The Future of Nearly Zero Energy Buildings (NZEBs) in a Warming Climate: Balancing Heating, Cooling, and Renewable Energy Strategies

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Abstract

As climate change accelerates, nearly zero-energy buildings (NZEBs) are emerging as a cornerstone of sustainable development. Rising global temperatures and shifting weather patterns necessitate innovative approaches to balancing heating and cooling demands while maximizing the integration of renewable energy sources. The study explores the future of NZEBs in the context of a warming climate, assessing the impact of global and regional climate change on building energy needs and adaptation strategies. It highlights cutting-edge technologies such as dynamic insulation, smart building envelopes, advanced energy management systems, and integrated HVAC solutions. Special emphasis is placed on modern passive cooling techniques, energy storage innovations, and the utilization of local renewable energy sources, including photovoltaics and geothermal systems. Additionally, the study examines the evolution of energy policies and building standards that facilitate NZEB development in the face of rising temperatures. Key challenges, including the increasing demand for cooling, the urban heat island effect, and the role of smart building management systems (BEMS) in optimizing energy performance, are critically analyzed Findings indicate that a holistic approach to the design and operation of NZEBs enhances energy efficiency while maintaining indoor comfort under changing climatic conditions.

Keywords: *Nearly Zero Energy Buildings (NZEBs), energy efficiency, climate change, renewable energy sources, passive cooling strategies, intelligent building systems*

1. Introduction

Global warming has become one of the most severe issues facing the modern world. It affects almost all sectors of the economy, particularly construction. This industry consumes massive amounts of energy and is a significant source of greenhouse gas emissions. As such, it has a significant impact on exacerbating and mitigating the effects of climate change. The relationship between construction and climate change is a self-reinforcing loop. Rising temperatures increase the demand for energy for cooling. At the same time, buildings generate high carbon dioxide emissions throughout their life cycle. This phenomenon powers global warming and requires urgent action to reduce emissions and improve the energy efficiency of buildings. [1].

According to a European Parliament directive, buildings are responsible for 36% of the EU's energy-related greenhouse gas emissions [2]. Every change in the design, construction and exploitation of buildings can significantly reduce their impact on the climate. Buildings must be durable and resilient to the effects of climate change. This requires modern technologies and changes in policy and regulations to facilitate the transformation of the sector.

One of the solutions on the path to energy-efficient and climate-resilient construction are nearly zero-energy buildings (NZEB). Their purpose is to reduce energy demand. This is achieved through high thermal insulation of the envelope, modern ventilation with heat recovery and the use of renewable energy sources. Among these, photovoltaic panels and heat pumps are most commonly used. This makes it possible to balance the energy needs of a building with its impact on the environment.

The problems that need to be solved include the instability of renewable energy sources, the impact of urban heat islands and the risk of buildings overheating in the future. Possible solutions include passive cooling methods, smart building envelopes, energy storage and building energy management systems. Each case requires the appropriate measures to be selected due to its unique circumstances. There is no universal set of solutions. In order to facilitate further growth, it is essential that climate policy and legislation provide support for the widespread implementation of NZEB. Financial incentives and support mechanisms for investors and developers are essential.

This study examines the future of NZEB in a warming climate, assessing the impact of climate change on building energy needs, emerging adaptation strategies and the changing policy landscape.

2. Overview of technologies and conditions

2.1. Passive cooling techniques

Climate change affects buildings in terms of building overheating, which increases the energy demand for cooling [3]. In order to minimise the amount of energy used to air-condition buildings, NZEBs should use passive cooling technologies. With proper building design and location, it is possible to significantly reduce energy consumption.

Passive cooling methods used in NZEB are presented in Tab. 1.

Tab. 1. Passive cooling technologies

Category	Technology		Ref.
Heat Gain Control	Shading	Shading devices such as louvres, canopies, awnings or plant screens reduce thermal gains by reducing solar radiation reaching the building interior	[4]
	Green roofs and walls	Vegetation on the roof or façade improves thermal insulation, reduces the urban heat island effect and reduces surface temperatures, resulting in a lower cooling requirement	[3]
	Reflective coatings	Highly reflective materials (e.g. white roofs, ceramic coatings) reduce the amount of heat absorbed and limit the temperature rise inside a building	[3]
	Optimised glazing	The use of adjustable-transparency glass, low-emissivity glazing or double façades allows the amount of light and heat entering a building to be controlled	[3]
	Earth air heat exchanger (EAHE)	Air passed through underground ducts is cooled in summer and heated in winter, reducing energy consumption for cooling and heating the building	[4]
Heat Dissipation	Natural ventilation	Properly designed airflow through the building allows the interior to be cooled without the need for air conditioning, especially at night	[5]
	Radiant cooling	The process of transferring heat from a building by long-wave radiation to the atmosphere, which is particularly effective at night	[4]
	Evaporative cooling	This involves passing hot air over a moist surface, resulting in cooling before entering the building	[4]
	Roof pond	The use of water ponds on roofs allows the building to be cooled efficiently by evaporating water and absorbing heat	[4]
Thermal Mass Cooling	Massive building materials (thermal mass of the building)	Utilising heavy building materials (e.g. concrete, bricks or stone) allows heat to be stored during the day and gradually released at night, stabilising the internal temperature of the building	[4]

The above methods should be selected taking into account the local climatic conditions and the function and location of the building.

2.2. Intelligent building envelope

Smart building envelopes are combining the traditional functions of the building envelope with advanced materials and intelligent control systems. With their ability to adaptively respond to environmental changes, they can improve the energy efficiency and indoor comfort of buildings.

The adaptability of smart building envelopes allows them to be classified into two categories:

1. **Self-adaptation** – The envelope adapts through its material and construction properties.
2. **System-controlled adaptation** – Changes to the envelope are implemented by external energy and control systems [6].

Intelligent non-transparent building coatings:

1. **Walls with phase change materials (PCMs)**: he use of Phase Change Materials (PCMs) in the building envelope allows for an increase in heat storage capacity and a reduction in the building's sensitivity to changes in ambient temperature [7].
2. **Dynamic insulated walls**: Dynamic insulated walls adapt their thermal insulation properties to weather conditions and the seasons [6].
3. **Radiation-cooled facades/roofs**: Radiation cooling involves lowering the surface temperature by emitting heat in the form of radiant heat into space, without the need for external power. This can provide a potential source of clean energy [8]. However, the practical application of this technology is hampered because radiative cooling works more effectively at night when the sky temperature is lower, while during the day buildings absorb solar radiation, limiting the effectiveness of the process.
4. **BIPV**: Building Integrated Photovoltaics (BIPV) technology allows the production of renewable energy and the improvement of a building's thermal comfort [9]. Photovoltaic panels can be integrated into the building façade, providing a partially or fully independent energy source by maximising the use of solar energy [6].

Intelligent transparent building coatings:

1. **Dual-band modulated color-changing glass** – electrochromic technology enables control over the transmittance of both visible and near-infrared light through the application of an electric field, allowing for efficient solar radiation management [6].
2. **Energy storage smart window** – modern windows can be integrated with traditional photovoltaic cells to create an advanced system for efficient energy management. Under optimal lighting conditions, they convert solar energy into electricity for immediate use and store surplus energy for later use [6].
3. **Adaptive shading** – smart shading technologies automatically adjust the position of sun shades in response to data from environmental sensors. In this way, they can improve the energy efficiency of buildings and optimise the use of natural light [6].
4. **Adaptive façade** – intelligent facades can dynamically change their shape and shading levels. The system developed by Formentini uses shape memory alloys (SMAs - Shape Memory Alloys) that autonomously adapt sun shading and ventilation to external conditions, improving energy efficiency and occupant comfort [10].

The optimisation of building envelopes, both at the level of individual components and entire systems, is key to maximising energy efficiency and occupant comfort. Smart façade technologies make it possible not only to save energy, but also to increase the durability of buildings and their ability to adapt to a changing climate [6].

2.3. Integration of RES

The use of Renewable Energy Sources is essential for achieving NZEB standards. Their use allows for minimising the need for energy from conventional sources and to reduce greenhouse gas emissions.

Renewable energy use in the NZEB:

1. **Solar energy** – photovoltaics and hybrid systems – solar energy is the most widely used renewable energy source in the NZEB, as it is readily available and can be efficiently integrated into building systems. In particular, photovoltaic (PV) technologies and photovoltaic/thermal (PV/T) hybrid systems are commonly used to produce electricity and useful heat. Studies have indicated that PV/T systems are gaining increasing interest due to their high efficiency in NZEB buildings [11].
2. **Wind energy** – Wind energy is a valuable source of energy in NZEB systems in regions with favourable wind conditions. Wind turbines can provide complementary energy to photovoltaic systems [11].
3. **Geothermal energy and heat pumps** – geothermal energy is mainly used for heating and cooling NZEB buildings through the use of Heat Pumps. The International Renewable Energy Agency (IRENA) highlights that geothermal technologies can significantly contribute to reducing emissions in buildings, making them increasingly implemented in NZEB heating and cooling systems [12].

Benefits of renewable energy sources in NZEB:

1. **Reduction of greenhouse gas emissions** – the use of RES reduces CO_2 emissions, which is crucial in the context of climate policy and carbon neutrality strategies [12].
2. **Energy self-sufficiency** – by using renewable energy sources combined with energy storage, NZEB buildings can achieve a high level of independence from the electricity grid [11].
3. **Optimisation of running costs** – investment in renewable energy sources contributes to a reduction in the long-term running costs of a building, making NZEBs more cost-effective in the long term [11].
4. **Regulatory requirements** – the implementation of RES technologies in NZEBs is often required by legislation and energy policies, such as the European Union's Energy Performance of Buildings Directive (EPBD) [11].

2.4. Energy storage systems in NZEBs

As mentioned in the previous subsection, the main disadvantage of RES – especially solar and wind energy – is their instability. They do not provide energy continuously. Energy production varies throughout the day, but also throughout the year. [13]. This enforces the use of energy from the power grid during periods of shortage. Most often, this energy comes from conventional sources [14]. On the other hand, there are periods of overproduction when the building is unable to use all the energy produced on an ongoing basis. Selling surplus energy to the power grid at market prices is hardly profitable. Energy sales prices are low during periods of peak production, while purchase prices are high during periods of high demand [15].

One way to overcome the instability of renewable energy sources is to integrate the power supply system of a facility with an energy storage system. This system allows surplus energy to be stored when it is not being consumed on an ongoing basis for the building's needs and offers the possibility to use it when the main power source using renewable energy is insufficient [11].

Three main electricity storage technologies can be distinguished: battery storage, hydrogen and pumped hydro storage. From the perspective of use in NZEBs, the first two are useful. These systems can also be combined to create hybrid systems. The main features of each system are shown in Tab. 2.

Tab. 2. Energy storage systems – summary [11]

Storage method	Role in NZEB	Typical Use Case	Key Advantages	Challenges
Battery	Short-term storage	PV output smoothing, load shifting	High efficiency, fast response	Limited lifespan; costs
Hydrogen	Long-term/seasonal storage	Off-grid backup, mobility integration	Seasonal capacity, multi-use	Lower efficiency, costs
Pumped Hydro	Large-scale, long-term	District-scale NZEB support	Mature, low-cost over life	Requires specific geography
Hybrid	Broad/optimized coverage	Mixed load scenarios	Balances speed; duration	More complex control systems

2.5. BEMS in NZEB energy management in the context of climate change

Building Energy Management Systems (BEMS) are beneficial in optimising energy consumption. They enable a reduction in energy consumption, but also its proper distribution over time. This allows, for example, for an increase of self-consumption of energy produced by RES [5].

BEMS use advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI) and building automation systems (BMS) to dynamically adjust energy consumption according to weather conditions and occupant preferences. Their core functions include:

1. **Energy consumption monitoring** – real-time analysis of energy consumption data to identify areas of high energy intensity [16].
2. **HVAC management** – optimising the operation of heating, ventilation and air conditioning systems based on weather forecasts, humidity levels and the number of building occupants [5].
3. **Integration with renewable energy sources** – efficient use of solar and wind energy and energy storage systems to minimise energy demand from the grid [16].
4. **Automatic regulation of indoor conditions** – systems that detect occupant presence and adjust temperature, lighting and ventilation to increase comfort and reduce energy loss [16].
5. **Prediction and machine learning** – analysing past energy consumption patterns and predicting future energy needs of a building, allowing for more precise management [5].

The implementation of advanced BEMS allows for significant reductions in energy consumption and carbon emissions. For instance:

1. A study conducted on office buildings showed that energy consumption was reduced from 147.13 kWh/m² per year to 96.31 kWh/m² per year through energy management systems, a reduction of approximately 34% [17].
2. Reducing CO_2 emissions - the implementation of intelligent energy systems has reduced emissions from 57.6 kg/m² per year compared to traditional buildings [17].
3. Minimising heat and cooling losses - optimised thermal insulation and dynamic management of internal temperatures reduce the need for intensive use of HVAC systems [17].

In the face of rising temperatures and extreme weather events, BEMS can help NZEB buildings to adapt by:

1. **Managing passive cooling** - integrating BEMS with passive cooling technologies (e.g. natural ventilation, radiant cooling) can reduce the need for air conditioning [11].
2. **Responding to weather forecasts** - intelligent algorithms analyse changing weather conditions and adapt the operation of energy systems to future conditions [16].
3. **Increasing resilience to power grid failures** - BEMS can interface with local energy storage systems, increasing building autonomy and resilience to power outages [11].
4. **Community-based energy management** - in smart grids, BEMS enable optimisation of energy consumption not only in individual buildings but also in entire neighbourhoods, improving the stability of the electricity grid [11].

2.6. Reducing the impact of urban heat islands

The temperature in cities is higher than in neighbouring rural areas. This phenomenon is known as the urban heat island effect (UHI). The main causes are:

1. Many heat-absorbing and low-albedo surfaces – increases the absorption of solar radiation.
2. Dense urban geometry – captures long-wave radiation and prevent radiative cooling.
3. Less vegetation and soil exposure – reduces evapotranspiration cooling.
4. Waste heat – traffic, HVAC systems and industry emit a lot of heat.

NZEB buildings have a significant role in counteracting the UHI effect through the use of high albedo coatings and cooling technologies. Highly reflective materials, such as cool and green roofs, reduce surface temperatures, limiting the heating of buildings and their impact on their surroundings [18].

In temperate and warm climates, traditional methods such as ventilated roofs and high thermal mass structures may be more effective than highly insulated envelopes in reducing heat gain [19]. Studies indicate that increasing the albedo of roofs can reduce cooling demand by up to 28% for uninsulated buildings, but this effect decreases significantly for well-insulated structures [20]. Although highly reflective materials can reduce overheating in summer, in the colder months they can simultaneously reduce beneficial heat gains, which can be detrimental in some climates [21]. In a study conducted by Tsoka et al. in 2021 [22], not including the UHI effect led to a 21% overestimation of energy demand for heating. Meanwhile, energy demand for cooling was underestimated by 22.4%. Considering all of the aforementioned points, strategies to counteract UHI in NZEB should be tailored to local climatic conditions, and their effectiveness requires further research.

2.7. Policy impact on NZEB

The promotion of Nearly Zero Energy Buildings (NZEBs) is deeply influenced by political decisions, policies, and regulations. Politics plays a critical role in setting the direction for energy efficiency standards, providing incentives, and establishing legal frameworks for sustainable building practices.

Regulatory and Policy Frameworks:

1. **European Union (EU) Policies**: One of the most significant political influences on NZEB promotion is the EU's Energy Performance of Buildings Directive (EPBD), which mandates that all new buildings must be Nearly Zero Energy Buildings by 2020. This directive sets the policy framework for all EU member states and influences national governments' legislation and regulations [2].
2. **National Legislation**: In many countries, the national governments are responsible for translating international directives into local building codes. For instance, countries like Germany and Sweden have stringent building codes and have long embraced NZEB standards, demonstrating how political will can accelerate the implementation of energy-efficient buildings [23].
3. **Incentives and Subsidies**: Governments often provide incentives, such as tax credits or grants, for the construction of NZEBs. For example, the U.S. and several EU countries have created financial incentives for homeowners and builders to adopt energy-efficient construction methods [23].

Climate Change Commitments:

1. Paris Agreement and National Contributions: Politics at the global level, especially through agreements like the Paris Climate Agreement, have pushed countries to meet emission reduction targets [24].
2. National Action Plans: Politicians use national commitments to climate change goals to drive domestic building policies that align with reducing carbon footprints [24].

Politics profoundly shapes the promotion and adoption of NZEBs, from international climate agreements to local economic and social policies. Governments must balance environmental goals with economic feasibility, industry interests, and social objectives. Legislative mandates, financial incentives, and international cooperation are critical political tools that influence the rate and success of NZEB adoption.

2.8. Climate change predictions

To calculate predicted energy demand for future buildings, it is necessary to create Future Weather Files (FWFs). Climate projections are based on greenhouse gas emission scenarios, referred to as Representative Concentration Pathways (RCPs), developed by the IPCC [25]. There are four main scenarios:

RCP2.6 – the most optimistic, which assumes a reduction in emissions and a reduction in temperature increase.

RCP4.5 i **RCP6.0** – intermediate scenarios, with moderate temperature increases.

RCP8.5 – the most pessimistic, assuming further increases in emissions and temperatures.

The main differences between RCPs are summarised in Tab. 3.

Tab. 3 Key differences between the RCPs [25]

Parameter	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Radiative forcing (in 2100)	2.6 W/m^2	4.5 W/m^2	6.0 W/m^2	8.5 W/m^2
Temperature rise (in 2010 rel. 1986-2005)	~1.5 °C	~2.5 °C	~3.0 °C	~4.5-5.0 °C
Net CO_2 emissions (in 2100)	Strongly negative	Moderately low	High	Very high

3. The impact of climate change on buildings – Case study analysis

In order to identify the resilience of NZEB buildings to climate change, three papers containing case studies were retrieved. The reviewed case studies have been compiled in Tab. 4.

Tab. 4. Case studies overview

	Netherlands – Apeldoorn	Italy – Milan	Spain – La Rioja
Study title	Future-proof energy retrofit strategy for an existing Dutch district	Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: Milan case	Adaptation of rural residential buildings in a Mediterranean climate to climate change: a case study of La Rioja (Spain)
Building types	Representative terraced, semi-detached, detached houses	Representative single-family house (SFH), multi-family house (MFH), and apartment block (AB) from 1946–1960 stock	Rural single-family prototypes and their NZEB retrofit variants
Climate scenarios & horizons	Future scenario combinations (heating setpoints, internal gains, +2 °C climate shift) evaluated across many permutations	RCP 4.5 and 8.5 with near-term (2021–2040) and long-term (2081–2099) weather files	Multiple RCPs (2.6, 4.5, 8.5) with climate-zone evolution to 2055 and 2085
Ref.	[26]	[27]	[28]

3.1. Apeldoorn case study

An article from 2022 presents an analysis of the energy saving potential and resilience to scenarios of various modernisation packages, using the example of a Dutch district in the city of Apeldoorn. The analysis included four types of buildings existing in the district: detached, semi-detached, terraced-middle and terraced-side [26]. For this article, the results for a detached building will be cited.

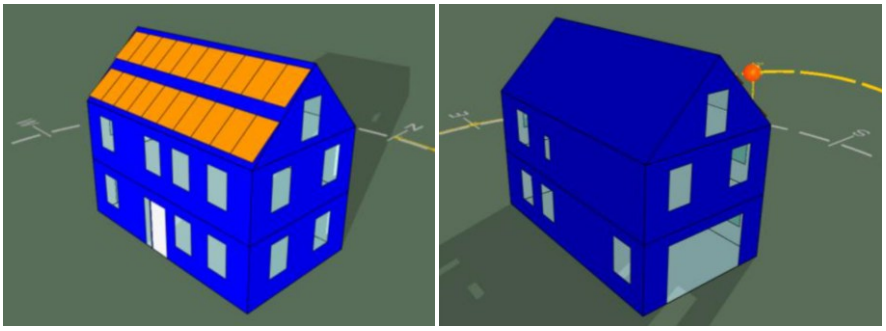

Fig. 1. Geometry of detached building in Apledoorn [26]

In this study, the methodology described in [29] was used. The original parameters of the building are presented in Tab. 5. During the calculations, the parameters of future scenarios presented in Tab. 6. were adopted. Six retrofit packages were considered during the analysis. They have been compiled on Fig. 4.

Tab. 5. Building envelope properties for detached building [26]

Building type	Construction year	Floor *Rc-value [m^2·K/W]*	Wall	Roof	Window + Frame *U-value [W/m^2·K]*	Infiltration $\left[\frac{l}{s \cdot m^2}\right]_*$
Detached	1975-91	0.52	1.30	1.30	2.90	0.6
	1965-74	0.17	0.43	0.86	2.90	0.8

*Based on floor area

Tab. 6. Future scenarios considered in the case study [26]

	Variable	Value
Usage	Heating setpoint	18-20-22 [°C]
	Lighting heat gain	1-3 [W/m^2]
	Appliance hest gain	1-3 [W/m^2]
Climate	W+	2 [°C] increase in global temperature by 2050 and change in air circulation patterns

The results of the analysis are presented in Fig. 3, Fig. 4 and Fig. 5.

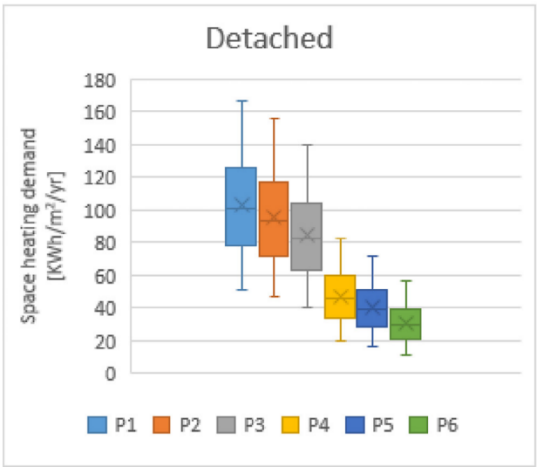

Fig. 2. Performance spread of retrofit packages through future scenarios [26]

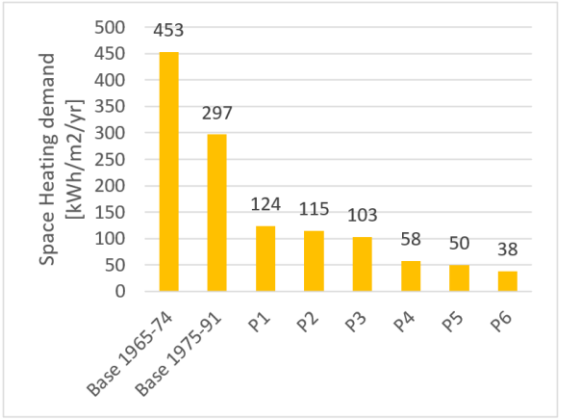

Fig. 3. Space heating demand per design for detached building type [26]

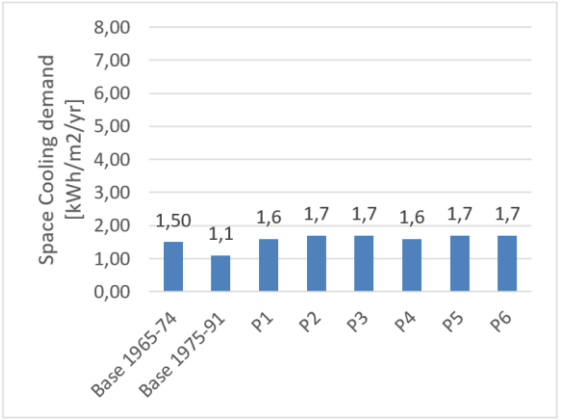

Fig. 4. Space cooling demand per design for detached building type [26]

Component	Unit	P1	P2	P3	P4	P5	P6
Roof	Rc-value [m².K/W]	6	8	10	6	8	10
Wall		4.5	6	8	4.5	6	8
Floor		3.5	5	6	3.5	5	6
Window + Frame	U-value [W/m².K]	1.8 (HR++)	1.8 (HR++)	1.4 (Triple)	1.8 (HR++)	1.8 (HR++)	1.4 (Triple)
Air tightness	[l/s.m²]	0.15	0.15	0.15	0.15	0.15	0.15
Ventilation		Natural	Natural	Natural	HRV 90%	HRV 90%	HRV 90%

Fig. 5. Energy retrofit packages [26].

Implementing the retrofit packages drives large reductions in heating demand for detached houses: P1 = 124 kWh/m^2·yr, P2 = 115 kWh/m^2·yr, P3 = 103 kWh/m^2·yr, and the HRV-equipped packages P4 = 58 kWh/m^2·yr, P5 = 50 kWh/m^2·yr, P6 = 38 kWh/m^2·yr. The switch from natural ventilation to heat-recovery ventilation (HRV) (comparing P1–P3 with P4–P6) produces one of the largest single-step reductions in space-heating demand. The study reports energy demand for cooling = 1.5 kWh/m2·yr for the older buildings (1965–74) and = 1.5 kWh/m^2·yr for the newer buildings (1975–91). For P1–P6 values oscillating around 1.6–1.7 kWh/m^2·yr. This implies a slight increase compared to the buildings prior to modernisation [26].

Robustness improves strongly with deeper retrofits and with HRV. The normalized maximum-regret results rank P6 as most robust, followed by P5 and P4, while P1–P3 are substantially less robust [26].

3.2. Milano case study

The analysis covered three types of buildings characteristic of the Italian residential building market. The buildings analysed were selected from the IEE-TABULA research project [30]. The selected buildings belong to the Milan climate zone and represent construction typical for the period 1946-1960. For the purposes of this publication, the parameters and results for a single-family residential building (SFH) will be cited. The geometry of the building is shown in Fig. 6.

For the refurbished building, U-values were set to meet the requirements for NZEB in Italy. The U-values for the envelope before and after modernisation are summarised in[27].

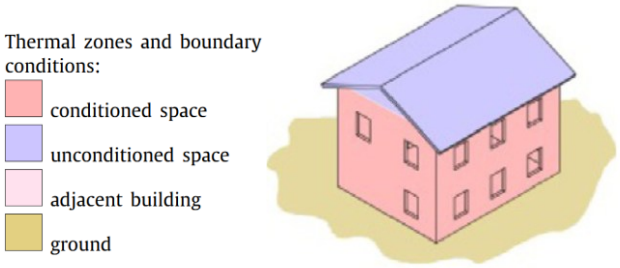

Fig. 6. SFH building geometry [27]

Tab. 7. Thermal transmittance values of the building envelope components [27].

Building envelope component	**U-value - Existing building** *[W/(m²·K)]*	**U-value - Refurbished building** *[W/(m²·K)]*
External wall	1.48	0.26
Upper floor (roof)	1.65	0.22
Bottom floor	2.00	0.26
Windows	4.90	1.40

Fig. 7. Thermal energy demand for heating and cooling normalized by conditioned floor area for single-family house (a) existing building (b) refurbished building under different future scenarios in Milan [27]

The values of primary energy demand for heating and cooling for individual climate scenarios are presented in Fig. 7. [27]. Values have been normalized by conditioned floor area.

Future climates cause a clear reduction in annual heating demand and a very large increase in cooling demand for the SFH case, producing a marked shift from heating- to cooling-dominated energy needs.

For existing building heating demand decreases up to 29.1% while cooling demand can increase up to 255.1% under the worst-case long-term RCP8.5 scenario. After upgrading envelope insulation to NZEB-reference U-values, heating demand reductions grow up to 35.6%, but cooling demand still increases up to 116.6%. Refurbishment reduces absolute heating energy but does not prevent large relative increases in cooling [27].

3.3. La Rioja case study

In a 2024 study, López-Ochoa et al. examine the adaptation of residential buildings to climate change. The buildings studied are located in La Rioja, Spain. Among the buildings studied in this publication, the results for a building located in Cervera del Río Alhama are cited. The geometry of the building is shown in Fig. 8. The study simulated the energy demand for the existing building and three NZEB variants. The thermal transmittance values for each variant are shown in Tab. 8.

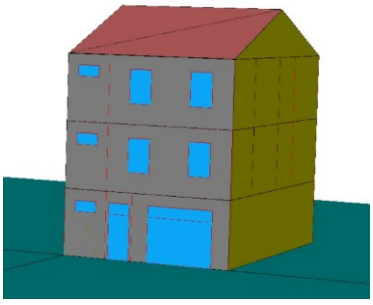

Fig. 8. La Rioja building geometry [27]

Tab. 8. Thermal transmittance of the building envelope, with insulation thickness highlighted [27]

	PreCTE-X		NZEB-XB		NZEB-XC		NZEB-XD	
	U *[W/(m²·K)]*	t *[m]*	U *[W/(m²·K)]*	Δt *[m]*	U *[W/(m²·K)]*	Δt *[m]*	U *[W/(m²·K)]*	Δt *[m]*
Roof	1.19	0.010	0.33	0.075	0.23	0.120	0.22	0.125
First-floor framework	1.24	0.010	1.05	0.005	0.91	0.010	0.80	0.015
Mezzanine framework	1.96	0.000	1.52	0.005	1.24	0.010	1.05	0.015
Roof-floor framework	1.24	0.010	1.05	0.005	0.91	0.010	0.80	0.015
Dividing walls	1.55	0.005	0.65	0.030	0.47	0.050	0.47	0.050
Walls	1.56	0.005	0.37	0.070	0.29	0.095	0.27	0.105
Vertical interior partitions	2.79	0.000	1.06	0.020	1.06	0.020	1.06	0.020
Ground floor	1.53	0.005	0.65	0.030	0.47	0.050	0.47	0.050
Windows	5.70	–	1.99	–	1.99	–	1.66	–
Doors	5.70	–	2.00	–	2.00	–	2.00	–

An energy simulation of the above building variants was carried out for 13 climate scenarios. One corresponding to RCP 2.6, three possible versions of RCP 4.5 and nine possible versions of RCP8.5. This gives a total of 52 simulations. The results of the energy demand for heating and cooling are presented in Fig. 9.

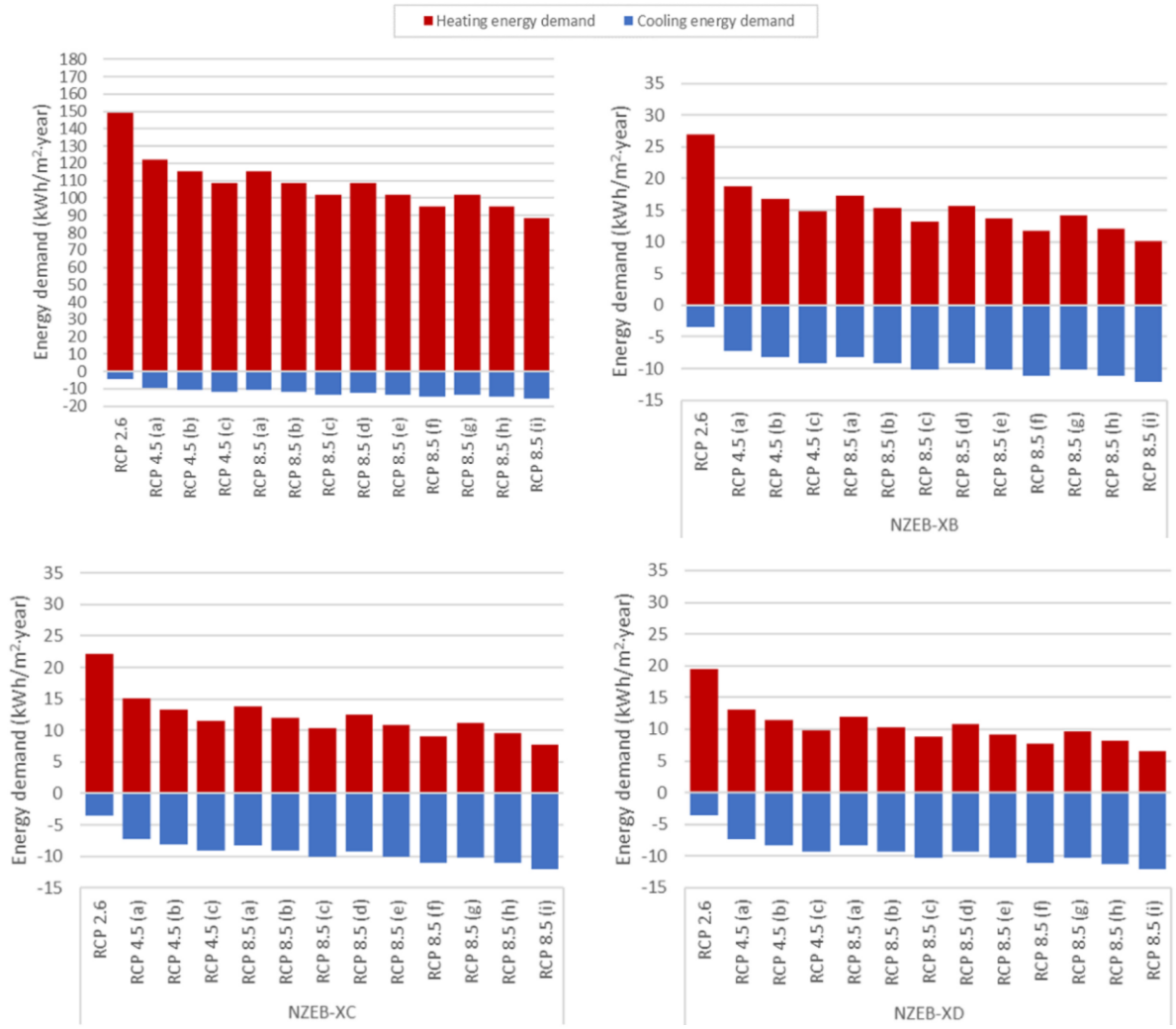

Fig. 9. Heating and cooling energy demands for the existing and energy-renovated study buildings in the different climate change scenarios [27]

NZEB-XD variant produced the largest reductions in both heating demand and total energy demand across RCP 4.5 and RCP 8.5 scenarios, outperforming the other NZEB variants. Absolute energy savings (NZEB-XD vs existing PreCTE-X) are large: total energy savings ≈ 130 kWh/m2·year in RCP 2.6 and ≈ 100–109 kWh/m2·year in RCP 4.5 scenarios. Heating demand falls more than cooling demand rises in all studied climate scenarios, so total energy demand decreases. Deeper insulation (lower U-values) reduces total energy demand but increases cooling demand and the risk of summer overheating, so NZEB designs must incorporate overheating mitigation such as shading, solar control, ventilation and passive measures [28].

4. Discussion

The case studies presented in this paper clearly highlight a common trend: the reduction in heating demand and the simultaneous increase in cooling demand under future climate scenarios. However, the scale of these changes differs significantly between regions and building types, which underlines the importance of local climatic conditions in designing Nearly Zero Energy Buildings (NZEBs).

In the Dutch Apeldoorn case study, the largest energy savings were obtained through the introduction of heat recovery ventilation. This solution reduced heating demand substantially and improved the robustness of retrofit packages. Cooling demand remained relatively low, showing that in temperate maritime climates, heating will remain the dominant challenge, even under warmer scenarios.

By contrast, the Milan case study revealed a dramatic increase in cooling needs, up to +255% under the RCP8.5 scenario. Even though insulation upgrades significantly reduced heating demand, they did not prevent a sharp growth in cooling energy use. This indicates that in Southern and Central Europe, where summers are hot and expected to intensify, NZEB standards focused only on insulation are insufficient. Instead, buildings must integrate passive cooling strategies, dynamic shading, and efficient HVAC systems to avoid overheating and excessive reliance on mechanical cooling.

The Spanish La Rioja case study showed that deeper insulation strategies (NZEB-XD variant) delivered the largest total energy savings. However, it also raised the risk of summer overheating, as cooling demand increased despite lower total energy use. This reflects findings in other research (e.g., Tootkaboni et al., [3]), which warn that improvements in airtightness and insulation, when applied without ventilation or shading, may actually reduce comfort in warmer future climates.

Taken together, the case studies confirm the growing importance of passive cooling techniques and advanced building control systems. The findings also align with Tsoka et al. [22], who showed that neglecting the urban heat island (UHI) effect can lead to a significant underestimation of cooling demand. As cities become denser and hotter, this factor will be decisive for the resilience of NZEBs.

Another important dimension is energy self-sufficiency. While insulation and envelope upgrades reduce demand, the volatility of renewable energy sources (RES) requires energy storage solutions and building energy management systems (BEMS). Without these, NZEBs risk shifting dependence from fossil fuels to unstable renewable supply, which does not guarantee resilience during peak demand or extreme weather.

This research also highlights limitations. Only three case studies were analysed, all from Southern and Western Europe. Socio-economic aspects, such as costs of retrofitting or user behaviour, were not considered. Moreover, climate projections are based on Representative Concentration Pathways (RCPs), which carry inherent uncertainty. Despite these limitations, the results provide a valuable basis for understanding the future direction of NZEBs.

Looking ahead, further studies should extend this type of analysis to other climatic zones, such as Northern Europe or arid regions, where cooling and heating balances may differ significantly. Research should also combine energy simulations with occupant comfort assessments and life cycle cost analyses. Only by integrating technological, climatic, and social dimensions can we fully understand the role of NZEBs in climate change mitigation and adaptation.

In summary, the discussion shows that NZEBs cannot be treated as a fixed standard based solely on insulation levels. They must evolve into adaptive, intelligent systems that respond dynamically to local climate conditions, integrate passive and active cooling strategies, and combine renewable energy with storage and management technologies. This holistic approach is essential for ensuring that NZEBs deliver not only energy efficiency but also long-term comfort and resilience in a warming climate.

5. Conclusions

Case studies from the Netherlands, Italy, and Spain highlight that retrofitting strategies, although effective in lowering overall energy consumption, must be carefully balanced with overheating risks and increased cooling needs. Key observations following the analysis of case studies include:

- The main trends are consistent across the presented case studies.
- Despite consistent trends, the energy balance varies depending on the case. In the Milan case study, total energy demand is increasing, while in the La Rioja case study it decreases.
- As observed in Milan case study the potential for savings in space heating through insulation can be counteracted by insufficient ventilation, thus resulting in an increased risk of overheating. This risk was more significant in cases of retrofit packages that rely on natural ventilation.
- Research shows that NZBE buildings are more resilient to climate change than traditional buildings.
- It is recommended that no airtightness improvements be implemented unless a mechanical ventilation/cooling system is installed, given the high risk of overheating and occupant discomfort during summer months.
- Existing analyses of the resilience of buildings to climate change focus on increasing the insulation of the building envelope.
- It is recommended to carry out analyses that take into account more advanced methods of increasing energy efficiency.
- It is recommended to conduct further analyses taking into account local conditions (including UHI).

This study demonstrates that nearly zero-energy buildings will play a pivotal role in mitigating the effects of climate change on the built environment. The analysis confirms that while improved insulation and energy efficiency measures significantly reduce heating demand, the growing importance of cooling in warmer future climates presents a major challenge.

The integration of passive cooling strategies, smart building envelopes, and renewable energy systems emerges as essential for maintaining thermal comfort while minimizing environmental impact. At the same time, energy storage technologies and advanced BEMS provide resilience against fluctuations in renewable energy production and rising cooling loads.

Policy frameworks, such as the EU's Energy Performance of Buildings Directive, are key to accelerating the adoption of NZEBs. To ensure wider implementation, clearer financial incentives, uniform assessment methods, and better alignment with climate goals are still needed.

Overall, NZEBs are a key part of sustainable construction in a warming climate. Their success depends on combining new technologies, supportive policies, and tailored design. Future efforts should focus on lowering heating needs and managing rising cooling demand to create efficient, resilient, and comfortable buildings. Future research should explore local climatic conditions and advanced methods of improving energy efficiency.

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