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Impact of climate change on the energy performance of building envelopes and implications on energy regulations across $Europe^{\Rightarrow}$

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ABSTRACT

This paper delves into the potential impact of a changing climate on the energy performance of European buildings. Research aims to provide a comprehensive evaluation of current energy requirements focusing on the envelope, considering existing regulations in national policies.

Energy simulations are conducted at 94 locations across the European Union to cover the climatic variability and Koppen climate classification. The research analyzes future climate scenarios for the years 2030, 2050, and 2070, using three different Representative Concentration Pathways (RCP 2.6, 4.5, 8.5).

According to a comprehensive analysis of heating, cooling, and overall energy performance, climate plays a significant role in buildings' energy balance. In moderately cool climate countries, the demand for air conditioning is projected to decrease in the years ahead. Conversely, in countries with a warm climate, there is a projected increase in the overall energy demand. Consequently, a revision of current energy regulations should be a priority.

Providing insights into the relation between building design, energy efficiency, and climate change, the research identifies policy adjustments to ensure buildings can effectively respond to changing climatic conditions. A holistic and dynamic approach can support building design accounting for long-term impacts of climate change to create resilient and energy-efficient structures.

1. Introduction

Tackling energy consumption in buildings is a crucial component of designing effective energy policies and supporting the transition to sustainable energy systems [1,2]. In Europe, the building stock accounts for approximately 36 % of energy-related greenhouse (GHG) emissions and 40 % of final energy consumption [3]. The European Union (EU) is taking significant steps to address these challenges, including the Green Deal which aims to reduce EU GHG emissions by 55 % by 2030 and achieve carbon neutrality by 2050 [4]. However, achieving these ambitious goals requires a substantial contribution from the building sector [5]. The REPowerEU Plan set the path towards decarbonization

and raised the renewable energy target to 45 % [6]. More recently, a revision of the Energy Performance of Buildings Directive (EPBD) recast [7] proposed ambitious plans to reach a climate-neutral Europe by 2050. To make progress towards these targets, policies are required to foster the transition to nearly zero energy buildings (NZEBs), that are characterized by a high energy performance, with a very low amount of energy widely covered by renewable energy sources [8].

Considering that the average lifespan of a building often exceeds 50 years and that across Europe the majority of the building stock was built before thermal standards and energy efficiency regulations [9], investing in building refurbishment is crucial to reduce energy consumption and greenhouse gas emissions in the EU. Furthermore, it is imperative to

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establish the correct design criteria for NZEBs constructed today, considering climate projections and long-term sustainability. Zero-energy buildings are designed to utilize low-energy technologies and passive design methods, which ensure high indoor environmental quality and minimize energy requirements. In recent years, substantial efforts have been directed towards identifying key design parameters that impact building performance, particularly in achieving zero or low-energy buildings. These parameters are fundamental for optimal building envelope design, which is essential in realizing NZEBs [10-13]. The energy performance of buildings is intrinsically linked to environmental conditions, both indoors and outdoors. In relation to the indoors, he building envelope plays a crucial role in controlling energy losses and gains due to heat transfer to and from the surroundings [14]. In turn, the interaction between envelope, indoor environmental conditions, and outdoor climate collectively determines the energy required for heating, ventilation, and air conditioning (HVAC) system to maintain acceptable thermal comfort inside the building [15]. Therefore, the envelope is a pivotal element to be analyzed when investigating the complex relationship between climate change and buildings.

The building envelope can be considered as a control surface that delimits the boundaries of the thermodynamic system [16,17]. It plays a multifaceted role, including: controlling the flow of energy, protecting the indoor space from extreme weather conditions, mitigating wide temperature fluctuations, reducing energy consumption for cooling and heating, ensuring comfort conditions and indoor air quality [18]. In the literature, extensive research has been conducted to assess how the position and quality of insulation within the building envelope influence the behavior dynamics [19] and its impacts on total heating and cooling loads [20].

Researchers have conducted comprehensive investigations into the characteristics of building envelopes in different climate zones [21-24]. Achieving high energy performance in buildings requires a proper combination of several factors, such as dynamic thermal transmittance and thermal admittance properties [25] as well as thermal mass [26]. Thermal transmittance values and thickness of insulation play a crucial role in the energy performance of a building in cold climate zones [27]. In warm climates, it is essential to have a proper design of solar shading systems and skylights [28], and the thermal inertia of the opaque envelope to mitigate temperature fluctuations [29,30]. For mild climate zones, a key consideration is the evaluation of the thermal characteristics of windows [31]. While these parameters are essential, it's important to note that their impact on building performance can vary significantly across different climate zones. Moreover, the influence of these factors is not always comprehensive enough to fully quantify their effects on building energy performance. Improving the thermal performance of the building envelope has mainly meant keeping the thermal transmittance values of opaque and transparent elements as low as possible. This approach is reflected in many national regulations governing energy conservation in buildings [32]. However, there is growing recognition of the limitations of a solely static approach based on stationary thermal transmittance values [33]. This is especially evident when considering the aspect of summer cooling.

In addition, a crucial aspect that can no longer be overlooked is the systematic assessment of climate change at the design stage. Luo and Oyedele [34] employed innovative life cycle optimization strategies to identify the optimal retrofitting solutions for buildings, taking into account climate change effects. Their research showed that neglecting the influence of climate change can lead to suboptimal retrofitting choices, emphasizing the importance of considering climate change impacts within building design. While there is a growing interest in understanding building performance under climate change, comparing results from different studies can be challenging due to the use of varying methodological approaches [35]. In tropical residential buildings, there is a general trend of improving the thermal insulation of the walls and building envelope to cope with future weather conditions while providing adequate interior lighting [36]. Analysis of the climate change

resilience of a real NZEB designed in the Mediterranean climate revealed that the reduction in heating demand could balance the increase in cooling [37]. The impacts of climate change on the energy performance and thermal comfort of European residential buildings [38] indicated that future conditions will necessitate more cooling and less heating. This shift will likely result in increased discomfort hours in cities where cooling is required, emphasizing the need for a building design that can adapt to changing climate conditions and ensure occupant comfort.

1.1. Problem statement

This study provides an exhaustive evaluation of the thermal transmittance regulations applied to building envelopes across Europe. It is the first time that such a comprehensive and detailed comparative analysis is carried out at European level. Indeed, the analysis encompasses data for each Member State, accounting for all climate zones, including the international Koppen climate classification as well as European, national, and local climatic regions.

Specifically, this study analyzes the impact of climate change on heating and cooling demand of residential buildings in several European locations designed according to the regulations currently in place. While climate change is extensively discussed in the literature for several issues, its implication in terms of energy efficiency standards and policies do not properly address the issue. Given that most new buildings will not undergo renovation for decades, the purpose of this analysis is to determine whether the current building design, that follows specific established energy requirements, will remain adequate and effective in the years ahead.

Our study closes a gap in the literature that currently does not analyze the performance of building envelopes as designed according to existing standards and regulations at European level. Furthermore, the study combines the European climate classification along with the Koppen climate classification, which allows for a broader panorama of Europe [39]. The research provides valuable insights into the evolving intersection of building design and energy efficiency with climate change, shedding light on the need for policy adjustments and proactive measures to ensure buildings can effectively respond to changing climatic conditions.

As such the paper introduces the following new contributions to the existing literature.

- a) assessment of climate change, also including (according to the Koppen classification) seasonal precipitation and temperature patterns and how this impacts building envelopes across European locations;
- b) analysis of thermal transmittance values imposed by the existing different regulations in Member States;
- c) evaluation of the building performance in the short, medium, and long term under different Representative Concentration Pathways (RCP) scenarios.

Specifically, the study explores the consistency and suitability of existing regulations with predicted climate scenarios, having the overarching objective to define a climate-dependent envelope design for future NZEBs. It investigates how the building envelope, designed according to the current existing requirements, responds to a changing climate to explore the geographical and location variability across 27 countries and 94 locations representative of the existing climatic areas in Europe.

A residential building prototype model is developed based on the thermal transmittance standard in force and it is evaluated for different years (2030, 2050, 2070) along with three RCPs (2.6, 4.5, 8.5) to enlighten differences among scenarios. This research critically analyzes the regulations applied to building envelopes at European level, and it aims to address a fundamental question:

Will the current design criteria for energy-efficient buildings



Fig. 1. Mapping of selected cities.

Overview of selected cities, indicating both the European climate area and Köppen-Geigen climate classification, countries, and cities.

EU Climate zone	Koppen climate zone		National climate zone	Country	City
Nordic	Cfb	Temperate oceanic climate	-	Denmark	Copenhagen
	Cfb	Temperate oceanic climate	-	Estonia	Kuressaare
	Dfb	Warm-summer humid continental climate	-		Tallinn
	Dfb	Warm-summer humid continental climate	-	Finland	Helsinki
	Dfc	Subarctic climate	-	* . •	Tampere
	CID	Temperate oceanic climate	-	Latvia	Riga
	Cfb	Temperate oceanic climate	_	Lithuania	Vlaipėda
	Dfb	Warm-summer humid continental climate	_	Liuluallia	Vilnius
	Cfb	Temperate oceanic climate	_	Sweden	Stockholm
	Dfb	Warm-summer humid continental climate	_		Karlstad
	Dfc	Subarctic climate	_		Östersund
Continental	Cfb	Temperate oceanic climate	_	Austria	Wien
	Dfb	Warm-summer humid continental climate	-		Mariazell
	Dfc	Subarctic climate	-		Landeck
	ET	Tundra climate	-	D 1 .	Sölden
	Cha (bordering on Cib)	Humid subtropical climate	-	Bulgaria	Sofia
	CID	Hot summer Mediterroneen elimete	-		Perilik Kordzbali
	Csh	Warm-summer Mediterranean climate	_		Zlatograd
	Dfb	Warm-summer humid continental climate	_		Pamporovo
	Dfc	Subarctic climate	_		Parangalitsa
	Cfb	Temperate oceanic climate	_	Poland	Warsaw
	Dfb	Warm-summer humid continental climate	_		Białystok
	Cfb	Temperate oceanic climate	_	Czech Republic	Prague
	Dfb	Warm-summer humid continental climate	-		Jesenik
	Cfa	Humid subtropical climate	-	Romania	Bucharest
	Cfb	Temperate oceanic climate	-		Oradea
	Dfb	Warm-summer humid continental climate	-		Bistrita
	Dfc (bordering on Cfb)	Subarctic climate	-		Obarșia-Cloșani
	BSK Cfb	Cold semi-arid climate	-	Clovelrie	Sulina
	Dfb	Warm summer humid continental climate	-	SIOVAKIA	Banská Bystrica
	Dfc	Subarctic climate	_		Telgart
	Cfb	Temperate oceanic climate	_	Slovenia	Liubliana
	Dfb (bordering on Cfb)	Warm-summer humid continental climate	_		Jesenice
	Dfc	Subarctic climate	_		Kranjska Gora
	ET (bordering Dfc)	Tundra climate	_		Ukanc
	Cfa	Humid subtropical climate	_	Hungary	Szeged
	Cfb	Temperate oceanic climate	-		Budapest
	Dfb	Warm-summer humid continental climate	-		Répáshuta
Oceanic	Cfb	Temperate oceanic climate	-	Belgium	Liege
	Cfb	Temperate oceanic climate	-		Gent
	Cib	Hot-summer Mediterranean climate	– H3	France	Marseille
	Csh	Warm-summer Mediterranean climate	H2	France	Riez
	Cfa	Humid subtropical climate	H2		Toulouse
	Cfb	Temperate oceanic climate	H1		Paris
	Cfc (bordering on Cfb)	Subpolar oceanic climate	НЗ		Saint Martin d'Entraunes
	Dfc	Subarctic climate	H1		Crevoux
	ET	Tundra climate	H1		Tignes
	Cfb	Temperate oceanic climate	_	Germany	Berlin
	Dfb	Warm-summer humid continental climate	-		Lohberg
	Cfb	Temperate oceanic climate	-	Ireland	Dublin
	Cfb	Temperate oceanic climate	-	Luxembourg	Luxembourg
Maditamanaan	CfD	Temperate oceanic climate	-	Netherlands	Amsterdam
Mediterranean	Csh (bordering on Csa)	Warm-summer Mediterranean climate	_	Cyprus	Kakopetria
	BSh	Hot semi-arid climate	_		Lamaca
	Csa	Hot-summer Mediterranean climate	_	Croatia	Split
	Csb (bordering on Csa)	Warm-summer Mediterranean climate	_		Dernis
	Cfa	Humid subtropical climate	_		Zagreb
	Cfb	Temperate oceanic climate	_		Ogulin
	Dfb	Warm-summer humid continental climate	-		Krasno Polje
	Csa	Hot-summer Mediterranean climate	В	Greece	Athens
	Csa	Hot-summer Mediterranean climate	A		Pylos
	Csb	Warm-summer Mediterranean climate	C		Papigo
	Cia (bordering on Cfb)	Humid subtropical climate	D C		Florina
	DOK	Loid semi-arid climate	L D	Italy	Larissa
	Coa Coa	Hot-summer Mediterranean climate	C C	italy	Lecce
	Csa	Hot-summer Mediterranean climate	В		Siracusa
	Csb	Warm-summer Mediterranean climate	E		Lagonegro
	Cfa	Humid subtropical climate	Е		Milan
	Cfb	Temperate oceanic climate	E		L'Aquila
					(continued on next page)

Table 1 (continued)

Cfc	Subpolar oceanic climate	F		Fenestrelle
BSk	Cold semi-arid climate	D		Foggia
Dfb	Warm-summer humid continental climate	F		Asiago
Dfc	Subarctic climate	F		Tarvisio
ET	Tundra climate	F		Livigno
Csa	Hot-summer Mediterranean climate	_	Malta	Valletta
Csa	Hot-summer Mediterranean climate	_	Portugal	Lisbon
Csb	Warm-summer Mediterranean climate	_		Porto
Csa	Hot-summer Mediterranean climate	B4	Spain	Seville
Csa	Hot-summer Mediterranean climate	A3		Malaga
Csb	Warm-summer Mediterranean climate	C1		La Coruna
Csb	Warm-summer Mediterranean climate	E1		Leon
Cfa	Humid subtropical climate	D2		Huesca
Cfb	Temperate oceanic climate	C1		Bilbao
BSh	Hot semi-arid climate	B3		Valencia
BSk (bordering on (Csa)	Cold semi-arid climate	D3		Madrid
Dfb (bordering on Cfb)	Warm-summer humid continental climate	D2		Villanua
BWh (bordering on BSk)	Hot desert climate	A2		Las Palmas
Dfc (bordering on Cfb)	Subarctic climate	D2		Anciles

effectively respond to the challenges posed by impending climate change?

2. Methodology

This section outlines the steps of the methodology designed to accomplish the goals of this study.

Step 1 Selected European locations

The first step involved the identification of the European locations for forecasting the future energy performance of reference buildings. First, the different European macro climate areas were identified in: Nordic, Continental, Oceanic, and Mediterranean according to Ref. [40]. Then, within each European macro climate area, all climate zones belonging to the Köppen-Geiger climate classification were pinpointed. The KMZ Google Earth files in high resolution were used for the selection of the locations as available to download from Ref. [41]. For each Member State, the capital and one representative city from each climate zone of the Köppen-Geiger climate classification were selected. It is possible to find locations with the same Köppen-Geiger climate classification within different European climate zones.

Step 2 Climate data

The tool Meteonorm version number 8 was used to generate annual hourly values of external temperature, wind speed, horizontal direct radiation, horizontal diffuse radiation and air pressure for each selected location. In the "locations" section of Meteonorm, each city was identified by choosing the "interpolated city" solution. Some locations (i.e., Anciles, Asiago, Banská Bystrica, Białystok, Bistrița, Crevoux, Dernis, Fenestrelle, Florina, Huesca, Jesenice, Jesenic, Kakopetria, Kardzhali, Kranjska Gora, Krasno Polje, Kuressaare, Valletta, Lagonegro, Landeck, L'Aquila, Livigno, Lohberg, Mariazell, Obârșia-Cloșani, Pamporovo, Papigo, Parangalitsa, Pernik, Pylos, Répáshuta, Riez, Saint Martin d'Entraunes, Sölden, Telgart, Tignes, Ukanc, Villanua, Zlatograd) not within the Meteonorm database were created by imposing longitude, latitude and altitude data in the "User defined - Add new" section. In the "Changes and data import" section, "Use Meteonorm climate data" was set. In "Calculation Settings," the selected period for each location is "Future"; for RCP 2.6, RCP 4.5 and RCP 8.5, climate data for the years 2030, 2050 and 2070 were extrapolated. In "Output formats" the outputs from the "custom" section were set, i.e., temperature, wind speed, horizontal direct radiation, horizontal diffuse radiation and air pressure were selected. In "Results and export" the previously set outputs were extrapolated in.csv format.

Step 3 European transmittance limits

The thermal transmittance limits of the opaque and glazed envelope were determined for each Member State, using current energy regulations. The majority of the energy requirements for the transmittance values were found within the EPBD reports. Detailed references and sources for each Member State have been provided and documented.

Step 4 Definition of the reference residential building

A three-story multi-residential building comprising three small apartments (one on each floor) was established as a basic prototype to be modified for each location. Notably, the analysis focused on the building envelope's thermal performance, and thus, the air conditioning and domestic water systems were excluded from the evaluation. The primary aim was to assess the behavior of the building envelope under varying conditions, regardless of the specific thermal systems in place.

Step 5 Building simulation

The energy performance of the building envelope was calculated using the Termolog tool version number 13 [42,43]. Annual hourly data, exported from Meteonorm, were imported in the software as monthly average data for each location, year, and RCP scenario.

To evaluate the building envelope's energy performance across various conditions and climate scenarios, results were plotted using thermal performance indices expressed in kWh/m², EP_{h,nd} and EP_{c,nd} for heating and cooling, respectively. The EP_{tot,nd} is the sum of EP_{h,nd} and EP_{c,nd}. Such indices are independent of the heating or cooling system used, calculated according to the specific indications of UNI TS 11300-1 [44].

The technical specification lays out the procedures for applying UNI EN ISO 13790:2008 specifically employing the monthly method for the computation of thermal energy requirements related to both heating and cooling. The technical specification is designed to cover a wide range of potential applications envisaged by UNI EN ISO 13790:2008, including design evaluation, energy assessment of buildings through calculations through standard condition calculations (asset rating), or under specific climatic and operational conditions (tailored rating).

2.1. Selected locations

The European climate variability can be grouped into four main climatic areas: Nordic, Continental, Oceanic, and Mediterranean [45]. In addition to this macro division, the Köppen-Geiger climate classification has also been employed to further refine and categorize European climatic conditions [46,47]. It categorizes climates into five main climate



Fig. 2. Statistical distribution of external temperature for Nordic and Continental locations over the years 2030, 2050, 2070 under RCP 2.6 (a-c).

groups, primarily based on precipitation and temperature patterns. Within the European climate variability, the following main areas can be identified: Csa (C: warm temperate, s: dry summer, a: hot summer), Dfb (D: cold, f: fully humid, b: warm summer), Cfb (C: warm temperate, f: without dry season, b: warm summer), Bsk (B: arid, s: dry summer, k: cold arid). A number of 94 locations were chosen among Member States to cover the European climate variability, as shown in Fig. 1.

• 29 cities for Continental climate, of which 3 Cfa, 8 Cfb, 8 Dfb, 5 Dfc, 1 Csa, 1 Csb, 1 BSk, 2 ET;



Fig. 3. Statistical distributions of external temperatures for Oceanic and Mediterranean locations over the years 2030, 2050, 2070 under RCP 2.6 (a-c).

- 12 cities for the Nordic climate, of which 5 Cfb, 5 Dfb and 2 Dfc;
- 15 cities for Oceanic climate, of which 1 Cfa, 8 Cfb, 1 Cfc, 1 Csa, 1 Csb, 1 Dfb, 1 Dfc, 1 ET;
- 38 cities for the Mediterranean climate, of which 4 Cfa, 3 Cfb, 1 Cfc, 11 Csa, 7 Csb, 3 Dfb, 2 Dfc, 2 BSh, 3 BSk, 1 BWh, 1 ET.

Among the chosen locations, all the capitals of Member State were selected. As shown in Table 1, certain cities identified within a specific climate zone may partially overlap with different climatic areas (e.g., Sofia, Obârșia-Cloșani, Jesenice, Saint Martin d'Entraunes, Kakopetria, Dernis, Florina, Madrid, Villanua, Las Palmas, Anciles). In these cases, the predominant climatic zone was taken into account (marked with "bordering on" in the second column). Table 1 also shows the national climate classification, for the countries where it is available, i.e. France, Greece, Italy, and Spain.

2.2. Climate data

This study conducts a comparative analysis of three RCP (Representative Concentration Pathways) scenarios: RCP 2.6, RCP 4.5, and RCP 8.5. These scenarios reflect increasing levels of climate change severity and are founded on the greenhouse gas concentration trajectories established by the Intergovernmental Panel on Climate Change (IPCC) in the fifth assessment [48], summarized as follows.



Fig. 4. Statistical distributions of external temperatures for Nordic and Continental locations over the years 2030, 2050, 2070 under RCP 4.5 (a-c).

- the RCP 2.6 represents a mitigation emission scenario, characterized by high efforts to reduce emissions;
- the RCP 4.5 is an intermediate pathway that considers a stabilization scenario, where efforts to reduce emissions are at a moderate level;
- the RCP 8.5 is an extreme scenario involving high emissions and limited efforts to reduce emissions, resulting in more rapid warming and severe climate change impacts.



Fig. 5. Statistical distributions of external temperatures for Oceanic and Mediterranean locations over the years 2030, 2050, and 2070 under RCP 4.5 (a-c).

The difference between RCPs can be relatively minor until the middle of the century as changes in greenhouse gas concentrations may have a gradual impact on the climate system. Beyond this timeframe, there should be a clear distinction between different RCPs, reflecting the varying levels of emissions and mitigation efforts.

An essential aspect of the model development involves the choice of the weather files to be used in energy simulations [49]. There are several databases designed for assessing typical and extreme weather conditions, providing future climate data [50,51]. Some of the commonly used CCWorldWeatherGen, WeatherShiftTM, and Meteonorm. Additionally, other tools have been developed for this purpose; for instance, Rodrigues et al. [52] introduced a novel open-source morphing tool characterized by enhanced resolution and optimized spatial interpolation. This study adopts Meteonorm version number 8.

Meteonorm is a comprehensive climatic file database that encompasses 8325 meteorological stations located worldwide. Its application and use are well-supported and validated by numerous studies and research [53,54]. Using the data provided by meteorological stations, it is feasible to acquire hourly temperature values for an entire year employing a stochastic model [55]. Meteonorm primarily relies on the statistical downscaling method to estimate climatic variables at local level using available meteorological data [56]. It incorporates the CMIP5 climate model and integrates a range of data sources, including satellite data, reanalysis data, and ground-based measurements, to



Fig. 6. Statistical distributions of external temperatures for Nordic and Continental locations over the years 2030, 2050, 2070 under RCP 8.5 (a-c).

construct a comprehensive climatic database. Meteonorm establishes empirical relationships between large-scale meteorological variables and local-scale parameters through statistical downscaling. It employs regression techniques and statistical models to downscale the available climatic data to the desired location, considering factors such as latitude, altitude, and geographic features to enhance data accuracy. The tool is based on global climate models (GCMs), as specified in the IPCC assessment report [57]. Meteonorm's final data represent a



Fig. 7. Statistical distributions of external temperatures for Oceanic and Mediterranean locations over the years 2030, 2050, and 2070 under RCP 8.5 (a-c).

comprehensive compilation of measured, calculated, and interpolated data [58–60] to calculate typical years at selected locations with a hourly resolution for future climate scenarios, offering a valuable resource for climate-related research and analysis.

External temperature data are shown for all cities, for the three RCPs and for the three years 2030, 2050, 2070 using box plots (Figs. 2–7). Box Plots are a graphical representation featuring rectangles divided into two parts, each with two segments. The rectangle (called the "box") is bounded by the first and third quartiles, and divided by the median; the segments (called "whiskers") are bounded by the minimum and maximum external temperature values for each location and chosen year. This visualization is an informative way to visualize the distribution and variability of external temperature data for the specified

scenarios and timeframes.

To better understand how the forecast temperature will be in 2070 compared to 2030, Table 2 shows the changes in annual minimum, average and maximum temperature for a selection of locations within each of the four European climate zones. For the most extreme scenario RCP 8.5, locations with significant deviations in each climate zone are highlighted in either green (indicating a minimum deviation) or red (indicating a maximum deviation). As example, Copenhagen (Dfb) exhibits the minimum variation (+2.3 °C colored in green) in annual minimum outdoor temperature, compared with the others locations within the Nordic climate zone. Forecasts show that in the RCP 8.5 scenario, in 2070, the lowest temperatures will be reached in Tampere (-20.2 °C in 2030 and -16.9 °C in 2070) while the highest is expected in

Minimum and maximum external temperature variations from 2030 to 2070. In the RCP 8.5 scenario, green denotes the minimum deviation achieved between locations belonging to the same climate zone, while red indicates the maximum deviation.

City	RCP	Min [°C]	Med [°C]	Max [°C]
Nordic				
Copenhagen	2.6	+0.5	+0.4	+0.2
1 0	4.5	+1.4	+1.0	+1.1
	8.5	+2.3	+2.1	+2.4
Klaipėda	2.6	+0.3	+0.5	+0.5
	4.5	+1.6	+1.2	+1.1
	8.5	+2.4	+2.2	+2.1
Daugavpils	2.6	+0.0	+0.4	+0.3
0 1	4.5	+3.6	+1.6	+1.0
	8.5	+3.8	+2.6	+2.8
Continental				
Kardzhali	2.6	+0.5	+0.5	+0.3
	4.5	+1.7	+1.4	+2
	8.5	+2.1	+2.7	+4.1
Warsaw	2.6	+0.8	+0.4	-0.1
	4.5	+2.2	+1.4	+1.2
	8.5	+2.5	+2.3	+2.8
Jesenik	2.6	+0.7	+0.4	+0.1
	4.5	+2	+1.4	+1.3
	8.5	+2.9	+2.4	+2.9
Pernik	2.6	+0.6	+0.5	+0.2
	4.5	+1.6	+1.3	+1.5
	8.5	+2.4	+2.7	+4.2
Oceanic			1	
Toulouse	2.6	+0.1	+0.2	+0.2
	4.5	+1.2	+1.2	+1.6
	8.5	+1.6	+2.3	+3.3
Ghent	2.6	+0.4	+0.3	-0.3
	4.5	+0.8	+0.8	+0.9
	8.5	+1.7	+1.9	+1.9
Berlin	2.6	+0.7	+0.4	+0.0
	4.5	+1.6	+1.1	+0.8
	8.5	+2.5	+2.2	+2.6
Tignes	2.6	+0.4	+0.3	+0.2
0	4.5	+1.4	+1.0	+1.7
	8.5	+2.4	+2.6	+3.8
Mediterranean				
Las Palmas	2.6	+0.2	+0.2	+0.4
	4.5	+0.5	+0.7	+0.8
	8.5	+0.9	+1.4	+1.8
Lisbon	2.6	+0.2	+0.2	+0.1
	4.5	+0.7	+0.7	+0.8
	8.5	+1.4	+1.5	+1.5
Tarvisio	2.6	+0.9	+0.4	+0.4
	4.5	+1.7	+1.3	+1.5
	8.5	+2.5	+2.7	+3.9
Krasno Polie	2.6	+0.6	+0.5	+0.1
rationo i orje	4.5	+1.7	+1.3	+16
	8.5	+2.3	+2.5	+3.9

Athens (+43.7 °C in 2030; +46.8 °C in 2070).

2.3. The reference residential building

The reference building used to carry out energy simulations is a newly constructed multi-residential structure. It consists of three aboveground floors corresponding to three small apartments having the same layout. For each apartment, the net surface area is 74 m², and the net volume area is 199 m². The building is analyzed without air conditioning systems in order to investigate the envelope performance with regard to the energy requirement limit in all selected locations.

The characteristics of the opaque envelope of the reference building are detailed in Table 3. The thickness of the insulation layer, which comprises expanded polystyrene, was adjusted at each location to meet the thermal transmittance limit imposed by the Member State regulation. This ensures that the building envelope complies with the thermal performance set by the respective national requirements. The thickness of the insulation was set as close as possible to the transmittance limit, with increments of 10 mm. The resulting trends of the thermal transmittances of the opaque envelope within these specified ranges are shown in Fig. 8, where the dots represent the effective EPS thicknesses used for the simulations.

Each apartment has seven windows (150 cm \times 160 cm) with 6 cm thick polyvinyl chloride frames and a 10 cm vertical partition. Each window is equipped with pastel-colored exterior shutters of opaque transparency and aluminum blinds. Notably, the analysis primarily concentrates on the design aspects, as the manual opening and closing of blinds is subjective and not typically within the control of the designer. For this reason, automatic closing of the blinds at night, from 8 p.m. to 8 a.m., has been implemented at all locations. Table 4 provides a comprehensive breakdown of all parameters related to the transparent envelope in terms of cavity gas (Gas), the stratigraphy of the glass (Glass), number of air chambers (N. Ch.), glazing coating (g), and glass transmittance (U_g).

The thermal transmittance limits established by each Member State are reported in Table 5. These limits were primarily gathered from the EPBD, with a preference for the most recent documents. Where data were not available, they were derived from national sources for France, Croatia, Spain, and from scientific articles for Romania. n the case of Luxembourg, where sources were lacking, the nearest country, Belgium, was chosen as a reference and the limit values of the city of Liège were set. The transmittance limits for new buildings were used whenever available. Where not available, limits for major renovations were used (i.e. for Bulgaria, Cyprus). For Latvia and Lithuania, temperature correction factors denoted as "k" were applied, which are closely associated with the prevailing temperatures of the region under consideration.

3. Results

Figs. 9–17 show the projected trends in thermal performance indices (EP) for the main European climate zones. Detailed numerical data corresponding to these figures can be found in the Supplementary Data file.

In general, it has been noted that the results for the RPC 2.6 scenario indicate a very limited variability in the controlled quantities. Therefore, they represent an optimal condition to be pursued in future years, but, as of now, it appears the least realistic scenario. Therefore, in analysing the results, the focus will be directed more towards the other two scenarios (RCP 4.5 and RCP 8.5), which seem more likely and indicative of a more challenging and impactful future climate. The trends across the different climatic zones are now described to highlight variations in thermal performance indices across different locations and over time, to derive implications for energy consumption and building management strategies.

3.1. Nordic climate

Under the RCP 4.5 scenario, there is a general reduction of $\rm EP_{tot,nd}$ in almost all locations. Exceptions are the cities of Klaipėda and Stockholm. Klaipėda shows a relatively insignificant increase in $\rm EP_{tot,nd}$ from 2030 to 2050 due to a slight increase in $\rm EP_{tot,nd}$, followed by a decrease from 2050 to 2070. For Stockholm, there is no change in $\rm EP_{tot,nd}$ from 2030 to 2050. Both cities exhibit a decline of $\rm EP_{tot,nd}$ in 2070 compared to 2030, with a reduction of -3.45% for Klaipėda and -7.15% for Stockholm during that period.

In the RCP 8.5 scenario, the overall energy demand is reduced in all locations. In 2070, the most significant decrease in overall heating demand compared to 2030 are observed in the cities of Tampere and Östersund, with reductions of -13.61 % and -19.04 %, respectively. Notably, among all Nordic locations, Östersund starts with the highest thermal energy requirement for heating in 2030, and it experiences a more pronounced decrease in the EP_{h,nd} index compared to the other

Characterization of the opaque envelope of the reference building. For each layer of the envelope, the thickness (d), the thermal conductivity (λ), and the density (ρ) are reported.



Elements	Layers (inside to outside)	d [mm]	$\lambda [W/mK]$	ρ [kg/m ³]
Roof	Plaster	10	0.700	1400
	Floor block with in-situ lightning elements	260	0.743	1800
	Vapour barrier	5	0.400	360
	Expanded polystyrene (EPS)	40-390	0.033	24
	Bituminous waterproofing membrane -	5	0.170	1200
	Concrete	100	0.940	1800
	Cement-mortar substrate	10	1.400	2000
	Ceramic-porcelain tiles	10	1.300	2300
External walls	Plaster	10	0.700	1400
	Brick blocks	250	0.400	1000
	Expanded polystyrene (EPS)	0-310	0.033	24
	Plaster	10	0.900	1800
Floor against the ground	Tiles	10	1.000	2300
	Cement mortar	10	1.400	2000
	Ordinary concrete screed for electrical and plumbing installations.	80	1.060	1700
	Vapour barrier	5	0.400	360
	Expanded polystyrene (EPS)	0-310	0.033	24
	Bituminous waterproofing membrane - RADON barrier	5	0.170	1200
	Reinforced concrete	80	1.910	2400
	Under-floor cavity with ventilated interspace	200	1.390	1200
	Lean concrete	80	1.000	2200
	Coarse gravel without clay	150	1.200	1700

locations. The cities of Riga and Daugavpils show the highest increase in $EP_{c,nd}$ from 2030 to 2070.

3.2. Continental climate

Under the RCP 4.5 scenario, the transition from 2030 to 2050 generally results in a decrease in $EP_{tot,nd}$ across most locations, with a few exceptions. Notably, there are significant increases in $EP_{tot,nd}$ in the cities of Pernik, Zlatograd, Parangalitsa, Bialystok, and Oradea, primarily due to an increase in $EP_{c,nd}$. There is a marginal increase in the city of Ljubljana. Shiftingg from 2030 to 2070, $EP_{tot,nd}$ decreases in almost all locations, except for Kardzhali, Parangalitsa, Oradea, and Jesenice. The most notable reduction in 2070 is observed in the city of Ukanc.

In the RCP 8.5 scenario, the most significant reduction in EP_{tot,nd} in 2070 is found in Sölden. Generally, when transitioning from 2030 to 2070, there is a decrease in EP_{tot,nd} for most cities. However, it's worth noting that, compared to the previous scenario, there is a higher number of cities that experience an increase in EP_{tot,nd} in 2070, primarily due to an increase in EP_{c,nd}. In 2070, the cities with the highest values of EP_{c,nd} are Sofia and Szeged.

3.3. Oceanic climate

Under the RCP 4.5 scenario, when transitioning from 2030 to 2050, most cities generally experience a decrease in $EP_{tot,nd}$, except for Marseille, Riez, and Crevoux, which exhibit a slight increase. In 2070, both Marseille and Paris also show a slight increase in $EP_{tot,nd}$.

In the RCP 8.5 scenario, from 2030 to 2050, most cities experience a decrease in EP_{tot,nd}. However, compared to the previous scenario, there is a higher number of cities that exhibit an increase in EP_{tot,nd}, including Ghent, Marseille, Saint Martin d'Entraunes, and Riez. More notable variations in EP_{tot,nd} between 2030 and 2070 are evident in the cities of Ghent, Marseille, and Riez.

It is evident that, for both RCP 4.5 and RCP 8.5 scenarios, there is an increase in EP_{c,nd}, except for the city of Tignes, where EP_{c,nd} remains consistently at zero. The maximum value of EP_{c,nd} is achieved by Marseille in 2070 across all scenarios.

3.4. Mediterranean climate

In the RCP4.5 scenario, nearly half of the cities (17) exhibit an increase in $\text{EP}_{\text{tot,nd}}$ in 2050 compared to 2030. However, in 2070, the



Fig. 8. Trend of the thermal transmittance of the roof, wall and floor as the thickness of the insulation layer changes.

Characterization of windows: cavity gas (Gas) with Argon (Ar) or Krypton (Kr), stratigraphy of the glass with double (D) or triple (T) glass, number of air chambers in the frame (N. Ch.), glazing coating (g) with normal (N) or Low-e (L), glass transmittance (U_g).

Туре	$U_{set} [W/m^2K]$	Gas	Glass	N. Ch.	g	U _g [W/m ² K]
W1	1.825	Ar	D	2	L	1.466
W2	1.618	Ar	D	5	L	1.466
W3	1.783	Ar	D	3	L	1.466
W4	2.782	Ar	D	2	Ν	2.716
W5	1.319	Ar	Т	6	L	1.141
W6	1.051	Kr	Т	6	L	0.807
W7	0.7	Kr	Т	6	L	0.4
W8	1.36	Ar	D	5	L	1.141
W9	4.972	NO	S	2	Ν	5.8
W10	2.575	Ar	D	5	Ν	2.716
W11	0.843	Kr	Т	6	L	0.541
W12	0.884	Kr	Т	5	L	0.541
W13	1.26	Kr	Т	3	L	0.807
W14	1.054	Ar	Т	6	L	0.807

number of cities experiencing an increase decreases to 13 cities. When transitioning from 2030 to 2070, the most significant decrease in $\rm EP_{tot,nd}$ is observed in Porto.

In the RCP8.5 scenario, when moving from 2030 to 2050, numerous cities (18) experience an increase in $\text{EP}_{tot,nd}$. However, by 2070, $\text{EP}_{tot,nd}$ increases in 21 cities compared to 2030, which represents more than half of the cities in the Mediterranean region. This increase is primarily attributed to a substantial rise in the need for cooling. In all scenarios,

the highest $\mathrm{EP}_{\mathrm{c,nd}}$ is attained in Athens, indicating high energy consumption for cooling.

The described trends highlight the varying impacts of different climate scenarios on thermal performance indices and energy consumption trends, reflecting the complex interplay between climate change and building energy demand across European regions.

3.5. Overall conditions

Results show that the balance between cooling and heating energy needs is expected to change dramatically over time and across European climatic areas.

Analysis of the results provided valuable insights into the relationship between future climatic conditions and building energy performance. It showed, in summary, an increase in the energy demand over the years for countries with a warm and mild climate, and a decrease in countries with a predominantly cold climate. In the first case, the growing demand is particularly for cooling purposes, while in the second the decrease is due to reduced heating needs as temperature increases. As a result, these regions may experience a more favorable energy balance, with less need for heating, which can lead to an overall decreased energy consumption.

Table 6 aims to answer the primary objective of this paper, as outlined in the introduction, which is to assess whether the existing design criteria for energy-efficient buildings can effectively address the challenges posed by climate change. The table provides a summary of the suitably of various national energy requirements for each country. A " \checkmark " indicates a decrease in EP_{tot,nd} in 2050 and 2070 compared to 2030, while an "x" indicates an increase in EP_{tot,nd} for all scenarios. As a consequence, if there is an overall increase in the value, a revision of current regulations and policies should be prioritized. The following main conclusions can be drawn.

- Member States falling within the Nordic climate could have lower climate change impacts on building energy consumption with existing national policies;
- Member States belonging to the Continental climate show a great variety of behaviour. Austria, Poland, Czech Republic and Slovakia show a higher level of resilience with, when identifiable, almost negligible increases in EP_{tot,nd};
- Across Member States belonging to the Oceanic climate, it is observed that Germany, Ireland and the Netherlands show resilience to climate change;
- Member States falling within the Mediterranean climate may not always able to adequately respond to climate change. The only cases with a decrease in EP_{tot,nd} are Portugal and Malta.
- In European Member States with very different climate zones, such as, for example, Italy, current energy regulations need to be revised to meet the expected increase in total energy demand for air conditioning in areas with a more temperate climate.

Overall, the research underscores the importance of national energy requirements and policies in addressing the challenges of a changing climate and related energy consumptions in buildings. It also highlights the need for continuous monitoring and adaptation to ensure an effective energy management in the sector.

4. Conclusions and policy implications

This paper investigates the impact of climate change on heating and cooling demands in several European locations. The buildings analyzed in this study were designed in compliance with the current national energy regulations in place in each Member State. As current regulations do not account for a dynamic adaptation to the changing climate effects, the performance of envelope design may not necessarily provide an adequate response to future climate conditions.

Countries	Cities	References	References NEW/	YEAR	Roof External Walls			Floor			Windows					
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					W/m ² K	W/ m ² K	mm	W/m ² K	W/ m ² K	mm	W/m ² K	W/ m ² K	mm	W/m ² K	W/ m ² K	Table 4]
Denmark	Copenhagen	[61]	Ν	2020	0.2	0.192	150	0.3	0.282	90	0.2	0.191	150	1.8	1.36	W8
Estonia	Kuressaare Tallinn	[62]	Ν	2016	0.11	0.109	280	0.22	0.21	130	NO VALUE	0.148	200	1.1	0.843	W11
Finland	Helsinki Tampere	[63]	Ν	2020	0.09	0.089	350	0.17	0.167	170	0.17	0.148	200	1	0.884	W12
Latvia	Riga	[64–66]	Ν	2020	0,15 k (k = 1)	0.149	200	0,18 k (k = 1)	0.176	160	0,15 k (k = 1)	0.148	200	1,3 k (k = 1)	1.26	W13
	Daugavpils				0,15 k (k = 0,94)	0.136	220	0,18 k (k = 0,94)	0.167	170	0,15 k (k = 0,94)	0.136	220	1,3 k (k = 0,94)	0.884	W12
Lithuania	Klaipėda	[67,68]	Ν	2020	0,08 k (k = 1,1)	0.086	360	0,1 k (k = 1,1)	0.107	270	0,1 k (k = 1,1)	0.109	280	0,7 k (k = 1,1)	0.7	W7
	Vilnius				0,08 k (k = 1,01)	0.08	390	0,1 k (k = 1,01)	0.099	310	0,1 k (k = 1,01)	0.098	310	0,7 k (k = 1,01)	0.7	W7
Sweden	Stockholm Karlstad Östersund	[69]	Ν	2021	0.13	0.126	240	0.18	0.176	160	0.15	0.148	200	1.2	1.054	W14
Austria	Wien Mariazell Landeck Sölden	[70]	Ν	2020	0.2	0.192	150	0.35	0.34	70	0.4	0.398	60	1.4	1.36	W8
Bulgaria	Sofia Pernik Kardzhali Zlatograd Pamporovo Parangalitsa	[71]	Ν	2020	0.25	0.232	120	0.28	0.26	100	0.4	0.398	60	1.4	1.36	W8
Poland	Warsaw Białystok	[72]	Ν	2020	0.15	0.149	200	0.2	0.198	140	0.3	0.292	90	0.9	0.884	W12
Czech Republic	Prague Jesenik	[73]	Ν	2020	0.24	0.232	120	0.3	0.282	90	0.6	0.524	40	1.8	1.783	W3
Romania	Bucharest Oradea Bistrița Obârșia-Cloșani Sulina	[74]	Ν	2005	0.2	0.192	150	0.55	0.492	40	0.22	0.216	130	1.29	1.26	W13
Slovakia	Bratislava Banská Bystrica Telgart	[75]	Ν	2020	0.15	0.149	200	0.22	0.21	130	NO VALUE	0.148	200	0.85	0.843	W11
Slovenia	Ljubljana Jesenice Kranjska Gora Ukanc	[76]	Ν	2020	0.18	0.172	170	0.2	0.198	140	0.35	0.321	80	1	0.884	W12
Hungary	Szeged Budabest Répáshuta	[77]	Ν	2020	0.17	0.163	180	0.24	0.224	120	0.3	0.292	90	1.15	1.054	W14
Belgium	Liege Ghent	[78–80]	Ν	2020	0.24	0.232	120	0.24	0.224	120	0.24	0.231	120	1.5	1.36	W8
France	Marseille	[81]	Ν	2016	0.24	0.232	120	0.24 0.4	0.224	120 60	0.3	0.292	90 70	1.8 2.1	1.783	w3 W1

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Krano Polje		Ogulin				0.25	0 232	120	0.3	0.282	90	0.4	0 398	60	16	1 36	W8
Greece Athens [87] N 2020 0.4 0.359 70 0.45 0.428 50 0.8 0.623 30 1.9 1.825 W1 Pylos 0.45 0.420 60 0.55 0.492 40 1.1 0.623 30 2.1 1.825 W1 Papigo 0.35 0.323 80 0.4 0.379 60 0.65 0.623 30 2.1 1.825 W1 Larissa Larissa 0.35 0.323 80 0.44 0.379 60 0.65 0.524 40 1.7 1.618 W2 Italy Rome [68] N 2020 0.26 0.252 110 0.29 0.282 90 0.29 0.288 100 1.8 1.73 W3 Foggia 0.33 0.323 80 0.34 0.308 80 0.38 0.355 70 2.2 1.825 W1 Lagonegro 0.35 0.323 80 0.34 0.308 80 0.344 0.398 <td< td=""><td></td><td>Krasno Polje</td><td></td><td></td><td></td><td>0.20</td><td>0.202</td><td>120</td><td>0.0</td><td>0.202</td><td>20</td><td>0.1</td><td>0.090</td><td>00</td><td>1.0</td><td>1.00</td><td></td></td<>		Krasno Polje				0.20	0.202	120	0.0	0.202	20	0.1	0.090	00	1.0	1.00	
Pylos 0.45 0.402 60 0.55 0.492 40 1.1 0.623 30 2.1 1.825 W1 Papigo 0.35 0.35 0.32 80 0.4 0.35 0.65 0.623 30 1.75 1.825 W1 Iraisa Florina 0.37 0.295 90 0.35 0.34 70 0.60 0.524 40 1.7 1.618 W2 Iraiya Rome [88] N 2020 0.26 0.252 110 0.29 0.282 90 0.268 100 1.8 1.783 W3 Foggia 0.33 0.323 80 0.34 0.308 80 0.385 70 2.2 1.825 W1 Agonegro 0.35 0.323 80 0.43 0.428 50 0.444 0.398 60 3 2.782 W4 Iagonegro 0.22 0.217 130 0.26 0.241 110 0.241 0.241 0.241 0.241 0.241 0	Greece	Athens	[87]	Ν	2020	0.4	0.359	70	0.45	0.428	50	0.8	0.623	30	1.9	1.825	W1
Papigo 0.35 0.323 80 0.4 0.379 60 0.65 0.623 30 1.75 1.618 W2 Larissa Florina 0.3 0.295 90 0.35 0.34 70 0.6 0.524 40 1.7 1.618 W2 Italy Rome [88] N 2020 0.26 0.252 110 0.29 0.282 90 0.268 100 1.8 W3 Foggia Iccce 0.33 0.323 80 0.34 0.308 80 0.355 70 2.2 1.825 W1 Siracusa Iccce 0.35 0.323 80 0.43 0.428 50 0.44 0.398 60 3 2.782 W4 Iagonegro Icagonegro		Pylos				0.45	0.402	60	0.55	0.492	40	1.1	0.623	30	2.1	1.825	W1
Iarissa Florina 0.295 9.0 0.35 0.34 7.0 0.6 0.524 4.0 1.7 1.618 W2 Italy Rome [88] N 2020 0.26 0.252 110 0.29 0.282 90 0.29 0.268 100 1.8 1.783 W3 Foggia - <t< td=""><td></td><td>Papigo</td><td></td><td></td><td></td><td>0.35</td><td>0.323</td><td>80</td><td>0.4</td><td>0.379</td><td>60</td><td>0.65</td><td>0.623</td><td>30</td><td>1.75</td><td>1.618</td><td>W2</td></t<>		Papigo				0.35	0.323	80	0.4	0.379	60	0.65	0.623	30	1.75	1.618	W2
Italy Rome [88] N 2020 0.26 0.29 0.30 0.34 70 0.66 0.524 400 1.7 1.618 W2 Italy Rome [88] N 2020 0.26 0.22 110 0.29 0.282 90 0.29 0.268 100 1.8 1.783 W3 Foggia Lecce 0.33 0.323 80 0.34 0.308 80 0.38 0.355 70 2.2 1.825 W1 Siracusa 0.35 0.323 80 0.43 0.428 50 0.444 0.398 60 3 2.782 W4 Lagonegro 0.22 0.217 130 0.26 0.241 110 0.26 0.248 110 1.4 1.319 W5 Milan L'Aquila Fenestrelle 0.2 0.192 150 0.24 0.24 0.231 120 1.1 1.051 W6 Asiago Tarvisio Livigno Tarvisio Tarvisio Tarvisio <thtarvisio< th=""> <thtarvisio< th=""> <t< td=""><td></td><td>Larissa</td><td></td><td></td><td></td><td>0.2</td><td>0.005</td><td>00</td><td>0.25</td><td>0.24</td><td>70</td><td>0.6</td><td>0.504</td><td>40</td><td>1 7</td><td>1 6 1 0</td><td>MO</td></t<></thtarvisio<></thtarvisio<>		Larissa				0.2	0.005	00	0.25	0.24	70	0.6	0.504	40	1 7	1 6 1 0	MO
Mary Rome	Italy	FIOTINA	[88]	N	2020	0.3	0.295	90 110	0.35	0.34	70 90	0.6	0.524	40	1.7	1.618	W2 W3
Locce 0.33 0.323 80 0.34 0.308 80 0.38 0.385 70 2.2 1.825 W1 Siracusa 0.35 0.323 80 0.43 0.428 50 0.44 0.398 60 3 2.782 W4 Lagonegro 0.22 0.217 130 0.26 0.241 110 0.26 0.248 110 1.4 1.319 W5 Milan L'Aquila Fenestrelle 0.2 0.192 150 0.24 120 0.231 120 1.1 1.051 W6 Asiago Tarvisio 1vigno 1vigno 1vigno 1vigno 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Malta Valletta [89] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4	itary	Foggia	[00]		2020	0.20	0.202	110	0.29	0.202	20	0.29	0.200	100	1.0	1.700	115
Siracusa 0.35 0.323 80 0.43 0.428 50 0.44 0.398 60 3 2.782 W4 Lagonegro 0.22 0.217 130 0.26 0.241 110 0.26 0.248 110 1.4 1.319 W5 Milan L'Aquila		Lecce				0.33	0.323	80	0.34	0.308	80	0.38	0.355	70	2.2	1.825	W1
Lagonegro 0.22 0.217 130 0.26 0.241 110 0.26 0.248 110 1.4 1.319 W5 Milan L'Aquila Enestrelle 0.2 0.192 150 0.24 0.24 120 0.231 120 1.1 1.051 W6 Asiago Tarvisio Tarvisio Tarvisio Tarvisio Tarvisio Tarvisio Tarvisio Tarvisio 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Malta Valletta [89] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4		Siracusa				0.35	0.323	80	0.43	0.428	50	0.44	0.398	60	3	2.782	W4
Milan L'Aquila Fenestrelle 0.2 0.192 150 0.24 120 0.231 120 1.1 1.051 W6 Asiago Tarvisio Ivigno Valletta [89] N 2006 0.592 0.532 40 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Portugal Lisbon [90] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4		Lagonegro				0.22	0.217	130	0.26	0.241	110	0.26	0.248	110	1.4	1.319	W5
Faquita Fenestrelle 0.2 0.192 150 0.24 120 0.231 120 1.1 1.051 W6 Asiago Tarvisio Ivigno 1 1.051 W6 W6 Malta Valletta [89] N 2006 0.592 0.532 40 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Portugal Lisbon [90] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4		Milan L'Aquila															
Asiago Tarvisio Livigno Malta Valletta [89] N 2006 0.592 1.57 1.21 1.57 1.21 1.57 1.21 1.57 1.57 1.57 1.58 1.57 1.58 1.57 1.438 0.58 4.972 1.59 1.50 1.50 1.57 1.438 0.58 2.59 0.59 0.52 1.57 1.438 0.58 2.782 W4		L'Aquila Fenestrelle				0.2	0 1 9 2	150	0.24	0 224	120	0.24	0.231	120	11	1 051	W6
Tarvisio Livigno Malta Valletta [89] N 2006 0.59 0.532 40 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Portugal Lisbon [90] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4		Asiago				0.2	0.172	150	0.24	0.224	120	0.24	0.251	120	1.1	1.051	***
Livigno Malta Valletta [89] N 2006 0.59 0.532 40 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Portugal Lisbon [90] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4		Tarvisio															
Malta Valletta [89] N 2006 0.59 0.532 40 1.57 1.219 0 1.57 1.438 0 5.8 4.972 W9 Portugal Lisbon [90] N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4		Livigno															
Portugal Lisbon 901 N 2020 0.4 0.359 70 0.5 0.492 40 0.4 0.398 60 2.8 2.782 W4	Malta	Valletta	[89]	N	2006	0.59	0.532	40	1.57	1.219	0	1.57	1.438	0	5.8	4.972	W9
	Portugal	Lisbon	[90]	Ν	2020	0.4	0.359	70	0.5	0.492	40	0.4	0.398	60	2.8	2.782	W4
rotto Snain Seville [91] N. 2016 0.44 0.402 60 0.56 0.492 40 0.56 0.524 40 2.3 1.825 W1	Snain	Seville	[91]	N	2016	0.44	0 402	60	0.56	0 492	40	0.56	0 524	40	23	1 825	W1
Valencia	opuni	Valencia	[)1]	14	2010	0.11	0.102	00	0.00	0.152	10	0.00	0.021	10	2.0	1.020	
Las Palmas 0.5 0.458 50 0.7 0.578 30 0.7 0.623 30 2.7 2.575 W10		Las Palmas				0.5	0.458	50	0.7	0.578	30	0.7	0.623	30	2.7	2.575	W10
Malaga		Malaga															
La Coruna 0.4 0.359 70 0.49 0.428 50 0.49 0.398 60 2.1 1.825 W1		La Coruna				0.4	0.359	70	0.49	0.428	50	0.49	0.398	60	2.1	1.825	W1
Bilbao Lorg		Bilbao				0.22	0 222	80	0.27	0.24	70	0.27	0.255	70	1.0	1 702	14/2
Huesca 0.35 0.323 60 0.37 0.34 70 0.37 0.353 70 1.8 1.783 W3		Huesca				0.35	0.323	80 80	0.37	0.379	70 60	0.37	0.398	70 60	1.0	1.783	W3
Madrid		Madrid				0.00	0.020	20	0.11	0.079	00	0.12	0.090		1.0	1.7 00	
Villanua		Villanua															
Anciles		Anciles															



Fig. 9. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Nordic locations.



Fig. 10. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Continental locations (from Wien to Parangalitsa).



Fig. 11. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Continental locations (from Warsaw to Bratislava).



Fig. 12. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Continental locations (from Banka Bystrica to Repashuta).



Fig. 13. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Oceanic locations (from Liege to Paris).



Fig. 14. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Oceanic locations (from Crevoux to Amstredam).



Fig. 15. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Mediterranean locations (from Nicosia to Milan).

A clear consideration emerges from the overall analysis of the results. In the coming years, there is an expected decrease in the total demand for air conditioning in European countries within moderately cold climates. Conversely, in countries characterized by an average warm climate, there is an expected increase in the total demand for air conditioning, primarily driven by a significant rise in summer cooling requirements. This marked difference can be also linked to the historical application of energy regulations that prioritized reducing winter energy usage over summer consumption. Therefore, in order to curb the escalating total demand for air conditioning in warmer climates, it



Fig. 16. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Mediterranean locations (from L'Aquila to Lisbon).







Fig. 17. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Mediterranean locations (from Porto to Anciles).

Will the actual design criteria for energy efficient buildings be able to respond to impending climate change? Summary of the impact of the various national policies for each country (" \checkmark ": decrease in EP_{tot,nd} in 2050 and 2070 compared to 2030; "x"; increase in EP_{tot,nd} for all scenarios).

EU climate zones					RCP 2.	6	RCP 4.	5	RCP 8.5	5
	Country	City	Koppen climate classification	National climate zones	2050	2070	2050	2070	2050	2070
Nordic	Denmark	Copenhagen	Cfb	-	1	1	~	1	1	1
	Estonia	Kuressaare	Cfb	-	1	1	-	1	1	1
		Tallinn	Dfb	-						
	Finland	Helsinki	Dfb	-	-	-	-	-	1	-
	Latria	l'ampere	Dic	-		,			,	
	Latvia	Riga	DB	-	•	•	•	•	•	•
	Lithuania	Klaipėda	Cfb	-			×			
	Liuiuailia	Vilnius	Dfb	_		,	2			
	Sweden	Stockholm	Cfb	_						
	oweden	Karlstad	Dfb	_	•	•		•		
		Östersund	Dfc	_						
Continental	Austria	Wien	Cfb	_	~	1	1	1	1	1
		Mariazell	Dfb	-	1	1	1	1	1	1
		Landeck	Dfc	-	~	×	1	1	1	1
		Sölden	ET	-	1	1	1	1	1	1
	Bulgaria	Sofia	Cfa (bordering on Cfb)	-	1	1	1	1	×	×
		Pernik	Cfb	-	~	~	×	×	1	×
		Kardzhali	Csa	-	×	×	1	×	1	×
		Zlatograd	Csb	-	×	1	×	1	1	1
		Pamporovo	Dfb	-	~	·	-	-	·	~
		Parangalitsa	Dfc	-	×	×	×	×	x	x
	Poland	Warsaw	Cfb	-			~			
	Court Doublin	Białystok	DfD	-			×			
	Czech Republic	Prague	CID	-	~	•			~	-
	Domonio	Bucharost	DID	-	~					
	Komama	Oradea	Cfb	-	2		×	Ŷ		ž
		Bistrita	Dfb	-			2	2		2
		Obârcia-Clocani	Dfc (bordering on Cfb)	_						
		Sulina	BSk	_						
	Slovakia	Bratislava	Cfb	_						
	biortalia	Banská Bystrica	Dfb	_						
		Telgart	Dfc	_						
	Slovenia	Ljubljana	Cfb	_	1	1	×	1	1	x
		Jesenice	Dfb (bordering on Cfb)	-	1	1	1	x	×	×
		Kranjska Gora	Dfc	-	1	1	1	1	1	1
		Ukanc	ET (bordering Dfc)	-	1	1	1	1	x	1
	Hungary	Szeged	Cfa	-	1	1	1	1	1	×
		Budapest	Cfb	-	×	~	1	1	1	×
		Répáshuta	Dfb	-	~	~	1	1	1	1
Oceanic	Belgium	Liege	Cfb	-	1	~	1	1	1	~
		Gent	Cfb	-	~	~	1	1	×	×
		Bruxelles	Cfb	-	~	-	-	1	1	1
	France	Marseille	Csa	H3	-	-	×	×	×	×
		Riez	Cta	H2			x	~	×	×
		Toulouse	CID Cfc (handaning on Cfb)	H2				×		
		Paris Coint Montin d'Entrounce	Cic (bordering on Cib)	HI					~	
			Dfa	пэ u1			~		2	
		Tignes	ET	ПI U1			2			
	Germany	Berlin	Cfb	-						
	Germany	Lobberg	Dfb	_		×				
	Ireland	Dublin	Cfb	_	1	1	1	1	1	1
	Luxembourg	Luxembourg	Cfb	_	1	1	1	1	1	1
	Netherlands	Amsterdam	Cfb	_	1	1	1	1	1	1
Mediterranean	Cyprus	Nicosia	Csa	_	1	1	1	1	×	x
	91	Kakopetria	Csb (bordering on Csa)	_	1	1	1	1	1	1
		Larnaca	BSh	-	1	~	1	1	×	x
	Croatia	Split	Csa	-	1	1	1	1	1	×
		Dernis	Csb (bordering on Csa)	-	1	1	×	1	×	x
		Zagreb	Cfa	-	1	1	1	1	1	1
		Ogulin	Cfb	-	1	1	×	1	1	1
		Krasno Polje	Dfb	-	1	1	1	1	1	~
	Greece	Athens	Csa	В	×	×	×	×	×	×
		Pylos	Csa	A	×	×	×	×	x	×
		Papigo	CSD DCI-	C	×		~		~	~
		Fiorina	BSK Cfa (handarina Oft-)	D C			×	~	×	×
	Italy	LdTISSd	Gia (Dordering on CfD)	с D	4	· ·	Ŷ	÷.	÷.	Ŷ
	nary	Lecce	Coa	р С	×	v v	Ŷ	÷.	Ŷ	÷.
		Siracusa	Csh	B	Ŷ	Ŷ	Ŷ	Ŷ	Ŷ	Ŷ
		Lagonegro	Cfa	E	~	~	~	~	x	x
				_	-	-	-	-	••	

(continued on next page)

Table 6 (continued)

,									
	Milan	Cfb	Е	1	×	1	1	×	x
	L'Aquila	Cfc	E	1	1	1	1	x	1
	Fenestrelle	BSk	F	1	1	1	1	1	1
	Foggia	Csa	D	×	x	x	x	×	x
	Asiago	Dfb	F	1	1	1	1	1	1
	Tarvisio	Dfc	F	1	1	1	1	1	x
	Livigno	ET	F	1	1	 Image: A second s	1	1	1
Malta	Valletta	Csa	-	1	1	 Image: A second s	1	1	1
Portugal	Lisbon	Csa	-	1	1	 Image: A second s	1	1	1
	Porto	Csb	-	1	1	1	1	1	1
Spain	Seville	Csa	B4	×	x	x	x	×	x
	Malaga	Csa	A3	×	x	x	x	×	x
	La Coruna	Cfa	C1	1	1	1	1	1	1
	Leon	BSh	E1	1	x	×	x	1	1
	Huesca	BSk (bordering on (Csa)	D2	x	x	×	x	x	x
	Bilbao	Cfb	C1	1	1	 Image: A second s	1	1	1
	Valencia	Csa	B3	x	x	×	x	x	x
	Madrid	Dfb (bordering on Cfb)	D3	1	1	×	x	1	x
	Villanua	BWh (bordering on BSk)	D2	1	x	×	1	1	1
	Las Palmas	Csb	A2	x	x	×	×	x	x
	Anciles	Dfc (bordering on Cfb)	D2	1	1	1	1	1	1

would be useful to revise and adapt energy regulations with a specific focus on controlling summer energy consumption. Therefore, two main approaches can be possible: periodic updates and evaluation of energy requirements for building, and flexibility in design compliance. Both approaches would be based on the energy efficiency first principle that encourages energy-efficient design solutions. The first would ensure that building codes and regulations remain relevant and effective in mitigating the effects of climate change accounting for heating and cooling building demands with the support of regulatory bodies responsible for setting energy efficiency standards. These should assess climate projections and make necessary adjustments to the regulations adopting a dynamic response to evolving climatic conditions. The second approach would allow designers with flexibility in complying with legal requirements, provided they can demonstrate through calculations and analysis that the proposed solutions are energy-efficient and climateresponsive, meeting the different climatic projected scenarios. This acknowledges that innovative design solutions can achieve lower energy consumption in buildings depending on specific climatic conditions.

Starting from these results, it is possible to extend the analysis to detail the countries that show an increase in energy consumption and to propose tailored modifications to the energy requirements limits imposed at regulatory level. This could anticipate building envelope interventions before the occurrence of climatic conditions.

Considering that buildings constructed today will be in use for the next 50–100 years, it is imperative to develop building design that are resilient to climate fluctuations. When investigating if current building regulations remain appropriate in future conditions, it is important to consider that current general refurbishment cycles are typically around 30–40 years, but those which lead to energy efficiency improvements occur at even longer intervals (60–80 years) [92]. Beside targeting NZEBS [93], it would be important also to increase the awareness of climate change impact in building consumption to encourage behavioural changes and drive consumer demand for energy-efficient solutions relying on specific measures [94]. Additionally, it would be useful to expand and strengthen technology standards and labels for building refurbishment technologies, products, and materials, as well as develop a technology roadmap for building refurbishment research and demonstration activities [95].

Furthermore, as current building regulations may not be sufficient to handle the long-term impacts of climate change, it would be also useful to consider more dynamic and adaptive approaches to building design and energy efficiency. This includes periodic updates to regulations, as well as flexibility in compliance, as previously discussed. Additionally, it is essential to promote sustainable and energy-efficient building practices to reduce the need for future interventions. As a consequence, there would be a shifting focus towards more holistic strategies that take into account the changing energy needs of buildings in response to seasonal variations and climate change. This shift would require a broader understanding of the complex interplay between the envelope and the evolving requirements for energy-efficient and climate-resilient designs.

CRediT authorship contribution statement

Delia D'Agostino: Conceptualization, Methodology, Resources, Writing - review & editing, Visualization. **Paolo Maria Congedo:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Paola Maria Albanese:** Investigation, Resources, Data curation. **Alessandro Rubino:** Formal analysis, Data curation. **Cristina Baglivo:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing original draft, Writing - review & editing, Visualization, Supervision.

Declaration of competing interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from paolo.congedo@unis alento.it.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi. org/10.1016/j.energy.2023.129886.

References

- [1] EC. A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. A clean Planet for all, COM. final; 2018. p. 773. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/? uri=CELEX:52018DC0773&from=EN.
- [2] Economidou M, Todeschi V, Bertoldi P, D'Agostino D, Zangheri P, Castellazzi L. Review of 50 years of EU energy efficiency policies for buildings. Energy Build 2020;225:110322.
- [3] 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 Strategy Rev 2022;44:101009. https://doi.org/10.1016/j. esr.2022.101009.
- [4] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, the European Green Deal, COM(2019) 640, 11.12.2019, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640% 3AFIN.
- [5] Regulation EU. The European parliament and of the council of 11 december 2018 on the governance of the energy union and climate action. 2018/1999 of. https ://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_2018.328.01.000 1.01.ENG&toc=OJ:L:2018:328:FULL.
- [6] Plan RE. COM(2022) 230 final. https://eur-lex.europa.eu/legal-content/EN/TXT/? uri=COM%3A2022%3A230%3AFIN&qid=1653033742483.
- [7] Amendments adopted by the European Parliament on 14 March 2023 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast). COM; 2021. p. 802. https://www. europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.html#title1.
- [8] D'Agostino D, Tsemekidi Tzeiranaki S, Zangheri P, Bertoldi P, Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe, Energy Strategy Reviews, https://doi.org/10.1016/j.esr.2021.100680.
- [9] https://ec.europa.eu/energy/eu-buildings-factsheets_en.
- [10] Zhang Yan, Wang Chenglong, Cai Rong, Lan Zhike, Shen Yaou, Zhang Dalin, Tian Wenxi, Su Guanghui, Qiu Suizheng. Experimental investigation on flow and heat transfer characteristics of lead–bismuth eutectic in circular tubes. Appl Therm Eng 2020;180:115820. https://doi.org/10.1016/j.applthermaleng.2020.115820. ISSN 1359-4311.
- [11] Yıldız Yusuf, Zeynep Durmuş Arsan. Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates. Energy 2011;36(Issue 7):4287–96. https://doi.org/10.1016/j. energy.2011.04.013. ISSN 0360-5442.
- [12] D'Agostino Delia, Zacà Ilaria, Baglivo Cristina, Maria Congedo Paolo. Economic and thermal evaluation of different uses of an existing structure in a warm climate. Energies 2017;10(5):658. https://doi.org/10.3390/en10050658.
- [13] Maria Congedo Paolo, Baglivo Cristina, Zacà Ilaria, D'Agostino Delia. High performance solutions and data for nZEBs offices located in warm climates. Data Brief 2015;5:502–5. https://doi.org/10.1016/j.dib.2015.09.041. ISSN 2352-3409.
- [14] Morewood J. Building energy performance monitoring through the lens of data quality: a review. Energy Build 2023;279:112701. https://doi.org/10.1016/j. enbuild.2022.112701.
- [15] D'Agostino D, Parker D, Epifani I, Crawley D, Lawrie L. How will future climate impact the design and performance of Nearly Zero Energy Buildings (NZEBs)? Energy 2022;240:122479. https://doi.org/10.1016/j.energy.2021.122479.
- [16] Raji Babak, Tenpierik Martin J, den Dobbelsteen Andy van. An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: a case study in The Netherlands. Energy Build 2016;124:210–21. https:// doi.org/10.1016/j.enbuild.2015.10.049. ISSN 0378-7788.
- [17] Mazzeo Domenico, Baglivo Cristina, Panico Simone, Maria Congedo Paolo. Solar greenhouses: climates, glass selection, and plant well-being. Sol Energy 2021;230: 222–41. https://doi.org/10.1016/j.solener.2021.10.031. ISSN 0038-092X.
- [18] Abraham E, Cherpak V, Senyuk B, et al. Highly transparent silanized cellulose aerogels for boosting energy efficiency of glazing in buildings. Nat Energy 2023. https://doi.org/10.1038/s41560-023-01226-7.
- [19] Asan H. Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view. Energy Build 2000;32(Issue 2): 197–203. https://doi.org/10.1016/S0378-7788(00)00044-X. ISSN 0378-7788.
- [20] Kossecka Elisabeth, Jan Kosny. Influence of insulation configuration on heating and cooling loads in a continuously used building. Energy Build 2002;34(Issue 4): 321–31. https://doi.org/10.1016/S0378-7788(01)00121-9. ISSN 0378-7788.
- [21] Baglivo Cristina, Maria Congedo Paolo. Design method of high performance precast external walls for warm climate by multi-objective optimization analysis. Energy 2015;90:1645–61. https://doi.org/10.1016/j.energy.2015.06.132. ISSN 0360-5442.

- [22] Baglivo Cristina, Maria Congedo Paolo. High performance precast external walls for cold climate by a multi-criteria methodology. Energy 2016;115:561–76. https://doi.org/10.1016/j.energy.2016.09.018. ISSN 0360-5442.
- [23] Chen Xi, Yang Hongxing, Zhang Weilong. Simulation-based approach to optimize passively designed buildings: a case study on a typical architectural form in hot and humid climates. Renew Sustain Energy Rev 2018;82:1712–25. https://doi.org/ 10.1016/j.rser.2017.06.018. ISSN 1364-0321.
- [24] Baglivo Cristina, Maria Congedo Paolo. Optimization of high efficiency slab-onground floor by multi-objective analysis for zero energy buildings in mediterranean climate. J Build Eng 2019;24:100733. https://doi.org/10.1016/j. jobe.2019.100733. ISSN 2352-7102.
- [25] Aste Niccolò, Angelotti Adriana, Buzzetti Michela. The influence of the external walls thermal inertia on the energy performance of well insulated buildings. Energy Build 2009;41(Issue 11):1181–7. https://doi.org/10.1016/j. enbuild.2009.06.005. ISSN 0378-7788.
- [26] Al-Sanea Sami A, Zedan MF, Al-Hussain SN. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. Appl Energy 2012;89(Issue 1):430–42. https://doi.org/10.1016/j. apenergy.2011.08.009. ISSN 0306-2619.
- [27] Zhao Mosha, Künzel Hartwig M, Antretter Florian. Parameters influencing the energy performance of residential buildings in different Chinese climate zones. Energy Build 2015;96:64–75. https://doi.org/10.1016/j.enbuild.2015.03.007. ISSN 0378-7788.
- [28] Li Hangxin, Wang Shengwei, Howard Cheung. Sensitivity analysis of design parameters and optimal design for zero/low energy buildings in subtropical regions. Appl Energy 2018;228:1280–91. https://doi.org/10.1016/j. apenergy.2018.07.023. ISSN 0306-2619.
- [29] Sambou V, Lartigue B, Monchoux F, Adj M. Thermal optimization of multilayered walls using genetic algorithms. Energy Build 2009;41(Issue 10). https://doi.org/ 10.1016/j.enbuild.2009.05.007. 1031-1036, ISSN 0378-7788.
- [30] Di Perna C, Stazi F, Ursini Casalena A, D'Orazio M. Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. Energy Build 2011;43(Issue 1):200–6. https://doi.org/10.1016/j. enbuild.2010.09.007. ISSN 0378-7788.
- [31] Chen Xi, Yang Hongxing. Integrated energy performance optimization of a passively designed high-rise residential building in different climatic zones of China. Appl Energy 2018;215:145–58. https://doi.org/10.1016/j. apenergy.2018.01.099. ISSN 0306-2619.
- [32] Filippidou F, Jimenez Navarro JP. Achieving the cost-effective energy transformation of Europe's buildings. Luxembourg: EUR 29906 EN, Publications Office of the European Union; 2019JRC117739. https://doi.org/10.2760/278207. ISBN 978-92-76-12394-1.
- [33] Congedo Paolo Maria, Baglivo Cristina, Kurnuc Seyhan Aslıhan, Marchetti Raffaele. Worldwide dynamic predictive analysis of building performance under long-term climate change conditions. J Build Eng 2021;42: 103057. https://doi.org/10.1016/j.jobe.2021.103057. ISSN 2352-7102.
- [34] Luo XJ, Oyedele Lukumon O. Life cycle optimisation of building retrofitting considering climate change effects. Energy Build 2022;258:111830. https://doi. org/10.1016/j.enbuild.2022.111830. ISSN 0378-7788.
- [35] Abolhassani Soroush Samareh, Joybari Mahmood Mastani, Hosseini Mirata, Parsaee Mojtaba, Eicker Ursula. A systematic methodological framework to study climate change impacts on heating and cooling demands of buildings. J Build Eng 2023;63:105428. https://doi.org/10.1016/j.jobe.2022.105428. ISSN 2352-7102.
- [36] Yan Hainan, Ji Guohua, Yan Ke. Data-driven prediction and optimization of residential building performance in Singapore considering the impact of climate change. Build Environ 2022;226:109735. https://doi.org/10.1016/j. buildenv.2022.109735. ISSN 0360-1323.
- [37] Ascione Fabrizio, Francesca De Masi Rosa, Gigante Antonio, Vanoli Giuseppe Peter. Resilience to the climate change of nearly zero energy-building designed according to the EPBD recast: monitoring, calibrated energy models and perspective simulations of a Mediterranean nZEB living lab. Energy Build 2022;262:112004. https://doi.org/10.1016/j.enbuild.2022.112004. ISSN 0378-7788.
- [38] Yang Yuchen, Javanroodi Kavan, Nik Vahid M. Climate change and energy performance of European residential building stocks – a comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment. Appl Energy 2021;298(117246). https://doi.org/ 10.1016/j.apenergy.2021.117246. ISSN 0306-2619.
- [39] Beck H, Zimmermann N, McVicar T, et al. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 2018;5:180214. https:// doi.org/10.1038/sdata.2018.214.
- [40] REHVA Journal 02/2014 nZEB definitions in Europe.
- [41] http://koeppen-geiger.vu-wien.ac.at/kmz/Global_1986-2010_KG_5m.kmz.zip.
 [42] Baglivo Cristina, Congedo Paolo Maria, Murrone Graziano, Lezzi Dalila. Long-term predictive energy analysis of a high-performance building in a Mediterranean climate under climate change. Energy 2022;238:121641. https://doi.org/10.1016/j.energy.2021.121641. ISSN 0360-5442.
- [43] Baglivo C. Dynamic evaluation of the effects of climate change on the energy renovation of a school in a mediterranean climate. Sustainability 2021;13:6375. https://doi.org/10.3390/su13116375.
- [44] UNI/TS 11300–1. Building energy performance Part 1: Evaluation of the energy need for space heating and cooling (in Italian). 2014.
- [45] Hermelink A, Schimschar S, Boermans T, Pagliano L, Zangheri P, Armani R, Voss K, Musall E, Politecnico di Milano/eERG, University of Wuppertal. In: Towards nearly zero-energy buildings. Definition of common principles under the EPBD; 2013. Final report (Project number: BESDE10788).

D. D'Agostino et al.

- [46] Chen Deliang, Chen Hans Weiteng. Using the Köppen classification to quantify climate variation and change: an example for 1901–2010, vol. 6. Environmental Development; 2013. p. 69–79. https://doi.org/10.1016/j.envdev.2013.03.007. ISSN 2211-4645.
- [47] Skandalos N, Wang M, Kapsalis V, D'Agostino D, Parker D, Suresh Bhuvad S, Udayraj, Peng J, Karamanis D. Building PV integration according to regional climate conditions: BIPV regional adaptability extending Köppen-Geiger climate classification against urban and climate-related temperature increases. Renew Sustain Energy Rev 2022;169:112950. https://doi.org/10.1016/j. rser.2022.112950.
- [48] IPCC. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental Panel on climate change. In: Climate change 2014: synthesis report. Geneva (Switzerland): IPCC; 2014. p. 151. https://www.ipcc.ch/report /ar5/syr/. February 2021.
- [49] Moazami A, Nik V, Carlucci S, Geving S. Impacts of future weather data typology on building energy performance – investigating long-term patterns of climate change and extreme weather conditions. Appl Energy 2019;238:696–720. https:// doi.org/10.1016/j.apenergy.2019.01.085.
- [50] Herrera M, Natarajan S, Coley DA, Kershaw T, Ramallo-Gonzalez AP, Eames M, Fosas D, Wood M. A review of current and future weather data for building simulation. Build Serv Eng Res Tecnol 2017;38(5):602–27.
- [51] Amin Moazami, Carlucci Salvatore, Geving Stig. Critical analysis of software tools aimed at generating future weather files with a view to their use in building performance simulation. Energy Proc 2017;132:640–5. https://doi.org/10.1016/j. egypro.2017.09.701. ISSN 1876-6102.
- [52] Rodrigues Eugénio, Fernandes Marco S, Carvalho David. Future weather generator for building performance research: an open-source morphing tool and an application. Build Environ 2023;233:110104. https://doi.org/10.1016/j. buildenv.2023.110104. ISSN 0360-1323.
- [53] Bellia Laura, Pedace Alessia, Fragliasso Francesca. The role of weather data files in Climate-based Daylight Modeling. Sol Energy 2015;112:169–82. https://doi.org/ 10.1016/j.solener.2014.11.033. ISSN 0038-092X.
- [54] Hatwaambo Sylvester, Jain Prem C, Perers Bengt, Karlsson Bjorn. Projected beam irradiation at low latitudes using Meteonorm database. Renew Energy 2009;34 (Issue 5):1394–8. https://doi.org/10.1016/j.renene.2008.09.011. ISSN 0960-1481.
- [55] METEONORM. Handbook Part II: theory. Switzerland: Bern; 2019., Version 7.3.1.
- [56] Zahra Jalali, Shamseldin Asaad Y, Ghaffarianhoseini Amir. Impact assessment of climate change on energy performance and thermal load of residential buildings in New Zealand. Build Environ 2023;243:110627. https://doi.org/10.1016/j. buildenv.2023.110627. ISSN 0360-1323.
- [57] Tootkaboni Mamak P, Ballarini Ilaria, Zinzi Michele, Corrado Vincenzo. A comparative analysis of different future weather data for building energy performance simulation. Climate 2021;9:37. https://doi.org/10.3390/cli9020037.
 [58] Meteonorm Meteotest. Handbook part I: software. 2020.
- [59] Remund JSCM. The use of Meteonorm weather generator for climate change studies. 2010.
- [60] Meteonorm Global Meteorological Database. Meteotest. 2012. https://meteonorm.com/en/.
- [61] https://epbd-ca.eu/wp-content/uploads/2021/07/Implementation-of-the-EPBD-in-Denmark-%E2%80%93-2020.pdf. October 2023.
- [62] https://epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/countries/e stonia. October 2023.
- [63] https://epbd-ca.eu/wp-content/uploads/2021/07/Implementation-of-the-EPBD-in-Finland-%E2%80%93-2020.pdf. October 2023.
- [64] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-the-Republic-of-Latvia-%E2%80%93-Status-in-2020.pdf. October 2023.
- [65] https://likumi.lv/ta/id/275015#piel0. October 2023.
- [66] https://likumi.lv/ta/id/309453-noteikumi-par-latvijas-buvnormativu-lbn-003-19-buvklimatologija. October 2023.
- [67] https://epbd-ca.eu/wp-content/uploads/2019/04/CA-EPBD-IV-Lithuania-2018.pd f. October 2023.
- [68] Aviza Donatas, Turskis Zenonas, Volvaciovas Robertas. Correlation analysis of thermo-insulation layer thickness and its payback period of the typical pitched roof detail. Procedia Eng 2013;57:120–6. https://doi.org/10.1016/j. proeng.2013.04.018 [accessed on 10th of October 2023].
- [69] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the -EPBD-in-Sweden.pdf. October 2023.

- [70] https://epbd-ca.eu/wp-content/uploads/2021/07/Implementation-of-the-EPBD-in-Austria-%E2%80%93-2020.pdf. October 2023.
- [71] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBD-in-Bulgaria-2020.pdf. October 2023.
- [72] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EP BD-in-Poland.pdf. October 2023.
- [73] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the -EPBD-in-the-Czech-Republic.pdf. October 2023.
- [74] Dan D, Tanasa C, Stoian V, Brata S, Stoian D, Nagy Gyorgy T, Florut SC. Passive house design—an efficient solution for residential buildings in Romania. Energy for Sustainable Development 2016;32:99–109. https://doi.org/10.1016/j. esd.2016.03.007. ISSN 0973-0826.
- [75] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBD-in -the-Slovak-Republic-2020.pdf. October 2023.
- [76] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the -EPBD-in-Slovenia.pdf. October 2023.
- [77] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-Hungary-2020.pdf. October 2023.
- [78] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-Belgium-2020-%E2%80%93-Walloon-Region.pdf. October 2023.
- [79] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-Belgium-2020-%E2%80%93-Flemish-Region.pdf. October 2023.
- [80] https://epbd-ca.eu/wp-content/uploads/2022/02/Implementation-of-the-E PBD-in-Belgium-2020-%E2%80%93-Brussels-Capital-Region.pdf. October 2023.
- [81] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-France-%E2%80%93-Status-in-2020.pdf. October 2023.
- [82] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-Germany-2020.pdf. October 2023.
- [83] https://epbd-ca.eu/wp-content/uploads/2022/03/Implementation-of-the-EPBDin-Ireland-2020.pdf. October 2023.
- [84] https://epbd-ca.eu/wp-content/uploads/2021/12/Implementation-of-the-EPBDin-The-Netherlands-2020.pdf. October 2023.
- [85] https://epbd-ca.eu/wp-content/uploads/2022/03/Implementation-of-the -EPBD-in-Cyprus.pdf. October 2023.
- [86] https://narodne-novine.nn.hr/clanci/sluzbeni/dodatni/438515.pdf. October 2023.
- [87] https://epbd-ca.eu/wp-content/uploads/2022/02/Implementation-of-the-EPBDin-Greece-2020.pdf. October 2023.
- [88] https://epbd-ca.eu/wp-content/uploads/2022/03/Implementation-of-the-EPBDin-Italy-2020.pdf. October 2023.
- [89] Services Division Building Regulations Office Malta. In: Technical guidance, conservation of fuel, energy and natural resources (minimum requirements on the energy performance of buildings regulations; 2006. avaible online, https://www. bing.com/ck/a?!&&p=ee94d88d6e16bce4JmltdHM9MTY5NTc3MjgwMCZpZ3Vp ZD0yMTk1ODMyOC05MGJkLTYyZDAtMzQ5MC05MTRkOTE4ZTYzN2YmaW5z aWQ9NTE5Ng&ptn=3&hsh=3&fclid=21958328-90bd-62d0-3490-914d918e 6376&psq=malta+thermal+transmittance+limit &u=a1aHR0cHM6Ly9lcGMuZ292Lm10L2ZpbGUuYXNweD9mPTI0&ntb=1. October 2023.
- [90] https://epbd-ca.eu/wp-content/uploads/2022/10/Implementation-of-the-EPBDin-Portugal-%E2%80%93-2020.pdf. October 2023.
- [91] Ministerio DETRANSPORTES, Movilidad Y, Urbana AGENDA, Documento BásicoHE, ahorro de énergia. https://www.codigotecnico.org/pdf/Documentos/ HE/DccHE.pdf. October 2023.
- [92] DG Energy. European commission DirectorateGeneral for energy. Consultation Paper Financial support for energy efficiency in buildings. Brussels: European Commission, DirectorateGeneral for Energy; 2012. https://energy.ec.europa. eu/system/files/2014-11/2012_eeb_consultation_paper_en_0.pdf.
- [93] D'Agostino Delia, Mazzarella Livio. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. J Build Eng 2019;21: 200–12. https://doi.org/10.1016/j.jobe.2018.10.019.
- [94] D'Agostino Delia, Becchio Cristina, Crespi Giulia, Corgnati Stefano Paolo. Assessment of passive and active buildings resilience to gas supply disruption in winter across European climates. Sustain Cities Soc 2023;92:104461. https://doi. org/10.1016/j.scs.2023.104461.
- [95] D'Agostino Delia, Mazzarella Livio. Data on energy consumption and Nearly zero energy buildings (NZEBs) in Europe. Data Brief 2018;21:2470–4. https://doi.org/ 10.1016/j.jobe.2018.10.019.