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Impact of climate change on the energy performance of building envelopes and implications on energy regulations across Europe[☆]

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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

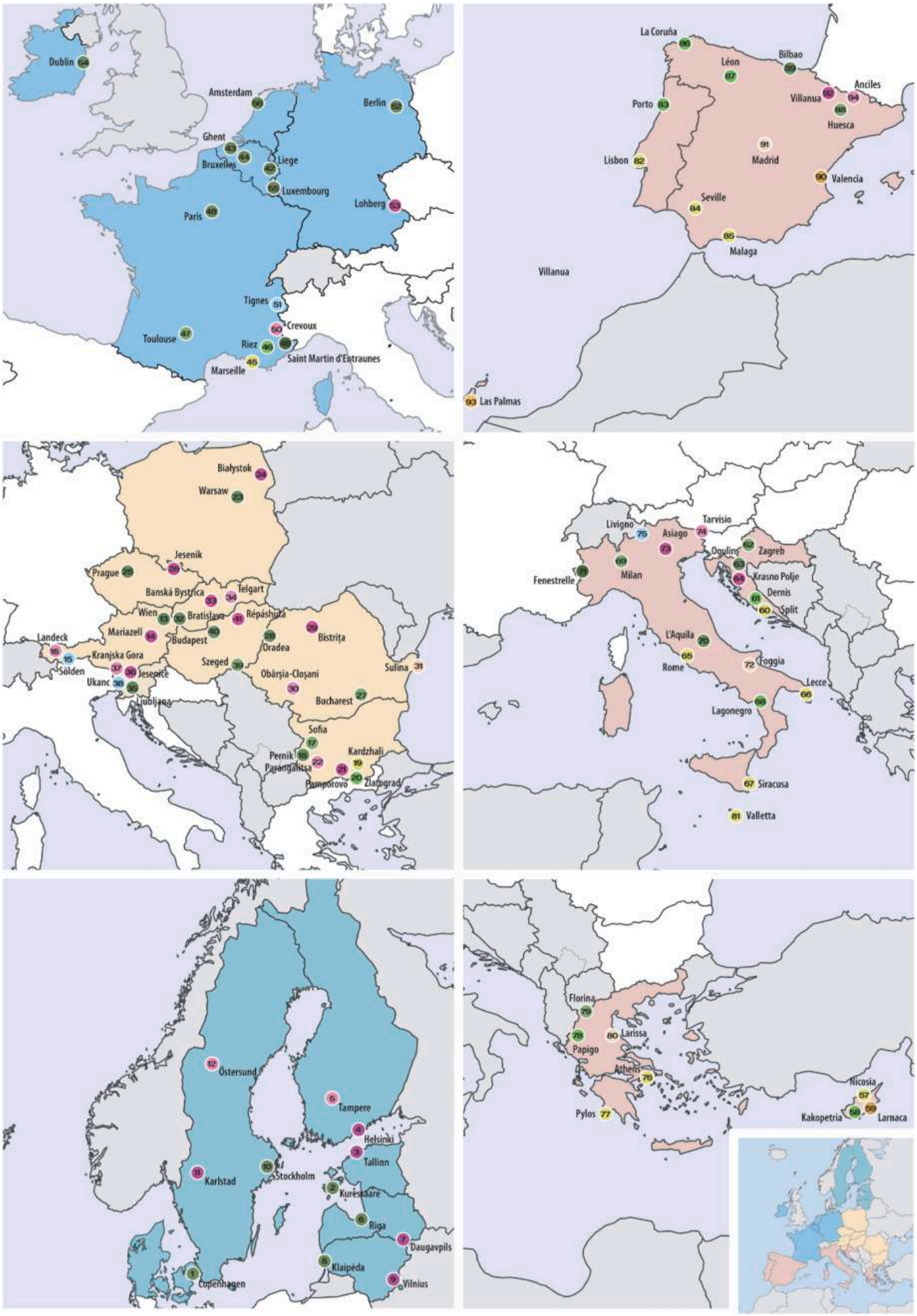


Fig. 1. Mapping of selected cities.

Table 1
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
	Cfb	Temperate oceanic climate	–	Latvia	Riga
	Dfb	Warm-summer humid continental climate	–		Daugavpils
	Cfb	Temperate oceanic climate	–	Lithuania	Klaipėda
	Dfb	Warm-summer humid continental climate	–		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	–		Sölden
	Cfa (bordering on Cfb)	Humid subtropical climate	–	Bulgaria	Sofia
	Cfb	Temperate oceanic climate	–		Pernik
	Csa	Hot-summer Mediterranean climate	–		Kardzhali
	Csb	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	–		Obârşia-Cloşani
	BSk	Cold semi-arid climate	–		Sulina
	Cfb	Temperate oceanic climate	–	Slovakia	Bratislava
	Dfb	Warm-summer humid continental climate	–		Banská Bystrica
	Dfc	Subarctic climate	–		Telgart
	Cfb	Temperate oceanic climate	–	Slovenia	Ljubljana
	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
	Cfb	Temperate oceanic climate	–		Bruxelles
	Csa	Hot-summer Mediterranean climate	H3	France	Marseille
	Csb	Warm-summer Mediterranean climate	H2		Riez
	Cfa	Humid subtropical climate	H2		Toulouse
	Cfb	Temperate oceanic climate	H1		Paris
	Cfc (bordering on Cfb)	Subpolar oceanic climate	H3		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
	Cfb	Temperate oceanic climate	–	Netherlands	Amsterdam
Mediterranean	Csa	Hot-summer Mediterranean climate	–	Cyprus	Nicosia
	Csb (bordering on Csa)	Warm-summer Mediterranean climate	–		Kakopetria
	BSh	Hot semi-arid climate	–		Larnaca
	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	B	Greece	Athens
	Csa	Hot-summer Mediterranean climate	A		Pylos
	Csb	Warm-summer Mediterranean climate	C		Papigo
	Cfa *(bordering on Cfb)*	Humid subtropical climate	D		Florina
	BSk	Cold semi-arid climate	C		Larissa
	Csa	Hot-summer Mediterranean climate	D	Italy	Rome
	Csa	Hot-summer Mediterranean climate	C		Lecce
	Csa	Hot-summer Mediterranean climate	B		Siracusa
	Csb	Warm-summer Mediterranean climate	E		Lagonegro
	Cfa	Humid subtropical climate	E		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, Bistriţa, 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/m^2, $EP_{h,nd}$ 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

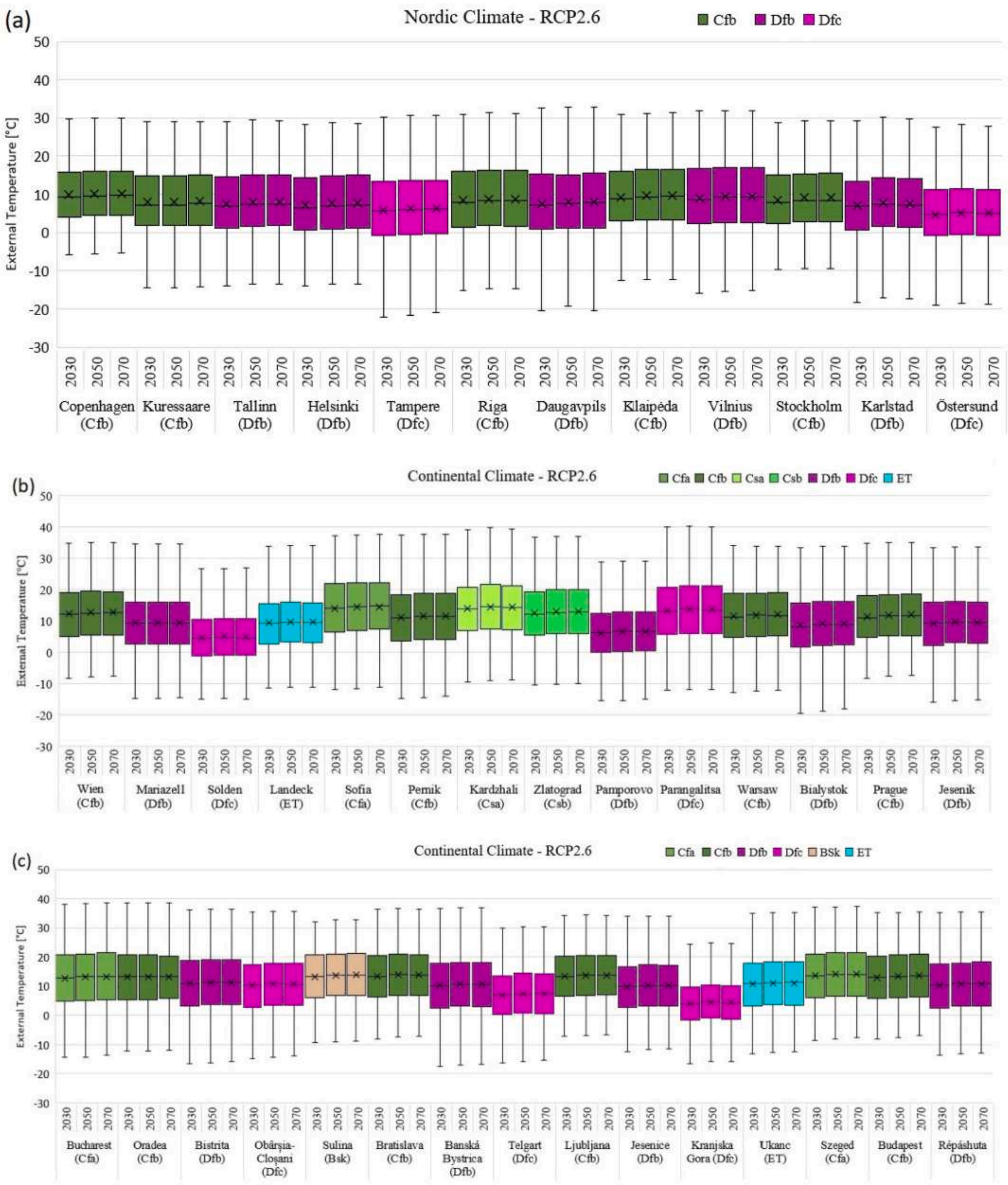


Fig. 2. Statistical distribution of external temperature for Nordic and Continental locations over the years 2030, 2050, 2070 under RCP 2.6 (a–c).

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;

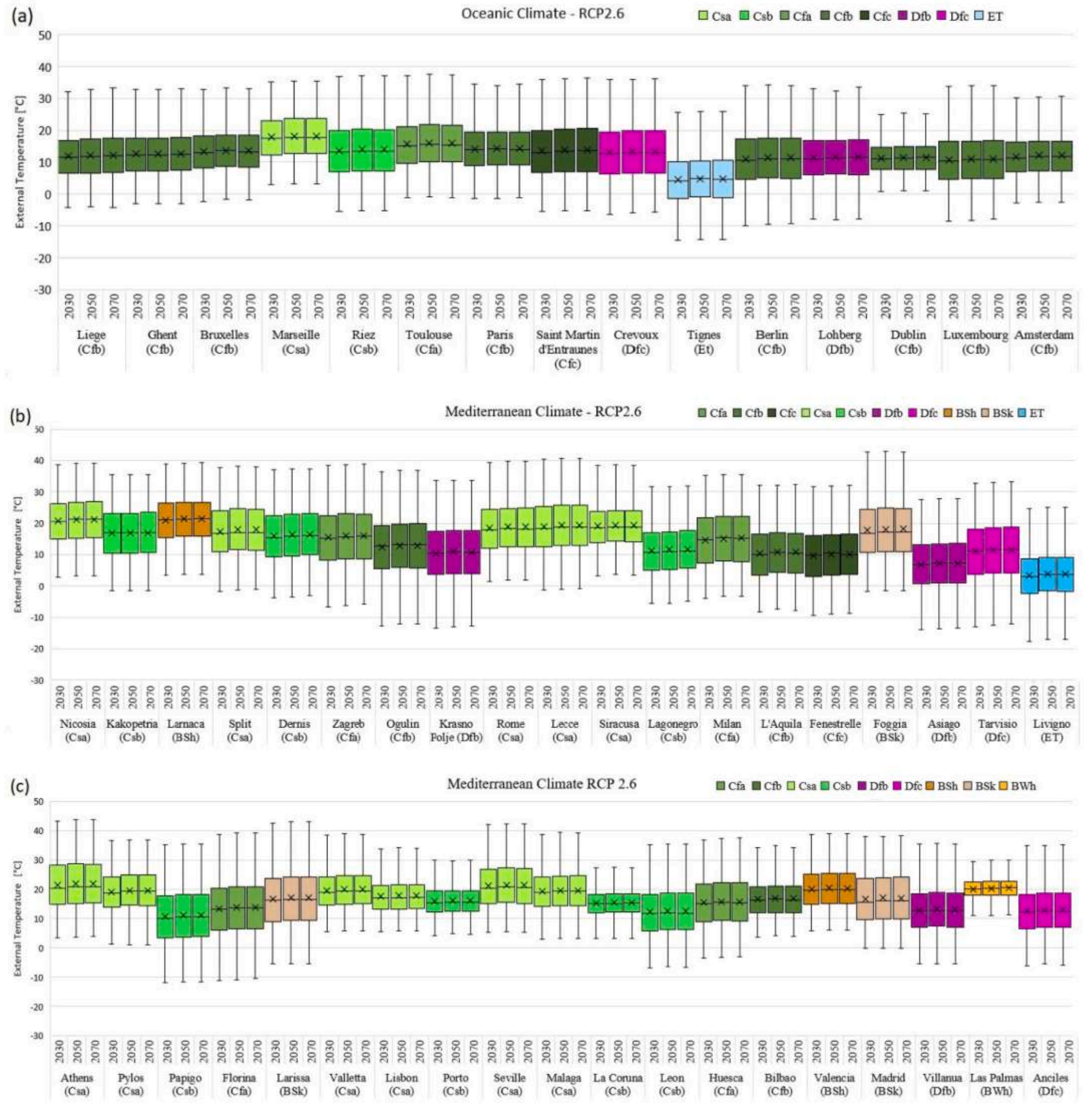


Fig. 3. Statistical distributions of external temperatures for Oceanic and Mediterranean locations over the years 2030, 2050, 2070 under RCP 2.6 (a–c).

- 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.

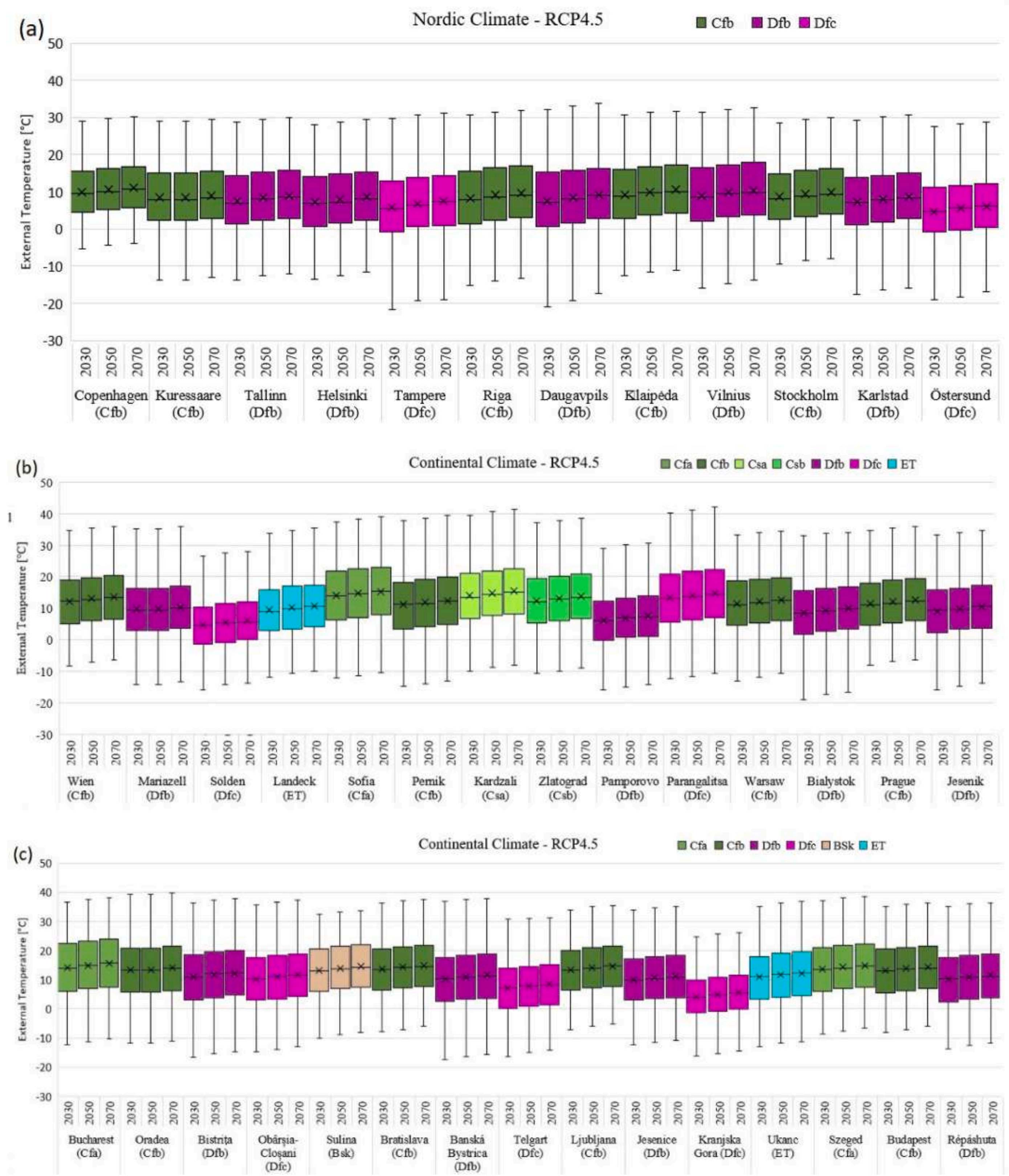


Fig. 4. Statistical distributions of external temperatures for Nordic and Continental locations over the years 2030, 2050, 2070 under RCP 4.5 (a–c).

- 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.

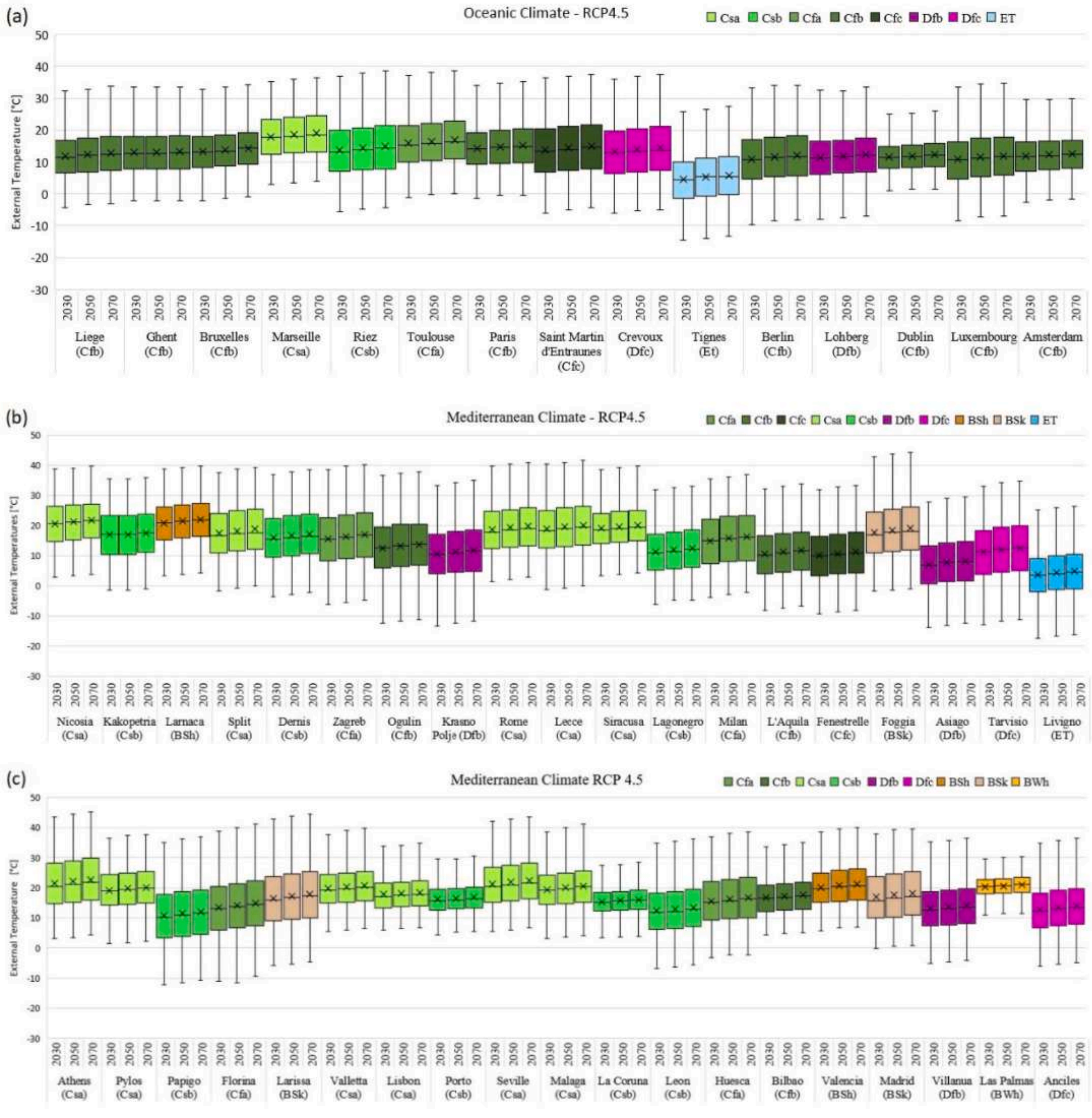


Fig. 5. Statistical distributions of external temperatures for Oceanic and Mediterranean locations over the years 2030, 2050, and 2070 under RCP 4.5 (a–c).

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

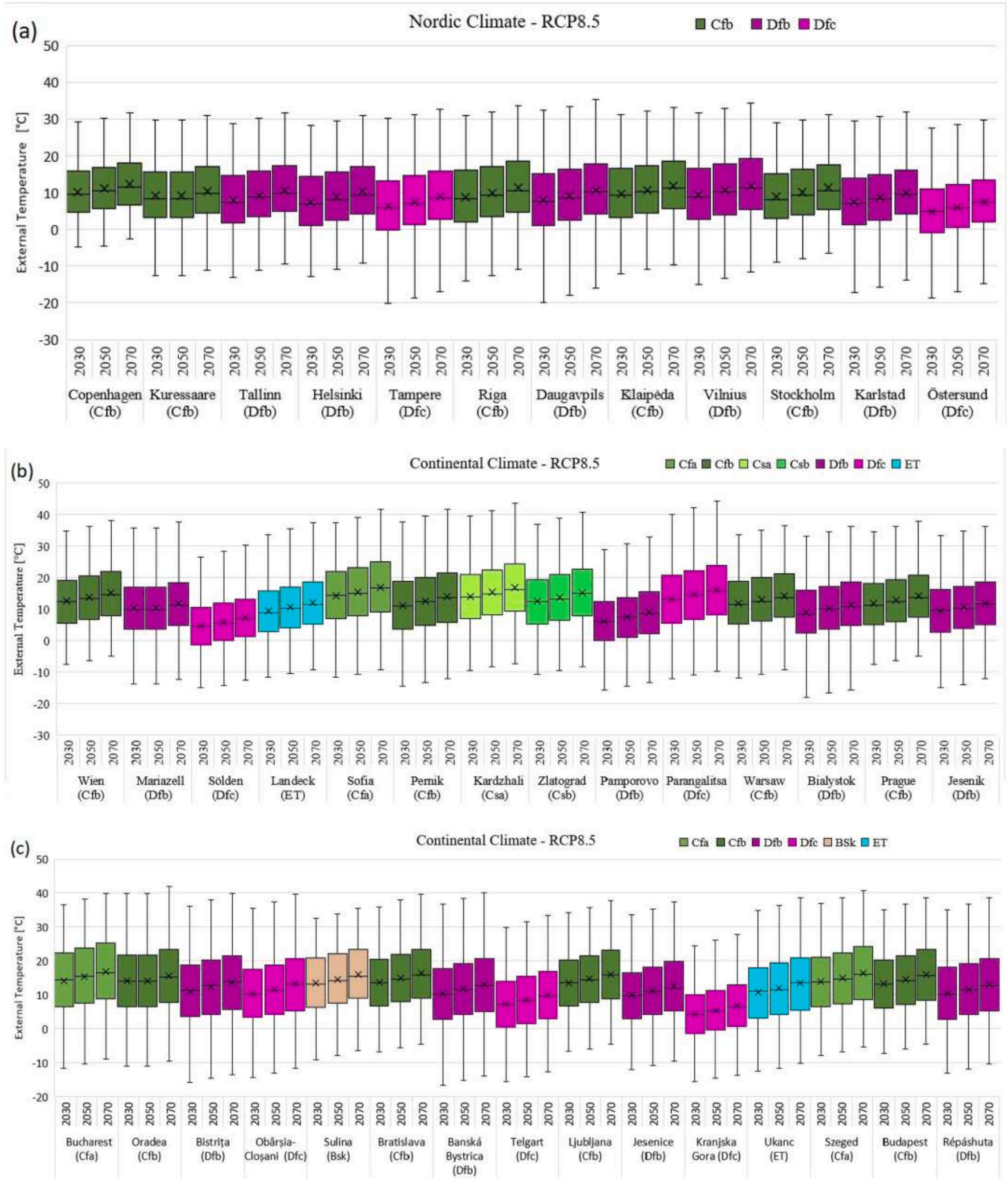


Fig. 6. Statistical distributions of external temperatures for Nordic and Continental locations over the years 2030, 2050, 2070 under RCP 8.5 (a–c).

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

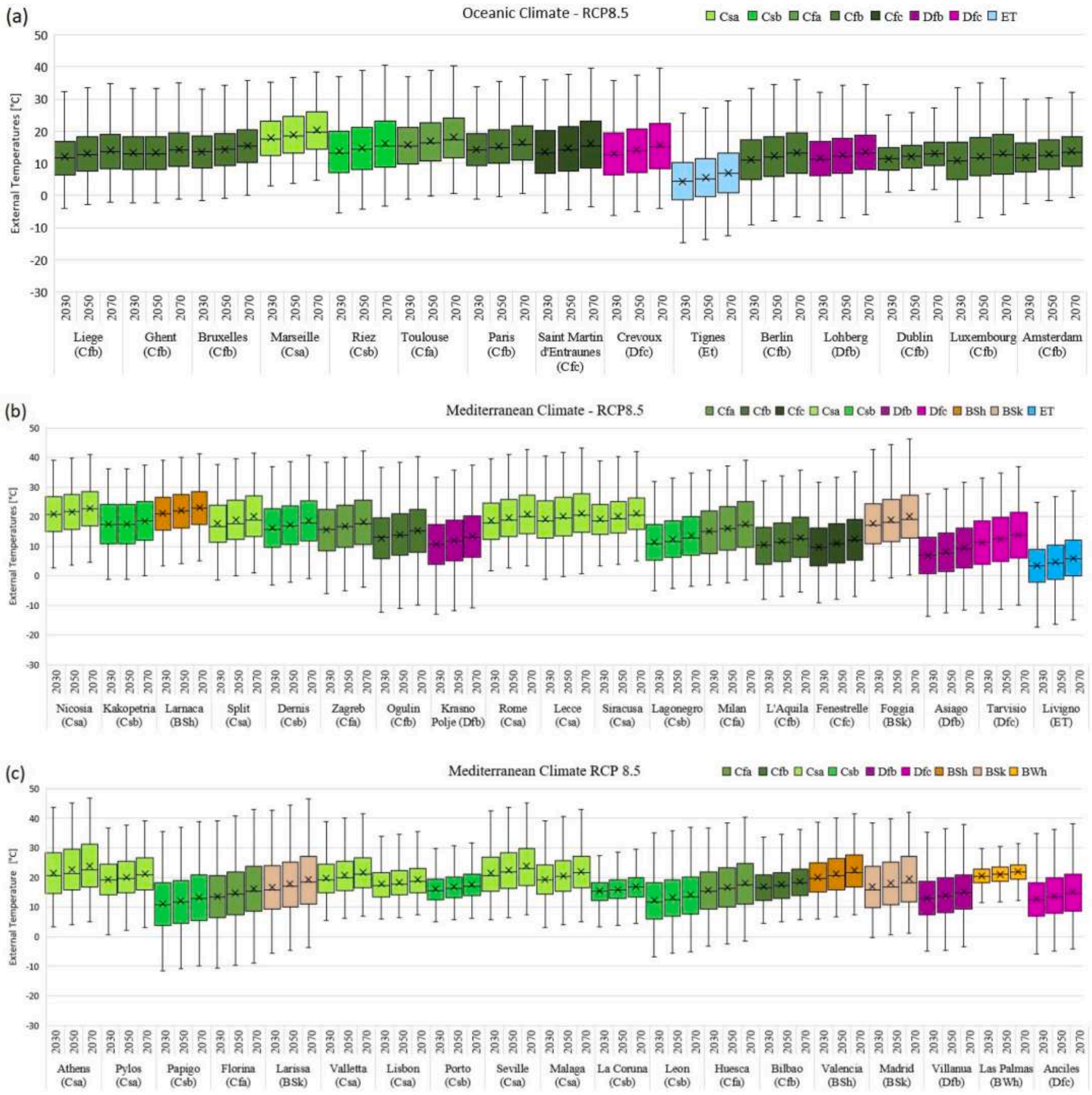


Fig. 7. Statistical distributions of external temperatures for Oceanic and Mediterranean locations over the years 2030, 2050, and 2070 under RCP 8.5 (a–c).

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

Table 2
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
	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
	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				
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
	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 Polje	2.6	+0.6	+0.5	+0.1
	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 above-ground floors corresponding to three small apartments having the same layout. For each apartment, the net surface area is 74 m^2, and the net volume area is 199 m^2. 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 × 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.

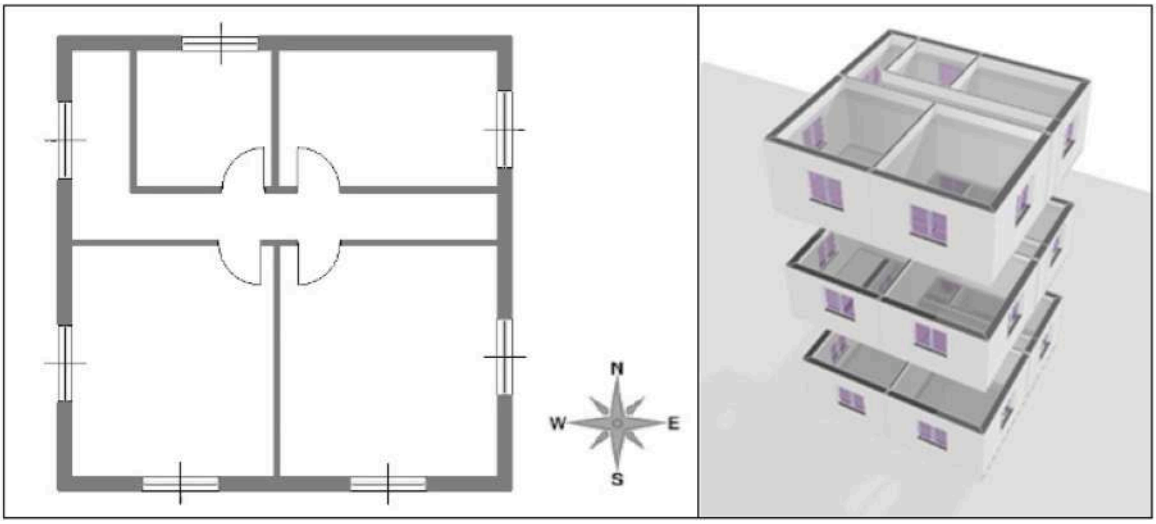
In general, it has been noted that the results for the RPC 2.6 scenario indicate a very limited variability in the controlled quantities. Therefore, they represent an optimal condition to be pursued in future years, but, as of now, it appears the least realistic scenario. Therefore, in analysing the 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 $EP_{tot,nd}$ in almost all locations. Exceptions are the cities of Klaipėda and Stockholm. Klaipėda shows a relatively insignificant increase in $EP_{tot,nd}$ from 2030 to 2050 due to a slight increase in $EP_{tot,nd}$, followed by a decrease from 2050 to 2070. For Stockholm, there is no change in $EP_{tot,nd}$ from 2030 to 2050. Both cities exhibit a decline of $EP_{tot,nd}$ 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

Table 3
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]	λ [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 $EP_{tot,nd}$ in 2050 compared to 2030. However, in 2070, the

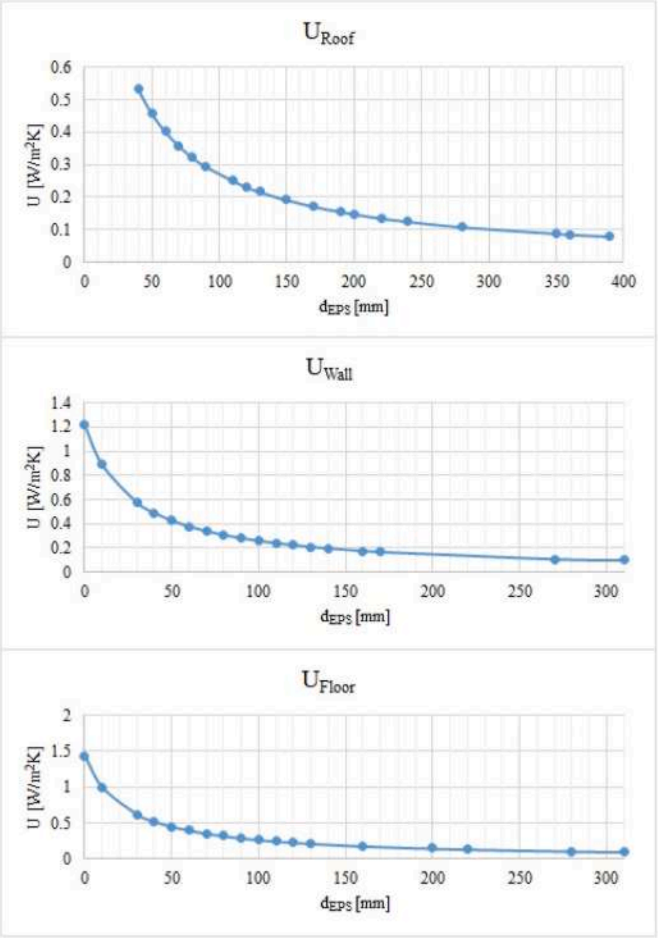


Fig. 8. Trend of the thermal transmittance of the roof, wall and floor as the thickness of the insulation layer changes.

Table 4

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).

Type	U_{set} [W/m^{2}K]	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	N	2.716
W5	1.319	Ar	T	6	L	1.141
W6	1.051	Kr	T	6	L	0.807
W7	0.7	Kr	T	6	L	0.4
W8	1.36	Ar	D	5	L	1.141
W9	4.972	NO	S	2	N	5.8
W10	2.575	Ar	D	5	N	2.716
W11	0.843	Kr	T	6	L	0.541
W12	0.884	Kr	T	5	L	0.541
W13	1.26	Kr	T	3	L	0.807
W14	1.054	Ar	T	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 $EP_{tot,nd}$ is observed in Porto.

In the RCP8.5 scenario, when moving from 2030 to 2050, numerous cities (18) experience an increase in $EP_{tot,nd}$. However, by 2070, $EP_{tot,nd}$ 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 $EP_{c,nd}$ 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 "✔" 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.

Table 5

Overview of transmittance limits and transmittances imposed by each country for roof, wall, floor and windows, along with the corresponding values of insulation thickness (d_{EPS}) and the code of window characteristics.

Countries	Cities	References	NEW/ RENOVATION	YEAR	Roof			External Walls			Floor			Windows		
					U_{lim} W/m^{2}K	U_{set} W/m^{2}K	d_{EPS} mm	U_{lim} W/m^{2}K	U_{set} W/m^{2}K	d_{EPS} mm	U_{lim} W/m^{2}K	U_{set} W/m^{2}K	d_{EPS} mm	U_{lim} W/m^{2}K	U_{set} W/m^{2}K	Type [Table 4]
Denmark	Copenhagen	[61]	N	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]	N	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]	N	2020	0.09	0.089	350	0.17	0.167	170	0.17	0.148	200	1	0.884	W12
Latvia	Riga	[64–66]	N	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]	N	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]	N	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]	N	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]	N	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]	N	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]	N	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]	N	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]	N	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]	N	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]	N	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]	N	2020	0.24	0.232	120	0.24	0.224	120	0.24	0.231	120	1.5	1.36	W8
	Bruxelles				0.24	0.232	120	0.24	0.224	120	0.3	0.292	90	1.8	1.783	W3
France	Marseille	[81]	N	2016	0.25	0.232	120	0.4	0.379	60	0.36	0.355	70	2.1	1.825	W1

(*continued on next page*)

Table 5 (*continued*)

Countries	Cities	References	NEW/ RENOVATION	YEAR	Roof			External Walls			Floor			Windows		
					U lim	U set	d_{EPS}	U lim	U set	d_{EPS}	U lim	U set	d_{EPS}	U lim	U set	Type [Table 4]
					W/m^2K	W/m^2K	mm	W/m^2K	W/m^2K	mm	W/m^2K	W/m^2K	mm	W/m^2K	W/m^2K	
	Saint Martin d'Entraunes															
	Riez				0.2	0.192	150	0.36	0.34	70	0.27	0.268	100	1.8	1.783	W3
	Toulouse															
	Paris															
	Crevoux															
	Tignes															
Germany	Berlin	[82]	N	2020	0.2	0.192	150	0.28	0.26	100	0.35	0.321	80	1.3	1.26	W13
	Lohberg															
Ireland	Dublin	[83]	N	2020	0.2	0.192	150	0.18	0.176	160	0.18	0.18	160	1.4	1.36	W8
Luxembourg	Luxembourg				0.24	0.232	120	0.24	0.224	120	0.24	0.231	120	1.5	1.36	W8
Netherlands	Amsterdam	[84]	N	2020	0.167	0.163	180	0.22	0.21	130	0.286	0.268	100	1.65	1.618	W2
Cyprus	Nicosia	[85]	R	2020	0.4	0.359	70	0.4	0.379	60	0.4	0.39	60	2.9	2.782	W4
	Kakopetria															
	Larnaca															
Croatia	Split	[86]	N	2015	0.3	0.295	90	0.45	0.428	50	0.5	0.452	50	1.8	1.783	W3
	Dernis															
	Zagreb															
	Ogulin				0.25	0.232	120	0.3	0.282	90	0.4	0.398	60	1.6	1.36	W8
	Krasno Polje															
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	0.402	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	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	0.29	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	0.44	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	0.224	120	0.24	0.231	120	1.1	1.051	W6
	Asiago															
	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
	Porto															
Spain	Seville	[91]	N	2016	0.44	0.402	60	0.56	0.492	40	0.56	0.524	40	2.3	1.825	W1
	Valencia															
	Las Palmas				0.5	0.458	50	0.7	0.578	30	0.7	0.623	30	2.7	2.575	W10
	Malaga															
	La Coruna				0.4	0.359	70	0.49	0.428	50	0.49	0.398	60	2.1	1.825	W1
	Bilbao															
	Leon				0.33	0.323	80	0.37	0.34	70	0.37	0.355	70	1.8	1.783	W3
	Huesca				0.35	0.323	80	0.41	0.379	60	0.41	0.398	60	1.8	1.783	W3
	Madrid															
	Villanua															
	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.

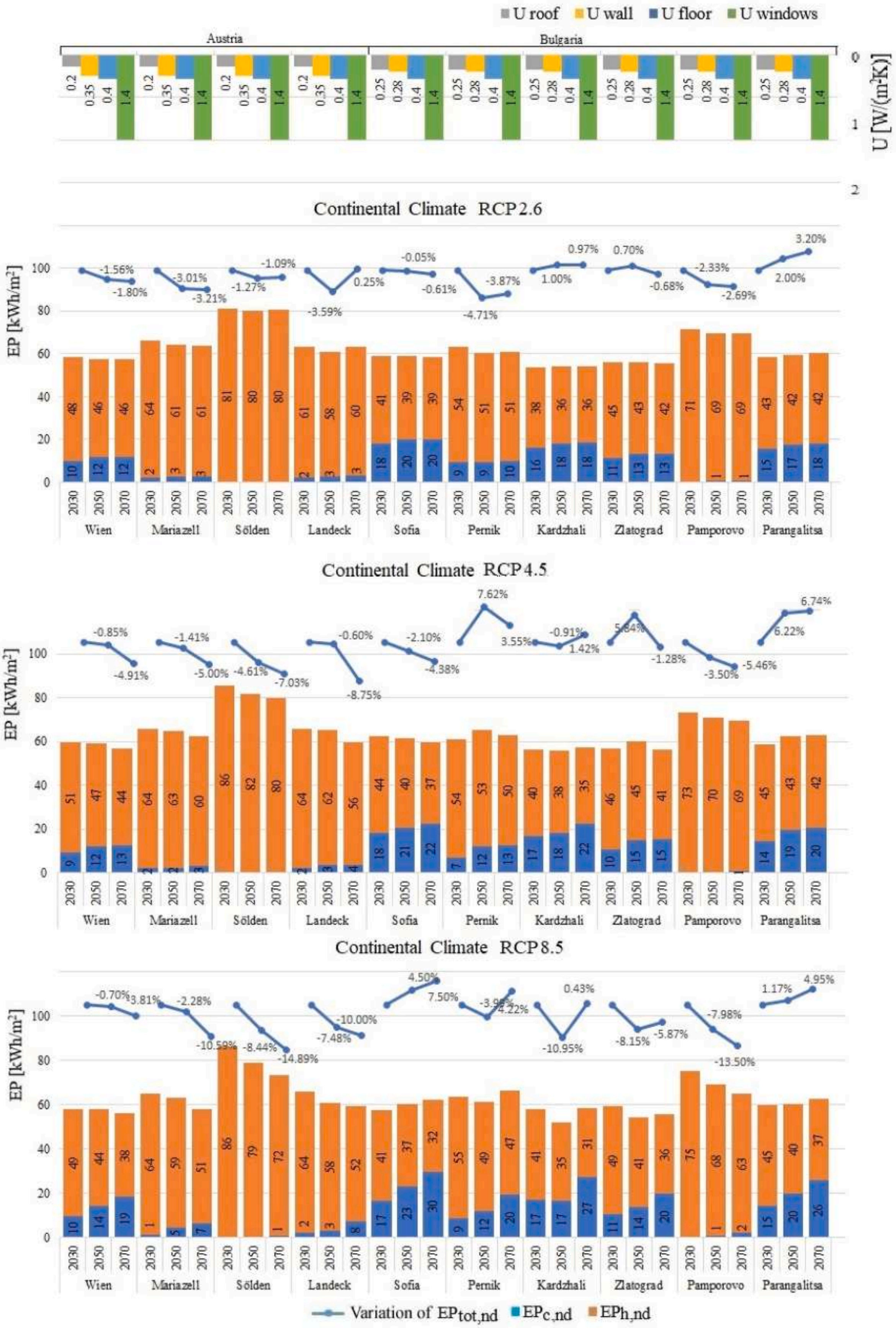


Fig. 10. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Continental locations (from Wien to Parangalitsa).

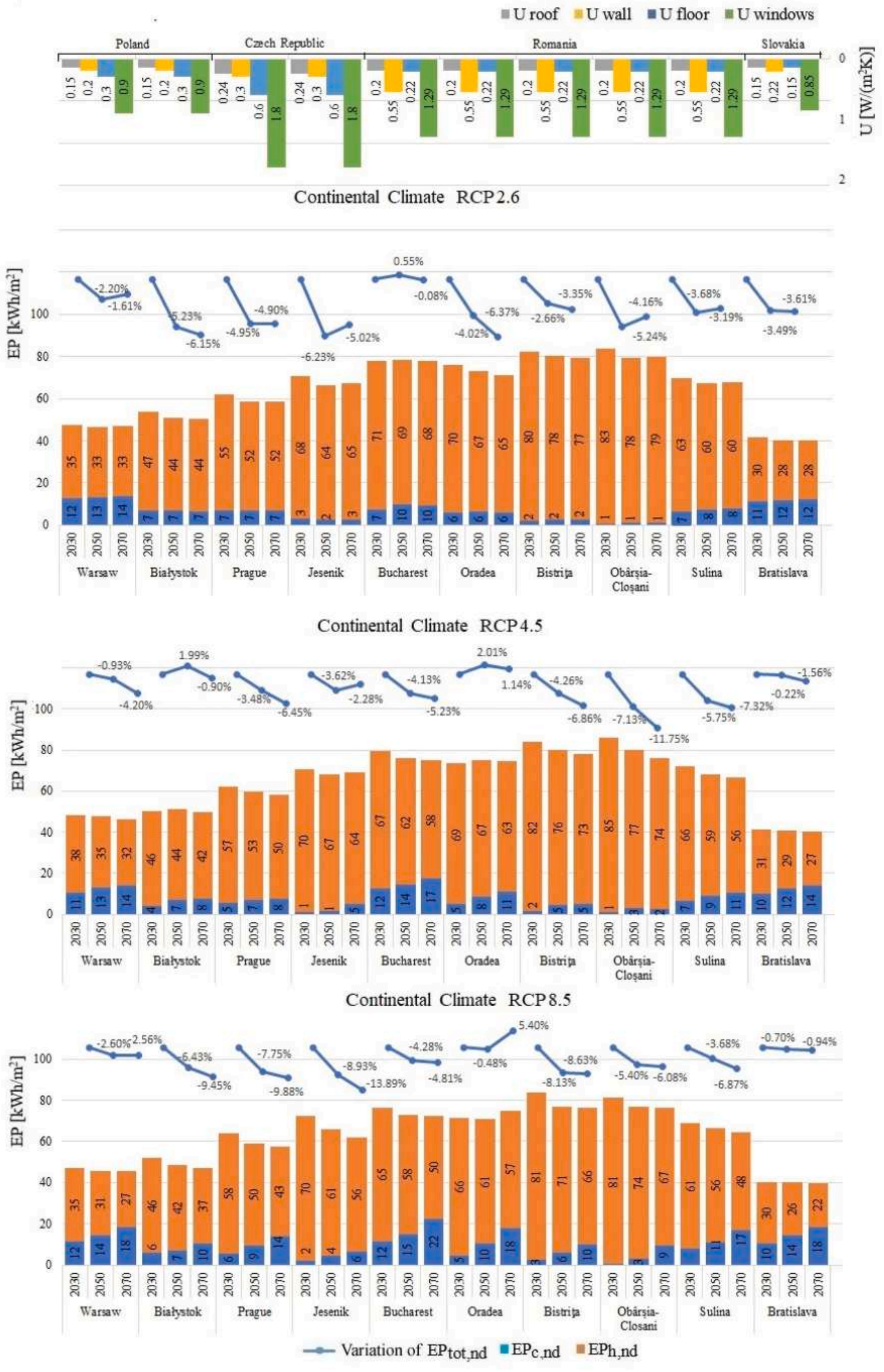


Fig. 11. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Continental locations (from Warsaw to Bratislava).

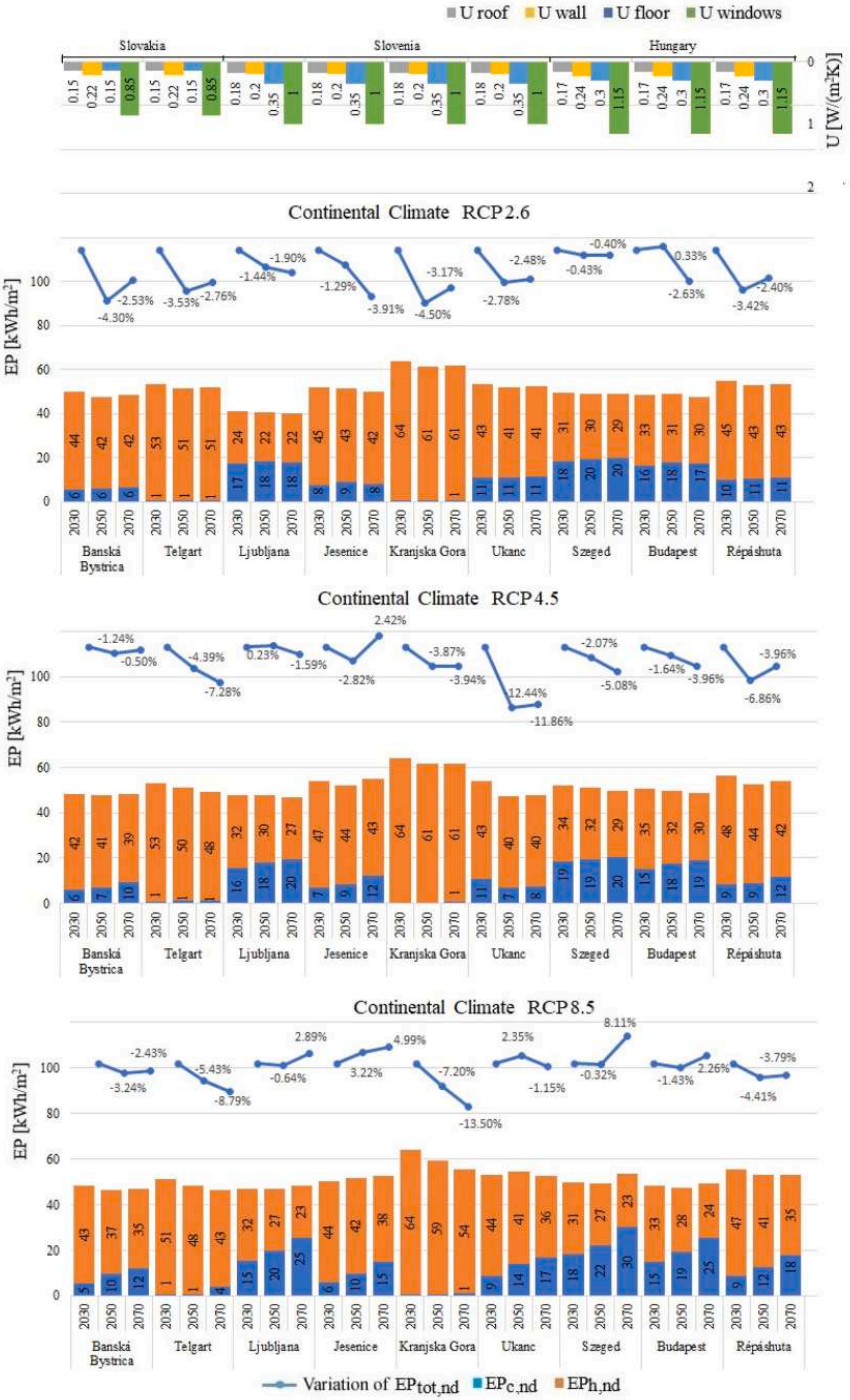


Fig. 12. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Continental locations (from Banka Bystrica to Repashuta).

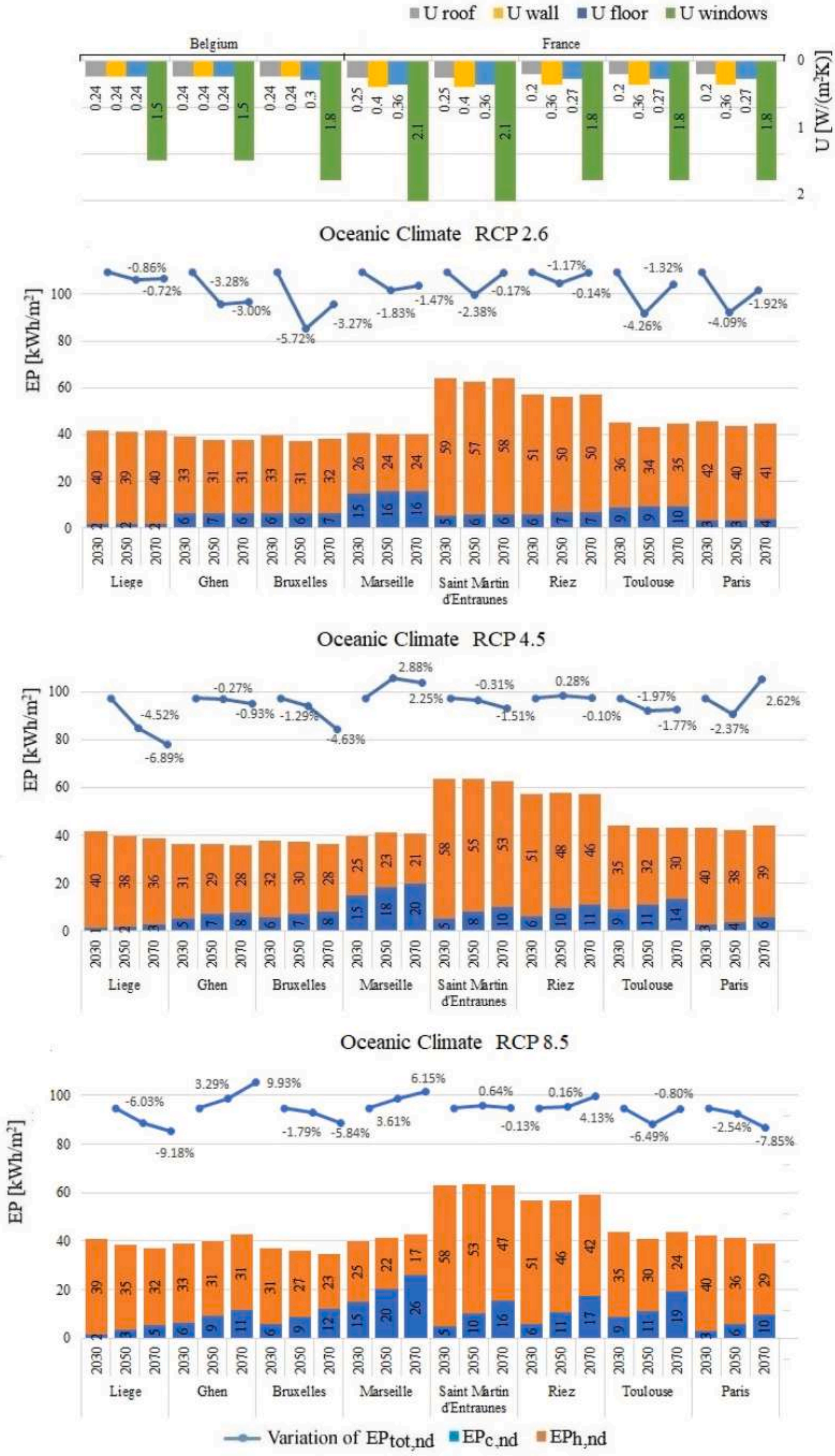


Fig. 13. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Oceanic locations (from Liege to Paris).

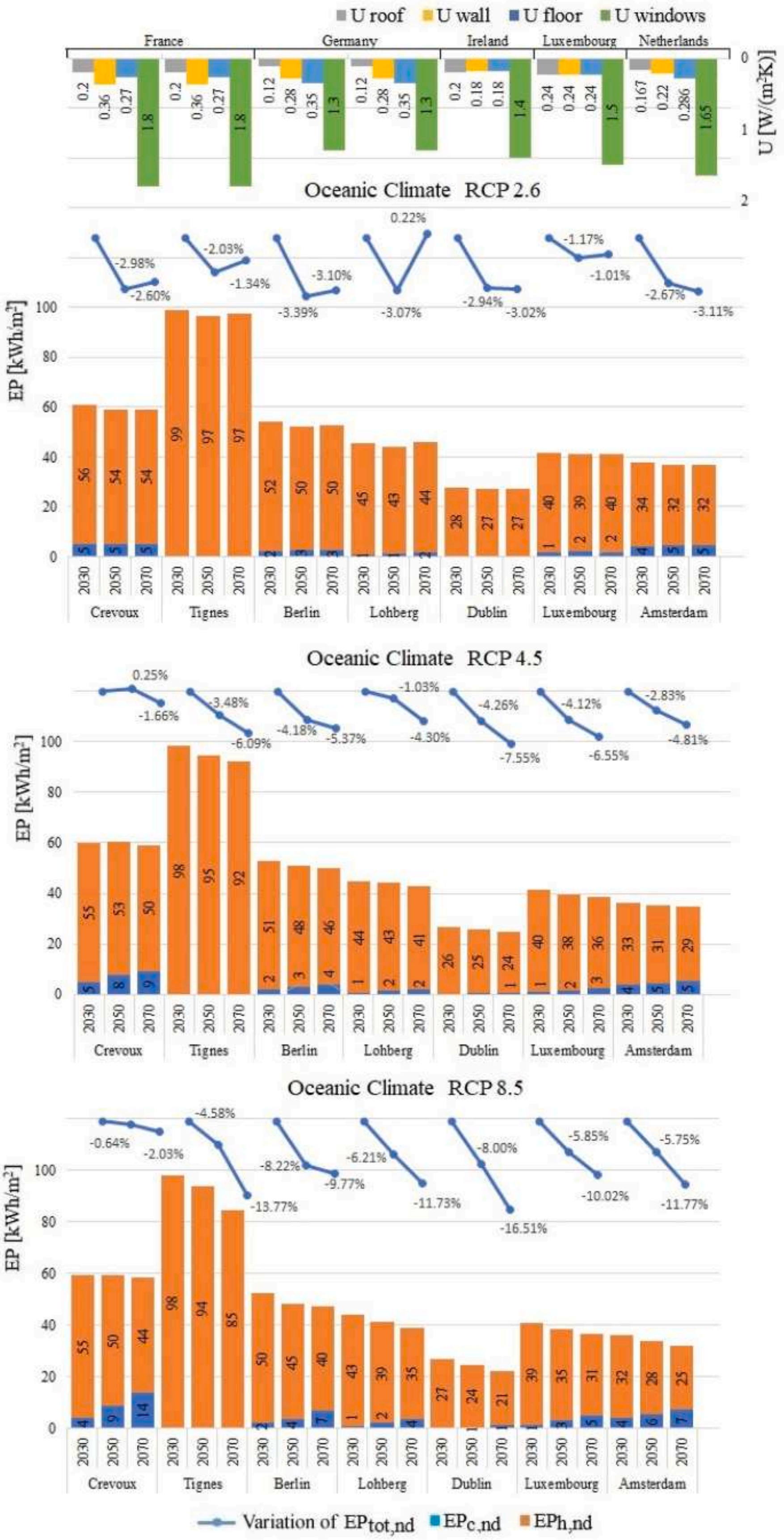


Fig. 14. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Oceanic locations (from Crevoux to Amstredam).

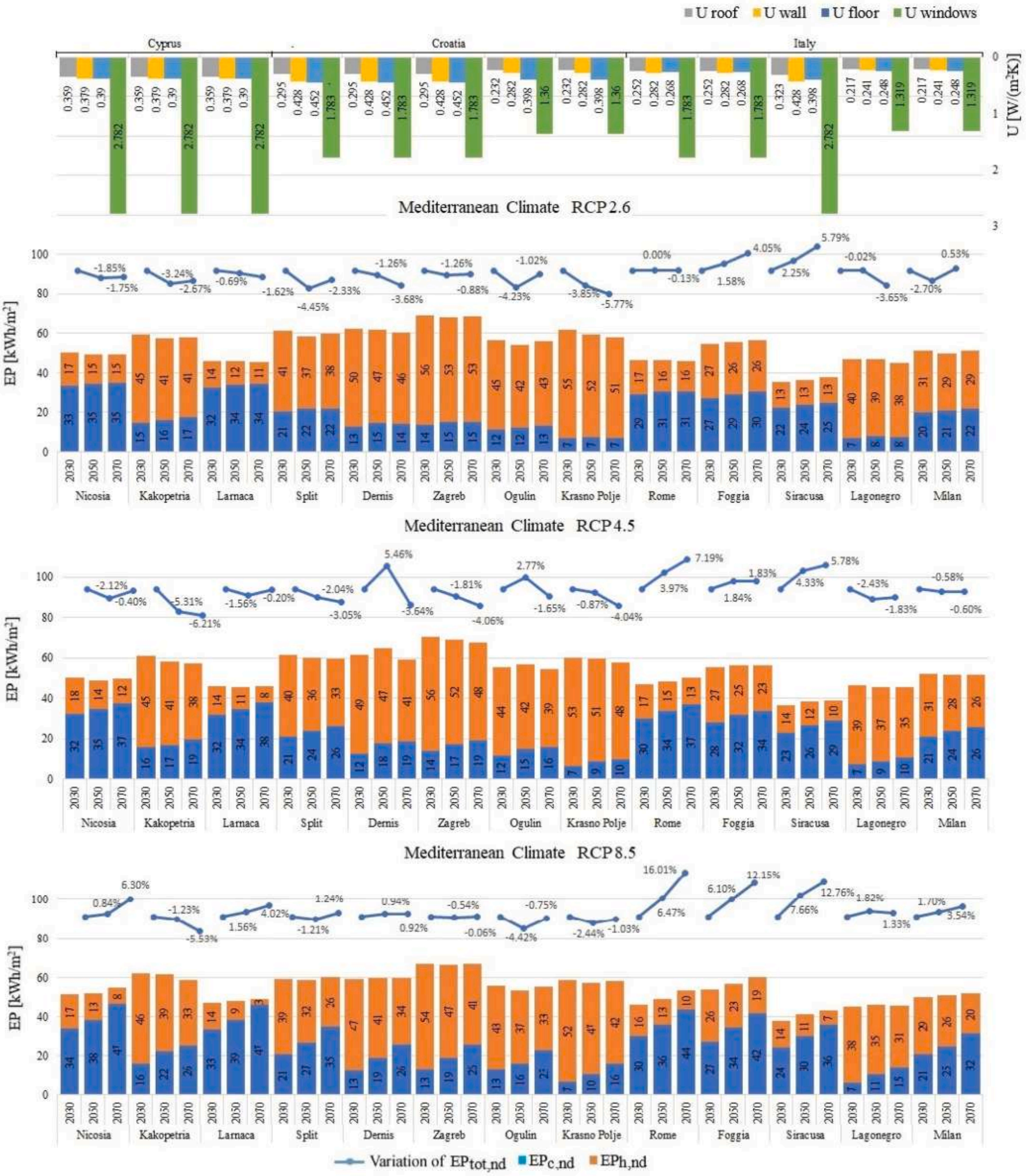


Fig. 15. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Mediterranean locations (from Nicosia to Milan).

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

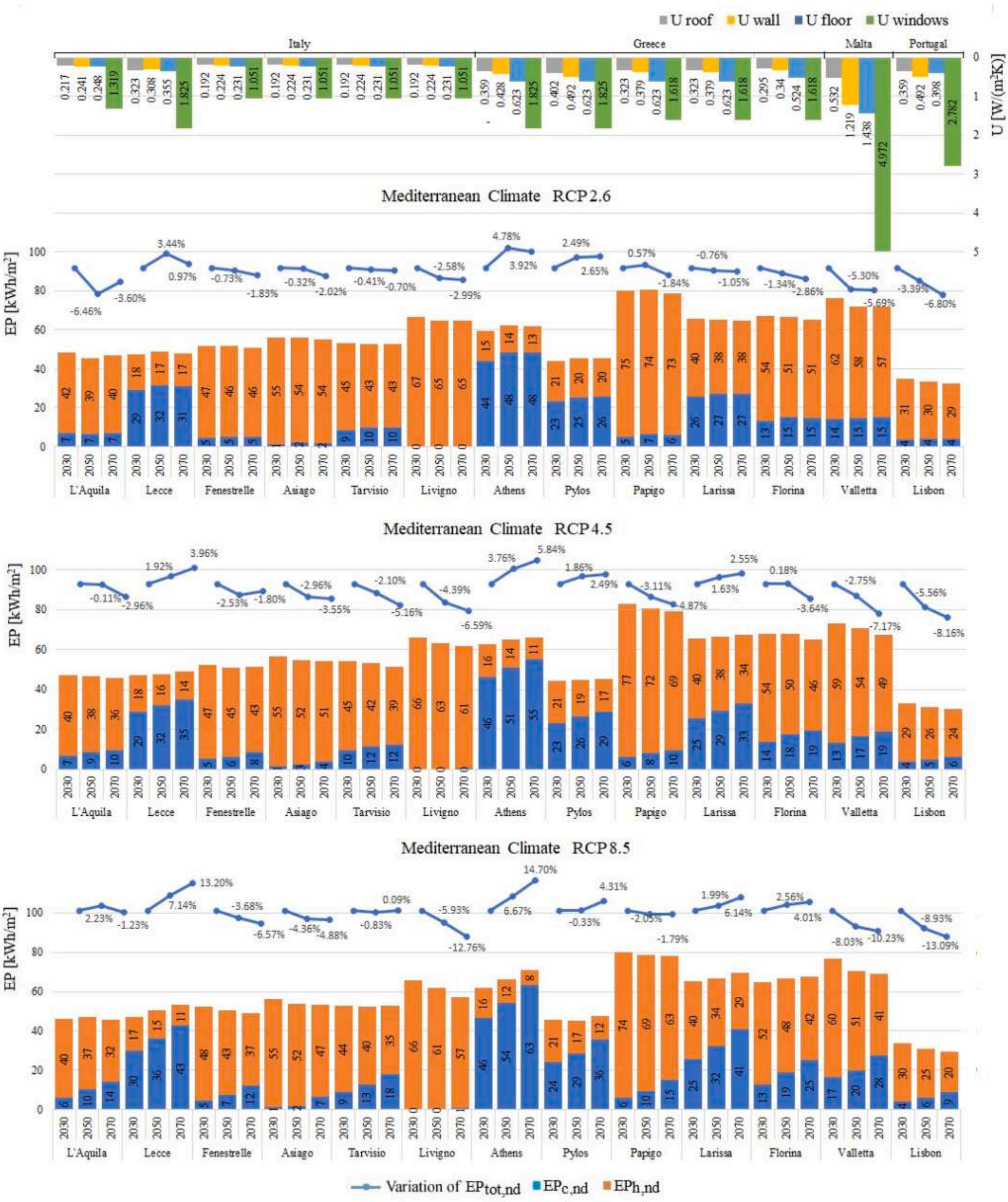


Fig. 16. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Mediterranean locations (from L'Aquila to Lisbon).

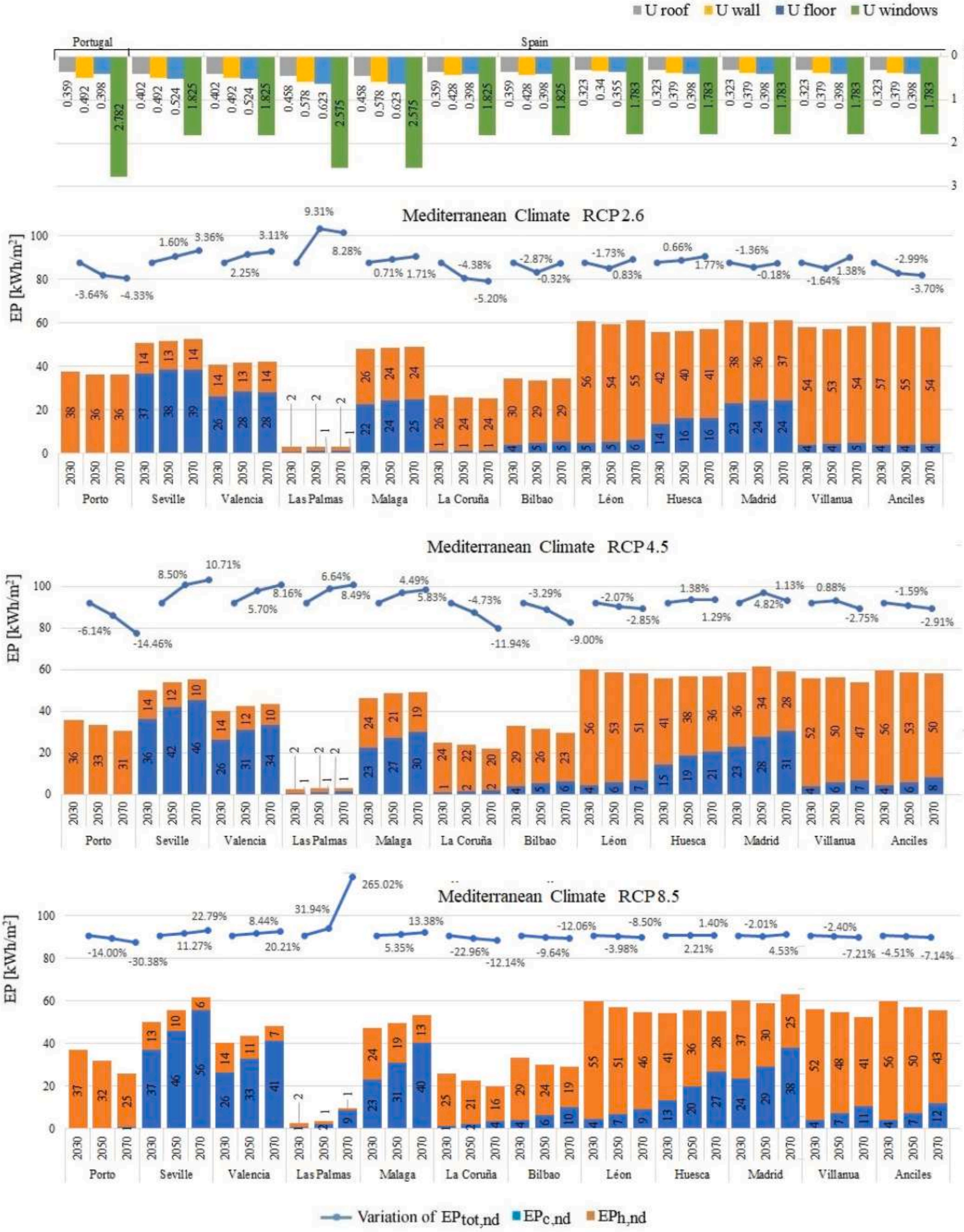


Fig. 17. Overview of the thermal transmittance limits and trends in thermal performance indexes (EP), over the years 2030, 2050, 2070 under RCP 2.6, 4.5 and 8.5 for Mediterranean locations (from Porto to Anciles).

Table 6

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 (“✔”: decrease in $\mathrm{EP}_{\mathrm{tot,nd}}$ in 2050 and 2070 compared to 2030; "*x*"; increase in $\mathrm{EP}_{\mathrm{tot,nd}}$ for all scenarios).

EU climate zones					RCP 2.6		RCP 4.5		RCP 8.5	
	Country	City	Koppen climate classification	National climate zones	2050	2070	2050	2070	2050	2070
Nordic	Denmark	Copenhagen	Cfb	–	✔	✔	✔	✔	✔	✔
	Estonia	Kuressaare	Cfb	–	✔	✔	✔	✔	✔	✔
		Tallinn	Dfb	–						
	Finland	Helsinki	Dfb	–	✔	✔	✔	✔	✔	✔
		Tampere	Dfc	–						
	Latvia	Riga	Cfb	–	✔	✔	✔	✔	✔	✔
		Daugavpils	Dfb	–						
	Lithuania	Klaipėda	Cfb	–	✔	✔	✘	✔	✔	✔
		Vilnius	Dfb	–	✔	✔	✔	✔	✔	✔
	Sweden	Stockholm	Cfb	–	✔	✔	✔	✔	✔	✔
		Karlstad	Dfb	–						
		Östersund	Dfc	–						
Continental	Austria	Wien	Cfb	–	✔	✔	✔	✔	✔	✔
		Mariazell	Dfb	–	✔	✔	✔	✔	✔	✔
		Landeck	Dfc	–	✔	✘	✔	✔	✔	✔
		Sölden	ET	–	✔	✔	✔	✔	✔	✔
	Bulgaria	Sofia	Cfa (bordering on Cfb)	–	✔	✔	✔	✔	✘	✘
		Pernik	Cfb	–	✔	✔	✘	✘	✔	✘
		Kardzhali	Csa	–	✘	✘	✔	✘	✔	✘
		Zlatograd	Csb	–	✘	✔	✘	✔	✔	✔
		Pamporovo	Dfb	–	✔	✔	✔	✔	✔	✔
		Parangalitsa	Dfc	–	✘	✘	✘	✘	✘	✘
	Poland	Warsaw	Cfb	–	✔	✔	✔	✔	✔	✔
		Białystok	Dfb	–	✔	✔	✘	✔	✔	✔
	Czech Republic	Prague	Cfb	–	✔	✔	✔	✔	✔	✔
		Jesenik	Dfb	–						
	Romania	Bucharest	Cfa	–	✘	✔	✔	✔	✔	✔
		Oradea	Cfb	–	✔	✔	✘	✘	✔	✘
		Bistrita	Dfb	–	✔	✔	✔	✔	✔	✔
		Obârșia-Cloșani	Dfc (bordering on Cfb)	–	✔	✔	✔	✔	✔	✔
		Sulina	BSk	–	✔	✔	✔	✔	✔	✔
	Slovakia	Bratislava	Cfb	–	✔	✔	✔	✔	✔	✔
		Banská Bystrica	Dfb	–						
		Telgart	Dfc	–						
	Slovenia	Ljubljana	Cfb	–	✔	✔	✘	✔	✔	✘
		Jesenice	Dfb (bordering on Cfb)	–	✔	✔	✔	✘	✘	✘
		Kranjska Gora	Dfc	–	✔	✔	✔	✔	✔	✔
		Ukanc	ET (bordering Dfc)	–	✔	✔	✔	✔	✘	✔
	Hungary	Szeged	Cfa	–	✔	✔	✔	✔	✔	✘
		Budapest	Cfb	–	✘	✔	✔	✔	✔	✘
		Répáshuta	Dfb	–	✔	✔	✔	✔	✔	✔
Oceanic	Belgium	Liege	Cfb	–	✔	✔	✔	✔	✔	✔
		Gent	Cfb	–	✔	✔	✔	✔	✘	✘
		Bruxelles	Cfb	–	✔	✔	✔	✔	✔	✔
	France	Marseille	Csa	H3	✔	✔	✘	✘	✘	✘
		Riez	Cfa	H2	✔	✔	✘	✔	✘	✘
		Toulouse	Cfb	H2	✔	✔	✔	✘	✔	✔
		Paris	Cfc (bordering on Cfb)	H1	✔	✔	✔	✔	✔	✔
		Saint Martin d’Entraunes	Csb	H3	✔	✔	✔	✔	✘	✔
		Crevoux	Dfc	H1	✔	✔	✘	✔	✔	✔
		Tignes	ET	H1	✔	✔	✔	✔	✔	✔
	Germany	Berlin	Cfb	–	✔	✔	✔	✔	✔	✔
		Lohberg	Dfb	–	✔	✘	✔	✔	✔	✔
	Ireland	Dublin	Cfb	–	✔	✔	✔	✔	✔	✔
	Luxembourg	Luxembourg	Cfb	–	✔	✔	✔	✔	✔	✔
	Netherlands	Amsterdam	Cfb	–	✔	✔	✔	✔	✔	✔
Mediterranean	Cyprus	Nicosia	Csa	–	✔	✔	✔	✔	✘	✘
		Kakopetria	Csb (bordering on Csa)	–	✔	✔	✔	✔	✔	✔
		Larnaca	BSh	–	✔	✔	✔	✔	✘	✘
	Croatia	Split	Csa	–	✔	✔	✔	✔	✔	✘
		Dernis	Csb (bordering on Csa)	–	✔	✔	✘	✔	✘	✘
		Zagreb	Cfa	–	✔	✔	✔	✔	✔	✔
		Ogulin	Cfb	–	✔	✔	✘	✔	✔	✔
		Krasno Polje	Dfb	–	✔	✔	✔	✔	✔	✔
	Greece	Athens	Csa	B	✘	✘	✘	✘	✘	✘
		Pylos	Csa	A	✘	✘	✘	✘	✘	✘
		Papigo	Csb	C	✘	✔	✔	✔	✔	✔
		Florina	BSk	D	✔	✔	✘	✔	✘	✘
		Larissa	Cfa (bordering on Cfb)	C	✔	✔	✘	✘	✘	✘
	Italy	Rome	Csa	D	✔	✔	✘	✘	✘	✘
		Lecce	Csa	C	✘	✘	✘	✘	✘	✘
		Siracusa	Csb	B	✘	✘	✘	✘	✘	✘
		Lagonegro	Cfa	E	✔	✔	✔	✔	✘	✘

(*continued on next page*)

Table 6 (*continued*)

	Milan	Cfb	E	✔	✘	✔	✔	✘	✘
	L’Aquila	Cfc	E	✔	✔	✔	✔	✘	✔
	Fenestrelle	BSk	F	✔	✔	✔	✔	✔	✔
	Foggia	Csa	D	✘	✘	✘	✘	✘	✘
	Asiago	Dfb	F	✔	✔	✔	✔	✔	✔
	Tarvisio	Dfc	F	✔	✔	✔	✔	✔	✘
	Livigno	ET	F	✔	✔	✔	✔	✔	✔
Malta	Valletta	Csa	–	✔	✔	✔	✔	✔	✔
Portugal	Lisbon	Csa	–	✔	✔	✔	✔	✔	✔
	Porto	Csb	–	✔	✔	✔	✔	✔	✔
Spain	Seville	Csa	B4	✘	✘	✘	✘	✘	✘
	Malaga	Csa	A3	✘	✘	✘	✘	✘	✘
	La Coruna	Cfa	C1	✔	✔	✔	✔	✔	✔
	Leon	BSh	E1	✔	✘	✘	✘	✔	✔
	Huesca	BSk (bordering on (Csa)	D2	✘	✘	✘	✘	✘	✘
	Bilbao	Cfb	C1	✔	✔	✔	✔	✔	✔
	Valencia	Csa	B3	✘	✘	✘	✘	✘	✘
	Madrid	Dfb (bordering on Cfb)	D3	✔	✔	✘	✘	✔	✘
	Villanua	BWh (bordering on BSk)	D2	✔	✘	✘	✔	✔	✔
	Las Palmas	Csb	A2	✘	✘	✘	✘	✘	✘
	Anciles	Dfc *(bordering on Cfb)*	D2	✔	✔	✔	✔	✔	✔

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 climate-responsive, 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@unisalento.it.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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