energies

Article

Toward Zero-Emission Buildings in Italy: A Holistic Approach to Identify Actions Under Current and Future Climates

Franz Bianco Mauthe Degerfeld *, Mamak P. Tootkaboni, Matteo Piro, Ilaria Ballarini and Vincenzo Corrado

Technology Energy Building Environment (TEBE) Research Group, Department of Energy "Galileo Ferraris", Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy; mamak.pourabdollahtootkaboni@polito.it (M.P.T.); matteo.piro@polito.it (M.P.); ilaria.ballarini@polito.it (I.B.); vincenzo.corrado@polito.it (V.C.)
* Correspondence: franz.bianco@polito.it; Tel.: +39-011-090-4549

Abstract: The European building sector significantly contributes to the EU's greenhouse gas reduction goals, with the 2024 Energy Performance of Buildings Directive (EPBD) aiming to achieve a decarbonised building stock by 2050. By focusing on an existing office building representative of the Italian building stock, this research evaluates various energy efficiency measures and integrates renewable energy systems to transform the building into a Zero-emission Building (ZeB). Moreover, it also utilises future weather data to address the effects of climate change. Results highlight the actions needed for an empirical ZeB transition, offering insights into challenges and key performance indicators across different intervention scenarios. The findings contribute to establishing national ZeB standards, emphasising the importance of the national building renovation plan in compliance with the EPBD recast requirements.

Keywords: energy performance of buildings directive; energy efficiency; zero-emission buildings; GHG emissions; building simulation; building energy refurbishment; climate change

Academic Editor: Christian Inard

Received: 30 April 2025
Revised: 19 May 2025
Accepted: 21 May 2025
Published: 23 May 2025

Citation: Bianco Mauthe Degerfeld, F.; Tootkaboni, M.P.; Piro, M.; Ballarini, I.; Corrado, V. Toward Zero-Emission Buildings in Italy: A Holistic Approach to Identify Actions Under Current and Future Climates. *Energies* **2025**, *18*, 2721. https://doi.org/10.3390/en18112721

1. Introduction

The new Energy Performance of Buildings Directive (EPBD IV) [1] is undoubtedly the most significant recent legal act supporting building sustainability in the European Union. It is part of the strategic initiatives of the Green Deal for a green transition, with the goal of achieving climate neutrality by 2050.

The focus of the new EPBD is the renovation of the entire building stock, which will represent a key step toward decarbonisation and modernisation, and will include system integration measures supported by appropriate financial instruments.

By 2030, all new buildings and, by 2050, all existing buildings, will be required to achieve the zero-emission target. A "zero-emission building" is defined as "a building with a very high energy performance, requiring zero or a very low amount of energy, producing zero on-site carbon emissions from fossil fuels and producing zero or a very low amount of operational greenhouse gas emissions" [1]. The total annual primary energy use of a Zero-emission Building may be covered by: (a) energy from renewable sources generated on-site or nearby, such as by means of solar thermal, geothermal or photovoltaic systems, heat pumps, hydropower plants, and biomass generators; (b) energy from renewable sources provided from a renewable energy community; (c) energy from an efficient district heating and cooling system; and (d) energy from other carbon-free sources.

A key tool for implementing the EPBD will be the development of a national building renovation plan, including an overview of the building stock, minimum energy performance standards, a roadmap with renovation targets, investment needs, and expected energy savings, as well as support measures for vulnerable households and those affected by energy poverty.

Advanced building automation systems, sustainable infrastructures, and solar technologies will be introduced, while fossil fuels will be gradually phased out. Holistic and advanced calculation methods will consider life-cycle emissions, indoor environmental quality, climate resilience, and smart readiness.

Energy efficiency measures can be classified as either passive or active technologies, targeting the building envelope and technical building systems, respectively. Another common taxonomy categorises retrofit measures based on the scale of intervention: local or global. Local retrofit refers to improving the efficiency of individual building components, while global retrofit scale aims to enhance the energy performance of the building as a whole. The concept of global building energy renovation is increasingly recognised as a key strategy for addressing the challenges of achieving carbon neutrality. Huovila et al. [2] reviewed the concept of carbon-free cities, emphasising the importance of replacing fossil fuels with renewables, reducing overall energy consumption, and improving energy efficiency. In this context, Tetteh et al. [3] found that "energy efficiency" retrofitting has been the foremost research focus, whereas attention toward "occupant behaviour" and "indoor environmental quality" (including comfort, satisfaction, and air quality) diminished. Therefore, to meet ambitious energy and environmental EU targets, the current retrofit rate of 0.2% [4] must not be hindered by regulatory, technical, or user-related barriers [5].

Additionally, other concepts, such as intelligent buildings and circular economy principles, are gradually influencing the landscape of existing building retrofitting. Sometimes, a post-occupancy evaluation has been conducted on low-carbon buildings, encompassing analysis of indoor environmental indicators and carbon reduction efforts. In this vein, the primary aim of the study by Qiao et al. [6] was to evaluate the post-occupancy performance of low-carbon buildings and provide guidance for their development toward achieving the zero-carbon goal.

A holistic approach to building performance has been usually adopted in the field of sustainability. For instance, the research of Marrero et al. [7] introduced a model that integrates the assessment of social and environmental impact indicators with cost control tools to evaluate the economic, environmental, and social dimensions of sustainability. Liu et al. [8] assessed the mitigation values and abatement costs associated with sixteen typical low-carbon technologies used in retrofitting buildings: a comprehensive incremental benefits model was developed, taking into account environmental, economic, and social impacts. Most of the works found in the literature tackle the holistic assessment of building performance by adopting multi-objective optimisation. In the work of Kang et al. [9], optimisation algorithms are applied to optimise the building design in terms of emissions, costs, and thermal comfort. By considering passive and active design strategies, the paper of Zong et al. [10] introduced a comprehensive two-phase multi-objective stochastic optimisation framework aimed at reducing both the environmental impact of global warming potential (*GWP*) and costs across the entire lifecycle of a building. Hou et al. [11] selected the minimisation of the building running cost, also accounting for load rebound, as the objective function for constructing a building demand response optimisation model. The authors considered the real-time carbon emission factor, load fluctuation reward, punishment factor, and real-time electricity price. The work of Zhong et al. [12] was instead focused on minimising the carbon emissions of the building and optimising its material utilisation and daylighting. From an environmental perspective, Maduta et al. [13] pointed out the urgent need for binding requirements for Zero-emission Buildings (ZeBs) to be considered holistically. The authors proposed a method for assessing ZeBs by aggregating energy usage and related emissions and outlined procedures for establishing specific benchmarks for operational energy. According to their findings, ZeBs play a pivotal role in the EU's strategy for achieving climate neutrality and can catalyse supplementary advantages, including resilience, recyclability, security, and health benefits. In assessing global warming potential, Izaola et al. [14] determined the whole-life carbon emissions of typical Spanish residential buildings from 1981 to 2010. Their analysis provided a detailed breakdown of both embodied carbon and operational carbon emissions. Bilardo et al. [15] introduced the Zero Power Building framework employing dynamic key performance indicators (KPIs) and demonstrating their effectiveness in overcoming traditional limitations in building energy evaluations. Applying this approach in a real-world district context could support stakeholders in making informed decisions. A similar objective of decision making was investigated by Walker et al. [16], who explored how modelling assumptions affect environmental performance and the reliability of retrofit decisions. They created a framework for comparing greenhouse gas emissions based on various modelling assumptions.

Recent works have addressed the resilience of low-carbon building design to climate change. As building energy consumption contributes to global warming, it also increases the demand for energy used in space conditioning. Breaking this loop is imperative for tackling pressing environmental issues and advancing both liveability and sustainability [17]. A comprehensive optimisation approach that integrates cost analysis and life-cycle assessment was proposed by Ansah et al. [18] to facilitate the transition toward carbon-neutral buildings. Their research highlights the importance of passive strategies and photovoltaic (PV) integration in minimising operational and embodied impacts under future climatic scenarios.

In addition to suggesting broad design recommendations, several studies have examined the nationwide impact of climate change on building performance. Tootkaboni et al. [19] examined the impact of projected climate conditions on the energy balance of nearly zero-energy buildings (NZEBs) across various regions in Italy. Their findings highlight the necessity for region-specific adaptation strategies to sustain long-term comfort and efficiency. Similarly, Rey-Hernández et al. [20] evaluated a zero-energy building (ZEB) in Spain under future weather scenarios, demonstrating that increased cooling demands due to climate change could compromise the building's net-zero status and place additional pressure on renewable energy systems. In the same vein, Viganò et al. [21] compared a traditional building and an NZEB in the UK in the context of projected climates for 2030, 2050, and 2080. Their results showed that NZEBs consistently consumed less energy and produced fewer emissions, even as cooling demands increased. The authors emphasised the importance of incorporating future weather data into the design process to ensure resilient performance over the building's lifespan. Finally, Kim et al. [22] studied office net-zero carbon buildings (NZCBs) under RCP 8.5 (Representative Concentration Pathway 8.5), a high-emission scenario from the IPCC's Fifth Assessment Report [23] that assumes continued fossil fuel use and limited climate mitigation. They found that increasing cooling demand would require PV systems with up to 10% more capacity by 2080 to maintain carbon neutrality. Their conclusions underscore the need to integrate high-performance cooling solutions into NZCB designs to meet future climatic challenges.

In summary, the reviewed literature confirms the significance of a comprehensive evaluation of building performance to achieve zero-carbon objectives and foster sustainable and resilient built environments.

The primary goal of this paper is to conduct an in-depth analysis of the steps required to achieve a ZeB. This includes systematising existing procedures and selecting relevant

KPIs to properly represent the building performance before and after the refurbishment. This study leverages current standardised methodologies to identify strengths, highlight existing weaknesses, and propose potential enhancements. Using a case study approach, the feasibility of converting a typical Italian office building into a Zero-emission Building (ZeB) is assessed. The evaluation includes the implementation of various energy efficiency measures (EEMs) to enhance energy performance, focusing on both the opaque and transparent building envelope, as well as on heating, cooling, and ventilation systems. Moreover, renewable energy systems are integrated into the analysis. To ensure a holistic approach, different KPIs are assessed, encompassing energy performance, operational greenhouse gas emissions, thermal comfort, climate change adaptation, and cost-effectiveness.

2. Theory and Methodology

2.1. Key Performance Indicators

In the definition of sustainability provided by the ISO 37100 technical standard [24], the interdependency between the environmental, social, and economic fields is highlighted. All of these domains are considered in this work, with the energy domain treated as a subset of the environmental system and thermal comfort seen as a direct indicator of social performance [25].

In the past, an exclusive focus on energy performance requirements for individual components has often led to suboptimal solutions, hindering improvements in other domains. Therefore, adopting a holistic approach that integrates multiple domains is essential for driving technological innovation and systemic change.

In this context, tailored KPIs are proposed in Table 1 for describing building performance from a holistic perspective. Each indicator includes details on symbology, terminology, unit of measure, and associated references.

Table 1. Crucial KPIs in different fields.

Field	Symbol	Quantity	Unit	Ref.
Energy performance				
	$EP_{\mathrm{H/C;nd}}$	Energy need for space heating or cooling per unit conditioned floor area	kWh·m^{-2}	[26,27]
	$EP_{\mathrm{gl;nren}}$	Overall non-renewable energy performance	kWh·m^{-2}	[26,28]
	$EP_{\mathrm{gl;tot}}$	Overall total energy performance	kWh·m^{-2}	[26,28]
	RER	Renewable energy ratio	–	[26]
Environmental performance				
		Annual operational greenhouse gas emissions	kg·m^{-2}	[29]
	GWP	Global warming potential	kg·m^{-2}	[29]
Economic assessment				
	$CG{\cdot}A_{\mathrm{use}}{}^{-1}$	Global Cost per unit conditioned floor area	€·m^{-2}	[30]
	PB	Payback Period	a	[30]
	$NPV{\cdot}CO_{\mathrm{inv}}{}^{-1}$	Ratio of net present value to initial investment cost	–	[30]
Thermal comfort				
	PDH	Percentage of discomfort hours	%	[31,32]
	$WHD_{\mathrm{w/c}}$	Warm/Cold Weighted Hours of Discomfort	h	[31,32]
	IOD	Indoor Overheating Degree	°C	[33]
	AWD	Ambient Warmness Degree	°C	[33]
	α	Overheating Escalation Factor	–	[33]
	$SET\ DH$	*Degree.hours* above the setpoint	°C·h	[34]
	Δ_{abs}	Absorptivity Time rate	°C·h	[34]
	Δ_{rec}	Recovery Time rate	°C·h	[34]

2.1.1. Energy Performance

The trias energetica is a three-step approach aimed at achieving climate neutrality. It involves the minimisation of energy need, the exploitation of renewable sources, and the maximisation of energy efficiency. This concept is closely associated with the vision of a ZeB outlined in the new EPBD recast [1].

Energy performance of the building (EPB) indicators are quantitative metrics derived from calculations, measurements, or a combination of both [26]. These indicators encompass the overall energy performance of buildings, partial energy performance, and energy performance of products [35]. The assessed system distinguishes between overall and partial EPB indicators. The former relates to the energy performance of the whole building, while the latter pertains to the performance of specific building elements, energy services, or their combination.

Examples of overall indicators include non-renewable primary energy use ($EP_{\mathrm{gl;nren}}$), total primary energy use ($EP_{\mathrm{gl;tot}}$), and the renewable energy ratio (*RER*) [26]. These indicators are significantly influenced by Primary Energy Factors (PEFs) [36] and can be provided at various temporal resolutions, such as hourly, monthly, or annually, depending on the availability of measured or calculated delivered/exported energy. The *RER*, defined as the ratio of renewable to total primary energy, reflects the potential to meet energy demand using renewable sources and depends on the chosen perimeter (on-site, nearby, or distant) [37].

Thermal energy needs for space heating and cooling ($EP_{\mathrm{H/C;nd}}$) are classified as partial indicators, as they are independent of the building's active systems. According to EN ISO 52000-1 [26], $EP_{\mathrm{H/C;nd}}$ should be calculated on a monthly or hourly basis using EN ISO 52016-1 [27], or through dynamic, detailed simulation tools using hourly or sub-hourly timesteps.

2.1.2. Environmental Performance

The environmental impact of EU buildings is a direct consequence of their energy consumption, emphasising the need for integrated consideration of energy and environmental aspects.

Building emissions are categorised as direct (related to operational energy use) and indirect (referred to as embodied carbon in construction materials). The newly approved EPBD requires the assessment of life-cycle *GWP* for new constructions and, where data are available, for existing buildings. Both operational greenhouse gas (GHG) emissions and the life-cycle *GWP* should be evaluated. To support the EU's climate neutrality goals, Member States have to set, by 2027, threshold values for life-cycle *GWP* in new buildings [1].

The *GWP* quantifies the building's contribution to climate change over a 50-year reference period, following the EN 15978 [29] methodology. Emission sources are classified as fossil or biogenic, depending on whether the CO_2 emissions are compensated by CO_2 absorption. While CO_2 is the most considered greenhouse gas, other gases (e.g., CH_4 or N_2O) may also be considered.

2.1.3. Thermal Comfort

Thermal comfort, as defined by ASHRAE Standard 55 [38], is defined as a mental state of satisfaction with the thermal environment and is generally assessed by subjective evaluation. It depends on several factors, such as metabolic rate, clothing insulation, air and mean radiant temperature, air velocity, and humidity [38]. Proper assessment of thermal comfort is essential for occupant quality of life and well-being.

Annex H of EN ISO 7730 [39] and Annex D of CEN/TR 16798-2 [32] specify several evaluation methods. A key indicator is a percentage of discomfort hours (*PDH*), calculated using method A, which identifies the occupied hours during which the Predicted Mean Vote (*PMV*) or the operative temperature exceeds acceptable ranges for a given indoor environmental quality (IEQ) category.

With the intensification of climate change effects, it is also important to assess thermal comfort under future climate scenarios, particularly considering risks such as overheating and heatwaves.

The IEA's Energy in Buildings and Community (EBC) program [40] has launched the Annex 80 "Resilient Cooling" project to support the adoption of resilient, low-energy, low-carbon cooling strategies [41]. Within this context, the Thermal Conditions Task Force [42] proposed a methodology developed by Hamdy et al. [33] to assess overheating risk using three indicators: Indoor Overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and Overheating Escalation Factor (α). *IOD* is the summation of positive deviations between the indoor operative temperature and the comfort limit during occupied hours. It is averaged over different thermal zones. *AWD* is the cumulative deviation of outdoor air temperature above a base temperature, determined by building type and climate. α is the slope of the regression line between *IOD* and *AWD*, representing building sensitivity to climate-driven overheating.

In free-floating conditions—when cooling systems are off or during power outages—the adaptive comfort model is recommended. A relevant metric for long-term thermal comfort assessment is the Weighted Hours of Discomfort (*WHD*), which measures hours during which indoor operative temperatures exceed adaptive thresholds, weighted by the extent of deviation

$$WHD_{\mathrm{w}} = \sum wf \cdot \tau, \quad \text{for } \theta_{\mathrm{o}} > \theta_{\mathrm{o,limit,upper}} \tag{1}$$

where wf is the weighting factor, τ is the time (in hours), θ_{o} is the indoor operative temperature (in °C), and $\theta_{\mathrm{o,limit,upper}}$ is the upper limit of the comfort range (in °C).

Using Equation (2) from EN ISO 7730 (Method B) [39], the weighting factor (wf) was calculated as

$$wf = 1 + (\theta_{\mathrm{o}} - \theta_{\mathrm{o,limit,upper}})/(\theta_{\mathrm{o,limit,upper}} - \theta_{\mathrm{o,c}}) \tag{2}$$

where $\theta_{\mathrm{o,c}}$ is the optimal operative temperature.

As previously mentioned, in addition to overheating, heat waves are another critical effect of climate change that significantly affects building performance. Sengupta et al. [34] assessed the effects of such disturbances on buildings using specific indicators. Among these indicators, Absorptivity Time (Δ_{abs}) is the duration required for the indoor temperature to rise to its maximum value during a disturbance. Recovery Time (Δ_{rec}) is the time taken for the indoor environment to return to thermally comfortable conditions once the disturbance ends or a recovery action becomes effective. Both Absorptivity and Recovery Time depend on many factors, including the type, severity, and duration of the shock, as well as building characteristics and features of HVAC systems. The authors also proposed a KPI for resilience, known as *degree.hours* (*SET DH*), which quantifies the occupied hours during which the indoor temperature exceeds a pre-defined threshold by 1 K.

2.1.4. Economic Assessment

Economic assessment is necessary for understanding and managing the financial implications of decisions in building design and retrofitting. Two key economic indicators are commonly used: Global Cost (*CG*) is the present value of all costs over a building's lifecycle, including initial investment, annual running, replacement and, where applicable, disposal costs; Payback Period (*PB*) is the time required for monetary savings to offset the initial investment costs. The calculation method of these indicators is detailed in EN 15459-1 [30].

The economic and energy-environmental aspects of building performance are closely linked. Enhancing energy efficiency leads to lower operational costs and reduced greenhouse gas emissions, often resulting in increased property value. For example, Fuerst et al. [43] demonstrated that homes with an A energy rating can sell for up to 14% more than equivalent G-rated properties. Integrating economic and environmental evaluations in the building sector thus supports both sustainable and cost-effective solutions in the long term.

2.2. Procedure for Verifying the Zero-Emission Building

As presented before, a building is classified as zero-emission when it fulfils three main conditions: all energy used in the building is derived from renewable sources, GHG emissions are zero or near zero, and the building has a very high energy performance, defined as at least 10% lower than the primary energy use of a nearly zero-energy building [1].

The procedure to determine the final state of the building developed for this work draws on Annex H of the overarching standard [26], applies the energy efficiency first principle [44], and is aligned with the Italian NZEB minimum requirements [45]. The first step is the building envelope refurbishment to meet NZEB-level minimum requirements. The second step is the assessment of the existing generation systems to identify and remove all existing fossil-based generation systems. The remaining generators should be analysed to determine if size and performance are compliant with the building energy and environmental requirements and, if necessary, should be removed. The third step is the installation of new generators, considering the compatibility with efficient district heating or cooling. In this phase, systems with operational greenhouse gas emissions close to zero should be considered. The last step is the comparison of the refurbished configuration with the NZEB benchmark to evaluate if the 10% primary energy reduction is obtained.

If the building fails to meet the criteria, the process is repeated from the first step, incorporating a cost-benefit analysis to determine further enhancements.

The performance of the final zero-emission configuration is assessed using five indicators, as presented in Table 1: (i) energy need for space heating and cooling, (ii) overall non-renewable energy performance, (iii) annual operational greenhouse gas emissions, (iv) ratio of net present value to initial investment cost, and (v) Warm Weighted Hours of Discomfort.

2.3. Future Weather Data Creation

To evaluate buildings' capacity to adapt to the impacts of climate change, this study assesses their future energy performance and thermal comfort using future weather data generated in alignment with the IEA-EBC ANNEX 80 Weather Data Task Group methodology [46].

The spatial resolution of Global Climate Models (GCMs), which are mathematical models for predicting changes in the climate on a global scale, normally ranges from 150 to 600 km^2 [23]. Nevertheless, finer resolution is necessary for building-scale energy simulations since the overmentioned range fails to capture the effects of climate change and extreme weather conditions associated with it at the local scale. Therefore, downscaling of GCM outputs to a spatial resolution of less than 100 km^2 and a temporal resolution finer than monthly averages is essential. In particular, the dynamical technique to generate climate data with finer spatial and temporal resolution, which uses Regional Climate Models (RCMs), is a popular and precise downscaling method that enables capturing the variability of local climate conditions and providing physically consistent data sets [47].

In this study, GERICS-REMO-2015 developed by the Climate Service Center Germany (GERICS) is used as the RCM, while the study's driving model is MPI-ESM-LR, since it is well-supported by the IPCC report on climate model evaluation [48]. The data originate from the EURO-CORDEX portal [49] through the Earth System Grid Federation (ESGF) for the European domain and are provided on a 0.11° rotated grid, corresponding to a 12.5 km^2 spatial resolution. Hourly meteorological data are obtained using the CORDEX Data Extractor tool for three time series: 2001–2020 (2010s), 2041–2060 (2050s), and 2081–2100 (2090s). The analysis is based on the RCP 8.5 (Representative Concentration Pathway) scenario from the IPCC's Fifth Assessment Report [23], which represented the most recent climate projection available at the time of this study. Furthermore, the bias of raw climate variables is corrected using measured data through quantile delta mapping (QDM) [50] and multivariate bias correction using N-dimensional probability density function transform (MBCn) [51]. Following this, by comparing the measured and bias-corrected data, the bias correction is technically validated.

The next step involved constructing the future typical meteorological year (TMY) using the 20 years of bias-adjusted climatic data and following the EN ISO 15927-4 [52] methodology to guide the selection of representative meteorological data for the assessment of the long-term mean energy use for heating and cooling. The twelve most representative months for each period—including historical (2001–2020), future medium-term (2041–2060), and future long-term (2081–2100)—were selected by comparing the Cumulative Distribution Function of every single year and reference dataset using Finkelstein–Schafer (FS) statistics [53]. This method was selected for this study as it accounts for global solar irradiance, relative humidity, dry-bulb air temperature, and wind speed.

3. Application

3.1. Building Description

The reference case study, located in Turin (Italy), is a building characterised by data extrapolated from the survey carried out by the CRESME for ENEA and the results of the BEEPS project [54]. The case study represents an office building with a reinforced concrete structure and large glazed surfaces. It consists of five stories above ground and is elevated from the ground by pilotis, which were added to the base configuration. The roof has a flat design. Table 2 shows the main geometric characteristics of the building.

Table 2. Main geometric data of the case study.

Parameter	Unit	Value
Number of floors	–	5
Building height	m	15
Length	m	30
Depth	m	16
Inter-floor height	m	3
Gross conditioned volume, V_g	m^3	7200
Net floor area, A_{fl}	m^2	2400
Envelope gross area, A_{env}	m^2	2340
Compactness ratio, A_{env}/V_g	m^{-1}	0.33

The building has a rectangular plan form with a central block containing two stairwells that provide access to the floors. As shown in Figure 1, the stairwells are separated by service spaces and surrounded by a corridor, which provides access to the office rooms and other spaces. The vertical opaque envelope consists of hollow brick walls with insulation, while the horizontal opaque structures are made of concrete. Window components include double-glazing and aluminium frames with internal window shades. The building is currently served by a traditional gas boiler, with fan coils as the heat emission system. There is no mechanical ventilation or summer air conditioning system installed.

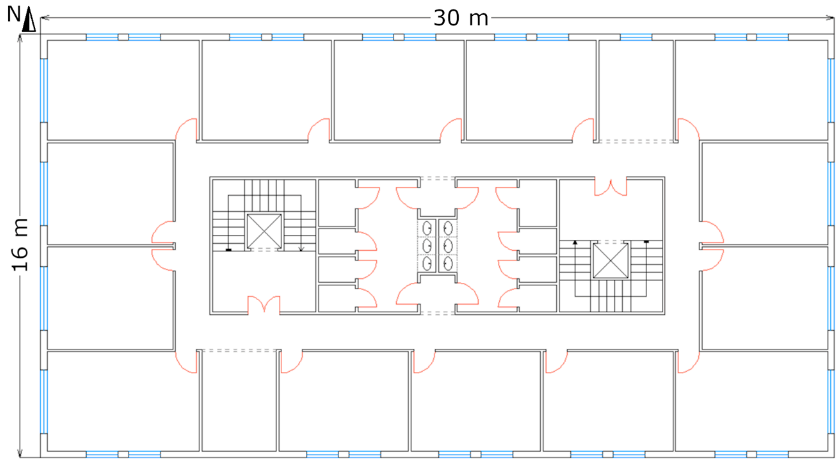

Figure 1. Plan type [54].

Table 3 shows the main thermal properties of the building envelope.

Table 3. Thermal properties of building envelope components.

Component	Thickness s [m]	Thermal Transmittance U $[\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}]$
External wall	0.45	0.964
Ground floor slab	0.30	1.127
Roof deck	0.30	0.849
Window	–	2.870

Occupancy profiles, as well as data for appliances, domestic hot water, and heating/cooling set points, were defined according to the EN 16798-1 [31] standard and its Italian National Annex [55]. The heating season was defined according to Italian legislation, while the cooling season was considered to extend from June to August.

3.2. Energy Efficiency Measures

Several improvement actions were implemented to enhance the building's energy performance. The opaque components (walls, roof, and floor adjacent to the external environment) were improved with an insulation layer, and the existing windows were replaced with high-performance glazing. Table 4 reports the reference thermal transmittance values required for the NZEB configuration, which served as the baseline for the refurbishment.

Table 4. Reference thermal properties for building envelope components.

Component	Thermal Transmittance U $[\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}]$
External wall	0.260
Ground floor slab	0.260
Roof deck	0.220
Window	1.400

A mechanical ventilation system equipped with a heat recovery system (HRV) was added. The HRV control system activates when the external air temperature is either below or above the zone air temperature, respectively, in heating and cooling conditions, with a 1 K deadband. This control logic was based on the methodology proposed in [56]. A summer air conditioning system was also introduced in the building. It uses the existing fan coils as emitters and is powered by an electric chiller. For heating, the existing boiler was replaced by a connection to the local district heating. Furthermore, a PV system with a minimum peak capacity of 12 kW—sized as the ground floor area multiplied by 0.025, according to Italian NZEB requirements [57]—was installed.

3.3. Economic Assessment Assumptions

The economic assessment was performed considering current component costs in Italy [58]. Energy price trends were based on Eurostat data for gas and electricity prices for non-household consumers in Italy [59,60].

Due to the absence of reliable future cost projections for both components and energy, the economic assessment was limited to the present time.

3.4. Warm Weighted Hours of Discomfort Assessment Assumptions

Indoor thermal comfort was assessed by analysing two representative office rooms differentiated for solar exposure: one north-facing and one south-facing, both located on intermediate floors. Table 5 presents the main geometric features of these rooms. The analysis was performed during the cooling season under free-floating conditions.

Table 5. Main geometric data of the considered representative offices.

Quantity	Unit	Value	
		North Office	South Office
Length	m	5.0	5.0
Depth	m	2.9	4.2
Conditioned net volume, V	m^3	39.7	56.8
Conditioned net floor area, A_{fl}	m^2	14.7	21.0

3.5. Modelling Assumptions

The building was simulated using EnergyPlus, considering the climatic conditions of the Bauducchi weather station (Latitude 44.96° N, Longitude 7.70° E, altitude 226 m.a.s.l.). Three climatic data sets were used: one for the present time (modelled and bias-corrected data for the period 2001–2020, referred to as the 2010s) and two for the future scenarios (bias-corrected projected data for the periods 2041–2060 and 2081–2100, corresponding to the 2050s and 2090s, respectively). Measured data from 2013 to 2023 from the Bauducchi weather station were used for bias adjustment of the modelled datasets.

The analysis employed non-renewable (f_{Pnren}), renewable (f_{Pren}), and total (f_{Ptot}) primary energy conversion factors, as defined by Italian legislation [45], along with the annual operational greenhouse gas emission coefficient (K_{CO2}) derived from the Italian Annex to EN ISO 52000-1 [61]. For district heating, the conversion factors provided by the local energy utility were used [62]. The conversion factors for the considered energy carriers are presented in Table 6.

Table 6. Conversion factors for primary energy and annual operational greenhouse gas emissions.

Energy carrier	f_{Pnren} [–]	f_{Pren} [–]	f_{Ptot} [–]	K_{CO2} [kg·kWh^{-1}]
Natural gas	1.05	0.00	1.05	0.21
Electricity from the grid	1.95	0.47	2.42	0.46
District heating	0.39	0.04	0.42	0.09
Electricity from PV	0.00	1.00	1.00	0.00

4. Results and Discussion

This section presents the main results of the procedure to achieve the Zero-emission Building.

The building was refurbished following the method presented in Section 2.2. The envelope's final thermal properties are presented in Table 7. The application of the refurbishment choice algorithm led to opaque envelope properties close to the NZEB-level minimum requirements, while the transparent components present a lower thermal transmittance than the minimum one. Thermal insulation layers with variable thicknesses and a thermal conductivity of 0.035 W·m^{-1}·K^{-1} were used to enhance the opaque envelope thermal properties. The final value of the total solar energy transmittance of the transparent components is 0.67. The enhancement of transparent components was preferred since it was more convenient than further improving the building's opaque envelope thermal properties.

Table 7. Thermal properties of building envelope components after the improving actions.

Component	Thickness s [m]	Thermal Transmittance U [W·m^{-2}·K^{-1}]
External wall	0.55	0.257
Ground floor slab	0.41	0.248
Roof deck	0.42	0.217
Window	–	1.200

The building's refurbished state is compliant with the energy efficiency requirements, with a total energy performance reduction of 12.3% compared to the NZEB configuration. While a significant reduction in the operative GHG emissions is achieved through the refurbishment action, as explained hereafter, a zero-emission target was impossible to reach with reasonable refurbishment solutions. For this reason, the GHG requirement was neglected.

The generators and the district heating heat exchanger were sized according to the building's needs as follows: chiller 167 kW, district heating thermal exchanger 38 kW, and thermal solar panels 24 kW.

The relevant indicators assessed for the building in the original state (OS) and for the refurbished building (RF) in the three time periods are presented in Tables 8–10. They present the relative variation of KPIs for the refurbished building compared to the original-state building and future periods compared to the current time, respectively.

Table 8. KPIs for the original-state (OS) and refurbished building (RF) in the three time periods.

KPI	OS			RF		
	2010s	2050s	2090s	2010s	2050s	2090s
$EP_{H;nd}$ [kWh·m^{-2}]	66.0	57.8	38.9	33.8	28.5	17.2
$EP_{C;nd}$ [kWh·m^{-2}]	34.6	39.5	58.1	35.6	39.4	53.2
$EP_{gl;nren}$ [kWh·m^{-2}]	122.3	112.0	68.5	37.6	39.3	47.4
Annual operational GHG emissions [kg·m^{-2}]	39.1	37.0	25.6	23.3	24.9	30.4
$NPV \cdot CO_{inv}{}^{-1}$ [–]	–	–	–	0.2	–	–
WHD_w (north office) [h]	4197	4772	6278	1298	1918	3451
WHD_w (south office) [h]	5070	5617	7000	1830	2462	3878

Table 9. Relative variation of KPIs for the refurbished building compared to the original state.

KPI	2010s	2050s	2090s
$EP_{H;nd}$ [kWh·m^{-2}]	−49%	−51%	−56%
$EP_{C;nd}$ [kWh·m^{-2}]	+3%	±0%	−8%
$EP_{gl;nren}$ [kWh·m^{-2}]	−69%	−65%	−31%
Annual operational GHG emissions [kg·m^{-2}]	−40%	−33%	+19%
$NPV \cdot CO_{inv}{}^{-1}$ [–]	–	–	–
WHD_w (north office) [h]	−69%	−60%	−45%
WHD_w (south office) [h]	−64%	−56%	−45%

Table 10. Relative variation of KPIs for the future times compared to 2010.

KPI	OS		RF	
	2050s	2090s	2050s	2090s
$EP_{H;nd}$ [kWh·m^{-2}]	−12%	−41%	−16%	−49%
$EP_{C;nd}$ [kWh·m^{-2}]	+14%	+68%	+11%	+50%
$EP_{gl;nren}$ [kWh·m^{-2}]	−8%	−44%	+5%	+26%
Annual operational GHG emissions [kg·m^{-2}]	−5%	−35%	+7%	+ 30%
$NPV \cdot CO_{inv}{}^{-1}$ [–]	–	–	–	–
WHD_w (north office) [h]	+14%	+50%	+48%	+166%
WHD_w (south office) [h]	+11%	+38%	+35%	+112%

The results show a reduction of close to 50% in the energy need for heating from the OS to the RF in all the cases. The energy need for cooling only increases in the 2010s dataset, while it decreases when considering future climates.

This trend, considering the time evolution as presented in Table 10, indicates a progressive decrease in the energy need for heating (around −15% for the 2050s and between −40 and −49% for the 2090s) for both the OS and the RF. Conversely, the energy need for cooling increases between +10% (RF) and +14% (OS) for the 2050s and between +50% (RF) and +70% (OS) for the 2090s. This result is coherent with the external temperature increase due to the global warming effect.

The differences in the overall non-renewable energy performance results mainly derive from three aspects: the difference in the energy needs for heating and cooling, the different use of energy carriers, and the differences in the provided energy services (i.e., the cooling system and the solar photovoltaic ones).

From the OS to the RF, there is a significant decrease (between −30 and −70%) due to the reduction of the energy need for heating but also due to the different energy carriers. The non-renewable energy conversion factor for the heating energy carrier is halved from the OS (natural gas) to the RF (district heating). The increase in energy use due to space cooling and mechanical ventilation services is counterbalanced by this effect and by the electrical production from the PV.

The trend, considering the time evolution as presented in Table 10, shows a reduction in the OS, −8% for the 2050s and −44% for the 2090s, and an increase in the RF, +5% for the 2050s and +26% for the 2090s. These results are coherent with the aforementioned effects.

The results in terms of annual operational greenhouse gas emissions are substantially similar to the overall non-renewable energy performance ones. This is because this KPI is a function of the overall total energy performance, derived from the overall non-renewable energy performance.

It is noticeable that, while a significant reduction in the emissions is achieved (−40% from the OS to the RF in the 2010s), the values are still far from the goal required in the EPBD.

The economic KPI, due to the aforementioned lack of future data, was assessed only for the current time, and further comparisons were not possible.

The results related to thermal comfort, evaluated through the Warm Weighted Hours of Discomfort (WHD_w), show a significant improvement in the refurbished building (RF) compared to the original state (OS). In the 2010s scenario, WHD_w are reduced by 70% in the north-facing office and 65% in the south-facing one. These results highlight the high contribution of passive energy efficiency measures in enhancing indoor thermal comfort.

In future climate scenarios, a progressive increase in discomfort hours is observed. Between the 2010s and 2090s, WHD_w increases by about 55% in both the north-facing and south-facing offices as a result of climate change. The WHD_w are significantly lower in the refurbished building than in the OS.

5. Conclusions

This work evaluates the transformation of a building into a Zero-emission Building under current national and EU legislative frameworks while also considering future climates.

A case study approach was adopted, focused on a building located in northern Italy. The current national and European legislations were applied to determine the requirements for achieving the ZeB target. A simplified algorithm was developed and implemented, integrating legislative requirements, the energy efficiency first principle, and economic viability. Five indicators—covering energy, economic, and comfort domains—were evaluated and compared.

The results show reasonable variations in the KPIs attributable to improvements in envelope and systems performance, changes in energy carriers, and the influence of future climatic conditions.

The main challenges were those related to the conversion factors for primary energy and annual operational greenhouse gas emissions. In Italy, the current primary energy conversion factor values were established in 2015 and have not been updated since. In the context of fast changes in energy production, these values are increasingly outdated. Given the European decarbonisation targets for the building sector, it is anticipated that the national electricity grid will progressively evolve to provide renewable and carbon-free energy. Unless the conversion factors are revised to reflect this evolution, the development of realistic and future-oriented refurbishment scenarios will remain constrained and potentially unreliable.

The result of this work shows that, under the current framework, the only viable option to achieve zero or close to zero operational greenhouse gas emissions involves complete disconnection from the energy grid. The use of district heating, district cooling, or electrical energy from the grid, according to the current conversion factors, results in non-negligible emissions. Therefore, only buildings that rely solely on electricity as an energy carrier and are able to completely meet their demands through on-site production with renewable generation seem to meet the established ZeB requirements.

Moreover, the smaller variation observed over time in the refurbished scenario—especially regarding cooling energy demand and Weighted Hours of Discomfort—indicates that the adopted retrofit actions have enhanced the building's resilience to future climate conditions. However, additional climate-resilient solutions are needed to address climate change adaptation.

Overall, this study contributes to advancing the current state of the art by organising calculation methods, indicators, and standardised procedures in a structured manner, highlighting strengths and gaps, and providing a basis for improving the design and evaluation of future ZeBs. Nevertheless, there are some limitations in this study. First, the economic assessment was restricted to current market conditions due to the unavailability of reliable projections for future energy prices and component costs. This constrains the ability to evaluate the long-term cost-effectiveness of refurbishment strategies. Another limitation concerns the use of future weather data: although the data were bias-corrected and validated against observations, only one Regional Climate Model (RCM), GERICS-REMO-2015, was employed. As a result, the analysis does not account for the uncertainty associated with using multiple climate models or emission scenarios.

Future research activities should focus on the development of tools and data to support refurbishment assessment aimed at long-term projections. This includes assessing the evolution of Primary Energy Factors (PEFs) up to at least 2050, in alignment with the European zero-carbon deadline, and forecasting future costs of building components and energy to enable robust economic evaluations. In addition, the inclusion of circular economy principles—such as material reuse, recyclability, and life-cycle resource efficiency—should be explored to enhance the sustainability and environmental performance of renovation strategies. Furthermore, future studies should investigate the integration of resilient cooling technologies into retrofit strategies, while incorporating occupant feedback through post-occupancy evaluation to support user-centred and climate-adaptive retrofit design.

Author Contributions: Conceptualization, F.B.M.D., M.P.T., I.B., and V.C.; methodology, F.B.M.D., M.P.T., M.P., I.B., and V.C.; software, F.B.M.D. and M.P.T.; validation, F.B.M.D. and M.P.T.; formal analysis, M.P. and M.P.T.; investigation, M.P.T. and M.P.; writing—original draft preparation, M.P.T., M.P., F.B.M.D., I.B., and V.C.; writing—review and editing, I.B. and V.C.; visualization, M.P.T. and F.B.M.D.; supervision, V.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Union. *Directive 2024/1275 of the European Parliament of the Council of 24 April 2024 on the Energy Performance of Buildings (Recast)*; European Union: Brussels, Belgium, 2024.
2. Huovila, A.; Siikavirta, H.; Rozado, C.A.; Rökman, J.; Tuominen, P.; Paiho, S.; Hedman, Å.; Ylén, P. Carbon-neutral cities: Critical review of theory and practice. *J. Clean. Prod.* **2022**, *341*, 130912. [CrossRef]
3. Tetteh, M.O.; Darko, A.; Chan, A.P.C.; Jafari, A.; Brilakis, I.; Chen, W.; Nani, G.; Yevu, S.K. Scientometric mapping of global research on green retrofitting of existing buildings (GREB): Pathway towards a holistic GREB framework. *Energy Build.* **2022**, *277*, 112532. [CrossRef]
4. Ibañez Iralde, N.S.; Pascual, J.; Salom, J. Energy retrofit of residential building clusters. A literature review of crossover recommended measures, policies instruments and allocated funds in Spain. *Energy Build.* **2021**, *252*, 111409. [CrossRef]
5. Huang, H.; Wang, H.; Hu, Y.J.; Li, C.; Wang, X. The development trends of existing building energy conservation and emission reduction—A comprehensive review. *Energy Rep.* **2022**, *8*, 13170–13188. [CrossRef]

6. Qiao, J.; Zhang, X.; Hao, C.; Liu, S.; Zhang, Y.; Xing, K.; Yang, P. Post-occupancy evaluation of the actual performance of a low-carbon building. *Energy Rep.* **2023**, *10*, 228–243. [CrossRef]
7. Marrero, M.; Rivero-Camacho, C.; Martinez-Rocamora, A.; Alba-Rodriguez, D.; Lucas-Ruiz, V. Holistic assessment of the economic, environmental, and social impact of building construction. Application to housing construction in Andalusia. *J. Clean. Prod.* **2024**, *434*, 140170. [CrossRef]
8. Liu, Y.; Xue, S.; Guo, X.; Zhang, B.; Sun, X.; Zhang, Q.; Wang, Y.; Dong, Y. Towards the goal of zero-carbon building retrofitting with variant application degrees of low-carbon technologies: Mitigation potential and cost-benefit analysis for a kindergarten in Beijing. *J. Clean. Prod.* **2023**, *393*, 136316. [CrossRef]
9. Kang, Y.; Zhang, D.; Cui, Y.; Xu, W.; Lu, S.; Wu, J.; Hu, Y. Integrated passive design method optimized for carbon emissions, economics, and thermal comfort of zero-carbon buildings. *Energy* **2023**, *295*, 131048. [CrossRef]
10. Zong, C.; Chen, X.; Deghim, F.; Staudt, J.; Geyer, P.; Lang, W. A holistic two-stage decision-making methodology for passive and active building design strategies under uncertainty. *Build. Environ.* **2023**, *251*, 111211. [CrossRef]
11. Hou, L.; Lin, H.; Yang, X.; Ren, H.; Shao, D. Low-carbon demand response strategy of buildings considering load rebound. *Energy Rep.* **2023**, *10*, 3599–3607. [CrossRef]
12. Zhong, Y.; Qin, Z.; Feng, R.; Liu, Y. Low-carbon design: Building optimization considering carbon emission, material utilization, and daylighting. *J. Clean. Prod.* **2024**, *434*, 140087. [CrossRef]
13. Maduta, C.; Melica, G.; D'Agostino, D.; Bertoldi, P. Towards a decarbonised building stock by 2050: The meaning and the role of zero emission buildings (ZEBs) in Europe. *Energy Strateg. Rev.* **2022**, *44*, 101009. [CrossRef]
14. Izaola, B.; Akizu-Gardoki, O.; Oregi, X. Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. *Sustain. Prod. Consum.* **2023**, *40*, 252–264. [CrossRef]
15. Bilardo, M.; Kämpf, J.; Fabrizio, E. From Zero Energy to Zero Power Buildings: A new paradigm for a sustainable transition of the building stock. *Sustain. Cities Soc.* **2024**, *101*, 105136. [CrossRef]
16. Walker, L.; Hischier, I.; Schlueter, A. The impact of modeling assumptions on retrofit decision-making for low-carbon buildings. *Build. Environ.* **2022**, *226*, 109683. [CrossRef]
17. Ascione, F.; Bianco, N.; De Masi, R.F.; Mauro, G.M.; Vanoli, G.P. Resilience of robust cost-optimal energy retrofit of buildings to global warming: A multi-stage, multi-objective approach. *Energy Build.* **2017**, *153*, 150–167. [CrossRef]
18. Ansah, M.K.; Chen, X.; Yang, H. A holistic environmental and economic design optimization of low carbon buildings considering climate change and confounding factors. *Sci. Total Environ.* **2022**, *821*, 153442. [CrossRef]
19. Tootkaboni, M.P.; De Luca, G.; Ballarini, I.; Corrado, V. Climate change impact on the future performance of nearly zero energy buildings: A case study base analysis. In Proceedings of the Building Simulation 2021: 17th Conference of IBPSA, Bruges, Belgium, 1–3 September 2021. [CrossRef]
20. Rey-Hernández, J.M.; Yousif, C.; Gatt, D.; Velasco-Gómez, E.; San José-Alonso, J.; Rey-Martínez, F.J. Modelling the long-term effect of climate change on a zero energy and carbon dioxide building through energy efficiency and renewables. *Energy Build.* **2018**, *174*, 85–96. [CrossRef]
21. Viganò, G.S.M.; Rugani, R.; Marengo, M.; Picco, M. Assessing the Impact of Climate Change on Building Energy Performance: A Future-Oriented Analysis on the UK. *Architecture* **2024**, *4*, 1201–1224. [CrossRef]
22. Kim, D.; Cho, H.; Mago, P.J.; Yoon, J.; Lee, H. Impact on renewable design requirements of net-zero carbon buildings under potential future climate scenarios. *Climate* **2021**, *9*, 17. [CrossRef]
23. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
24. *ISO 37100*; Sustainable Cities and Communities—Vocabulary. International Organization for Standardization (ISO): Geneva, Switzerland, 2016.
25. *EN 15643*; Sustainability of Construction Works—Framework for Assessment of Buildings and Civil Engineering Works. European Committee for Standardisation (CEN): Brussels, Belgium, 2021.
26. *EN ISO 52000-1*; Energy Performance of Buildings—Overarching EPB Assessment—Part 1: General Framework and Procedures. European Committee for Standardisation (CEN): Brussels, Belgium, 2017.
27. *EN ISO 52016-1*; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads—Part 1: Calculation Procedures. European Committee for Standardisation (CEN): Brussels, Belgium, 2017.
28. *EN ISO 52003-1*; Energy Performance of Buildings—Indicators, Requirements, Ratings and Certificates—Part 1: General Aspects and Application to the Overall Energy Performance. European Committee for Standardisation (CEN): Brussels, Belgium, 2017.
29. *EN 15978*; Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. European Committee for Standardisation (CEN): Brussels, Belgium, 2011.
30. *EN 15459-1*; Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings—Part 1: Calculation Procedures, Module M1-14. European Committee for Standardisation (CEN): Brussels, Belgium, 2017.

31. *EN 16798-1*; Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics—Module M1-6. European Committee for Standardisation (CEN): Brussels, Belgium, 2019.
32. *CEN/TR 16798-2*; Energy Performance of Buildings—Ventilation for Buildings—Part 2: Interpretation of the Requirements in EN 16798-1—Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics (Module M1-6). European Committee for Standardisation (CEN): Brussels, Belgium, 2019.
33. Hamdy, M.; Carlucci, S.; Hoes, P.J.; Hensen, J.L. The impact of climate change on the overheating risk in dwellings—A Dutch case study. *Build. Environ.* **2017**, *122*, 307–323. [CrossRef]
34. Sengupta, A.; Al Assaad, D.; Bastero, J.B.; Steeman, M.; Breesh, H. Impact of heatwaves and system shocks on a nearly zero energy educational building: Is it resilient to overheating? *Build. Environ.* **2023**, *234*, 110152. [CrossRef]
35. *ISO 52018-1*; Energy Performance of Buildings—Indicators for Partial EPB Requirements Related to Thermal Energy Balance and Fabric Features—Part 1: Overview of Options. European Committee for Standardisation (CEN): Brussels, Belgium, 2017.
36. *EN 17423*; Energy Performance of Buildings—Determination and Reporting of Primary Energy Factors (PEF) and CO2 Emission Coefficient—General Principles, Module M1-7. European Committee for Standardisation (CEN): Brussels, Belgium, 2020.
37. European Commission. *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast)*; European Union: Brussels, Belgium, 2018.
38. *ANSI/ASHRAE Standard 55-2023*; Thermal Environmental Conditions for Human Occupancy. American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE): Atlanta, GA, USA, 2023.
39. *EN ISO 7730*; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. European Committee for Standardisation (CEN): Brussels, Belgium, 2005.
40. Energy in Buildings and Communities Programme (EBC) Website. Available online: https://www.iea-ebc.org/ (accessed on 6 April 2025).
41. Attia, S.; Rahif, R.; Corrado, V.; Levinson, R.; Laouadi, A.; Wang, L.; Sodagar, B.; Machard, A.; Gupta, R.; Olesen, B.W.; et al. *Framework to Evaluate the Resilience of Different Cooling Technologies*; IEA Annex 80, Thermal Conditions Task Force; SBD Lab: Liege, Belgium, 2021. [CrossRef]
42. Zhang, C.; Kazanci, O.B.; Attia, S.; Levinson, R.; Lee, S.H.; Holzer, P.; Salvatif, A.; Machard, A.; Tootkaboni, M.P.; Gaur, A.; et al. *IEA EBC Annex 80—Dynamic Simulation Guideline for the Performance Testing of Resilient Cooling Strategies*; DCE Technical Reports 299; Department of the Built Environment, Aalborg University: Aalborg, Denmark, 2021.
43. Fuerst, F.; Cardia Haddad, M.F.; Adan, H. Is there an economic case for energy-efficient dwellings in the UK private rental market? *J. Clean. Prod.* **2020**, *245*, 118642. [CrossRef]
44. European Union. *Regulation (EU) 2018/1999 of the European Parliament of the Council of 11 December 2018 on the Governance of the Energy Union Climate Action Amending Regulations (EC) No, 6.6.3./.2.0.0.9.; (EC) No 715/2009 of the European Parliament of the Council Directives, 9.4./.2.2./.E.C.; 98/70/EC; 2009/31/EC; 2009/73/EC; 2010/31/EU; 2012/27/EU; 2013/30/EU of the European Parliament of the Council Council Directives, 2.0.0.9./.1.1.9./.E.C.; (EU), 2.0.1.5./.6.5.2.; Repealing Regulation (EU) No 525/2013 of the European Parliament of the Council (Text with EEARelevance)*; European Union: Brussels, Belgium, 2018.
45. Italian Republic. Decreto Interministeriale 26 Giugno 2015—Applicazione Delle Metodologie di Calcolo Delle Prestazioni Energetiche e Definizione Delle Prescrizioni e dei Requisiti Minimi Degli Edifici. 2015. Available online: https://www.mimit.gov.it/index.php/it/normativa/decreti-interministeriali/decreto-interministeriale-26-giugno-2015-adeguamento-linee-guida-nazionali-per-la-certificazione-energetica-degli-edifici (accessed on 31 March 2025).
46. Machard, A.; Salvati, A.; Tootkaboni, M.P.; Gaur, A.; Zou, J.; Wang, L.L.; Baba, F.; Ge, H.; Bre, F.; Bozonnet, E.; et al. Typical and extreme weather datasets for studying the resilience of buildings to climate change and heatwaves. *Sci. Data.* **2024**, *11*, 531. [CrossRef] [PubMed]
47. Soares, P.M.; Cardoso, R.M.; Miranda, P.M.; de Medeiros, J.; Belo-Pereira, M.; Espirito-Santo, F. WRF high resolution dynamical downscaling of ERA-Interim for Portugal. *Clim. Dyn.* **2012**, *39*, 2497–2522. [CrossRef]
48. Flato, G.; Marotzke, J.; Abiodun, B.; Braconnot, P.; Chou, S.C.; Collins, W.; Cox, P.; Driouech, F.; Emori, S.; Eyring, V.; et al. Evaluation of Climate Models. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
49. EURO-CORDEX: The European Branch of the Coordinated Regional Downscaling Experiment. Available online: https://www.euro-cordex.net/ (accessed on 31 March 2025).
50. Cannon, A.J.; Sobie, S.R.; Murdock, T.Q. Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes? *J. Clim.* **2015**, *28*, 6938–6959. [CrossRef]
51. Cannon, A.J. Multivariate quantile mapping bias correction: An N-dimensional probability density function transform for climate model simulations of multiple variables. *Clim. Dyn.* **2018**, *50*, 31–49. [CrossRef]

52. *EN ISO 15927-4*; Hygrothermal Performance of Buildings Calculation and Presentation of Climatic Data, Part 4: Hourly Data for Assessing the Annual Energy Use for Heating and Cooling. European Committee for Standardisation (CEN): Brussels, Belgium, 2005.
53. Finkelstein, J.M.; Schafer, R.E. Improved goodness-of-fit tests. *Biometrika* **1971**, *58*, 641–645. [CrossRef]
54. Citterio, M. *Analisi Statistica sul Parco Edilizio non Residenziale e Sviluppo di Modelli di Calcolo Semplificati*; Report RSE/2009/161; ENEA, Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile: Rome, Italy, 2009.
55. Italian Thermo-technical Committee (CTI). *Italian National Annex to EN 16798-1 (Draft), Document No. 024100360*; Restricted Document; Italian Thermo-technical Committee (CTI): Milan, Italy, 2022.
56. Guillén-Lambea, S.; Rodríguez-Soria, B.; Marín, J.M. Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB—Quantitative analysis of the air conditioning demand. *Energy Build.* **2017**, *146*, 271–282. [CrossRef]
57. Italian Republic. Legislative Decree 2021/199 Attuazione della direttiva (UE) 2018/2001 del Parlamento europeo e del Consiglio, dell'11 dicembre 2018, sulla promozione dell'uso dell'energia da fonti rinnovabili. *Off. J. Ital. Repub. Ser. Gen.* **2021**, *285*, 1–197.
58. DEI. *Prezzi Informativi dell'Edilizia—Recupero Ristrutturazione Manutenzione 1° Semestre 2024*; DEI: Milan, Italy, 2024.
59. Gas Prices Components for Non-Household Consumers—Annual Data. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203_c/default/table?lang=en&category=nrg.nrg_price.nrg_pc (accessed on 31 March 2025).
60. Electricity Prices Components for Non-Household Consumers—Annual Data (from 2007 Onwards). Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205_c/default/table?lang=en&category=nrg.nrg_price.nrg_pc (accessed on 31 March 2025).
61. Italian Thermo-Technical Committee (CTI). *Italian National Annex to EN ISO 52000-1 (Draft), Document No. 20400124*; Restricted Document; Italian Thermo-Technical Committee (CTI): Milan, Italy, 2022.
62. Validazione del Fattore di Emissione del Teleriscaldamento—Validazione dei Fattori di Conversione in Energia Primaria del Teleriscaldamento. Available online: https://www.gruppoiren.it/content/dam/iren/documents/it/i-nostri-servizi/teleriscaldamento/2023/FETR-PECF-015-IREN_ENERGIA_TLR_TORINO.pdf?view=yes/ (accessed on 31 March 2025).