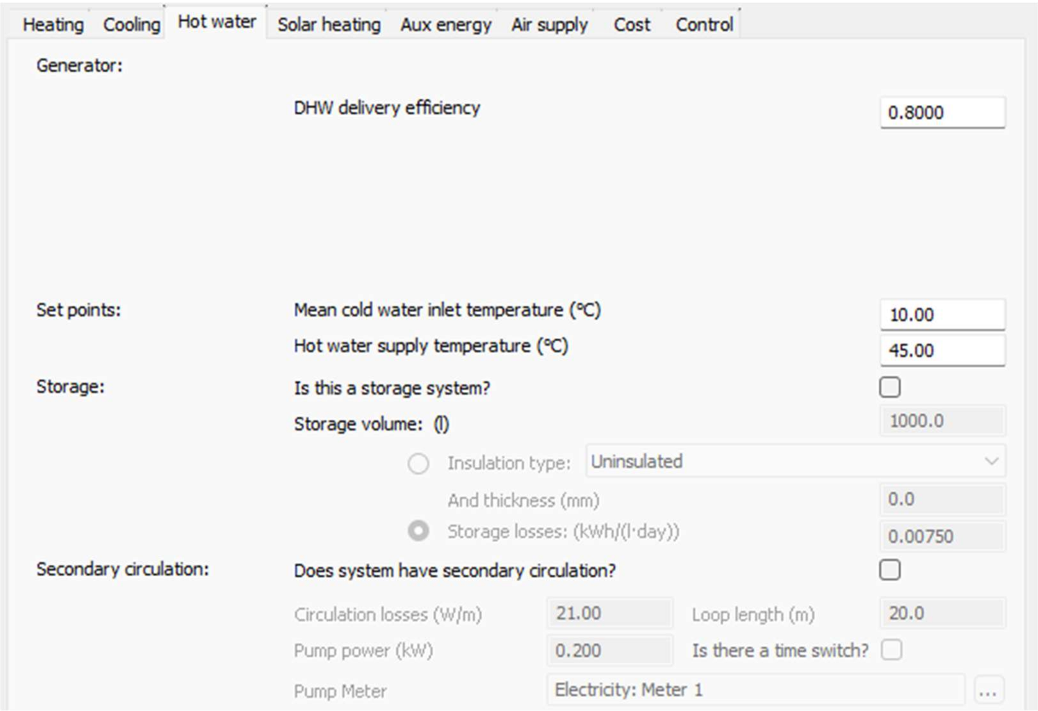
CH(C)P:
Is this heat source used in conjunction with CHP? ☐
What ranking does this heat source have after the CH(C)P plant? 1



Generator:
Cooling/ventilation mechanism: Air conditioning
Meter: Electricity: Meter 1 ...
Nominal EER* kW/kW 3.0000
Seasonal EER kW/kW 3.0000
Delivery efficiency 1.0000
SSEER kW/kW 3.0000
Generator size kW 20.17
Absorption chiller ☐

Operation:
Changeover mixed mode free cooling*: Not a CMM system

Heat rejection:
Pump & fan power (% of rejected heat) 0.0

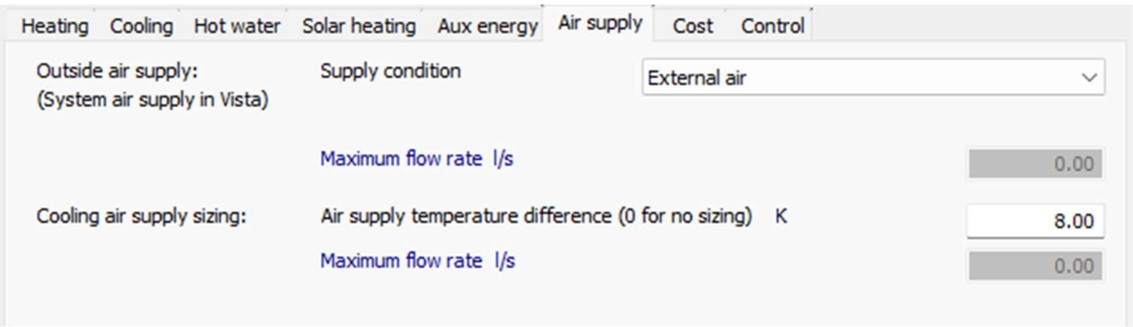


Generator:
DHW delivery efficiency 0.8000

Set points:
Mean cold water inlet temperature (°C) 10.00
Hot water supply temperature (°C) 45.00

Storage:
Is this a storage system? ☐
Storage volume: (l) 1000.0
○ Insulation type: Uninsulated
And thickness (mm) 0.0
● Storage losses: (kWh/(l·day)) 0.00750

Secondary circulation:
Does system have secondary circulation? ☐
Circulation losses (W/m) 21.00
Loop length (m) 20.0
Pump power (kW) 0.200
Is there a time switch? ☐
Pump Meter: Electricity: Meter 1 ...



Outside air supply:
(System air supply in Vista)

Supply condition: External air

Maximum flow rate l/s: 0.00

Cooling air supply sizing:

Air supply temperature difference (0 for no sizing) K: 8.00

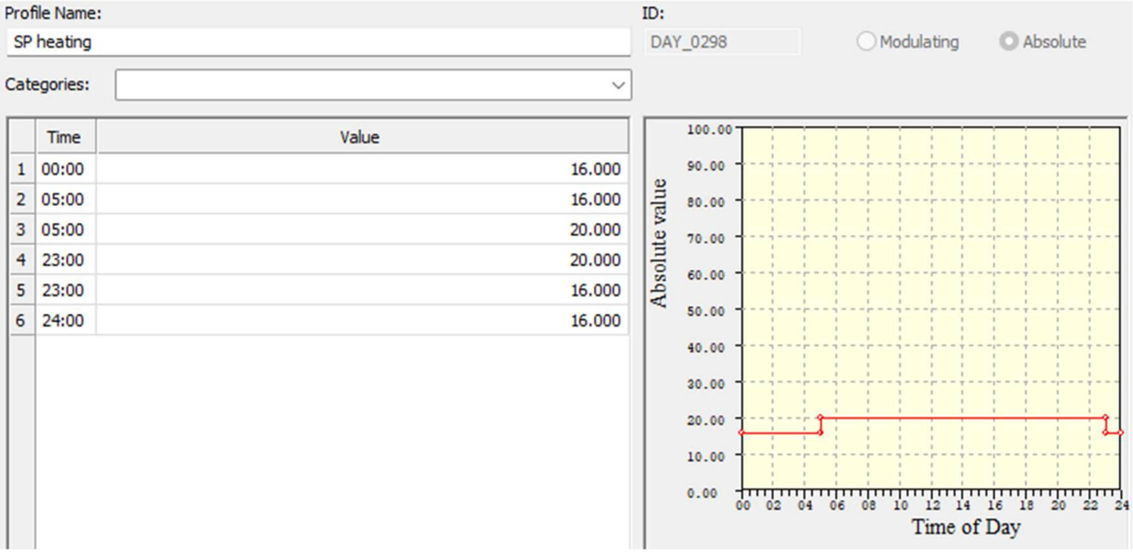
Maximum flow rate l/s: 0.00

Figure 17 System's settings

At this point, the system modelling proceeds with the creation of the operational profile. In fact, heating, cooling and DHW are not delivered each single day of the year in the same quantity: for this reason, it must be set when each service is provided during the day but also throughout the year.

<u>Heating operational profile</u>

Starting from the daily heating profile, reported in the Figure 18, it can be seen that it is an absolute profile called "SP heating", where room internal temperature does not drop below the 20 °C from 5 a.m. to 23 p.m., while during night hours it can go down to the limit at 16 °C.



Profile Name: SP heating

ID: DAY_0298

○ Modulating ● Absolute

Categories:

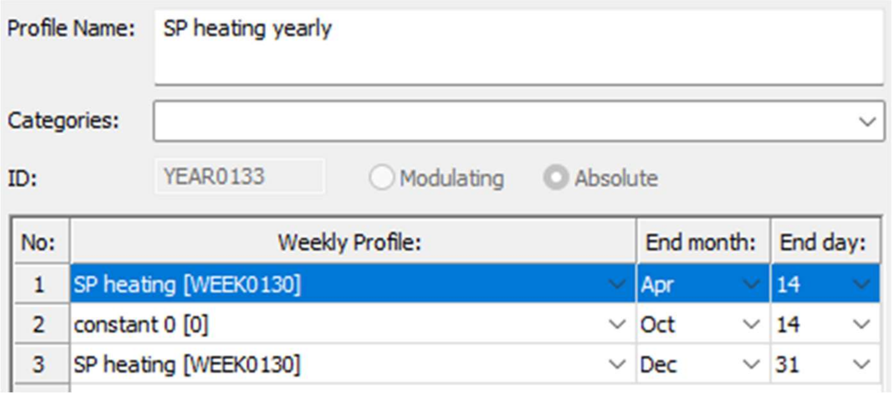
	Time	Value
1	00:00	16.000
2	05:00	16.000
3	05:00	20.000
4	23:00	20.000
5	23:00	16.000
6	24:00	16.000

Figure 18 Daily heating operational profile

On the other hand, a fictitious profile of a constant temperature of 0 °C is created under the name "constant0", in order to have a reference profile to assign during months in which heating is not delivered.

Then, the barely mentioned daily profiles are assigned to two weekly profiles, setting the same trend for all the days of the week, dealing with a residence where occupancy is potentially year-round.

In conclusion, a yearly profile called “SP heating yearly” is created, setting the heating activation from the 15th of October to the 14th of April, and turning off the system the rest of the year, in accordance with the DPR 412/93 for the climatic zone E.



Profile Name: SP heating yearly

Categories:

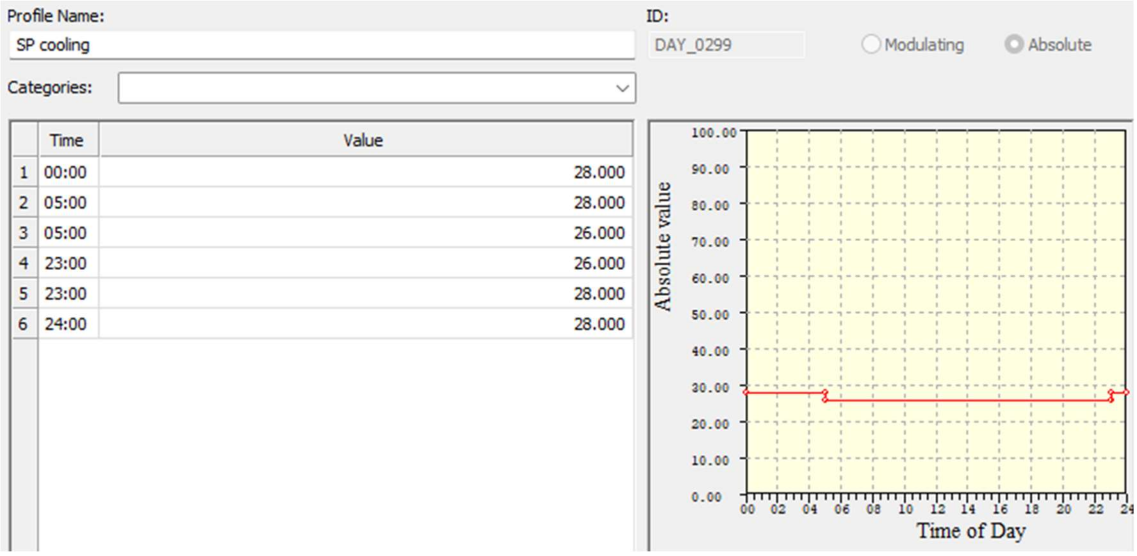
ID: YEAR0133 ○ Modulating ● Absolute

No:	Weekly Profile:	End month:	End day:
1	SP heating [WEEK0130]	Apr	14
2	constant 0 [0]	Oct	14
3	SP heating [WEEK0130]	Dec	31

Figure 19 Annual heating operational profile

<u>Cooling operational profile</u>

In parallel, the cooling profile was created following the same steps. However, unlike the previous profile, cooling is set daily so that the temperature of the room does not exceed 26°C during the day, and the 28°C during the night, as shown in the graph below.



Profile Name: SP cooling

ID: DAY_0299 ○ Modulating ● Absolute

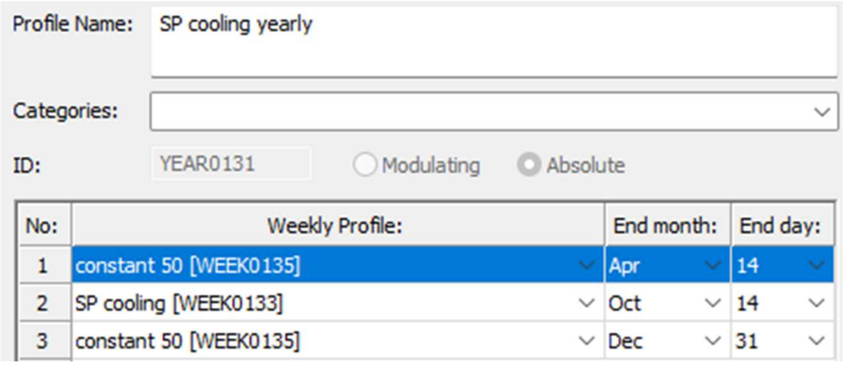
Categories:

	Time	Value
1	00:00	28.000
2	05:00	28.000
3	05:00	26.000
4	23:00	26.000
5	23:00	28.000
6	24:00	28.000

Figure 20 Daily cooling operational profile

Also in this case, a fictitious daily profile is required to turn off the system in months when it is not required. So, the profile “constant50” is created: it sets a fixed temperature of 50°C, which is impossible to reach inside the building.

At this point, once assigned daily profile to the weekly profile of the same name, a yearly profile called “SP cooling yearly” is created: as shown in Figure 21, the cooling is provided from the 15th of April to the 14th of October, referring to the Italian regulations.



Profile Name: SP cooling yearly

Categories:

ID: YEAR0131 ○ Modulating ● Absolute

No:	Weekly Profile:	End month:	End day:
1	constant 50 [WEEK0135]	Apr	14
2	SP cooling [WEEK0133]	Oct	14
3	constant 50 [WEEK0135]	Dec	31

Figure 21 Annual cooling operational profile

<u>DHW profile</u>

For the domestic hot water, the modelling is different, considering that the delivery of the service does not vary in relation to the season, but it is the same each day of the year, but it varies during the hours of the day. So, the quantity of DHW required by occupants is set in relation to the occupancy of the building, considering an average need of 40 l/(d*pers), split during the day as 2,88 l/(h* pers).

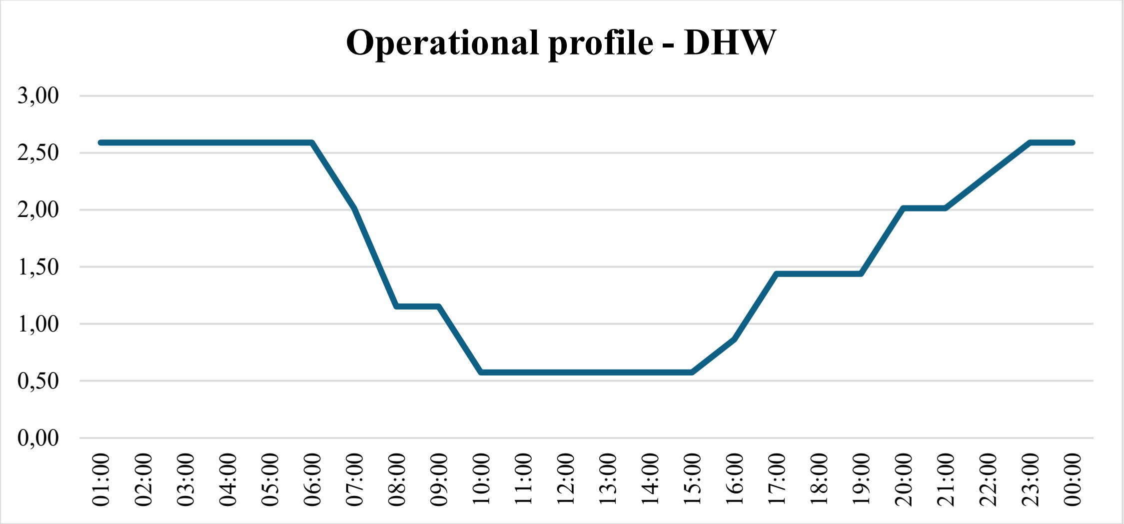


Figure 22 Daily DHW operational profile

Photovoltaic system

Since the presence of PVs (Photovoltaic system) is mandatory, the system installation is also planned in this project. These panels are free standing, with an installed peak PV power of 22 kWp, with panels of dimension of 1,8 m^2 of 440 kW each one, for an amount of 50 modules, which cover an area of 90 m^2, located on the courtyard of the complex of buildings as represented in Figure 23.

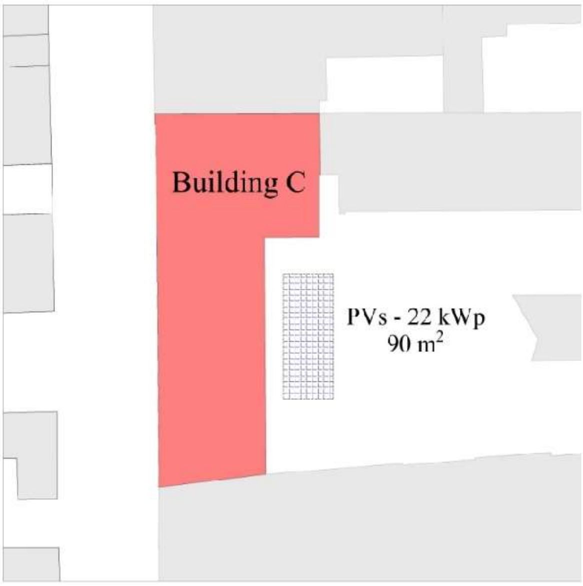


Figure 23 PVs 22kWp location

The monthly electrical energy producibility of the system is reported in Table 2.

Month	Average monthly electricity production [kWh]
Jan	1944,8
Feb	2048,2
Mar	2690,6
Apr	2728
May	2893
Jun	2994,2
Jul	3282,4
Aug	3108,6
Sep	2622,4
Oct	2010,8
Nov	1634,6
Dec	1702,8

Table 2 Average monthly electricity production of 22 kWp PV system

To provide a clearer view of this data, a bar chart is also available in the following figure: obviously the producibility of the Photovoltaic System will be higher in summer months when there will be a greater amount of solar radiation.

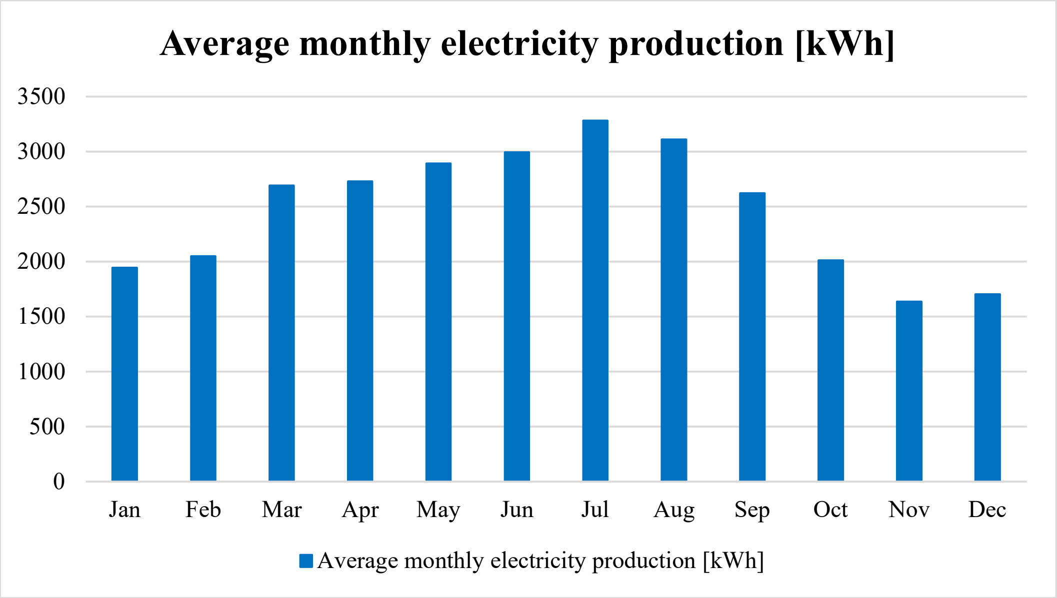


Figure 24 Average monthly electricity production histogram of 22 kWp PV system

So, since the output of the simulations will provide electricity demand of the building, the energy which comes from the PVs has to be subtracted to this demand, to get a correct estimation of the annual electricity required from the power grid.

Simulations

Once the building and its system have been created inside the software, the model is ready for simulation, except for the selection of the weather file, which is chosen based on the specific analyzed scenario time-by-time.

To facilitate results interpretation, it was necessary to code the simulations, referring to the following method.

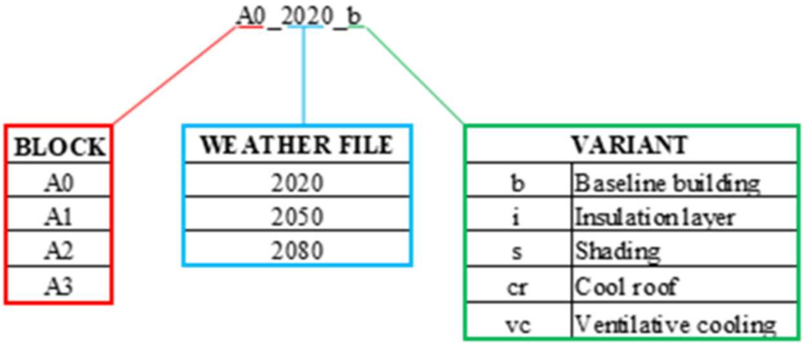


Figure 25 Explanatory scheme of the simulation's nomenclature

Output definition

In order to accurately analyze the results of the simulations made for this study, it was considered appropriate to select a number of parameters to be evaluated in order to have a clear view of all the fundamental aspects which influence and define the building's energy performance. This led to the selection of parameters described in the following paragraphs.

The first parameters to be extrapolated from the analysis are $EP_{h,nd}$ and $EP_{c,nd}$ in order to get an overview of the building's heating and cooling requirements. The values will be normalized with the conditioned useful surface area of 1247 m^2, giving a value of kWh/m^2. Where:

- $EP_{c,nd}$: is the useful thermal energy demand of the building for cooling, normalized with respect to the conditioned useful surface area of the building,
- $EP_{h,nd}$: is the useful heat energy demand of the building for heating, normalized with respect to the conditioned useful surface area of the building.

The second useful output for analyzing building performance is the graph of peak values for the 2 middle weeks of January for the heating load, and of July for the cooling load. In this case, the values will be in kW on an hourly basis, relative to the middle 15 days of the above-mentioned months, in order to visualize the specific behavior of the building with values that are not normalized with respect to the conditioned surface.

The third and last parameter to consider during the evaluation of the energy simulation results is the internal temperature of two bedrooms, in order to highlight how the system setpoints influence it. For the longitudinal development of the building considered, it was deemed appropriate to investigate the internal temperature of a room on the North side and a room on the South, in order to also assess how the parameter varies according to orientation.

In particular, the chosen bedrooms are the *C_P0_BED9* for the South and the *C_P0_BED15* for the North, both on the ground floor, located as shown in the following plan.

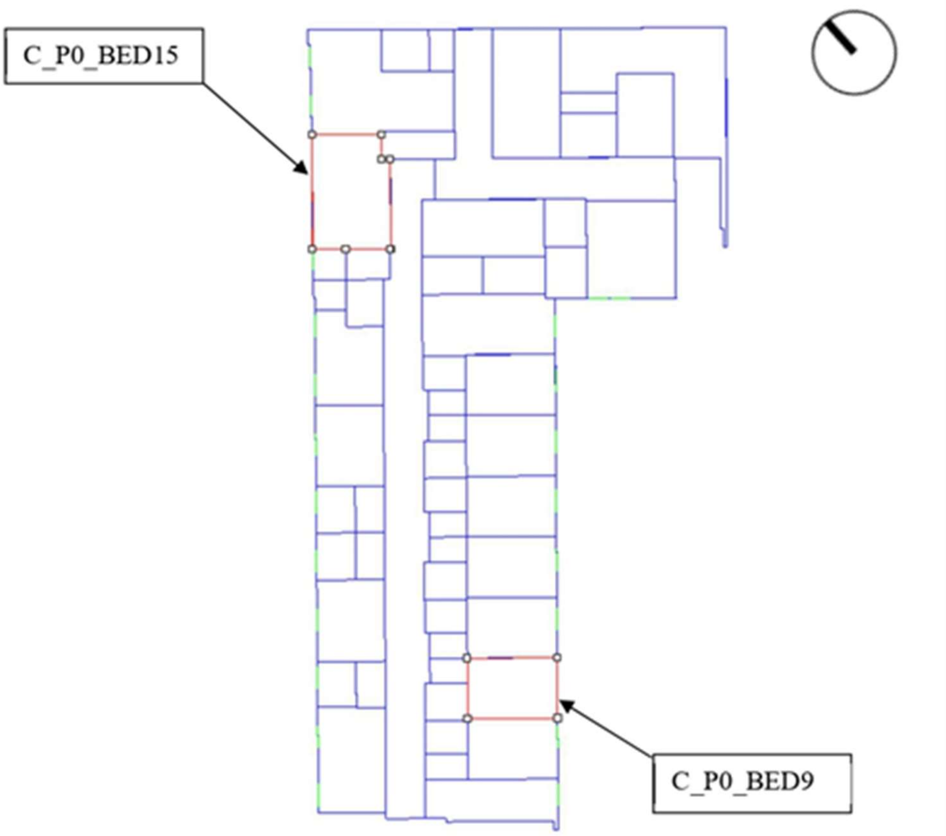


Figure 26 Rooms location in ground floor plan

For this output, the selected periods of time which would be analyzed are the two middle weeks of January and July, to understand how the temperature inside the room varies respectively in mid-winter and in mid-summer, when the weather outside reaches positive and negative peak temperatures. Moreover, the deep understanding of the internal temperature concerns also the investigation during the mid-seasons: for this reason, the variation of this parameter during the two middle weeks of May and October is also reported, when temperature fluctuations are expected.

Furthermore, since during the analysis of the results, the evaluation of electricity consumption also takes place, in relation to the contribution made by the presence of the photovoltaic system, an in-depth study of the building's consumption is added to these parameters. In particular, consumptions related to heating, cooling, domestic hot water and lighting are taken into consideration and transformed into primary energy using the conversion factors provided by the DM 26/06/2015 Minimum Requirements.

6.1. Baseline building

In this chapter, the features of the baseline building as designed are described in detail, with the aim of providing a comprehensive understanding of the starting point of the analysis. By thoroughly outlining the building's characteristics, such as its stratigraphies and materials used, this section offers a clear reference for comparing and contrasting the various variants that will be presented later. This detailed description serves as a foundation for the analysis, ensuring that any subsequent changes or adaptations can be better understood in relation to the initial design, allowing for a more informed evaluation of their impact and effectiveness.

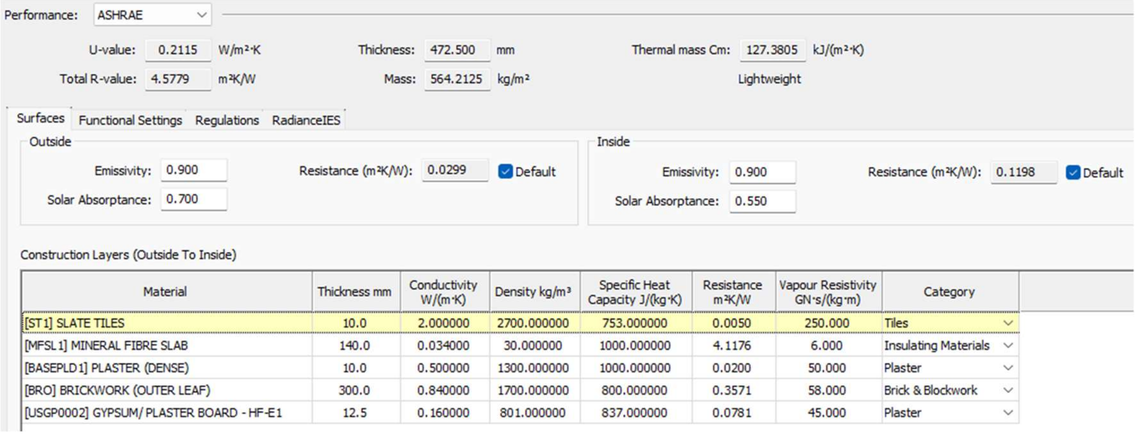
Envelope description

As described in the first part of Chapter 6, the geometric model consists also in the stratigraphies assignment to each construction component. In this chapter the construction components are described in detail.

External wall

The design external wall, since it is a renovation of an existing building, includes an external layer of thermal insulation, made of a stone wool panel with a thickness of 14cm, as shown in Figure 27.

The whole of the layers results in a thermal transmittance of 0.2115 W/m^{2}K.



Performance: ASHRAE

U-value: 0.2115 W/m²·K
Total R-value: 4.5779 m²K/W
Thickness: 472.500 mm
Mass: 564.2125 kg/m²
Thermal mass Cm: 127.3805 kJ/(m²·K)
Lightweight

Outside
Emissivity: 0.900
Solar Absorptance: 0.700
Resistance (m²K/W): 0.0299 ☑ Default

Inside
Emissivity: 0.900
Solar Absorptance: 0.550
Resistance (m²K/W): 0.1198 ☑ Default

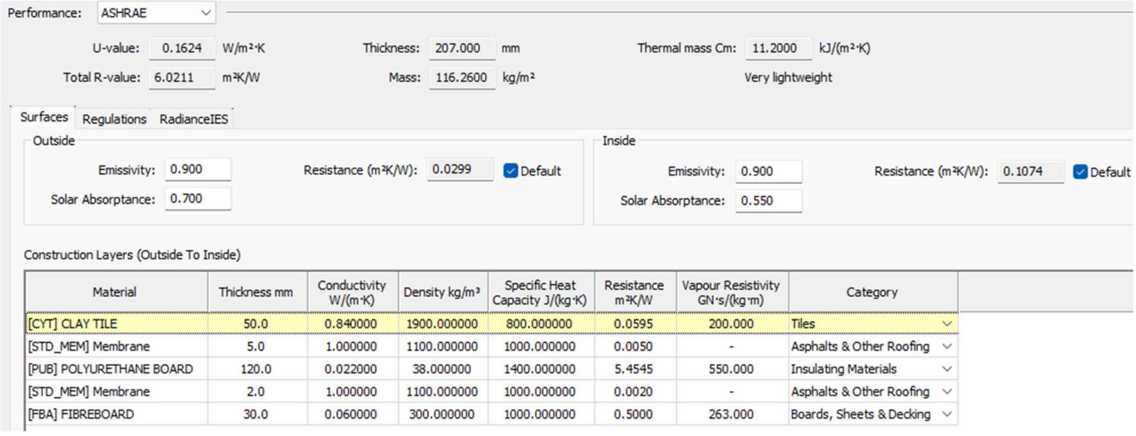
Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[ST1] SLATE TILES	10.0	2.000000	2700.000000	753.000000	0.0050	250.000	Tiles
[MFSL1] MINERAL FIBRE SLAB	140.0	0.034000	30.000000	1000.000000	4.1176	6.000	Insulating Materials
[BASEPLD1] PLASTER (DENSE)	10.0	0.500000	1300.000000	1000.000000	0.0200	50.000	Plaster
[BRO] BRICKWORK (OUTER LEAF)	300.0	0.840000	1700.000000	800.000000	0.3571	58.000	Brick & Blockwork
[USGP0002] GYPSUM/ PLASTER BOARD - HF-E1	12.5	0.160000	801.000000	837.000000	0.0781	45.000	Plaster

Figure 27 External wall stratigraphy

Roof

The roof of the building in question is a traditional roof consisting of an outer insulation layer, included in the insulation strategy, and an outer tile covering as result, the thermal transmittance of this construction component is equal to 0.1624 W/m^{2}K.



Performance: ASHRAE

U-value: 0.1624 W/m²·K

Total R-value: 6.0211 m²K/W

Thickness: 207.000 mm

Mass: 116.2600 kg/m²

Thermal mass Cm: 11.2000 kJ/(m²·K)

Very lightweight

Outside

Emissivity: 0.900

Solar Absorptance: 0.700

Resistance (m²K/W): 0.0299 ☑ Default

Inside

Emissivity: 0.900

Solar Absorptance: 0.550

Resistance (m²K/W): 0.1074 ☑ Default

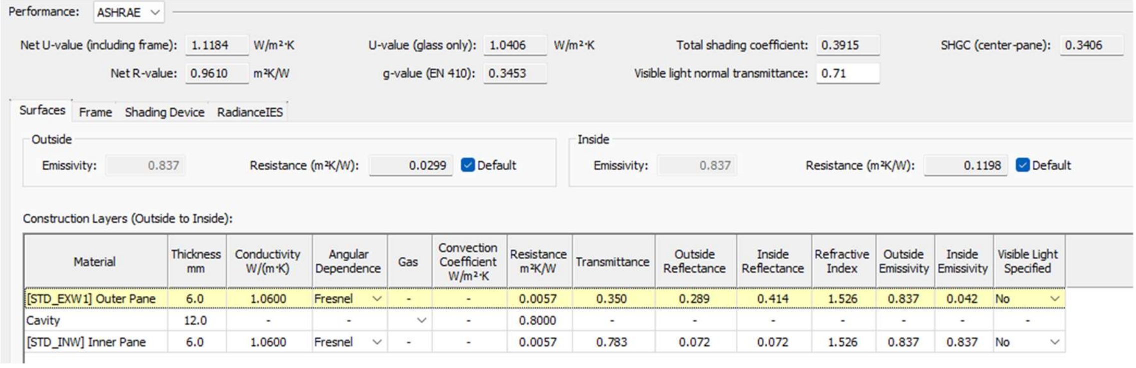
Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[CYT] CLAY TILE	50.0	0.840000	1900.000000	800.000000	0.0595	200.000	Tiles
[STD_MEM] Membrane	5.0	1.000000	1100.000000	1000.000000	0.0050	-	Asphalts & Other Roofing
[PUB] POLYURETHANE BOARD	120.0	0.022000	38.000000	1400.000000	5.4545	550.000	Insulating Materials
[STD_MEM] Membrane	2.0	1.000000	1100.000000	1000.000000	0.0020	-	Asphalts & Other Roofing
[FBA] FIBREBOARD	30.0	0.060000	300.000000	1000.000000	0.5000	263.000	Boards, Sheets & Decking

Figure 28 Roof stratigraphy

External glazing

As far as glazed elements are concerned, the project includes the use of windows and doors composed of a high-performance double-glazing and a 12 mm dividing cavity. Its characteristic parameters are a thermal transmittance of 1.1184 W/m^{2}K and a g-value of 0.345.



Performance: ASHRAE

Net U-value (including frame): 1.1184 W/m²·K

Net R-value: 0.9610 m²K/W

U-value (glass only): 1.0406 W/m²·K

g-value (EN 410): 0.3453

Total shading coefficient: 0.3915

Visible light normal transmittance: 0.71

SHGC (center-pane): 0.3406

Outside

Emissivity: 0.837

Resistance (m²K/W): 0.0299 ☑ Default

Inside

Emissivity: 0.837

Resistance (m²K/W): 0.1198 ☑ Default

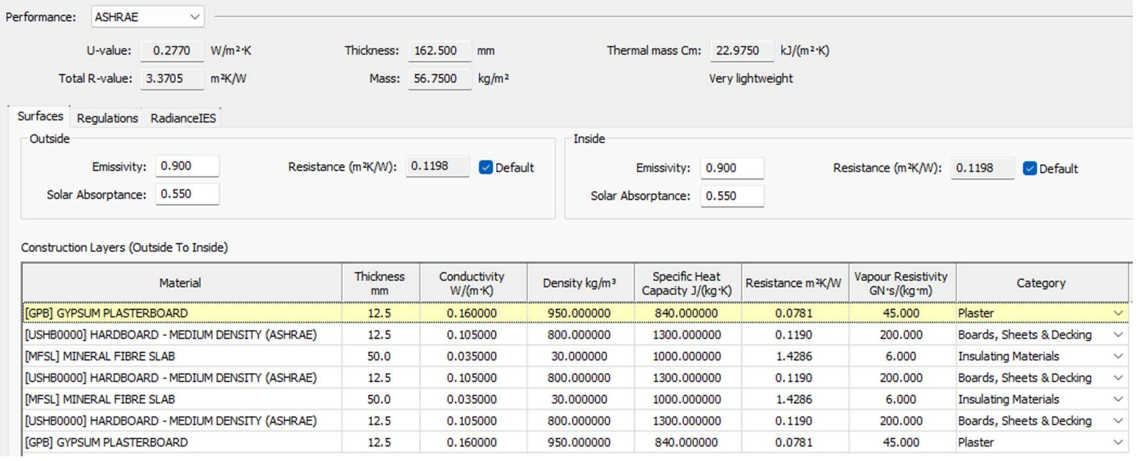
Construction Layers (Outside to Inside):

Material	Thickness mm	Conductivity W/(m·K)	Angular Dependence	Gas	Convection Coefficient W/m²·K	Resistance m²K/W	Transmittance	Outside Reflectance	Inside Reflectance	Refractive Index	Outside Emissivity	Inside Emissivity	Visible Light Specified
[STD_EXW1] Outer Pane	6.0	1.0600	Fresnel	-	-	0.0057	0.350	0.289	0.414	1.526	0.837	0.042	No
Cavity	12.0	-	-		-	0.8000	-	-	-	-	-	-	-
[STD_INW] Inner Pane	6.0	1.0600	Fresnel	-	-	0.0057	0.783	0.072	0.072	1.526	0.837	0.837	No

Figure 29 Glazed element stratigraphy

Internal partition

For the internal partitions, the design envisages a stratigraphy composed of two double sheets of plasterboard, separated by two layers of insulating material.



Performance: ASHRAE

U-value: 0.2770 W/m²·K
Total R-value: 3.3705 m²K/W
Thickness: 162.500 mm
Mass: 56.7500 kg/m²
Thermal mass Cm: 22.9750 kJ/(m²·K)
Very lightweight

Outside
Emissivity: 0.900
Solar Absorptance: 0.550
Resistance (m²K/W): 0.1198 ☑ Default

Inside
Emissivity: 0.900
Solar Absorptance: 0.550
Resistance (m²K/W): 0.1198 ☑ Default

Construction Layers (Outside To Inside)

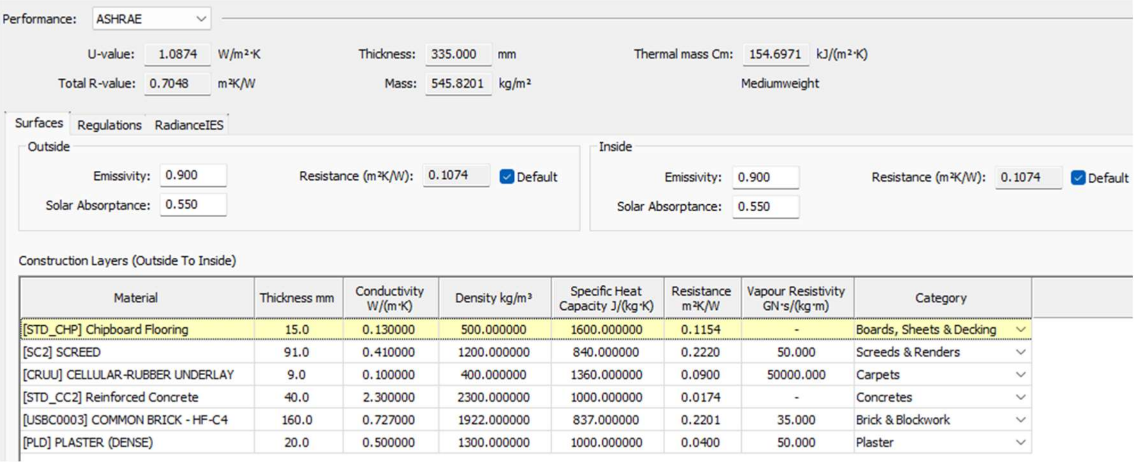
Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[GPB] GYPSUM PLASTERBOARD	12.5	0.160000	950.000000	840.000000	0.0781	45.000	Plaster
[USHB0000] HARDBOARD - MEDIUM DENSITY (ASHRAE)	12.5	0.105000	800.000000	1300.000000	0.1190	200.000	Boards, Sheets & Decking
[MFSL] MINERAL FIBRE SLAB	50.0	0.035000	30.000000	1000.000000	1.4286	6.000	Insulating Materials
[USHB0000] HARDBOARD - MEDIUM DENSITY (ASHRAE)	12.5	0.105000	800.000000	1300.000000	0.1190	200.000	Boards, Sheets & Decking
[MFSL] MINERAL FIBRE SLAB	50.0	0.035000	30.000000	1000.000000	1.4286	6.000	Insulating Materials
[USHB0000] HARDBOARD - MEDIUM DENSITY (ASHRAE)	12.5	0.105000	800.000000	1300.000000	0.1190	200.000	Boards, Sheets & Decking
[GPB] GYPSUM PLASTERBOARD	12.5	0.160000	950.000000	840.000000	0.0781	45.000	Plaster

Figure 30 Internal partition stratigraphy

Internal Ceiling/Floor

As regards inter-floor ceilings, there are two different stratigraphies that stand out inside the building: one for the separation of above-ground floors and another one which divides the basement from the ground floor.

Inter-floor slab



Performance: ASHRAE

U-value: 1.0874 W/m²·K
Total R-value: 0.7048 m²K/W
Thickness: 335.000 mm
Mass: 545.8201 kg/m²
Thermal mass Cm: 154.6971 kJ/(m²·K)
Mediumweight

Outside
Emissivity: 0.900
Solar Absorptance: 0.550
Resistance (m²K/W): 0.1074 ☑ Default

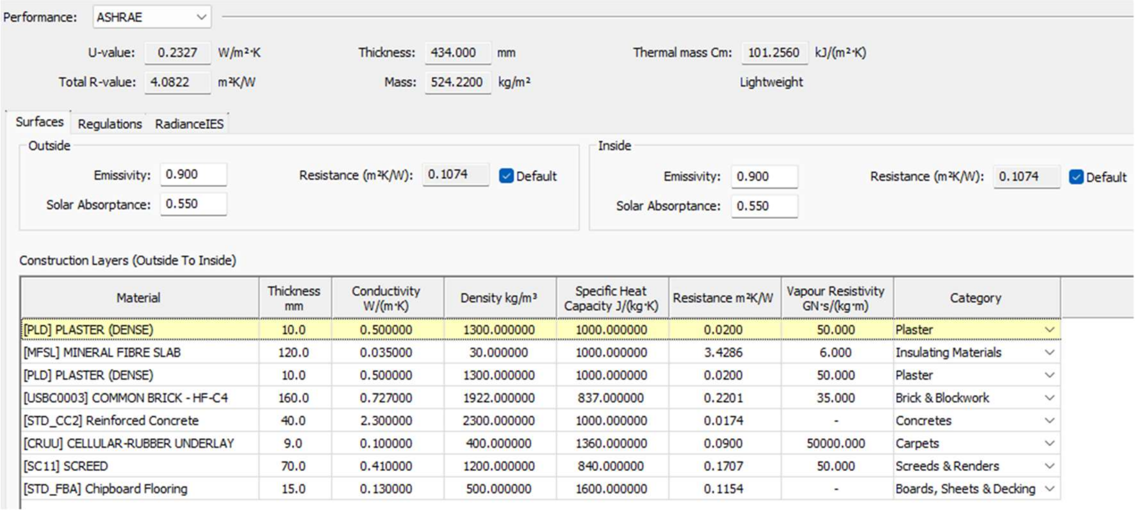
Inside
Emissivity: 0.900
Solar Absorptance: 0.550
Resistance (m²K/W): 0.1074 ☑ Default

Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[STD_CHP] Chipboard Flooring	15.0	0.130000	500.000000	1600.000000	0.1154	-	Boards, Sheets & Decking
[SC2] SCREED	91.0	0.410000	1200.000000	840.000000	0.2220	50.000	Screeds & Renders
[CRUU] CELLULAR-RUBBER UNDERLAY	9.0	0.100000	400.000000	1360.000000	0.0900	50000.000	Carpets
[STD_CC2] Reinforced Concrete	40.0	2.300000	2300.000000	1000.000000	0.0174	-	Concretes
[USBC0003] COMMON BRICK - HF-C4	160.0	0.727000	1922.000000	837.000000	0.2201	35.000	Brick & Blockwork
[PLD] PLASTER (DENSE)	20.0	0.500000	1300.000000	1000.000000	0.0400	50.000	Plaster

Figure 31 Inter-floor slab stratigraphy

Slab basement-ground floor



Performance: ASHRAE

U-value: 0.2327 W/m²·K

Total R-value: 4.0822 m²K/W

Thickness: 434.000 mm

Mass: 524.2200 kg/m²

Thermal mass Cm: 101.2560 kJ/(m²·K)

Lightweight

Outside

Emissivity: 0.900

Solar Absorptance: 0.550

Resistance (m²K/W): 0.1074 ☑ Default

Inside

Emissivity: 0.900

Solar Absorptance: 0.550

Resistance (m²K/W): 0.1074 ☑ Default

Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[PLD] PLASTER (DENSE)	10.0	0.500000	1300.000000	1000.000000	0.0200	50.000	Plaster
[MFSL] MINERAL FIBRE SLAB	120.0	0.035000	30.000000	1000.000000	3.4286	6.000	Insulating Materials
[PLD] PLASTER (DENSE)	10.0	0.500000	1300.000000	1000.000000	0.0200	50.000	Plaster
[USBC0003] COMMON BRICK - HF-C4	160.0	0.727000	1922.000000	837.000000	0.2201	35.000	Brick & Blockwork
[STD_CC2] Reinforced Concrete	40.0	2.300000	2300.000000	1000.000000	0.0174	-	Concretes
[CRUU] CELLULAR-RUBBER UNDERLAY	9.0	0.100000	400.000000	1360.000000	0.0900	50000.000	Carpets
[SC11] SCREED	70.0	0.410000	1200.000000	840.000000	0.1707	50.000	Screeds & Renders
[STD_FBA] Chipboard Flooring	15.0	0.130000	500.000000	1600.000000	0.1154	-	Boards, Sheets & Decking

Figure 32 Slab basement-ground floor stratigraphy

AO – Output

In this section all the outputs that come from the simulation of the baseline building are reported in order to have a clear view of which is the starting point of the analysis. The study of these results begins with the useful thermal energy demand of the building for heating and cooling each meter square.

Heating

The first graph reported is the monthly thermal energy demand for heating, comparing each month the results of the three different weather scenarios. As it can be seen, the histogram exactly respects the operating profile set for heating system, which is in use from the 15th of October to the 14th of April and thus keeps the $EP_{h,nd}$ equal to zero for the rest of the year.

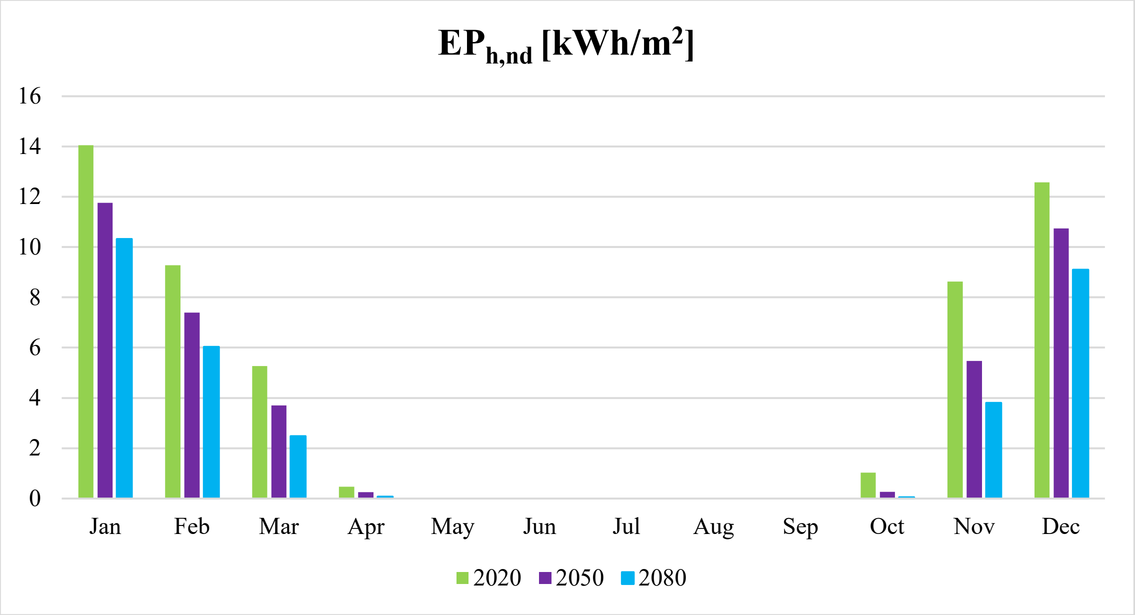


Figure 33 Monthly useful thermal performance index for winter heating - A0

Another clear trend, especially from the summary histogram of the annual results (Figure 34), is that the heating need of the building will be lower and lower as the years go by, due precisely to the rising temperatures.

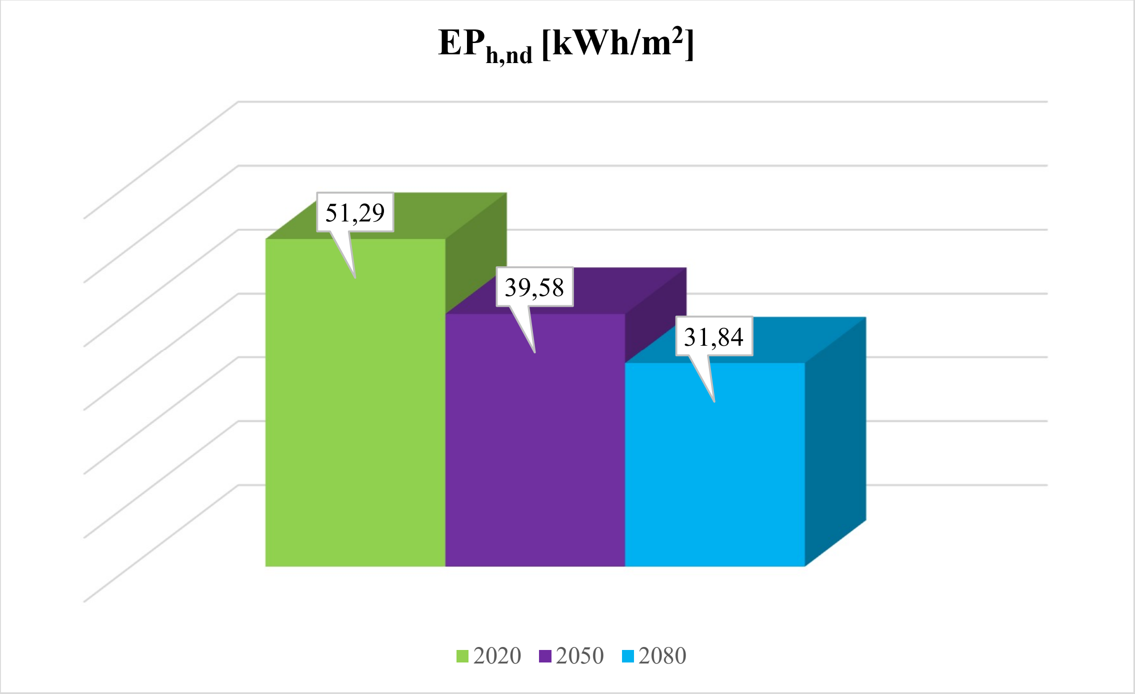


Figure 34 Annual useful thermal performance index for winter heating - A0

The second type of results which it can be useful to observe are the peak values of the sensible load (kW) during the two middle weeks of January for the heating.

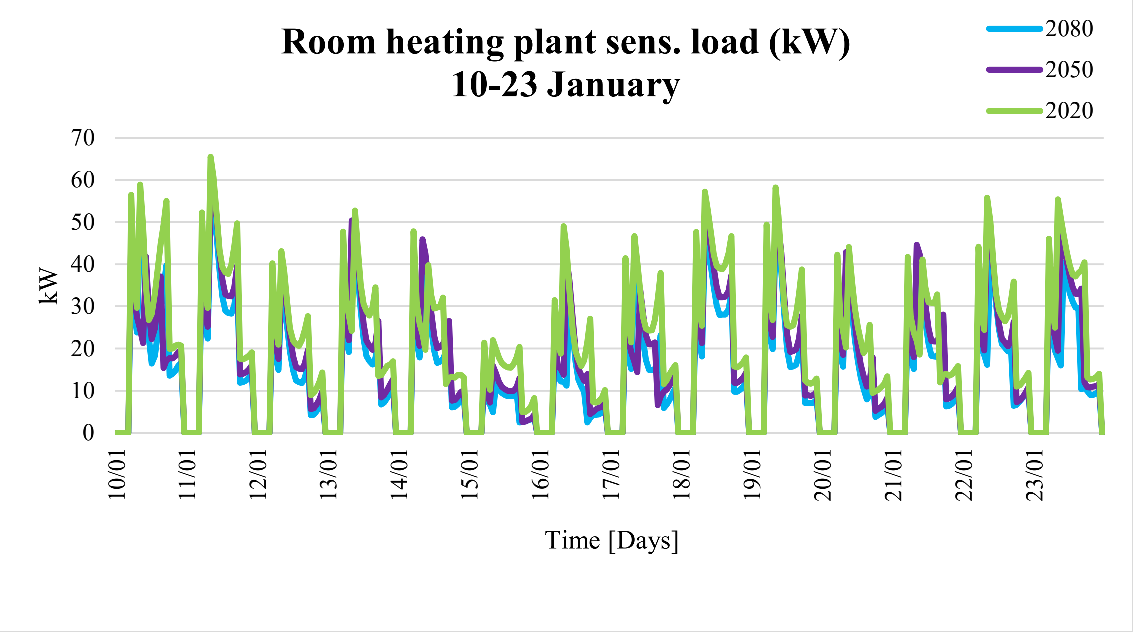


Figure 35 Peak values of heating sensible load during 10-23 January

In this first graph, it is evident how peak values are recorded during the current scenario, while the middle-term and the long-term situations show a reduction.

<u>Cooling</u>

The monthly cooling demand also respect the operating profile of the cooling system, so from 15th April to 14th October.

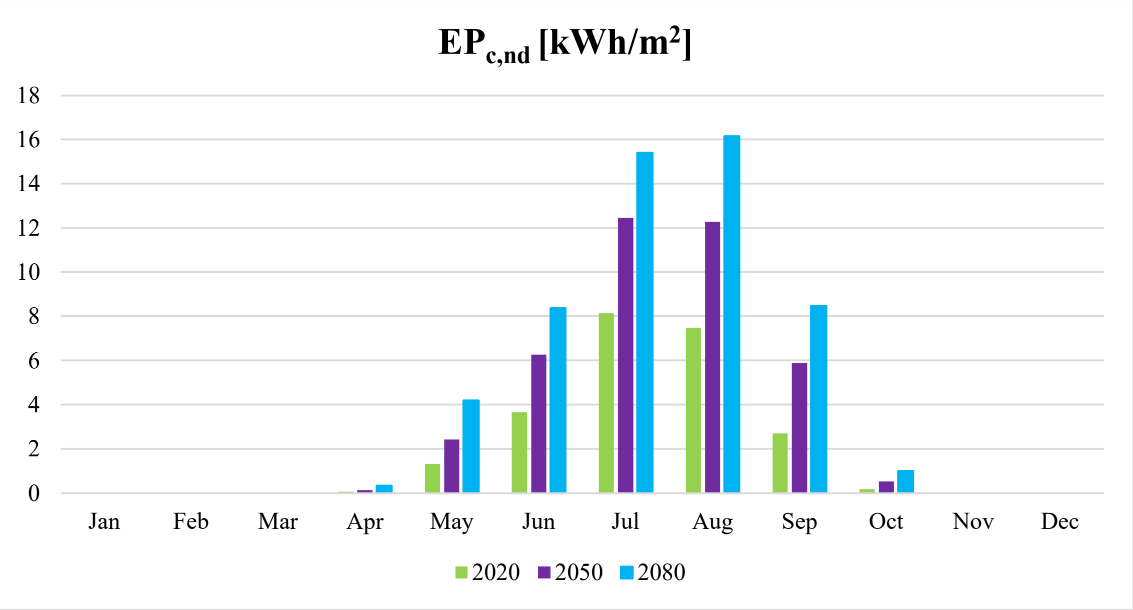


Figure 36 Monthly useful thermal performance index for cooling - A0

In comparison to heating, however, the trend is upward over the years, reaching an annual peak of 53.92 kWh/m^2 in 2080.

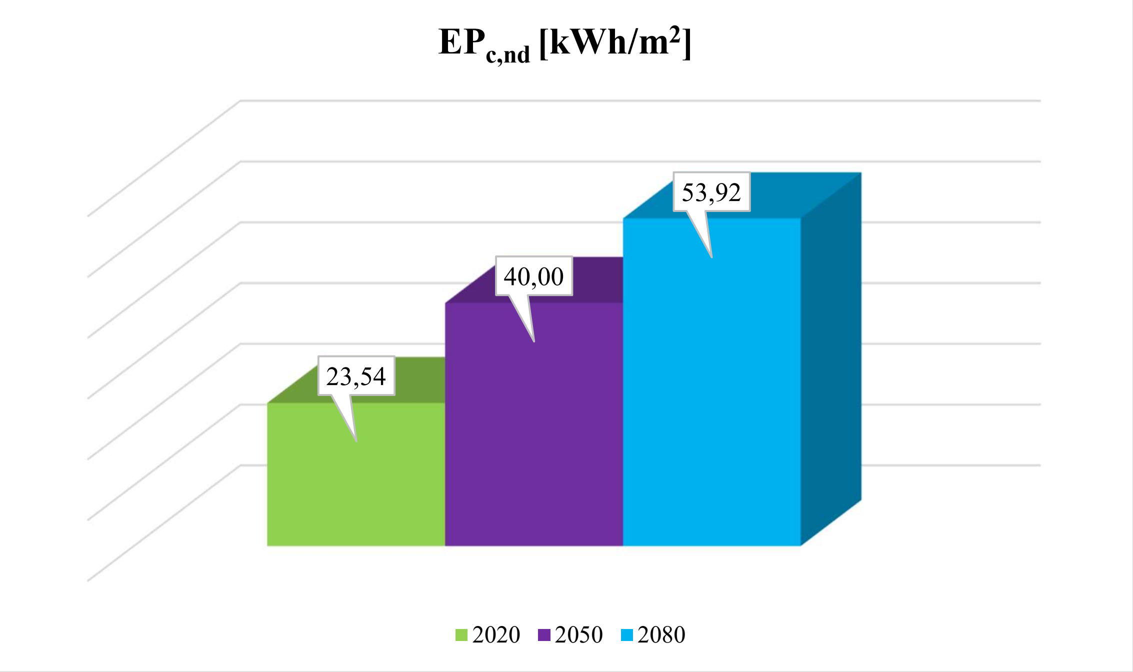


Figure 37 Annual useful thermal performance index for cooling - A0

Also in this case, it is useful to observe peak values of the sensible load (kW) during the two middle weeks of July for the cooling.

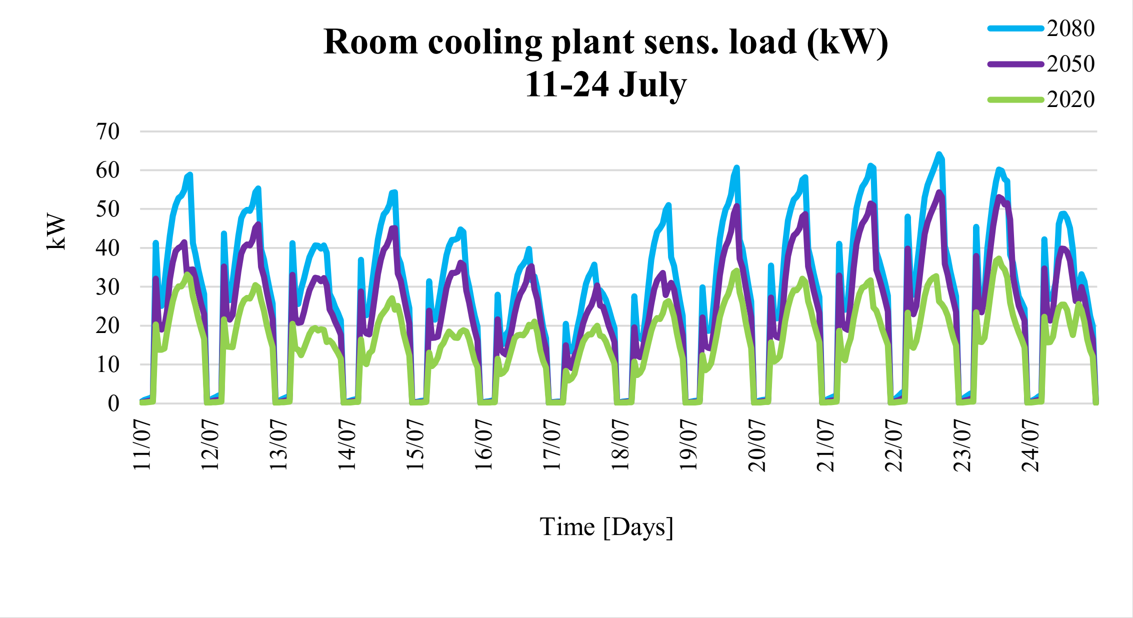


Figure 38 Peak values of cooling sensible load during 11-24 July

For the cooling, the opposite condition is represented, peaks during the long-term scenario, reaching the 60-kW threshold in 2080 for six days in row.

Results heating and cooling

Having defined the heating and cooling needs of the building, it is helpful to evaluate the $EP_{h,nd}$ and $EP_{c,nd}$ parameters together to understand the variation of them in different weather scenarios.

In the graph shown in Figure 39, it can be seen how the situation evolves under the three climate scenarios in relation to energy needs for heating and cooling. In particular, with the same model, a gradual reduction in heating needs can be seen, while cooling needs increase exponentially over 50 years. This phenomenon can be attributed to ongoing climate change, which leads to an increase in average temperatures, thus leading to an increase in the demand for cooling to maintain comfortable environmental conditions in buildings, while the need for heating decreases due to milder winters. As a result, it can be deduced that not the overall energy demand will change, but rather the dominant energy use will switch from heating to cooling.

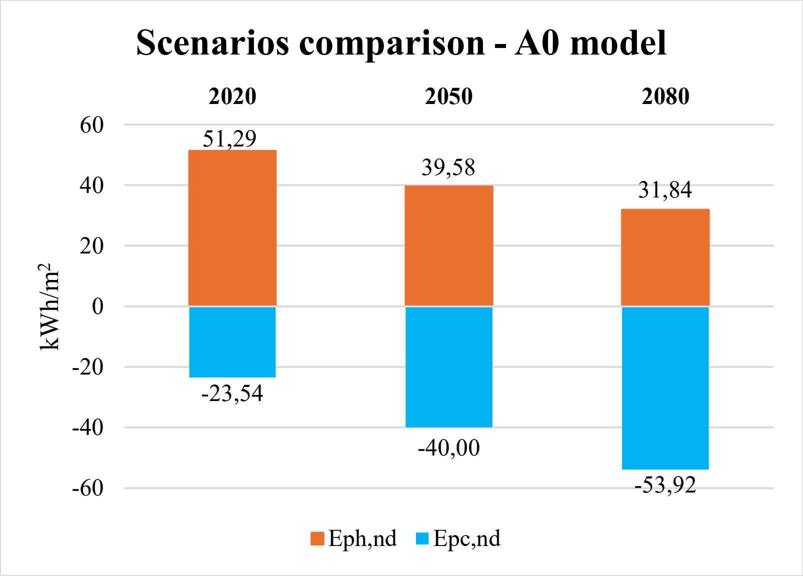


Figure 39 $EP_{h,nd}$ and $EP_{c,nd}$ scenarios comparison – A0 model

Electricity consumption

The last key result of the analysis is the electricity consumption required by the building. In fact, since we are only dealing with electric pumps, electricity consumption will be a fundamental parameter in assessing the energy efficiency of the building. In particular, we want to highlight how much electricity of the total required by the building, it is possible to obtain from the photovoltaic panel system and, in terms of primary energy, the percentage of renewable energy in the total.

The analysis of the electricity consumption starts by determining the electricity required for each service. The main uses considered are heating, cooling, domestic hot water (DHW) and lighting, the latter included in the calculation, according to regulations, only for residential buildings.

With regard to the determination of the electrical energy required for heating and cooling: considering that the COP of the heat pump is 3.5, dividing the consumption by this value gives the kWh required by the building each month. In the same way, also the electricity demand for the Domestic Hot Water is computed, obtaining results shown below.

As far as lighting consumption is concerned, this is already electricity consumption, so the output values are taken and reported in the table, without any division.

All these electricity consumptions are reported in Table 3 and represented as bar chart in Figure 40.

Annual electricity consumption contribution [kWh]

Scenario	Heating	Cooling	DHW	Lighting
2020	18272	8387	10331	54257
2050	14099	14251	10331	54257
2080	11341	19209	10331	54257

Table 3 Annual electricity consumption contribution

As it could be seen from the graph below (Figure 40), the lighting consumption constitutes almost the 60% of the overall building electricity demand compared to other services, demonstrating how much it is important the lighting design.

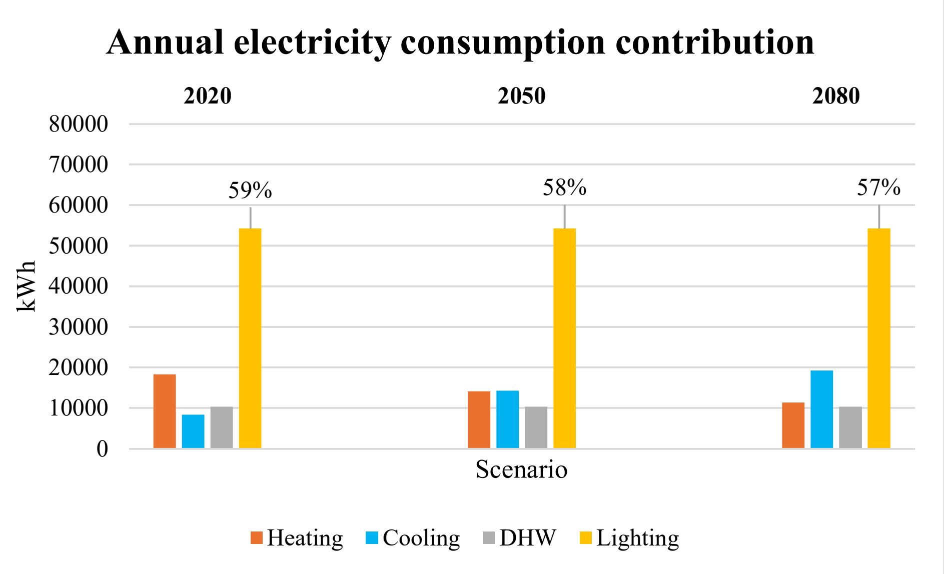


Figure 40 Annual electricity consumption contribution

In view of this, the monthly electricity consumption of the building is obtained from the sum of these four different end-uses mentioned above. The bar graphs in Figures 41, 42 and 43 show, for each month in the three scenarios, a bar obtained from the sum of these contributions (represented with different colors) and next to it the bar of the photovoltaic system's producibility, which covers the requirement of a percentage shown in the graph.

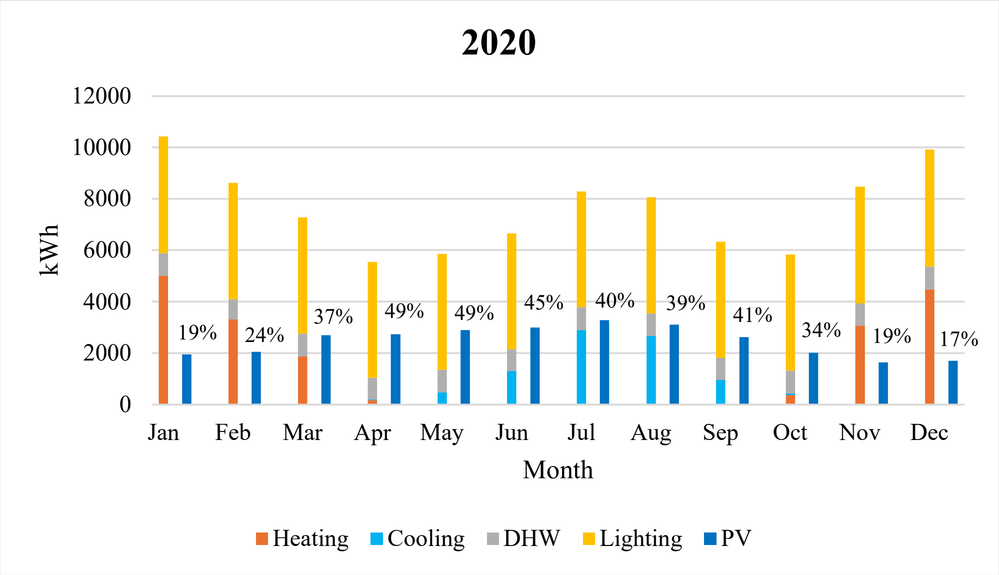


Figure 41 Electricity consumption – A0_2020_b

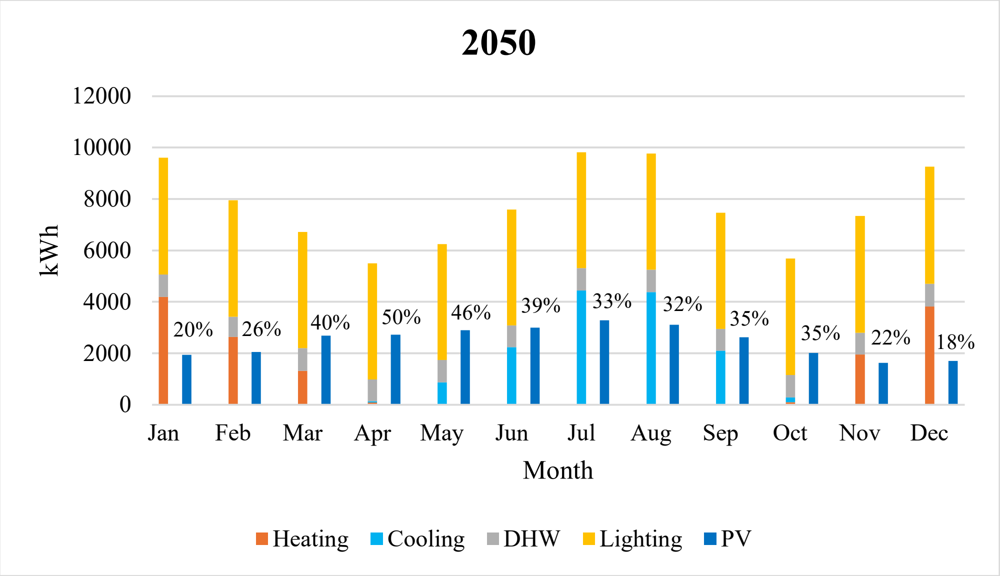


Figure 42 Electricity consumption – A0_2050_b

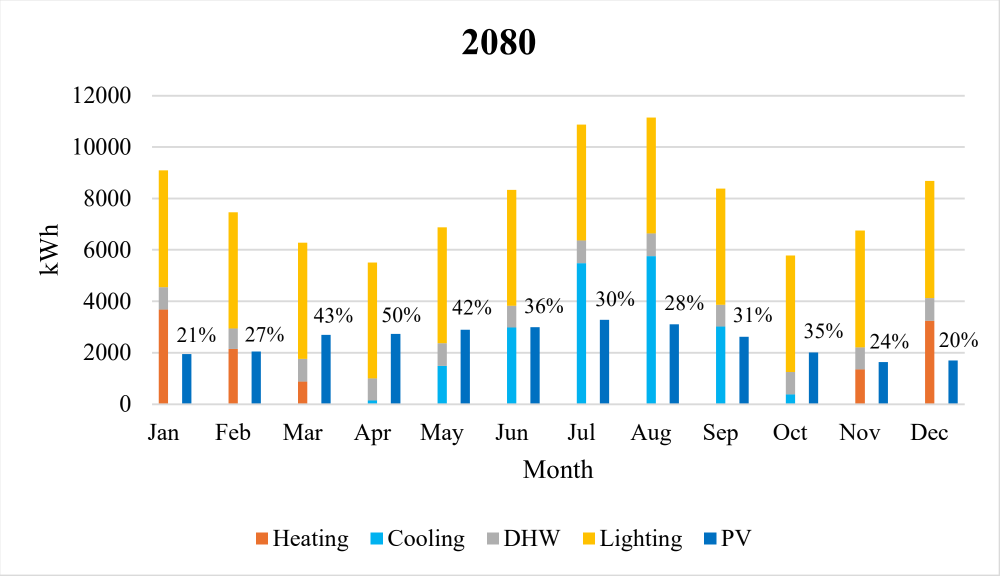


Figure 43 Electricity consumption – A0_2080_b

It can be seen from the charts that, as the photovoltaic output is the same in all scenarios while building's electricity consumption increases in parallel, the percentage of PVs electricity coverage decreases over the years.

Finally, in order to calculate the percentage of renewable energy of the entire system, it is necessary to perform an evaluation in terms of primary energy. This process starts with the previously analyzed electricity consumption and proceeds by subtracting the amount of electricity produced by the photovoltaic system. The resulting value represents the energy required by the electricity grid to meet the overall electricity need of the building under study.

Therefore, the obtained electricity consumption must be multiplied by the primary energy conversion factors, established by DM 26/06/2015 Minimum Requirements, reported in Table 4.

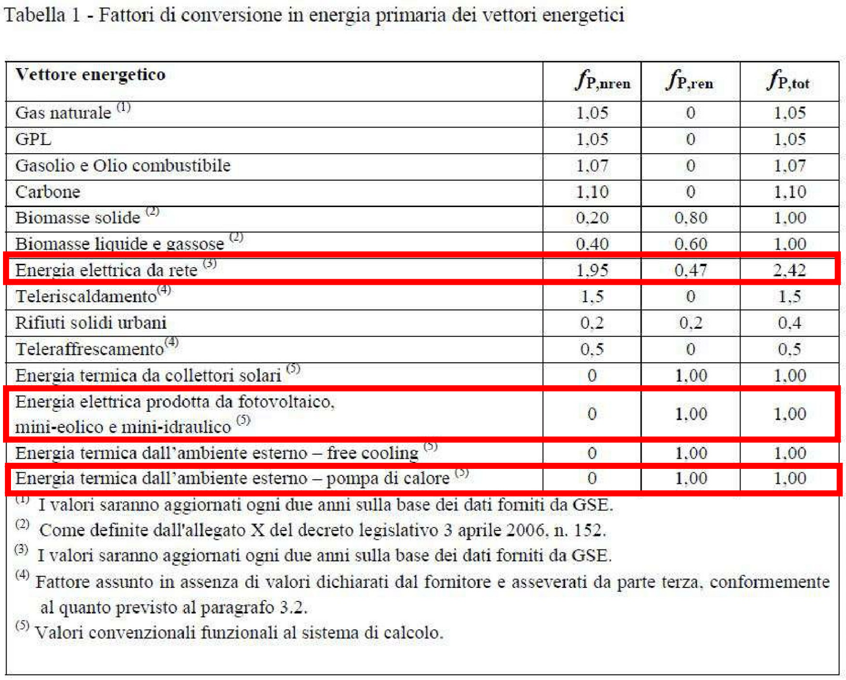


Tabella 1 - Fattori di conversione in energia primaria dei vettori energetici

Vettore energetico	$f_{P,nren}$	$f_{P,ren}$	$f_{P,tot}$
Gas naturale (1)	1,05	0	1,05
GPL	1,05	0	1,05
Gasolio e Olio combustibile	1,07	0	1,07
Carbone	1,10	0	1,10
Biomasse solide (2)	0,20	0,80	1,00
Biomasse liquide e gassose (2)	0,40	0,60	1,00
Energia elettrica da rete (3)	1,95	0,47	2,42
Teleriscaldamento (4)	1,5	0	1,5
Rifiuti solidi urbani	0,2	0,2	0,4
Teleraffrescamento (4)	0,5	0	0,5
Energia termica da collettori solari (5)	0	1,00	1,00
Energia elettrica prodotta da fotovoltaico, mini-eolico e mini-idraulico (5)	0	1,00	1,00
Energia termica dall'ambiente esterno – free cooling (5)	0	1,00	1,00
Energia termica dall'ambiente esterno – pompa di calore (5)	0	1,00	1,00

(1) I valori saranno aggiornati ogni due anni sulla base dei dati forniti da GSE.
(2) Come definite dall'allegato X del decreto legislativo 3 aprile 2006, n. 152.
(3) I valori saranno aggiornati ogni due anni sulla base dei dati forniti da GSE.
(4) Fattore assunto in assenza di valori dichiarati dal fornitore e asseverati da parte terza, conformemente al quanto previsto al paragrafo 3.2.
(5) Valori convenzionali funzionali al sistema di calcolo.

Table 4 Primary energy conversion factor - DM 26/06/2015

The conversion factors taken into account in this primary energy calculation are highlighted in red and they are related to:

- Energy from the grid, which is split into a renewable portion (obtained multiplying the value for 1.95) and a not renewable portion (obtained multiplying the value for 0.47);
- Energy from the Photovoltaic System: 100% renewable;
- Energy of the Heat Pump which comes from the external environment, related only to the heating and DHW consumption: 100% renewable;

Based on these factors, the results of primary energy obtained are summarized in the graph shown in Figure 44.

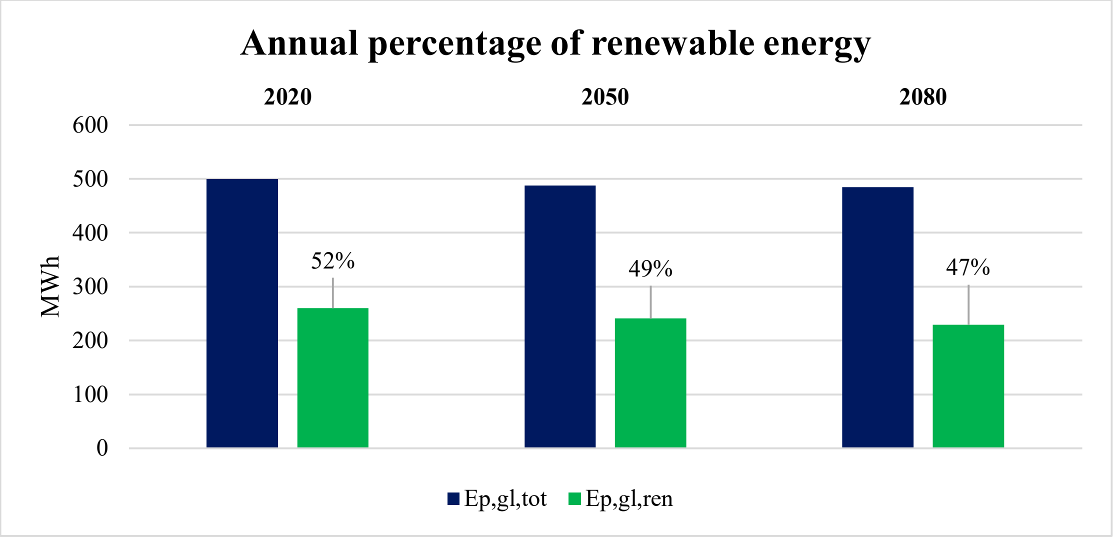


Figure 44 Annual percentage of renewable energy – A0 model

As it can be seen from the bar chart, the percentage of renewable energy decreases over the years, this is because a large part of this is provided by the contribution of the heat pump which is directly proportional to the consumption required by the building. As the share of renewable energy from the heat pump is calculated for heating and hot water consumption only, without considering cooling demand, the gradual decrease in heating demand over time leads to a reduction also in renewable portion of energy concerning it: as a consequence, the percentages show a negative trend over time, as consumption grows due to increased demand for cooling, linked to rising temperatures.

<u>Insight: system off in May and October</u>

For the purpose of the investigation, it was considered interesting to analyse also the behaviour of the temperatures inside the rooms during the months of May and October, i.e. during periods of the year when the use of cooling should be marginal, as there are mid-seasons.

In the following part the room temperature of the bedroom *C_P0_BED15*, located on the North Part of the building, is plotted for the two-middle week of May (Figure 45) and October (Figure 46).

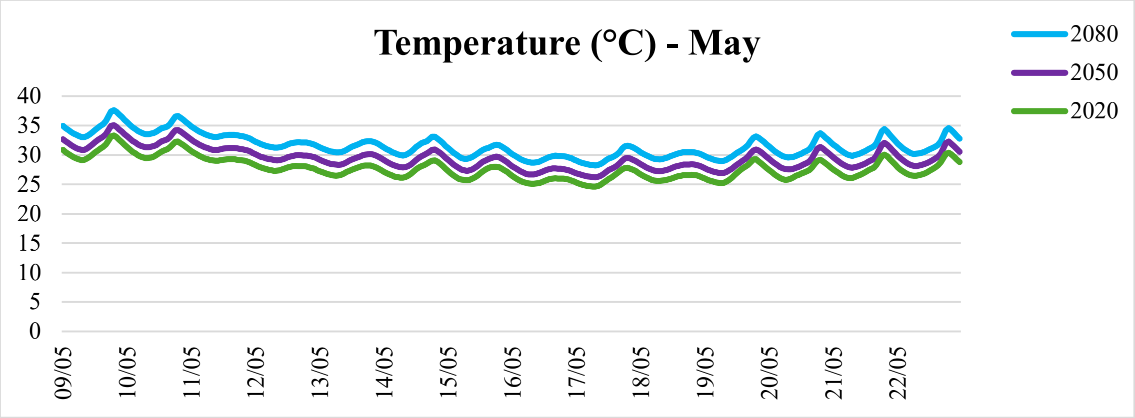


Figure 45 May internal temperature C_P0_BED15 - North side – A0 model

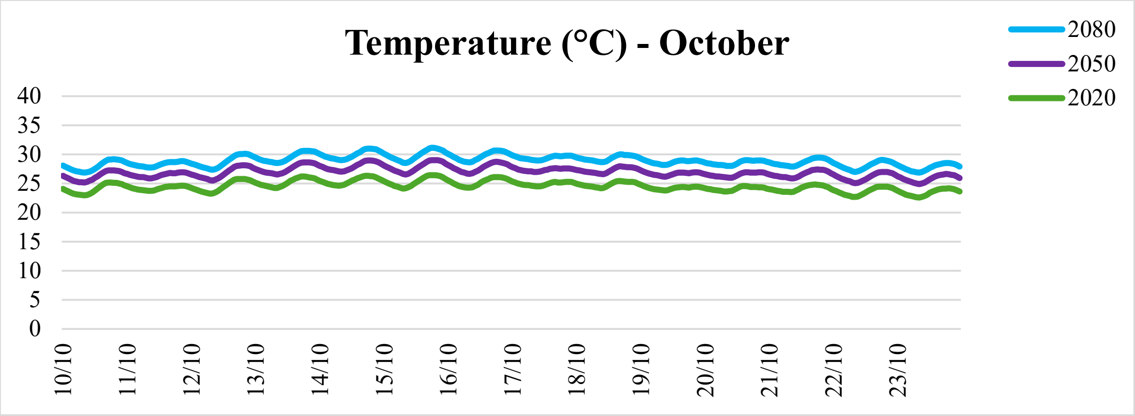


Figure 46 October internal temperature C_P0_BED15 - North side – A0 model

As it can be seen from the graphs above, as the years progress and there is no active cooling system, the temperatures inside the room will tend to rise progressively, becoming more and more unsustainable and requiring ever more energy for cooling. This phenomenon is particularly evident in the context of the climate change predicted for the 2080 scenario, where indoor temperatures could reach extreme peaks of up to 36°C. In particular, the month of May presents itself as one of the most critical periods, with a significant increase in temperatures, putting the well-being and healthiness of the environment at risk, without the system intervention. These scenarios emphasize the importance of adopting energy efficiency solutions to prevent rising temperatures from becoming an increasingly difficult problem to manage in construction sector.

By analysing the room's internal and external loads, it can be identified as the main cause of these temperature peaks the contributions of the internal equipment that keeps the room temperature always above a certain threshold, even when the external environment is not so high.

Another piece of information that emerges from this study concerns the fact that, over the next 50 years, the possibility of turning on the heating system from 15th October onwards may become insignificant. Indeed, in a future scenario of higher temperatures, the need of heating at this time of year will become progressively less important. On the contrary, climate change predictions suggest that there will be an increasing need for cooling systems also in this period of the year. The higher temperatures during the autumn and winter months, predicted by climate scenarios, make traditional heating switch-on schedules obsolete, as it will increasingly be a matter of dealing with heat rather than cold.

This change calls for reflection on the need to review energy policies and climate solutions to meet the challenges of the future, trying also to achieve acceptable internal temperature for occupants' comfort during mid-seasons without the need of activating the cooling system.

6.2. Envelope enhancement

In this chapter starts the building analysis with a first in-depth study aimed at improving building stratigraphies. In particular, the objective is the identification of the most suitable solutions for the layers in this specific case study, considering climate change over the next years. This approach comes to the awareness that energy efficiency and occupant comfort depend on the external envelope capacity of responding appropriately to the new climatic conditions.

So, though targeted research, the aim is to propose solutions that not only improve the building's thermal performance but are also sustainable and adaptable to future scenarios. Specifically, the model variants simulated in this first block of the analysis are referred to two possible conditions:

- Insulation thickness optimization;
- Shading device integration;

In the following paragraphs these variants are described in more depth and outputs are reported.

Insulation thickness optimization

In detail, the first investigation regards the modification of the thermal insulation thickness in order to understand how this parametric variation influences energy consumption results.

Starting from the baseline building with a stratigraphy which contains a stone wool panel of 14 cm as thermal insulation layer, the intention is to study the behavior of the envelope with panels of 8 cm, 10 cm, 12 cm and 16 cm.

The decreasing of the thickness respects the reference building comes from the need of understanding if this reduction implies not sustainable conditions in the short-time scenario, taking into consideration the advantageous effects in the mid-time and the long-time, due to future temperature rises.

Moreover, to complete the parametric analysis, another series of simulations is carried out concerning the possibility of also increasing the thickness of the stone panel to 16 cm, in order to evaluate the building response also in this case. In the table below the thermal transmittance of the potential external wall stratigraphies are listed.

Name (ID)	**U-value (W/m^{2}K)**
ME_i8	0.338
ME_i10	0.282
ME_i12	0.242
ME_i16	0.188

Table 5 list of stratigraphies and their respective thermal transmittance

In the following part, simulations outputs are reported, following the nomenclature, previously explained.

Heating

The graph in Figure 47 summarizes results which come from simulations of the model with the use of the stratigraphies cited above. This first line graph emphasizes an obvious reduction in the heating demand directly proportional to the increase in the thermal insulation thickness.

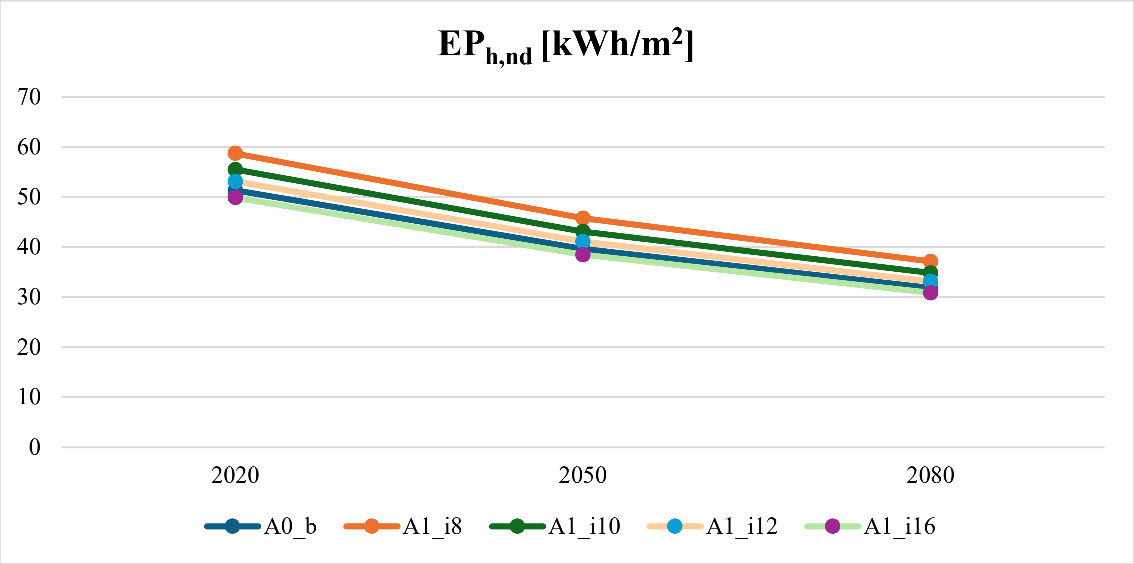


Figure 47 EP$_{h,nd}$ with different stratigraphies applied

So, according to the data analysis, it emerges that an increasement of the insulation layer of 8 cm produces a reduction of the EP$_{h,nd}$ value of around 15% in all the scenarios: this is a predictable result in accordance with thermal insulation behaviour.

Cooling

On the other hand, concerning the cooling demand, all simulations differ of small quantities: as a consequence, it could be assessed that the thickness variation has a smaller influence on this parameter, respect the heating one.

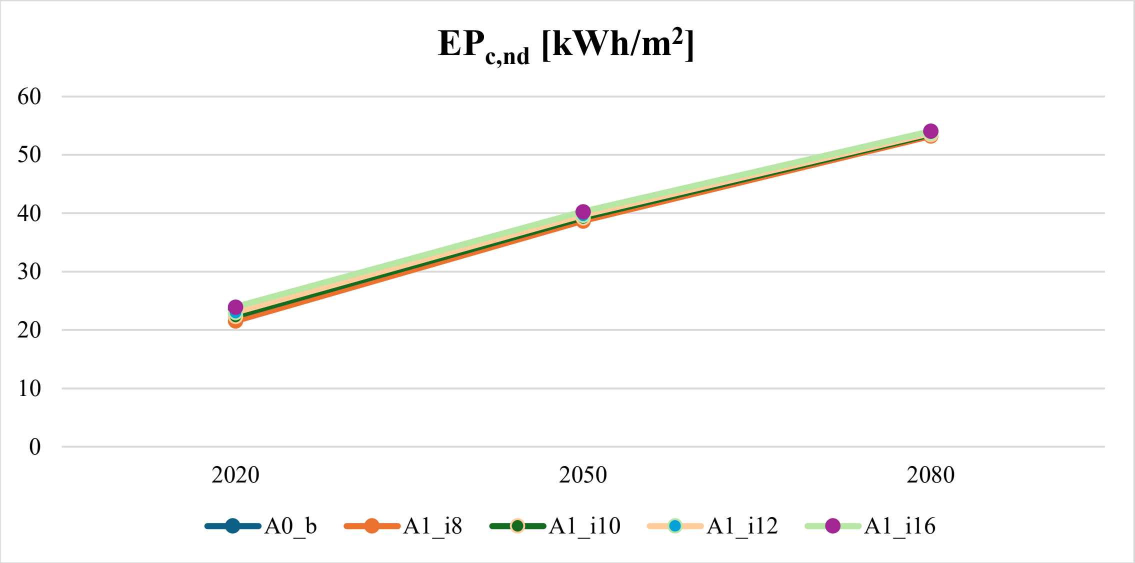


Figure 48 Ep$_{c,nd}$ of different stratigraphies applied

So, from these first outputs it is interesting to point out how the best improvement of the model comes from the use of the stratigraphy with 16 cm of stone wool: it is able of producing a reduction of the $EP_{h,nd}$ of around 5% respect the baseline model, maintaining at the same time the $EP_{c.nd}$ unchanged.

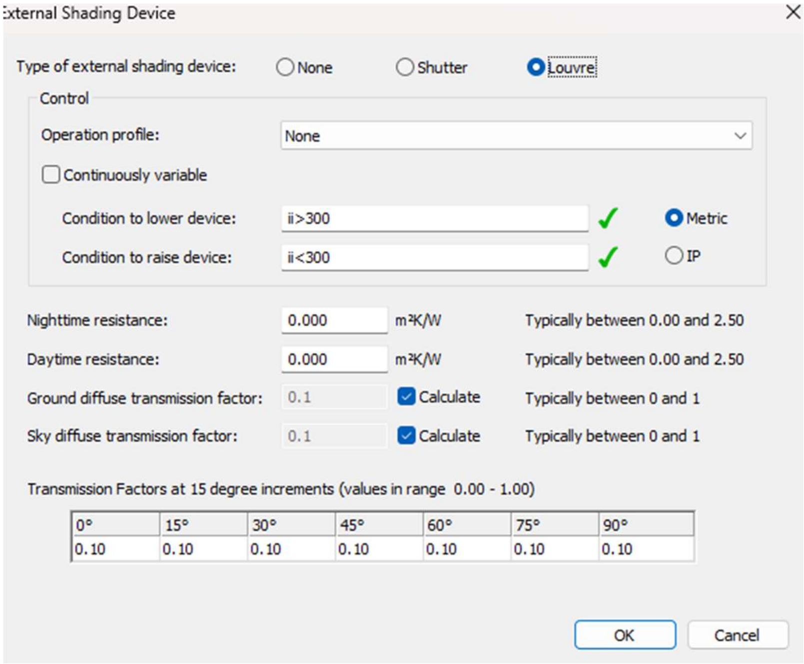
Shading device integration

The second variant, as anticipated above, regards the addition of shading devices to glazed elements, with the will to reduce the cooling need, especially in summer months.

Indeed, the decision to consider this solution comes from the desire to protect the building from the increased solar radiation to which it will be subjected in the coming years.

Therefore, for this integration, it was chosen the modelling of mechanized louvres which have the capability to lower and raise themselves in relation to the incident radiation to which they are subjected. In particular, it is set an incident radiation value of 300 kW/m^2 for which, in case it is exceeded louvres come down, otherwise they go up again.

In the image below, all characteristics of the modelling are reported:



Type of external shading device: ○ None ○ Shutter ● Louvre

Control

Operation profile: None

☐ Continuously variable

Condition to lower device: ii>300 ✓ ● Metric

Condition to raise device: ii<300 ✓ ○ IP

Nighttime resistance: 0.000 m²K/W Typically between 0.00 and 2.50

Daytime resistance: 0.000 m²K/W Typically between 0.00 and 2.50

Ground diffuse transmission factor: 0.1 ☑ Calculate Typically between 0 and 1

Sky diffuse transmission factor: 0.1 ☑ Calculate Typically between 0 and 1

Transmission Factors at 15 degree increments (values in range 0.00 - 1.00)

0°	15°	30°	45°	60°	75°	90°
0.10	0.10	0.10	0.10	0.10	0.10	0.10

Figure 49 Louvres modelling

The following part shows the results of simulations regarding the variants of the baseline model with the addition of the shading devices, described in the previous section.

Heading

The graph below (Figure 50) highlights a slight difference between the results of the model with or without the integration of the shading devices. A little increment of the $EP_{h,nd}$ is due to the reduction of radiation that enters inside the building through glazed elements, thanks to the louvres. However, this contribution from solar radiation only minimally influences the need of the building respect the heating demand, in fact screening the building from it, the analyzed parameter results almost unchanged.

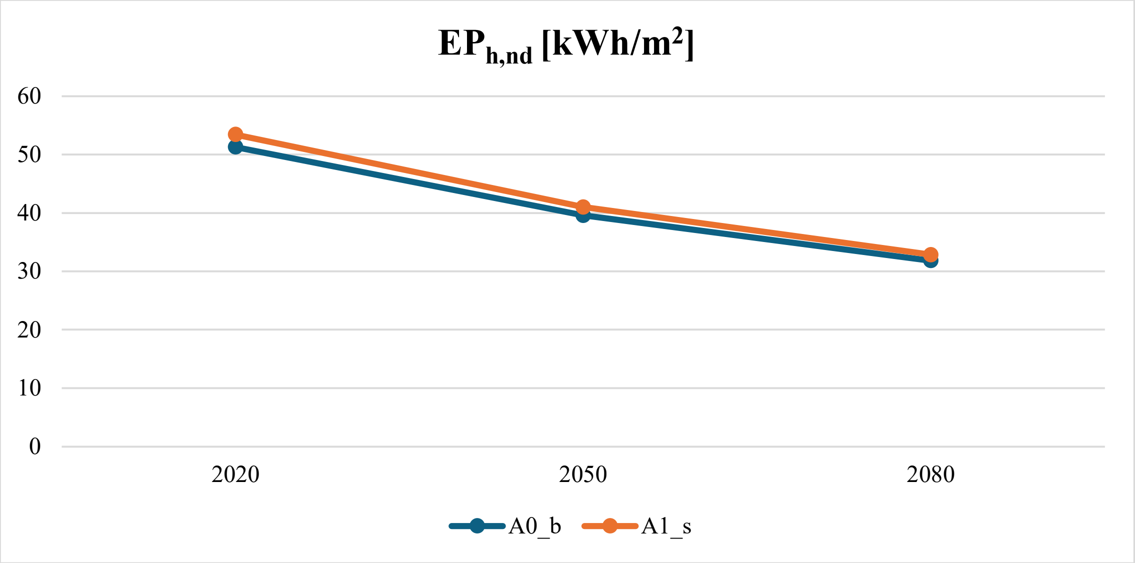


Figure 50 $Ep_{h,nd}$ with shading device integration

Cooling

On the opposite, a considerable improvement can be seen by analyzing the output values of the building's cooling demand: these show that the use of louvres, modelled as described above, results in a reduction in $EP_{c,nd}$ of 20% in the current scenario, 16% in the mid-time scenario and 14% in the long-term scenario.

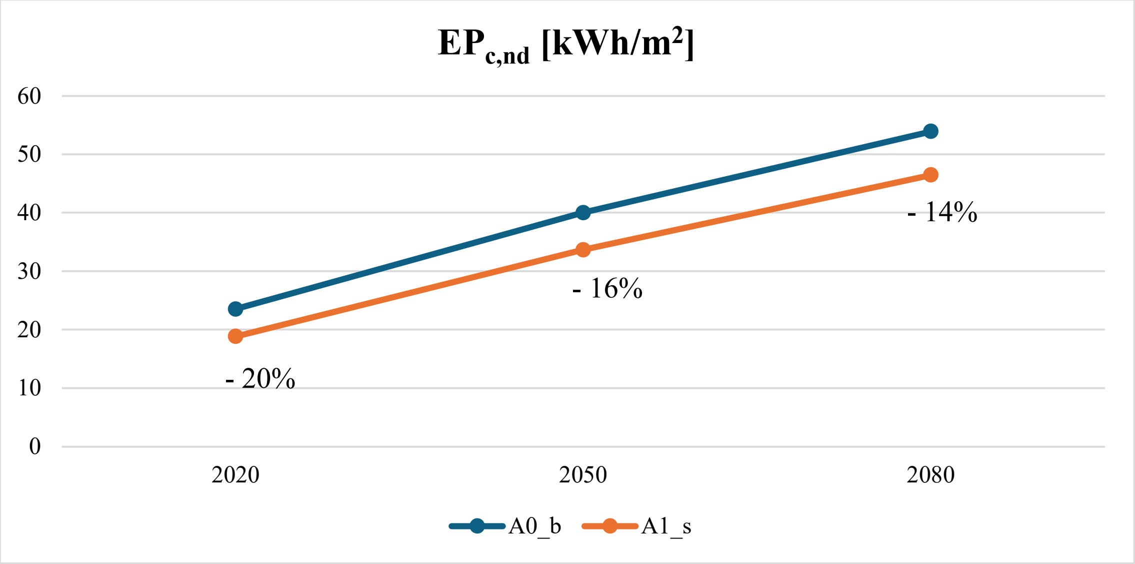


Figure 51 $EP_{c,nd}$ with shading device integration

The percentage downward trend, as the years go by, does not mean a lower effectiveness of the shading device solution, but it is merely the consequence of the increase in demand for cooling.

Envelope enhancement - Output

Once variants singular effects are analyzed, combinations of these solutions are investigated. Since simulation of the baseline model with an insulation thickness modification and a shading device integration does not result in a sum of individual effects, an additional step is necessary to evaluate how the combination of these variations influence the envelope behavior on the whole.

However, as these solutions affect the building's thermal load in opposite ways, the most appropriate combination will be defined on the basis of the results of the integrated simulations, which cannot be reduced to a simple mathematical sum of effects.

In the following part, for each weather scenario results of different simulations are condensed: the bar charts show in orange the heating demand while in blue the cooling demand, reporting also the percentage of increase of decrease of those parameters respect the baseline building ones.

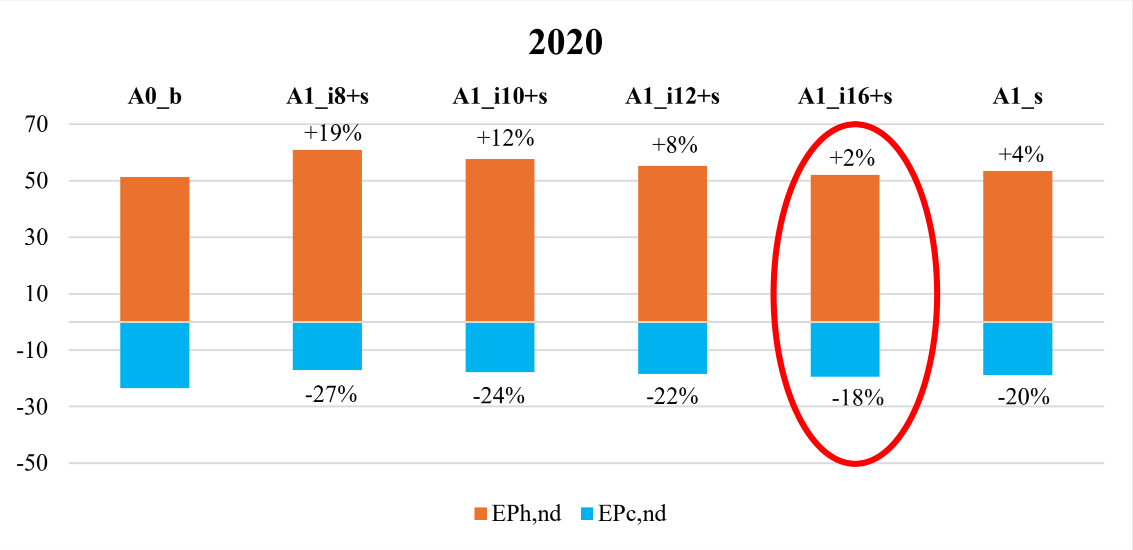


Figure 52 $EP_{h,nd}$ and $EP_{c,nd}$ with shading device integration and different stratigraphies - 2020

In the current scenario, the simulation which obtains the best compromise between a low increase in $EP_{h,nd}$ and a significant decrease in cooling demand is the model with shading and insulation made from 16 cm-thick panels, whose is circled in red.

Also, in the Figure 53 the 2050 scenario underlines how the same solution, previously identify how the best choice, confirms the evaluation with a minimal increase of 1% respect the heating parameter and a reduction of 15% of $EP_{c,nd}$. Taking into consideration just the blue bars it seems strange the choice of define as best solution the A1_i16+s because it does not actually correspond to the model with the greatest reduction in cooling requirements.

However, for an informed and accurate assessment, it is necessary to take a broader view of the parameters and not focus on just one to avoid making the mistake of improving one condition but at the same time worsening another. In fact, the best solution is not the one that reduces the cooling demand the most, which will inevitably represent the greatest consumption in the years to come, but rather the real challenge lies in finding alternatives that find the best compromise for all the building's performance.

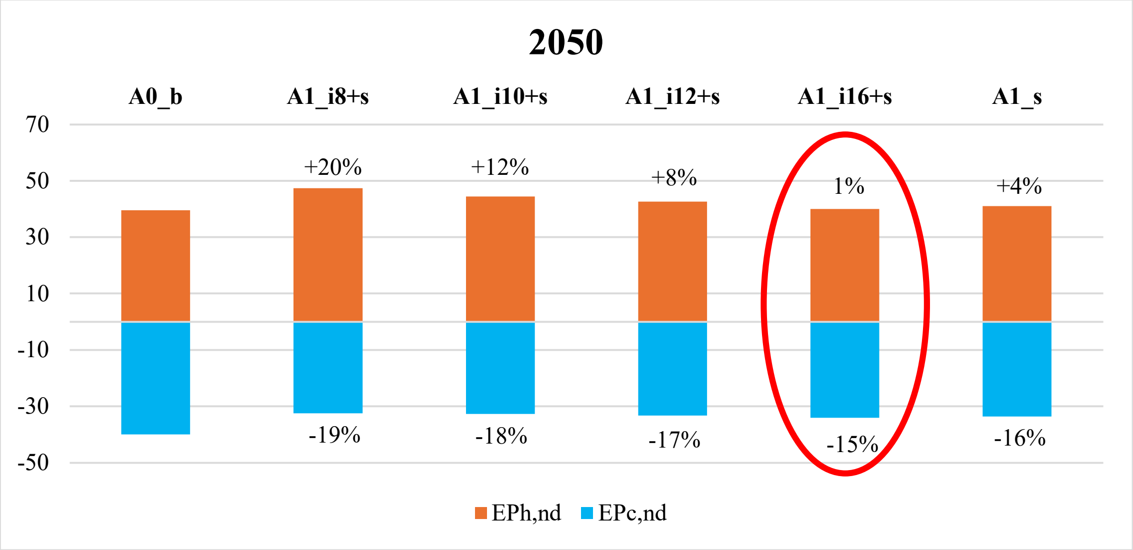


Figure 53 EP$_{h,nd}$ and EP$_{c,nd}$ with shading device integration and different stratigraphies - 2050

Last but not least, the long-term scenario definitively establishes the A1_i16+s model as the best alternative for pursuing the goal of optimizing the building envelope and lowering consumption through energy-efficient and resilient strategy.

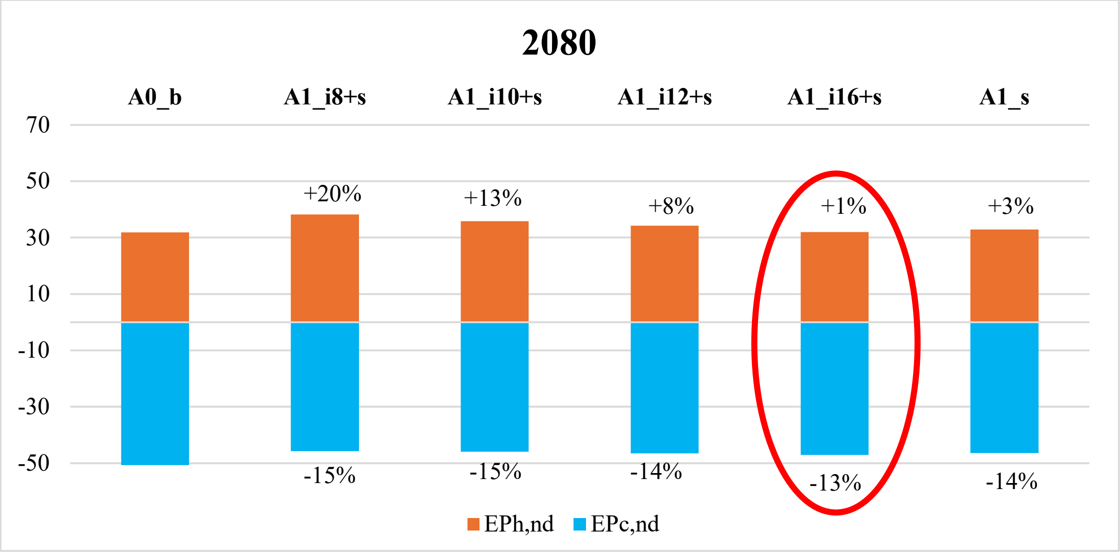


Figure 54 $EP_{h,nd}$ and $EP_{c,nd}$ with shading device integration and different stratigraphies - 2080

So, from now on, the model used for the following simulations, with the integration of new solution, is represented by the A1_i16+s model.

A sum up of the outputs is reported below in Figure 55, where there are also the percentage of increment and decrement respect the baseline model, for each scenario.

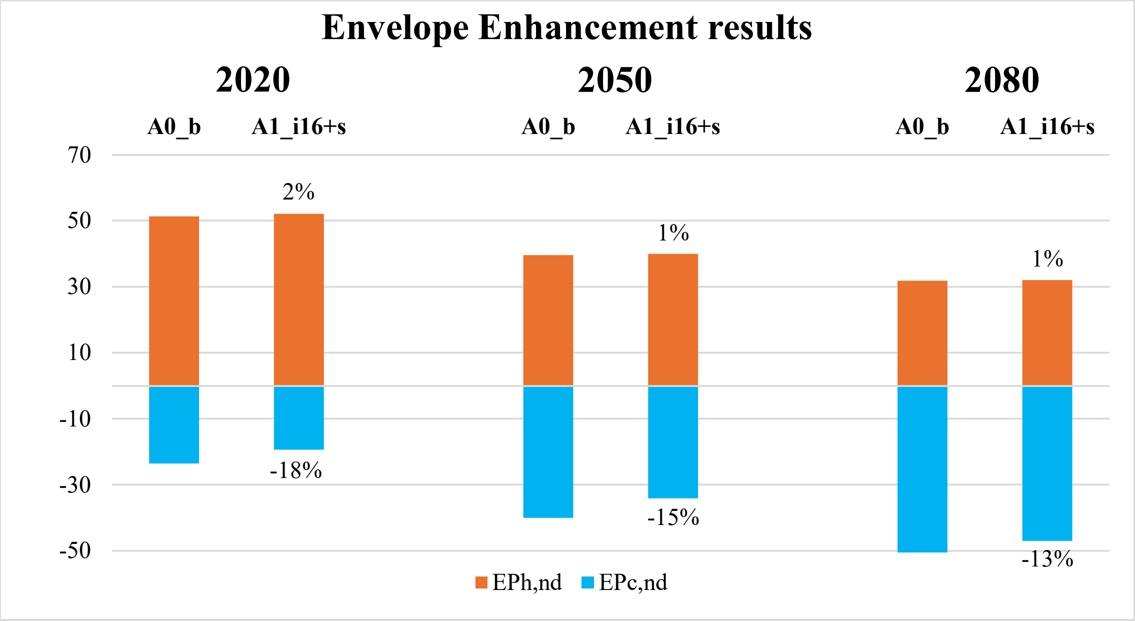


Figure 55 $EP_{h,nd}$ and $EP_{c,nd}$ scenarios comparison – A1_i16+s model

It is evident how the design choice of increasing the thickness of the thermal insulation by 2 cm and integrating automated shading devices leads to an increase of only 1% in heating demand and a substantial decrease in cooling, the percentage of which declines over the years due to the increase in that need as temperatures rise.

6.3. Cool roof strategy

Introduction to cool roof

The cool roof represents one of the most efficient and sustainable solutions to address energy and environmental challenges related to urban warming and growing energy demand. In the context of climate change and rising urbanization, the adoption of this technique results fundamental to improve building energy efficiency and to counteract heat island effect. In the following sections, principles, benefits and implications of the cool roof solution are described.

Working principle

The cool roof is based on the use of materials with high reflectance, which are able to reflect a great percentage of solar radiance, reducing the heat absorption by the building. The materials used for such roofs are generally reflective paints, membranes or tiles treated with special coatings that increase their reflectivity (albedo) and reduce heat emission. A cool roof could reduce the roof surface temperature of also 10-15° respect traditional one, thanks to its capacity of reflecting 60-80% of solar radiation, while the conventional solution can absorb 80% of it.

This reflectivity leads to a direct reduction of buildings' internal temperature, because the heat, which is generally accumulated in the structure, is dissipated before it can be transmitted inside. As a consequence, the load on the air conditioning system is reduced, improving the energy efficiency of the building.

In the following part the main benefits provided by this solution are listed:

- Reduction of energy consumption

One of the cool roof main advantages is the reduction of energy consumption for building cooling. In fact, during summer months, the adoption of a reflective roof contributes to maintain a cooler indoor temperature, decreasing the need for air-conditioning systems. This solution results in a significant reduction in energy consumption, which in turn reduces the operating costs for building owners and the environmental impacts of energy production. As demonstrated in the research undertaken by Rosenfeld (1995), the implementation of cool roofs has been shown to result in a potential reduction of up to 20% in energy consumption within residential and commercial buildings.

- Countering the urban heat island

Another important benefit is the contrast to the Urban Heat Island (UHI) effect. Cities, due to the density of buildings, roads and other hard surfaces, tend to experience higher temperatures than the surrounding rural areas. This phenomenon is worsened by the heat accumulated by built-up surfaces, which is inclined to be released during the night, creating a continuous heating cycle. In regard to this aspect, cool roofs could significantly reduce building surface temperatures and contribute to the overall cooling of the urban environment.

- Public health benefits

The adoption of a cool roof solution does not represent just an energy advantage, but it constitutes also an important measure for the improvement of public health. High summer temperatures cause an increased risk of heat-related illnesses such as heat stroke, heat exhaustion and other respiratory diseases, especially in densely populated urban areas. In fact, cities are more vulnerable to the effects of extreme heat due to the concentration of buildings and the scarcity of vegetation.

Therefore, it is deducted that cool roofs help to reduce ambient temperatures, resulting in a lower risk of heat-related illnesses and improved air quality.

- Architectonical integration

Cool roofs could also have a positive impact on urban aesthetics. With the innovation of reflective materials, nowadays it is possible to integrate this technology in a harmonious way also in residential and commercial buildings. The materials used for this solution are available in a wide range of colors and finishes, allowing architects and designers to preserve or improve the aesthetic appearance of buildings without compromising functionality.

Moreover, cool roofs could be combined with other sustainable solutions, such as rainwater harvesting or the installation of photovoltaic systems, to further enhance the sustainability of buildings.

Costs and economic implications

The implementation of cool roofs, although it initially results more expensive respect the traditional roofs one, represents a long-term investment thanks to the energy saving derived from the reduction of air-conditioning requirements and potential government incentives for sustainable construction. According to California Energy Commission (2008), the payback for cool roof installation is generally positive, with a recovery period ranging from 3 to 5 years, depending on the size of the building and local climatic conditions.

Choice motivation

In brief, cool roofs represent a versatile and high advantageous technology for all these aspects described above. With rising global temperatures and the increasing need to reduce the environmental impact of urban activities, the potential integration of cool roofs is a key solution for mitigating climate change and improving urban well-being.

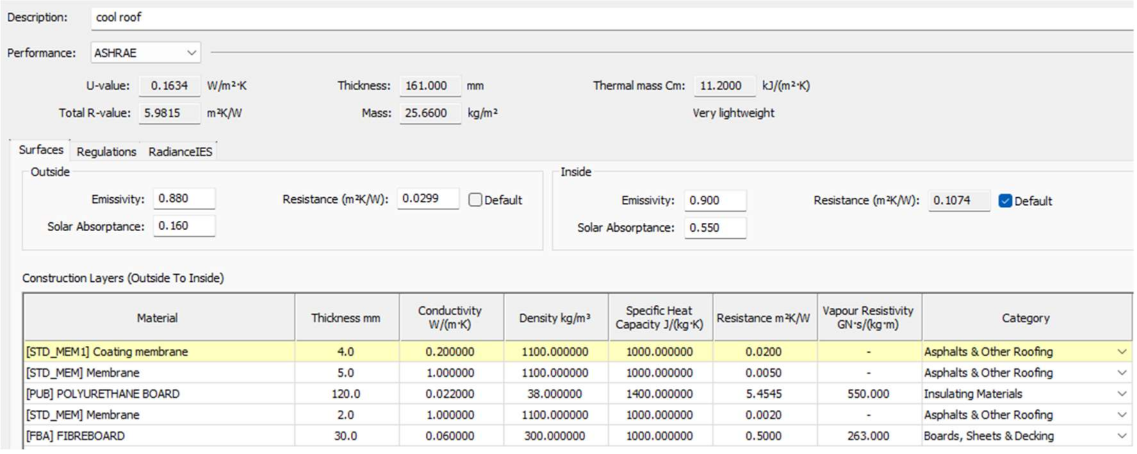
For all these reasons, the cool roof addition was chosen as a variant for the third block of simulations. As in the previous analysis, the intention is to individually study the solution by applying it to baseline building and then combine its effects with the changes made in the previous simulations to find the condition that maximizes the benefits for the building.

Cool roof modelling

For this variant of the model, a new roof stratigraphy had to be created: specifically, the roof stratigraphy applied to the baseline building was duplicated so that only the external cladding layer was modified.

Therefore, the layer composed of the tiles is removed and replaced by an elastoplastomeric polymer-bitumen waterproofing membrane with a thickness of 4 mm, also assuming the application of a white solvent paint for the protection of the polymer-bitumen membranes with high reflectance and emissivity.

In particular, the characteristic values of this paint are an emissivity of 88% and a reflectance of 84%, which translates into a solar absorptance of 16% (the sum of these two values being 100%). The image below described properties of all layers contains in the cool roof modeled:



Description: cool roof

Performance: ASHRAE

U-value: 0.1634 W/m²·K

Total R-value: 5.9815 m²K/W

Thickness: 161.000 mm

Mass: 25.6600 kg/m²

Thermal mass Cm: 11.2000 kJ/(m²·K)

Very lightweight

Outside

Emissivity: 0.880

Solar Absorptance: 0.160

Resistance (m²K/W): 0.0299 ☐ Default

Inside

Emissivity: 0.900

Solar Absorptance: 0.550

Resistance (m²K/W): 0.1074 ☑ Default

Construction Layers (Outside To Inside)

Material	Thickness mm	Conductivity W/(m·K)	Density kg/m³	Specific Heat Capacity J/(kg·K)	Resistance m²K/W	Vapour Resistivity GN·s/(kg·m)	Category
[STD_MEM1] Coating membrane	4.0	0.200000	1100.000000	1000.000000	0.0200	-	Asphalts & Other Roofing
[STD_MEM] Membrane	5.0	1.000000	1100.000000	1000.000000	0.0050	-	Asphalts & Other Roofing
[PUB] POLYURETHANE BOARD	120.0	0.022000	38.000000	1400.000000	5.4545	550.000	Insulating Materials
[STD_MEM] Membrane	2.0	1.000000	1100.000000	1000.000000	0.0020	-	Asphalts & Other Roofing
[FBA] FIBREBOARD	30.0	0.060000	300.000000	1000.000000	0.5000	263.000	Boards, Sheets & Decking

Figure 56 Cool roof modelling

Cool roof strategy - Output

In regard to simulations involving the integration of the cool roof, the following graph highlights the outputs derived from the analysis of both the $EP_{h,nd}$ and $EP_{c,nd}$. The graph presents the percentages of increase or decrease relative to the A1 model in the 2020 scenario, offering a clear overview of how the implementation of a cool roof affects the overall energy performance of the building.

Specifically, it shows how the cooling energy demand tends to decrease, while the heating energy demand remains largely unchanged, demonstrating the positive impact of the cool roof on the building’s cooling efficiency, although with a modest effect on heating energy requirements.

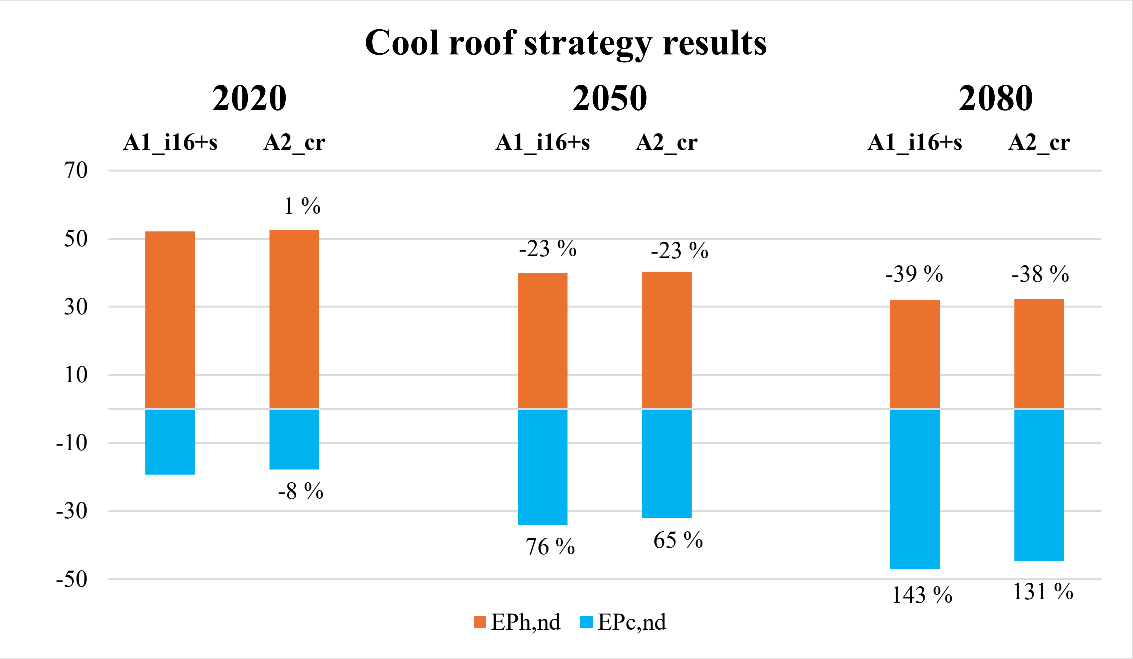


Figure 57 EP$_{h,nd}$ *and EP*$_{c,nd}$ *scenarios comparison respect previous model – A2 model*

So it can be stated that the cool roof strategy, in general, does not have a significant impact on the heating demand of a building, since the main effect of this technology is the reduction of the heat accumulated by the building surface during warmer periods. Although it does not contribute significantly to the reduction of the heating demand, the cool roof makes a positive contribution in improving the overall energy efficiency of the building, leading to a reduction of the EP$_{c,nd}$.

However, this reduction is quite small, around 10%, as the action of the cool roof is more oriented towards counteracting summer heating, limiting the use of cooling systems, rather than directly influencing the winter heating demand.

6.4. Ventilative cooling strategy

Introduction to the ventilative cooling

Ventilative cooling is an energy-efficient strategy that uses natural or mechanical airflow to reduce the internal temperatures of buildings, by exploiting the temperature differences between the inside and the outside conditions. The working principle is based on the air capacity of transferring heat by convection, which allows interior spaces to be cooled without the use of active cooling systems such as air conditioning.

There are several modes of ventilative cooling:

- Natural ventilation takes advantage of openings and pressure differences to circulate air through the building;
- Mechanical ventilation which uses forced ventilation systems to regulate the air flow: in this specific case the air is circulated without heat treatment by activating the fans, maintaining the outside air temperature unchanged;

The mechanical approach is very useful when the internal temperature results higher respect the external one, activating the mechanical ventilation system only when it is necessary. Practically, the system is automatically activated to drive the fans, promoting the passage of air through the building, thus reducing the internal loas and restoring optimal comfort without the use of energy to cool the air.

In some cases, systems could be combined to obtain hybrid ventilation, in which external air is introduced during night, when external temperature is lower, cooling the internal ambient. If these systems are designed correctly, they can provide optimal thermal comfort, limiting the use of cooling systems that consume more energy.

The ventilative cooling presents various advantages, starting from the significant energy savings. In opposition to active cooling systems, which require high electrical energy to operate, ventilated cooling uses the thermal energy available in the external environment, minimizing energy consumption and, consequently, greenhouse gas emissions.

Moreover, this solution contributes to the improvement of thermal comfort inside the buildings, guaranteeing cooler internal temperatures during warm periods with no excessive humidity effect that could be caused by systems such as evaporative cooling.

Another important benefit is the low maintenance required by this kind of systems respect traditional air conditioners, diminishing long-term operational costs.

Finally, the adoption of this technology fits perfectly into the context of environmental sustainability, promoting an ecological approach to the thermal management of buildings and fostering the transition towards more resilient and environmentally friendly building solutions.

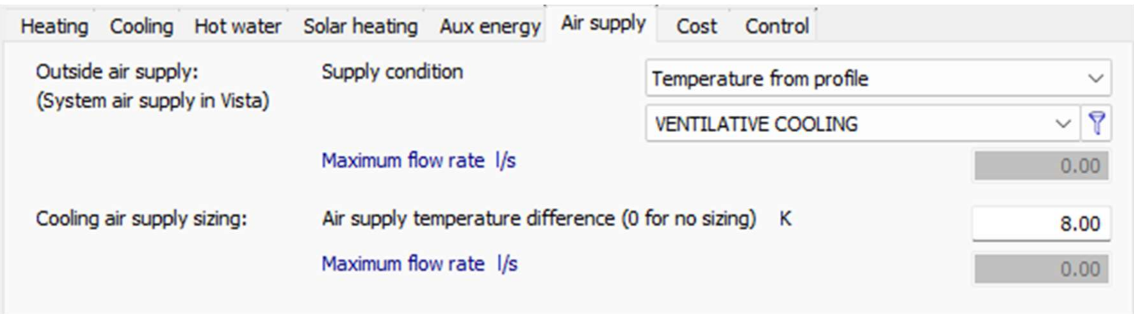
The ventilative cooling is one of the most promising techniques for buildings sustainable cooling, with significant benefits both in terms of energy savings and environmental comfort. However, its effectiveness strongly depends on climatic conditions and good building design: ventilative cooling, integrated with other solutions as in this case study, it could represent a key element in the realization of building with low environmental impact and high energy efficiency.

Ventilative cooling modelling

This variant modelling starts with the duplication of the “Prototype system”: this new version of the system has to be modified in order to provide all the features of a plan that also handle ventilative cooling.

In detail, in the “Heating” Tab the *ventilation heat recovery effectiveness* is fixed at 0.7, while the *ventilation heat recovery return air temperature* set at 20°C.

While in the “Cooling” Tab, the *Changeover mixed mode free cooling* passes from not being a CMM system to “Mechanical ventilation”. In this way the system is able to switch from the air conditioning to a simple mechanical ventilation which creates a free cooling solution, supplying external air without any thermal treatment of it. Moreover, in the “Air supply” Tab the profile of the temperature has to be set in order to input at which condition the mechanism is activated. So, once set “Temperature from profile” option, a yearly profile is needed to establish when the free cooling should be activated.



Outside air supply:
(System air supply in Vista)

Supply condition: Temperature from profile

VENTILATIVE COOLING

Maximum flow rate l/s 0.00

Cooling air supply sizing:

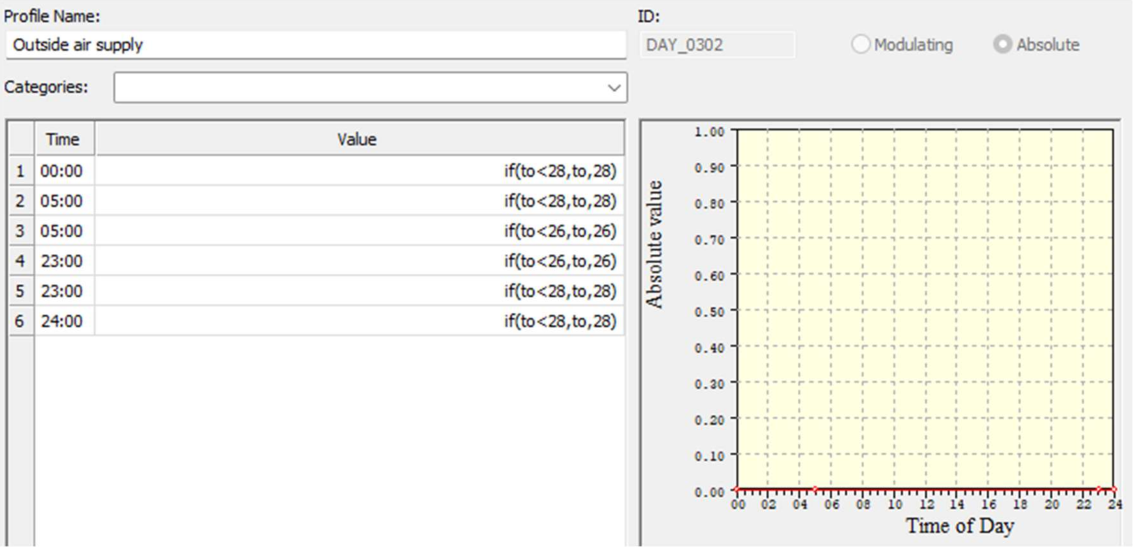
Air supply temperature difference (0 for no sizing) K 8.00

Maximum flow rate l/s 0.00

Figure 58 Ventilative cooling modelling

Therefore, the creation of the operational profile starts also in this case from the daily profile: for this use the profile needed is a Modulating profile.

The first daily profile created is the “Outside air supply”: it follows cooling timetables and defines that in case the external temperature is less than 26°C during the day and less than 28°C during night, the air supply will be at the temperature of the outside environment, otherwise at the cooling setpoints temperature.



Profile Name: Outside air supply

ID: DAY_0302

○ Modulating ● Absolute

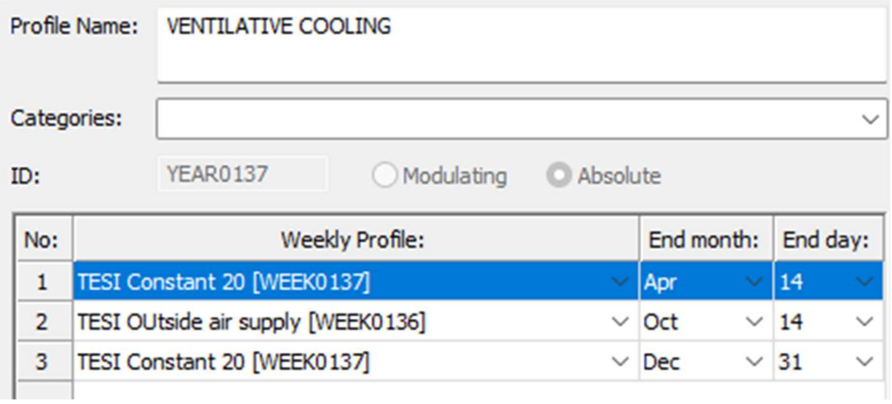
Categories:

	Time	Value
1	00:00	if(to<28,to,28)
2	05:00	if(to<28,to,28)
3	05:00	if(to<26,to,26)
4	23:00	if(to<26,to,26)
5	23:00	if(to<28,to,28)
6	24:00	if(to<28,to,28)

Figure 59 Daily ventilative cooling operational profile

Additionally, a fictitious profile is necessary to set the mechanism off during heating months: this profile defines a constant temperature of 20 °C.

Having the daily and the weekly temperature profile, the final annual profile called “Ventilative cooling” is created, with the following conditions:


Profile Name: VENTILATIVE COOLING

Categories:

ID: YEAR0137 ○ Modulating ● Absolute

No:	Weekly Profile:	End month:	End day:
1	TESI Constant 20 [WEEK0137]	Apr	14
2	TESI OUtside air supply [WEEK0136]	Oct	14
3	TESI Constant 20 [WEEK0137]	Dec	31

Figure 60 Annual ventilative cooling operational profile

And it is assigned to the supply condition of the "Air supply" Tab.

Since the design specifications already provide air extraction from the bathrooms and air supply in the corridors, while air exchange is only achieved by natural ventilation in the bedrooms, it was considered appropriate to model free cooling only in the rooms, deleting the natural ventilation contribution (considered in the previous simulations).

At this point, the template "Dormitory - Living quarters", assigned to all the bedrooms has also to be modified in order to model the ventilative cooling in those rooms. The *System outside air supply* is set with a flow rate of 2.8 ach with a profile continuously on. This strategy of ventilation is applied just in the bedrooms, where in the beginning only natural ventilation was provided: air supply is maintained in the corridor and exhaust air in the bathrooms as per regulations.

Ventilative cooling strategy - Output

The effectiveness of this strategy is immediately visible when observing the results of $EP_{h,nd}$ and $EP_{c,nd}$ in comparison with those obtained from A2 simulation block, shown in Figure 61.

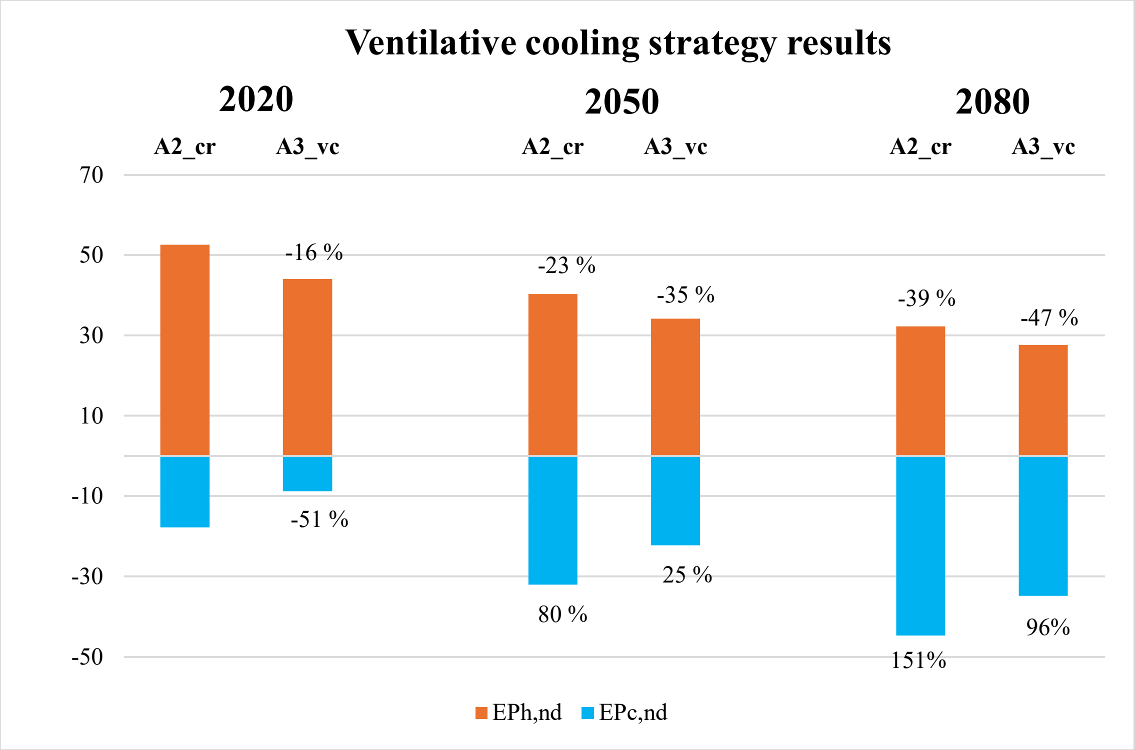


Figure 61 $EP_{h,nd}$ and $EP_{c,nd}$ scenarios comparison respect previous model – A3 model

The application of ventilative cooling strategy, as reported in the bar chart above, provide a positive contribution, in terms of consumption reduction, not just for the cooling demand but also for the heating one. This is because the natural ventilation, previously modelled for all the year, it is set continuously off in this specific model, and therefore the heating required to increase the internal temperature (influenced by natural ventilation) is not necessary anymore.

In general, it could be assessed that the ventilative cooling represents a very promising solution for the objective of lowering the energy consumption of a building as it exploits resources already present in the environment (outside temperature) to achieve indoor comfort, without using energy to thermally treat the supplied air.

Insight: system off in May and October

For the purpose of assessing the real effectiveness of the solutions provided so far, as the model is progressively optimised, it is interesting to simulate again the condition of the plant being switched off in May and October, as previously done with the A0 model.

As the diagrams below show, with this model, even without the support of the cooling system, in mid-season weeks the internal room temperatures remain acceptable, even in the 2080 scenario.

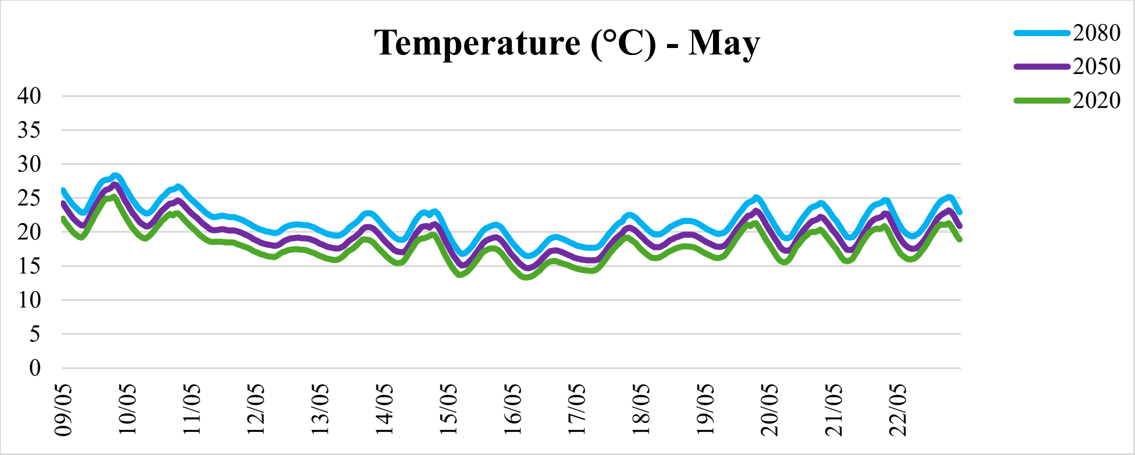


Figure 62 May internal temperature C_P0_BED15 - North side – A3 model

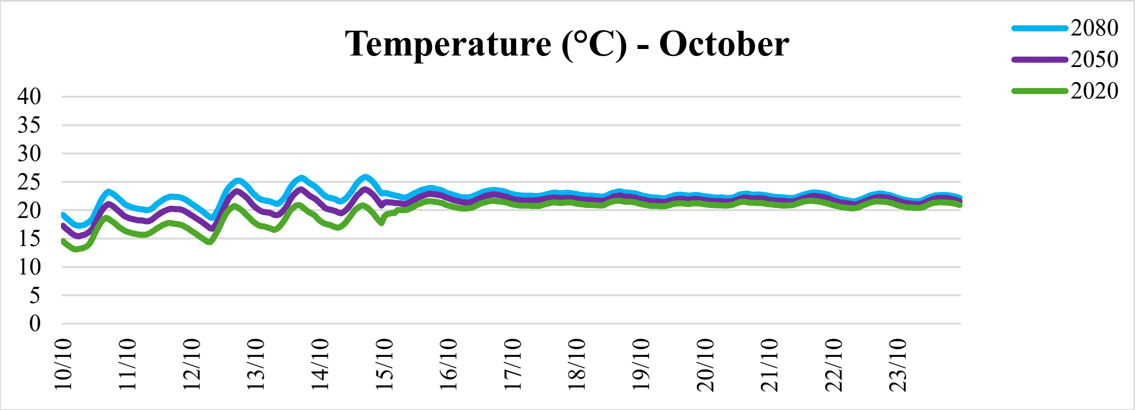


Figure 63 October internal temperature C_P0_BED15 - North side – A3 model

It can be seen that the combined use of ventilative cooling, cool roof and solar shading integrations contributes substantially to maintaining thermal comfort indoors, allowing temperatures to be kept below 27 °C without burdening energy consumption, unlike traditional cooling systems. These approaches exploit natural resources, reducing the need for high-consumption electrical systems and improving the overall energy efficiency of buildings without compromising occupant comfort.

6.5. PV System variant

The last version of the model provides a significant variant of the photovoltaic system, with the objective of optimize the coverage of the building's electricity consumption. In particular, it is intended to investigate the system size in order to satisfy most energy needs without exceeding unrealistic dimensions, taking into account the urban context in which the case study is embedded.

Thus, this approach fits into an already established project, in which electricity is to be supplied by a 22 kWp PV system. The analysis seeks to find a balance between adequate power for the building's needs and the feasibility of the system, in relation to the specificities of the context in which it fits.

Constraints which limit the extension of the photovoltaic system derive from different factors. First of all, the available space is crucial: the area of the roof or the surroundings accessible areas may be insufficient for a large system; in addition, urban regulations and building constraints, such as those relating to historic buildings or protected areas, could impose restrictions on the PVs installation. Other limiting factors include the orientation and the shading of the roof pitches, which influence system efficiency and high installation and maintenance costs for big plant.

Lastly, the capacity of the power grid and the limits imposed by energy supply contracts could reduce the effectiveness of an expansion by imposing restrictions on the amount of energy that can be fed in or self-consumed.

In consideration of this, the variant of the photovoltaic system consists in the possibility of adding to the number of panels already present, another part to be placed doubling the surface covered by modules.

In particular, for this variant the same panels are used as in the design solutions, but with a significant increase in the number of modules to 100. This new configuration allows a total surface area of 180 m^2 to be covered, as shown in Figure 65, providing a total power output of 44 kWp: the increase in the number of modules improves the overall efficiency of the system, optimizing energy production capacity and better adapting to specific consumption needs.

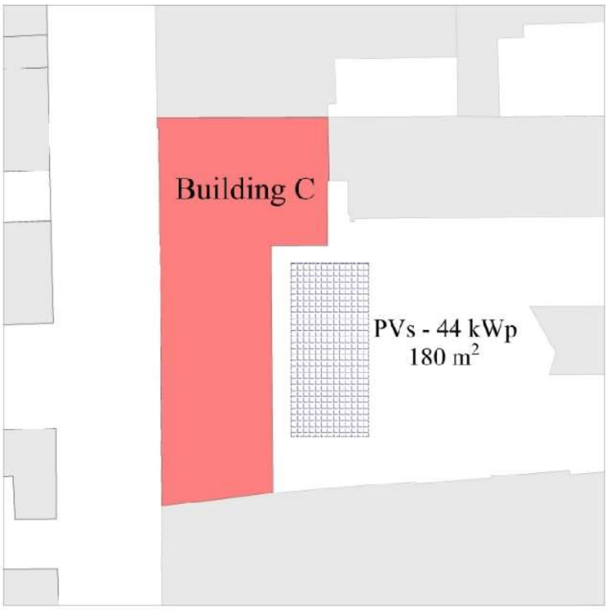


Figure 64 PVs 44 kWp location

Thanks to this increment in the size of the PV system, the average monthly electricity production achieves the values reported in Table 6 and plotted in the bar chart below.

Month	**Average monthly electricity production [kWh]**
Jan	3889,6
Feb	4096,4
Mar	5381,2
Apr	5456
May	5786
Jun	5988,4
Jul	6564,8
Aug	6217,2
Sep	5244,8
Oct	4021,6
Nov	3269,2
Dec	3405,6

Table 6 Average monthly electricity production of 44 kWp PV system

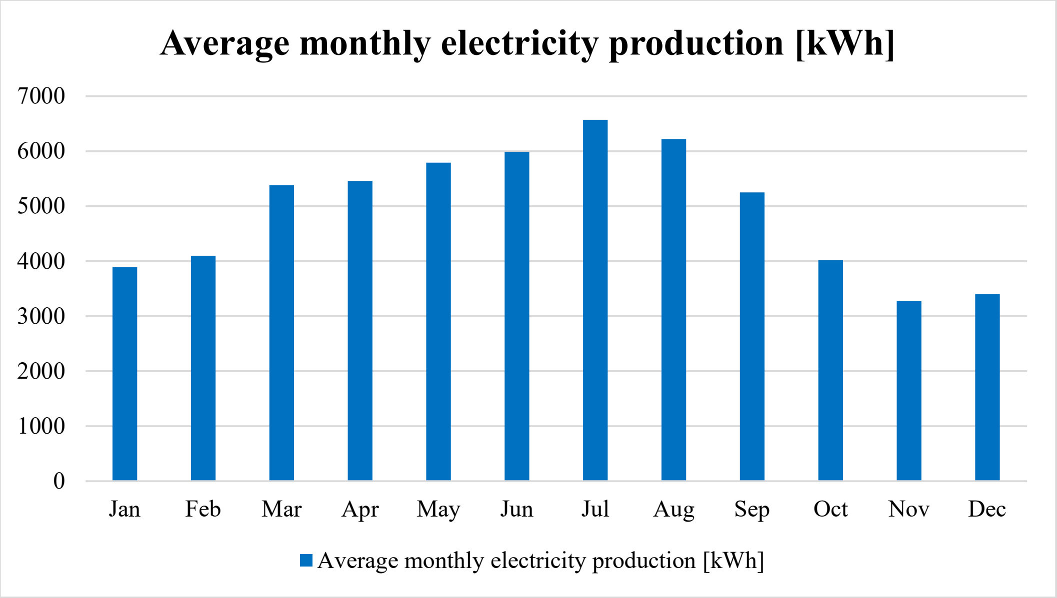


Figure 65 Average monthly electricity production histogram of 44 kWp PV system

PV System variant – Output

In this subchapter, it is evaluated the results of the electricity consumption obtained once the size of the photovoltaic system is increased.

In general, what emerges is that, in all three climate scenarios, the percentage of electricity covered by the photovoltaic system obviously increases compared to the initial case, covering almost the entire demand in the cooling season, especially in 2020. This is because in those months cooling demand is low (due to the application of energy-efficient and climate resilient solutions) and solar radiation incident on photovoltaic panels reaches maximum value.

As a result, in some months such as April and May in 2020 scenario, the photovoltaic producibility potentially covers the overall electricity demand of the building.

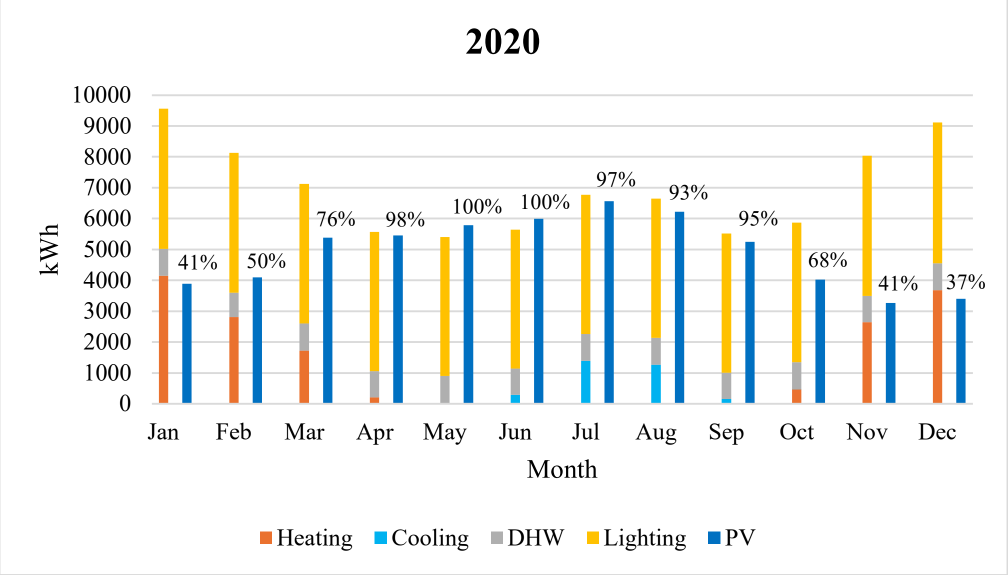


Figure 66 Electricity consumption – A4_2020_sv

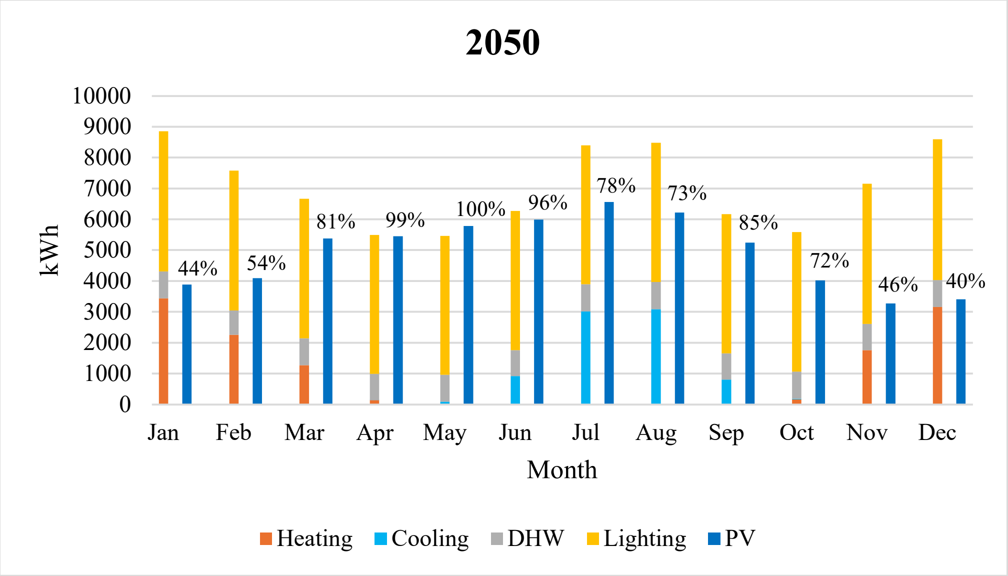


Figure 67 Electricity consumption – A4_2050_sv

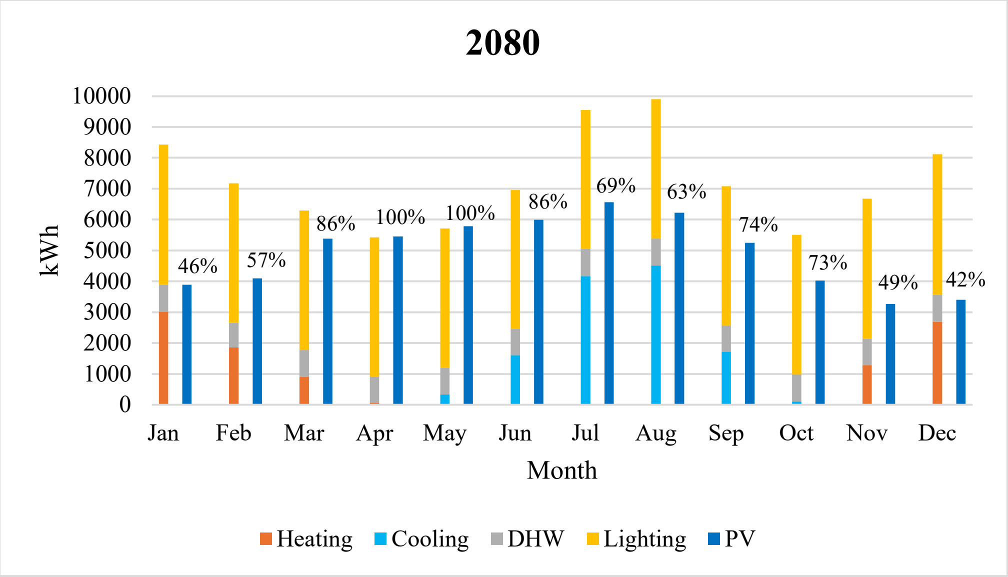


Figure 68 Electricity consumption – A4_2080_sv

It is evident how the electricity required for lighting constitutes the main contribution, even after having reduced cooling consumption, it remains unchanged. In order to optimize energy efficiency, it is therefore crucial to act on several fronts, adopting effective shading, selective glazing that limits solar heat gain, appropriate furniture that minimize heat build-up and automated lighting systems (BACs) that can adjust light intensity according to presence and available daylight.

It is clear, from Figure 69, that the overall annual percentage of renewable energy increases reaching at least 70% in all three climatic scenarios, emphasizing how effective it is to maximize the performance of the photovoltaic system.

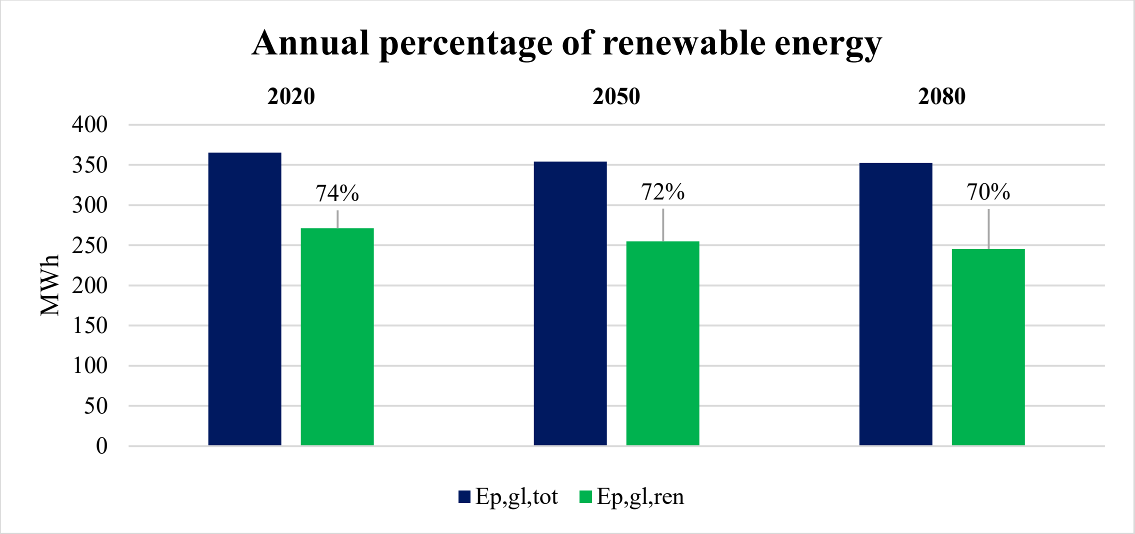


Figure 69 Annual percentage of renewable energy – A4 model

7. DISCUSSION

In this chapter, the main results of the research carried out in this thesis are reported through the comparison of the outputs of the different simulations.

Firstly, it is evident that an integrated approach is fundamental to maximizing the benefits of these solutions. In fact, it is not possible to observe the effects that technology brings to a single parameter, but rather it is necessary to evaluate the consequences of a specific technology, as it may improve in one aspect, but at the same time worsen performance in other aspects.

Effectiveness of climate-resilient strategies

The first part of discussion concerns the effectiveness of different strategies applied in this analysis to the building taken as case study, in order to assess which are more impactful and how much change the response of the building to these integrations.

From the bar charts below it is highlighted that, over the years, a building's energy demand will shift from heating to cooling consumption, but thanks to the integration of energy-efficient strategies, explained in the chapters above, there is a palpable improvement in results.

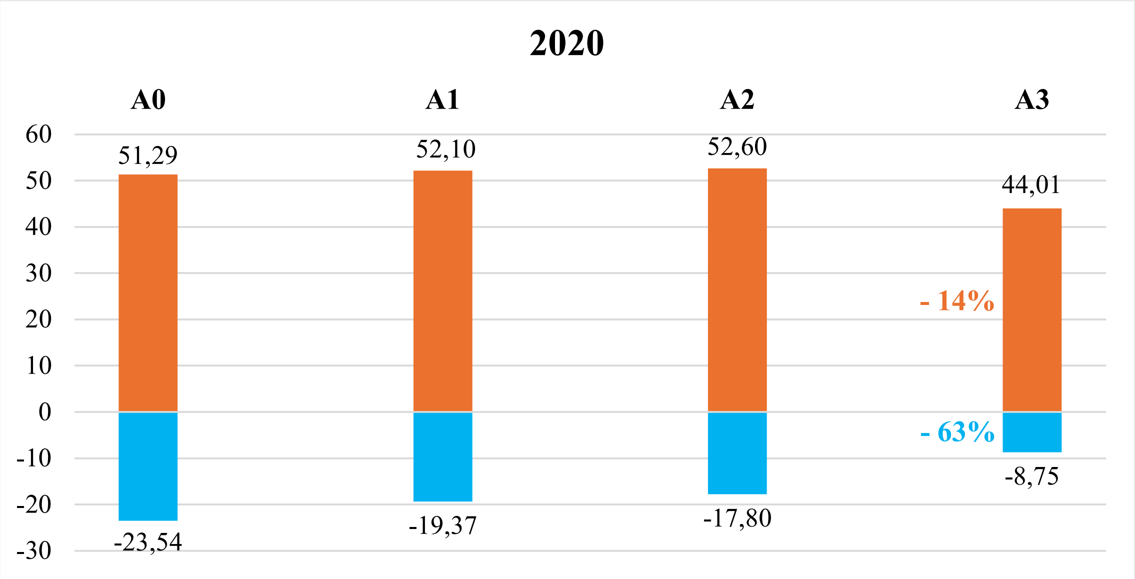


Figure 70 Models $EP_{h,nd}$ *and* $EP_{c,nd}$ *results comparison - 2020*

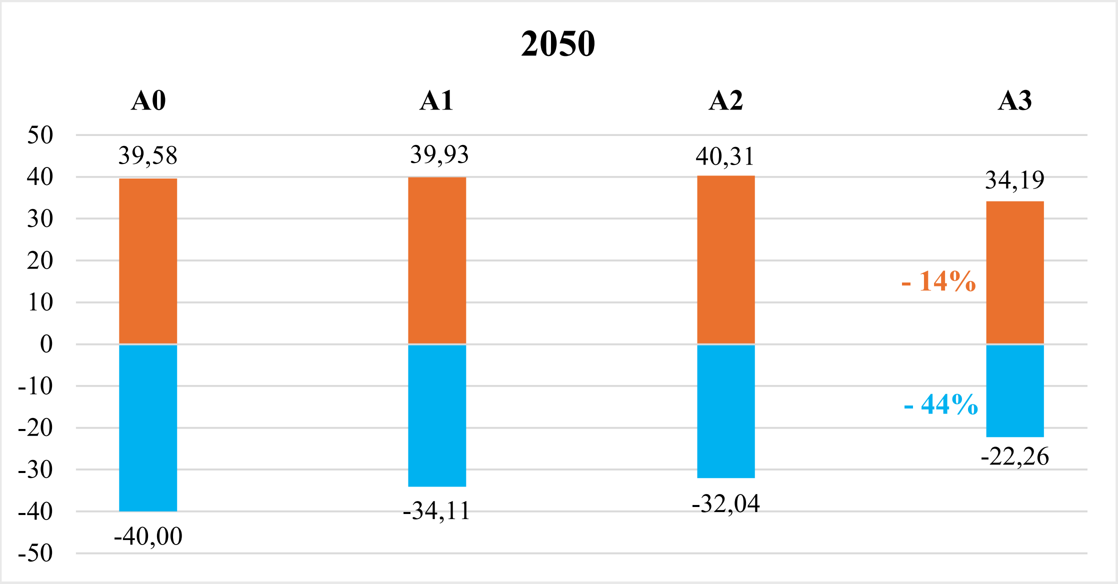


Figure 71 Models $EP_{h,nd}$ and $EP_{c,nd}$ results comparison - 2050

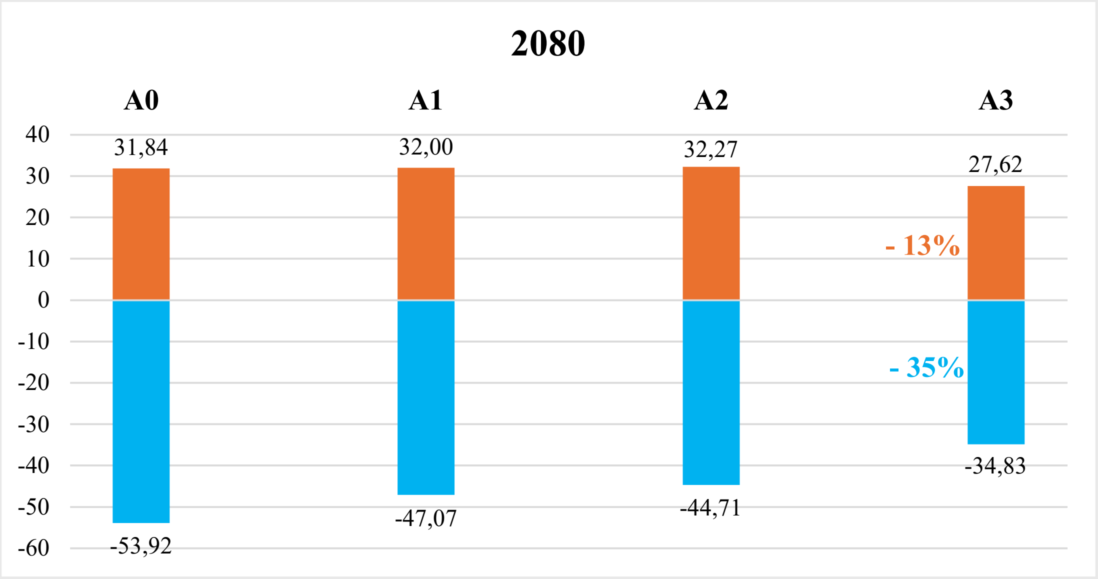


Figure 72 Models $EP_{h,nd}$ and $EP_{c,nd}$ results comparison - 2080

The main findings of the study show that increasing the thickness of the insulation layer of the building envelope has a greater influence on reducing heating in winter than on increasing cooling in summer. Furthermore, the analysis demonstrates that the cool roof solution is effective but not as much as the use of automated shading in relation to the reduction of cooling demand.

On the other hand, if one observes the decrease in value by switching from model A2 to model A3, which concerns the integration of ventilative cooling, it can be noted that this strategy is able to provide a substantial contribution to the decrease of building consumption, in each climatic scenario.

In general, the graphs show the percentage of decrease of the final model (A3) respect the original condition of the building, represented by the A0 model, confirming that the application of climate-resilient solutions is fundamental to improve the building energy efficiency.

Another result to be taken into account is that, when analyzing the temperature behavior with the system switched off in May and October, a considerable fluctuation is observed, with peaks as high as 30 degrees in baseline building simulations, during periods that should theoretically belong to the mid-seasons. This is particularly worrying, as in October, after the 15th, temperatures rise significantly, postponing the time when the heating should be switched on.

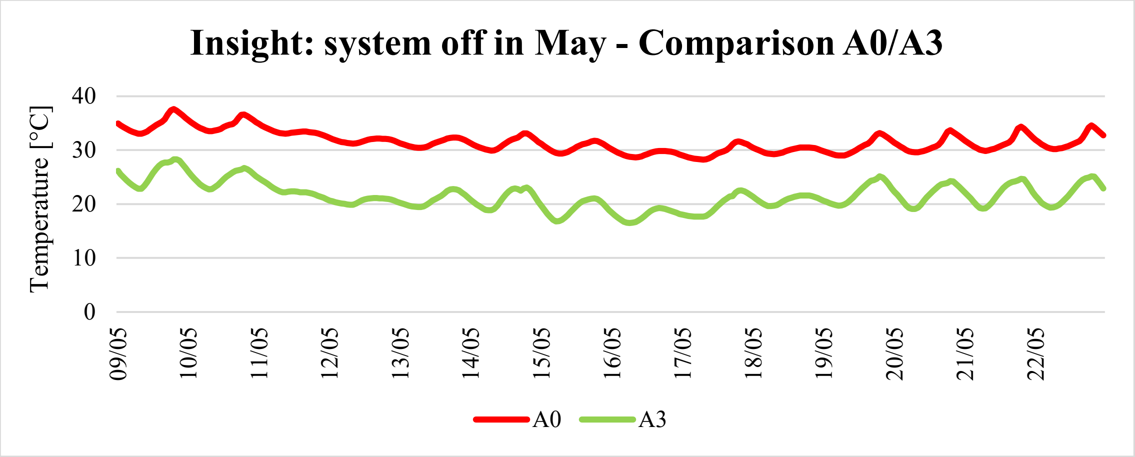


Figure 73 Insight: system off in May – Comparison

It can be seen from Figure 73 that the application of the different solutions mentioned above is an effective strategy in terms of lowering temperatures in the mid-season. In fact, considering the system switched off, model A3 (green line), including envelope optimization, cool roof and ventilated cooling strategy, shows a clear lowering of the temperature curve of approximately 10°C respect the A0 case (red line), thanks above all to the use of external air to ventilate the rooms.

Electricity consumption assessment

In this second part of discussion, attention should be drawn to the results of electricity consumption, to assess how efficient the building is.

Starting from an analysis of electricity consumption, categorized by end uses, Figure 74 shows that the lighting energy demand represents the main contribution to the overall electricity consumption, regardless of how much cooling demand is reduced.

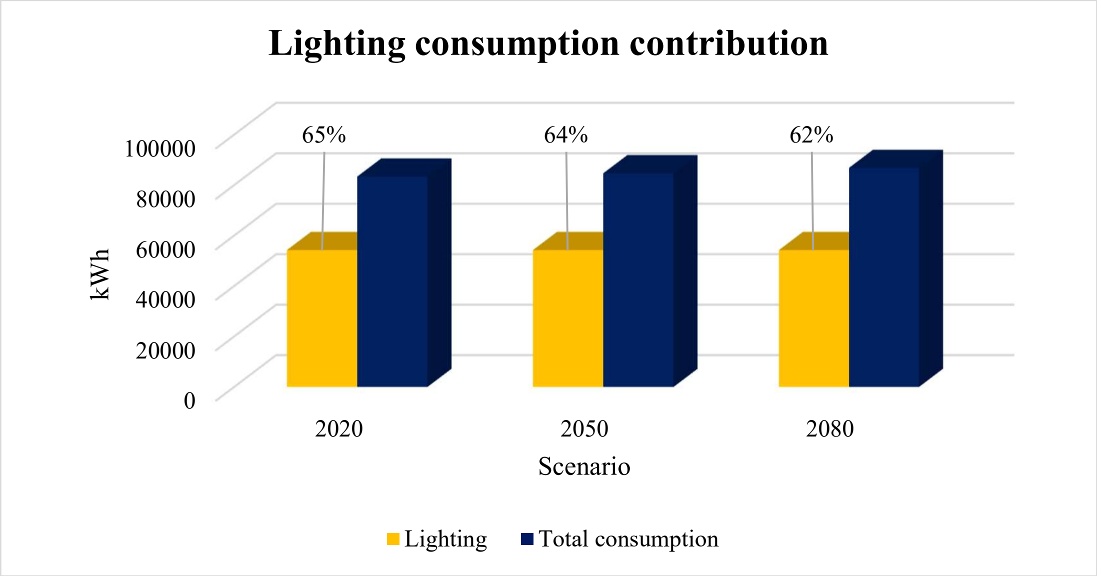


Figure 74 Lighting consumption contribution

Consequently, solutions such as solar shading, selective glazing, appropriate furnishings and automated lighting systems (BACS) are needed to optimize energy consumption: dimming systems will be essential in order to dim the power of lighting devices based on the luminosity of the spaces in real time, thus dosing consumption exclusively according to needs.

In the end, comparing the PVs sizes coverage, it follows that the use of Photovoltaic System, while very extensive, is not sufficient to cover all the energy needs of a building, especially considering the limitations imposed by the urban contexts in which most buildings in Italy are located. In fact, a doubling of the surface area, from 90 m^2 to 180 m^2 corresponds to an increment of around 20% in terms of renewable energy.

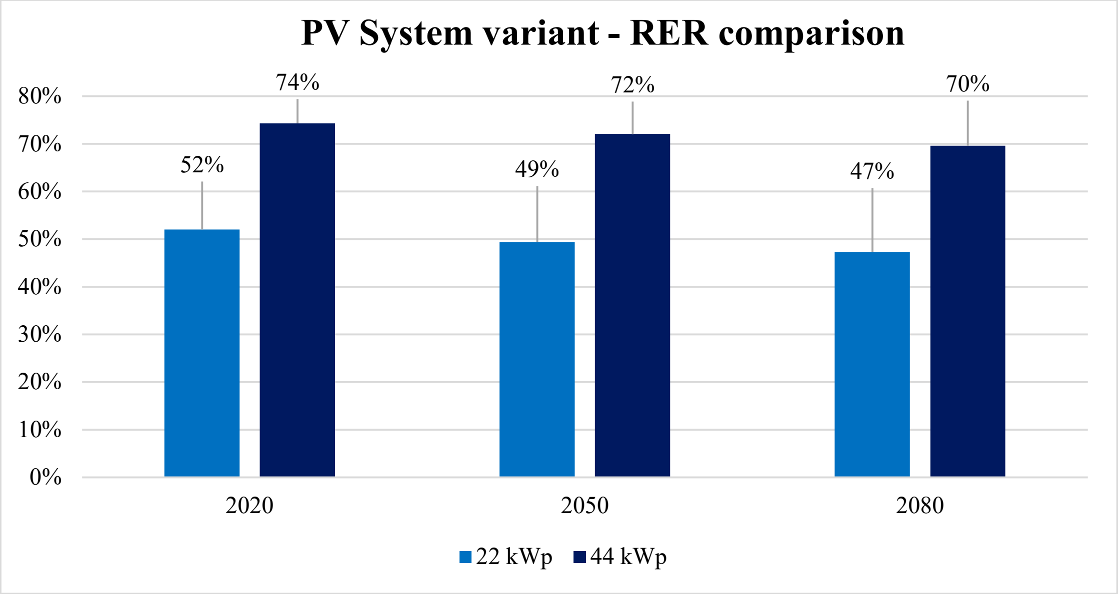


Figure 75 Comparison between renewable energy coverage by PV systems

Therefore, it follows that it is essential to consider an integrated approach that combines different solutions to obtain the maximum benefit, cause the idea of covering all the annual electricity need by the Photovoltaic system is not realistically achievable.

Thus, it is concluded that the adoption of energy-efficient and climate resilient solutions, although complex, can lead to substantial changes in the building's energy balance, bringing the building progressively closer to the NZEB (Nearly Zero Energy Building) concept.

8. CONCLUSION

This study analyzed the impact of energy-efficient and climate resilient strategies on the energy requirements of a building in relation to the climate challenge to which it will be subjected in the coming years.

An analysis of the showed simulation outputs highlights the effectiveness of these solutions applied, especially of automated shading devices and ventilative cooling strategies, which have the ability to significantly reduce cooling demand over the years while keeping that energy vector low.

Despite the application of these improvement strategies, it emerges that the total energy consumption of the building still remains high due to the lighting vector, which accounts for a large part of it and remains fixed by taking action only on the envelope. It emerges that it is necessary, alongside the improvement of the building envelope, to optimize the lighting load through the use lighting systems equipped with sensors, able to dim the power of lighting devices according to the amount of light entering the room.

This investigative study analyzed the effectiveness of envelope and natural ventilation strategies in enhancing the building's resilience to climate change. Additionally, it aimed to maximize the use of renewable energy to move closer to the goal of reducing CO_2 emissions, striving for a Zero Emission Building.

This thesis work, with its strong design component, points out also the importance of integrated design that goes hand with energy analysis, which is becoming an indispensable element in projects as it provides the information needed to optimize design choices.

On the basis of these considerations, it is possible to state that the use of solutions which are energy efficient and climate resilient, in a combined manner, is able to make substantial changes to the building’s energy consumption which results in a move towards the ZEB concept.

BIBLIOGRAPHY

1. ASviS. (2024). *Rapporto ASviS 2024: L'Italia e gli Obiettivi di Sviluppo Sostenibile*. ASviS.
2. Intergovernmental Panel on Climate Change (IPCC). (2023). *Summary for policymakers: Climate change 2023: Synthesis report* (IPCC AR6 Synthesis Report). Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/synthesis-report/
3. Global Alliance for Buildings and Construction (GlobalABC). (2023). *Global status report on buildings and construction 2023*. United Nations Environment Programme (UNEP). https://www.unep.org/resources/report/global-status-report-buildings-and-construction-2023
4. Commissione Europea (2024), *Direttiva EU 2024/1275 del Parlamento europeo e del Consiglio del 24 aprile 2024 sulla prestazione energetica nell'edilizia (recast).* http://data.europa.eu/eli/dir/2024/1275/oj
5. Commissione Europea (2021), *Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (recast)*. https://eur-lex.europa.eu.
6. Commissione Europea - *Energy Efficiency in Buildings*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en
7. Buildings Performance Institute Europe (BPIE) (2022). *The Road to Climate-Neutral Building Stock by 2050: Impact Assessment of the EPBD Recast on the European Building Sector*. https://www.bpie.eu.
8. Eurostat (2021) - *Energy Statistics – Consumption of Energy in Buildings*. https://ec.europa.eu/eurostat.
9. Agenzia delle Entrate (Italia), *Guida al Superbonus 110%.* https://www.agenziaentrate.gov.it.
10. International Energy Agency (IEA), *Energy Efficiency 2021 Report*. https://www.iea.org/reports/energy-efficiency-2021
11. World Green Building Council (WGBC), *Net Zero Carbon Buildings – A Framework for Action*. https://www.worldgbc.org.
12. Agenzia Internazionale per l'Energia Rinnovabile (IRENA) (2020), *Smart Grids and Renewables: A Guide for Effective Deployment*. https://www.irena.org.
13. European Commission – Energy Performance of Buildings Directive (EPBD) - https://energy.ec.europa.eu.
14. European Environmental Bureau (EEB) - *Citizens' Guide to the EPBD Recast*. https://eeb.org.

15. European Environmental Bureau (EEB) - *The Socio-Economic Impact of the EPBD on Member States*. https://eeb.org.
16. World Green Building Council (WGBC) - *Overcoming Barriers to Green Building Adoption in Europe*. https://www.worldgbc.org.
17. Buildings Performance Institute Europe (BPIE) - *On the Path to 2050: Future-proofing the Buildings Sector with the EPBD Recast*. https://www.bpie.eu
18. European Environmental Bureau (EEB) - *Overcoming Barriers to a Just Energy Transition: EPBD and Social Equity in Member States*. https://eeb.org
19. World Green Building Council (WGBC) - *Building a Greener Future: EU Green Building Policies and the Potential for Job Creation*. https://www.worldgbc.org
20. Green Finance Institute - *Financing the Future: Unlocking Green Investments for the EPBD Recast Goals*. https://www.greenfinanceinstitute.co.uk
21. The IES Virtual Environment - User Guide (VE 2015) https://www.iesve.com/downloads/help/VE2015/VirtualEnvironment.pdf
22. IPCC Data Distribution Centre, HadCM3 Climate scenario data download page, http://www.ipcc-data.org/sres/hadcm3_download.html
23. Microsoft Word - manual_weather_tool_v1.9.docx
24. Climate Change World Weather File Generator for World-Wide Weather Data - CCWorldWeatherGen - University of Southampton Blogs
25. Akbari, H., Pomerantz, M., & Taha, H. (2001). *Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas*. Solar Energy, 70(3), 295-310.
26. California Energy Commission. (2008). *Cool Roofs and Their Benefits*. California Energy Commission.
27. Gago, E. J., Roldan, J. L., & Montávez, J. P. (2013). *The effect of the installation of cool roofs on the energy consumption in buildings*. Journal of Building Performance, 4(3), 218-229.
28. Santamouris, M., & Kolokotsa, D. (2015). *On the impact of urban heat island and cool roofs on energy and environmental sustainability*. Renewable and Sustainable Energy Reviews, 51, 269-283.
29. Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). (2022). *Building simulation applications (BSA 2022)*. 5th IBPSA-Italy Conference, Bozen-Bolzano, 29th June – 1st July 2022.
30. AICARR. (2022). *38° Convegno Nazionale AICARR: Edifici e impianti per il clima futuro*. Convegno Expocomfort, Fieramilano - Rho, 29 giugno 2022.
31. Saelens, D., Laverge, J., Boydens, W., & Helsen, L. (Eds.). (2021). *Proceedings of Building Simulation 2021: 17th Conference of IBPSA*.

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