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THE ENERGY REFURBISHMENT OF EXISTING BUILDINGS FOR
THE GOAL OF THE NET OR NEARLY ZERO ENERGY TARGET TO
FRONT THE CLIMATE CHANGE

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Index

Index of Acronyms	5
Abstract: structure, methodology and purposes of the research	8
I) Performance investigation of nearly zero energy designs:	10
II) Impact of climate change on building needs and consumption:	11
Chapter 1: Strategies applied for reducing the energy and environmental impact of building sector	13
1.1 Overview on climate changes and building sector impact.....	13
1.1.1 Building sector's energy consumption	14
1.1.2 Global warming and Urban Heat Island	15
1.2 International actions and regulations	20
1.2.1 European regulations: strategies for improving energy performance of buildings.....	20
1.2.2 Italian legislation framework about energy performance of envelope/HVAC systems.....	22
1.3 Nearly zero energy target: objectives and results	23
1.3.1 Diffusion and results in Europe	25
1.3.2 Diffusion and results in Italy	29
Chapter 2: Methodological approach for verifying the NZEB standard	32
2.1 Numerical analysis.....	32
2.2 Building Energy Simulation for building-HVAC system	36
2.2.1 Semi-steady-state tools	42
2.2.2 Dynamic tools	47
2.3 CFD for building envelope elements	52
2.4 The models for the climate change projections.....	57
Chapter 3: Performance investigation about nearly zero energy designs	64

3.1 Thermal comfort analysis of a bedroom using CFD modelling	70
3.1.2 Method	74
3.1.3 Results	75
3.1.4 Conclusions.....	79
3.2 Sensitivity analysis about the effectiveness of the energy efficiency measures for residential building under the Italian incentive opportunities ...	81
3.2.1 Methodological approach	82
3.2.2 Existing state and energy refurbishment scenario	83
3.2.3 Results	86
3.2.4 Conclusions.....	89
3.3 Application of energy regulations to a residential building in a temperate climate	91
3.3.1 Research method.....	94
3.3.2 Results	95
3.3.3 Conclusions.....	97
3.4 Social Housing regeneration: qualifying and making sustainable buildings and public spaces. A case study	99
3.4.1 Model description	100
3.4.2 Smart Thermal Energy Hub System	101
3.4.3 Results	103
3.4.4 Urban Heat Island (UHI) effect on the case study	105
3.4.5 Conclusions.....	108
Chapter 4: Impact of climate change on building energy needs and consumption	111
4.1 Forecasting future climate with a neural network trained on monitored data: an analysis of the energy demand of a detached house	115

4.1.1 Methodological approach	116
4.1.2 Results	120
4.1.3 Conclusions.....	122
4.2 Optimized neural network architectures for climate data and photovoltaic production forecasting	124
4.2.1 Methodological approach	125
4.2.2 Results	127
4.2.3 Conclusions.....	132
4.3 Impact of glazing system on the energy performance of a nZEB under climate change scenarios	134
4.3.1 Methodological approach	135
4.3.2 Results	136
4.3.3 Conclusions.....	141
4.4 Effect of degradation and size selection for the photovoltaic system installed in a nearly zero energy building in Tropical Climate.....	143
4.4.1 Methodological approach	143
4.4.2 Results	145
4.4.3 Conclusions.....	149
4.5 Sensitivity analysis on the energy performance evaluation of buildings designed as nearly zero energy in the current climatic scenario and climate change evolution	151
4.5.1 Methodological approach	151
4.5.2 Results	155
4.5.3 Conclusions.....	164
Conclusions.....	167
I) Performance Investigation of Nearly Zero-Energy Designs.....	169

II) Impact of Climate Change on Building Energy Needs and Consumption	171
Recommendations for Practitioners.....	174
List of papers	175
References	177
Index of Figures	195
Index of Tables.....	199

Index of Acronyms

- ANN: Artificial Neural Network
- APE: Attestato di Prestazione Energetica
- AQE: Attestato di Qualificazione Energetica
- AR5: Fifth Assessment Report
- BACS: Building Automation and Control Systems
- BES: Building Energy Simulation
- BIM: Building Information Modeling
- BIPV: Building Integrated Photovoltaics
- BnZEB: Benevento Nearly Zero Energy Building
- BPS: Building Performance Simulation
- CAM: Criteri Ambientali Minimi
- CDW: Construction and Demolition Waste
- CE: Circular Economy
- CFD: Computational Fluid Dynamics
- CMV: Controlled Mechanical Ventilation
- CV(RMSE): Coefficient of Variation of the Root Mean Square Error
- DBT: Dry Bulb Temperature
- DHW: Domestic Hot Water
- DOE: Department of Energy
- EED: Energy Efficiency Directive
- EEMs: Energy Efficiency Measures
- EPBD: Energy Performance of Buildings Directive
- EPC: Energy Performance Certificate
- $EP_{gl,NREN}$: Overall Non-renewable Primary Energy Performance Index
- $EP_{gl,tot}$: Overall building energy performance index
- EPS: Expanded Polystyrene
- EV: Electric Vehicle

- FDM: Finite Difference Method
- FEM: Finite Element Method
- FVM: Finite Volume Method
- GBC: Green Building Council
- GCMs: Global Climate Models / General Circulation Models
- GHG: Greenhouse Gases
- GHI: Global Horizontal Irradiance
- GMST: Global Mean Surface Temperature
- GND: Green New Deal
- GRU: Gated Recurrent Unit
- GSR: Global Solar Radiation
- GWP: Global Warming Potential
- HDD: Heating Degree Days
- HP: Heat Pump
- HVAC: Heating, Ventilation and Air Conditioning
- IDSB: Innovative Demonstration Social Building
- IPCC: Intergovernmental Panel on Climate Change
- ISI: Investment-Saving Index
- ISO: International Organization for Standardization
- LCA: Life Cycle Analysis / Assessment
- LEED: Leadership in Energy and Environmental Design
- Low-E: Low-Emissivity
- LSTM: Long Short-Term Memory
- MBE: Mean Bias Error
- MRT: Mean Radiant Temperature
- NDCs: Nationally Determined Contributions
- NN: Neural Network
- nZEB: nearly Zero Energy Building
- PCM: Phase Change Materials
- PEB: Plus Energy Building

- PET: Physiological Equivalent Temperature
- PMV: Predicted Mean Vote
- PPD: Predicted Percentage Dissatisfied
- PV: Photovoltaic
- R^2 : Coefficient of Determination
- RCMs: Regional Climate Models
- RCP: Representative Concentration Pathways
- REHOUSE: Renovation packagEs for HOlistic improvement of EU's bUildingS Efficiency
- SEM: Structural Equation Model
- SET Plan: Strategic Energy Technology Plan
- SIAPE: Sistema Informativo sugli Attestati di Prestazione Energetica
- SRES: Special Report on Emissions Scenarios
- SRI: Smart Readiness Indicator
- SUDS: Sustainable Urban Drainage Systems
- TMY: Typical Meteorological Year
- TRL: Technology Readiness Level
- TRNSYS: TRaNsient SYstem Simulation program
- UHI: Urban Heat Island
- UNFCCC: United Nations Framework Convention on Climate Change
- UNI/TS: Ente Nazionale Italiano di Unificazione / Technical Specification
- W2W: Water-to-Water
- X-Lam: Cross-Laminated Timber
- XPS: Extruded Polystyrene
- ZEB: Zero-Emission Building

Abstract: structure, methodology and purposes of the research

The ongoing climate crisis represents, for many people, a concern for their lives and livelihoods. Considering fires, floods and storms, almost every part of the globe has been affected by climate-related disasters in recent years, with catastrophic consequences for millions of people. The majority of the scientific community agrees that human activity is one of the main causes of the current climate change. Whether or not one agrees with this view, it is important to limit the consumption of both material and energy resources to live in harmony with the planet, allowing their regeneration at a rate at least equal to that of consumption and reducing the release of waste into the ecosystem.

Among the energy sectors with the greatest impact, but also with the greatest potential for improvement, is the building sector. In particular, energy-related CO₂ emissions from buildings have increased in recent years, after a period of stability between 2013 and 2016. Several factors have contributed to this increase, including the growing demand for energy for heating and cooling, due to the increasing spread of air conditioners and extreme weather events. Until a few years ago, the heating of residential structures was largely carried out by generation systems based on fossil fuels, while in recent years there has been an increasing use of systems powered by electricity (and therefore potentially capable of exploiting renewable energy). Furthermore, thanks also to the tax incentive policies implemented by some countries such as Italy, there has been a strong push for the energy efficiency of buildings, also in terms of the building envelope and, therefore, the reduction of energy needs. EU countries, in relation to residential and tertiary uses, have highlighted that one of the main challenges to mitigate the effects of human activities on the climate is the search for new high-efficiency construction standards.

Therefore, improving the energy performance of buildings is a key objective for achieving the long-term goals of the EU's shared climate strategy for a low-carbon economy by 2050, with complete decarbonization of the European building stock. For these reasons, the commitment of the EU member countries is aimed at achieving the nearly zero-energy building (nZEB) standard, as required by Directive 2024/1275, which updates Directive 2018/844 on the energy performance of buildings (EPBD-recast). The directive will be reviewed starting from 2028 to adapt it to the changes that will have occurred in the first 4 years of application.

The introduction of the reference for calculating the average starting consumption of the building stock in 2020 represents an advantage for Italy, since it was in July 2020 that the much-discussed "Superbonus 110%" law was introduced. Therefore, all buildings made more efficient through the aforementioned tax relief will contribute to the achievement of the objectives imposed on Italy by the European Union, making the path towards the targets set for 2033 and 2035 easier and less expensive (from now on).

In Northern European countries, standards and guidelines for the design and construction of passive houses and high-energy-efficiency buildings began to be issued as early as the 1990s. Their design had to meet detailed criteria regarding the energy demand for space heating and air tightness, with a strong focus on the building envelope, heat loss through it and the air ventilation system to meet comfort conditions inside the building while minimizing energy consumption. Reaching the present day, the introduction of nearly Zero Energy Buildings (nZEBs) first and Zero Energy Buildings (ZEBs) later, is based on a new concept of high-performance design, based on the energy balance between consumption and production from renewable sources. Therefore, in addition to reducing the heat loss of the building envelope and installing systems with higher efficiency, the focus is also on the use of generators powered by renewable sources produced on-site.

In this context, researchers are making considerable efforts to optimize the design and operation of buildings and their systems through new materials, technologies, solutions, design criteria and management strategies.

However, as emerges from the literature, some important issues related to the design and construction of low or zero-emission buildings are still under discussion. During the doctoral course, some of these issues related to nearly zero-energy buildings and the retrofit of the existing building stock were studied. The work carried out is reported in this thesis.

More specifically, the research activity developed can be divided into two macro-areas:

I) Performance investigation of nearly zero energy designs:

First, the research activity focused on the analysis of interventions designed and implemented in the civil construction sector, mainly residential, aimed at achieving the nZEB standard, as defined by the Italian legislation currently in force. Although the definition of nZEB and the requirements for achieving the standard are very different among the laws of the various European countries, the common goal is certainly the minimization of energy needs and greenhouse gas emissions during the operational life. Based on specific and actually implemented interventions or on already existing nZEB buildings, the energy savings obtained, as well as, in some cases, the level of perceived comfort using CFD methods and on-site measurements, were quantified using the tools provided by current Italian legislation and the most modern tools not yet implemented in current legislation. However, the achievement of these savings and comfort objectives requires careful use of building materials and plant systems that are often innovative and therefore have a higher cost than those used for traditional construction. For example, the insulation standard for the building envelope may in many cases require high thicknesses, if the use of the most common insulating materials is considered and,

in the case of renovation of existing buildings, it is not always possible to increase the thickness of the external walls by the 10-15cm (on average) required. Therefore, it may be necessary to resort to innovative materials that involve a significantly higher cost. The same applies to Heating, Ventilation and Air Conditioning (HVAC) systems that use renewable sources (mainly modern electric absorption heat pumps), which entail a significant increase in costs compared to a standard or condensing boiler. In light of these considerations, an attempt was therefore made to answer the question of the economic convenience, from the point of view of the property owner, of carrying out interventions of this type and the possibility to introduce more or less important incentives to accelerate the energy transition. Furthermore, an attempt was made to apply the concept, not yet regulated, of PEB (Plus-Energy Building), evaluating the possible use of this surplus energy, produced by on-site renewable energy production plants, for recharging electric vehicles. In some of these studies, the need to understand how much the methodologies currently proposed by the legislation returned results that were in line with reality was highlighted.

II) Impact of climate change on building needs and consumption:

The second research topic during the three years of the doctorate concerns the analysis of the building solutions currently adopted and the variation in their performance in the coming decades in light of the climate changes currently underway and which the majority of the scientific community assumes may continue in the coming years. Therefore, often in parallel with the study of the topics of macro-area I, the performance of buildings and some of the plant systems was evaluated using calculation models already validated for estimating external temperatures in 2050 and 2080. The final purpose of this evaluation is to understand whether the design choices largely adopted and calibrated on the climatic conditions currently provided for by the legislation are actually valid and

effective even if the forecasts of the scientific community should actually come true. The answer to this question is not obvious since the design of interventions for the reduction of winter energy needs often conflicts with the design of interventions for the reduction of summer needs. It is vitally important to carefully evaluate the design of interventions to avoid the construction of buildings that do not respond efficiently to the climatic conditions expected for their entire useful life. We therefore focused on the analysis of the validity and the correspondence to reality of the results provided by the calculation models currently proposed by the legislation (monthly, therefore semi-steady-state type) comparing them with the results obtained with dynamic hourly methods, such as those that will soon be provided for by national legislation following the introduction of the same at European level, in the EPBD IV.

Chapter 1: Strategies applied for reducing the energy and environmental impact of building sector

1.1 Overview on climate changes and building sector impact

The Green New Deal (GND) [1] and the REPowerEU plan [2] drive the global transition toward a low-carbon economy, targeting a 55% reduction in greenhouse gas emissions by 2030 and a 42.5% renewable capacity. These policies address anthropogenic global warming, which the IPCC warns will likely exceed the 1.5°C threshold between 2030 and 2052 [3] if current trends persist.

As illustrated by the global mean surface temperature (GMST) anomalies in Figure 1, this warming trend underscores the critical role of the building sector.

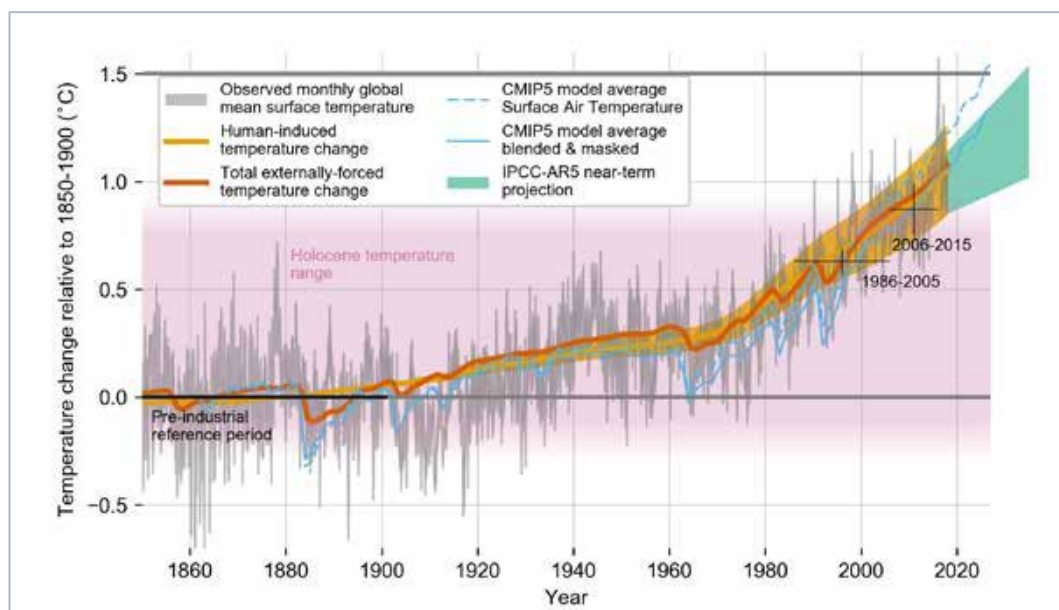


Figure 1: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Are shown: in grey colour the GMST in the HadCRUT4, NOAAGlobalTemp, GISTEMP and Cowtan-Way datasets; in yellow the Human induced contributions to GMST; in orange the total (human- and naturally-forced) contributions to GMST; in blue the modelled global mean surface air temperature (dashed) and blended surface air and sea surface temperature (solid) from the CMIP5 historical ensemble; in shading pink the range for temperature fluctuations over the Holocene; in light green plume the IPCC prediction in 2014 for average GMST over 2016–2035. Ref. [50]

In 2018, buildings accounted for 20% of global energy consumption [4], with the residential sector alone contributing approximately 24% [5]. Within the EU-28, the sector represents 27.2% of final energy use [6], indicating a vast potential for savings. Similarly, in Italy, the residential and tertiary sectors are responsible for roughly one-third of the national final energy consumption.

1.1.1 Building sector's energy consumption

Global urbanization is a primary driver of energy demand; a 1% increase in urban population correlates to a 2.2% rise in energy consumption [7]. By 2050, 68% of the global population is projected to reside in urban areas, with concentrations exceeding 70% in North America, Europe, and Latin America [8]. In developing regions of Asia and Africa, rapid economic growth and cooling requirements make electricity the dominant energy carrier in buildings (Figure 2) [9].

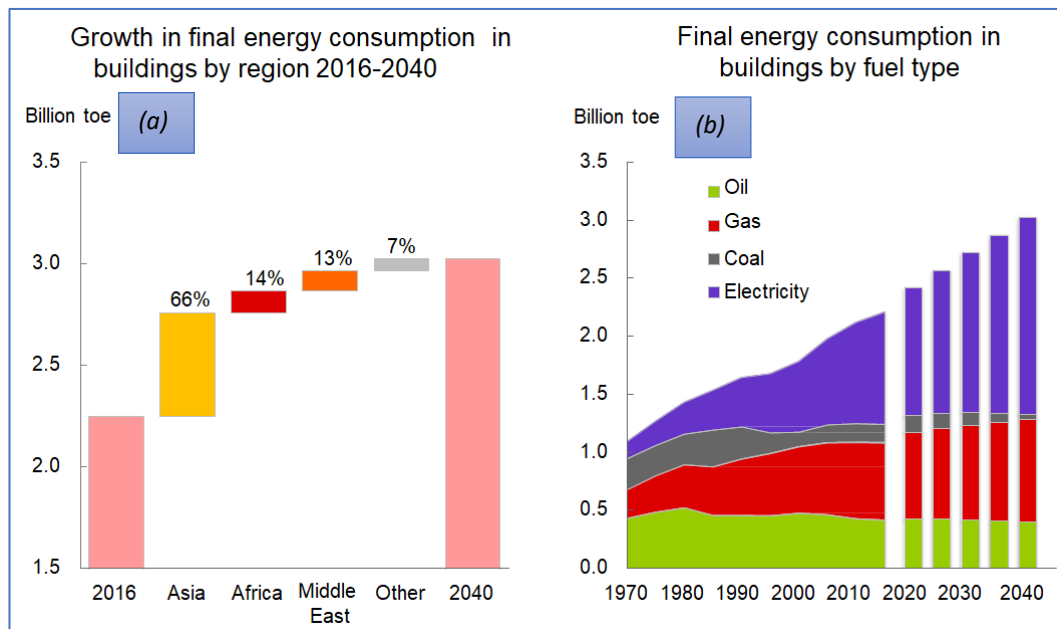


Figure 2 Final energy consumption in buildings: growth by region (a); by fuel type (b). Ref [9].

According to the 2021 Emissions Gap Report [10], the building and construction sector accounted for 37% of global energy-related CO₂ emissions in 2020. Despite improvements in energy intensity per square meter, the expansion of total floor area continues to drive absolute consumption upward. This trend is reflected in the primary energy consumption trajectories from 1970 to 2020, with 2040 projections under an 'Evolving Transition' (ET) scenario (Figure 3).

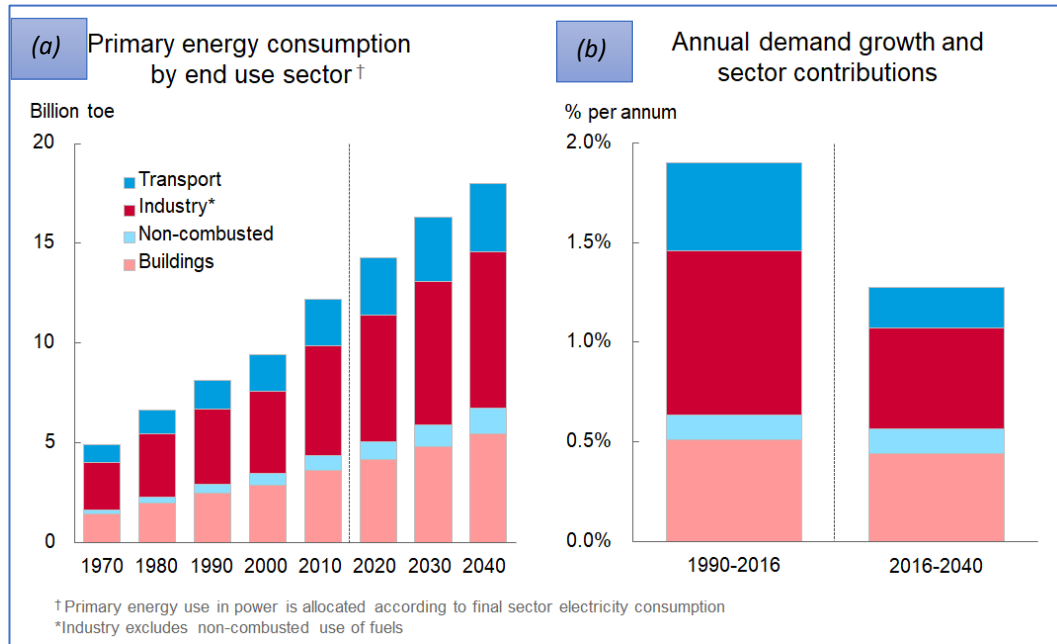


Figure 3 Primary energy consumption by end use sector (a); annual demand growth and sector contributions (b). Ref [9].

1.1.2 Global warming and Urban Heat Island

Global warming exacerbates extreme weather events and health risks [3], with climate impacts dictated by the cumulative emission of long-lived GHGs and the emission rates of short-lived forcings [11]. In urban environments, this is compounded by the Urban Heat Island (UHI) effect, where temperatures significantly exceed those of surrounding rural areas [12]. This phenomenon results from replacing natural surfaces with impermeable, high-thermal-capacity

materials that absorb solar radiation [13]. As illustrated for New York City in Figure 4, dense vegetation directly correlates with lower surface temperatures. Other factors include urban geometry, anthropogenic heat, and air pollution [14, 15].

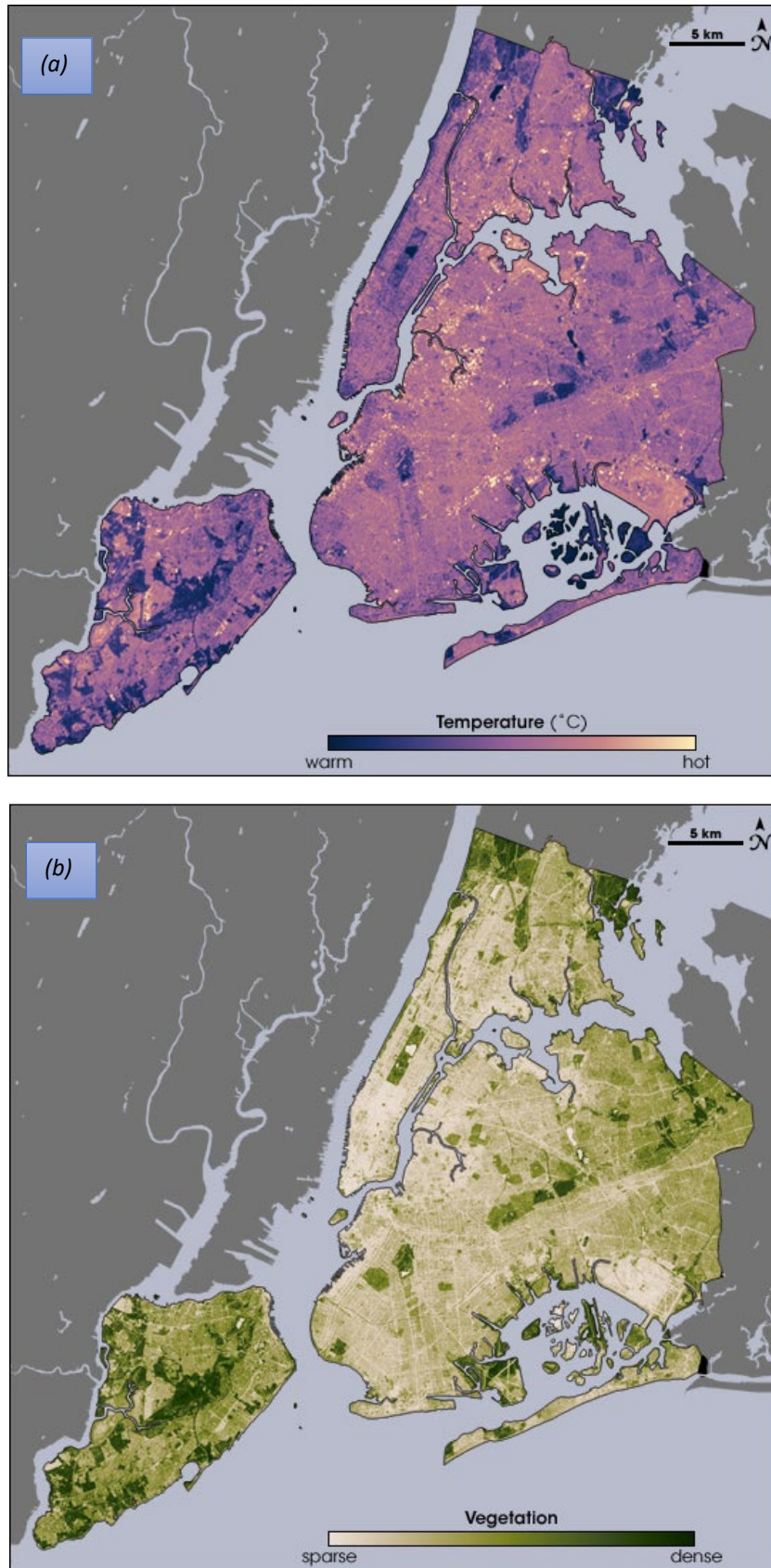


Figure 4 Surface temperature (a) and city-wide land cover (b) maps of New York City in August 4th, 2002. Ref. [51].

The UHI increases cooling energy demand and heat-related mortality [16]. In European cities, UHI typically raises summer temperatures by 0.5–2.5°C [17, 18]. Experimental data from approximately 110 European cities, gathered through various monitoring methodologies [52], show average UHI intensities ranging from 1.08 K (fixed stations) to 3.2 K (non-standard devices), as shown in Figure 5.

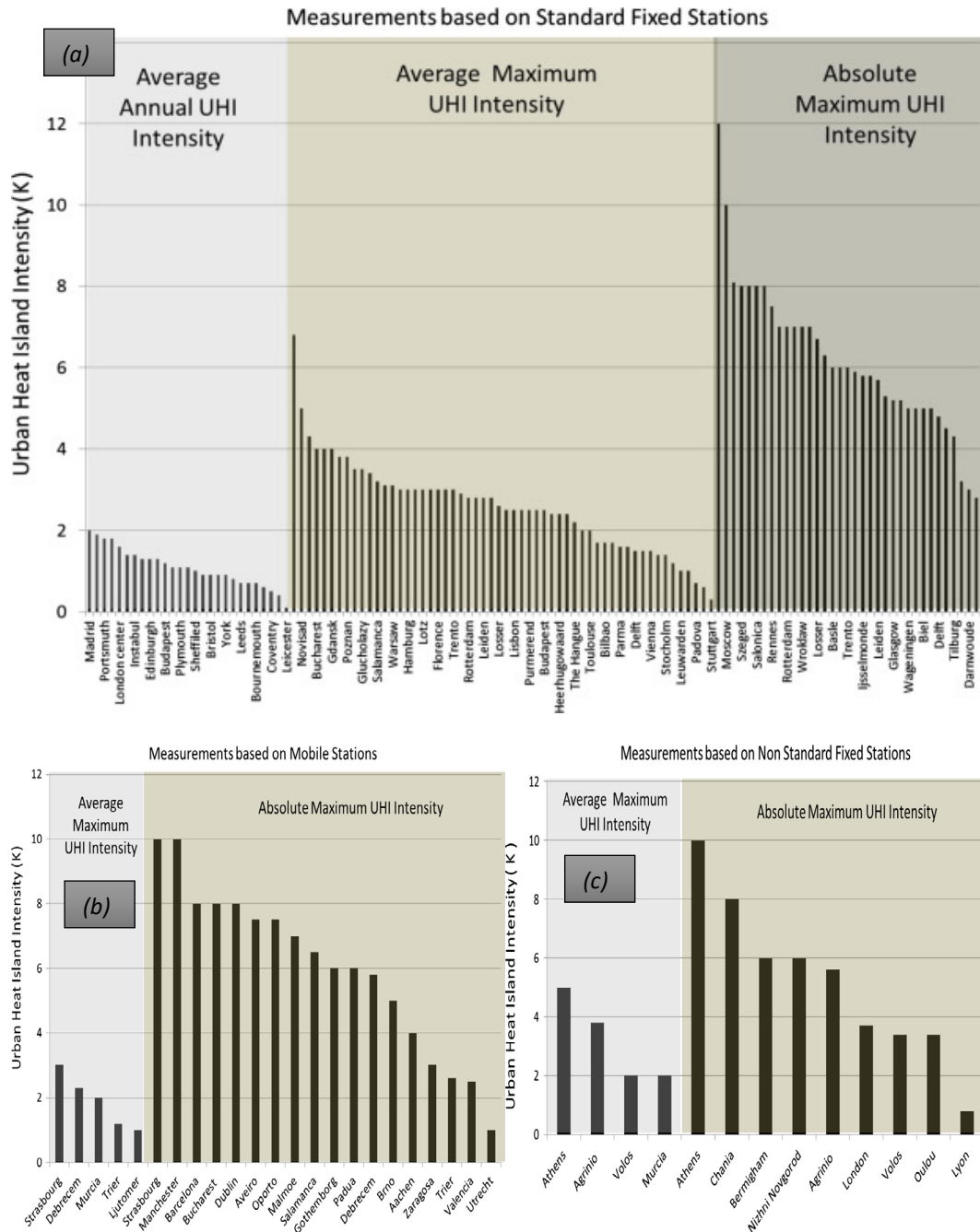


Figure 5 Measured annual urban heat island intensity for all experiments based on the use of: standard fixed meteorological stations(a); non standard fixed meteorological stations (b); mobile traverses (c). Ref. [52].

Crucially, this thermal elevation increases cooling demand by 5% to 20% for every degree Celsius of temperature rise [19, 20]. Mitigation strategies focus on four pillars:

- Urban Vegetation: Increasing green infrastructure (roofs, walls, and parks) to leverage shading and evapotranspiration.
- Cool Materials: Using high-reflectance and high-emissivity surfaces to reduce heat absorption.
- Urban Ventilation: Optimizing urban design to promote air circulation.
- Stormwater Management: Implementing sustainable urban drainage systems (SUDS) to facilitate cooling through evaporation.

1.2 International actions and regulations

To mitigate greenhouse gas (GHG) emissions and adapt to global warming, the international community has established frameworks aimed at a low-carbon transition, with the building sector at the core of these actions.

The scientific foundation for these policies is provided by the IPCC, which evaluates global climate knowledge to guide policymakers. A key milestone was the 1992 UNFCCC [21], which introduced the principle of "common but differentiated responsibilities." This was followed by the Kyoto Protocol (1997) [22], the first legally binding agreement for industrialized nations.

The Paris Agreement (2015) [23] marked a shift toward universal commitment, aiming to limit global temperature rise to well below 2°C, and ideally 1.5°C. Under this framework, countries submit Nationally Determined Contributions (NDCs) to progressively increase climate ambition.

1.2.1 European regulations: strategies for improving energy performance of buildings

The EU has evolved its energy strategy from supply security to a focus on full decarbonization. This trajectory is defined by several key milestones:

- The SET Plan (2007) [24]: Accelerated low-carbon technological innovation.
- 20-20-20 Package (2008) [25]: Set 20% targets for GHG reduction, renewable energy, and efficiency.
- 2030 Climate and Energy Framework (2014) [26-28]: Raised targets to 40% GHG reduction and 32.5% efficiency.

- 2050 Long-term Strategy [29]: Aiming for climate neutrality (net-zero emissions).

The Energy Performance of Buildings Directive (EPBD) represents the specific regulatory pillar for this sector:

- Directive 2002/91/EC [30]: Introduced Energy Performance Certificates (EPC).
- Directive 2010/31/EU (EPBD Recast) [31]: Introduced "cost-optimal" levels and the nZEB standard for all new buildings from 2021.
- Directive 2012/27/EU (EED) [32] & (EU) 2018/844 [33]: Focused on accelerating the renovation of existing stocks and introducing the Smart Readiness Indicator (SRI).
- Directive (EU) 2023/1791 [34]: Increased the 2030 reduction target to 11.7% and mandated a 3% annual renovation rate for public buildings.

The latest EPBD IV (Directive (EU) 2024/1275) [35] transitions the target from nZEB to Zero Emission Buildings (ZEB). Key requirements include:

- Renovation Passports: Personalized roadmaps for building upgrades.
- GWP Disclosure: EPCs must now include Life Cycle Assessment (Global Warming Potential).
- Mandatory Solar: Gradual installation on public, non-residential, and new residential buildings by 2030.
- Fossil Fuel Phase-out: A ban on incentives for fossil fuel boilers from 2025, with a full installation ban by 2040.

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

Italy transposed the EPBD through several legislative steps, creating a framework that increasingly mandates high-performance standards:

- D.Lgs. 192/2005 [36]: Initial transposition of the first EPBD.
- D.Lgs. 63/2013 [37]: Introduced the "reference building" concept and nZEB deadlines.
- Ministerial Decree 26/06/2015 ("Minimum Requirements") [38]: This is the current technical benchmark. It defines calculation methodologies based on the UNI/TS 11300 standards [39-42].

Methodological Note: A significant limitation within the current Italian framework is its reliance on semi-steady-state analysis with monthly climatic data (UNI/TS 11300). While sufficient for standard compliance, this approach often fails to account for hourly thermal fluctuations and extreme events exacerbated by climate change. As will be discussed in this thesis, such tools can be misleading when assessing the long-term resilience of buildings, highlighting the need for a transition toward hourly dynamic simulations.

- D.Lgs. 48/2020 [43]: Latest major update, integrating smart technologies and electric mobility into building energy policies.

1.3 Nearly zero energy target: objectives and results

The nZEB approach should not be seen merely as a tool for reducing the environmental impact of a building during its operational life, but it also integrates with the principles of the circular economy (CE). The use of recycled and recyclable materials, designing for durability and disassembly of buildings and the reduction of construction and demolition waste (CDW) are fundamental aspects for reducing the environmental impact of the building sector. The RE4 project [44] represents a concrete example of the application of circular economy principles in the construction sector, with the aim of developing high-energy-efficiency prefabricated elements using recycled materials from CDW.

Focusing on energy efficiency during the operational life of buildings, it can be noted that designers often tend to concentrate on reducing energy demand for winter heating, neglecting the risk of summer overheating, which is particularly relevant in Mediterranean climates. This tendency is partly understandable, given that historically regulations and incentives have focused on thermal insulation to reduce winter heat losses. However, in Mediterranean climates, characterized by hot and sunny summers, controlling the summer thermal load is equally crucial, if not more so, to ensure thermal comfort and contain energy consumption.

In Mediterranean climates, achieving the nZEB standard requires careful evaluation of the balance between winter heating and summer cooling needs. Excessive attention to thermal insulation, without adequate consideration of solar radiation management and ventilation, can lead to summer overheating and an increase in cooling demand. Passive strategies, such as shading, natural ventilation, the use of high thermal mass materials and the use of "cool materials," play a fundamental role in containing the summer thermal load. The integration of efficient active systems, such as high-efficiency heat pumps and controlled mechanical ventilation systems with heat recovery, is often necessary to achieve the nZEB target. The use of renewable sources, in particular solar photovoltaics

but also solar thermal, is essential to cover a significant part of the residual energy demand.

Below is a brief overview of the types of interventions and/or design objectives to be pursued to improve the performance and comfort of new buildings or in the case of renovation, dividing them between those relating to the building envelope (and therefore aimed at reducing energy needs) and those relating to systems and on-site energy production (and therefore aimed at improving efficiency and shifting consumption from fossil fuels to renewable sources).

Regarding the building envelope:

- Insulation: Thermal insulation is essential to reduce winter heat losses, but its thickness and position (inside, outside, or in the cavity) must be carefully evaluated in relation to the climate and the characteristics of the building.
- Thermal mass: Materials with high thermal capacity (such as concrete, wood, or stone) can store heat during the day and release it gradually at night, helping to stabilize the internal temperature and reduce peak thermal loads.
- "Cool materials": The use of materials with high solar reflectance and high thermal emissivity (such as "cool" paints) can significantly reduce the surface temperature of the envelope, limiting heat absorption.
- Solar shading: Shading devices (fixed or mobile) are essential to control the input of solar radiation, especially during the summer.
- Natural ventilation: If designed and used correctly, it can contribute to cooling the rooms, especially at night.

Regarding HVAC:

- Heat pumps: High-efficiency heat pumps represent an effective solution for both heating and cooling, especially when combined with low-temperature emission systems.
- Controlled mechanical ventilation (CMV): CMV with heat recovery allows for adequate air exchange, minimizing heat loss in winter and heat gain in summer.
- Advanced control systems: Automation and intelligent control of systems (building automation) can optimize the operation of systems based on the real needs of the occupants and external climatic conditions.

Per quanto riguarda i sistemi di produzione di energia da fonti rinnovabili:

- Solar photovoltaic: The installation of photovoltaic panels allows for the production of electricity on-site, reducing dependence on the grid and CO₂ emissions.
- Solar thermal: Solar thermal panels can be used for the production of domestic hot water and, in some cases, for space heating.

1.3.1 Diffusion and results in Europe

As established by Directive 2010/31/EU (EPBD recast), the Nearly Zero-Energy Building (nZEB) represents the new standard for construction in Europe. While the directive defines the nZEB in general terms (a building with very high energy performance, with a very low or nearly zero energy demand covered to a significant extent by renewable sources produced on-site or nearby), it left it to the Member States to define the specific requirements, adapting them to different climatic conditions, building types and national energy policies [45, 46].

This flexibility, while allowing national specificities to be taken into account, has led to considerable heterogeneity in the nZEB definitions and requirements adopted by the various European countries [47]. The differences concern several aspects, including:

- Primary energy threshold values: The maximum limits of primary energy consumption (when defined) vary widely, from 20 kWh/(m²year) in some countries to over 200 kWh/(m²year) in others [48]. This variability reflects not only climatic differences, but also different interpretations of the concept of "very low or nearly zero energy demand."
- Renewable energy share: The percentage of energy demand that must be covered by renewable sources also varies significantly, from 25% to 56% [48], or in some cases is not specified.
- Energy performance indicators: Most Member States use an annual energy balance to assess nZEB performance [48], but the units of measurement and normalization methods (e.g., per useful floor area, gross floor area, or volume) may differ.
- Building types: Some countries have defined differentiated nZEB requirements for different building types (residential, offices, etc.), while others have adopted uniform requirements.
- New vs. existing buildings: Some countries distinguish between new buildings and existing buildings undergoing major renovation, applying different requirements.

Below are some examples of specific requirements required by different European states [49]:

- Austria, Denmark, Germany, Ireland and Romania: These are the only countries that include specific requirements on greenhouse gas emissions in their NZEB definitions.

- Cyprus, Greece and Malta: These Mediterranean countries have less ambitious NZEB thresholds, with a high consumption of non-renewable primary energy, in particular for residential buildings.
- Flanders, Luxembourg and the Netherlands: These countries have shown a good level of ambition, with stricter NZEB thresholds and a greater contribution from renewable energy.
- Finland and Lithuania: They have achieved more ambitious NZEB performance levels than the benchmarks recommended by the European Commission, both for new and renovated buildings.
- Bulgaria: It stands out for the high share of renewable energy required in NZEB buildings, equal to 55% for all types of buildings.
- Spain and Italy: They have differentiated NZEB thresholds based on climatic zones, with stricter requirements for colder areas.

Despite this heterogeneity, it is possible to identify some common trends in the implementation of nZEBs in Europe:

- Focus on the building envelope: Most countries have placed a strong emphasis on improving the performance of the building envelope, with stringent requirements in terms of thermal insulation, airtightness and control of solar radiation. This approach is particularly evident in Northern and Central European countries, where heating demand is dominant.
- Integration of renewable sources: The use of renewable sources, in particular solar photovoltaics and, to a lesser extent, solar thermal, has become a key element in achieving the nZEB standard in many countries. In some cases, specific incentives are provided for the installation of renewable energy systems in buildings.
- Efficient building systems: The adoption of high-efficiency building systems, such as heat pumps, controlled mechanical ventilation systems

with heat recovery and LED lighting systems, is another common element in nZEB strategies.

- Building automation: The use of automation and control systems (BACS – Building Automation and Control Systems) to optimize the operation of systems and reduce energy waste is becoming increasingly widespread, also thanks to the incentives provided by some national regulations.

The concept of nearly zero-energy building (NZEB) is well established and average energy performance has improved by around 10% in the last four years. New NZEBs have an energy demand that is approximately 30% lower than NZEB-level renovations. Some countries and regions have successfully reduced their NZEB thresholds and introduced more ambitious standards for new and renovated buildings in recent years [49]. These advances demonstrate that, while EU-wide harmonization is complex, targeted national revisions can drive significant improvements in energy performance. Overall, therefore, the number of nZEB buildings in Europe is constantly growing, but the speed of diffusion varies considerably between the different countries. Despite the progress made, some challenges remain, including:

- Costs: The initial costs of constructing or renovating an nZEB building may be higher than those of a traditional building, although operating costs (energy bills) are significantly lower.
- Skills: The design and construction of nZEB buildings require specific skills on the part of designers, installers and building operators.
- Awareness: It is necessary to increase the awareness of citizens and professionals about the benefits of nZEBs and the available technologies.

- **Monitoring:** A system for monitoring the energy performance of nZEB buildings is essential to verify the effective achievement of the objectives and to identify any areas for improvement.
- **Refurbishment:** The real challenge remains the energy requalification of the existing building stock which represents the vast majority of the buildings in Europe.

1.3.2 Diffusion and results in Italy

Italy has transposed Directive 2010/31/EU (EPBD recast) and subsequent amendments through a series of legislative measures, culminating in the Ministerial Decree of June 26, 2015 ("Minimum Requirements Decree") [37] and Legislative Decree No. 48 of June 10, 2020 [43]. These decrees established the minimum energy performance requirements for new and existing buildings and defined the characteristics of Nearly Zero-Energy Buildings (nZEBs), making them mandatory for all new constructions starting from January 1, 2021 (from January 1, 2019 for public buildings).

State incentives, such as the Ecobonus and the Superbonus 110% (now scaled down), have played an important role in promoting the energy renovation of buildings, albeit with variable results and some critical issues related to the complexity of the procedures and long-term financial sustainability. The Superbonus, in particular, generated a significant increase in renovation projects, but also raised concerns about the increase in material prices and the quality of the interventions.

In Italy, new nZEB buildings demonstrate promising energy performance. New single-family houses have a non-renewable primary energy consumption of approximately 30 kWh/(m²y), while newly constructed office buildings stand at 27 kWh/(m²y). [49] These values indicate a commitment to reducing energy demand in new building construction. However, nZEB renovations show room for

improvement. The non-renewable primary energy consumption for renovated single-family houses is 46 kWh/(m²y), while for renovated office buildings it rises to 60 kWh/(m²y) [49]. It is therefore evident that Italy must intensify efforts to improve energy efficiency in renovations, in order to align with the decarbonization objectives of the building sector. A positive aspect is the share of renewable energy integrated into Italian nZEB buildings, which stands at 50% for both new constructions and renovations. Furthermore, public buildings have a more ambitious requirement, with a renewable energy share of 60% [49]. This demonstrates a concrete commitment to the use of clean energy sources in the building sector.

Despite this progress, Italy, like other European countries, faces several challenges for the transition to zero-emission buildings (ZEBs). In particular, the need to:

- Define stricter thresholds for total primary energy demand, in order to promote a further reduction in energy consumption.
- Increase the integration of renewable energies, to achieve the goal of zero on-site carbon emissions.
- Establish operational greenhouse gas emission thresholds, to monitor and reduce the environmental impact of buildings.

In conclusion, Italy has made significant progress in adopting nZEB standards, but must face further challenges to achieve the decarbonization objectives of the building sector. The integration of renewable energies, the reduction of energy demand and the definition of greenhouse gas emission thresholds will be crucial for the transition to ZEBs. A joint commitment by institutions, professionals, businesses and citizens is also necessary to overcome existing challenges and seize the opportunities offered by the transition to low-environmental-impact construction. A key role is played by research and technological innovation, which

can contribute to developing increasingly efficient, economical and suitable solutions for the specificities of the Italian context.

The nZEB target represents a significant challenge, but also an opportunity for the building sector. The adoption of an integrated design approach, which takes into account climatic and construction specificities and the use of innovative and sustainable technologies are essential to achieve this goal and contribute to the transition to a low-carbon economy. The analysis of the energy efficiency of nZEB buildings, with particular attention to the adaptability of technologies to climate change and the comparison of calculation methods, is the main subject of this thesis.

Chapter 2: Methodological approach for verifying the NZEB standard

2.1 Numerical analysis

Numerical analysis is a methodological tool of primary importance in the field of thermal engineering and, in particular, in the study of nearly zero-energy buildings (nZEBs). Its relevance stems from its ability to address the intrinsic complexity of the thermo-physical phenomena that govern the energy behavior of buildings. Through numerical analysis, it is possible to obtain an in-depth understanding of energy dynamics, overcoming the limitations of traditional analytical approaches and offering a detailed framework for performance evaluation and optimization of design solutions.

The fundamental principle of numerical analysis lies in the discretization of the continuous physical domain into a finite set of discrete elements, such as points, segments, surfaces, or volumes. This discretization process transforms the differential equations, which describe physical phenomena in a continuous form, into systems of algebraic equations. These systems, although approximations of the original problem, can be effectively solved through computational algorithms. The numerical solution obtained therefore represents an estimate, with a controllable degree of accuracy, of the behavior of the real physical system.

In the specific context of nZEBs, numerical analysis proves to be a versatile tool applicable to various problems, including:

- Energy performance assessment: Numerical simulation allows for the precise quantification of a building's energy needs across a wide spectrum of operating and climatic conditions. This makes it possible to verify the project's compliance with the stringent regulatory requirements imposed for nZEBs and to make objective comparisons

between different design alternatives in terms of energy efficiency. Numerical analysis can simulate diverse operating scenarios, considering variables such as occupancy, usage schedules and external climatic conditions, providing a realistic estimate of annual energy consumption.

- Detailed thermo-hygrometric analysis: Numerical analysis offers the possibility of studying the thermo-hygrometric behavior of the building envelope components and the building as a whole with a high degree of spatial and temporal detail. It is possible to accurately assess the risk of condensation formation, both surface and interstitial, monitor the trend of internal and external surface temperatures and analyze other crucial parameters to ensure the comfort of the occupants and the durability of building components over time. These analyses are essential to prevent problems related to the healthiness of the environments and the degradation of materials.
- Advanced energy optimization: Thanks to integration with numerical optimization techniques, numerical analysis lends itself to identifying design solutions that minimize overall energy consumption or maximize the level of internal thermal comfort. These optimization processes can take into account a multitude of constraints, both economic (investment costs, operating costs) and performance-related (comfort requirements, architectural constraints, technological limits), guiding the designer towards the most effective and efficient choices.
- Study of complex and innovative building systems: Numerical analysis is particularly suitable for simulating the behavior of advanced building systems, which often characterize nZEBs. These include heat pumps, controlled mechanical ventilation (CMV) systems with heat recovery, thermal storage systems (both sensible and latent) and hybrid systems that integrate different technologies. Numerical simulation allows for the evaluation of their effectiveness in different operating conditions,

the optimization of their management and the analysis of their synergistic interaction with the building envelope, in order to maximize the overall performance of the building.

Within the scope of numerical analysis applied to nZEBs, different methodologies are used, each with specific characteristics and fields of application. Among the most widespread methods are:

- Finite Element Method (FEM): FEM is a powerful and versatile numerical technique, particularly suitable for the analysis of complex problems with irregular geometries and heterogeneous boundary conditions. In the context of nZEBs, FEM can be used for the thermo-structural analysis of complex building elements, for the study of thermal bridges with high precision and for the simulation of heat and mass transfer phenomena in porous media. [53]
- Finite Volume Method (FVM): FVM is a conservative method, particularly suitable for the simulation of fluid dynamic problems and convective-diffusive heat transfer. It is often applied in Computational Fluid Dynamics (CFD). The latter represents an advanced numerical methodology for the detailed analysis of fluid dynamic and thermal phenomena, particularly useful for the study of the building envelope and its components. CFD allows for modeling the complex interaction between air flows, heat transfer and the geometry of building elements, providing valuable information for optimizing energy performance and comfort. [54]
- Finite Difference Method (FDM): FDM is a numerical method that is conceptually and computationally simpler than FEM and FVM, particularly suitable for problems with regular geometries and simple boundary conditions. In the context of nZEBs, FDM can be used for simplified thermal analyses of building elements, for simulating the

thermal behavior of buildings with simple geometric configurations and for modeling transient heat conduction phenomena. [55]

The choice of the most appropriate numerical method depends on a series of factors, including the nature of the problem under consideration, the desired level of detail, the geometric complexity of the system and the available computational resources. In many cases, the integration of different numerical methods, combined with the use of advanced simulation software, allows for effectively addressing the complexity of nZEB energy analysis, providing valuable decision support for the design of increasingly efficient and sustainable buildings.

2.2 Building Energy Simulation for building-HVAC system

The Building Energy Simulation (BES) is emerging as an analytical methodology of fundamental importance within the methodological approach for verifying the construction standards of nearly zero-energy buildings (nZEBs). In a global context increasingly oriented towards sustainability and energy efficiency, BES emerges as an essential tool for designers, builders and policymakers. BES constitutes a sophisticated virtual environment in which it is possible to create a detailed and complete digital model of the building and its HVAC (Heating, Ventilation and Air Conditioning) systems. This holistic approach allows for an integrated and synergistic analysis of the energy behavior of the complex building-plant system, overcoming the limitations of partial and simplified analyses and providing an accurate, dynamic and multidimensional estimate of energy consumption, heat and mass flows and indoor environmental comfort. BES is, therefore, not just a mere calculation tool, but a true strategic decision support, essential for the design, optimization, performance verification and energy certification of nearly zero-energy buildings.

The core of BES lies in its ability to model, through complex mathematical equations, the heat and mass transfer phenomena that govern the thermo-energetic behavior of buildings. These mathematical models, implemented in sophisticated simulation software, are able to faithfully and accurately represent a wide range of factors that influence the energy performance of a building. Among the parameters considered, the thermo-physical characteristics of the building envelope, analyzed in its various components, stand out: opaque structures (walls, roofs, floors), windows (windows, doors), thermal bridges (critical points of the envelope where a different heat transmission occurs between the internal and external environment) and shading and solar control systems. The performance of building systems can also be modeled, including heat and cold generators (boilers, heat pumps, chillers), distribution systems (pipe networks, air ducts), emission

terminals (radiators, fan coils, radiant panels), ventilation systems (natural, controlled mechanical), artificial lighting systems and the complex regulation and control systems that govern the operation of the systems based on needs and environmental conditions. The consideration of external climatic conditions is also fundamental, with the input of meteorological data describing the time evolution of external air temperature, relative humidity, direct and diffuse solar radiation, wind speed and direction and precipitation. No less important are the internal gains of latent and sensible heat, generated by the occupants of the building, artificial lighting, electrical and electronic equipment and any production processes that take place inside the building. The control and management strategies of the building, such as set-point temperature regulation, the hourly scheduling of systems, the management of lighting in function of the contribution of natural light and natural and mechanical ventilation strategies, are also integrated into BES models to realistically simulate the behavior of the building under real operating conditions. The numerical solution of these complex mathematical models, through advanced algorithms and dedicated simulation software, generates a vast amount of interconnected and highly informative results, ranging from energy consumption broken down by energy carrier (gas, electricity, biomass, etc.) or by end-use (heating, cooling, lighting, ventilation, domestic hot water, etc.) to the internal operative temperatures in each room of the building, from the temporal profiles of relative humidity rates to the levels of natural and artificial illumination, up to the detailed quantification of heat flows through the various components of the building envelope and the evaluation of the contribution of the different energy sources (renewable and non-renewable).

The adoption of BES translates into a wide range of concrete and measurable advantages in the design and verification of nZEB buildings, contributing significantly to the achievement of the ambitious goals of energy efficiency, environmental sustainability, comfort and well-being of the occupants:

- Integrated and holistic evaluation of the building-plant system, overcoming the compartmentalized vision: One of the main strengths of

BES lies in its ability to overcome the traditional compartmentalized vision that often characterizes the energy analysis of buildings. Instead of considering the building envelope and the building systems separately, BES adopts a systemic approach, analyzing the dynamic and complex interaction that is established between these two fundamental elements. This integrated perspective is of crucial importance for nZEBs, where energy performance does not simply derive from the sum of the performance of the individual components, but emerges from the virtuous synergy between the characteristics of the envelope, the intrinsic efficiency of the systems and their coordinated and optimized management. BES allows for a precise and reliable assessment of how design choices related to the envelope (for example, increasing thermal insulation, selecting high-performance windows, adopting solar shading systems) are reflected in the reduction of the building's thermal loads and how, consequently, this influences the optimal sizing and efficient operation of the building systems. Conversely, BES allows for analyzing how the characteristics and control strategies of HVAC systems can interact with the building envelope, making the most of the potential of thermal mass, optimizing the use of free solar gains and modulating the building's response to external climatic variations.

- Dynamic and transient analysis, capturing the complexity of real behavior: Some BES software stands out for their intrinsic ability to simulate the dynamic and transient behavior of the building and not just the semi-steady-state behavior. This means that they are able to faithfully represent the building's response to the continuous temporal variations of external climatic conditions (solar radiation that varies throughout the day and seasons, temperature fluctuations, variations in humidity and wind) and internal gains (variable occupancy profiles, discontinuous use of lighting and equipment). This level of dynamic detail is of fundamental importance for the correct evaluation of the

energy performance of nZEBs, which are often based on advanced design strategies, such as the exploitation of free solar gains through passive and active systems, the use of thermal storage systems to level out peaks in energy demand and optimize the use of renewable sources and the implementation of sophisticated control strategies that modulate the operation of systems in real time based on environmental conditions and the specific needs of the occupants. Dynamic simulation, therefore, allows for capturing transient phenomena, analyzing the complex interactions between the building and the environment and assessing with greater accuracy the real effectiveness of these innovative strategies in different operating conditions, providing a more reliable and realistic estimate of annual energy consumption and the internal comfort perceived by users.

- Objective and quantitative comparison of multiple design alternatives, supporting informed decisions: BES constitutes a decision-making tool of extraordinary power, as it offers designers and clients the possibility to rigorously, objectively and quantitatively compare a wide range of alternative design solutions, evaluating their implications in terms of energy performance, environmental comfort levels, initial investment costs and operating costs over the building's life cycle. Through energy simulation, it is possible to analyze in detail the impact of different design choices related to the building envelope (for example, varying the thickness and type of thermal insulation, selecting windows with different thermal transmittance and solar factor performance, adopting fixed or mobile solar shading systems, optimizing the orientation and shape of the building), on building systems (the choice between different types of heat and cold generators, such as condensing boilers, electric or gas heat pumps, trigeneration systems, the adoption of low-temperature distribution systems such as radiant panels, the selection of mechanical ventilation systems with high-efficiency heat recovery,

the integration of renewable energy production systems such as solar thermal and photovoltaic panels, the choice of advanced control systems and building automation) and on building management and operation strategies (the definition of set-point temperature profiles differentiated by zone and time slot, the optimized scheduling of systems according to occupancy and climatic conditions, the implementation of monitoring and energy consumption accounting systems). This decision support based on simulated data, derived from rigorous and reliable analyses, allows for optimizing the design process, guiding the project team towards the identification of the most high-performing, environmentally and economically sustainable solutions and capable of guaranteeing high standards of comfort and well-being for the occupants.

- Verification of regulatory compliance and a tool for energy certification, facilitating the authorization process: BES has acquired a central and increasingly recognized role as a tool for verifying compliance with mandatory regulatory requirements regarding the energy efficiency of buildings. In numerous regulatory contexts, both at national and international levels, the execution of detailed energy simulations has become a mandatory practice to demonstrate during the design phase compliance with the prescribed limits for primary energy demand, specific energy consumption, minimum performance of the building envelope and technical systems and for the minimum shares of renewable energy to be integrated into the building. Furthermore, BES constitutes the calculation basis for determining energy performance indices and for the subsequent classification of the building into a specific energy class, within the framework of building energy certification systems. Energy certification, in turn, is often an indispensable requirement for obtaining building permits, economic incentives and for the real estate valuation of the building on the

market. BES, therefore, provides detailed, complete, transparent and verifiable technical documentation, which unequivocally certifies the energy performance of the nZEB, facilitating the authorization process, simplifying the demonstration of regulatory compliance and providing a solid basis for communication and transparency towards clients, end-users and competent authorities.

The wide range of software tools available for Building Energy Simulation offers a vast choice of options, which differ in a heterogeneous set of characteristics, including the level of detail and accuracy of the modeling offered, the ability to perform dynamic and transient simulations, the range of building systems and building components that can be modeled, the flexibility and customizability of the user interface, the ease of use and learning curve and, last but not least, the degree of experimental validation and the recognized accuracy of the calculation results. As mentioned above, a consolidated and widely adopted classification distinguishes BES tools into two main macro-categories: "semi-steady-state" and "dynamic" tools, a conceptual distinction that will be further explored and detailed in the following pages. The selection of the most appropriate BES tool for a specific nZEB project represents a crucial phase, which requires careful evaluation of the specific design needs, the desired level of analytical detail, the design phase (preliminary or executive), the available computational and time resources and, last but not least, the user's skills and experience in using energy simulation software. In any case, a fundamental principle that should guide the choice is the preference for software tools that have been subjected to rigorous experimental validation processes, that are recognized and accepted by the scientific and technical community of reference and that allow for the adoption of accurate, transparent and verifiable modeling methodologies, in order to guarantee the maximum reliability of the results obtained and the soundness of the conclusions that are drawn on the basis of the BES.

2.2.1 Semi-steady-state tools

Semi-steady-state BES simulation tools, also referred to as "semi-steady-state" or "simplified" tools, represent a category of software for the energy analysis of buildings that adopts a modeling approach based on simplifying the intrinsic complexity of thermo-physical phenomena. These tools are distinguished by the assumption of stationary, or more precisely semi-steady-state, conditions during the analysis time frame, i.e., the assumption that the state variables of the system (temperatures, heat flows, etc.) vary slowly over time, or that they can be considered constant in discrete time intervals. This methodological simplification translates into the adoption of inherently simplified calculation models, often based on aggregated energy balances at the monthly, seasonal, or annual level and the elimination, or strong attenuation, of the dynamic effects and rapid temporal variations that characterize the real thermo-energetic behavior of buildings. The current Italian legislation provides for the use of semi-steady-state calculation models as indicated by the technical standards UNI/TS 11300 [39-40-41-42].

As specified in the methodological note in Chapter 1, this calculation method involves significant approximations that preclude a dynamic, and thus realistic, assessment of building behavior.

The distinctive characteristics of semi-steady-state tools, which define their scope of application and influence their performance, include:

- Stationary or semi-steady-state analysis, neglecting dynamic effects: Simulations conducted with semi-steady-state tools are based on the assumption of climatic and operating conditions that remain constant, or that vary gradually and predictably, over the analysis time frame. This methodological approach implies neglecting the rapid fluctuations and transient effects that characterize the real behavior of buildings, such as temperature variations throughout the day, sudden changes in solar radiation due to cloud cover and variations in internal loads related to

the actual use of spaces. Stationary or semi-steady-state analysis, while significantly simplifying the computational problem, can introduce significant approximations and limitations in the evaluation of energy performance, especially for buildings characterized by high thermal mass, advanced control systems, or strategies for exploiting free solar gains.

- Intrinsically reduced calculation times, favoring the speed of analysis: By virtue of the simplification of physical modeling and the adoption of a stationary or semi-steady-state approach, semi-steady-state tools are characterized by their intrinsic calculation speed. Energy simulations can be performed in significantly shorter times than those required by dynamic tools, often in the order of a few seconds or minutes, even for complex building models. This characteristic of speed makes semi-steady-state tools particularly suitable for preliminary analyses, high-level comparative evaluations and sensitivity studies in the early stages of design, when it is necessary to quickly explore a wide range of design solutions and obtain answers in a short time.
- Ease of use and lower complexity of input and output, facilitating the approach for non-expert users: Semi-steady-state tools are generally characterized by greater ease of use and less complexity in the input phase of design data and interpretation of simulation results. The user interface is often more intuitive and guided, the required input parameters are fewer and easier to find and the simulation outputs are generally more aggregated and immediately understandable. This ease of use makes semi-steady-state tools accessible even to users who are not experts in energy simulation, who can use them to obtain an initial assessment of a building's energy performance or to carry out high-level checks in the preliminary phase.

Despite the inherent methodological simplifications, semi-steady-state tools retain considerable utility in specific phases and contexts of nZEB design, particularly in the preliminary, conceptual and high-level phases, where speed of analysis and ease of use are priority requirements. The main applications of semi-steady-state tools include:

- Preliminary comparative evaluations between different design options: Semi-steady-state tools lend themselves effectively to the rapid and iterative comparison between different alternative design solutions, both at the level of the building envelope (different types of insulation, windows, solar shading systems) and of building systems (different types of generators, simplified distribution systems). In this preliminary phase, the objective is not so much to obtain a precise and absolute estimate of energy performance, but rather to identify the most promising design options in terms of relative energy efficiency and to screen out the less performing alternatives, directing design choices towards the most effective solutions.
- Sensitivity analysis and identification of the most influential design parameters: Semi-steady-state tools can be profitably used to conduct sensitivity analyses, aimed at evaluating how the energy performance of the building reacts to variations in specific design parameters. For example, it is possible to analyze the sensitivity of energy demand to variations in the thickness of thermal insulation, the performance of windows, the efficiency of heat generators, or other relevant parameters. These analyses make it possible to identify the design parameters that exert the greatest influence on energy performance, allowing design efforts and economic resources to be concentrated on the most critical aspects and to maximize the return in terms of energy efficiency.
- High-level checks and consistency checks with regulatory requirements: Semi-steady-state tools can provide a first estimate, albeit approximate,

of the building's energy demand, allowing for conformity checks with basic regulatory requirements in terms of energy efficiency. These high-level checks can be useful for ensuring that the project meets the minimum limits imposed by regulations and for identifying any critical issues or significant deviations from the desired performance objectives, already in the initial stages of design.

However, it is essential to emphasize the intrinsic limits of semi-steady-state tools, which may be inadequate and misleading for the accurate and reliable modeling of nZEB buildings characterized by high plant complexity, the adoption of advanced and dynamic control strategies and a high level of design detail. In these contexts, where dynamic effects and complex interactions play a preponderant role, it is essential to resort to dynamic simulation tools, which are able to capture the richness and complexity of the real thermo-energetic behavior of nZEB buildings, providing more accurate and reliable results for design and performance verification.

Among the modeling software, all certified by the Italian Thermotechnical Committee (CTI), that use the semi-steady-state method currently proposed by Italian legislation, the most widespread are:

- TERMOLOG by Logical Soft: This BIM software is designed for the design and verification of Law 10, including nZEB (nearly zero-energy) buildings. It offers functionalities for legal verifications according to the Minimum Requirements Decree, the management of renewable energies, the calculation of summer and winter thermal load and the verification of condensation. TERMOLOG also includes an artificial intelligence system, GAIA, to assist in legal verifications and supports sustainability protocols such as CasaClima, LEED, GBC and CAM. It also allows for the calculation of thermal bridges. [56]

- EC701 by Edilclima: This software is specifically dedicated to building-plant design and verifications according to Law 10. EC701 manages practices relating to multiple real estate units and different interventions, automatically processing the legal verifications required by Decree 26.6.2015 (including nZEB buildings), the verification of coverage from renewable sources (Legislative Decree No. 199/2021), CAM verifications (Decree 23.06.2022) and the Energy Qualification Certificate (AQE). It also allows for the thermo-hygrometric verification of components. [57]
- Termiko by Italsoft Group: Termiko is a software for energy certification and Law 10. Termiko offers various functionalities, including the drafting of the Law 10 technical report, thermo-hygrometric verification and additional modules for heat accounting and the analysis of energy improvement interventions. It has different versions, including Termiko One APE for the drafting of the APE only and Termiko CAD for the graphic input of data. [58]
- TerMus by ACCA software: TerMus is a BIM software for the energy modeling of buildings, which allows for performing Law 10 calculations and nZEB verifications with real-time diagnostics and 3D thermography. It supports current national and regional regulations and allows for automatically obtaining the Law 10 technical report, the Energy Performance Certificate (APE), the Energy Qualification Certificate (AQE) and other useful documents. It is available in different versions, including TerMus CE and TerMus PRO, with scalable and modular functionalities for certification, systems, air conditioning and thermal bridges. [59]
- Termo by Namirial: Termo is a software for the energetic certification and the Law 10, up to date with UNI/TS 11300 and certified by CTI. It's able to calculate the energetic performances of residential and non-residential buildings and offers a double modality of data input (tabular

and CAD). The software includes a specific module for the Law 10, tools for interventions of improvement and energetic diagnosis. It has even an App for data acquisition in the field. [60]

- Blumatica Energy: Energy is a complete software suite for complying with Law 10 and performing energy certifications. It handles verifications, energy performance certificates (APE), energy qualification certificates (AQE) and energy diagnostics. It offers advanced features like artificial intelligence, is up-to-date with regulations and integrates with BIM. [61]

For the semi-steady-state analyses carried out during the doctoral course, the TerMus BIM [59] modeling software by ACCA software was used.

2.2.2 Dynamic tools

Dynamic BES simulation tools, in contrast to semi-steady-state approaches, represent the most advanced and complete frontier in the field of building energy modeling. These software programs are based on intrinsically dynamic and time-dependent calculation methodologies, capable of simulating in detail and realistically the temporal evolution of thermo-physical variables within the building and its HVAC systems. Unlike simplified tools that assume stationary or semi-steady-state conditions, dynamic tools solve the fundamental equations of heat and mass transfer in a transient regime, explicitly taking into account the thermal inertia of building components, hour-by-hour or smaller time-step variations in external climatic conditions, time-varying internal load profiles and the operating dynamics of building systems and their controls. This ability to model time dependence and dynamic effects makes dynamic BES tools particularly suitable for the performance analysis of nearly zero-energy buildings (nZEBs),

characterized by advanced design strategies that exploit thermal inertia, free solar gains and sophisticated control systems.

The distinctive characteristics of dynamic tools, which define their superior performance and wide range of applications, include:

- Detailed and transient-oriented physical modeling: Dynamic tools are based on complex and detailed mathematical models for the representation of the building envelope, building systems and interactions with the external environment. The modeling of the building envelope includes the accurate description of the three-dimensional geometry of the building, the multi-layer stratigraphy of all opaque and transparent components, the detailed characterization of thermal bridges and the modeling of the effects of shading from external and internal elements. Building systems are modeled considering their operating dynamics, part-load efficiencies, distribution losses, regulation and control strategies (climate thermoregulation, zonal control, ventilation management, etc.) and interaction with the building envelope and external environmental conditions. Internal and external gains are also modeled dynamically, using hourly profiles of occupancy, lighting and sensible and latent loads and considering the variability of external climatic conditions throughout the year, month, day and hour.
- Dynamic and time-dependent analysis, capturing transient effects and thermal inertia: The fundamental peculiarity of dynamic tools lies in their ability to conduct dynamic analysis, i.e., to simulate the temporal evolution of the thermo-physical variables of the building-plant system in response to external and internal stresses. These tools solve the energy and mass balance equations in transient form, taking into account the thermal inertia of all building components, i.e., their ability to store and release heat over time. Dynamic modeling allows capturing complex phenomena such as thermal lag and the damping of

temperature oscillations, the accumulation and release of thermal energy in materials, the influence of rapid climatic variations on building behavior and the interaction between envelope thermal inertia and plant control systems. This dynamic analysis capability is essential for the accurate evaluation of the energy performance of nZEBs, where thermal inertia and transient effects play a crucial role in determining energy consumption and internal comfort.

- Greater accuracy and reliability of results, essential for nZEB design: Thanks to detailed physical modeling and the dynamic approach, dynamic BES tools offer a level of accuracy and reliability of simulation results significantly higher than semi-steady-state tools. The ability to capture dynamic effects, to consider the geometric and stratigraphic complexity of the envelope and to model in detail the building systems and their controls, allows for obtaining more precise and realistic estimates of energy consumption, thermal loads, internal temperatures and other performance parameters relevant to nZEBs. This greater accuracy is fundamental for the design and performance verification of high-energy-efficiency buildings, where even small variations in design parameters can have a significant impact on overall performance.
- Wide range of applications and advanced analyses, supporting design optimization: Dynamic tools, thanks to their versatility and accuracy, lend themselves to a wide range of applications and advanced analyses in the context of nZEB design. In addition to estimating annual and monthly energy consumption, these tools allow for evaluating in detail peak thermal loads for system sizing, analyzing internal thermo-hygrometric comfort in a dynamic regime, studying the behavior of the building under different climatic and operating conditions, optimizing plant control strategies, evaluating the effectiveness of passive and active systems for the exploitation of renewable energies and conducting life cycle analyses (LCA) and environmental and economic

sustainability assessments. The wealth of information and the analytical flexibility offered by dynamic tools make them indispensable instruments for the integrated and holistic design of nZEBs, supporting the designer in all phases of the decision-making process and guiding them towards increasingly high-performing and innovative design solutions.

Within the scope of dynamic BES tools, there are different types of software, which differ in the numerical methodologies implemented, the functionalities offered, the user interface and the degree of specialization. Among the most widespread and internationally recognized dynamic software, the following can be mentioned:

- **EnergyPlus:** EnergyPlus is a building energy simulation engine developed by the U.S. Department of Energy (DOE). It is an open-source software, widely validated and used globally, considered a reference standard for advanced dynamic simulation. EnergyPlus offers a high level of detail in physical modeling, a wide range of functionalities for simulating complex building systems and great flexibility and customizability. [62] In combination with the calculation engine, DesignBuilder is available, a software that acts as a graphical user interface, greatly simplifying the process of building energy modeling and simulation. It is distinguished by its intuitive and easy-to-use 3D interface, which allows even non-expert users to quickly create complex models. DesignBuilder offers a wide range of functionalities, including 3D modeling, dynamic energy simulation based on EnergyPlus, CFD (Computational Fluid Dynamics) analysis, natural lighting study with Radiance and design optimization. [63] ACCA Software has developed a version of the TerMus software called Termus Plus for the evaluation of the building envelope (and therefore energy needs) using a graphical

interface very similar to that of its commercial software Termus and the EnergyPlus calculation engine. [64]

- TRNSYS: TRNSYS (TRaNsient SYstem Simulation program) is commercial software, but with a strong research and development component, focused on the dynamic simulation of complex energy systems, including buildings and HVAC systems. TRNSYS is distinguished by its modular and flexible architecture, which allows for modeling complex and unconventional systems and for its ability to simulate renewable energy systems and thermal storage systems. [65]
- IDA ICE: IDA ICE (Indoor Climate and Energy) is another commercial dynamic simulation software, known for its intuitive and user-friendly interface and for its ability to integrate energy simulations and simulations of thermo-hygrometric comfort and indoor air quality. IDA ICE offers a good compromise between modeling detail, ease of use and calculation speed. [66]

The choice of the most appropriate dynamic tool depends on the specific needs of the project, the level of detail required, the user's skills and the available resources. In any case, it is essential to acquire a solid competence in the use of these software programs and to adopt rigorous and verified modeling methodologies, to ensure the reliability of the results and to fully exploit the potential of dynamic BES tools in the design and optimization of nZEB buildings.

For the dynamic analyses carried out during the doctoral course, the EnergyPlus calculation engine combined with the DesignBuilder graphical user interface was used in some cases, while in others the TerMus-PLUS software by ACCA software was used.

2.3 CFD for building envelope elements

Computational Fluid Dynamics (CFD) represents an advanced and increasingly widespread numerical methodology for the detailed analysis of thermo-fluid dynamic phenomena affecting the building envelope and interior spaces of buildings. In contrast to conventional Building Energy Simulation (BES) tools, which typically rely on simplified, lumped-parameter models for the characterization of airflows and convective heat transfer to estimate the overall building energy performance (as discussed in Section 3.4), Computational Fluid Dynamics (CFD) is based on the numerical resolution of the fundamental governing equations of fluid dynamics. Specifically, it solves the Navier-Stokes equations, along with the conservation of mass and energy, allowing for a detailed, three-dimensional description of the local thermal and fluid-dynamic fields. This computational approach allows for the three-dimensional and dynamic simulation of fluid (air) behavior and the associated heat transfer, taking into account the complex geometry of building elements, time-varying boundary conditions and the interactions between airflows, temperature fields and solid surfaces. CFD is, therefore, a powerful and versatile tool for addressing complex problems related to energy efficiency, environmental comfort and air quality in buildings, particularly in the context of nearly zero-energy buildings (nZEBs) where the precision and detail of the analysis are fundamental requirements.

The potential of CFD in the analysis of the building envelope and interior spaces is manifested in a wide range of applications, ranging from the evaluation of thermo-energetic performance to the verification of environmental comfort, to the study of indoor air quality and ventilation:

- Detailed analysis of thermal bridges and heat losses: CFD is particularly effective for the accurate analysis of thermal bridges, which are those areas of the building envelope characterized by greater heat loss due to geometric or material discontinuities. Through CFD simulation, it is

possible to model in detail the three-dimensional geometry of the thermal bridge, consider the thermal conductivity of the different constituent materials and solve the equations of heat transfer by conduction and convection, obtaining a detailed map of heat flows and surface temperatures at the thermal bridge. This information is valuable for accurately quantifying the additional heat losses due to thermal bridges, evaluating the effectiveness of corrective and mitigation measures and optimizing the design of the envelope to minimize heat losses and improve overall energy efficiency. [67]

- Study of natural and mechanical ventilation and internal convective motions: CFD represents an ideal tool for the in-depth study of ventilation phenomena, both natural and mechanical, inside buildings. Through CFD simulation, it is possible to model the geometry of the internal environments, the ventilation openings (windows, grilles, ducts), the external climatic conditions (wind, temperature) and the characteristics of the mechanical ventilation systems (air flow rates, positioning of the vents). The solution of the fluid dynamics equations allows for visualizing and quantifying the air velocity fields, the flow trajectories, the air change rates and the effectiveness of ventilation in removing pollutants and ensuring good indoor air quality. Furthermore, CFD allows for studying the natural convective motions that are established inside the environments due to temperature differences and for evaluating their influence on the temperature distribution and thermal comfort.
- Evaluation of thermal comfort and temperature distribution: CFD offers the possibility of analyzing in detail the thermal comfort inside the environments, evaluating the spatial distribution of air temperatures, radiant temperatures, air velocity and relative humidity. Through CFD simulation, it is possible to calculate thermo-hygrometric comfort indices, such as the PMV (Predicted Mean Vote) and the PPD (Predicted

Percentage Dissatisfied) and to identify any areas of thermal discomfort inside the environments. These analyses are fundamental for optimizing the design of air conditioning systems, the positioning of emission terminals and control strategies, in order to guarantee optimal comfort conditions for the occupants and minimize the risk of thermal dissatisfaction.

- Analysis of wind-building interaction and surface pressures: CFD lends itself to the study of the interaction between the wind and the building, modeling the wind velocity field around the building, the distribution of pressures on the external surface of the envelope and the aerodynamic forces acting on the structure. These analyses are important for evaluating the influence of the wind on natural ventilation, for estimating air infiltration through the envelope, for correctly sizing mechanical ventilation systems and for evaluating the structural behavior of the building in the presence of wind loads.
- Optimization of the shape and orientation of the building for the exploitation of natural resources: CFD can be used in the conceptual design phase to evaluate the influence of the building's shape and orientation on energy performance and comfort. Through parametric CFD simulations, it is possible to analyze different geometric configurations and different orientations, evaluating their impact on natural ventilation, shading, wind exposure and the distribution of surface temperatures. These analyses can guide the designer in choosing the optimal shape and orientation to maximize the exploitation of natural resources (wind, sun) and minimize energy needs for air conditioning and lighting.

Despite its undoubted potential, the use of CFD in building analysis also presents some challenges and limitations, mainly related to computational complexity and the need for specialized skills:

- High computational cost and significant calculation times: CFD simulations, especially three-dimensional and dynamic ones, require considerable computing power and significant simulation times, which can vary from hours to days, depending on the complexity of the model, the granularity of the calculation mesh and the simulation conditions. This high computational cost can be a limitation, especially in the preliminary stages of design, when it is necessary to quickly explore a large number of design alternatives.
- Need for specialized skills and dedicated software: The effective use of CFD requires specialized skills in the field of computational fluid dynamics, numerical modeling and the use of dedicated CFD software. The preparation of the geometric model, the definition of boundary conditions, the generation of the calculation mesh, the choice of turbulence models and the interpretation of results require a solid theoretical basis and specific practical experience. This can represent a barrier to entry for non-specialist designers and require collaboration with expert CFD consultants.
- Sensitivity of results to mesh quality and turbulence models: The accuracy of the results obtained with CFD depends strongly on the quality of the calculation mesh, i.e., the discretization of the fluid-dynamic domain into finite elements or finite volumes. A mesh that is too coarse or inadequate can introduce discretization errors and compromise the reliability of the results. Similarly, the choice of the appropriate turbulence model, to simulate the turbulent flows that characterize most applications in the building sector, represents a critical phase, which requires in-depth knowledge of the available models and their validity depending on the type of flow and the geometry considered.

Despite these challenges, CFD is confirmed as an increasingly valuable and indispensable analysis tool for the design and optimization of high-energy-efficiency buildings, in particular for nZEBs, where the detailed understanding of thermo-fluid dynamic phenomena and the maximization of building envelope performance represent priority objectives. The continuous evolution of computational capabilities, the growing availability of more user-friendly CFD software integrated with BIM tools and the increasing spread of specialized skills, contribute to making CFD increasingly accessible and applicable in design practice, promoting its adoption as a standard tool for the energy analysis and optimization of future buildings.

For the CFD analyses carried out during the doctoral course, the EnergyPlus calculation engine combined with the DesignBuilder graphical user interface was used.

2.4 The models for the climate change projections

An accurate and forward-looking assessment of the energy performance of nearly zero-energy buildings (nZEBs) cannot disregard a profound and articulated consideration of the impacts induced by current and future climate change. Climate projections developed by the international scientific community unequivocally indicate a trend of increasing average global and regional temperatures, together with significant variations in the frequency, intensity and duration of extreme weather events, such as increasingly intense and prolonged summer heat waves, less frequent but still possible winter cold waves and substantial changes in precipitation patterns, with an increased risk of drought in some areas and extreme rainfall events in others. These future climate changes will exert a profound and multifaceted influence on the energy demand of buildings, on thermal and hygrometric comfort for occupants, on the durability and reliability of building materials and components and on the resilience of the buildings themselves to extreme events. Therefore, integrating the future climate variable into the design and verification of nZEBs is no longer an option, but an essential necessity to ensure the sustainability, resilience and long-term performance of the building stock.

To address this crucial challenge and systematically and rigorously integrate the effects of climate change into the design and evaluation of nZEBs, it is essential to resort to the use of climate projection models validated and recognized by the international scientific community. These projection models, based on greenhouse gas emission scenarios (which represent different plausible trajectories of atmospheric concentration of climate-altering gases as a function of global socio-economic choices), provide probabilistic forecasts of climate variables of interest to the building sector (primarily air temperature, relative humidity, solar radiation in its various components, wind speed and direction, precipitation) for the future, generally over medium- to long-term time horizons, ranging from decades to

centuries, depending on the emission scenarios considered and the purposes of the analysis. The use of these future climate projections allows overcoming the intrinsic limitations of using historical climate data (representative of the past climate and not the future climate) and to design and evaluate nZEBs in a climate scenario consistent with the evolutionary trends of the climate at the global and local level.

The most commonly used and recognized climate projection models in the field of research in the building sector and in particular for the design and energy-environmental assessment of nZEBs, mainly include the following types:

- **IPCC Scenarios (Intergovernmental Panel on Climate Change):** The Intergovernmental Panel on Climate Change (IPCC), the leading international scientific organization for the assessment of climate change, periodically defines and updates a series of greenhouse gas emission scenarios, called RCPs - Representative Concentration Pathways. These RCP scenarios represent different future trajectories of greenhouse gas concentrations in the Earth's atmosphere, resulting from different assumptions about demographic, economic, technological and political evolution at the global level. The best known and used RCP scenarios include RCP2.6 (low emission scenario, compatible with the goal of limiting global warming to within 2°C), RCP4.5 and RCP6.0 (intermediate scenarios) and RCP8.5 (high emission scenario, "business-as-usual"). The IPCC RCP scenarios constitute the fundamental reference input for global and regional climate models, providing the basis for the generation of consistent and comparable climate projections at the international level.
- **Global Climate Models (GCMs):** Global Climate Models (GCMs), also known as General Circulation Models, represent the most complex and sophisticated category of numerical models for simulating the Earth's climate system in its entirety and completeness. GCMs are three-dimensional models that simulate the physical, chemical and biological

processes that regulate the planet's climate, including the atmosphere, oceans, cryosphere (ice and snow), land surfaces and the biosphere, including their mutual interactions. These models, developed and managed by leading climate research centers around the world, require high computational power and are able to provide climate projections on a global scale, with a spatial resolution typically on the order of hundreds of kilometers (e.g., grids of 100-300 km per side). The climate projections generated by GCMs include fundamental atmospheric and oceanic variables, such as temperature, precipitation, wind, humidity, solar radiation, cloud cover, atmospheric pressure, ocean currents and many others.

- **Regional Climate Models (RCMs):** Regional Climate Models (RCMs) represent a higher level of detail than GCMs, offering high spatial resolution climate projections, typically on the order of tens of kilometers (e.g., grids of 10-50 km per side), focused on specific geographic regions. RCMs are numerical models that simulate the climate of a limited region of the globe, using GCM projections as boundary conditions, i.e., as input to describe the evolution of the large-scale climate that influences the region of interest. Thanks to the higher spatial resolution, RCMs are able to more accurately represent local geographical features (orography, coastlines, land use, etc.) and small-scale climate processes (e.g., convective storms, local winds, valley and slope effects), providing more detailed, accurate and relevant climate projections for impact analyses at the regional and local level, such as those related to the building sector and nZEBs.

The effective and methodologically correct integration of climate projection models into the nZEB design and verification process involves articulation in several sequential and interconnected phases:

- Choice of the reference climate scenario: The first crucial phase consists in the selection of one or more climate scenarios (RCPs) that define a plausible and representative range of future climate changes for the geographical area of interest. The choice of the scenario, or set of scenarios, should be guided by a careful assessment of the client's risk aversion level, the time horizon considered for the useful life of the building (typically 30-50 years for residential and commercial buildings and even longer for infrastructure) and the availability of projected climate data for the selected scenarios and for the specific location where the building will be located. In general, it is advisable to consider at least one intermediate scenario (e.g., RCP4.5) and one pessimistic scenario (e.g., RCP8.5) to assess the range of uncertainty associated with climate projections and to test the resilience of the project under diversified future climate conditions.
- Selection of relevant projected climate data: Once the reference climate scenarios have been defined, it is necessary to proceed with the selection of projected climate data (hourly or sub-hourly time series of air temperature, relative humidity, solar radiation in its various components, wind speed and direction, precipitation) for the specific location where the building is planned to be located. This data must be obtained from climate models that are consistent with the selected RCP climate scenarios. There are several databases and web portals that provide projected climate data at different spatial and temporal scales, derived from different climate models and emission scenarios. It is important to select projected climate data that have undergone validation and bias correction processes to minimize errors and uncertainties and that are representative of the climate variables of greatest relevance for building energy simulations.
- Integration of projected climate data into BES simulations: The next phase consists in operationally integrating the projected climate data

into the Building Energy Simulation (BES) tools that will be used for the energy evaluation of the building. In practice, this involves replacing the historical climate data (representative of the past climate) usually used in BES simulations with the projected climate data (representative of the future climate) corresponding to the selected climate scenarios and the time horizon of interest. This replacement allows for directly and quantitatively evaluating the energy performance of the nZEB building under future climate conditions, taking into account the projected changes in the climate variables that influence the thermo-energetic behavior of buildings. The integration of projected climate data into BES simulations can be carried out manually, by replacing the input climate files, or, in some more advanced software, in a more automated way, through specific functionalities for importing and managing future climate data.

- Analysis of results and optimization of design for climate resilience: The last, but no less important, phase of the process of integrating climate projections consists in the critical and in-depth analysis of the results of the BES simulations conducted with projected climate data. The main objective of this analysis is to quantitatively and qualitatively evaluate the impact of the projected climate changes on the energy performance of the nZEB (primary energy demand, energy consumption by carrier, greenhouse gas emissions), on indoor thermal and hygrometric comfort (operative temperatures, relative humidity, comfort indices) and on the risk of summer overheating or other negative impacts induced by climate change. Based on this analysis, it is possible to identify any criticalities or vulnerabilities of the project with respect to the future climate and to optimize the design of the nZEB, intervening on parameters such as thermal insulation, thermal mass, solar shading systems, natural and mechanical ventilation, air conditioning systems and control strategies, in order to make the building more resilient to

climate change, minimize negative impacts and maximize benefits in terms of energy efficiency, comfort and long-term sustainability.

To facilitate the practical use of climate projections in building design, there are specialized software that integrate and process data from global and regional climate models, combining them with data measured by local weather stations. These tools perform spatial and temporal interpolations, statistical corrections and downscaling, to provide high-resolution projected climate datasets specific to the location of interest. An example of widely used software in this field is Meteonorm [68], a global climate database that provides meteorological data for any location in the world, both historical and future climate projections based on different IPCC scenarios. Meteonorm uses data from thousands of weather stations and global climate models, applying sophisticated interpolation and modeling techniques to generate complete and reliable climate datasets [69], ready to be used as input in building energy simulation software. The use of tools like Meteonorm greatly simplifies the process of integrating climate projections into nZEB design, making the use of high-quality and location-specific future climate data accessible to designers.

The integration of climate change projections into the design and evaluation of nZEBs represents a complex and multidisciplinary design and methodological challenge, but at the same time crucial and no longer postponable, to ensure that the nearly zero-energy buildings of the future are truly sustainable, high-performing and resilient in the context of a rapidly changing climate. The correct application of climate projection methodologies and tools, together with bioclimatic design and targeted adaptation strategies, will make it possible to create nZEBs (or ZEBs) capable of maintaining high standards of performance and comfort even in the future climate, contributing significantly to the mitigation of climate change and the construction of a more sustainable future for the building sector and for society as a whole.

For the implementation of climate data, during the doctoral course, the Meteonorm software was used alongside the climate data provided by Italian legislation.

Chapter 3: Performance investigation about nearly zero energy designs

The research activity underpinning this chapter is grounded in specific interventions that have been implemented in real-world scenarios or on existing nZEB buildings. The analysis employs a variety of tools and methods to quantify the energy savings achieved and, in certain cases, to assess the level of comfort perceived. These tools include those provided by current Italian and European legislation, Computational Fluid Dynamics (CFD) methods for detailed airflow and thermal analysis, on-site measurements for real-world validation.

The post-pandemic period has led to a growing focus on thermal comfort and indoor air quality in buildings. These aspects cannot be managed in isolation but require careful design that finds a trade-off between occupant well-being and energy-saving requirements. This balance is particularly crucial in the design of nearly zero-energy buildings (nZEBs), where energy efficiency is a primary objective.

Scientific literature highlights how different HVAC and ventilation strategies can significantly influence both comfort and energy consumption. For example, Dezfouli et al. [70] demonstrated that, in a tropical climate, a desiccant cooling system can ensure adequate thermal comfort with an average monthly energy saving of 37.5% compared to traditional fan coil units. However, a multi-objective analysis conducted by Tang et al. [71] showed that the solution with the greatest energy savings (59%) resulted in a worsening of thermal comfort conditions compared to the baseline scenario.

Ventilation strategy, in particular, plays a fundamental role in ensuring homogeneous air distribution and avoiding discomfort phenomena such as "cold air sinking" (accumulation of cold air at the bottom) and "warm air rising" (stratification of warm air at the top) [72]. In nZEBs, mixed-mode ventilation, often

combined with thermodynamic heat recovery [73], is a common solution, although it is not essential in some warm climates [74].

To more accurately analyze the spatial distribution of indoor comfort variables, it is possible to use Computational Fluid Dynamics (CFD) tools [75]. These tools allow, for example, to evaluate the influence of the size and position of openings on natural ventilation [76] or to optimize passive cooling strategies in hot and humid climates [77]. Furthermore, CFD can be used to study the possibility of dividing an environment into subzones with different set-point temperatures, thus avoiding overcooling problems [78].

However, it is also important to consider the impact of global warming, especially in Mediterranean climates. Anomalous heat waves, increasingly frequent even in winter, can put a strain on HVAC systems, causing increased energy consumption and a worsening of thermal comfort.

The Italian building stock has a significant percentage of buildings with low energy performance. According to data from SIAPE (Energy Performance Certificates Information System) updated to December 2020, about 60% of buildings are in the least efficient energy classes (F and G), while classes E, D, and C represent approximately 16%, 11%, and 5%, respectively [79].

Improving the performance of existing buildings is possible through the use of established technologies, and as demonstrated by some studies, retrofitting can bring older buildings to performance levels comparable to those of new constructions [80]. However, to correctly assess building performance, it is essential to consider the limitations of the calculation methodology used for the drafting of national Energy Performance Certificates (EPCs). Actual consumption data can differ significantly from those obtained through the EPC, mainly due to incorrect settings of active systems [81, 82]. A possible solution could be to collect data directly from building owners [83], but this technique requires further investigation before it can integrate or replace the current EPC calculation methodology. Another limitation of the current Italian system is the slowness in

updating important data, such as conversion factors, which can lead to an overestimation of primary energy consumption in the case of electricity-based active systems [84].

To compare different types of interventions and identify the most suitable one in relation to the specific characteristics of the building, it is possible to use models such as the Structural Equation Model (SEM) [85]. In some cases, such as for buildings of historical and cultural value, the usable retrofit techniques are limited, but it is still possible to improve energy performance without compromising cultural value [86].

It is also necessary, when carrying out a retrofit, to take into account the effects of climate change. It is predicted that in 50-100 years there will be a slight reduction in heating demand and a more substantial increase in cooling demand. These changes will be less significant for buildings with high-performance envelopes [87].

The recent Italian public incentive policy, known as "Superbonus 110%", deserves in-depth analysis. Scientific literature often neglects to consider key energy and economic indicators in the evaluation of building energy requalification. Furthermore, available studies tend not to consider climatic differences within the same country, focusing instead on different buildings in the same climatic area.

The global push towards decarbonization and sustainable energy practices has intensified in recent years, driven by the urgent need to mitigate climate change and its impacts. The building sector is undergoing a significant transformation with the goal of climate neutrality by 2050. The latest revision of the Energy Performance of Buildings Directive (EPBD) [88], adopted in 2023, emphasizes the importance of deep renovations and the integration of renewable energy sources to achieve the standard of nearly zero-energy building (nZEB), which is a building that operates with low energy consumption mainly produced by on-site renewable sources. The progress of nZEB development in Europe is assessed in [89].

In Italy, national legislation has been continuously updated to align with European directives, and several research papers have highlighted how to design retrofits for residential buildings [87], offices [90], or school buildings [91], even those with historical value [92]. More recently, Legislative Decree No. 48/2020 [93], implementing the recast of the 2018 EPBD [94], introduced several important new features:

- Inclusion of electric vehicle (EV) charging infrastructure in new and renovated buildings.
- Deep renovations and adoption of renewable energy solutions in existing buildings.
- Introduction of a "building intelligence readiness indicator" to quantify the ability of buildings to use new technologies and electronic systems.

Following the impetus of the legislative approach, the scientific community has introduced the new challenge of Plus Energy Buildings (PEBs); these are buildings that generate more energy than they consume. The literature offers a wide range of definitions and assessment methods [95]. Some studies define PEBs based on their annual energy balance between on-site generation and self-consumption; other studies add additional factors such as energy storage, grid interaction, and life-cycle assessments. The choice of metrics, balancing periods, and calculation approaches significantly influences the evaluation of PEB performance. The literature review highlights the need for a clear and consistent definition to facilitate its widespread adoption and evaluation. Two examples of PEBs are: X HOUSE at Solar Decathlon Middle East 2021, which provides a reference and methodology for design in the Middle East [96], and the Fotovoltaica/UFSC Laboratory, which demonstrates the potential of BIPV in enabling positive-energy buildings [97]. Several studies emphasize that the main simple strategy to achieve the new standards is to oversize the photovoltaic system [98], and thresholds and figures that guide towards effective architectural decisions can be found in [99].

Finally, recognizing the importance of accurate and reliable energy performance assessments, the chapter critically examines the methodologies currently prescribed by Italian legislation. It compares the results obtained from semi-steady-state calculation models, which are prevalent in the current regulations, with those generated by dynamic hourly methods. This comparative analysis sheds light on the validity and accuracy of the existing methodologies, highlighting potential areas for improvement and refinement to ensure that the regulatory framework remains robust and aligned with the evolving needs of nZEB design and evaluation.

The subsequent subchapters will provide a detailed exposition of four specific studies conducted within this research area:

- “Sensitivity analysis of energy efficiency measures for residential buildings under Italian incentive opportunities”: This study critically analyzes the effectiveness of various energy efficiency measures across different climatic zones in Italy, taking into account the economic implications and the influence of incentive systems.
- “Thermal comfort analysis of a bedroom using CFD modeling”: This study employs CFD analysis to conduct a comprehensive evaluation of the thermal comfort conditions within a representative room of a real nZEB building. It considers various scenarios for HVAC system operation and the impact of extreme weather conditions on comfort levels.
- “Application of energy regulations to a residential building in a temperate climate”: This study focuses on the application of Italian energy efficiency regulations to a newly designed residential building. It explores the technical feasibility of achieving the PEB standard and the integration of electric vehicle charging infrastructure within the building design, considering the associated challenges and opportunities.
- “Social Housing regeneration: qualifying and making sustainable buildings and public spaces. A case study”: This study discusses an energy upgrading on a social housing building and the relationship with

urban heating island. The building is one of the pilot sites of the REHOUSE project (funded by Horizon Europe Programme), specifically located in one of the most socially vulnerable areas.

Each of these studies will be presented in detail in the following subchapters, encompassing their respective methodologies, results, and conclusions.

3.1 Thermal comfort analysis of a bedroom using CFD modelling

The case study focuses on a representative room within a real nearly Zero-Energy Building (nZEB) located in Benevento, Italy, named BnZEB. This building has been described in detail in reference [73]. In summary, the opaque envelope is constructed of cross-laminated timber (X-Lam) panels combined with wood fiber insulation. The thermal transmittance values are very low ($U_{\text{wall}} 0.172 \text{ W/m}^2\text{K}$; $U_{\text{roof}} 0.229 \text{ W/m}^2\text{K}$), exceeding the requirements of current legislation [38].

The windows are low-emissivity (Low-E) double-glazed units with argon-filled cavities ($U_g = 1.1 \text{ W/m}^2\text{K}$). The solar factor (g-value) is 0.58, and the light transmittance is 0.79. The windows utilize PVC frames ($U_f = 1.17 \text{ W/m}^2\text{K}$). The room under investigation is a south-facing single bedroom (Figure 6). It features two transparent elements, both facing south: a window measuring 1.6 m x 1.4 m and an adjacent French door measuring 0.8 m x 2.4 m. The room contains a single bed, a bunk wardrobe, and a desk positioned under the window. Other geometric features are detailed in Table 1.

The building is primarily served by an air-to-air heat pump that provides air conditioning (heating and cooling), mechanical ventilation, and dehumidification during the summer.

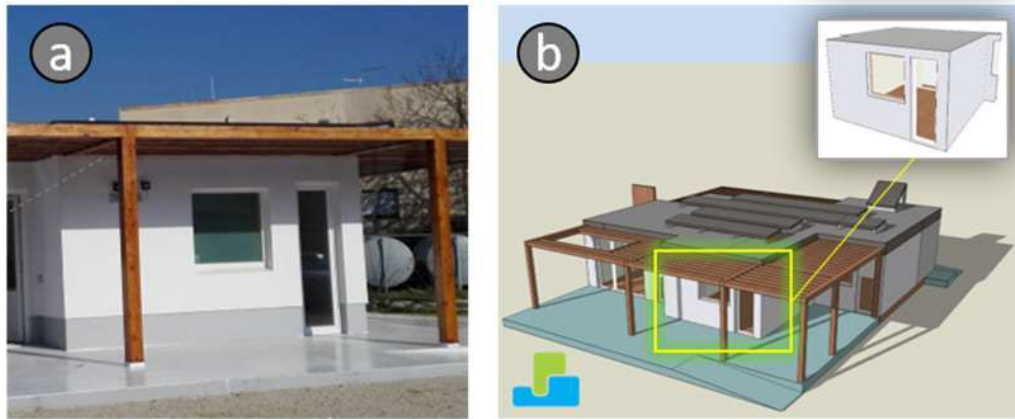


Figure 6 a) Real case study; b) Building simulation model.

<i>Usable Floor Area</i>	15 m ²
<i>Net Conditioned Volume</i>	41 m ³
<i>Gross Window-Wall Ratio</i>	14% (3.8 m ²)

Table 1 Geometrical features

A duct system delivers conditioned air directly to the rooms through diffusers. In the examined room, the terminal unit is centrally located on the false ceiling. The building's numerical model was created in EnergyPlus [62] using the DesignBuilder [63] user-friendly graphical interface. The same software was used for the Computational Fluid Dynamics (CFD) calculations.

The study is based on a real-world monitoring campaign, which enabled calibration of the bedroom model. This calibration was necessary to ensure the reliability of the CFD analysis, since standard default boundary conditions were applied. The following indoor microclimatic variables were considered for calibration: internal surface temperature (T_s) of the external walls and the bedroom's air temperature (T_a). Specifically, two Pt100 thermoresistances [100] were used to measure T_s , while T_a was recorded using a thermo-hygrometric probe [101] (see setup in Figure 7).

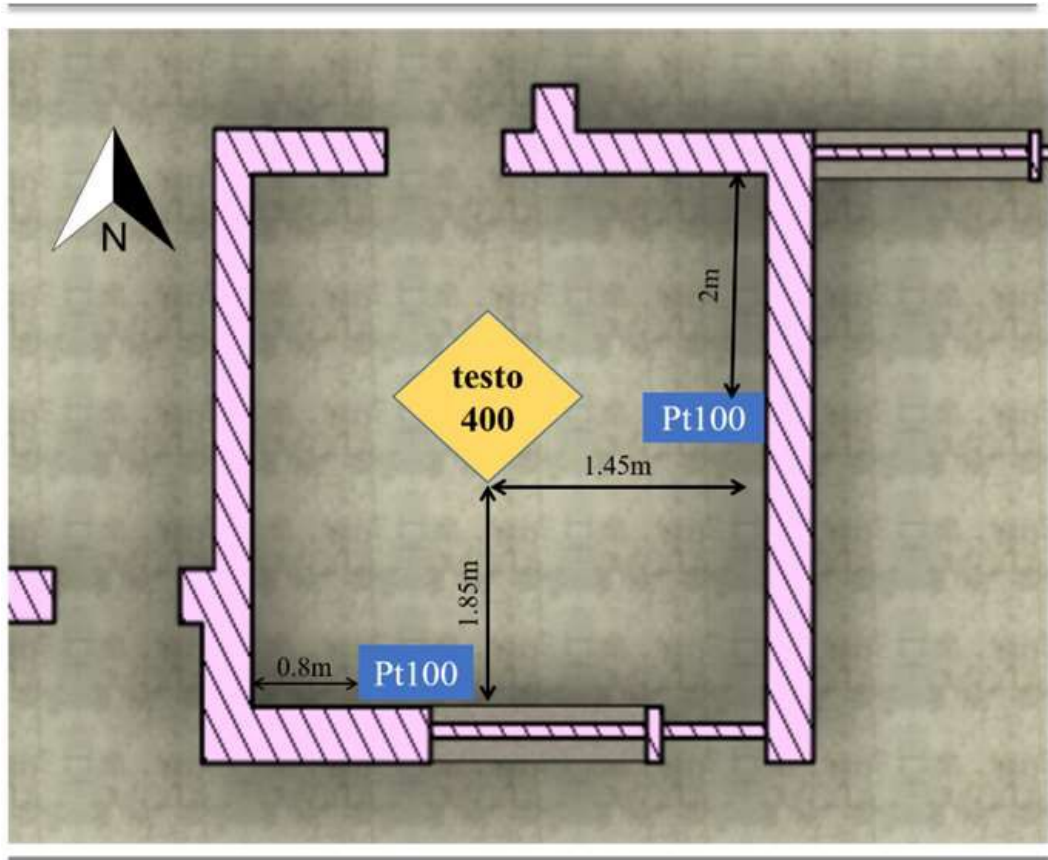


Figure 7 Bedroom monitoring campaign setup

The calibration used hourly data monitored from February 20th to 22nd, 2022. Weather data recorded during the same month by a climate station installed at the laboratory were used for both the dynamic energy simulations in EnergyPlus and the CFD analysis. Figure 8 compares the simulation outputs with the measured data.

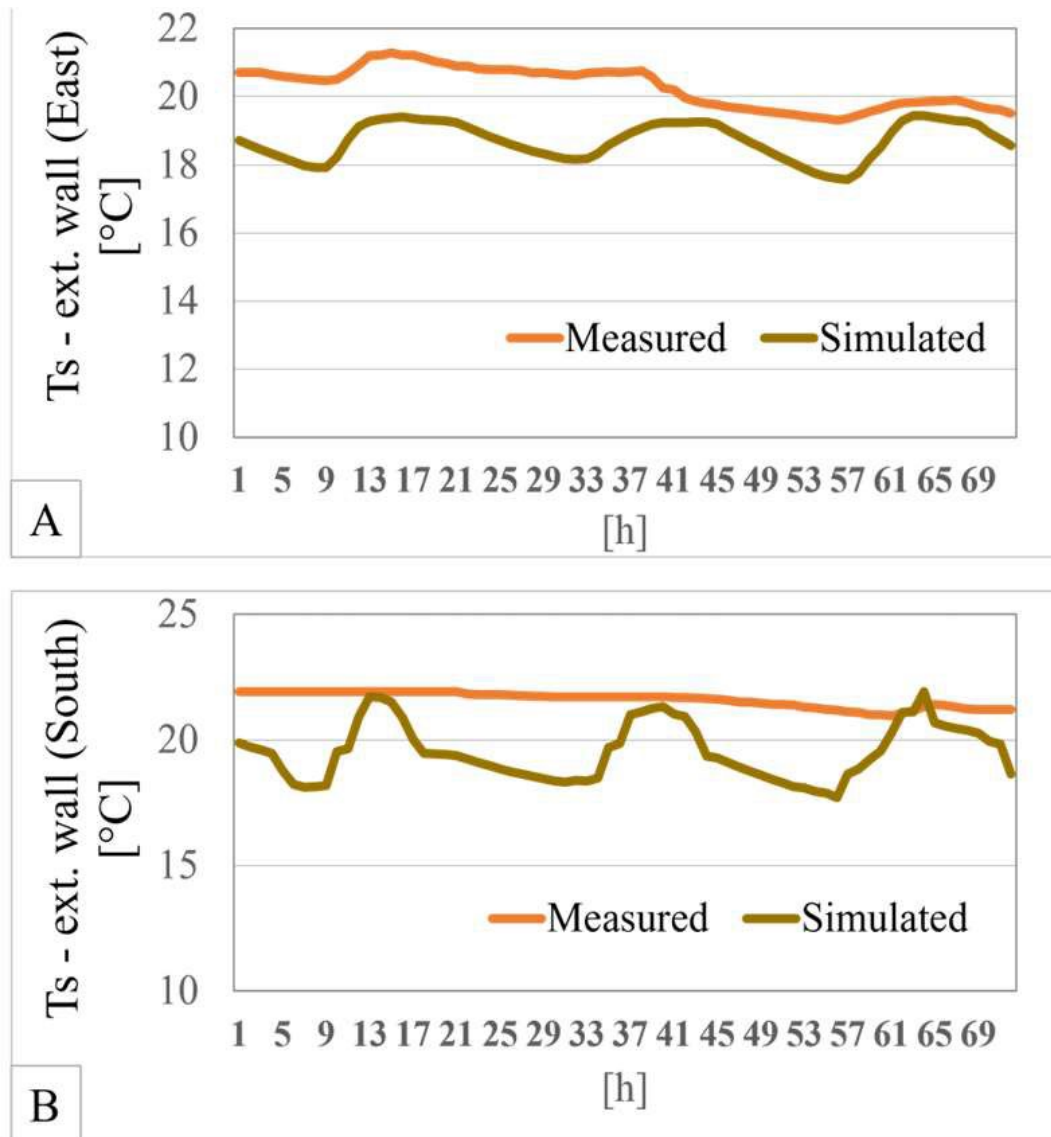


Figure 8 a) Air Temperature; b) Internal surface temperature (East); c) Internal surface temperature (South)

The mean bias error (MBE) and the coefficient of variation of the root mean square error, CV(RMSE), were calculated following the M&V Guidelines [102].

On the east side, the simulated and measured data show a similar trend. On the southern exposure, the internal surface temperature is less affected by external temperature fluctuations due to the increased solar gains from incident solar radiation. This effect is less pronounced in the numerical model.

Compared to the calibration thresholds, the model can be considered well-calibrated (Table 2).

<i>Index</i>	<i>Acceptable Value</i>	<i>Tsi (East)</i>	<i>Tsi (South)</i>
<i>Cv (RMSE) %</i>	30%	8.44	12.88
<i>MBE %</i>	±10%	-7.77	-9.69

Table 2 Calibration Results

3.1.2 Method

Following the calibration of the bedroom model, the internal CFD analysis was performed according to the schematization in Table 3.

<i>CFD analysis</i>	<i>Displaying Results: 3D contours plot</i>
	Air Temperature PMV PPD
	<i>Indoor conditions</i>
	1) HVAC system on: $T_{\text{set-point}}=20^{\circ}\text{C}$; 2) HVAC system shut down.
	<i>Outdoor conditions</i>
	1) h 12.00 p. m. (maximum solar height): DBT_{max} ; DBT_{min} ; GHI_{max} ; GHI_{min} . 2) h 18.00 p. m. (total absence of GHI): DBT_{max} ; DBT_{min} .

Table 3 Design variables

Indoor conditions were analyzed both with and without the HVAC system activated. In the first case, a set-point temperature of 20°C was used. For each indoor condition, results were evaluated during extreme climatic events at two representative times: 12:00 (maximum solar altitude) and 18:00 (absence of Global Horizontal Irradiance - GHI). The maximum and minimum values of Dry Bulb

Temperature (DBT) and GHI (at noon) during the month under consideration were analyzed. 3D contour plots of air temperature and PMV are presented. The distributions of these variables within the bedroom were compared with the environmental data generated by the DesignBuilder-EnergyPlus simulation during the same hours. The average hourly values of the following outputs were considered:

- PMV: Fanger Predicted Mean Vote, calculated according to ISO 7730 [103].
- Relative Humidity: The calculated average relative humidity of the air (%).
- Internal air temperature – the calculated average temperature of the air, °C.

3.1.3 Results

The most significant results of the CFD analysis are presented below. The first representative scenario (S1) is without air conditioning, when the maximum DBT occurs at 12:00 PM on February 19, 2022. The observed DBT is approximately 17.2°C, while the GHI is 511 W/m². These conditions represent an anomalous heat wave for the winter season. According to the energy simulation, the comfort parameters are entirely satisfactory based on the adopted comfort standard, as shown in Table 4.

<i>Indoor (simulated)</i>	<i>R.H. [%]</i>	<i>PMV</i>	<i>Ta [°C]</i>
	40	-0.20	21.6

Table 4 Indoor Conditions (S1)

The same holds true for the 3D distributions (Figure 9). The air temperature (Figure 9a) is consistently higher than the set-point temperature (20°C). The PMV

ranges from -0.05 to 0.35, and the PPD is always below 10% (Figure 9b). This extreme climatic event, therefore, results in both energy savings and thermal comfort. If the HVAC system were activated, the external weather parameters would contribute to reaching the desired conditions more quickly. However, as this is a residential building, the occupant can adjust the internal parameters. The occupant is unlikely to be able to predict the magnitude of the heat wave, and their actions could, at worst, negatively impact energy savings. Therefore, the benefits associated with external gains on the building's energy demand depend on the set-point temperature established during the early morning hours.

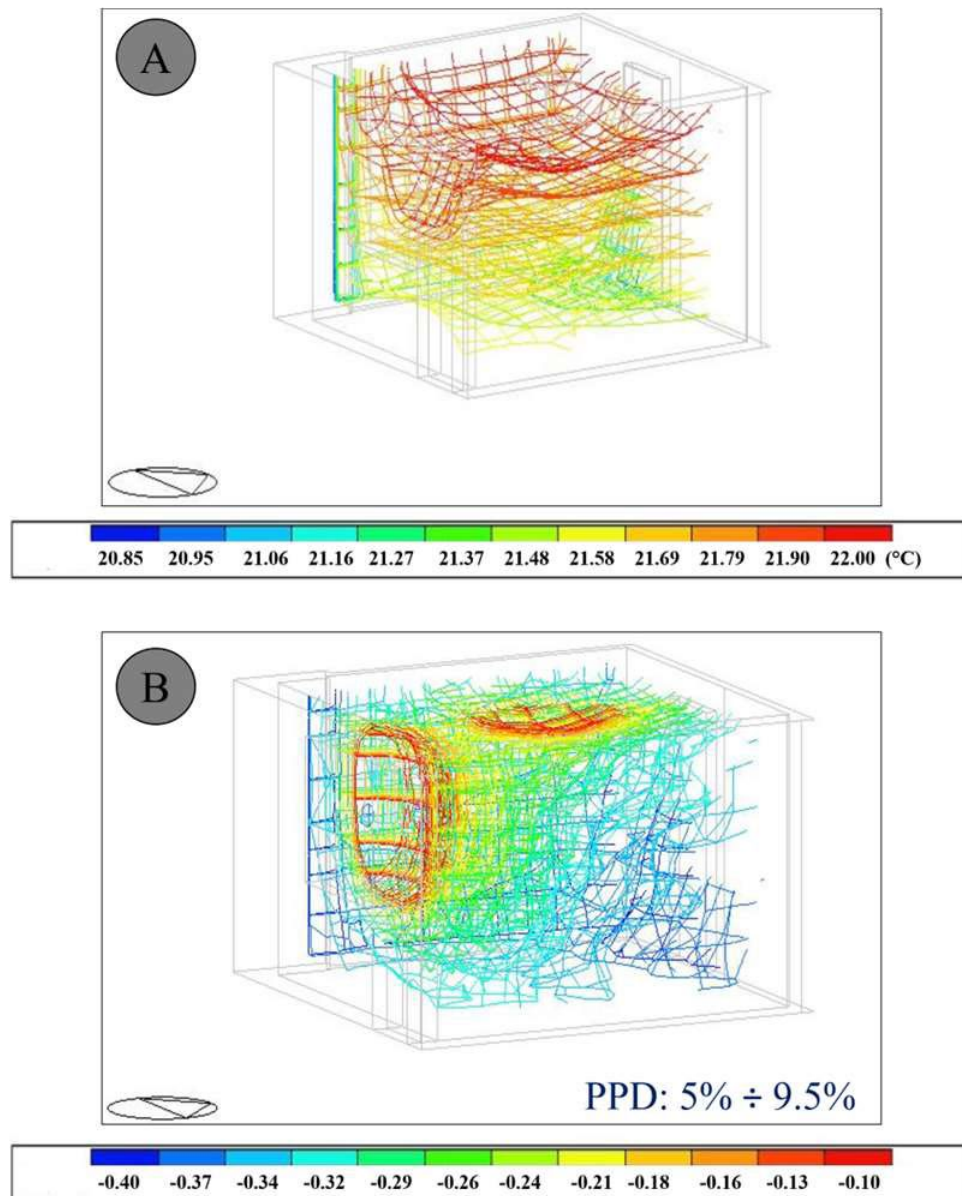


Figure 9 3D contours plot (S1): a) Air Temperature; b) PMV

The second significant result concerns the day with the maximum GHI detected at 12:00 PM. The recorded DBT is 16.5°C, while the GHI is 610 W/m². In this scenario (S2), even with the HVAC system activated, the 3D distributions are less favorable than those observed in the previous case (Figure 10).

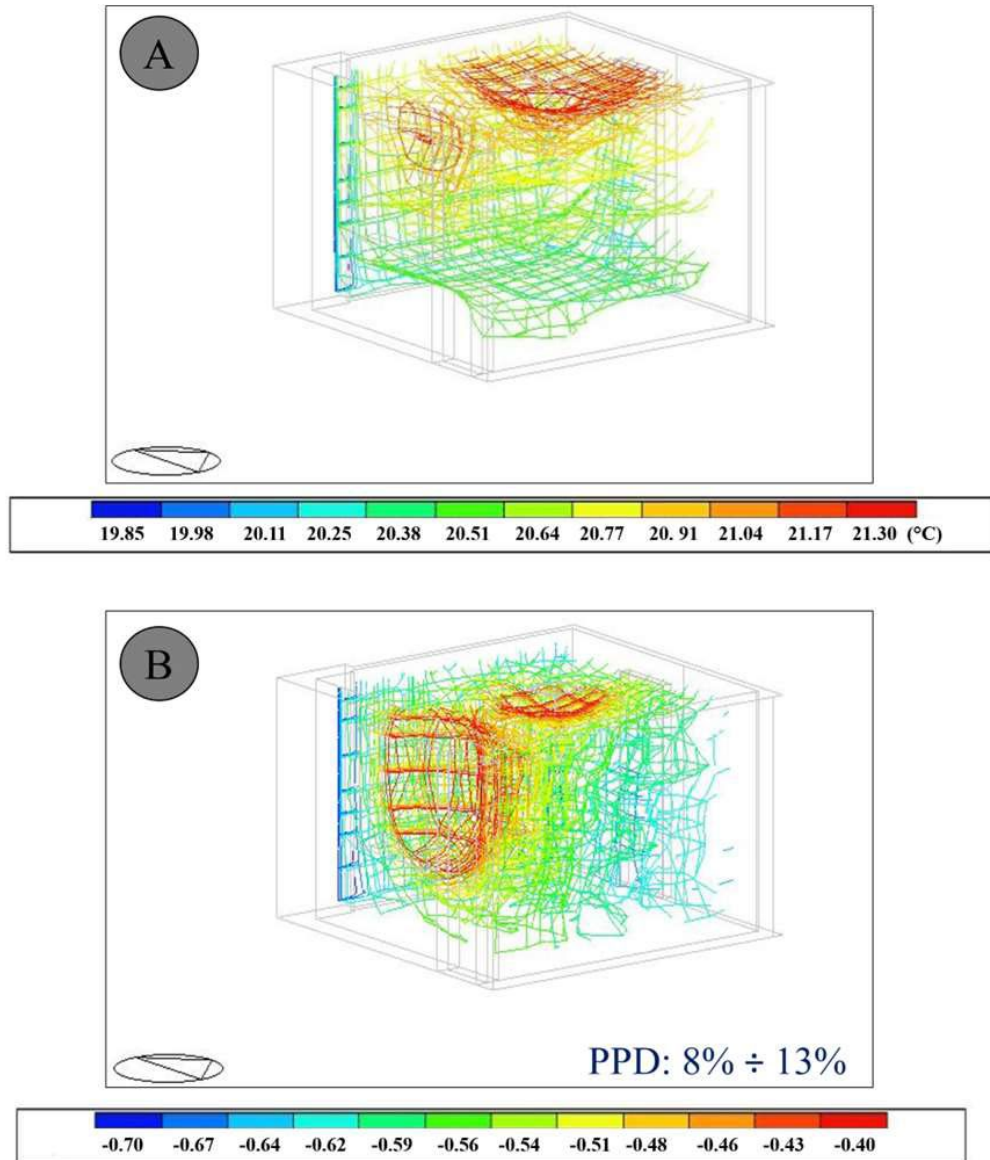


Figure 10 3D contours plot (S2): a) Air Temperature; b) PMV

Despite solar gains through the transparent components, the lower external temperature results in T_a values below 20°C in many areas of the room. The PMV also frequently falls below -0.5, reaching a minimum of -0.70, indicating a slightly cold thermal sensation for occupants. This is particularly noticeable near the

internal partitions. The PMV value simulated according to the standard is -0.55 (Table 5), which is not representative of the entire tested environment. In fact, an occupant seated at the desk would likely experience thermal comfort.

<i>Indoor (simulated)</i>	<i>R.H. [%]</i>	<i>PMV</i>	<i>Ta [°C]</i>
	42	-0.55	20.6

Table 5 Indoor Conditions (S2)

From an air-conditioning perspective, if the room thermostat were located on the internal wall facing west, it would not register the set-point temperature. The most probable scenario in this situation is localized discomfort, specifically, radiative asymmetry. Conversely, the thermostat could display a temperature value greater than or equal to the set-point, even if the comfort indices (PMV and PPD) are not consistently met throughout the room. This case illustrates how, during winter, outdoor temperature has a greater influence on internal conditions than GHI. Finally, the last case examined concerns the maximum external temperature recorded at 6:00 PM (without GHI). In this case (S3), the monitored DBT is approximately 14.8°C. As shown in Table 6, the simulated comfort indices fall well within the comfort ranges.

<i>Indoor (simulated)</i>	<i>R.H. [%]</i>	<i>PMV</i>	<i>Ta [°C]</i>
	48	-0.49	20.7

Table 6 Indoor Conditions (S3)

The 3D distributions (Figure 11) are not substantially worse than in the previous case, as the indoor environment has likely been air-conditioned for a longer duration at 6:00 PM compared to 12:00 PM. Specifically, due to the absence of solar gains, occupants might experience a slightly cold thermal sensation (PMV = -0.55) and be inclined to increase the set-point temperature by at least 1°C. Consequently, in this scenario, the occupant's actions, driven by comfort needs, could again impact energy savings.

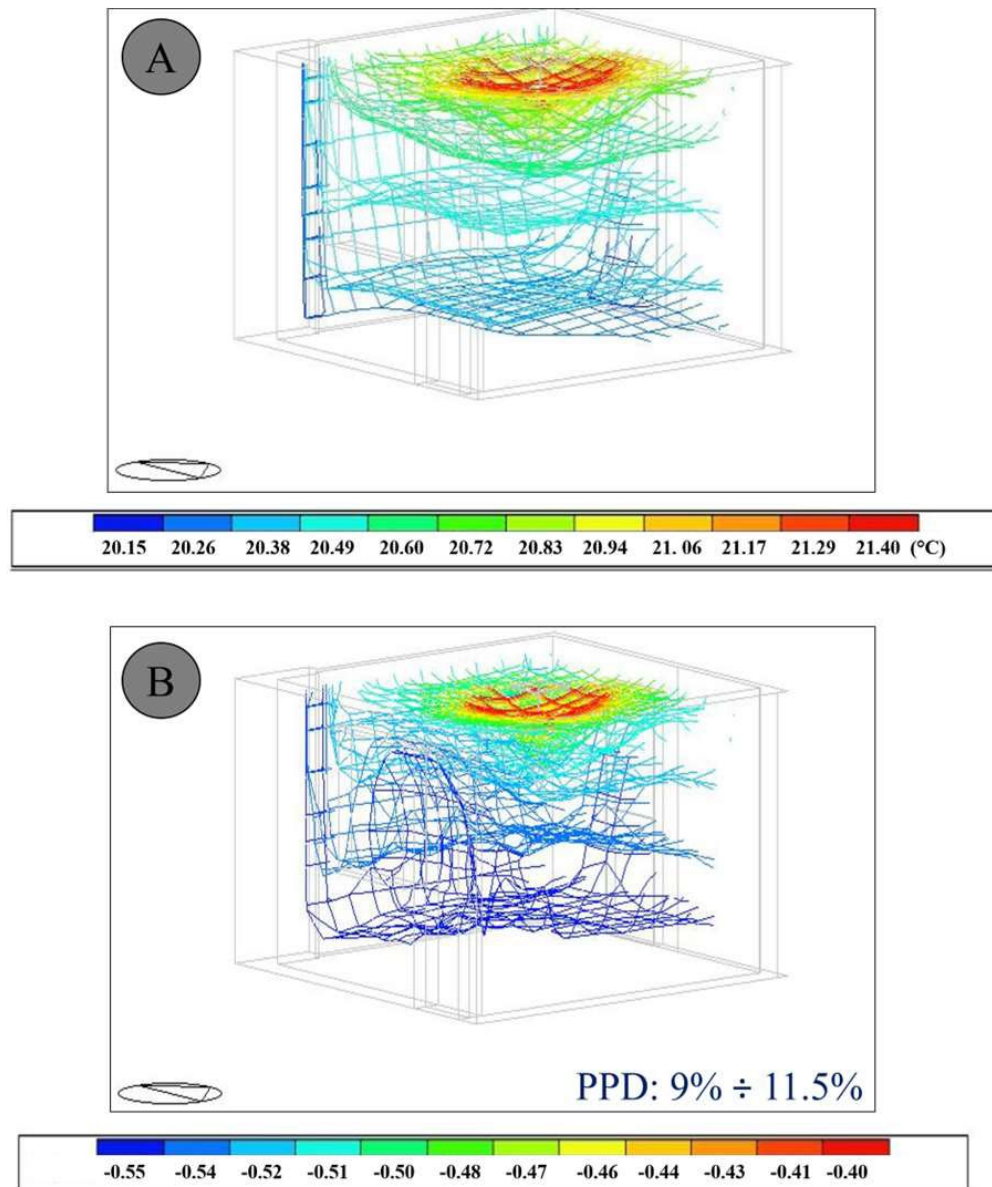


Figure 11 3D contours plot (S3): a) Air Temperature; b) PMV

3.1.4 Conclusions

Thermal comfort in buildings is a fundamental consideration, as is energy conservation. In this regard, the present study demonstrates that CFD analysis can provide valuable insights into the evolution of internal building conditions. This is particularly true during the occurrence of extreme weather events. Currently, even during typical winter months, anomalous heat waves are being observed. In these

cases, it has been shown that solar gains through the transparent envelope can be sufficient to eliminate the need for HVAC system activation. For example, when the DBT is 17.2°C and the GHI is 511 W/m², the internal air temperature is consistently above 20°C and the PMV is always below -0.5, even with the HVAC system deactivated. In such instances, the occupant's management of the set-point temperature has a direct impact on energy savings.

Conversely, there are scenarios where the simulated PMV is within the comfort range, but the same is not observed in the 3D contour plots of this index derived from the CFD analysis. This discrepancy raises a significant question about the efficacy of a single-zone thermostat. Therefore, this study serves as a starting point for a more comprehensive investigation of thermal comfort within residential buildings using CFD analysis, and for understanding the potential impacts on the energy performance of nZEBs. Future developments of this work could include a comparison of CFD analyses under different mechanical and natural ventilation scenarios, focusing, for instance, on days that are most representative in terms of wind speed and relative humidity. Furthermore, the building's energy performance could be calculated in relation to the most significant cases identified through the CFD analysis.

3.2 Sensitivity analysis about the effectiveness of the energy efficiency measures for residential building under the Italian incentive opportunities

In recent years, the Italian construction sector has been significantly impacted by the introduction of the "Superbonus 110%" incentive, included in the so-called "Relaunch Decree," which was converted into Law 77 on July 17, 2020. This bonus was introduced with the dual aim of supporting companies in the construction sector facing difficulties caused by COVID-19 and improving the quality of the Italian building stock, both in terms of seismic resistance and energy efficiency. From July 2020 to December 31, 2021, an amount equal to 110% of the incurred expenses could be deducted in five annual installments. For interventions carried out from January 1, 2022, to December 31, 2023, the same amount is repaid in four annual installments instead of five. For single-family dwellings, the incentive was available only for interventions that had reached a state of progress of at least 30% by September 30, 2022, with a requirement to complete the works by March 31, 2023. For condominiums and similar buildings, the deadline for submitting building applications was set for November 25, 2022, while the deadline for completing the works is currently December 31, 2023. Regarding energy efficiency measures (EEMs), access to the bonus is contingent upon carrying out at least one of the following "driving measures":

- Thermal insulation of the building, covering a surface area greater than 25% of the total gross dispersing surface, using materials that meet minimum environmental criteria.
- Replacement of the existing heating system with a heat pump, a condensing boiler, a micro-cogeneration system, or other innovative systems.

In addition to the driving measures, it is also possible to access "driven measures," such as window replacement, installation of photovoltaic panels, battery storage systems, home automation systems, shading systems, and charging systems for electric vehicles. A fundamental condition for accessing the energy efficiency incentives is to achieve an improvement of two energy classes, or to reach class A4, through the combination of adopted interventions.

The case study involves an existing condominium in Biccari, a small town in southern Italy. This town falls within climatic zone D (warm and temperate), with 1926 heating degree days (HDD), and its winter design temperature is -2.54°C [104]. The building, constructed in 1983, comprises six apartments spread over two floors. Six garages, one for each apartment, are located on the ground floor. There are two stairwells; one serves two apartments, and the other serves four. The building is constructed of concrete block walls and brick-and-concrete floors, without any insulation. Regarding the windows, there are variations between apartments because some tenants have already retrofitted their windows. All apartments are heated by gas boilers with radiators, and some are equipped with air conditioning units. Each apartment has a net floor area of approximately 106 m^2 . To provide an indication of the average insulation level, the mean global thermal transmittance coefficient (H'_{τ}) is $1.54\text{ W/m}^2\text{K}$. To give a sense of the building envelope's quality, the limit value for this climatic zone is $0.58\text{ W/m}^2\text{K}$. The average efficiency of the heating systems is 64.96%.

This building-HVAC system configuration represents the typical design of the 1980s.

3.2.1 Methodological approach

The energy assessments were conducted in accordance with European and Italian regulations and technical standards. The energy simulations were performed using TerMus BIM [59], a software program accredited by the Italian

Thermo-Technical Committee (CTI). TerMus BIM is capable of calculating the energy label and several other parameters; moreover, it facilitates the acquisition of all information necessary to verify eligibility for the incentives.

To make the desired evaluations, the following energy and environmental indices were considered:

- $EP_{gl,tot}$: The overall building energy performance index, corresponding to the total primary energy requirement per unit of surface area for heating, domestic hot water, and, potentially, cooling under standard usage conditions (kWh/m²year).
- $EP_{h,tot}$: The building's heating energy performance index, corresponding to the total primary energy requirement per unit of surface area for heating under standard usage conditions (kWh/m²year).
- $EP_{c,tot}$: The building's cooling energy performance index, corresponding to the total primary energy requirement per unit of surface area for cooling under standard usage conditions (kWh/m²year).
- ISI: The investment-saving index, defined as the ratio between the investment cost and the annual savings in total primary energy (€ year/kWh).

To evaluate the different results obtainable by applying the same efficiency measures in different climatic zones, several simulations were performed for the following cities: Porto Empedocle (Climatic Zone A – 579 HDD), Reggio Calabria (Climatic Zone B – 772 HDD), Benevento (Climatic Zone C – 1316 HDD), Biccari (Climatic Zone D – 1926 HDD), Torino (Climatic Zone E – 2617 HDD), and Cuneo (Climatic Zone F – 3012 HDD).

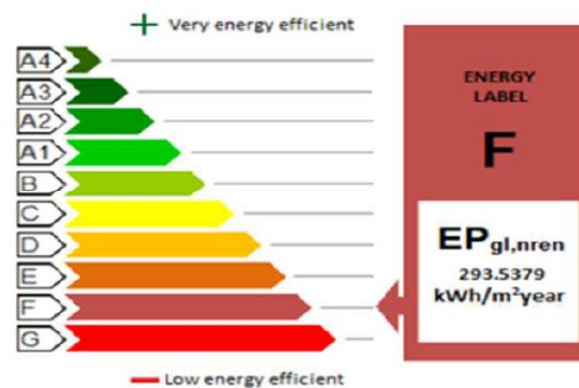
3.2.2 Existing state and energy refurbishment scenario

Figure 12 shows a rendering of the simulation model and the results of the ante-operam energy label, considering the building's current location (Biccari). The building falls into energy class F with an $EP_{gl,nren}$ of 293.5 kWh/(m²year), significantly different from its reference building. Figure 12c presents the overall classification for the building envelope; it is classified in the lowest class for both winter and summer performance.

a)



b)



c)

		HVAC-building performance	
INVERNO	ESTATE		
		$EP_{gl,nren}$	293.54 kWh/m ² y
		$EP_{gl,ren}$	3.34 kWh/m ² y
		$EP_{gl,tot}$	296.88 kWh/m ² y
		CO ₂	332.92 kWh/m ² y
Envelope performance			
Surface/volume ratio		0.65 1/m	
Thermal performance index useful for heating the building ($EP_{H,nd}$)		171.04 kWh/m ² y	
Summer equivalent solar area / useful surface of the building (A_{sef}/A_{sup})		0.0533	
Periodic thermal transmittance module Y_{IE}		0.4604 W/m ² K	

Figure 12 Render (a), energy label (b) and performance indices (c) of the case study in the existing state. (Biccari, Climatic Zone D).

According to Italian regulations, a building can still achieve a high energy class despite having a very low-quality envelope, thanks to efficient HVAC systems or by using a renewable energy source (e.g., solid biomass). In this particular case, all apartments are heated by standard or low-temperature methane boilers, so in addition to a low-quality envelope, the heating systems are also inefficient.

Considering the other climates, the same poor efficiency condition is observed. Indeed, the lowest energy class (G) is achieved in Torino and Cuneo, where the $EP_{gl,nren}$ would be 352.6 kWh/(m²year) and 392.1 kWh/(m²year), respectively. This trend, of course, follows that of the heating demand, since the primary energy demand is primarily due to heating and DHW needs, as there is no cooling system. In the hottest zones, the achievable energy class is E for the present configuration, with $EP_{gl,nren}$ values of 118.9 and 137.6 kWh/(m²year) for Porto Empedocle and Reggio Calabria, respectively.

The proposed intervention for the building under consideration includes both envelope and system upgrades:

- Insulation of external walls and pilotis with 12 cm of EPS with graphite ($\lambda = 0.031$ W/mK).
- Insulation of the roof with 14 cm of XPS ($\lambda = 0.034$ W/mK).
- 5 cm of Aerogel on some balconies ($\lambda = 0.015$ W/mK).
- Insulation of thermal bridges to ensure a minimum internal temperature of 17°C.
- A highly reflective finishing layer for the roof.
- Installation of a 6.4 kWp photovoltaic system for each apartment and one for shared spaces.
- Installation of a 16 kW electric heat pump and a 200 L tank for DHW and heating.
- Installation of new steel radiators sized to operate with a 55°C flow temperature, with automated thermostatic valves.

- Window replacement, where necessary ($U_w = 1.26-1.28 \text{ W/m}^2\text{K}$, $g = 0.59-0.63$).
- Installation of solar shading.

All these measures comply with the limits established by law and are eligible for the Superbonus 110% incentive. The estimated cost of the intervention is €1,135,682.67.

3.2.3 Results

The application of the energy efficiency measures ensures, in all climates, an improvement of more than two energy class levels, as the achievable label is A4 in all climates except Torino and Cuneo, where the obtainable label may be A3. All designs can be classified as nearly zero-energy buildings (NZEBs), with renewable energy sources covering approximately 53% of energy needs in the two colder cities and between 70% and 100% in all other locations. Definitively, the selected measures optimize energy performance and could be a solution for the desired improvement of the residential sector across all climatic conditions. More specifically, Figure 13 shows the variation in $EP_{gl,nren}$. It is noteworthy that a similar magnitude of savings is observed across all locations, indicating that the selected measures have a comparable impact on the existing conditions.

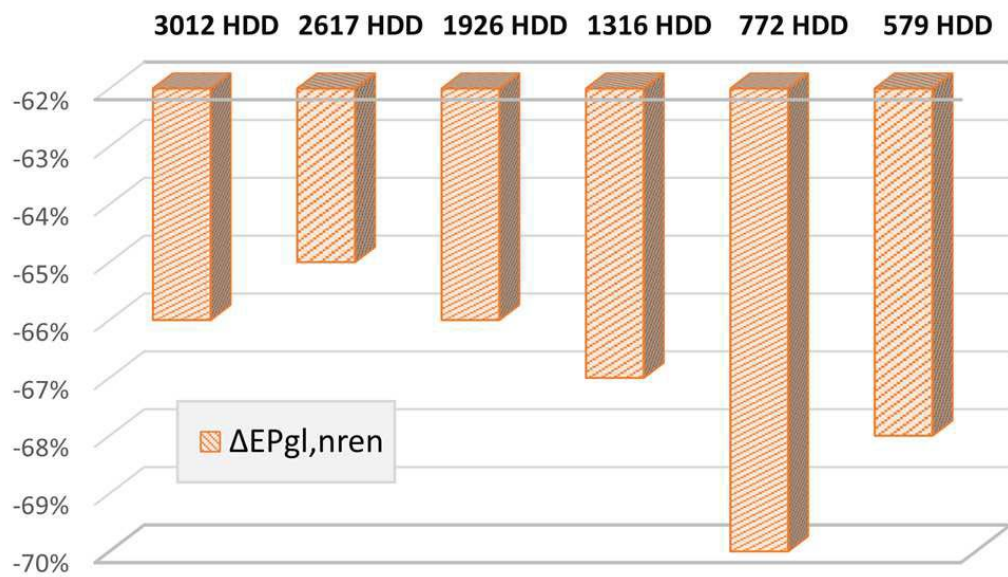


Figure 13 Energy saving in term of $EP_{gl,nren}$ by varying the climatic zone.

Figure 14 reports the calculated energy savings, considering only heating requirements. A more noticeable difference is observed across the different climate zones. In the warmer zones, the combination of less severe temperatures and good insulation results in energy savings of approximately 86%.

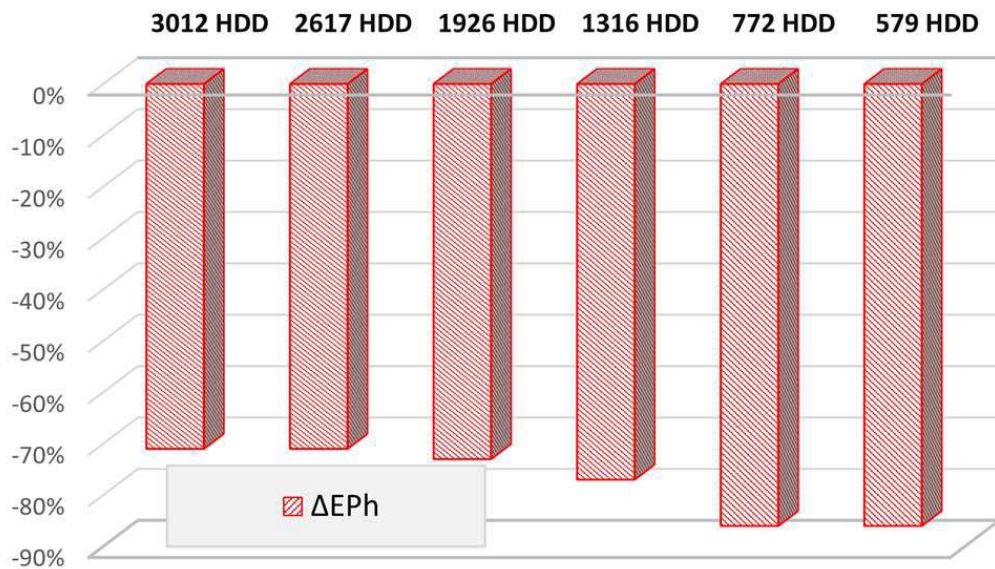


Figure 14 Heating energy saving by varying the climatic zone.

In contrast, the variation in the EP_c index (Figure 15) suggests that the refurbishment is most effective in warm and temperate climates, such as Reggio Calabria (-49%), while the results are comparable for Porto Empedocle and Benevento (-35%). It is important to emphasize that reducing cooling demand is a crucial challenge to address in the coming years due to climate change. From this perspective, the most impactful measures are the cool roof and the application of shading systems, which do not negatively influence the winter energy balance. However, these efficiency measures appear less appropriate for colder zones, particularly in Torino, where an increase in cooling demand is observed. In Torino, the overheating induced by a high level of insulation and the use of windows that maximize the greenhouse effect seems to be the dominant factor. The increase observed for Cuneo is not reported in Figure 15 because the calculated percentage change would be misleading. Indeed, in the current condition, there is no cooling energy need; however, after the refurbishment, it would be 1.9 kWh/(m²year).

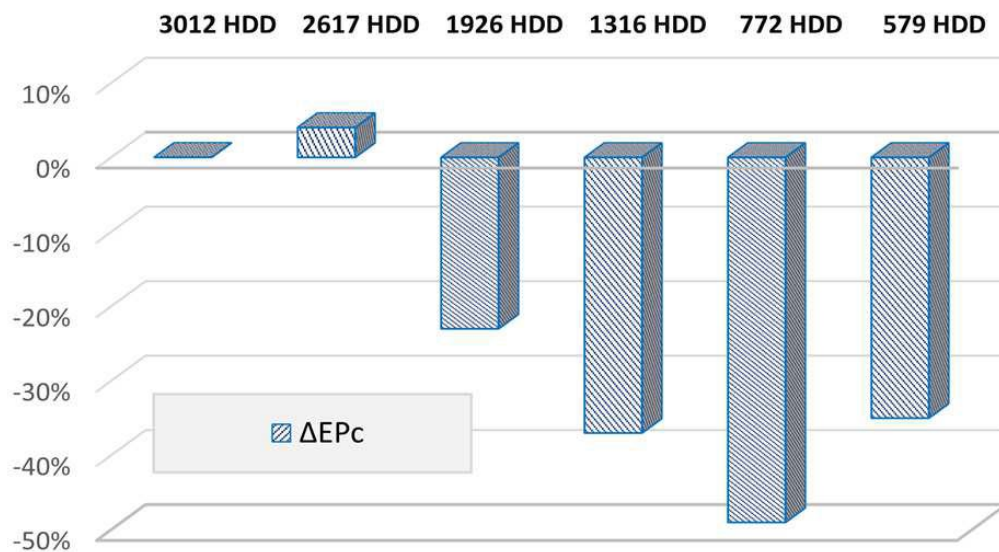


Figure 15 Cooling energy saving by varying the climatic zone.

Finally, Figure 16 presents the results of the economic analysis, clearly showing that without adequate incentive support, even with significant energy savings achieved, economic profitability is questionable. Only in the colder climates is the introduced index (ISI) acceptable (6.9 € year/kWh). The calculation of other

economic indices, such as the simple or discounted payback period, is not reported because the results would be insignificant, with payback periods exceeding 50 years. This underscores the necessity of supporting private investment to initiate the transition toward nearly zero-energy buildings (NZEBS).

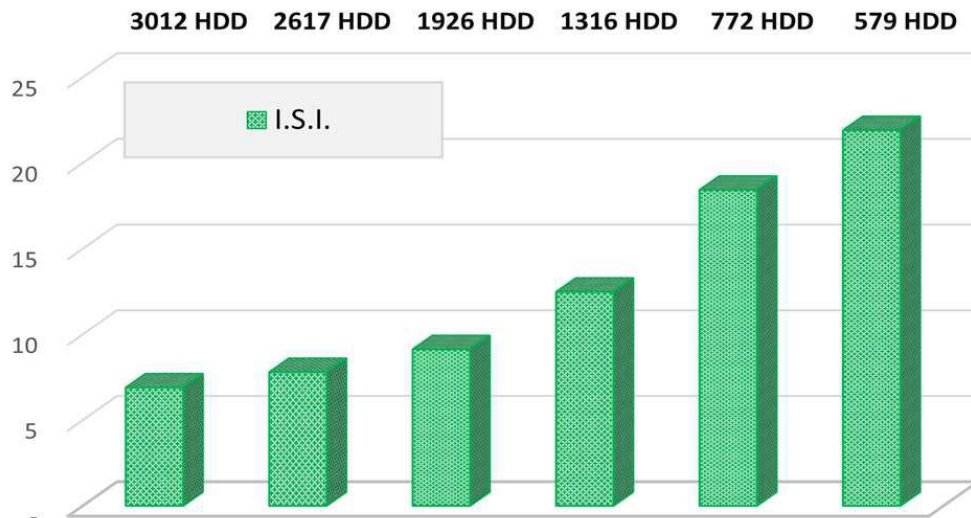


Figure 16 I.S.I. by varying the climatic zone.

3.2.4 Conclusions

In this study has been investigated, from both energy and economic perspectives, the refurbishment of a typical 1980s building-HVAC system, considering the same efficiency measures across all climatic zones of Italy. Due to the Italian government's incentives, specifically a benefit equal to 110% of the investment cost, it is possible in all climatic conditions to achieve nearly zero-energy building (NZEB) status through: insulation of the opaque and glazed envelope, correction of thermal bridges, adoption of heat pumps and radiators, and the installation of a PV system. The application of a deep refurbishment can lead to a reduction in total primary energy demand of more than 60% in all considered cities and the attainment of the highest energy class. However, this outcome is only feasible under the current incentives; otherwise, the payback period, and also the Investment-Saving Index (ISI) (the ratio between investment cost and energy saved), would not be attractive to private investors. In general,

the proposed approach could certainly serve as an inspiration for other European countries, given the climatic variability of Italy. In this context, limitations might be related to the method used for the energy classification of buildings (a semi-steady-state approach) and to compliance with requirements specific to the characteristics of the existing Italian building stock. Future studies could evaluate new energy efficiency measures, or a subset of those examined here, in order to optimize the economic indicators. This would be particularly relevant given that the incentive will be reduced (from 110% to 90%).

3.3 Application of energy regulations to a residential building in a temperate climate

As highlighted by the literature review, the Performance Energy Building (PEB) standard requires new design strategies to achieve both the minimization of energy demand and the maximization of on-site renewable energy generation. In this context, the expanding market for electric vehicles (EVs) presents both challenges and opportunities. The integration of EV charging infrastructure into building refurbishment design necessitates careful planning to ensure that the additional energy demand does not compromise the building's energy performance or its ability to meet the PEB standard. Simultaneously, EVs can also function as flexible energy storage units, potentially mitigating the emerging issue of national power grid stability. Focusing on these topics and using a case study approach, the study addresses the following key questions:

- How can current Italian energy regulations be applied to new constructions in temperate climates to achieve PEB standards?
- What are the technical challenges and opportunities associated with integrating EV charging infrastructure into these buildings?
- How do different retrofitting interventions and renewable energy system configurations impact the energy performance and PEB potential of the building?

By addressing these questions, the study aims to provide valuable insights for architects, engineers, and policymakers involved in the design and implementation of sustainable buildings. The findings can contribute to the development of best practices for achieving the PEB standard and promoting the integration of renewable energy and electric mobility within the building sector.

Through a case study of a newly constructed residential building, this study proposes the application of energy efficiency regulations, critically highlighting the

adoption of a full-electric scheme and the installation of electric car sharing positions. The results of the case study suggest several design guidelines for achieving the Plus Energy label in temperate climates.

The case study building is a five-story residential structure with 13 flats; its rendering, created using TerMus-BIM software, is shown in Figure 17a. It has a rectangular footprint with maximum dimensions of 31 x 17 m² (Figure 17b) and an overall height of 20 m. The ground floor is dedicated to garages and cellars, while the upper floors contain apartments. The building envelope was designed to achieve the following thermal transmittance values: 0.125 W/ m²K for the external walls, 0.08 W/ m²K for the roof, 0.117 W/ m²K for the slabs between the floors, and 0.164 W/ m²K for the walls between the flats. This high level of insulation was achieved for passive control, also ensuring a periodic thermal transmittance of 0.003 W/ m²K for the walls and 0.004 W/m²K for the roof. The windows are triple-glazed, low-emissivity units with PVC frames. The building is equipped with ten independent air-based heating, cooling, and ventilation systems, each powered by a reversible air-to-water heat pump with an integrated hydronic unit. Three apartments are served by multi-split direct expansion heat pumps. The building also features a photovoltaic system consisting of 13 independent subsystems, each with a peak power of 3.00 kWp.



Figure 17a: Rendering: South-West exposure

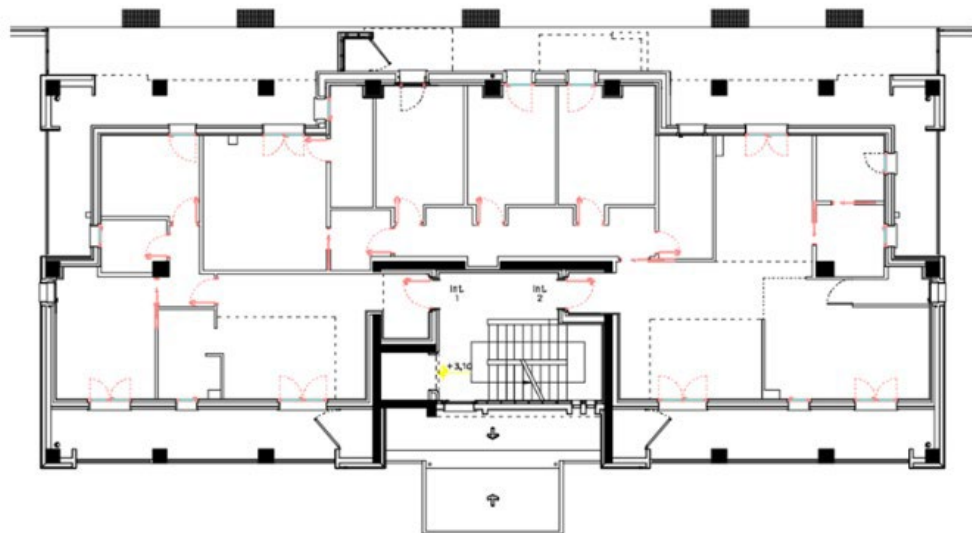


Figure 17b: First floor plan

The building is located in Campobasso, a city in central Italy with relatively cold winters and warm summers. The average temperature of the coldest month (January) is 4.7°C, and that of the warmest month (July) is 23.2°C.

3.3.1 Research method

Starting from the base design configuration, several scenarios were simulated, considering stricter requirements for the building-HVAC system, including five EV charging options. The considered improvements to the design are:

- A higher insulation thickness that reduces the thermal transmittance by 5%.
- Installation of a heat pump with a performance coefficient 20% higher.
- An increase in the installed power of the photovoltaic system from 43 kWp to 124 kWp.
- A combination of all previous interventions.

Regarding the EV charging scenarios, the assumption is that each charging station must completely charge a vehicle with a 40 kWh battery once per day. The technical data are presented in the Table 7.

Scenario	Charging station model	N° of station	Daily demand [kWh]	Monthly demand [kWh]
Scenario 1	COMBO WALL E TOWER 3.7 kW	7	284.9	8547
Scenario 2	JUICEBOX PRO 7.6 kW	7	310.8	9324
Scenario 3	COMBO WALL E TOWER 3.7 kW	3	122.1	3663
Scenario 4	JUICEBOX PRO 7.6 kW	3	133.2	3996
Scenario 5	COMBO WALL E TOWER 3.7 kW	2	81.4	2442

Table 7 EV Charging scenarios

The energy performance of each scenario is evaluated using key indicators such as the global renewable and non-renewable energy performance indices ($EP_{gl,REN}$ and $EP_{gl,NREN}$), CO₂ emissions, energy class, self-consumed photovoltaic energy, electricity drawn from the grid, and the surplus energy to be injected into the grid. The analysis considers both annual and monthly energy balances to capture the dynamic nature of energy demand and generation throughout the year.

3.3.2 Results

The simulation results for the state of fact indicate that the building already achieves a high level of energy performance. All apartments attain the highest energy class (A4) with minimal CO₂ emissions that vary in the range 0.05-0.45 kg/m². The electricity drawn from the grid is considerably lower (519 kWh for the whole building) than the in-situ consumption of photovoltaic energy, which varies between 713 kWh (April) and 2238 kWh (July) for the whole building indicating a net positive energy balance. Further analysis reveals that four apartments (2, 4, 7, and 10) achieve a global non-renewable energy performance index ($EP_{gl,NREN}$) of zero, meaning their entire energy demand is met by renewable sources. These apartments share a southwest orientation and are equipped with multi-split direct expansion heat pumps. Figure 18 compares the available surplus electricity and the required one from the EV charging stations; the results show that even if the building has very low energy requirements, the designed measures can only support the scenario with the lowest number of charging stations whose request can be covered from surplus electricity in summer and intermediate months. The monthly analysis further reveals that even with two charging stations, the building may experience an energy deficit during winter months due to increased energy demand and reduced photovoltaic production. This highlights the importance of considering seasonal variations in energy demand and generation when evaluating the feasibility of integrating EV charging infrastructure.

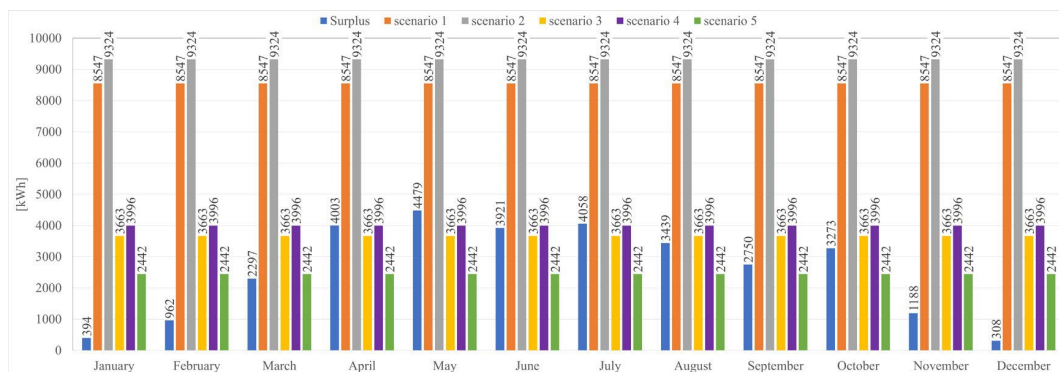


Figure 18: Monthly electricity: state of fact and 5 EV charging scenarios

Considering the proposed improvements for the building's HVAC system, it was found that the insulation upgrade leads to a marginal reduction of the annual energy consumption (0.5%), primarily during winter months. This suggests that the building envelope is already well-insulated, and further improvements in this area offer limited benefits. The installation of more efficient plants results in a more substantial decrease in energy demand (-20%, yearly) and the surplus energy available becomes 34'215 kWh; also, if increased compared to the base case (31'071) also in this case only the scenario 5 for the EV station is applicable. The most significant impact is observed with the expansion of the photovoltaic system since the surplus energy becomes 121'690 kWh. This highlights the crucial role of on-site renewable energy generation in achieving the PEB standard and the diffusion of electric vehicles. The best case is the combination of all previous measures and the comparison with the EV scenarios is proposed in Figure 19. In this case the available surplus is 125'450 kWh. In this design configuration, it is achievable the PEB classification and in the summer months all EV scenarios are sustainable for the tenants meanwhile considering the annual perspective scenarios 3,4 and 5 become suitable.

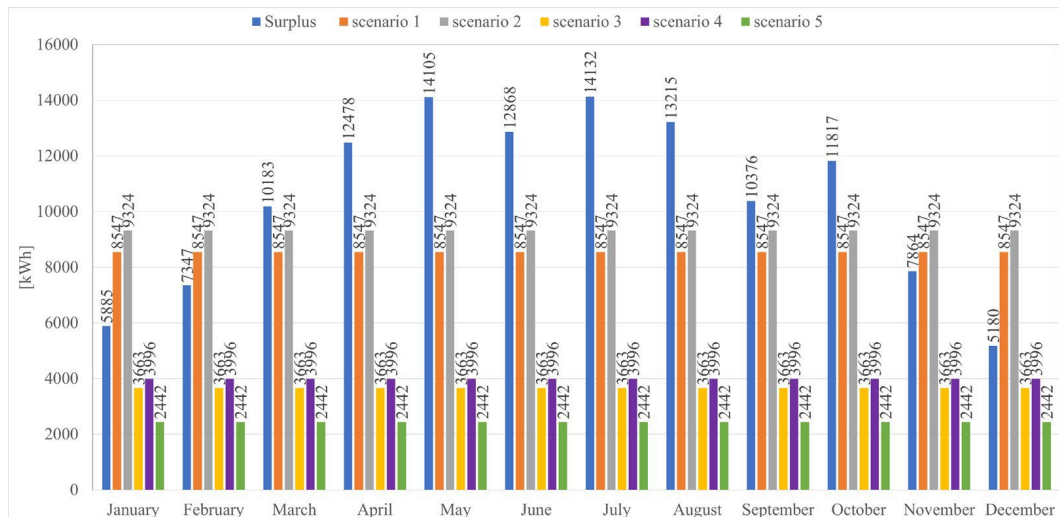


Figure 19 Combined scenario building energy surplus and 5 EV charging scenarios

In summary, the results of this study demonstrate that achieving the PEB standard is technically feasible for new residential constructions in temperate

climates. However, it requires careful consideration of various factors, including building envelope design, efficient technical systems, on-site renewable energy generation, and the integration of EV charging infrastructure. The study also highlights the importance of conducting detailed energy performance evaluations on both annual and monthly time scales to capture the dynamic nature of energy demand and generation and ensure that the building maintains a positive energy balance throughout the year.

3.3.3 Conclusions

Overall, this research contributes to the ongoing dialogue on sustainable building design and energy management. The findings provide valuable insights for stakeholders involved in the transition towards a decarbonized building sector and highlight the potential of PEBs as a key component of a sustainable energy future. By adopting a holistic approach that combines energy efficiency, renewable energy generation, and the integration of electric mobility, the building sector can play a crucial role in mitigating climate change and achieving a sustainable energy future. The study demonstrates that the achievement of PEB standard is feasible through a combination of optimized building design, energy-efficient technologies, and the integration of renewable energy sources. The research also underlines the importance of considering the growing demand for EV charging infrastructure in building design. While the integration of such infrastructure can pose challenges to maintaining a positive energy balance, the study shows that it is possible to accommodate EV charging needs through careful planning and the implementation of appropriate energy efficiency measures. The findings of the case study suggest that a combination of improved insulation, highly efficient heating/cooling systems, and expanded photovoltaic capacity can significantly reduce energy consumption and increase on-site renewable energy generation. This enables the building to accommodate a substantial number of EV charging stations while maintaining a positive energy balance throughout the year. This

study has some limitations, including its focus on a single building and the use of annual energy balances, which suggest avenues for future research. Further investigations could explore the implications of PEBs within larger energy communities, considering the potential for energy sharing and grid interaction. Additionally, future research could develop more sophisticated simulation tools that enable detailed energy performance evaluations on shorter time scales (e.g. hourly time scale), capturing the dynamic nature of energy demand and generation.

3.4 Social Housing regeneration: qualifying and making sustainable buildings and public spaces. A case study

The buildings energy renovation is a key point of energy policies, as buildings in Europe account for 40% of final energy use and 36% of greenhouse gas emissions related to energy. Additionally, around 75% of buildings are considered inefficient.

Acting on social housing is a strategic way to reach people in energy poverty. These buildings are often 40–50 years [105] old and were built in a historical period with different socio-economic needs and different societal ideals. The article proposes a case study of social housing renovations and how it impacts on neighborhood in terms of Urban Heat Island. The case study of Margherita di Savoia is the pilot case of the REHOSUE (Renovation packagEs for HOlistic improvement of EU's bUildingS Efficiency) project, funded by Horizon Europe research Program aims to design and demonstrate, in an operational environment, innovative energy technologies called Renovation Packages. Over the four years of the project, eight innovative and holistic solutions are applying, and by demonstrating their validity in efficient, cost-effective, and sustainable renovation processes, they are moving from a TRL (Technology Readiness Level) of 4/5 to a TRL 8.

The building of the pilot case is located an area faces significant socioeconomic challenges, with socially vulnerable communities. The area around the building is characterized by the lack of accessible meeting areas and green spaces exacerbates social isolation. Improving shared spaces through urban regeneration strategies can enhance both social cohesion and climate resilience, reinforcing the connection between environmental sustainability and social inclusion [106]. Two innovative renovation packages, using off-site construction approach, are designed and applied to a social housing reinforced concrete demonstration building located in Margherita di Savoia (Apulia region, Italy). The renovation packages consist of (i) an eso-skeleton with multipurpose façade able to provide thermal insulation (using sustainable materials) and renewable energy production through PV colored

panels, also able to give a new aesthetic look to the building and (ii) an efficient heat pump system to provide heating, cooling and DHW minimizing energy consumption and increasing the living comfort. While the renovation packages are being developed by some of the project partners, a careful seismic assessment and retrofit is carried out along with a social mediation toward the building tenants to explain the needs of the assessment process and the purposes of the interventions that will be carried out while listening inhabitants' needs [107]. Paying attention to social aspects also means that all the structural investigations needed to gather the necessary knowledge about the structure are made through low impact activities, for example, avoiding making destructive investigations inside the apartments.

3.4.1 Model description

The energy audit was carried out through an analysis of the actual consumption in the current state of the building-plant system. The objective is to define a baseline consumption, to be used for the evaluation of the energy improvement interventions. In this way, actions on the envelope and on thermal and electrical systems can be defined. These actions can be completed through monitoring systems and integrated with renewable sources. The energy audit has been carried out using TerMus BIM [59] tool. The starting point was the creation of the BIM model of the IDSB. In Figures 20, the three-dimensional model created is shown, in the initial and design conditions. All apartments are supplied with an independent heating system. Five dwellings have a condensing boiler, while the remaining units have a standard boiler. Three apartments have an air conditioning system with heat pump. It can also be used as a heating system. No thermostats or building automation and control devices are present.

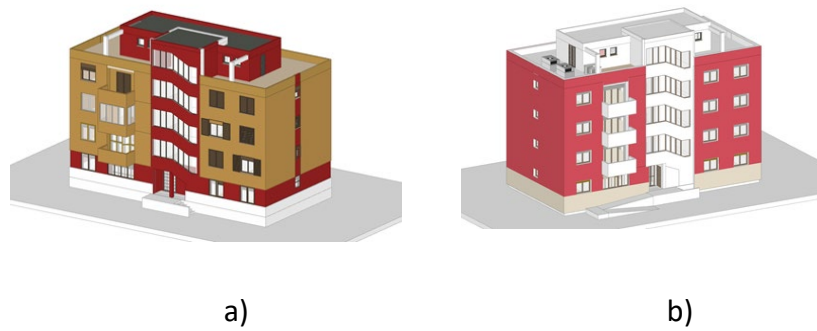


Figure 20 The three-dimensional model: a) initial condition and b) design condition.
(Extracted from TerMus BIM software)

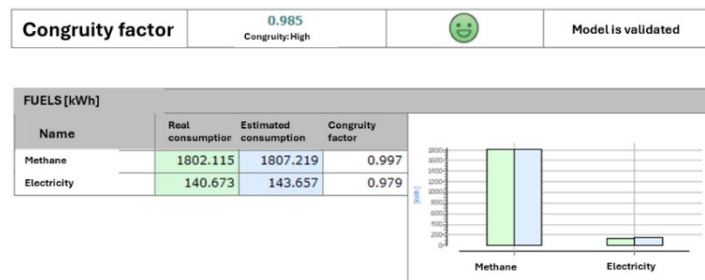


Figure 21 Validation Model

It is planned to create thermal insulation of the building envelope, replacing the external windows and doors, providing the building with energy autonomy by energy production systems from renewable sources (Vertical PV panels) and introducing a centralized thermal generation system based on innovative storage technologies, protected by patent. Therefore, to calibrate the model, a consumption analysis was carried out, acting, for each apartment, on the turn-on period of the winter and summer air conditioning systems, as in Figure 21.

3.4.2 Smart Thermal Energy Hub System

One of the innovative solutions tested in the demo site deals with the heating/cooling/DHW system (Smart Thermal Energy Hub). The heating system will be changed: now each apartment has a single boiler, at the end of the renovation process a centralized heating system will be installed, and two boilers

will be positioned on the roof. The final energy consumption must remain below the annual energy production of the façade-integrated photovoltaic system, also implemented within the REHouse project. The innovation consists of installing a Smart Thermal Energy Hub constituted by two thermal energy storage tanks using Phase Change Materials (PCMs) of a nominal storage energy of 35 kWh developed and manufactured by Steel Tech srl, coupled with a pair of commercially available high temperature Water-to-Water (W2W) heat pumps of nominal power of 30 kW each. The decision to install dual storage tanks and heat pumps was made to ensure redundancy and enhance reliability. To guarantee service continuity, particularly during the experimental phase which may involve interruptions of the innovative part of the system, a centralized condensing boiler will be installed. The beforementioned Smart Thermal Energy Hub has seven internal layers with differentiated temperatures (4°, 8°, 23°, 37°, 48°, 58°, 68°), operating either as a source or a sink depending on energy demand and the heat pump's operational state, according to the control logic. The reverse process occurs when cooling is required. The heating system will continue to utilize the existing radiators, now equipped with thermostatic radiator valves, as the emission system, whereas cooling emission will be provided by four ceiling-mounted fan coil units per apartment. The system is therefore distinguished by the use of heat pumps that do not utilize external air as a heat source, but rather the thermal energy contained within the water and PCMs allocated in the tanks. These are commercially available W2W high temperature (up to 85°C) heat pumps specifically selected for their technical characteristics, suitable for operation in combination with the proposed Smart Energy Hub System based on PCM. Furthermore, the system will be equipped with dry-coolers that, in the event of excessive and prolonged demand for thermal energy from users, exchange energy between the 'source layers' within the tanks and the external environment. The entire heating system will be automatically managed and monitored by control systems governed by algorithms that will be optimized during the experimental phase to maximize efficiency. Figure 22 shows a schematic diagram of the central heating system as envisioned during

the detailed design phase. The Smart Thermal Energy Hub system provide all the required DHW with an energy efficient way of gradually heating from 23°C layer up to 68°C. To eliminate on of the many limits of the centralized DHW, the need of a recirculation system to avoid having more than 30 seconds for the hot water release, additional 40-liter nominal capacity PCM storage tanks are planned within the apartments. This measure ensures an almost immediate supply of DHW, and the PCM has a function of self-recharging when the centralized hot water cross the local tank, helping to reduce water and electricity waste. Such waste of energy for loss and recirculation is a typical problem in centralized systems that use recirculation.

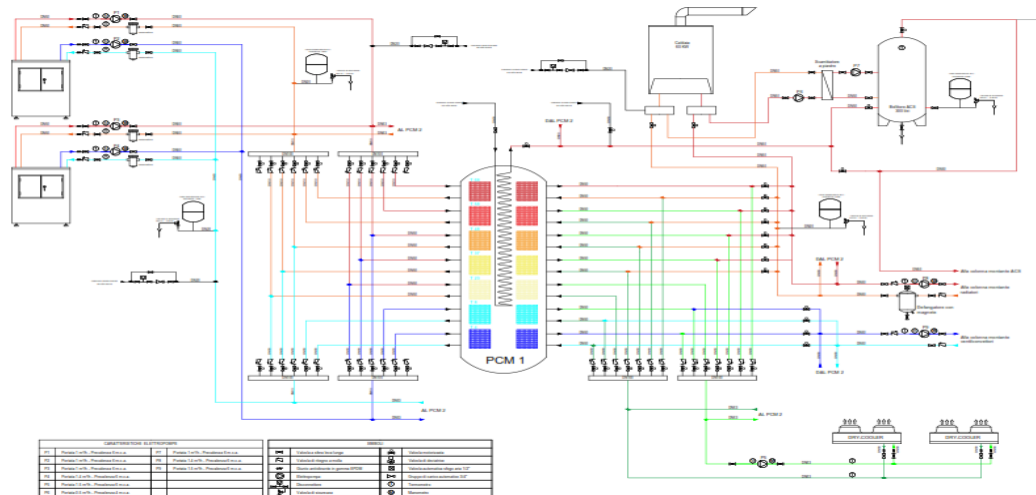


Figure 22 Boiler Diagram

3.4.3 Results

To assess the benefits achievable through energy efficiency measures, an energy diagnosis was carried out, taking into account five different improvement scenario, which are listed as follows: Scenario A: Insulation of opaque surfaces and replacement of window frames; Scenario B: Insulation of opaque surfaces, replacement of fixtures plus Installation of photovoltaic system; Scenario C: Replacement of the central heating plant; Scenario D: Replacement of thermal

power plant plus Installation of photovoltaic system; Scenario E: Scenario that includes all improvements.

Figure 23 shows the total CO₂ emissions: as the energy efficiency of the building improves, CO₂ emissions drop dramatically. Even for scenario C, which involves the total replacement of the heating system, it can be observed that CO₂ emissions are zero.

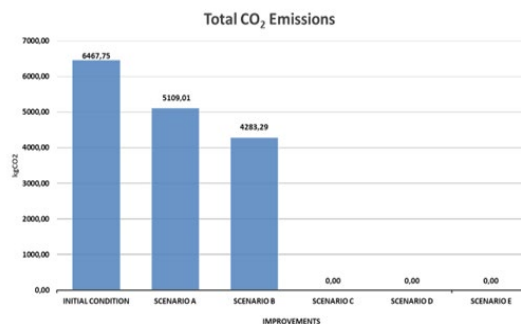


Figure 23 Total CO₂ Emissions

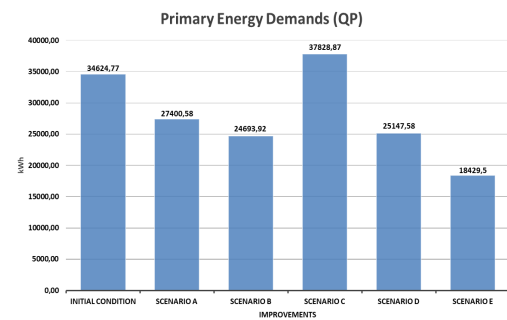


Figure 24 Primary Energy Demands

In Figure 24, it can be noted that the configuration requiring the highest primary energy demand is scenario C. This is due to the new thermal power plant, which provides cooling service to all 8 units that make up the entire building. From the initial condition, in fact, only three residential units (apartments) have summer air conditioning. As designed, the configuration that requires less primary energy demand is scenario E, which includes all the improvements.

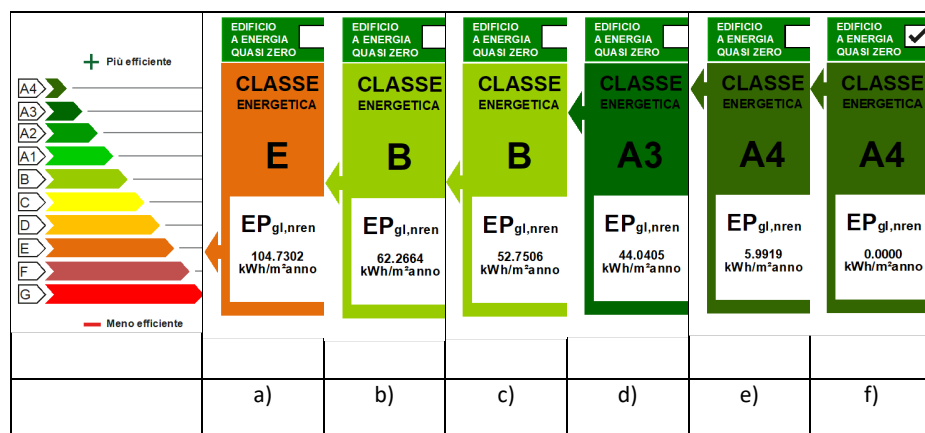


Figure 25 - Energy classes: a) Initial condition; b) Scenario A; c) Scenario B; d) Scenario C; e) Scenario D; f) Scenario E.

In Figure 25, which shows the energy classes for each of the scenarios considered, it is verified, as expected, that the building's energy efficiency improves with the implementation of the proposed energy efficiency enhancements. It is shown that due to the replacement of the thermal power plant and the installation of photovoltaics, scenario D, the building reaches energy class A4. However, the building achieves nZEB status only by performing all the proposed design improvements.

3.4.4 Urban Heat Island (UHI) effect on the case study

One of the most critical issues impacting residents' health and well-being is the Urban Heat Island (UHI) effect. The increasing number of heat-related deaths in Italy underscores the urgency of addressing urban microclimate conditions, particularly in highly exposed areas like the case study site, where extreme summer temperatures pose a significant risk to its inhabitants [108]. Consequently, alongside energy requalification studies for the building, simulations on the urban microclimate were conducted using the LITE version of ENVI-met, a high-resolution 3D microclimate simulation tool. This software employs a Computational Fluid Dynamics (CFD) model to analyze interactions between buildings, vegetation, and atmospheric conditions. Site-specific materials were stored, and a model area was created (Figure 26).

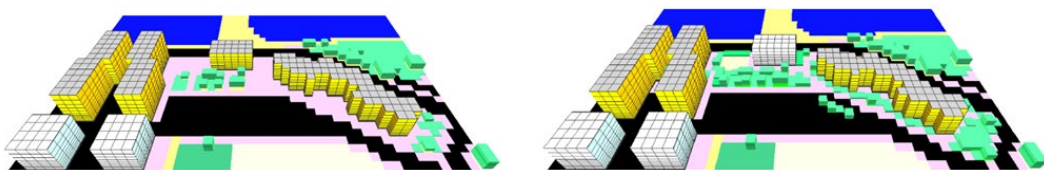


Figure 26 – model area created with ENVI-met Spaces. As-built scenario (left) and the scenario after building and area renovations (right).

One limitation of CFD software is its long calculation time (ten hours in this case). To optimize the study, a representative day from the hottest month—July—was selected. This day was identified by analyzing hourly air temperature data from 2020 to 2024, choosing the one with the smallest sum of the hourly root

means square deviations of air temperature (representative day technique) [109]. In the simulation settings, climate data from July 21st, 2022, were entered, and the model was run for ten hours, from 10:00 to 20:00. Results from 15:00 were selected for analysis. The potential air temperature surrounding the building ranged from a minimum of 26.94°C in the salt pan area to a maximum of 35.65°C, with values above 30°C corresponding mostly to cemented areas. Relative humidity varied inversely, between 29.28% and 53.85%. Another crucial parameter for assessing thermal comfort is the mean radiant temperature, which ranged from a minimum of 32.81°C (in shaded areas) to a maximum of 78.79°C, particularly in the southern parts of the buildings. Combined with wind velocity and two thermo-physiological factors (clothing and human activity level), these parameters contribute to calculating the PET (Physiological Equivalent Temperature) index, one of the most widely used metrics for outdoor thermal comfort assessment [110]. The PET values ranged from 32.04°C to 58.71°C, mirroring the mean radiant temperature distribution. A second simulation was conducted, modifying the characteristics of the walls and roof of the ReHouse building according to Renovation Package 05: Multipurpose Façade System with Bio-Based Insulation and BIPV. Consequently, the absorption coefficient of the walls drastically increases, the reflection coefficient decreases, and emissivity slightly decreases due to the material changes, replacing yellow plaster with photovoltaic panels. Comparing the two scenarios, it was observed that material modifications led to a slight overall increase in potential air temperature, a slight decrease in relative humidity, and a notable reduction in mean radiant temperature, particularly along the building's southern wall. However, on the northwest side, the mean radiant temperature increased. As previously mentioned, these factors contribute to the PET index (Figure 27). These results align with the changes in the building materials: the increase in absorption coefficient, combined with the decrease in thermal conductivity and density, leads to higher surface temperatures but reduced heat storage and reduced delayed heat release. During the daytime, the calculated potential air temperature is higher, but it is expected to be lower at

night. The simulation runs only until 10:00 PM, and the beginning of this inverse trend can already be observed in the final hour. Higher surface temperatures may contribute to localized warming, but this heat is not deeply stored within the material. The mean radiant temperature, instead, decreases on the southern façade due to the low reflectivity of the solar panels. On the northwest side, however, it follows the trend of the potential air temperature: during daily hours it's higher, but by the last hour of the simulation (10:00 PM), it becomes equal to or lower than in the initial scenario. Finally, the PET index follows the same pattern, as at 10:00 PM it decreases (or remains equal) all around the building. The third simulation included added vegetation, green spaces, and permeable pavements around the ReHouse building and nearby structures (Figure 26, right). Comparing the as-built scenario to this greener version, some considerations can be made. The potential air temperature difference during daytime remains negative around the ReHouse building: the greening intervention is not sufficient to fully compensate for the heat emission from the building materials. However, the minimum values in the two scenarios show a slight mitigation of this phenomenon thanks to the vegetation. In the surrounding areas, lower temperatures are observed. Relative humidity shows a similar behaviour: vegetation mitigates the increase in relative humidity around the building (due to the change in materials) and reduces relative humidity in the surrounding area. The mean radiant temperature difference shows some peaks of both decrease and increase near the green areas. Vegetation interacting with solar radiation and other urban reflective surfaces can increase the complexity of the calculation, resulting in a heterogeneous spatial distribution of MRT [111], but an overall reduction was noted. Finally, the PET index shows a similar trend to MRT (in terms of peaks), but with evident improvements in thermal comfort (Figure 28).

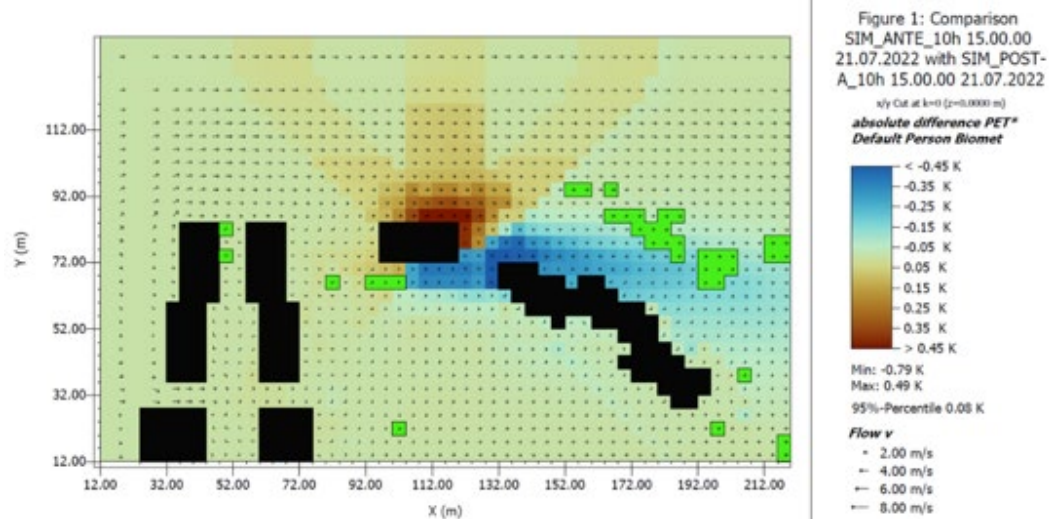


Figure 27 PET index variation after the renovation of the building

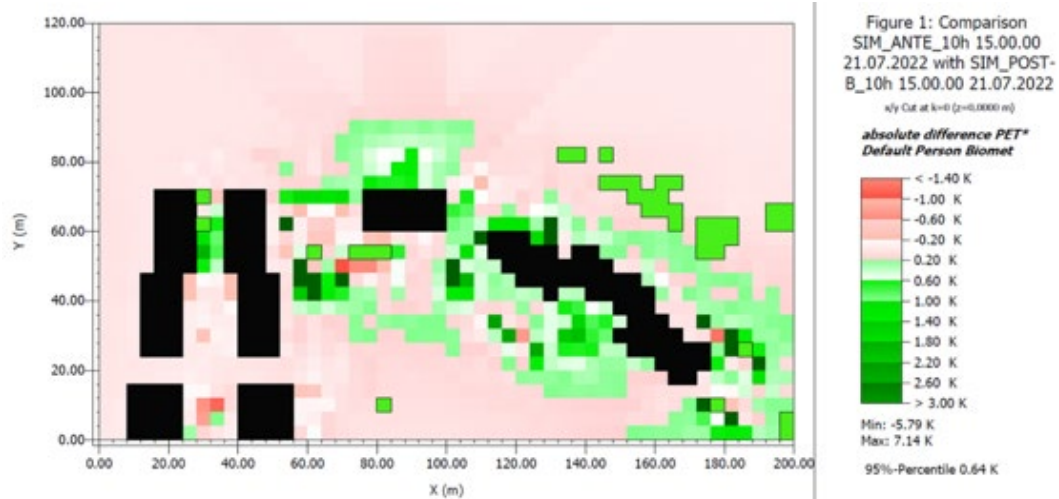


Figure 28 PET index variation after the building and area renovations

3.4.5 Conclusions

Energy poverty has now been recognized as being on a par with other forms of social hardship that need to be prevented and treated. Meeting the ambitious goals that Europe has set with the EPBD, while it may be difficult for homeowners who do not live in particular conditions of economic and social hardship, becomes even more complicated for those who live in poverty. For this reason, as already highlighted by other authors [112, 113, 114, 115], identifying low-cost ways to increase the energy efficiency of a building stock built mainly after the Second

World War and now obsolete, both from a structural point of view and even more so from an energy efficiency point of view, becomes a significant research and development objective. After an initial phase dedicated to the energy audit, essential for understanding the functioning of the building both in terms of dispersion from the external envelope and in terms of efficiency in the production and use of energy sources, the research objective has been to define a baseline consumption, to be used for the evaluation of the energy improvement interventions modelling innovative technology with TRL5. So, energy efficiency measures have been tested on the building envelope and the heating system one. An innovative centralized system has been built using a thermal stratified storage tank, the Smart Thermal Energy Hub. Using these solutions the benefits achievable through energy efficiency measures have been assessed, taking into account five different improvement scenarios, where the last one includes all improvements. It has been observed that CO₂ emissions are zero and it is shown that due to the replacement of the thermal power plant and with the installation of photovoltaics, in the scenario D, the building reaches energy class A4, but the building achieves nZEB status only by performing all the proposed design improvements in the last scenario E. After reaching a possible satisfactory solution with respect to the building's performance, its relationship with the external areas was investigated to understand the relationship between the interventions on the building's skin, the insertion of greenery in the external parts, currently mainly made of waterproof materials, with respect to the heat island phenomenon. As already known in literature, favoring green developments can have positive effect also for the health of the population by providing places favorable for the protection of ultraviolet radiation and adapted to the practice of physical activity, in addition to the improvement of air quality [116, 117, 118]. Also in this case, different scenarios have been produced in which, in fact, results show a slight mitigation of the heat island phenomenon due to vegetation. Lower temperatures are observed in the surrounding areas. The mean radiant temperature difference shows some peaks of both decrease and increase in proximity to green areas. The changes in the

building materials have shown the increase in absorption coefficient, combined with the decrease in thermal conductivity and density, leads to higher surface temperatures but reduced heat storage and reduced delayed heat release. These results need to be integrated with further analyses of external conditions starting from the trend of winds or the dimensions of the spaces compared with those of the surfaces of the buildings overlooking such spaces to better understand where it can be more productive to increase efforts. Rethinking the significant quantity of public housing buildings existing today in Italy as well as in other European nations certainly means rethinking the performances offered by these buildings, but without limiting ourselves to the intervention on the single building but taking advantage of transforming these interventions into opportunities for urban regeneration.

Chapter 4: Impact of climate change on building energy needs and consumption

Climate change, primarily caused by human activities such as the burning of fossil fuels and deforestation [119], represents one of the most urgent global challenges of our time. The consequences of this phenomenon manifest in rising global temperatures, alterations in precipitation patterns and wind patterns, sea-level rise, and an increased frequency of extreme events, with significant impacts on biodiversity and ecosystems [119]. In this context, the need for concrete actions to reduce greenhouse gas emissions becomes imperative, requiring a joint commitment at the level of economic resources and awareness of local administrations [120].

The building sector, responsible for a significant share of global energy consumption and emissions, is at the heart of this challenge. Understanding and mitigating the impact of climate change on building energy performance has become a crucial area of research. Mathematical models and advanced simulation techniques are increasingly used to project future climate scenarios (e.g., for the years 2050 and 2080) and to predict long-term trends in building energy demand [121]. Recent studies have demonstrated how climate change can significantly alter energy demand. For example, using stochastic methods, a decrease in heating demand and an increase in cooling demand in office buildings were found [122]. Similarly, the impact of future downscaled weather data has been evaluated, highlighting a substantial increase (up to 278.8% by the end of the century) in cooling energy demand in residential buildings located in Hong Kong [123]. Employing explainable artificial intelligence models, an 87% increase in cooling demand in warm humid climates between 2000 and 2010 was predicted [124]. Analyses conducted on 15 US cities, using the HadCM3 model and various CO₂ emission scenarios, confirmed a widespread increase in cooling demand and a reduction in heating demand, although with significant geographical variations

(125). Using the WYEC2 procedure, it was highlighted how atypical meteorological years can lead to notable differences in building energy demand compared to typical years [126].

In this scenario, the design of the transparent building envelope assumes a role of primary importance. Windows, in particular, significantly influence thermal losses and direct solar gains, with a consequent risk of overheating [119, 127]. Although dynamic or "smart" windows offer potential advantages in terms of energy performance even when facing the effects of climate change, their diffusion is still limited by critical issues such as high costs and switching speed [128]. Alternatively, static solutions based on the control of solar gain or heat loss remain relevant [129]. Despite the crucial role of glazing systems in nearly zero energy buildings (nZEBs), the scientific literature highlights a lack of in-depth studies on this topic, particularly for the design of climate change-resilient nZEBs [130, 131]. It has indeed been observed that the optimal design of an nZEB should differ in climate change scenarios compared to estimates based on the current climate, requiring, for example, slightly lower levels of insulation, a more efficient envelope, highly reflective exterior surfaces, and better solar control from windows to reduce cooling needs [131]. Part of research activity therefore focuses on the need for long-term analyses of static glazing solutions, in order to define effective design strategies for new constructions and energy retrofit interventions, considering the present and future effects of efficient glazing in Mediterranean climates.

Parallel to envelope efficiency, the transition to renewable energy sources, such as solar photovoltaic energy, represents a global priority to address climate change and ensure energy security. In climatic contexts such as the tropics, characterized by high solar irradiation, the integration of photovoltaics into buildings emerges as a promising strategy to diversify energy sources, ensure sustainable access to electricity, and promote economic and social development. Building-integrated photovoltaic (BIPV) systems offer advantages in terms of efficient use of available surfaces, potential building cooling, and reduction of carbon emissions [132]. However, the effectiveness of PV systems can be compromised by changing

climatic conditions, particularly in tropical climates, where high temperatures, humidity, and atmospheric dust can accelerate the performance degradation of solar panels [133]. Specific studies have quantified the degradation rate of photovoltaic modules in different climates, highlighting the need for mitigation strategies and careful design and maintenance to maximize the potential of this renewable technology [134, 135, 136]. Despite the importance of photovoltaics in the context of nZEB buildings, current scientific literature shows a gap in studies on the influence of climate change on the energy balance of buildings designed to be nZEB, especially in hot and humid climates, also considering the effect of performance degradation of in-situ renewable plants.

The subsequent subchapters will provide a detailed exposition of five specific studies conducted within this research area:

- “Forecasting future climate with a neural network trained on monitored data: an analysis of the energy demand of a detached house”: This study introduces a neural network-based approach for short-term climate forecasting and the evaluation of the energy demand of a residential building in Italy.
- “Optimized neural network architectures for climate data and photovoltaic production forecasting”: This study aims to investigate and demonstrate the problems and difficulties associated with the use of neural networks for predicting photovoltaic production.
- “Impact of glazing system on the energy performance of a nZEB under climate change scenarios”: This study critically analyzes the impact of different types of glazing on the energy performance of nZEB buildings in Mediterranean climates in climate change scenarios.
- “Effect of degradation and size selection for the photovoltaic system installed in a nearly zero energy building in Tropical Climate”: This study explores the effect of degradation and size selection for photovoltaic systems installed in nZEB buildings in tropical climates, with a focus on the Dominican Republic.

- “Sensitivity analysis on the energy performance evaluation of buildings designed as nearly zero energy in the current climatic scenario and climate change evolution”: This study compares the effectiveness of a retrofit intervention in both the current climate scenario and future climate scenarios. The comparison is performed using the semi-steady-state method and the hourly dynamic method.

Each of these studies will be presented in detail in the following subchapters, encompassing their respective methodologies, results, and conclusions.

4.1 Forecasting future climate with a neural network trained on monitored data: an analysis of the energy demand of a detached house

The case study focuses on a detached, single-family home constructed in 1985, which was established as a reference building within the TABULA project [137]. The building consists of three levels, including a semi-underground garage. The total conditioned floor area is 198 m², with a surface-to-volume ratio of 0.65 m⁻¹. Figure 20(a) provides a table outlining the thermophysical characteristics of the building's envelope. Heating and domestic hot water (DHW) are supplied by a natural gas boiler, housed within the garage, achieving an overall efficiency of 0.73. The heating system utilizes radiators in each room, with a supply water temperature of 80°C. A DX multi-split system, with a nominal energy efficiency ratio (EER) of 3.45, handles the cooling load. The indoor set-point temperatures are maintained at 20°C during the heating season and 26°C during the cooling season. A rendered visualization of the building's original, or 'base case' condition, is presented in Figure 29(b). Furthermore, an upgraded, or 'refurbished' scenario is explored, which implements 2 cm vacuum insulation panels (VIP) on the exterior walls, successfully lowering the thermal transmittance to 0.26 W/m²K.

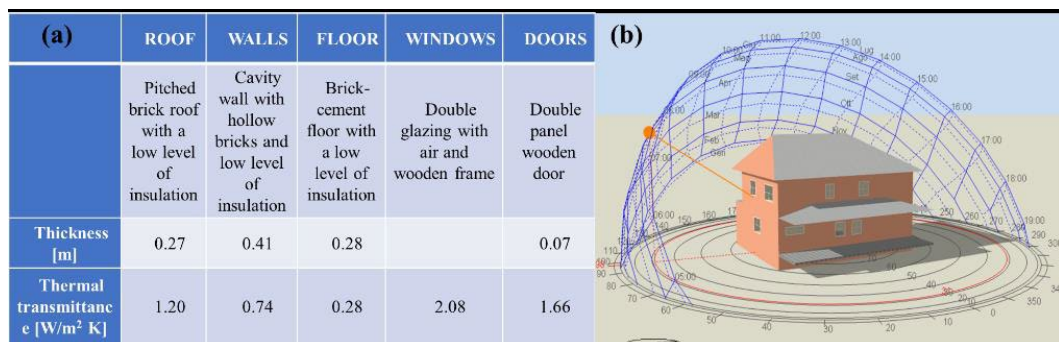


Figure 29 Envelope thermo-physics characteristics (b) and render view (a) of the case study

4.1.1 Methodological approach

Neural Networks (NNs) can predict the behavior of non-linear systems without requiring a predefined mathematical model. They find applications in diverse areas, including price forecasting [138] and climate change predictions [139, 140]. An NN is an algorithm that attempts to emulate the functioning of the human brain [141, 142]. NNs consist of interconnected "neurons" organized in layers. Each neuron receives inputs and produces an output. Neurons are connected via synapses, which are associated with weights representing the relative importance of each input. NNs can be broadly categorized into:

- Feedforward networks
- Recurrent networks

Feedforward networks are NNs where neurons are arranged in layers, and connections flow in a single direction, from the input layer to the output layer. Recurrent networks allow neurons to receive inputs from neurons in earlier or later layers. NNs are trained on large datasets using "supervised learning," where correct outputs are provided for each input, enabling the NN to "learn" and generate accurate predictions for similar inputs. NNs can be trained for local-scale predictions or forecasts across various time scales. Furthermore, their adaptability to new data makes them suitable for applications with rapidly changing input.

In this study, NNs are implemented within the MATLAB environment to predict short-term future temperatures based on monitored in-field data. The NN is trained using temperature data recorded from January 1, 2016, to December 31, 2022, at the climatic station within the engineering department laboratory at the University of Sannio, in Benevento. While the source data has a sampling rate of six samples per hour, the daily average temperature is used due to computational efficiency. These temperature forecasts are then incorporated into dynamic energy simulations of a single-family building to assess the variation in primary energy

demand for heating and cooling. The building's numerical model is developed using the EnergyPlus engine.

Figure 30 illustrates the methodological approach. The dataset of daily mean temperatures from 2016 to 2021 serves as input for training the NN. Upon reaching a stopping criterion, the NN generates a list of predicted values for 2022, denoted as 2022_s (simulated). Various stopping criteria can be employed, such as Mean Absolute Error (MAE) or Root Mean Square Error (RMSE). In this paper, the Mean Squared Error (MSE) is utilized. The 2022_s list is then compared with the monitored data for 2022, denoted as 2022_m (monitored). If the simulated and measured data for 2022 exhibit a close match, then forecasts for 2023 and 2027 are performed. If the simulated and measured data for 2022 exhibit a close match, then forecasts for 2023 and 2027 are performed.

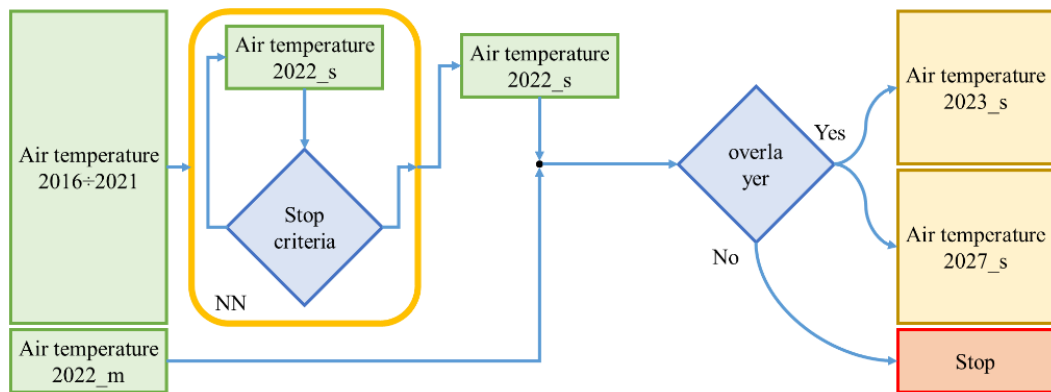


Figure 30 Methodological approach developed

The following steps were taken to implement the Neural Network (NN):

- Data Collection: Gathering air temperature data.
- Data Preprocessing:
 - Removing outlier values.
 - Normalizing data for variable comparability.
 - Splitting data into training and testing sets.
- NN Creation: Designing the neural network architecture.
- NN Training: Employing supervised learning to train the NN.

- NN Validation: Assessing the network's performance on test data to ensure accurate predictions.
- Prediction Generation: Utilizing the trained NN to make forecasts.

The algorithm, as depicted in Figure 31, begins with standardizing the input data to optimize computational speed. The data is structured into two sets: input and target. The input data comprises an array of dimensions $\text{lag} \times (n - \text{lag})$, where:

- 'lag' represents the number of preceding data points used for future prediction.
- 'n' is the total amount of monitored data points.

The target data consists of the $\text{lag} + 1$ most recent values from the temperature dataset. The input data is further divided into:

- Training Data: Used to train the NN, enabling it to recognize patterns and make predictions on new data. During training, the NN adjusts its weights.
- Validation Data: Used to evaluate the NN's performance during the training process.
- Test Data: Used after training to assess the NN's performance on unseen data.

Bias (b) is a value that shifts the neuron's activation function, allowing the NN to produce a non-zero output even with zero inputs and mitigating overfitting. Weights (w) represent the importance of synapses and are adjusted during training to enhance NN performance. The activation function, applied to each neuron, determines its output and enables the NN to learn non-linear relationships.

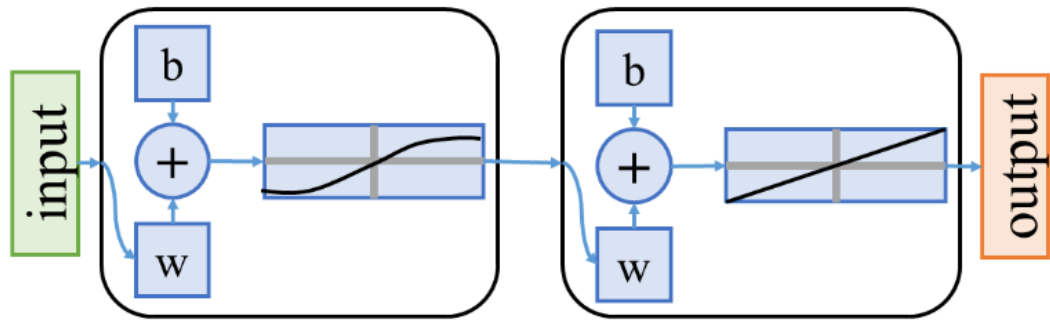


Figure 31 Neural Network used

A temperature vector of length $(n\text{-lag}+1)$, termed the 'window', is iteratively fed as input. The NN returns a value that occupies the last position in the window, and the first value in the list is discarded. This process is repeated to predict air temperatures for Benevento up to 2027.

The monitored data in Figure 32 (blue solid line) exhibits annual seasonality and a slight upward trend. The NN results accurately reflect this seasonality, both for the 2023 simulation (orange solid line) and the 2027 projection (green solid line). The increasing trend is also correctly captured in the output data.

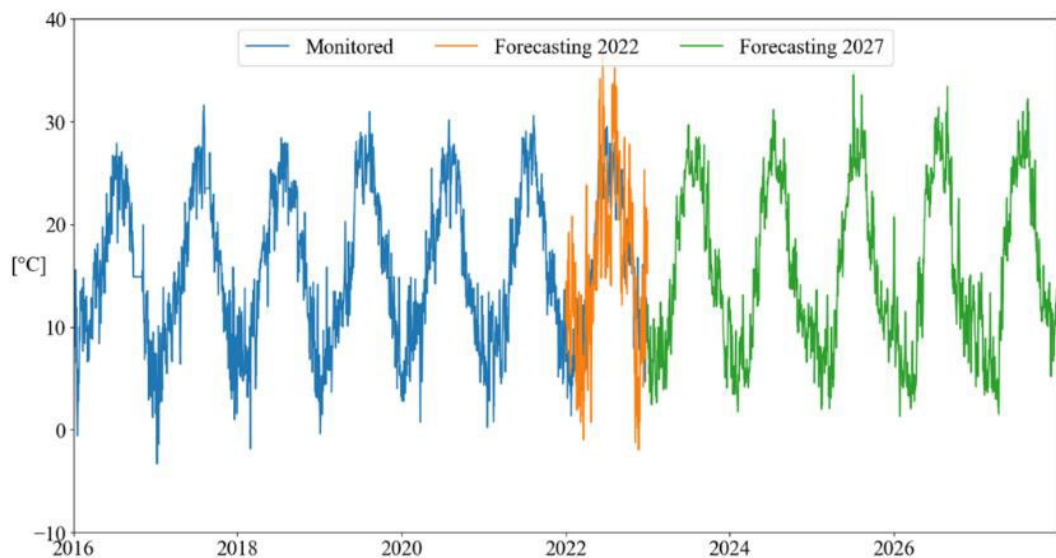


Figure 32 Monitored data, forecast to 2023 and forecast to 2027

Table 8 presents the maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperatures for each year. A clear increasing trend in maximum air temperature is observed. A similar, though less pronounced, trend is visible for minimum temperatures.

$T_{\min}$ [°C]	$T_{\max}$ [°C]	
-0.6	27.9	2016_m
-3.3	31.6	2017_m
-1.9	28.4	2018_m
-0.3	31.0	2019_m
0.7	30.2	2020_m
0.3	30.6	2021_m
1.4	29.5	2022_m
-1.9	36.6	2022_s
2.5	29.7	2023_s
1.8	31.2	2024_s
2.0	34.5	2025_s
1.3	33.4	2026_s
1.6	32.2	2027_s

Table 8 Maximum and minimum temperature for each year

4.1.2 Results

Figure 33 presents a histogram illustrating the primary energy consumption for cooling across the analyzed years. Compared to the 2016_m baseline, a progressive increase is observed. For the base case, this increase ranges from 22% to 59%, while the refurbished case shows an increase between 20% and 54%. The

primary energy consumption difference between the base and refurbished cases remains consistent, ranging from approximately 6% to 10% across all years. Comparing the 2022_m (monitored) and 2022_s (simulated) data reveals a 10% percentage difference in primary energy demand for cooling in both scenarios. This increase is attributed to the rising air temperatures predicted by the developed Neural Network (NN).



Figure 33 Primary energy for cooling

Figure 34 depicts the primary energy demand results for the heating period. Notably, for both monitored (2016_m and 2022_m) and simulated (2022_s, 2023_s, and 2027_s) years, the base case consistently exhibits approximately 40% higher primary energy demand than the refurbished case. An increase in primary energy demand is evident for both the base and refurbished cases when compared to the 2016_m baseline. Specifically, the base case demand increases by 8% to 17%, while the refurbished case increases by 8% to 20%. Furthermore, analyzing the monitored (2022_m) and simulated (2022_s) data for 2022 reveals deviations of 9% and 11% for the base and refurbished cases, respectively. The observed increase in primary energy demand for heating is attributed to the predicted future temperatures reaching lower minimum values.



Figure 34 Primary energy for heating

4.1.3 Conclusions

This study successfully utilized a neural network within the MATLAB environment to forecast the outdoor temperature of Benevento city. Based on six years of in-field monitoring data, predictions were generated up to 2027. Using a reference building case study, the following conclusions were drawn:

- The proposed method demonstrates an approximate 10% error in predicting cooling and heating energy demand, as validated by comparing simulated and measured data for the year 2022.
- Compared to 2016, the cooling energy demand in 2027 is projected to increase by 59% for a building with poor insulation and by 54% for a well-insulated building envelope.
- The heating energy demand also shows an increase compared to 2016, attributed to the predicted reduction in minimum temperatures over the years. This increase reaches a maximum of 17% in 2027 for both the base and refurbished building configurations.

The limitations of this work stem from its focus on temperature as the sole climatic parameter. To accurately assess future building energy needs, it is

necessary to incorporate other climatic variables, such as radiation, wind speed, and rainfall. Furthermore, the impact of material and thermal system aging should be evaluated. These factors will be addressed in future research.

4.2 Optimized neural network architectures for climate data and photovoltaic production forecasting

The transition towards a renewable-based system introduces significant technological challenges. The intrinsically intermittent and non-dispatchable nature of solar generation, contingent upon highly variable meteorological conditions, represents one of the primary obstacles to the stability and efficiency of modern electrical grids. Unlike traditional sources, photovoltaic (PV) production cannot be dispatched on demand, creating potential imbalances between supply and demand that jeopardize grid stability.

Effective management of such variability necessitates the development of increasingly accurate and reliable forecasting tools capable of anticipating energy production and the climatic parameters that determine it. Historically, forecasting has relied on physical and deterministic models, such as Numerical Weather Prediction (NWP) models. Although rigorous, these approaches exhibit inherent limitations: they require profound a priori knowledge of the system, substantial computational power, and struggle to capture non-linearities and stochastic dynamics at a local scale.

In response to these challenges, the last decade has witnessed the ascent of data-driven approaches, propelled by advancements in Artificial Intelligence (AI) and, specifically, Machine Learning (ML). Rather than explicitly modeling the system's physics, ML models "learn" the complex relationships between variables directly from historical data. Within this landscape, Artificial Neural Networks (ANNs) have established themselves as one of the most potent tools, excelling at learning non-linear patterns from large volumes of data.

This study is situated within this context with the primary aim of analyzing, designing, and validating advanced artificial neural network architectures for

forecasting climatic variables and the consequent photovoltaic energy generation. The specific objective is to investigate and demonstrate the problems and difficulties associated with the use of neural networks for predicting photovoltaic production, a crucial task for enabling smart energy management and optimizing the integration of renewables in the building sector and power grids.

4.2.1 Methodological approach

The first phase consisted of an in-depth and critical review of the state-of-the-art regarding the use of neural networks in the solar forecasting domain¹³. The analysis focused on the evolution of architectures, starting from simple models like the Multilayer Perceptron (MLP) and advancing to networks specialized for time series, such as Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU)

From this analysis, a clear progression emerged from simple networks to hybrid and optimized models, with an increasing use of attention mechanisms to push the limits of predictive accuracy.

The second phase, the operational one, focused on the practical implementation of predictive models, implemented using Python and the TensorFlow/Keras library. The approach was distinguished by the simultaneous multi-target forecasting of three correlated variables: Global Solar Radiation (GSR), photovoltaic (PV) power generation, and ambient temperature (T). The underlying premise is that a model capable of learning the interdependencies among these variables can achieve superior accuracy.

Data were acquired from the NZEB (Near Zero Energy Building) in Benevento. The PV plant (Figure 35) consists of 16 BENQ 330W modules (total peak power 5.3 kW), oriented south with a 5° inclination, coupled with a SOLAX inverter and an LG RESU 6.5 kWh lithium-ion battery storage system.

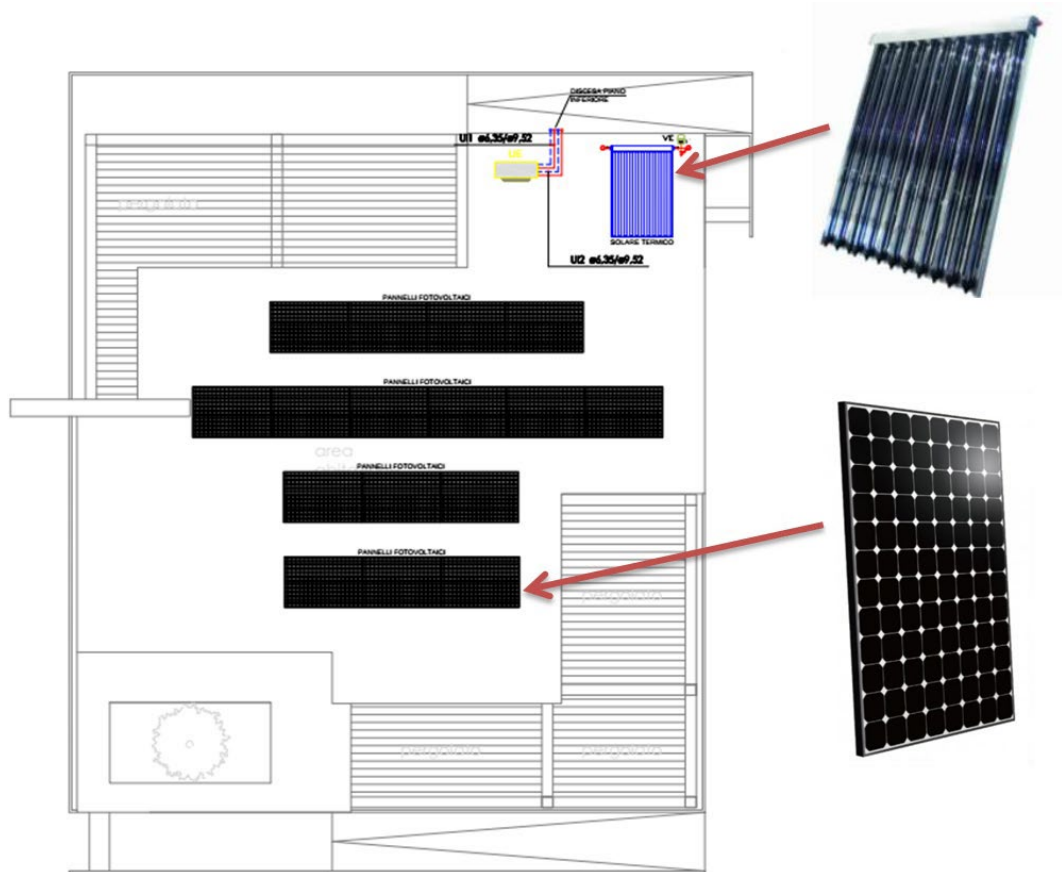


Figure 35: Photovoltaic and solar thermal plant

The dataset covers a time span of six and a half years (January 2018 – July 2024) at a 15-minute resolution. The data were split while maintaining temporal continuity:

- Training Set: January 2018 – December 2023 (6 years).
- Validation Set: January 2024 – July 2024 (7 months).
- Test Set: A specific day in August 2025, to evaluate generalization.

Pre-processing included: resampling, imputation of missing values (linear interpolation), creation of trigonometric periodic features (to capture daily, weekly, and annual cyclicity), and outlier removal using the robust statistical IQR (Interquartile Range) method.

The experimental study compared the two recurrent architectures (LSTM and GRU), configured with a lookback window (past data) of 168 hours (7 days) and a predictive horizon of 24 hours. The training strategy utilized the Adam optimizer (learning rate 0.001), Mean Squared Error (MSE) as the loss function, and an early stopping mechanism (with a patience of 10 epochs) to prevent overfitting.

Finally, a systematic hyperparameter optimization analysis (evaluating combinations of layers [1-4] and neurons [4-128]) led to the selection of the optimal architectures:

- For PV and GSR: 2 layers with 128 neurons, to capture the high complexity and non-linearities.
- For T: 2 layers with 4 neurons, a leaner architecture sufficient for the relative stationarity of the thermal series.

4.2.2 Results

The performance evaluation of the LSTM and GRU models was conducted using three standard statistical metrics. The metrics employed are:

- R^2 : Coefficient of Determination): Measures the proportion of the variance in the dependent variable that is predictable from the model. A value close to 1 indicates an excellent fit to the data.
- MBE (Mean Bias Error): Measures the average tendency of the model to overestimate (positive value) or underestimate (negative value) the predictions. An ideal value is close to 0.
- CV(RMSE) (Coefficient of Variation of the Root Mean Square Error): This is a normalized root mean square error, expressed as a percentage. It represents a measure of relative error; lower values indicate greater accuracy.

Hereafter, a detailed analysis for each target variable is provided:

Temperature was confirmed to be the most predictable variable, with performance approaching excellence (Figures 36 and 37).

- R^2 : The LSTM architecture achieved an exceptional value of 0.95, surpassing the GRU (0.91) and demonstrating a near-perfect capability to capture thermal dynamics.
- MBE: Both models exhibited a negligible positive bias (GRU: +2.00, LSTM: +2.33).
- CV(RMSE): The relative error was found to be very low for both (GRU: 10.40%, LSTM: 10.63%).

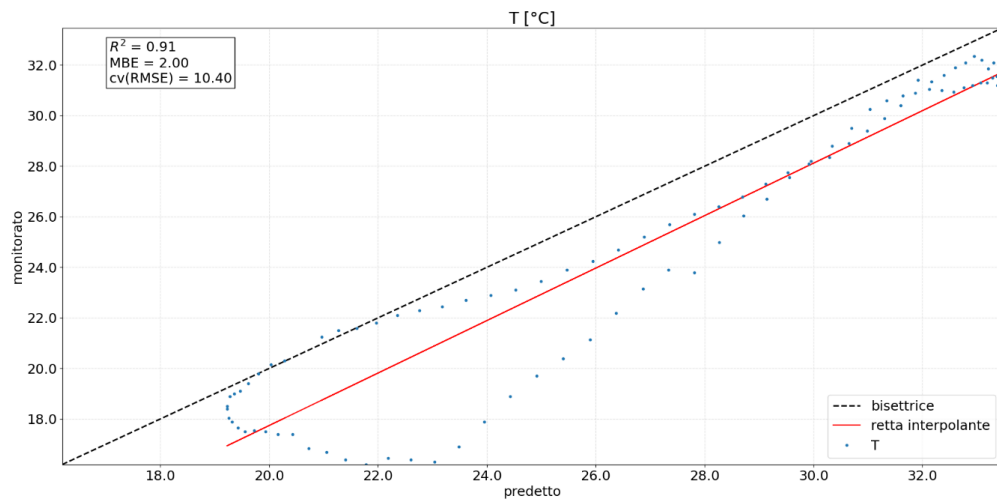


Figure 36 T forecast with GRU

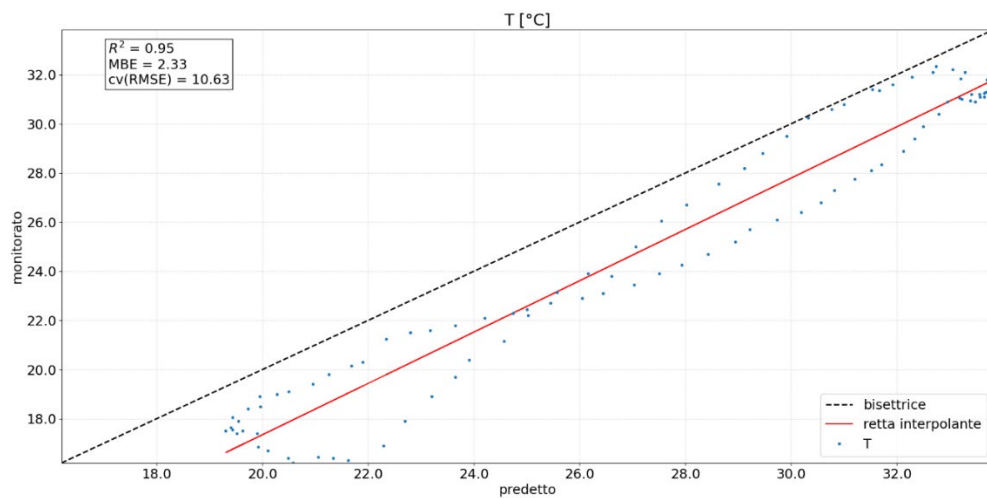


Figure 37 T forecast with LSTM

These excellent results are justifiable by the intrinsically stationary and cyclical nature of the temperature time series, characterized by highly repetitive daily and seasonal patterns and gradual transitions. The loss curves confirmed a stable learning process devoid of overfitting.

Both architectures demonstrated high-level predictive capabilities for Global Solar Radiation (GSR) as well (Figures 38 and 39).

- R^2 : The LSTM distinguished itself marginally with a value of 0.91 compared to the GRU's 0.90.
- CV(RMSE): The LSTM showed a lower dispersion of relative errors, with a CV(RMSE) of 35.28% compared to 36.87% for the GRU.
- MBE: Both models exhibited a slight negative bias (GRU: -10.10, LSTM: -11.01), suggesting a conservative systematic underestimation. This behavior is physiological and often preferable in operational contexts, where overestimating the solar resource can lead to more critical dispatch decisions.

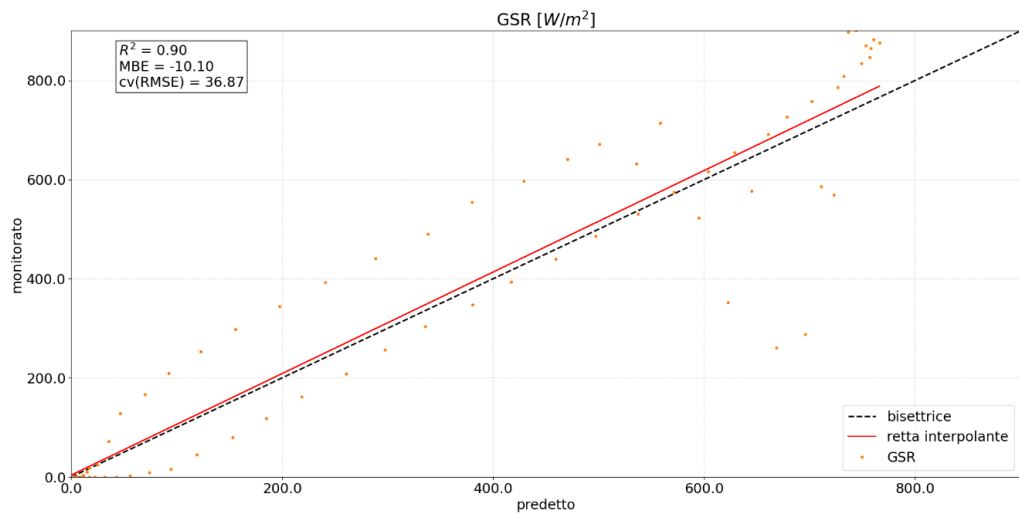


Figure 38 GSR Forecast with GRU

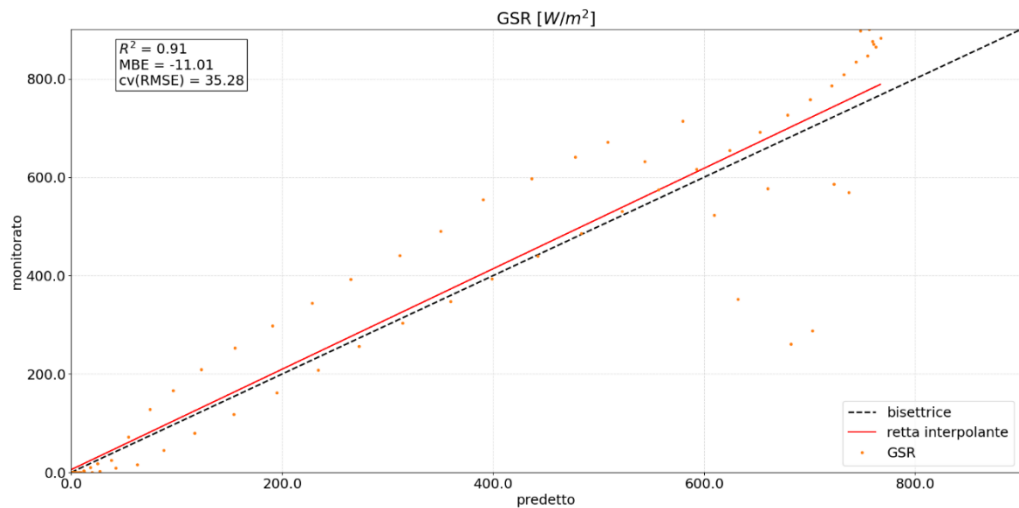
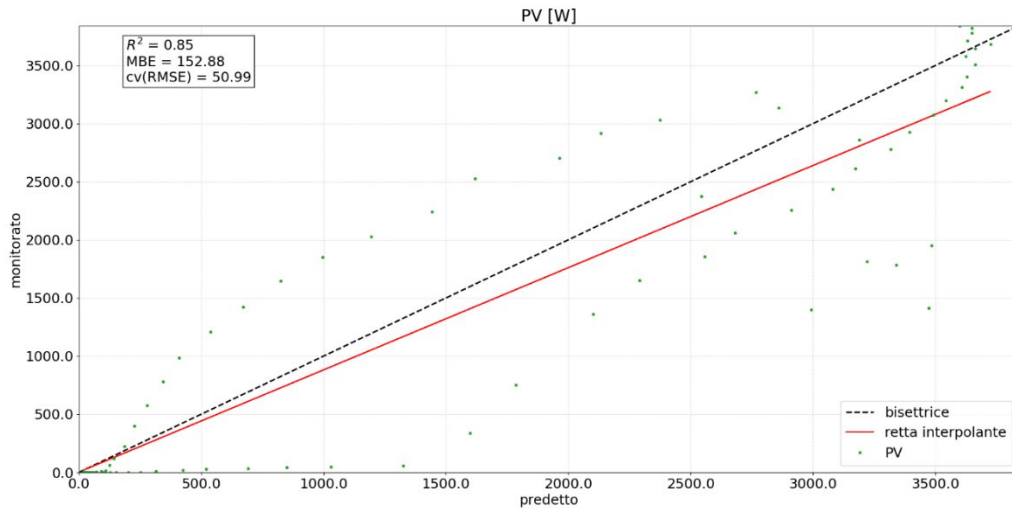


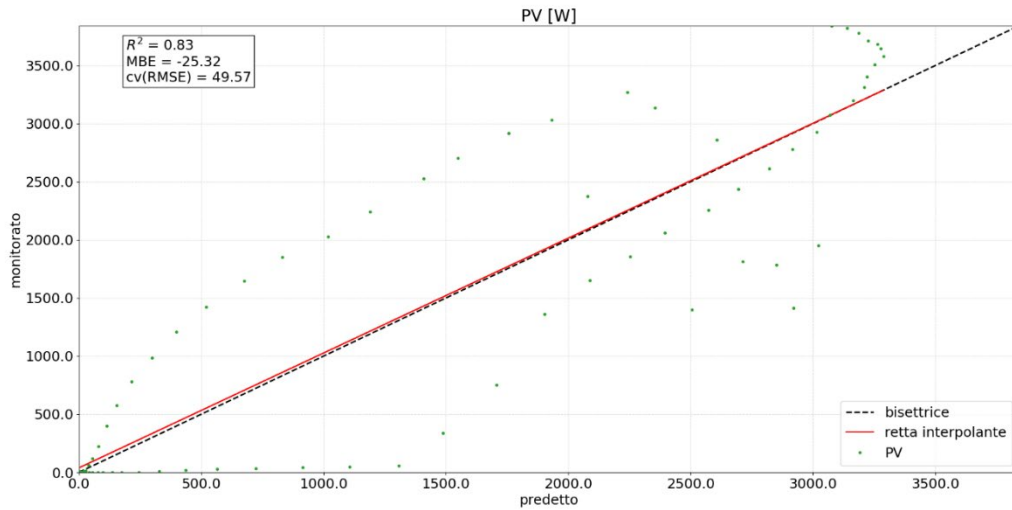
Figure 39 GSR Forecast with LSTM

PV variable presented the greatest predictive complexities, reflecting the composite and non-linear nature of the energy conversion process. Here, a significant trade-off emerged between the two architectures (Figures 40 and 41):

- GRU: Achieved a superior R^2 (0.85 vs 0.83 for the LSTM). However, this result came at the cost of a very marked positive bias (MBE) (+152.88 W), indicating a structural and problematic tendency to overestimate.
- LSTM: Despite a slightly lower explanatory power (R^2 of 0.83), it exhibited much more controlled bias behavior, with a contained negative MBE (-25.32 W). This renders the LSTM's average estimation more reliable.
- CV(RMSE): The relative error was high for both (LSTM: 49.57%, GRU: 50.99%), confirming the difficulty of the task.



- Figure 40 PV Forecast with GRU



- Figure 41 PV Forecast with LSTM

The bias analysis revealed a systematically different behavior: the GRU shows a propensity for overestimation (especially for PV), whereas the LSTM is more conservative (slight underestimation for GSR and PV). This divergence was attributed to architectural differences: the simplified gates of the GRU seem to follow positive trends more aggressively, while the more complex structure of the LSTM (with its dedicated cell state) allows for finer control of the information flow.

The high error (CV(RMSE)) in PV production reflects an intrinsic challenge in neural modeling: handling critical transitions (dawn and dusk). Photovoltaic power

exhibits "first-kind" discontinuities at these points (production ceases or commences abruptly). The standard activation functions of neural networks (such as ReLU, sigmoid, tanh), which are continuous and differentiable, inherently struggle to model these instantaneous transitions.

Indeed, the error analysis showed recurring patterns:

- A systematic overestimation in the 30-60 minutes preceding sunset.
- A systematic underestimation during the first minutes of morning production.
- A lag in predicting the exact instant of production onset and cessation.

Finally, it was highlighted that hardware limitations (the absence of dedicated GPUs with > 8GB of memory) precluded the exploration of more complex architectures, which could have potentially led to better results.

4.2.3 Conclusions

The challenge of solar forecasting was addressed through a dual approach: a critical analysis of the scientific literature and the development of a multivariate experimental case study

The literature review clearly revealed that neural networks, particularly recurrent (LSTM, GRU) and hybrid architectures (CNN-LSTM, models with attention mechanisms), represent the state-of-the-art in this domain. They overcome the limitations of traditional physical and statistical models in capturing non-linear relationships and complex patterns. The evolutionary trend is towards increasingly specialized models, automatically optimized and equipped with attention mechanisms to maximize accuracy, especially for very short-term horizons.

The experimental case study yielded significant results. The systematic comparison between LSTM and GRU confirmed the excellent predictive capability of both models for temperature (T) and Global Solar Radiation (GSR), thereby

validating the robustness of the multivariate approach. However, for the most critical and complex variable, photovoltaic (PV) production, specific behavioral traits emerged: the GRU exhibited a tendency for overestimation, whereas the LSTM showed a more contained bias. The high error observed for PV, concentrated during the transition phases (dawn and dusk), confirmed an intrinsic challenge for data-driven models, linked to the physically discontinuous nature of the production function.

In conclusion, this work confirms the potential of recurrent neural networks as a reliable tool for decision support in smart energy management. The choice between architectures such as LSTM and GRU is not a matter of absolute superiority, but rather a trade-off between accuracy R^2 , bias stability (MBE), and computational efficiency. This trade-off must be carefully evaluated based on specific application requirements.

Solar Power Forecasting is transforming the role of energy in the building sector. It is no longer a tool reserved solely for system operators but a fundamental technology for every building equipped with a photovoltaic system. The ability to accurately predict solar generation is the essential prerequisite for optimizing self-consumption, intelligently managing storage systems, reducing energy costs, and minimizing environmental impact.

The evolution towards increasingly sophisticated AI models, combined with more powerful and accessible hardware, is making these technologies ready for mass adoption. Through forecasting, the building ceases to be a passive island in the energy system and becomes an intelligent, flexible, and proactive "prosumer"—a fundamental building block for constructing the smart grids and sustainable cities of the future. Future research trajectories must explore hybrid architectures specifically designed to manage discontinuities, differentiated attention mechanisms, and the integration of physics-informed knowledge within learning models.

4.3 Impact of glazing system on the energy performance of a nZEB under climate change scenarios

For the purposes of this study, a nearly zero-energy building (nZEB) situated in a typical Mediterranean climate was selected as the case study. Specifically, the building, located in Benevento, is designated as BnZEB (Figure 42a). This case study was chosen as it represents a real experimental laboratory of the University of Sannio in Benevento.

The building envelope comprises cross-laminated timber with two layers of fiber-wood insulation of varying densities. The windows are double-glazed units with argon-filled cavities, low-e coatings, and PVC frames.

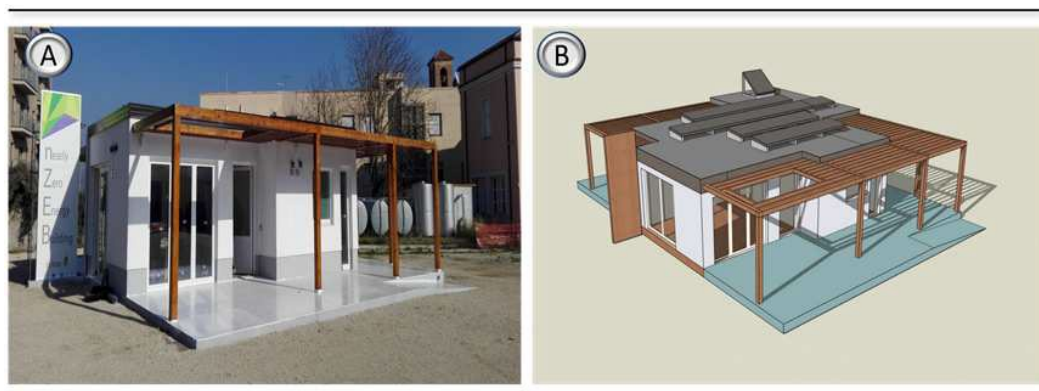


Figure 42 a) Real case study; b) Building simulation model

An air-source heat pump provides heating, cooling, domestic hot water, and mechanical ventilation, incorporating an internal filter and active thermodynamic heat recovery.

A comprehensive description of the technical solutions has been previously detailed by Ascione et al. [73]. The authors also presented the development and validation of the BnZEB numerical model (Figure 42b). In brief, DesignBuilder [63] was used for graphical construction, and simulations were performed with EnergyPlus [62]. The simulation outputs were then compared with monitored data

(both consumption and indoor parameters) following the methodology outlined in the M&V Guidelines [102].

4.3.1 Methodological approach

For this case study, a weather file (.epw extension) was created directly from meteorological data collected between 2015 and 2020. This data was monitored by a weather station located on the roof of the MATRIX test-room, approximately 7.20 meters above ground level [143], in the urban center of Benevento (41°07'54.1"N, 14°47'03.7"E).

As detailed in [121], a typical meteorological year (TMY) was derived from this data using the Sandia method [144]. Furthermore, two future climate projections were generated, starting from the TMY. The CCWorldWeatherGen [145] weather generator, provided by the University of Southampton, was employed. Medium-term (2041-2070, '2050s') and long-term (2071-2100, '2080s') climate projections were generated, denoted as CC_MT and CC_LT, respectively.

The primary objective of this paper is to assess the building's response to current and future solar radiation levels by varying the glazing system. Eight glazing models were evaluated, encompassing double and triple glazing with argon or air fills, clear or tinted glass, and static or dynamic behavior (Table 9).

Initially, using the TMY results, comparisons were made in terms of heating and cooling energy needs, as well as the percentage change in the building's total primary energy consumption (ΔEP).

For the future climate projection results, comparisons of heating and cooling energy needs were presented from a dual perspective, relevant to building designers: for the design of a new nearly zero-energy building (ΔH_n and ΔC_n) and for a retrofit intervention on an existing building (ΔH_r and ΔC_r).

In the former case, for each alternative glazing solution, the energy needs in the medium and long-term scenarios were compared to the same building configuration simulated using the TMY. In the latter case, comparisons were made relative to the existing building (Base Case) evaluated under current climatic conditions (TMY).

<i>Variable</i>	<i>ID</i>	<i>Description</i>
<i>Glazing type</i>	<i>Base Case</i>	Clear low-e double glazing, 3/13/3, Argon: $U_g \approx 1.1 \text{ W/(m}^2\text{K)}$, $g=0.58$.
	<i>D_C 3-13 Arg</i>	Clear double glazing, 3/13/3, Argon: $U_g \approx 2.56 \text{ W/(m}^2\text{K)}$, $g=0.76$.
	<i>D_B 6-13 Arg</i>	Colored (blue) double glazing, 6/13/6, Argon: $U_g \approx 2.51 \text{ W/(m}^2\text{K)}$, $g=0.49$.
	<i>D_LESSC 6-13 Arg</i>	Clear low-e, selective spectral double glazing, 6/13/6, Argon: $U_g \approx 1.34 \text{ W/(m}^2\text{K)}$, $g=0.42$.
	<i>D_CLI 3-13 Arg</i>	Clear low-iron double glazing, 3/13/3, Arg, $U_g \approx 2.56 \text{ W/(m}^2\text{K)}$, $g=0.83$.
	<i>T_C 3-13 Arg</i>	Clear triple glazing, 3/13/3/13/3, Argon: $U_g \approx 1.62 \text{ W/(m}^2\text{K)}$, $g=0.69$.
	<i>T_LEC 3-13 Arg</i>	Clear low-e triple glazing, 3/13/3/13/3, Argon: $U_g \approx 1.06 \text{ W/(m}^2\text{K)}$, $g=0.58$.
	<i>T_LEFC 3-13 Air</i>	Low-e triple glazing with polyester film (88), 3/13/3/13/3, Air: $U_g \approx 1.30 \text{ W/(m}^2\text{K)}$, $g=0.58$.
	<i>Thermochromic</i>	Thermochromic triple glazing, 6/6/6/6/6, Air: $U_g \approx 2.13 \text{ W/(m}^2\text{K)}$, solar trasmission from 0.68 (@24°C) to 0.33 (@75°C).
<i>Shield</i>	<i>Internal</i>	Blind with high reflectivity slats with seasonal schedule
	<i>External</i>	Horizontal protrusions, 1.0 m Overhang

Table 9 Design variables

4.3.2 Results

Figure 43 shows the simulation results with the replacement of glazing type in the current conditions (TMY file). In terms of heating and cooling energy demand, the most significant variations compared to the Base Case (with low-e double

glass) are observed with the solutions identified as D_B 6-13 Arg, D_LESSC 6-13 Arg, and Thermochromic.

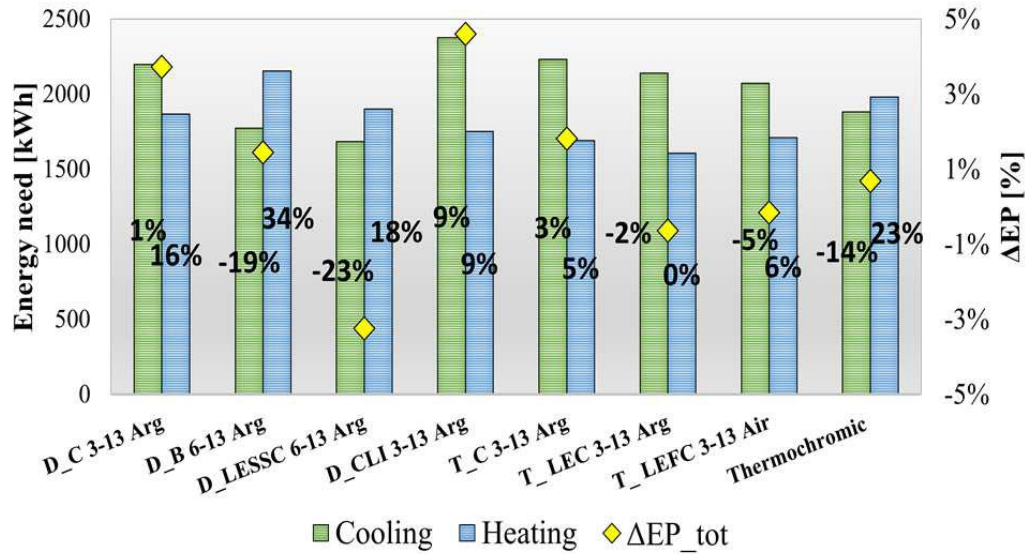


Figure 43 Energy simulation results with current climate file (TMY)

As reported in Table 9, colored double glass (D_B 6-13 Arg) is particularly opaque to solar radiation ($g=0.49$). Furthermore, it has a high thermal transmittance value, equal to $2.51 \text{ W}/(\text{m}^2\text{K})$. Therefore, the reduced incoming solar gains and the low level of thermal insulation cause the greatest percentage increase in the energy need for heating (+43%). Compared to the Base Case, the percentage variation of total primary energy is negligible. Thermochromic coating changes its colour by varying its crystal structure above a particular environmental temperature. In detail, solar transmission of this glass varies between 0.68 at 24°C to 0.33 at 75°C . The observed results show that the glazed surfaces, in the current climate conditions (TMY), are characterized, due to their exposure, by incoming solar radiation for many hours even in the winter months. Consequently, the thermochromic coating is also activated in the heating period and hinders solar gain. The energy need for heating increases by 29% and the cooling one decreases by 14%. These percentage variations have a negligible effect on the total primary energy demand of the building. The spectral selective double glass, unlike thermochromic glass, is a static solution. However, in the climate conditions under

investigation, the solution D_LESSC 6-13 Arg minimizes the solar gain in the cooling period, since it is characterized by the lower value of the solar factor ($g=0.42$). Furthermore, the thermal transmittance of this solution is equal to $1.13 \text{ W/m}^2\text{K}$ and it involves a lower increase in the energy need for heating, compared to thermochromic glass. Compared to the Base Case, heating energy need increases by around +18% and cooling energy need decreases by -23%. Consequently, on an annual basis, an overall reduction in total primary energy of about 3% is observed.

Low-iron double glass (D_CLi 3-13 Arg) is a type of high-clarity glass that is made from silica with very low amount of iron. This type of glass allows the passage of light radiation and the solar gains. Indeed, with the application of this component, the maximum increase in energy need for cooling is observed, compared to the Base Case (+9%). At the same time, despite the maximum value of the solar factor ($g=0.83$), this glass is affected by its low level of thermal insulation ($U_g=2.56 \text{ W/m}^2\text{K}$) and leads to an increase of 12% of the energy need for heating. Solutions with triple glazing do not lead to significant improvements or worsening of energy needs for heating and cooling. However, the solution identified as T_LEC 3-13 Arg is the only one that leads to a negligible variation in the heating energy need, with a percentage decrease of cooling energy need, approximately equal to -2%. In terms of total primary energy, the maximum percentage increase, with respect to the Base Case, was observed with the solution identified as D_CLi 3-13 Arg (+5%).

Therefore, the observed variations are comparable but with less impact with glasses based on solar gains control. This effect, albeit minimal, is positive as the transition to a climate dominated by cooling is predictable for Benevento in future. In particular, the building resilience in relation to possible future climate change was assessed on the basis of two points of view, both for a new building and for the energy retrofit of an existing building. In the first case, for each solution simulated with CC_MT (2050s) and CC_LT (2080s), the percentage variations of the energy requirements, ΔH_n and ΔC_n respectively, were assessed with respect to the same solution simulated with TMY. In the second case, all the alternative solutions simulated with the future climate projections were compared with the Base Case

simulated with TMY. The findings are shown in Figure 44 and Figure 45 for the medium-term and long-term scenario, respectively.

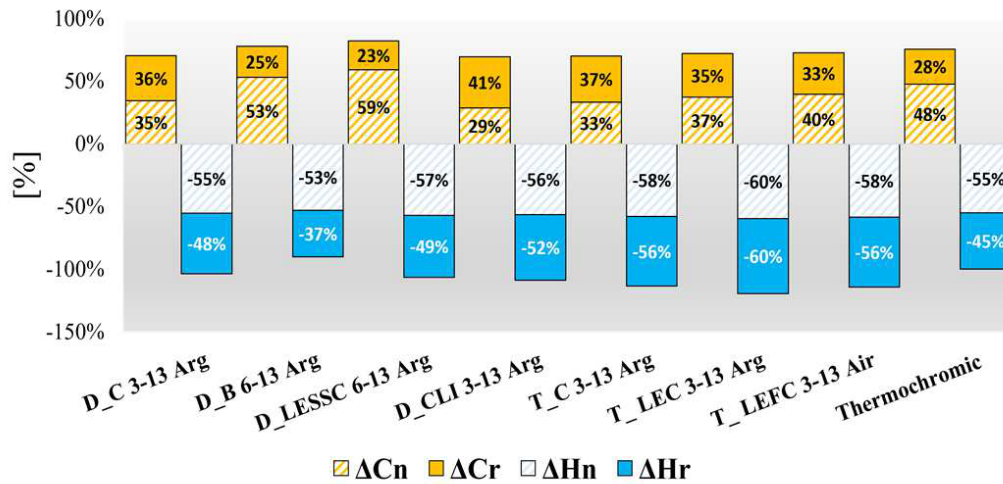


Figure 44 Percentage variations in energy needs for heating and cooling - CC_2050.

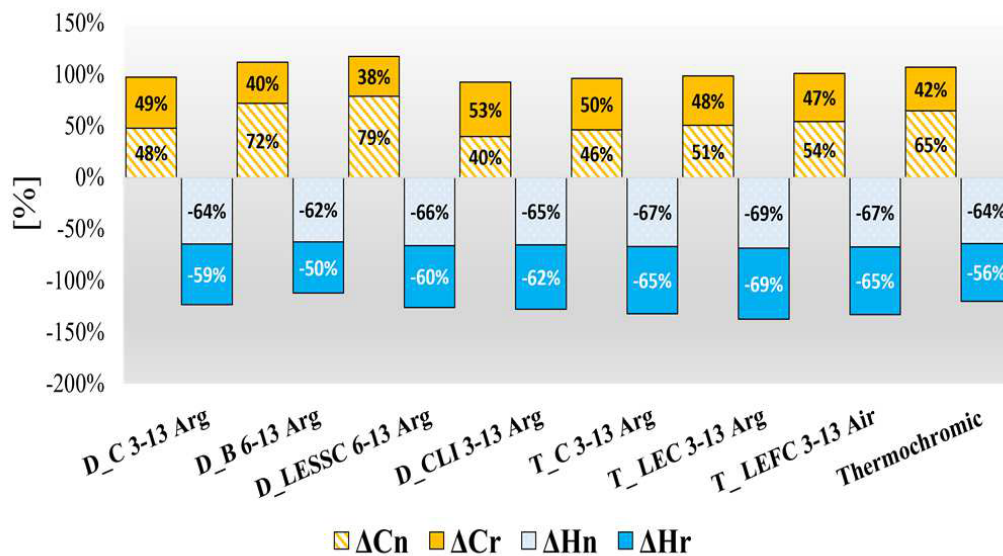


Figure 45 Percentage variations in energy needs for heating and cooling - CC_2080.

From the point of view of new construction and energy retrofit, climate change favors the building resilience in winter season with all glazing types considered. On average, with CC_MT and CC_LT, both ΔH_n and ΔH_r are equal to -56% and -66%, respectively. Some interesting observations can be made in terms of energy needs

for cooling. First of all, no solution has an adaptive behavior with respect to climate change. However, different mitigating effects of the increased internal overheating were found. In this sense, thermochromic glass surprises most of all. This dynamic component, compared to the current climate condition (TMY), proves not yet able to improve the obstruction of further solar gains due to higher levels of temperature and solar radiation in the future. Moreover, the designer could make different choices depending on the point of view adopted. Indeed, although the goal is to minimize energy needs and, therefore, the total primary energy of building, different observations can be made in terms of the resilience of the alternative solutions proposed with respect to the expected climate change. In the perspective to design a new building, ΔC_n is around +42% and +57% with CC_MT and CC_LT, respectively. In particular, the maximum percentage increase was observed with the solutions identified as D_LESSC 6-13 Arg and D_B 6-13 Arg, with which ΔC_n is about 59% and 53%, respectively, at 2050. As shown in Figure 46, this result is also confirmed in terms of energy need for cooling (ΔE_c). Taking the time horizon to 2050 as a reference, the maximum value is observed with the spectral selective double glazing (+995 kWh). The second highest increase is that with colored double glazing (+944 kWh), while the minimum increase was observed with the solution called D_CLI 3-13 Arg (+687 kWh).

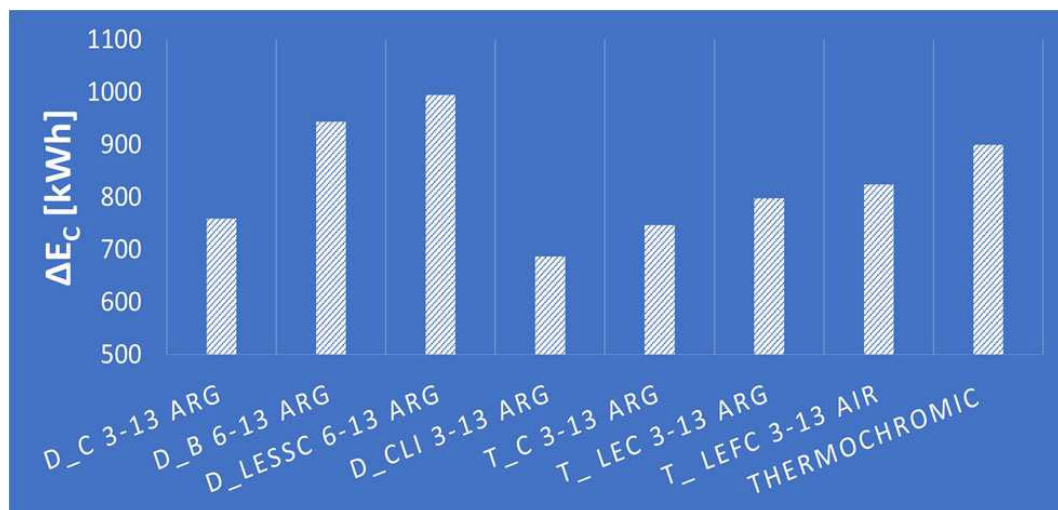


Figure 46 Difference (kWh) in energy need for cooling.

The explanation for these observations may lie in the fact that optimized solutions to favor solar gains are less affected by the transition to a cooling-dominated climate. On the contrary, climate change would seem to penalize static glasses opaquer to solar radiation, such as the spectral selective and the double colored one. This result allows to understand the importance of building resilience. The same findings lead to different conclusions when the aim is the design of energy retrofit. Taking Base Case simulated with TMY as reference, with CC_MT the energy need for cooling increases by 9% with D_LESSC 6-13 Arg and by 10% with D_B 6-13 Arg. These are the lowest observed percentage differences. The maximum percentage increase was observed with low-iron double glazing with low ferrous content. The same is true with CC_LT. In this case the energy need for cooling increases of 15% and 16%, respectively with D_LESSC 6-13 Arg and D_B 6-13 Arg. Instead, with the application of D_CLI 3-13 Arg the maximum percentage increase in the cooling energy demand becomes approximately of 40%. With reference to the transparent envelope of a real nZEB, the global relevance of the main results observed is that the analysis of the building resilience with respect to climate change may not always favor the choice of the most efficient solution to reduce energy demand. A more efficient solution under current climate conditions may perform worse due to climate change. However, although the legislations of European Countries impose the nZEB target for new buildings, the decarbonization goal mainly depends on the retrofitting of existing buildings. In this sense, the study shows that, if the solution is a static glass, the effects of climate change could have less influence on the analysis of the best solutions. However, further advances in numerical modeling of dynamic glasses are needed to be able to make reliable comparisons with static solutions.

4.3.3 Conclusions

Achieving decarbonization goals necessitates meticulous design of nearly zero-energy buildings, considering both current and projected climatic conditions. This paper evaluates the resilience of design choices for the BnZEB, a nearly zero-energy building in Benevento, Southern Italy. Under current climatic conditions, the impacts of various static glazing types on heating and cooling energy needs are diverse. The maximum reduction in primary energy was observed with spectral selective low-e double glazing ($\Delta EP \approx -3\%$). When analyzing future climates, minimizing primary energy is closely tied to controlling cooling energy demand. For retrofit interventions, D_LESSC 6-13 Arg and D_B 6-13 Arg are the most effective static solutions, resulting in ΔCr values of approximately 25% and 23%, respectively, by 2050. Spectral selective low-e double glazing consistently minimizes cooling energy demand under both current (TMY) and future (CC_MT and CC_LT) climate conditions. This static solution effectively optimizes solar gain and heat loss control. However, despite the potential shift towards a cooling-dominated climate in Benevento, this glazing exhibits the lowest resilience, showing the highest kWh increase in cooling energy demand ($\Delta E_c \approx 995 \text{ kWh}$) when compared to simulations under current climate conditions (TMY). Future developments of this study may involve analyzing the short and long-term effects on the BnZEB's energy balance and indoor comfort. For instance, the examined glazing types could be compared in terms of variations in building electricity self-consumption and discomfort hours.

4.4 Effect of degradation and size selection for the photovoltaic system installed in a nearly zero energy building in Tropical Climate

The case study was modeled using a previously calibrated model based on experimental data from Benevento [73]. In terms of systems, the building is served by a compact heat pump system that addresses heating, cooling, domestic hot water, and mechanical ventilation requirements. To further optimize on-site renewable resource utilization, the system incorporates geothermal probes, solar collectors, circulation pumps, and thermal storage tanks for pretreating incoming air. For this analysis, the building includes a rooftop photovoltaic (PV) system connected to the grid and 6.5 kWh storage batteries via a SOLAX SK-TL(SU)5000 inverter, boasting a maximum efficiency of 97.6%. The PV system comprises 16 SunFortePM096B00 BenQ monocrystalline silicon panels, each with a peak power of 330 W and an efficiency of 20.3%.

4.4.1 Methodological approach

This analysis utilized dynamic building simulation, employing the EnergyPlus simulation engine with the DesignBuilder graphical interface, to assess a building classified as nZEB in the tropical climate of Santo Domingo.

The methodological approach builds upon the study by De Masi et al. [146], adapting it to the tropical climate of Santo Domingo. Initially, the building's energy balance was analyzed using the available Santo Domingo climate file, focusing on the percentage of self-consumption ($SELF_{el}$) relative to total energy demand ($E_{el,tot}$) and photovoltaic (PV) electricity generation (GEN_{el}).

Subsequently, short-term (2030s), medium-term (2050s), and long-term (2080s) climate scenarios were considered. The medium- and long-term climate files were generated using the CCWorldWeatherGen generator, based on the current climate file for the short-term scenario. These projections adhere to the A2 family scenarios from the IPCC's Third and Fourth Assessment Reports, which depict a world with high population growth, economic development, and fossil fuel reliance, leading to significant greenhouse gas emissions and climate change impacts.

A PV system degradation rate of 0.8%/year was applied [147]. The Performance Ratio (PR) was used to evaluate PV system performance, calculated using Equation 1:

$$PR = \frac{Y}{\frac{G_i}{G_{STC}}} \quad (1)$$

where Y is the specific efficiency (energy produced per rated power), G_i is the global tilted irradiance, and G_{STC} is the incident radiation at standard test conditions (STC). For long-term analyses, PV system replacements every 20 years were incorporated. To account for the environmental impact of PV degradation, the penalty index on operational carbon dioxide equivalent emissions (IP_{OE}) was calculated using Equation 2:

$$IP_{OE} = \frac{SELF_{PV,nDEG} - SELF_{PV,DEG}}{SELF_{PV,nDEG}} \quad (2)$$

where $SELF_{PV,nDEG}$ is on-site electricity consumption without considering PV degradation, and $SELF_{PV,DEG}$ is on-site electricity consumption with degradation.

Three PV system sizes were evaluated, reflecting varying south-facing roof availability: 5.28 kWp (maximum), 1.98 kWp (minimum), and 3.60 kWp (average).

For each scenario, the annual ratio of self-consumed energy to required energy was calculated. This ratio, according to national and international standards, should generally exceed 50%. Finally, to determine if the building qualifies as a Positive Energy Building (PEB), the number of months with production exceeding consumption was calculated.

The overall methodological approach is summarized in Figure 47.

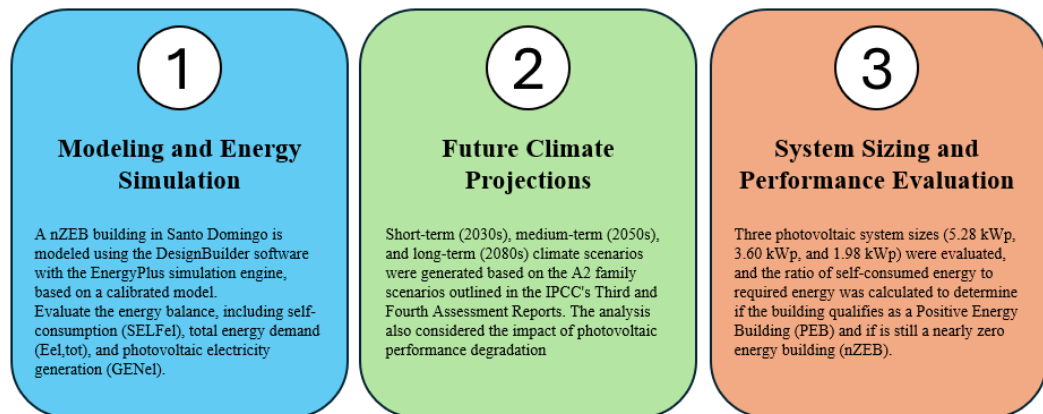


Figure 47 Methodological approach

4.4.2 Results

Figure 48 illustrates the results for electricity consumption (Eel,tot), PV generation (GENel), and self-consumption (SElFel). The building exhibits lower energy values during winter, with a minimum generation of 559 kWh in November, and higher values during summer, peaking at approximately 784 kWh in August. Electricity consumption shows a significant increase in summer due to cooling demands, with monthly summer demand exceeding four times the demand in other months. Self-consumption trends mirror these consumption patterns.

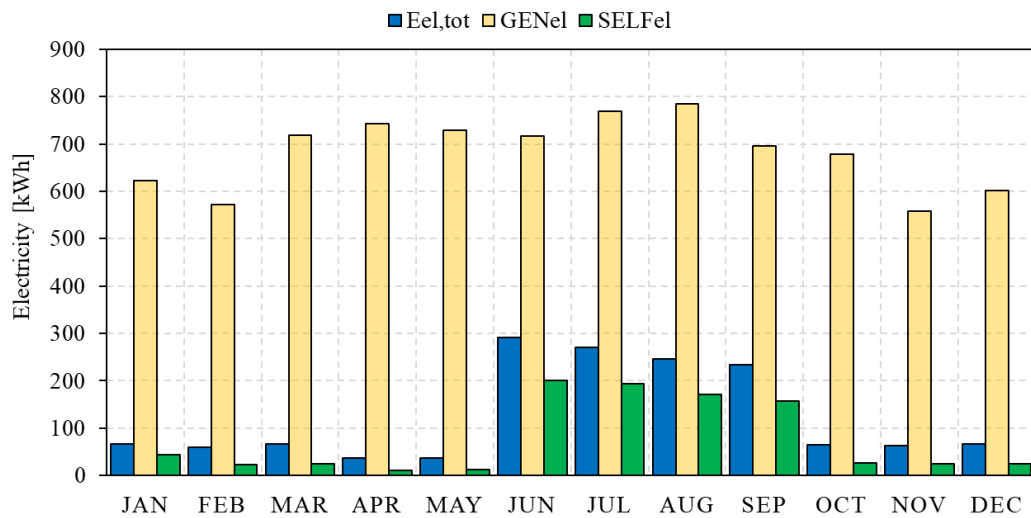


Figure 48 Building energy balance

Figure 49 depicts the changes in operational emissions considering PV degradation. By the 2050s, approximately 30 years from now, the PV system is expected to reach its end-of-life. In the 2080s, the system is assumed to be replaced, maintaining the short-term (2030s) performance. Medium-term analysis reveals notably higher penalties, potentially resulting in a 6% increase in operational emissions due to PV degradation. Long-term projections show slightly reduced penalties compared to the medium term, possibly due to decreased winter consumption from rising outdoor temperatures and increased PV productivity from higher solar radiation.

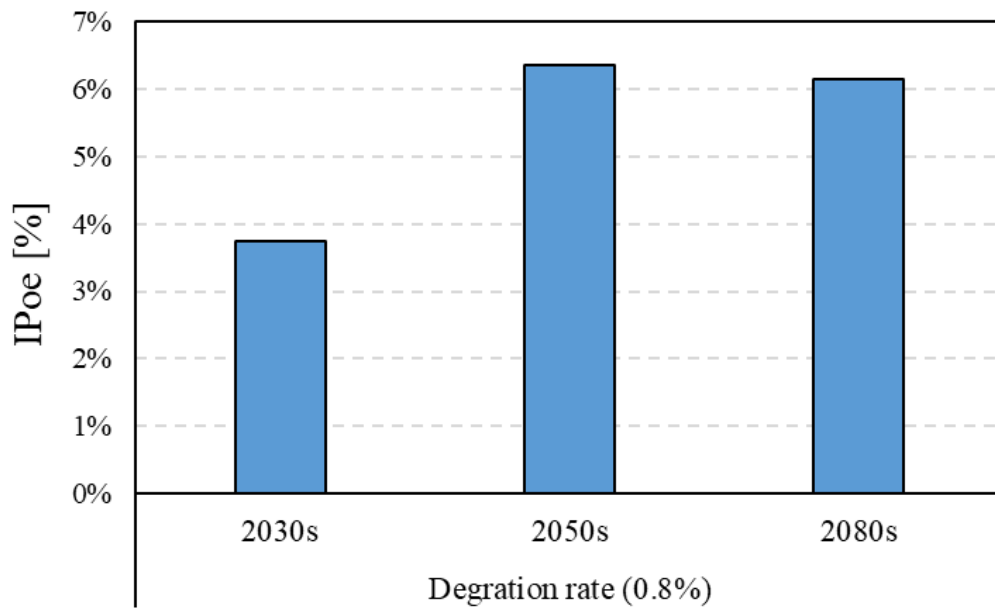


Figure 49 Penalty index on the building's operational carbon dioxide equivalent emissions

The results for varying PV system sizes in Santo Domingo, considering performance degradation, are shown in Figure 50. The electrical self-consumption analysis indicates the building consistently meets the nZEB target with the actual (5.28 kWp) or average (3.60 kWp) rated PV power. Despite potential operational emission shortcomings, the actual PV output ensures continuous efficiency. However, in the short-term projection, only the minimum installable power (1.98kWp) achieves nZEB classification, with a ratio of 51.35%.

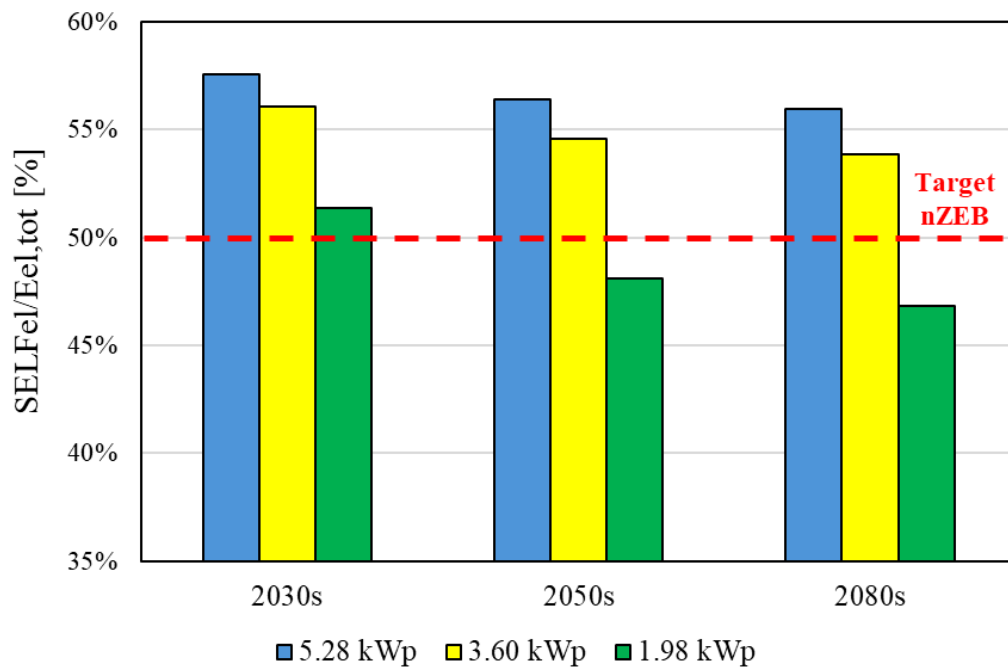


Figure 50 the nZEB target

Across future projections, a percentage decrease in on-site renewable consumption is observed. However, with the same rated power, results remain comparable. This equilibrium reflects the impacts of global warming, particularly the anticipated shift towards increased cooling demands in Santo Domingo. Consequently, temperature and solar irradiance variations similarly affect renewable energy production, self-consumption, and building electrical demand in each scenario.

Finally, Figure 51 presents the analysis results for potential Positive Energy Building (PEB) classification. With the maximum installed capacity (5.28 kWp), electrical production consistently exceeds consumption for all 12 months, across all climate scenarios. This is also true for the average installed power (3.60 kWp). However, with the minimum power (1.98 kWp), the number of months with surplus production slightly decreases in the medium and long-term projections. This reflects the interplay between negative effects from degradation and positive effects from increased solar radiation due to climate change.

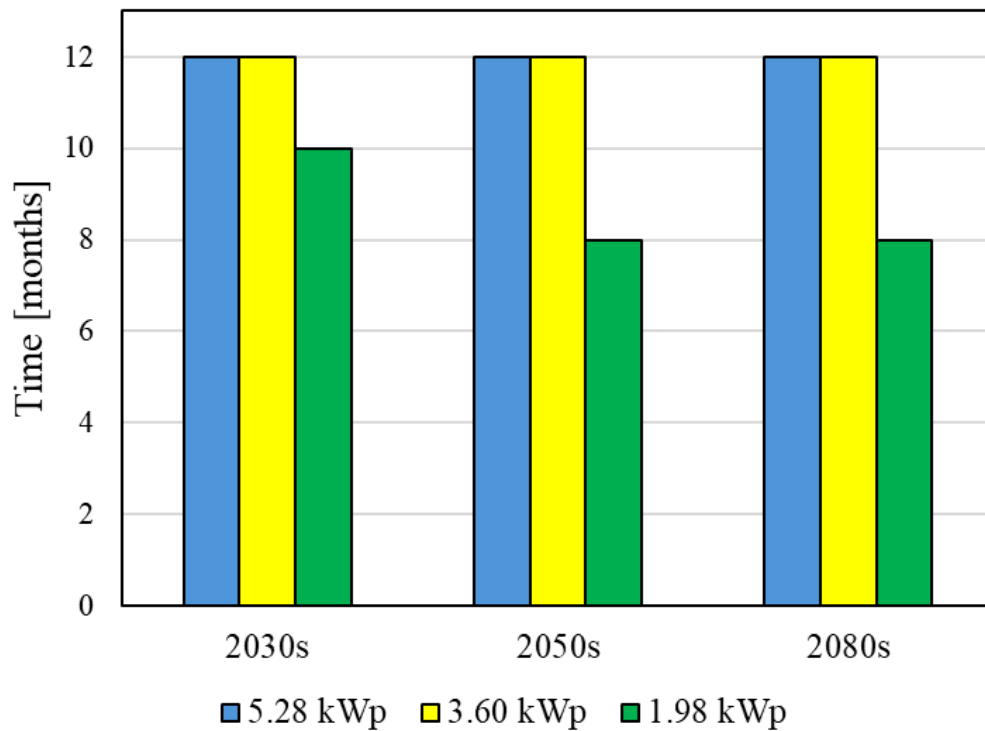


Figure 51 Number of months in which generation exceeds demand

4.4.3 Conclusions

This study comprehensively assessed the benefits of photovoltaic (PV) system installation in buildings located in Santo Domingo. Through dynamic simulations and short, medium, and long-term future climate projections, energy balances were analyzed, considering optimal system sizing and PV panel aging-related performance degradation. The results indicate that, despite degradation, the building maintains adequate electrical self-consumption to qualify as a nearly Zero Energy Building (nZEB), particularly with higher or average rated PV power. However, panel degradation leads to increased operational emissions, especially in intermediate periods, highlighting the need for maintenance or replacement strategies throughout the system's lifespan. Furthermore, the analysis revealed a shift in the building's energy dynamics due to global warming, specifically an increased energy demand for cooling. The building's potential classification as a

Positive Energy Building (PEB) was also evaluated. Results show that with higher or average installed PV power, the building can produce more energy than it consumes annually, regardless of climate scenarios. However, lower power installations result in a decrease in the number of months with surplus production, indicating that installation size is a crucial factor for PEB classification. Overall, this study provides valuable insights for the design and optimization of PV systems in tropical urban environments, emphasizing the necessity to consider not only current system performance but also long-term degradation and future climate conditions.

4.5 Sensitivity analysis on the energy performance evaluation of buildings designed as nearly zero energy in the current climatic scenario and climate change evolution

The design of building refurbishment is usually based on the adoption of simulation tools that require an input weather file. The type of adopted methodology, the site and the period of monitored data as well as the emissions scenarios due to climate change, influence the simulation' results and thus the evaluation of the resilience of the efficiency measures selected for the refurbishment. With a complete statistical and critical approach, the research analyzes the importance of these aspects by means of a case study simulated in several cities representative of all Italian climatic zones.

The resilience of the building is evaluated by comparing the energy performance provided by the current scenarios and by the weather file projections but also different tools for simulating the energy performance. The discrepancy in the external forcing modifies the evaluation of the benefit of a proposed measure mainly when it influences the radiative exchange and the control of solar inner gains.

4.5.1 Methodological approach

The case study is the same of 3.2 subchapter. It involves an existing condominium in Biccari, a small town in southern Italy. This town falls within climatic zone D (warm and temperate), with 1926 heating degree days (HDD), and its winter design temperature is -2.54°C.

The energy assessments were conducted in accordance with European and Italian regulations and technical standards. The energy simulations were performed using TerMus BIM [59]. To evaluate the different results obtainable by applying the same efficiency measures in different climatic zones, several simulations were performed for the following cities: Porto Empedocle (Climatic Zone A – 579 HDD), Reggio Calabria (Climatic Zone B – 772 HDD), Benevento (Climatic Zone C – 1316

HDD), Biccari (Climatic Zone D – 1926 HDD), Torino (Climatic Zone E – 2617 HDD), and Cuneo (Climatic Zone F – 3012 HDD). The simulation was done considering both data for semi-steady-state and evaluation under current climate as proposed by the Italian normative but also considering some future climate projections are also generated on medium-term (2050s) considering different global circulation models emission scenarios. The same was done using the hourly dynamic simulation under both current weather conditions and medium-term (2050s) projections. The climate projections are generated starting from the outputs of general / global circulation models (GCMs) or Regional Climate Models (RCMs) and take into account the emission scenarios of the third and fourth IPCC (SRES) or the Representative Concentration Pathways (RCP) reports) of the fifth IPCC report (AR5). The RCP scenarios are based on a different approach to SRES scenarios and “they are not necessarily more capable of representing future developments than the SRES scenarios”. Each RCP represents a different trajectory of GHGs emissions, shaped by various factors such as population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy. The proposed approach considers two paths:

- RCP 4.5 (intermediate scenario): moderately reduced GHGs emissions reveal a future with some mitigation measures but are not as stringent as RCP 2.6.
- RCP 8.5 (high emissions scenario): it represents a future with very limited climate policies and very high global emissions of radiatively active substances, promoting a substantial environmental impact.

To make the desired evaluations, the following energy and environmental indices were considered:

- $EP_{gl,tot}$: The overall building energy performance index, corresponding to the total primary energy requirement per unit of surface area for

heating, domestic hot water, and, potentially, cooling under standard usage conditions (kWh/m²year).

- $EP_{h,tot}$: The building's heating energy performance index, corresponding to the total primary energy requirement per unit of surface area for heating under standard usage conditions (kWh/m²year).
- $EP_{c,tot}$: The building's cooling energy performance index, corresponding to the total primary energy requirement per unit of surface area for cooling under standard usage conditions (kWh/m²year).
- $EP_{h,nd}$: The building's heating needs, corresponding to the total energy required for heating under standard usage conditions (kWh/m²year).
- $EP_{c,nd}$: The building's cooling needs, corresponding to the total energy required for cooling under standard usage conditions (kWh/m²year).
- ISI: The investment-saving index, defined as the ratio between the investment cost and the annual savings in total primary energy (€ year/kWh).

The analysis of variation of these indicators between the state of fact and the refurbished configuration is made by considering three approaches. The first one, according a traditional method, consists in the calculation of the energy saving considering in both simulations the same weather file; for instance, the base case simulated in the current scenario, for the prevision of the energy improvement, with the refurbished configuration simulated with the current scenario. More in detail, in the discussion, $\Delta EP_{gl,tot}$ will be the primary energy saving considering only the heating and cooling services; $\Delta E_{h,tot}$ and $\Delta E_{c,tot}$ will indicate the reduction of the primary energy for heating and cooling meanwhile $\Delta E_{h,nd}$ and $\Delta E_{c,nd}$ the reduction of the energy need for heating and cooling respectively. In this case, the designer can know the effect of considered efficiency measures on the near term and that is, until the environmental conditions can be described with the weather file, without considering extreme events or climate changes.

The second approach, more appropriate for the evaluation of the resilience of designed interventions, is based on the estimation of the energy saving on the long term; this means that the base case simulated under current climate is compared with the refurbished scenarios simulated with the weather file created by projections of climate change. For this discussion, $\Delta EP_{cl,ch}$ will be the primary energy saving considering only the heating and cooling services; $\Delta E_{H,cl,ch}$ and $\Delta E_{C,cl,ch}$ indicate the reduction of the primary energy for heating and cooling meanwhile $\Delta E_{h,nd}$ and $\Delta E_{c,nd}$ the reduction of the energy need for heating and cooling respectively. This type of comparison which is not common in the scientific literature and in the design approach, can be helpful for understanding if the choices done considering the current climatic conditions will be also appropriate to respond to climate changes. In other words, the aim is to find a method for evaluating the resilience of a refurbishment design that can guide the choices of designer and owner thinking about the building of the future, without necessarily requiring further interventions.

Finally, the third approach involves performing simulations using hourly dynamic calculation carried out with the ACCA Termus-Plus software, which is based on the EnergyPlus calculation engine. This type of simulation only considers the heating ($Ep_{h,nd}$) and cooling ($Ep_{c,nd}$) demands, focusing on the variations caused by the envelope retrofitting and how climate change affects the effectiveness of the building interventions. Furthermore, it aims to verify whether the results obtained with the semi-steady-state calculation stipulated by the standard are confirmed by a more complex calculation that is closer to reality, such as the hourly dynamic one. The BIM model created with ACCA Termus BIM was imported into the ACCA Termus Plus software to ensure the envelope was modeled as similarly as possible between the two calculation methodologies. The winter and summer setpoint temperatures were fixed at 20°C and 26°C, respectively. Apart from this, however, the hourly dynamic calculation required a larger number of inputs. Specifically, an air change rate value with a $DPa=50P$ of 8 vol/h was entered for both the pre- and post-retrofit scenarios (the semi-steady-state method required

by the standard does not account for the air permeability of the envelope in the case of natural ventilation, so the same condition was replicated in this model). Additionally, the use of window shading devices was configured to reduce energy entry to a maximum value of 300 W/m². Regarding internal gains, a value corresponding to that stipulated by the standard for the semi-steady-state method was entered for both the Pre- and Post-retrofit scenarios.

4.5.2 Results

The data presented in the table 10 reveals a crucial dual-effect of the energy retrofit according to the traditional approach. First of all, as expected, the post-retrofit configuration shows a drastic reduction in the primary energy needed for heating ($\Delta E_{h,tot}$) across all cities and climate scenarios, generally ranging from -68% to -92%. This confirms the effectiveness of the insulation and efficiency measures in reducing winter energy consumption.

The most critical insight from the data is the consistent increase in cooling energy demand ($EP_{c,nd}$) after the retrofit. While the pre-retrofit building (ANTE-OPERAM) has a low or even negligible cooling demand in colder zones like Cuneo, the highly insulated post-retrofit building traps more heat. This leads to a higher reliance on active cooling, especially in warmer climates and future scenarios. This phenomenon highlights a significant overheating risk, where measures designed for winter performance create a negative consequence in summer. For example, in Porto Empedocle (Zone A), the post-retrofit cooling need ($EP_{c,nd}$) increases by 32% under the actual climate and this penalty worsens in future scenarios. This suggests that the building envelope, while efficient, is not well-adapted to dissipate heat from solar and internal gains.

City	Winter degree days		Climatic data	Energy label	% renewable integration	I.S.I.	$\Delta EP_{gl,tor}$	$\Delta E_{h,tor}$	$\Delta EP_{h,nd}$	$\Delta E_{c,tot}$	$\Delta EP_{c,nd}$
Porto Empedocle	579	ANTE-OPERAM	Actual climate	E	2.27%						
			Future 2050 - RCP 4.5	D	4.11%	/	/	/	/	/	/
			Future 2050 - RCP 8.5	D	4.30%						
		POST-OPERAM	Actual climate	A4	100.00%	21.91	-68%	-86%	-82%	-35%	32%
			Future 2050 - RCP 4.5	A4	100.00%	26.14	-68%	-91%	-88%	-56%	-20%
			Future 2050 - RCP 8.5	A4	100.00%	28.47	-66%	-92%	-89%	-53%	-14%
Reggio Calabria	772	ANTE-OPERAM	Actual climate	E	2.53%						
			Future 2050 - RCP 4.5	D	3.61%	/	/	/	/	/	/
			Future 2050 - RCP 8.5	C	1.52%						
		POST-OPERAM	Actual climate	A4	99.33%	18.43	-70%	-86%	-81%	-49%	-3%
			Future 2050 - RCP 4.5	A4	100.00%	23.09	-69%	-90%	-87%	-52%	-16%
			Future 2050 - RCP 8.5	A4	100.00%	31.73	-63%	-91%	-88%	666%	149%
Benevento	1316	ANTE-OPERAM	Actual climate	F	1.48%						
			Future 2050 - RCP 4.5	D	2.43%	/	/	/	/	/	/
			Future 2050 - RCP 8.5	E	2.45%						
		POST-OPERAM	Actual climate	A4	84.66%	12.48	-67%	-77%	-74%	-37%	28%
			Future 2050 - RCP 4.5	A4	89.57%	14.32	-70%	-81%	-78%	-57%	-22%
			Future 2050 - RCP 8.5	A4	90.86%	14.95	-70%	-82%	-78%	-52%	-19%
Biccari	1926	ANTE-OPERAM	Actual climate	F	1.04%						
			Future 2050 - RCP 4.5	F	1.44%	/	/	/	/	/	/
			Future 2050 - RCP 8.5	F	1.64%						
		POST-OPERAM	Actual climate	A4	72.41%	9.13	-66%	-73%	-72%	-23%	73%
			Future 2050 - RCP 4.5	A4	78.65%	11.30	-67%	-76%	-75%	-28%	31%

			Future 2050 - RCP 8.5	A4	79.85%	11.50	-68%	-77%	-76%	-40%	8%
Torino	2617	ANTE-OPERAM	Actual climate	G	0.89%						
			Future 2050 - RCP 4.5	G	1.33%	/	/	/	/	/	/
			Future 2050 - RCP 8.5	G	1.37%						
	2617	POST-OPERAM	Actual climate	A3	53.28%	7.80	-65%	-71%	-72%	4%	171%
			Future 2050 - RCP 4.5	A4	71.22%	9.08	-66%	-73%	-73%	-47%	2%
			Future 2050 - RCP 8.5	A4	72.04%	9.34	-66%	-73%	-74%	-45%	-1%
Cuneo	3012	ANTE-OPERAM	Actual climate	G	0.70%						
			Future 2050 - RCP 4.5	G	0.86%	/	/	/	/	/	/
			Future 2050 - RCP 8.5	G	1.14%						
		POST-OPERAM	Actual climate	A3	53.60%	6.90	-66%	-71%	-72%	-	2638 %
			Future 2050 - RCP 4.5	A4	69.41%	6.11	-75%	-81%	-81%	-	3538 %
			Future 2050 - RCP 8.5	A4	73.88%	9.04	-68%	-75%	-75%	-31%	44%

Table 10 Simulation results

The data for the warmest and coldest zones under future scenarios is particularly revealing.

- **Extreme Cooling Penalty:** In Reggio Calabria (Zone B), the post-retrofit simulation under the RCP 8.5 future scenario shows a staggering 666% increase in the primary energy for cooling ($\Delta E_{c,tot}$). This extreme value indicates a potential tipping point where the combination of a highly insulated envelope and future heatwaves transform the building into a "heat trap," making active cooling essential for habitability.
- **The Low-Base Effect:** In Cuneo (Zone F), the percentage increases in cooling needs are enormous. This is a "low-base effect": because the initial cooling demand was zero, any new demand results in an infinite or extremely large percentage increase. The key takeaway is not the percentage itself, but the *introduction* of a cooling need where none previously existed.

These points underscore the study's core theme: the impact of an energy retrofit is profoundly dependent on the local climate zone and its future trajectory.

Moreover, it can be observed that for the pre-retrofit building, its energy label often gets better in future scenarios. For instance, in Porto Empedocle, the building moves from class E under the actual climate to class D in both the RCP 4.5 and 8.5 scenarios for 2050. This occurs because the EPC calculation is heavily weighted by heating demand, which naturally decreases as winters become milder.

This presents a significant issue for policy and consumer awareness: a building owner might see an "improved" energy rating and assume the building is becoming more climate-resilient. In reality, this rating completely hides the fact that the cooling demand is simultaneously increasing, indicating a growing risk of summer overheating and higher cooling costs. This challenges the validity of using current energy labeling methodologies for future-proofing assessments. An

energy label that improves while the building's actual livability worsens is not a reliable indicator of long-term performance.

The climate projection scenarios reveal that the economic case for a given retrofit strategy is not static but highly sensitive to future weather patterns.

The financial benefit of the retrofit is primarily driven by the reduction in total primary energy. In heating-dominated climates (e.g., Biccari, Torino, Cuneo), the overall energy savings remain robust or even increase in the medium term because the reduction in heating demand is so profound. In cooling-dominated climates (e.g., Porto Empedocle, Reggio Calabria), the total energy savings tend to decrease in future scenarios. This happens because the initial heating problem was smaller, and while it's nearly eliminated, the new and growing cooling demand begins to offset those gains.

This suggests that the Investment-Saving Index (ISI) would worsen over time in warmer regions if evaluated dynamically. A project that seems economically sound based on today's climate might offer diminishing returns as the climate warms, unless the rising cost of cooling is explicitly included as a "cost avoided" in the calculation. However, the investment-saving index (ISI) should be re-evaluated. While heating cost savings are high, the new and growing cost of summer cooling could significantly impact the long-term economic viability of the retrofit, an effect that is not fully captured in the current analysis. When projecting to 2050, it should be taken into account probably a different energy mix in the calculation of renewable energy source coverage.

Table 11 proposes the results for the other approach.

The future climate projections do not simply shift the baseline for energy performance; they actively amplify the trade-off between winter heating savings and summer cooling penalties. The data shows that a retrofit designed for today's climate can become progressively less suitable as the climate warms, converting an energy-efficient solution into a future liability.

City	Climatic data	$\Delta EP_{cl,ch}$	$\Delta EP_{hycl,ch}$	$\Delta EP_{h,nd}$	$\Delta EP_{c,cl,ch}$	$\Delta EP_{c,nd}$
Porto Empedocle	Future 2050 - RCP 4.5	-73%	-94%	-92%	-2%	120%
	Future 2050 - RCP 8.5	-73%	-95%	-93%	4%	139%
Reggio Calabria	Future 2050 - RCP 4.5	-75%	-93%	-91%	-32%	41%
	Future 2050 - RCP 8.5	-76%	-94%	-93%	-27%	53%
Benevento	Future 2050 - RCP 4.5	-74%	-85%	-83%	-10%	101%
	Future 2050 - RCP 8.5	-75%	-86%	-84%	-3%	120%
Biccari	Future 2050 - RCP 4.5	-74%	-82%	-81%	32%	242%
	Future 2050 - RCP 8.5	-75%	-83%	-82%	42%	274%
Torino	Future 2050 - RCP 4.5	-71%	-78%	-78%	45%	349%
	Future 2050 - RCP 8.5	-73%	-79%	-79%	53%	382%
Cuneo	Future 2050 - RCP 4.5	-75%	-81%	-81%	-	6151%
	Future 2050 - RCP 8.5	-76%	-82%	-82%	-	6868%

Table 11: Second approach results

This amplification effect is most evident in the cooling demand indicators. For the case study building in Biccari (Zone D), the post-retrofit increase in cooling energy need is a significant 73% under the actual climate. However, this penalty skyrockets to 242% under the RCP 4.5 scenario and 274% under the more extreme RCP 8.5 scenario. This demonstrates that the highly insulated envelope, intended to reduce heat loss, becomes increasingly problematic by trapping heat during the hotter and longer summers projected for the future.

The same trend holds across different zones. In Torino (Zone E), the cooling need penalty grows from 171% in the current climate to 382% under RCP 8.5. This consistent trend indicates that the retrofit lacks climate resilience, and its negative summer performance is directly correlated with the severity of future warming.

A crucial insight from the future scenario analysis is how key performance indicators can become misleading, potentially masking the true long-term performance of the retrofit. The overall primary energy saving for heating and cooling ($\Delta EP_{cl,ch}$) generally appears to improve in future scenarios. For instance, in Benevento, the savings increase from -67% (Actual) to -75% (RCP 8.5). This occurs because heating is the dominant energy use in the inefficient pre-retrofit building. As warmer winters drastically reduce this initial heating demand, the retrofit's large percentage savings on a smaller problem still outweigh the growing cooling

penalty. Relying on this single metric would lead to the erroneous conclusion that the intervention performs better in a warmer climate, while ignoring the severe degradation in summer comfort and performance. Similarly, the percentage of heating savings ($\Delta EP_{h,cl,ch}$) consistently increases in future projections for all cities. This does not mean the insulation is physically performing better. Instead, it reflects a mathematical artifact where the baseline (pre-retrofit heating demand) shrinks faster than the post-retrofit demand, making the relative savings appear larger.

These metrics, while standard, prove to be poor indicators of climate adaptation and could encourage designs that are not resilient to future conditions. The variation across future scenarios confirms that the initial climate zone is a primary determinant of a retrofit's long-term viability.

Conversely, using the third approach, namely, the analysis via hourly dynamic calculation using the ACCA Termus Plus software, reveals a situation completely different from that obtained with the semi-steady-state calculation. As shown in Table 12, following the retrofit interventions, the typical significant reduction in heating thermal energy demand is coupled with an unexpected reduction in cooling thermal energy demand.

Comune	Dati climatici	Modello	Eph,nd [kWh/m2]	Epc,nd [kWh/m2]	ΔEph,nd Futuro-Presente	ΔEpc,nd Futuro-Presente
Porto Empedocle	Oggi	Ante	58.231	28.886		
		Post	22.991	19.922		
		Variazione Ante-Post	-60.52%	-31.03%		
	2050 RCP 4.5	Ante	44.710	43.677	-23.22%	51.21%
		Post	16.817	30.371	-26.85%	52.44%
		Variazione Ante-Post	-62.39%	-30.47%		
	2050 RCP 8.5	Ante	41.328	50.836	-29.03%	75.99%
		Post	15.341	35.406	-33.27%	77.72%
		Variazione Ante-Post	-62.88%	-30.35%		
Reggio Calabria	Oggi	Ante	61.435	33.215		
		Post	24.361	22.569		
		Variazione Ante-Post	-60.35%	-32.05%		
	2050 RCP 4.5	Ante	47.283	47.994	-23.04%	44.49%
		Post	17.768	32.404	-27.06%	43.58%
		Variazione Ante-Post	-62.42%	-32.48%		
	2050 RCP 8.5	Ante	43.628	55.240	-28.98%	66.31%
		Post	16.232	37.204	-33.37%	64.84%
		Variazione Ante-Post	-62.80%	-32.65%		
Benevento	Oggi	Ante	113.240	21.215		
		Post	50.344	14.542		
		Variazione Ante-Post	-55.54%	-31.45%		
	2050 RCP 4.5	Ante	92.450	38.565	-18.36%	81.78%
		Post	40.022	26.099	-20.50%	79.47%
		Variazione Ante-Post	-56.71%	-32.32%		
	2050 RCP 8.5	Ante	86.010	43.156	-24.05%	103.42%
		Post	36.803	29.649	-26.90%	103.88%
		Variazione Ante-Post	-57.21%	-31.30%		
Biccarì	Oggi	Ante	144.540	10.503		
		Post	65.588	7.250		
		Variazione Ante-Post	-54.62%	-30.97%		
	2050 RCP 4.5	Ante	122.101	28.096	-15.52%	167.51%
		Post	54.304	19.139	-17.20%	163.99%
		Variazione Ante-Post	-55.53%	-31.88%		
	2050 RCP 8.5	Ante	118.676	34.207	-17.89%	225.69%
		Post	52.578	22.924	-19.84%	216.20%
		Variazione Ante-Post	-55.70%	-32.98%		
Torino	Oggi	Ante	188.872	5.036		
		Post	89.000	3.650		
		Variazione Ante-Post	-52.88%	-27.53%		
	2050 RCP 4.5	Ante	161.319	20.655	-14.59%	310.14%
		Post	75.527	14.270	-15.14%	290.99%
		Variazione Ante-Post	-53.18%	-30.91%		
	2050 RCP 8.5	Ante	152.408	20.133	-19.31%	299.77%
		Post	70.680	14.413	-20.58%	294.93%
Cuneo	Oggi	Ante	192.232	0.770		
		Post	88.917	0.131		
		Variazione Ante-Post	-53.74%	-82.96%		
	2050 RCP 4.5	Ante	165.874	9.178	-13.71%	1092.60%
		Post	76.022	5.889	-14.50%	4390.57%
		Variazione Ante-Post	-54.17%	-35.84%		
	2050 RCP 8.5	Ante	160.907	12.705	-16.30%	1550.85%
		Post	73.506	8.714	-17.33%	6544.97%
		Variazione Ante-Post	-54.32%	-31.41%		

Table 12 Hourly dynamic simulation results

A detailed examination of the table shows that in every climate zone and under each proposed scenario (current climate, 2050 RCP 4.5, and 2050 RCP 8.5), the intervention results in an improvement in terms of both summer and winter demands. The proposed retrofit generates a reduction in heating thermal energy demand of between 53% and 63%, depending on the climate zone and scenario. As for the cooling thermal energy demand, there is a reduction of between 28% and 36%, with the exception of a peak reduction of 83% in the current scenario in

Cuneo. This is due to the low-baseline effect, as was already illustrated in some cases with the semi-steady-state method.

The difference in results compared to the semi-steady-state calculation method may be due to multiple factors. Firstly, the use of hourly climate data instead of monthly data makes it possible to account for the dynamic summer behavior of the building envelope. Frequently, especially in colder climate zones, the monthly average temperature is lower than, or very close to, the 26°C internal temperature setpoint. This makes the dissipation of internal and solar gains difficult (if not impossible) in the semi-steady-state calculation model. The hourly dynamic calculation method, however, correctly accounts for the fact that during summer days, temperature peaks far exceeding the internal setpoint are reached, followed by nights when the temperature drops by several degrees. It is clear, therefore, that when the external temperature is higher, during the daytime hours of summer days, heat transfer occurs from the inside to the outside and not the reverse, as occurs with a monthly average temperature lower than the internal setpoint. Therefore, when the external temperature is higher than the internal one (as happens for most summer hours in the hourly dynamic model), the presence of greater envelope insulation slows the entry of heat into the apartments, thus proving advantageous. Furthermore, in addition to the external air temperature, the external surface temperature is important for a more realistic modeling of the envelope's dynamic behavior. Thus, incident solar radiation on the opaque envelope leads to a significant increase in the external surface temperature, consequently increasing heat gain into the apartments. Considering this factor, the presence of external insulation helps to curb this phenomenon, making the intervention advantageous even during the cooling period. It is also important to note that, post-insulation, the most significant impact on energy demands, aside from internal and solar gains, comes from heat gains due to ventilation (both intentional and unintentional, i.e., infiltration or "drafts"). Therefore, improving the building's airtightness by adopting technical measures and installing a Mechanical Ventilation with Heat Recovery system could further reduce demands

in both summer and winter regimes. The improvement in airtightness, although implemented in the actual case study, was not considered in the modeling. This was done both to avoid introducing an additional variable, preferring to focus exclusively on the impact of the building envelope insulation, and to align with the calculation method stipulated by UNI 11300-1. Finally, the fact that the hourly dynamic modeling considered the use of shading devices aimed at limiting solar energy entry to a maximum of 300W/m², replicating the normal behavior in the use of shading systems, contributed to a significant reduction in solar gains, thus further reducing the cooling demand. The difference in results between the semi-steady-state and the hourly dynamic method, especially in the summer regime, could be explained by these aspects.

4.5.3 Conclusions

This study conducted a sensitivity analysis on the energy performance assessment of a building undergoing an nZEB retrofit, comparing different climate scenarios (current and future) and, above all, different calculation methodologies. The analysis revealed a fundamental and critical discrepancy between the results obtained with the semi-steady-state calculation method, stipulated by Italian standards, and the hourly dynamic calculation method.

According to the traditional (semi-steady-state) approach, the energy retrofit, while leading to a drastic reduction in heating demand (generally between -68% and -92%), introduces a significant risk of summer overheating. This method showed a consistent increase in the cooling energy demand ($EP_{c,nd}$) after the intervention, as the highly insulated envelope tends to trap heat. This negative effect is not only present in current scenarios, but is significantly amplified in future climate projections (RCP 4.5 and RCP 8.5). For example, in Biccari the cooling demand increased by 73% in the current scenario, rising to 274% in the RCP 8.5 scenario, and in Reggio Calabria an extreme increase of 666% in primary energy

for cooling ($\Delta E_{c,tot}$) was recorded in the RCP 8.5 scenario, transforming the building into a "heat trap"

Furthermore, the semi-steady-state analysis highlighted how current performance indicators, such as energy labels, can be misleading for assessing climate resilience. It was observed that the pre-retrofit building "improves" its energy class in future scenarios (e.g., from E to D) due to milder winters, completely masking the simultaneous increase in overheating risk.

Conversely, the use of an hourly dynamic calculation engine (EnergyPlus) yielded a "completely different" situation. This methodology (the third approach) showed that the retrofit intervention produces a significant reduction in both the thermal demand for heating (between 53% and 63%) and, unexpectedly, the thermal demand for cooling (between 28% and 36%). This positive result was found in all climate zones and in all scenarios, including future ones.

The study attributes this divergence to several key factors that only the dynamic model can capture:

- Hourly climate data: The use of hourly data allows for the correct simulation of summer dynamic behavior, including temperature oscillations between day and night, unlike monthly averages which make heat dissipation impossible in the semi-steady-state model.
- Reversal of heat flow: The dynamic model correctly detects that during the hottest summer hours, the external temperature exceeds the internal one; in this condition, insulation acts advantageously by slowing heat entry.
- Solar radiation: The dynamic calculation considers solar radiation on opaque surfaces, a factor that increases the external surface temperature. External insulation (ETICS) mitigates this phenomenon, bringing benefits even during the cooling period.

- Shading systems: The dynamic model included the use of solar shading configured to limit energy entry (max 300 W/m²), significantly reducing solar gains and, consequently, cooling demand.

In conclusion, the study strongly suggests that reliance solely on semi-steady-state calculation methods is inadequate for assessing the climate resilience of buildings, as it can lead to erroneous conclusions about their summer performance. The design of resilient nZEB buildings requires the adoption of hourly dynamic simulations.

However, to confirm the extent of these discrepancies and generalize the results obtained, further research is necessary. It will be essential to conduct new sensitivity analyses to evaluate how the dynamic model's results vary according to parameters not explored in detail here, such as different usage profiles for shading devices, different occupancy and internal gain profiles, and different conditions of envelope air permeability. This more extensive comparative analysis represents the future direction of this research path, aiming to provide increasingly reliable assessment tools for the design of future-proof buildings.

Conclusions

This research is contextualized within the global climate crisis—a phenomenon representing not only a profound environmental threat but also a tangible risk to economic stability and human well-being. The construction sector is a primary contributor to this challenge; it remains among the largest global energy consumers, accounting for approximately 37% of energy-related CO₂ emissions, and acts as a massive consumer of raw materials and a producer of waste. In this context, global strategies such as the Green New Deal, alongside EU policies like the REPowerEU plan, are mandating a decisive transition toward a low-carbon economy, imposing stringent decarbonization targets on the building sector.

Recent European legislation, particularly the evolution of the Energy Performance of Buildings Directive (EPBD) from its 2010 iteration to the latest 2024/1275 revision (EPBD IV), establishes a stringent and unequivocal trajectory. The objective has fundamentally shifted from the "nearly Zero Energy Building" (nZEB) standard to the mandated achievement of a Zero-Emission Building (ZEB) stock by 2050. This new directive introduces transformative elements, shifting the focus from singular operational performance to holistic, life-cycle sustainability. Key features include the mandatory calculation of life-cycle Global Warming Potential (GWP) for new constructions, the promotion of smart technologies via the Smart Readiness Indicator (SRI), the integration of electric mobility infrastructure, and the progressive installation of solar energy systems.

This new regulatory paradigm necessitates a departure from the traditional design focus, which was almost exclusively concentrated on energy performance during the operational phase (life cycle stage B6). Sustainable design must now adopt a holistic framework, integrating principles of the Circular Economy (CE) and the utilization of recycled materials, such as those derived from Construction and Demolition Waste (CDW). Thus, the means of achieving efficiency (i.e., material selection) has become as fundamental as the efficiency itself. Concurrently, the

imperative to retrofit the existing, largely inefficient building stock (in Italy, approximately 60% falls within energy classes F-G) must be reconciled with the need for economic sustainability. Initiatives like the Italian "Superbonus 110%" have highlighted the critical role of incentives while simultaneously exposing the need for rigorous cost-benefit evaluations under diverse climatic conditions.

Finally, a complex challenge addressed in the second part of this work is that of resilience. The energy performance of buildings, designed and optimized using historical or semi-stationary climate data, is now being severely tested by accelerating climate change. Rising mean temperatures and the increased frequency of extreme weather events (e.g., heatwaves) raise fundamental questions about the long-term viability of current nZEB solutions. Strategies optimized for heating-dominated climates may risk transforming into "heat traps" during summer, negating their intended benefits.

The primary objective of this doctoral research was to critically and holistically evaluate nZEB (nearly Zero Energy Building) and PEB (Positive Energy Building) design solutions. The analysis examines their verified performance, economic sustainability, resultant indoor comfort, and, critically, their resilience to future climate change. The multi-scale methodological approach, detailed in Chapter 2, combined multiple investigative techniques: semi-steady-state modeling (compliant with Italian standard UNI/TS 11300), hourly dynamic simulations (EnergyPlus), Computational Fluid Dynamics (CFD) for local comfort analysis, urban microclimate modeling (ENVI-met), and Neural Networks (NN) for predictive analytics.

The research program was structured into two principal macro-areas:

I. Performance investigation of nearly zero-energy designs, evaluating real-world interventions, their economic sustainability, impacts on occupant comfort, and the integration of new loads, such as electric mobility.

II. Impact of climate data (current and future) on the resilience of energy performance, analyzing the robustness of design solutions over time and the fidelity of regulatory calculation methods relative to dynamic simulations.

I) Performance Investigation of Nearly Zero-Energy Designs

The first macro-area of this work (Chapter 3) critically analyzed design and retrofit solutions, contextualized within the current regulatory, economic, and technological landscape, with a strong emphasis on validation under realistic or real-world conditions.

The initial study (Chapter 3.1) addressed local thermal-hygrometric comfort within a real nZEB: the BnZEB (Benevento Nearly Zero Energy Building). The objective was to transcend the limitations of traditional Building Performance Simulation (BPS) tools, which typically operate on a single-node basis and provide zonal averages that risk masking thermal inhomogeneities and localized discomfort. Using Computational Fluid Dynamics (CFD), a bedroom was analyzed under winter conditions, with the model calibrated against in-situ experimental data. The calibration achieved high fidelity, with CV(RMSE) (8.44% - 12.88%) and MBE (-7.77% - -9.69%) indices falling well within M&V guideline limits.

The results highlighted a significant discrepancy between aggregated performance and local comfort. Scenario S1 (anomalous winter heatwave: DBT 17.2°C, GHI 511 W/m²) was found to be energetically advantageous: the HVAC system remained inactive, yet comfort conditions were fully met (T_a 21.6°C, PMV - 0.20, PPD < 10%). This scenario underscored that real-world energy savings are critically dependent on occupant-driven set-point control in the presence of solar gains and anomalous external forcings. Conversely, in Scenario S2 (high GHI, lower DBT 16.5°C), while the aggregated BPS simulation indicated acceptable conditions (PMV -0.55), the CFD analysis revealed that large zones—particularly those distant from solar gain—exhibited clear local discomfort (PMV down to -0.70, PPD 8-13%). Scenario S3 (evening, DBT 14.8°C, no GHI) produced similar discrepancies. These findings demonstrate the inadequacy of single-thermostat control systems in high-

performance envelopes and suggest the necessity of CFD analysis to mitigate localized discomfort (e.g., radiant asymmetry).

The second study (Chapter 3.2) evaluated the energy and economic sustainability of the Italian "Superbonus 110%" fiscal incentive. A real case study (a 1983 apartment building in Biccari, Climate Zone D, Class F, $H'_T = 1.54 \text{ W/m}^2\text{K}$) was analyzed. The same deep retrofit package was simulated across six different Italian climate zones (A-F) using the regulatory semi-steady-state method (TerMus). The analysis confirmed the intervention's high energy effectiveness, achieving Class A4 (nZEB) in nearly all zones, with substantial reductions in non-renewable primary energy ($EP_{gl,nren}$: -62% to -70%) and thermal demand (ΔEP_h up to -86%). However, two fundamental criticalities emerged. First, a risk of summer overheating was detected in colder climates (e.g., Turin, Zone E), and in Cuneo (Zone F), a cooling demand (1.9 kWh/m^2) was induced where none previously existed (the "low-base effect"). Second, financial viability in the absence of incentives proved problematic. The ISI index (investment/savings) was acceptable only in cold climates (6.9 €/kWh in Cuneo) but increased exponentially in milder climates (22.8 €/kWh in Porto Empedocle). This study quantitatively demonstrates that such massive interventions, while effective, are not economically viable for private investors in milder climates without significant public incentives.

The third study (Chapter 3.3) explored the transition from nZEB to PEB (Positive Energy Building) and the integration of electric mobility (EV). A new, high-performance residential building (Class A4, U-wall $0.125 \text{ W/m}^2\text{K}$) was analyzed. The building achieved PEB status with its base 43 kWp PV system, exporting 31,071 kWh/year. However, integrating EV charging presented a critical challenge. Even a PEB with an annual surplus enters an energy deficit on a monthly basis—particularly in winter—when realistic EV charging loads (e.g., 7 stations @ 7.6 kW) are applied. In January, the production surplus (4-5 MWh) was insufficient to cover the charging demand (8.5-9.3 MWh). Only the most advanced design scenario (124 kWp PV, +20% HP efficiency) could support minimal charging loads. This highlights

the urgent need to size generation and storage based not only on building demand but also on the stochastic loads from integrated electric mobility.

The fourth study (Chapter 3.4), part of the Horizon REHOUSE project, addressed social housing regeneration via a holistic energy, seismic, and social approach. At the Margherita di Savoia pilot site, an innovative package was evaluated, including a multifunctional exoskeleton with colored BIPV and a centralized "Smart Thermal Energy Hub" with PCM storage and water-to-water heat pumps. Beyond achieving nZEB targets ($EP_{gl,nren} = 0.0000$), ENVI-met simulations were used to assess the urban microclimate impact. The retrofit (Scenario 2) significantly reduced the Mean Radiant Temperature (MRT) on the south facade due to the BIPV's low reflectivity. The addition of green and permeable surfaces (Scenario 3) proved crucial for mitigating the Urban Heat Island (UHI) effect, improving the outdoor PET comfort index. This study demonstrated the necessity of linking building retrofits to the regeneration of their surrounding urban and social spaces.

II) Impact of Climate Change on Building Energy Needs and Consumption

The second macro-area (Chapter 4) addressed the critical limitations of climate data and calculation methodologies used in design, assessing both short-term predictive tools and the long-term resilience of nZEB solutions to climate change (2050-2080).

The first studies (Chapters 4.1, 4.2) explored Neural Networks (NN) for short-term prediction. Study 4.1 demonstrated an NN's ability to predict external temperature trends, correctly identifying seasonality while capturing a trend of increasing T_{max} (+7.7°C, 2016 vs. 2022) and decreasing T_{min} . The energy impact was significant, increasing both cooling (+59% in 2027) and heating (+17% in 2027) demands. Study 4.2 optimized NN architectures (LSTM vs. GRU) for multivariate prediction (Temperature, Radiation, PV Power). While R^2 exceeded 0.90 for temperature and radiation, PV power prediction was less accurate ($R^2 \sim 0.83-0.85$). An intrinsic physical limitation was identified: NNs, using continuous activation functions, struggle to model the physically discontinuous nature of PV production

(i.e., the 0 W state), leading to systematic errors during sunrise and sunset transitions. These studies confirm NN potential for "prosumer" management but highlight their physical limitations.

Subsequent studies (Chapters 4.3, 4.4, 4.5) analyzed long-term nZEB resilience (2050-2080) using standard climate projections (RCP 4.5 and 8.5).

The analysis of glazing systems (Chapter 4.3) revealed a fundamental paradox for resilient design. Glazing optimized for the current climate (TMY) was not necessarily the most resilient. The best-performing current solution (D_LESSC, selective glass, $g=0.42$) showed the most severe performance degradation in future climates (CC_MT, CC_LT), with cooling demand (ΔC_n) increasing by +59% (2050s) and +79% (2080s). Conversely, less efficient current solutions (D_CLI, clear glass, $g=0.83$) exhibited proportionally lower summer performance degradation. This result is critical: designing for current optimality can result in non-resilient buildings.

The analysis of photovoltaic degradation (Chapter 4.4), transposing the BnZEB model to a tropical climate (Santo Domingo), confirmed this vulnerability. The combined impact of (a) climate-change-induced cooling demand and (b) physical panel degradation (0.8%/year) creates a significant penalty on operational emissions (IPOE), reaching +6% in the 2050s. This dual impact jeopardizes long-term nZEB/PEB status. The sizing analysis showed that while 5.28 kWp and 3.60 kWp capacities remained resilient, the 1.98 kWp capacity failed the nZEB target even in the short term. Adequate initial oversizing is therefore a key resilience strategy.

Finally, the study in Chapter 4.5 revealed a fundamental methodological criticality in the current Italian standard. A comparison of the semi-steady-state (UNI/TS 11300) and hourly-dynamic (EnergyPlus) methods for the same building, interventions, and climate scenarios yielded diametrically opposed results. The regulatory (semi-steady-state) model predicted a disastrous increase in post-intervention summer demand, with insulation creating a "heat trap" (e.g., +274%

cooling demand in RCP 8.5) and showing "false improvements" in non-retrofitted buildings. Conversely, the hourly-dynamic model—capturing inertia, radiation on opaque surfaces, and shading—calculated a net benefit and a reduction in summer thermal demand (between -28% and -36%) in all scenarios. This fundamental discrepancy demonstrates that the current regulatory semi-steady-state method is not only inadequate for assessing climate resilience but is physically incorrect in modeling the summer behavior of insulated buildings, leading to misleading design conclusions that penalize effective interventions.

This research has demonstrated that achieving the Green New Deal objectives requires transcending the nZEB approach focused solely on operational energy. A holistic framework is necessary, integrating material sustainability (LCA/recycling), granular local comfort (CFD), and urban microclimate (UHI) impacts.

Critically, this work highlights the urgent need to transition from semi-steady-state calculation methods toward hourly dynamic simulations. As demonstrated, only the latter, when coupled with future climate projections, can correctly assess the resilience of design choices. The analyses have shown that component and system performance is not static but evolves—often radically—in response to future climate scenarios.

Continuing to design with outdated tools and historical climate data risks engineering buildings that are efficient for a climate that no longer exists, potentially transforming today's investments into tomorrow's energy and comfort liabilities. Further research is indispensable to validate the magnitude of these discrepancies and broaden their applicability. The next phase of this research will involve wider-ranging sensitivity analyses to determine how dynamic model outputs fluctuate with parameters not yet fully investigated, aiming to deliver dependable assessment methods for truly climate-resilient design. Future research must integrate these methodologies: utilizing validated Digital Twins to test innovative material resilience, feeding predictive NN models for prosumer optimization, and systematically including LCA, as mandated by the new EPBD, to ensure the ZEB transition is sustainable throughout its entire life cycle.

Recommendations for Practitioners

To bridge the gap between academic research and professional practice, the following recommendations are provided for engineers and designers:

- **Shift to Dynamic Modeling:** Practitioners should transition from semi-steady-state calculations to hourly dynamic simulations for any nZEB/ZEB design. This is the only way to accurately evaluate summer comfort and prevent future "heat trap" liabilities.
- **Future-Proofing via Over-Sizing:** Designers should consider a "resilience margin" for PV installations (approx. +10-15%) to account for the dual impact of future increased cooling demand and the physical degradation of panels over time.
- **Incentive Evaluation:** Economic assessments for deep retrofits (e.g., Superbonus type) must consider climate-specific ROI. In milder climates, thermal insulation alone may not be financially viable without prioritizing active cooling systems and renewable integration.

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- [III] R. F. De Masi, A. Gigante, M. Parrotta, S. Ruggiero, A. Russo. Application of energy regulations to a residential building in a temperate climate. (under publication)
- [IV] M. Misceo, F. Rotondo, A. Di Micco, S. Tamburrino, G. Pascucci, M. Parrotta, T. Bibbò, V. Loverre. Social Housing regeneration: qualifying and making sustainable buildings and public spaces. A case study. Proceedings of 3rd International Conference Construction, Energy, Environment & Sustainability CEES 2025, 11-13 June 2025
- [V] V. Festa, R. F. De Masi, A. Gigante, M. Parrotta, S. Ruggiero, A. Russo. Forecasting future climate with a neural network trained on monitored data: an analysis of the energy demand of a detached house. Green Energy and Technology, 2024, Part F2329, pp. 419-427
- [VI] R. F. De Masi, N. Del Regno, A. Gigante, M. Parrotta, S. Ruggiero, G. P. Vanoli. Impact of glazing system on the energy performance of a nZEB under climate change scenarios. 2023 8th International Conference on Smart and Sustainable Technologies SpliTech 2023, 20-23 June 2023
- [VII] R. F. De Masi, A. Gigante, M. Parrotta, S. Ruggiero, A. Russo. Effect of degradation and size selection for the photovoltaic system installed in a nearly zero

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Index of Figures

Page 11 - Figure 1: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Are shown: in grey colour the GMST in the HadCRUT4, NOAAGlobalTemp, GISTEMP and Cowtan-Way datasets; in yellow the Human induced contributions to GMST; in orange the total (human- and naturally-forced) contributions to GMST; in blue the modelled global mean surface air temperature (dashed) and blended surface air and sea surface temperature (solid) from the CMIP5 historical ensemble; in shading pink the range for temperature fluctuations over the Holocene; in light green plume the IPCC prediction in 2014 for average GMST over 2016-2035. Ref. [50]

Page 13 - Figure 2: Final energy consumption in buildings: growth by region (a); by fuel type (b). Ref [9].

Page 14 - Figure 3: Primary energy consumption by end use sector (a); annual demand growth and sector contributions (b). Ref [9].

Page 16 - Figure 4: Surface temperature (a) and city-wide land cover (b) maps of New York City in August 4th 2002. Ref. [51].

Page 18 - Figure 5: Measured annual urban heat island intensity for all experiments based on the use of: standard fixed meteorological stations(a); non standard fixed meteorological stations (b); mobile traverses (c). Ref. [52].

Page 77 - Figure 6: a) Real case study; b) Building simulation model.

Page 78 - Figure 7: Bedroom monitoring campaign setup

Page 79 - Figure 8: a) Air Temperature; b) Internal surface temperature (East); c) Internal surface temperature (South).

Page 82 - Figure 9: 3D contours plot (S1): a) Air Temperature; b) PMV

Page 83 - Figure 10: 3D contours plot (S2): a) Air Temperature; b) PMV

Page 85 - Figure 11: 3D contours plot (S3): a) Air Temperature; b) PMV

Page 90 - Figure 12: Render (a), energy label (b) and performance indices (c) of the case study in the existing state. (Biccari, Climatic Zone D).

Page 93 - Figure 13: Energy saving in term of EPgl, nren by varying the climatic zone.

Page 93 - Figure 14: Heating energy saving by varying the climatic zone.

Page 94 - Figure 15: Cooling energy saving by varying the climatic zone.

Page 95 - Figure 16: I.S.I. by varying the climatic zone.

Page 99 - Figure 17a: Rendering: South-West exposure

Page 99 - Figure 17b: First floor plan

Page 101 - Figure 18: Monthly electricity: state of fact and 5 EV charging scenarios

Page 102 - Figure 19: Combined scenario building energy surplus and 5 EV charging scenarios

Page 107 - Figure 20: The three-dimensional model: a) initial condition and b) design condition. (Extracted from TerMus BIM software)

Page 107 - Figure 21: Validation Model

Page 109 - Figure 22: Boiler Diagram

Page 109 - Figure 23: Total CO2 Emissions

Page 109 - Figure 24: Primary Energy Demands

Page 110 - Figure 25: Energy classes: a) Initial condition; b) Scenario A; c) Scenario B; d) Scenario C; e) Scenario D; f) Scenario E.

Page 111 - Figure 26: model area created with ENVI-met Spaces. As-built scenario (left) and the scenario after building and area renovations (right).

Page 114 - Figure 27: PET index variation after the renovation of the building

Page 114 - Figure 28: PET index variation after the building and area renovations

Page 121 - Figure 29: Envelope thermo-physics characteristics (b) and render view (a) of the case study

Page 123 - Figure 30: Methodological approach developed

Page 125 - Figure 31: Neural Network used

Page 125 - Figure 32: Monitored data, forecast to 2023 and forecast to 2027

Page 127 - Figure 33: Primary energy for cooling

Page 128 - Figure 34: Primary energy for heating

Page 132 - Figure 35: Photovoltaic and solar thermal plant

Page 134 - Figure 36: T forecast with GRU

Page 134 - Figure 37: T forecast with LSTM

Page 135 - Figure 38: GSR Forecast with GRU

Page 136 - Figure 39: GSR Forecast with LSTM

Page 137 - Figure 40: GSR Forecast with GRU

Page 137 - Figure 41: GSR Forecast with LSTM

Page 140 - Figure 42: a) Real case study; b) Building simulation model

Page 142 - Figure 43: Energy simulation results with current climate file (TMY)

Page 145 - Figure 44: Percentage variations in energy needs for heating and cooling - CC_2050.

Page 145 - Figure 45: Percentage variations in energy needs for heating and cooling - CC_2080.

Page 146 - Figure 46: Difference (kWh) in energy need for cooling.

Page 151 - Figure 47: Methodological approach

Page 152 - Figure 48: Building energy balance

Page 153 - Figure 49: Penalty index on the building's operational carbon dioxide equivalent emissions

Page 154 - Figure 50: the nZEB target

Page 155 - Figure 51: Number of months in which generation exceeds demand

Index of Tables

Page – 76 Table 1: Geometrical features

Page – 80 Table 2: Calibration Results

Page – 80 Table 3: Design variables

Page – 81 Table 4: Indoor Conditions (S1)

Page – 84 Table 5: Indoor Conditions (S2)

Page – 84 Table 6: Indoor Conditions (S3)

Page – 100 Table 7: EV Charging scenarios

Page – 126 Table 8: Maximum and minimum temperature for each year

Page – 142 Table 9: Design variables

Page – 163 Table 10: Simulation results

Page – 166 Table 11: Second approach results

Page – 168 Table 12: Hourly dynamic simulation results