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The role of total solar energy transmittance for normal incidence of the glazed system in climate change adaptation under Italy energy efficiency policies

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ABSTRACT

This study investigates the effectiveness of envelope regulations in mitigating climate change impact on building energy demand in different locations and Representative Concentration Pathway (RCP) scenarios. It aims to assess the building thermal performance ($EP_{tot,nd}$) in compliance with main Italian energy policies (issued in 2005, 2015, 2020). It specifically examines how variations in total solar energy transmittance of glazed systems ($g_{gl,n}$) impact heat regulation and overall energy efficiency. Results are variable depending on the national climate zone (from A to F) and related standards. Whereas climate zone E does not show significant gains from $g_{gl,n}$ modifications, in zone A reducing $g_{gl,n}$ (from 0.67 to 0.50) enhances resilience in buildings adhering to 2005 regulation (L.D. 192/2005). In climate zone C, $g_{gl,n}$ reduction benefits all standards, while in zone B this adjustment affects buildings following 2020 regulation (M.D. 06/08/2020), particularly under RCP 8.5. In climate zone F, decreasing $g_{gl,n}$ results in higher $EP_{tot,nd}$, thereby compromising resilience. It is observed that buildings designed in accordance with L.D. 192/2005, compared to other regulations, show a smaller variation of $EP_{tot,nd}$ over time. In particular, moving from 2020 to 2070, climate zone BSh (Koppen climate classification) is the climate zone that sees the largest $EP_{tot,nd}$ increases over the years, while Cfc is the only zone that shows $EP_{tot,nd}$ decreases in all scenarios. For the other zones, a mixed behaviour is observed, with heterogeneous variations and results. Due to climate change, increased insulation in warm areas has contributed to an increase in overall annual consumption. Effective regulatory planning requires a comprehensive future climate assessment to optimize building energy performance.

1. Introduction

Climate change is a pressing global issue, characterized by rising temperatures, sea level rise, extreme weather events, and ecosystem disruption. To address this challenge, we must reduce emissions, enhance energy efficiency, promote renewable energy, and adopt sustainable practices [1,2]. Major energy consumers include industry, buildings, and transportation [3]. Buildings significantly contribute to greenhouse gas emissions [4], making the residential sector a focal point for energy efficiency and resource conservation policies [5]. To mitigate climate change, it is crucial to implement suitable building design strategies that effectively reduce energy consumption and emissions. Many nations are aligning their practices with global efforts to combat climate change [6], particularly through policies and regulations that promote energy-efficient buildings [7]. Building resilience to climate change involves preparing buildings to withstand and adapt to its impacts, which includes sustainable design, renewable energy use, and occupant awareness [8]. Energy-efficient buildings not only combat climate change but also reduce energy costs and improve the built environment for the future. Solutions include insulation, efficient windows, energy-efficient HVAC (Heating, ventilation, and air conditioning) systems, appliances, and optimized lighting [9]. The European Union (EU) has been promoting energy efficiency since the 1970s, with a strong focus on buildings since the 1980s. Policies have been reinforced to combat climate change and enhance energy security through EU directives, national regulations, energy efficiency policies and standards. Key directives include the Energy Efficiency Directive [10], EPBD (Energy Performance of Buildings Directive, 2010/31/EU, replacing 2002/

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91/EC) [11], Ecodesign [12] and Energy Services Directives [13], with subsequent enhancements. The EPBD has been instrumental in advancing building energy efficiency, although standards vary among European countries [14]. For example, the Italian legislative framework has evolved to prioritize energy efficiency over the last decades. Specifically, the Legislative Decree 192/2005 (L.D. 192/2005) [15] is the principal national legislative document governing obligations and measures aimed at enhancing building energy efficiency. It represents the implementation of Directive 2002/91/EC. Subsequently, the Ministerial Decree of June 26, 2015 (M.D. 26/06/2015) [16] establishes the minimum requirements for energy efficiency and energy needs in buildings, in transposition of Directive 2010/31/EU. It defines and regulates minimum energy performance criteria during building design and energy performance certification mandatory for new buildings and property sales and rentals. Following that, the Ministerial Decree of August 6, 2020 (M.D. 06/08/2020) [17] outlines technical requirements for eligibility for tax deductions related to energy efficiency improvements in the real estate sector. Notably, the implementation of these policies led to a significant reduction in thermal transmittance limits in building envelopes (especially from L.D. 192/2005 to M.D. 26/06/2015).

A previous study [18] examined the resilience of the building envelope to climate change within the context of these Italian energy policies, resulting that the building resilience to climate change is minimally influenced by the thermal transmittance of its components.

This paper analysed an additional key parameter, namely the total transmittance of solar energy under normal incidence conditions for glazed systems, and performed a predictive analysis of its role in the context of climate change.

1.1. The state of the art

Currently, it is imperative to consider climate change as a crucial factor in the sustainable design of buildings, as there is an unequivocal correlation between climatic conditions and building performance [19]. In this context, an increase in energy demand for cooling is expected, especially in densely populated regions [20,21]. A study [22] analyzed the impact of climate change on indoor comfort in different climate zones, revealing a marked warming in the Mediterranean basin within Europe [23]. To improve the resilience of buildings, it is essential to implement energy efficiency measures, including passive strategies [24], and increase the self-sufficiency of buildings through the use of renewable energy sources to ensure continuity of services even in the event of energy supply disruptions [25]. Nearly zero-energy buildings are expected to reduce heating demand [26]. On the other hand, however, a future increase in cooling demand could pose overheating problems and a consequent increase in energy consumption in hot climates [27]. Systems such as heat pumps, which are widely used, may ease the transition from fossil fuel generators for winter heating [28]. However, problems may arise in hot areas, which may lead to the deactivation of heat pumps in extremely hot areas.

A well-designed building envelope is crucial for reducing energy consumption and enhancing thermal comfort [29]. In hot and humid climates, passive envelope solutions can cut thermal discomfort by up to 77 % [30]. Buildings with high thermal conductivity, low thermal mass, and low solar absorption in the envelope contribute to increased energy use and CO_2 emissions [31]. Windows, with approximately 60 % heat loss in residential buildings, significantly impact energy efficiency [32]. The design of glazing elements in building envelopes plays a key role in energy balance, natural light, visual comfort, and illuminance consumption [33,34]. Window replacement in existing buildings provides benefits in occupant comfort, energy savings, and natural lighting [35].

Thalfeldt et al., [36] examined various façade configurations in a nearly zero-energy building and found that improving the thermal characteristics of windows significantly improved energy performance. In hot-humid areas, solar heat gain and heat transfer coefficients of transparent surfaces significantly influence the energy performance of buildings [37]. In hot and humid continental summer climates, double-pane windows show promise for improving resilience. However, innovative solutions need to be implemented for humid subtropical and Mediterranean climates characterised by hot summers, as even dynamic systems such as electrochromic windows may not guarantee future energy savings [38].

Therefore, characterizing glazing systems is essential for assessing the overall performance of buildings. Typically, glazing systems are evaluated using thermal transmittance (U-value) and solar factor (g-value) [39]. Numerous studies have analyzed factors such as window-wall ratio, glass properties (U-value, solar heat gain coefficient, and visual transmissivity), and the use of shading devices [40–42]. Yıldız et al [43] highlighted the influence of window parameters, including total area, transmissivity, solar heat gain coefficient, and orientation, especially in hot and humid climates. They found that controlling solar heat gain through windows and other openings is essential for improving building efficiency, reducing individual energy consumption, and mitigating peak demand on electrical systems, especially in summer.

The Solar Factor is a critical indicator of the energy performance of windows and glazing [44]. Oliveti et al., [45] developed a model to estimate solar heat gain through glazed surfaces, simplifying the determination of thermal energy requirements for air-conditioned buildings. De Luca et al., [46] emphasized the importance of considering solar angles and time-dependent correction factors in the energy modelling of buildings. Despite substantial evidence of the impact of climate change on buildings and energy systems [47], many energy analyses still focus on current conditions, neglecting future climate scenarios.

The significance of the correlation between current climate conditions and building performance cannot be overstated. Overlooking the impact of climate change, particularly in establishing building standards, would be a dangerous omission. This acknowledgment underscores the necessity to evaluate the thermal adaptability of buildings in the context of climate change. This involves monitoring a parameter often overlooked in current Italian standards as climate conditions change: the total solar energy transmittance for normal incidence of the glazed system ($g_{gl,n}$). Through simulations utilizing semi-stationary thermal regime models, we provide concise and reproducible assessments of the effects of climate change on buildings constructed in accordance with evolving energy standards.

1.2. Thermal Regulation Evolution in Italy

Before examining the Italian regulatory framework, it is essential to pay attention to the Italian climate classification. This is important because different thermal transmittance limits are applied for each climatic zone in which Italy can be divided. The Italian climate classification is based on Degree Days, measuring temperature variations by summing only positive differences between the base temperature and the daily average external temperature, extended over all days of a conventional year. Heating Degree Days (HDD) measure positive differences between the base temperature and outdoor temperature only in days when the external temperature falls below the design temperature during the heating period. Conversely, Cooling Degree Days (CDD) calculate differences only in days when the external temperature exceeds the design temperature during the cooling period [48]. In Italy, this classification relies on HDD as defined by UNI EN ISO 15927–6:2008 [49], which calculates the sum of positive differences between internal design temperatures (set at 20 °C) and external temperatures (only if positive) throughout a year.

Over the years, the Italian construction sector has seen the implementation of various energy regulations. This study identifies three significant regulations influencing the design of building envelopes with increasingly stringent transmittance limits in all Italian climatic zones:

- Legislative Decree 192/2005 (L.D. 192/2005).
- Ministerial Decree of 26 June 2015 (M.D. 26/06/2015).
- Ministerial Decree of 6 August 2020 (M.D. 06/08/2020).

Specifically, L.D. 192/2005 came into force on January 1, 2006, requiring the verification of thermal transmittance limits for new buildings and all uses, excluding horizontal elements and industrial building windows. It introduced additional transmittance limits for accessing tax renovation deductions, although they were not mandatory and were not taken into account.

The M.D. 26/06/2015 introduces the concept of a 'reference building', a building similar to the one under consideration in terms of geometry (outline, volumes, floor area, surfaces of building elements and components), orientation, spatial location, intended use, boundary situation, and having thermal characteristics and energy parameters predetermined in accordance with Appendix A of Annex 1 of Ministerial Decree 26/6/15. For all input data and undefined parameters, the values of the real building are used. For the reference building transmittance limits, the values valid from 1 January 2019 for public buildings and from 1 January 2021 for residential buildings were taken. As in the previous decree, there are slightly different values for the verification of individual components during renovation.

The M.D. 06/08/2020 defined the new limit values allowed for access to tax renovation deductions for residential buildings.

Table 1 presents transmittance limits for roofs (U_{roof}), walls (U_{wall}), floors (U_{floor}), and windows (U_{wind}) in all Italian climatic zones (from A to F), in accordance with the three national regulations. Notably, a significant reduction in thermal transmittance limits is observed during the transition from L.D. 192/2005 to M.D. 26/06/2015, with a further slight reduction from M.D. 26/06/2015 to the latest decree M.D. 06/08/2020.

2. Methodology

Energy performance analyses were carried out on a residential building model located in diverse cities across Italy, each characterized by distinct climates. The building envelope was configured in accordance with three Italian regulatory limits established by Legislative Decree 192/2005 (L.D. 192/2005), Ministerial Decree of 26 June 2015 (M.D. 26/06/2015), and Ministerial Decree of 6 August 2020 (M.D. 06/08/2020). The analysis also incorporated an extra parameter related to the total solar energy transmittance for the normal incidence of the glazed system ($g_{gln,n}$). Two values of $g_{gln,n}$ were tested in all scenarios. Fig. 1 summarizes the layout of the research framework.

Table 1
Thermal transmittance limits in compliance with L.D. 192/2005, M.D. 26/06/2015, and M.D. 06/08/2020.

Italian climate zones	Envelope components	U [W/m^{2}K]		
		L.D. 192/2005	M.D. 26/6/2015	M.D. 6/8/2020
A HDD $\leq$ 600	U_{roof}	0.80	0.35	0.27
	U_{wall}	0.85	0.43	0.38
	U_{floor}	0.80	0.44	0.40
	U_{window}	5.50	3.00	2.60
B 600 < HDD $\leq$ 900	U_{roof}	0.60	0.35	0.27
	U_{wall}	0.64	0.43	0.38
	U_{floor}	0.60	0.44	0.40
	U_{window}	4.00	3.00	2.60
C 900 < HDD $\leq$ 1400	U_{roof}	0.55	0.33	0.27
	U_{wall}	0.57	0.34	0.30
	U_{floor}	0.55	0.38	0.30
	U_{window}	3.30	2.20	1.75
D 1400 < HDD $\leq$ 2100	U_{roof}	0.46	0.26	0.22
	U_{wall}	0.50	0.29	0.26
	U_{floor}	0.46	0.29	0.28
	U_{window}	3.10	1.80	1.67
E 2100 < HDD $\leq$ 3000	U_{roof}	0.43	0.22	0.20
	U_{wall}	0.46	0.26	0.23
	U_{floor}	0.43	0.26	0.25
	U_{window}	2.80	1.40	1.30
F HDD. > 3000	U_{roof}	0.41	0.20	0.19
	U_{wall}	0.44	0.24	0.22
	U_{floor}	0.41	0.24	0.23
	U_{window}	2.40	1.10	1.00

Energy analyses were conducted using the Termolog software tool (version 13) [50], which processed annual hourly climatic data extracted from Meteonorm on a monthly basis. The building performance was evaluated for the years 2030, 2050, and 2070, considering three RCP scenarios: 2.6, 4.5, and 8.5. The results were reported in terms of:

- $EP_{h,nd}$: Heating thermal performance index [kWh/m^2].
- $EP_{c,nd}$: Cooling thermal performance index [kWh/m^2].
- $EP_{tot,nd}$: Total thermal performance index [kWh/m^2].

These indices are not influenced by the heating or cooling system in use and are computed based on the specific guidelines outlined in UNI TS 11300–1 [51].

2.1. Analysis of uncertainty

Climate change is a phenomenon in which uncertainties abound but are not always highlighted, and are often overlooked in both the description of climate projections and the analysis of the resulting data.

When considering the hypothesis of climate change and analyzing observed data, it is crucial to acknowledge the limitations imposed by the data's temporal window to avoid projecting beyond what the data allows or extrapolating intensities for excessively long return periods. Conversely, when having data derived from climate models, it's important to have a precise understanding of what they represent, the basic assumptions in their processing (model, scenarios), and the uncertainties considered.

A rigorous quantitative treatment of uncertainties associated with any analysis considering climate change and model-derived projections is practically impossible. Therefore, an assessment of quantifiable uncertainties is more than necessary, not only to give more meaning to the obtained results but also to clarify the implications of the conclusions.

The report [52] shows that the forecast climate data used for RCP scenarios 2.6 and 8.4 for Italy show a level of uncertainty of about +/-15, which remains about the same for the different scenarios and for the different years considered.

The hourly values used by Meteonorm are, nonetheless, the result of a stochastic calculation based on monthly values (data from weather stations, interpolated data, or imported data). Therefore, with the aim of not increasing uncertainty, the monthly climatic values in Meteonorm were used for the building calculations, without resorting to hourly data, which would have been the result of manipulation.

Termolog is one of the software implementations of UNI/TS 11,300 and must be validated by the CTI (Italian Thermotechnical Committee). Validation, introduced by Annex III of Legislative Decree 115/08 and reiterated by Article 7 of Ministerial Decree 26/6/15, involves verifying a maximum deviation of plus or minus 5 % compared to predetermined case studies. The validation requirement applies only to the calculation part related to UNI/TS 11,300 (i.e., the calculation of the energy requirements of buildings), and no CTI validation is required for all other analyses referred to by Ministerial Decree 26/6/15 (transmittance, condensation, mold, thermal bridges, etc.).

Therefore, the overall uncertainty in building energy calculations with climatic forecast data for scenarios from RCP 2.6 to RCP 8.5 is overall approximately +/- 20 %.

2.2. Climates of the selected Italian locations

As already mentioned, Italy is divided into six climate zones, labeled

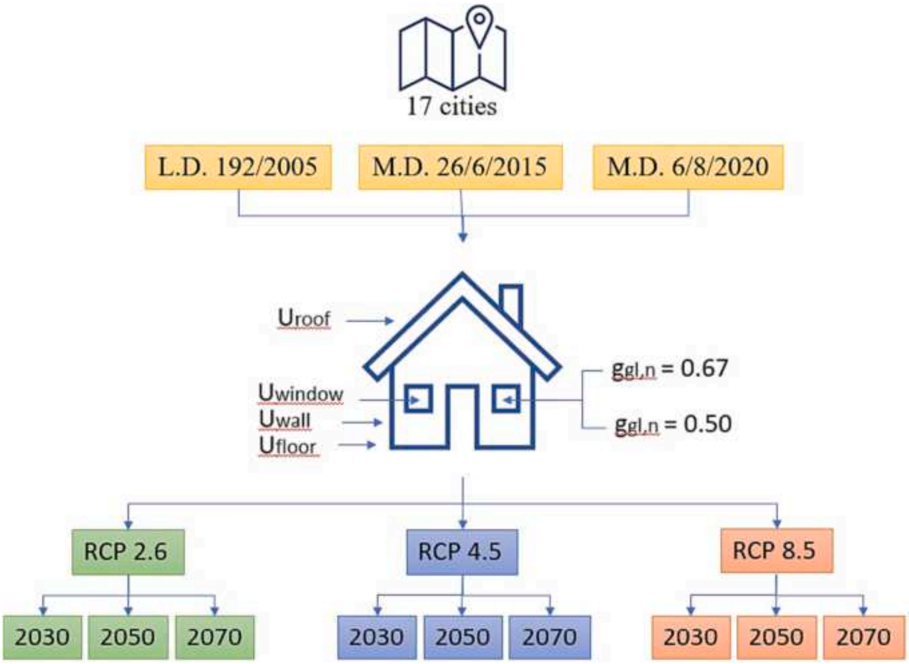


Fig. 1. Layout of the working framework.

A to F. To broaden the scope of the study, the analysis was not limited to H.D.D.-based climate zoning. In this regard, in addition to the chosen six cities representing the six climate zones derived from the national climate classification, additional cities belonging to the same climate zone but characterized by different Köppen-Geiger climate classifications were also considered. The Köppen-Geiger climate classification, on which this work is based, covers the years from 1991 to 2020, this period was chosen as it is representative of the period in which the three Italian energy regulations fall [53,54].

This approach led to the selection of 17 locations (as shown in Table 2). The main selection criterion was provincial capitals. When a particular climate did not include a provincial capital, other cities within that climate area were chosen.

2.3. RCP scenarios for all Italian climate zones

The RCPs are scenarios for greenhouse gas concentrations in the 21st century, as adopted by the IPCC. They depict different plausible climate futures based on projected emissions [55]. This study selected three scenarios from the IPCC range of trajectories: RCP 2.6, RCP 4.5, and RCP 8.5. RCP 2.6 emphasizes ambitious emission reductions, in line with decarbonization goals. RCP 4.5 represents an intermediate stabilization pathway, while RCP 8.5 depicts a high-emission scenario with limited emission reduction efforts, leading to more adverse outcomes. RCP 8.5 projects a global temperature increase of 2.6 to 4.8 °C. During the initial years until mid-century, the differences between the RCP scenarios may be relatively minor as greenhouse gas concentrations take time to influence the climate system. However, as time progresses, the distinct characteristics of each RCP become more evident, with their impacts and consequences becoming increasingly apparent in the latter half of the century, according to the IPCC.

Meteonorm 8 [56] is a climate database providing climate data for different time periods (2030, 2050, and 2070) and scenarios (RCP 2.6, 4.5, and 8.5) worldwide. It includes typical meteorological years and current data, such as outdoor temperature, wind speed, solar radiation, and atmospheric pressure.

Supplementary Data 01 shows the average outdoor monthly temperatures for the cities representing different climate zones in Italy, based on both the Köppen-Geigen climate and Italian national classification. These temperature charts are generated using Meteonorm and

Table 2
List of selected locations.

City	Latitude	Longitude	Italian climate zone	H.D.D.	Köppen-Geiger climate classification	Description of Köppen-Geiger classification
Lampedusa	35°30′	12°36′	A	568	BSh	Hot semi-arid climate
Porto Empedocle	37°17′	13°31′	A	579	Csa	Hot-summer Mediterranean climate
Siracusa	37°4′	15°17′	B	799	Csa	Hot-summer Mediterranean climate
Lecce	40°21′	18°10′	C	1153	Csa	Hot-summer Mediterranean climate
Foggia	41°27′	15°33′	D	1530	BSk	Cold semi-arid climate
Pescara	42°27′	14°12′	D	1718	Cfa	Humid subtropical climate
Farindola	42°26′	13°49′	D	2070	Cfb	Temperate oceanic climate
Rome	41′53°	12°28′	D	1415	Csa	Hot-summer Mediterranean climate
Stazzema	43°59′	10°17′	D	1726	Csb	Warm-summer Mediterranean climate
Ferrara	44°50′	11°37′	E	2326	Cfa	Humid subtropical climate
L'Aquila	42°21′	13°23′	E	2514	Cfb	Temperate oceanic climate
Arezzo	43°27′	11°52′	E	2104	Csa	Hot-summer Mediterranean climate
Lagonegro	40°7′	15°46′	E	2120	Csb	Warm-summer Mediterranean climate
Belluno	46°8′	12°13′	F	3043	Cfb	Temperate oceanic climate
Fenestrelle	45°2′	7°3′	F	3781	Cfc	Subpolar oceanic climate
Asiago	45°52′	11°30′	F	4163	Dfb	Warm-summer humid continental climate
Tarvisio	46°30′	13°35′	F	3959	Dfc	Subarctic climate

showcase data for the years 2030, 2050, and 2070. Each graph illustrates three RCP scenarios: RCP 2.6, RCP 4.5, and RCP 8.

2.4. The representative residential building

In this section, the characteristics of the reference building are defined. It is well known that each location is characterised by its traditions and architecture, however, differentiating building types would have made the comparison less effective. Therefore, a reinforced concrete building with insulated walls was chosen for its strength and durability. This choice appears common in many climatic areas due to its ability to withstand adverse weather conditions and provide a safe and comfortable environment for occupants at a lower construction cost. The building is a simple square plan, insulated to have the contribution of solar radiation across all orientations. It consists of three identical floors, featuring a net surface area of 74 m^2 and a net volume area of 199 m^2. Fig. 2 shows a typical floor plan of an apartment of the multi-residential building. The analysis focuses on the building envelope without air conditioning. The envelope design complies with the energy regulations of each location. While the results pertain to this specific building type, its simplicity allows for comparisons with many other buildings on the territory. Therefore, the trends observed in the results can serve as a reference for similar construction types.

The thermal and geometric characterization of the building envelope is shown in Fig. 3. For the opaque envelope details such as thickness (d), thermal conductivity (λ), and density (ρ) of all layers are provided. To reach the transmittance values specified by the three regulatory limits, only the insulation thickness (EPS) was adjusted. The allowable range of thickness variations (d) is highlighted in grey. Specifically, modifications were limited to the thickness of the insulating materials while keeping other material properties constant.

The building envelope is configured to approach the thermal transmittance limits set by Legislative Decree 192 of 2005 (L.D. 192/2005), Ministerial Decree (M.D. 26/06/2015) and Ministerial Decree (M.D. 06/08/2020) as closely as possible. Table 3 presents the thicknesses applied to the opaque envelope in each climatic zone, along with their

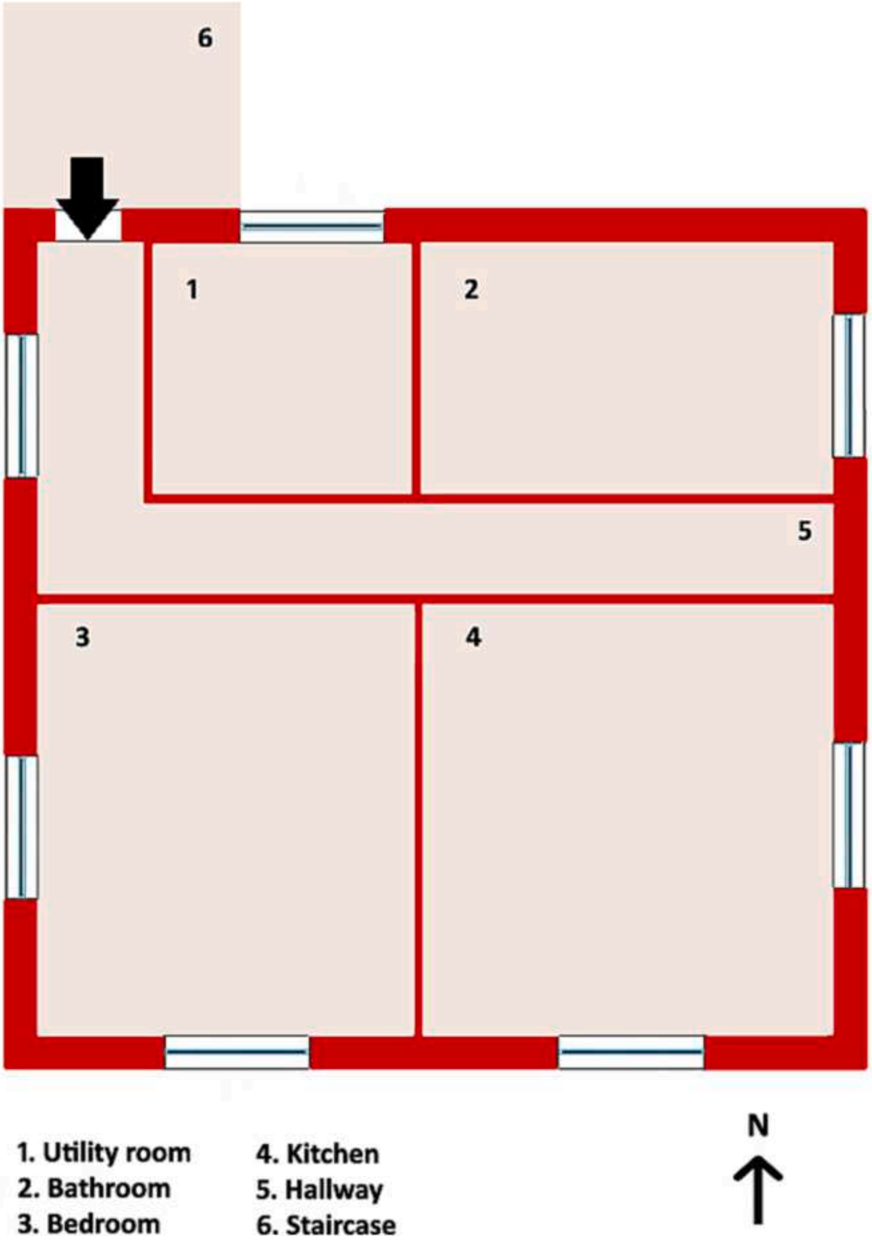
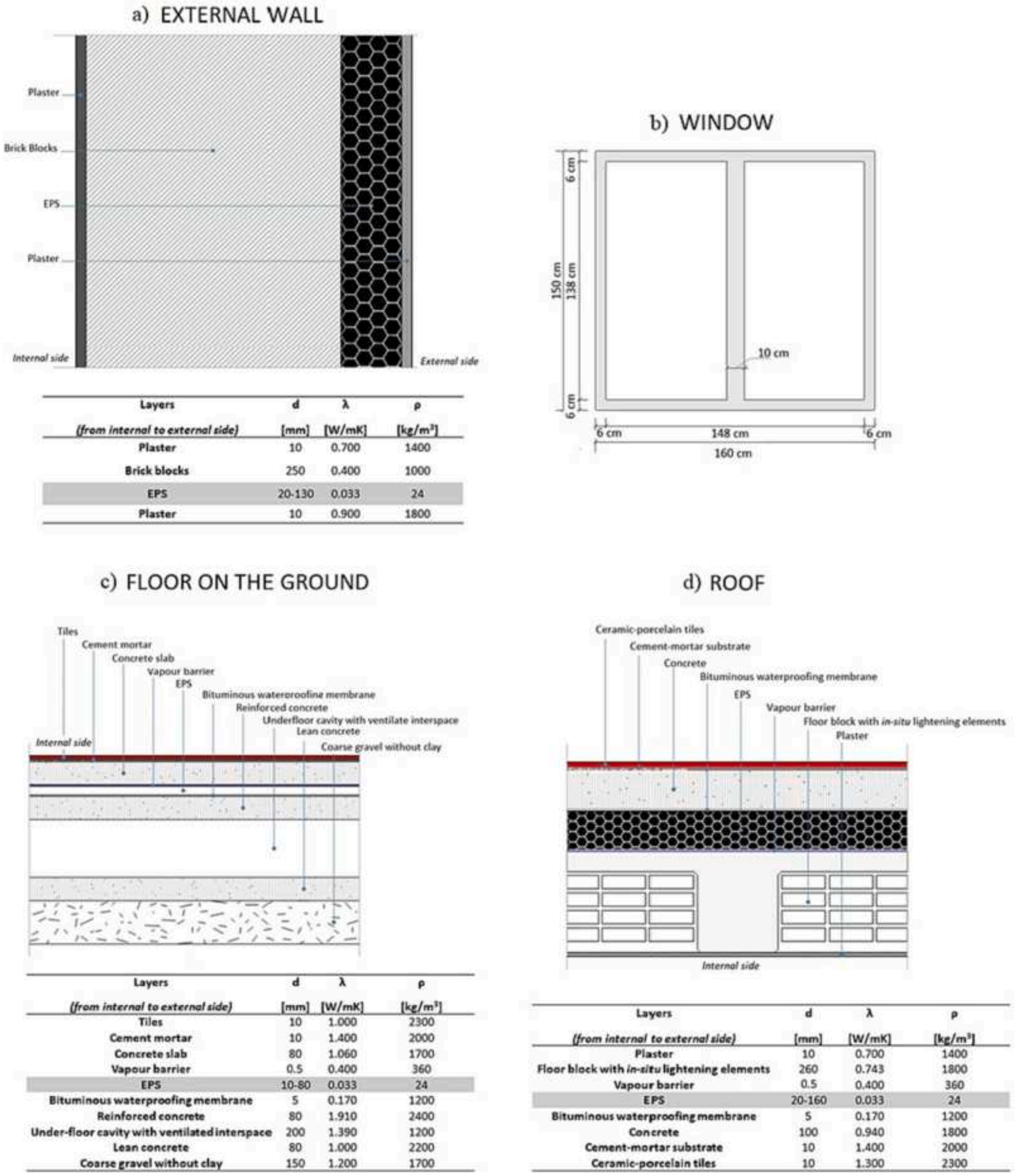


Fig. 2. Floor plan of an apartment of the multi-residential building.



Layers	**d**	**λ**	**ρ**
(from internal to external side)	**[mm]**	**[W/mK]**	**[kg/m³]**
Plaster	10	0.700	1400
Brick blocks	250	0.400	1000
EPS	20-130	0.033	24
Plaster	10	0.900	1800

Layers	**d**	**λ**	**ρ**
(from internal to external side)	**[mm]**	**[W/mK]**	**[kg/m³]**
Tiles	10	1.000	2300
Cement mortar	10	1.400	2000
Concrete slab	80	1.060	1700
Vapour barrier	0.5	0.400	360
EPS	10-80	0.033	24
Bituminous waterproofing membrane	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

Layers	**d**	**λ**	**ρ**
(from internal to external side)	**[mm]**	**[W/mK]**	**[kg/m³]**
Plaster	10	0.700	1400
Floor block with *in-situ* lightening elements	260	0.743	1800
Vapour barrier	0.5	0.400	360
EPS	20-160	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

Fig. 3. Thermal and geometric characterization of the building envelope: external wall (a), window (b), floor on the ground (c), roof (d).

corresponding legal limits.

Each apartment is equipped with seven identical windows measuring 150 cm x 160 cm. These windows feature PVC frames that are 6 cm thick, accompanied by a 10 cm vertical partition. Moreover, the windows are furnished with pastel-colored exterior shutters of opaque transparency and aluminum blinds.

As regards the windows, the following parameters are modified:

- Gas used within the cavity (argon or krypton).
- Glazing stratigraphy (double or triple glazing).
- Type of frame (varying the number of air chambers).
- Glazing coating (options include regular glass, low-emissivity glass with coating applied to the outer side of the innermost glass, or low-emissivity glass with coating on the outer side of the inner glass and additional coating on the inner side of the outermost glass).

Table 4 provides a comprehensive description of the transparent envelope characteristics required by regulations. It showcases various parameters, including the cavity gas options (Argon or Krypton), glass stratigraphy (double or triple glazing), the number of air chambers in the frame, and the glass coating variations (normal or Low-e). Additionally, it specifies whether the Low-e treatment is applied on the inner or outer side of the glass. Specifically, “low e 1″ denotes treatment on the outer side of the inner glass, while ”low e 2″ signifies treatment on both the outer side of the inner glass and the inner side of the outer glass. The resulting window transmittance (U_w) ranges from 0.843 to 5.014 W/m^{2}K.

2.5. *The total solar energy transmittance for normal incidence of the glazed system ($g_{gl,n}$)*

The $g_{gl,n}$ can be determined as the sum of the transmission coefficient ($\tau_{b,n}$) and the secondary heat transfer factor (q_i) [45]. Table 5 and 6 report these parameters for different glazed systems.

As reported above, this study tested the performances of the same buildings with the total solar energy transmittance for normal incidence

Table 3
Opaque envelope characterization in compliance with L.D. 192/2005, M.D. 26/06/2015, and M.D. 06/08/2020 legal provisions.

Italian Climate	Regulation	Insulation thickness [cm]			U_{set} [W/m^{2}K]		
		Wall	Roof	Floor	Wall	Roof	Floor
A	L.D. 192/2005	2	2	1	0.701	0.785	0.463
	M.D. 2015	5	8	2	0.428	0.323	0.404
	M.D. 2020	6	10	3	0.379	0.270	0.357
B	L.D. 192/2005	3	4	2	0.578	0.532	0.404
	M.D. 2015	5	8	2	0.428	0.323	0.404
	M.D. 2020	6	10	3	0.379	0.270	0.357
C	L.D. 192/2005	4	4	2	0.492	0.532	0.404
	M.D. 2015	7	8	3	0.340	0.323	0.357
	M.D. 2020	9	10	5	0.282	0.270	0.288
D	L.D. 192/2005	4	5	2	0.492	0.458	0.404
	M.D. 2015	9	11	5	0.282	0.250	0.288
	M.D. 2020	10	13	6	0.260	0.217	0.265
E	L.D. 192/2005	5	6	2	0.428	0.402	0.404
	M.D. 2015	11	13	7	0.241	0.217	0.246
	M.D. 2020	12	15	7	0.224	0.192	0.246
F	L.D. 192/2005	5	6	2	0.428	0.402	0.404
	M.D. 2015	12	15	8	0.224	0.192	0.229
	M.D. 2020	13	16	8	0.210	0.181	0.229

Table 4
Characterization of the windows in compliance with the regulations outlined in L.D. 192/2005, M.D. 26/06/2015, and M.D. 06/08/2020.

Italian Climate	Regulation	Windows				
		Cavity gas	Glass	N. chambers	Coating	U_w[W/m^{2}K]
A	L.D. 192/2005	–	Single	2	normal	5.014
	M.D. 2015	Argon	Double	2	normal	2.782
	M.D. 2020	Argon	Double	6	normal	2.534
B	L.D. 192/2005	Argon	Double	2	normal	2.782
	M.D. 2015	Argon	Double	2	normal	2.782
	M.D. 2020	Argon	Double	6	normal	2.534
C	L.D. 192/2005	Argon	Double	2	normal	2.782
	M.D. 2015	Argon	Double	2	low-e 1	1.825
	M.D. 2020	Argon	Double	2	low-e 2	1.727
D	L.D. 192/2005	Argon	Double	2	normal	2.782
	M.D. 2015	Argon	Double	3	low e 1	1.783
	M.D. 2020	Argon	Double	5	low e 1	1.584
E	L.D. 192/2005	Argon	Double	2	normal	2.782
	M.D. 2015	Argon	Triple	6	low-e 1	1.319
	M.D. 2020	Argon	Triple	3	low-e 2	1.287
F	L.D. 192/2005	Argon	Double	2	low-e 1	1.825
	M.D. 2015	Krypton	Triple	6	low-e 1	1.054
	M.D. 2020	Krypton	Triple	6	low-e 2	0.843

Table 5
Approximate values of the transmission coefficients for normal incidence ($\tau_{b,n}$) in the visible range of certain glazed systems.

GLAZED SYSTEM	$\tau_{b,n}$
Single clear float glass	0.80–0.90
Single absorbent float glass	0.70–0.80
Patterned single glass	0.85
Single mass-coloured float glass (depending on colour)	0.30–0.60
Single reflective float glass	0.35–0.60
Single low-emissivity float glass	0.50–0.75
Double glazing 6–12-6 (clear float glass)	0.65–0.75
Double glazing 6–12-6 with low-emissivity coating (clear float glass)	0.60
Clear polycarbonate	0.80–0.90
Translucent plastic sheets	0.10–0.80

Table 6
Value of the secondary heat transfer factor (q_i) depending on the type of glazing.

GLAZED SYSTEM	q_i
Single	0.027
Double	0.068
Triple	0.081

of the glazed system ($g_{gl,n}$) set at 0.67 and 0.50.

3. Results and discussions

The first part of this section presents considerations on external temperatures (Section 3.1). Supplementary Data 01 reports the average monthly outdoor temperatures for all selected locations and scenarios.

The subsequent part details the analysis of the building's thermal performance across all climate zones. Initially (Sections 3.2-3.6), the results for each climate zone are presented with a focus on a single representative city. Subsequently, overall considerations (Section 3.7) encompass a comprehensive presentation of the results, comparing them with the current thermal performances. Detailed outcomes for all chosen locations, considering both $g_{gl,n}$ values of 0.67 and 0.50, are available in Supplementary Data 02.

3.1. Considerations on the external temperatures

Overall, a monthly average external temperature increase between 2030 and 2070 is evident, especially considering the case with RCP 8.5. In most locations, maximum temperatures rise more than minimum temperatures. Under the RCP 4.5 scenario, temperature variations between 2030 and 2070 range from 1.1 °C. (Lampedusa, climate zone A) to 1.77 °C (Asiago, climate zone F). Locations with higher temperature variations include (climate zone F), experiencing a change of 2.16 °C, L'Aquila (climate zone E) with a variation of 1.86 °C, and Belluno (climate zone F) with a variation of 1.82 °C. In Lecce (climate zone F), the temperature change is minimal, around 0.77 °C. Under the RCP 8.5 scenario, the temperature variation is most pronounced. The temperature difference between maximum values in 2070 and 2030 shows a significant increase from climate zone A to climate zone E. In climate zone A, the outdoor temperature rises by approximately 2.12 °C (Porto Empedocle) to 2.3 °C (Lampedusa) in 2070 compared to 2030. In climate zone B, the increase is 2.34 °C (Siracusa), while in climate zone C, it reaches 2.85 °C (Lecce). Climate zone D experiences an increase ranging from 3.15 °C (Rome) to 3.91 °C (Pescara), while climate zone E sees an increase between 3.18 °C (Lagonegro) and 3.86 °C (L'Aquila). In climate zone F, the temperature rise ranges from 3.66 °C (Belluno, climate F) to 4.36 °C (Asiago). However, minimum temperatures do not increase by more than 2.5 °C in 2070 compared to 2030. The most significant temperature differences are observed in climatic zones F and E between 2030 and 2070, with even more pronounced variations under scenario RCP 8.5. For instance, in the RCP 8.5 scenario, by the year 2070, the city of Farindola, located in the Italian climate zone D and Koppen Cfb climate zone, experiences a maximum average monthly temperature of 32.97 °C.

3.2. Building thermal performances in climate zone a

From the analysis of the graphs obtained for the three Representative Concentration Pathways (RCPs), clear trends emerge for $EP_{h,nd}$, $EP_{c,nd}$, and EPtot, which are consistent across all cities within the considered climate zone. These trends are summarized in the following bullet points:

1) **Reduction in $EP_{h,nd}$ for all three RCP scenarios considered, less evident reduction observed for buildings constructed per M.D. 06/08/2020 standards.** M.D. 06/08/2020 constructions exhibit greater resilience to climate change. Notably, when comparing $EP_{h,nd}$ values between 2030 and 2050 and 2030–2070, a general decrease is evident, even though it is less pronounced for building constructed according to M.D. 06/08/2020. Overall, $EP_{h,nd}$ reduction is more conspicuous for cases with $g_{gl,n}$ equal to 0.50. However, the distinction between the values obtained with $g_{gl,n}$ 0.50 and $g_{gl,n}$ 0.67 diminishes when considering buildings adhering to M.D. 06/08/2020 standards.
2) **Increase in $EP_{c,nd}$ across all three RCP scenarios with a more significant rise under LD 192/2005 regulations.** The rise in $EP_{c,nd}$ values between 2030 and 2050 and 2030–2070, at equal RCP, is more pronounced for cases with $g_{gl,n}$ at 0.50. Similarly to $EP_{h,nd}$, when considering MD 2020, values obtained for $g_{gl,n}$ 0.67 and 0.50 are equivalent.
3) **Increase in $EP_{tot,nd}$ across all considered scenarios, with a more notable rise for LD 192/2005 at $g_{gl,n}$ equal to 0.67.** $EP_{tot,nd}$ demonstrates an overall increase across the spectrum of considered scenarios, notably showcasing a more pronounced increment specifically within LD 192/2005 regulations at $g_{gl,n}$ set at 0.67.

Fig. 4 presents the temporal trends of the thermal performance indices for the location of Lampedusa.

3.3. Building thermal performances in climate zone B

Analysing the graphs obtained for the three Representative Concentration Pathways (RCPs), clear trends emerge for $EP_{h,nd}$, $EP_{c,nd}$, and $EP_{tot,nd}$, which are consistent across all cities within the considered climate zone. These trends are summarized in the following bullet points:

1) **Reduction in $EP_{h,nd}$ for all three RCP scenarios considered, similar behaviour observed for both $g_{gl,n}$ 0.50 and 0.67.** M.D. 26/06/2015 and M.D. 06/08/2020 constructions exhibit greater resilience to climate change. Notably, when comparing $EP_{h,nd}$ values between 2030 and 2050 and 2030–2070, a general decrease is evident, and it is more pronounced for building constructed according to L.D. 192/2005. The values obtained with $g_{gl,n}$ 0.50 and $g_{gl,n}$ 0.67 are similar and present a similar decreasing trend.
2) **Similar increase in $EP_{c,nd}$ across RCP scenarios 2.6 and 4.5 for both $g_{gl,n}$ 0.50 and $g_{gl,n}$ 0.67, major increase for RCP scenario 8.5 for $g_{gl,n}$ 0.67**. $EP_{c,nd}$ demonstrates a consistent upward trend, considering 2030 and 2050 and 2030 and 2070 values, across RCP scenarios 2.6 and 4.5, showing a parallel increase for both $g_{gl,n}$ 0.50 and $g_{gl,n}$ 0.67. However, notably, there's a substantial rise observed in the $EP_{c,nd}$ values specifically within RCP scenario 8.5 for buildings designed with $g_{gl,n}$ 0.67.
3) **Increase in $EP_{tot,nd}$ across all considered scenarios.** For each considered scenario, comparing EP_{tot} values between 2030 and 2050 and between 2030 and 2070 reveals a similar magnitude of increase, irrespective of the g_{gln} considered.

Fig. 5 presents the temporal trends of the thermal performance indices for the location of Siracusa.

3.4. Building thermal performances in climate zone C

From the analysis of the graphs obtained for the three Representative Concentration Pathways (RCPs), clear trends emerge for $EP_{h,nd}$, $EP_{c,nd}$, and EPtot, which are consistent across all cities within the considered climate zone. These trends are summarized in the following bullet points:

1) **Reduction in $EP_{h,nd}$ for all three RCP scenarios considered.** Between 2030 and 2050, as well as between 2030 and 2070, there is a discernible decline in $EP_{h,nd}$ values, prominently emphasized within the RCP 8.5 scenario. This reduction manifests similarly across both $g_{gl,n}$ 0.67 and 0.50, indicating a consistent trend of decrease irrespective of the specific $g_{gl,n}$ value considered, thereby suggesting a parallel impact on $EP_{h,nd}$ values over these RCP and regulations scenarios.
2) **Increase in $EP_{c,nd}$ across all three RCP scenarios with a more significant rise under M.D. 06/08/2020 and M.D. 26/06/2015 regulation with $g_{gl,n}$ 0.50.** An increase in $EP_{c,nd}$ values is observed between 2030 and 2050, as well as between 2030 and 2070, particularly accentuated when considering $g_{gl,n}$ 0.67. This rise indicates a distinct trend of augmentation specifically associated with $g_{gl,n}$ 0.67 over the specified time frames, showcasing a more prominent impact of this $g_{gl,n}$ value.
3) **Increase in $EP_{tot,nd}$ across all considered scenarios, with a more notable rise for LD 192/2005 at $g_{gl,n}$ equal to 0.67.** An increase in $EP_{tot,nd}$ values is observed between 2030 and 2050, as well as between 2030 and 2070, particularly accentuated when considering $g_{gl,n}$ 0.67. This rise indicates a distinct trend of augmentation specifically associated with $g_{gl,n}$ 0.67 over the specified time frames, showcasing a more prominent impact on the resilience to climate change.

Fig. 6 presents the temporal trends of the thermal performance indices for the location of Lecce.

3.5. Building thermal performances in climate zone D

From the analysis of the graphs obtained for the three Representative Concentration Pathways (RCPs), clear trends emerge for $EP_{h,nd}$, $EP_{c,nd}$, and EPtot, which are consistent across all cities within the considered climate zone. These trends are summarized in the following bullet points:

1) **Reduction in $EP_{h,nd}$ for all three RCP scenarios considered.** Across all scenarios and construction regulations, there is a consistent decrease in $EP_{h,nd}$ values between 2030 and 2050, and between 2030 and 2070. This reduction remains similar for $g_{gl,n}$ 0.67 and 0.50 across most regulations, except notably within the MD 2020 case, where the reduction with $g_{gl,n}$ 0.67 is more pronounced. This discrepancy underscores a distinct impact of $g_{gl,n}$ values within the MD 26/06/2015 framework, indicating a greater reduction in $EP_{h,nd}$ values for $g_{gl,n}$ 0.67 compared to $g_{gl,n}$ 0.50.
2) **Increase in $EP_{c,nd}$ across all three RCP scenarios with a more significant rise under M.D. 06/08/2020 and M.D. 26/06/2015 regulation with $g_{gl,n}$ 0.50.** There is an increase in $EP_{c,nd}$ values between 2030 and 2050, and between 2030 and 2070, particularly notable in cases where $g_{gl,n}$ is set at 0.50, especially considering the regulations of 2020 and 2015. This more pronounced increase underscores a differential impact of the specific $g_{gl,n}$ 0.50 compared to 0.67 within the different regulations of M.D. 06/08/2020 and M.D. 26/06/2015.
3) **Slight increase in $EP_{tot,nd}$ across RCP 4.5 and 8.5 scenarios, decrease in $EP_{tot,nd}$ across RCP 2.6 scenario.** There is a marginal rise observed in $EP_{tot,nd}$ within both RCP 4.5 and 8.5 scenarios, while there is a decrease noted in $EP_{tot,nd}$ for the RCP 2.6 scenario. These contrasting trends in $EP_{tot,nd}$ indicate varying trajectories of change across different RCP scenarios, emphasizing differential impacts on the overall $EP_{tot,nd}$ values.

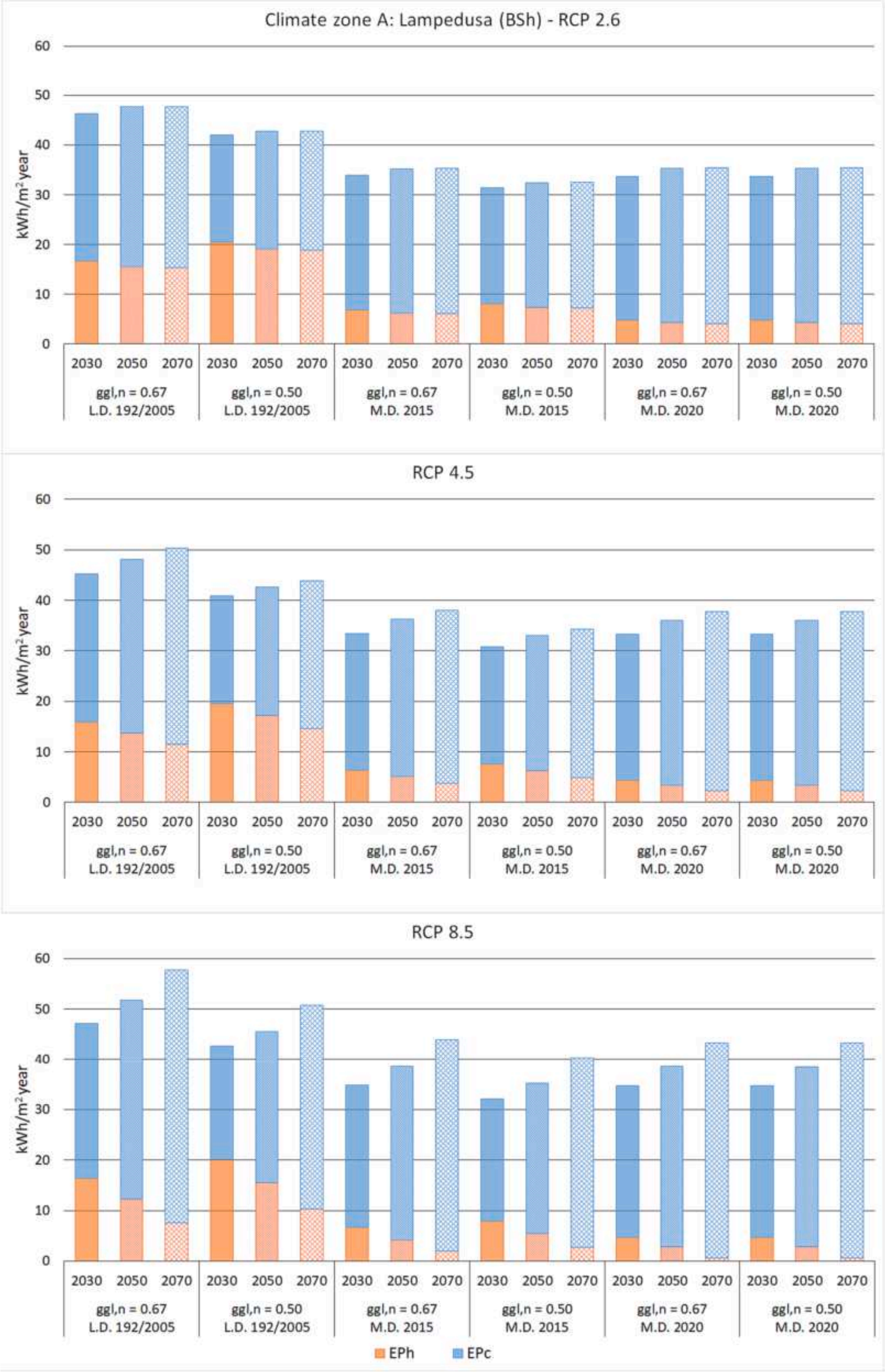


Fig. 4. Trends of thermal performance indices over the years in climate zone A.

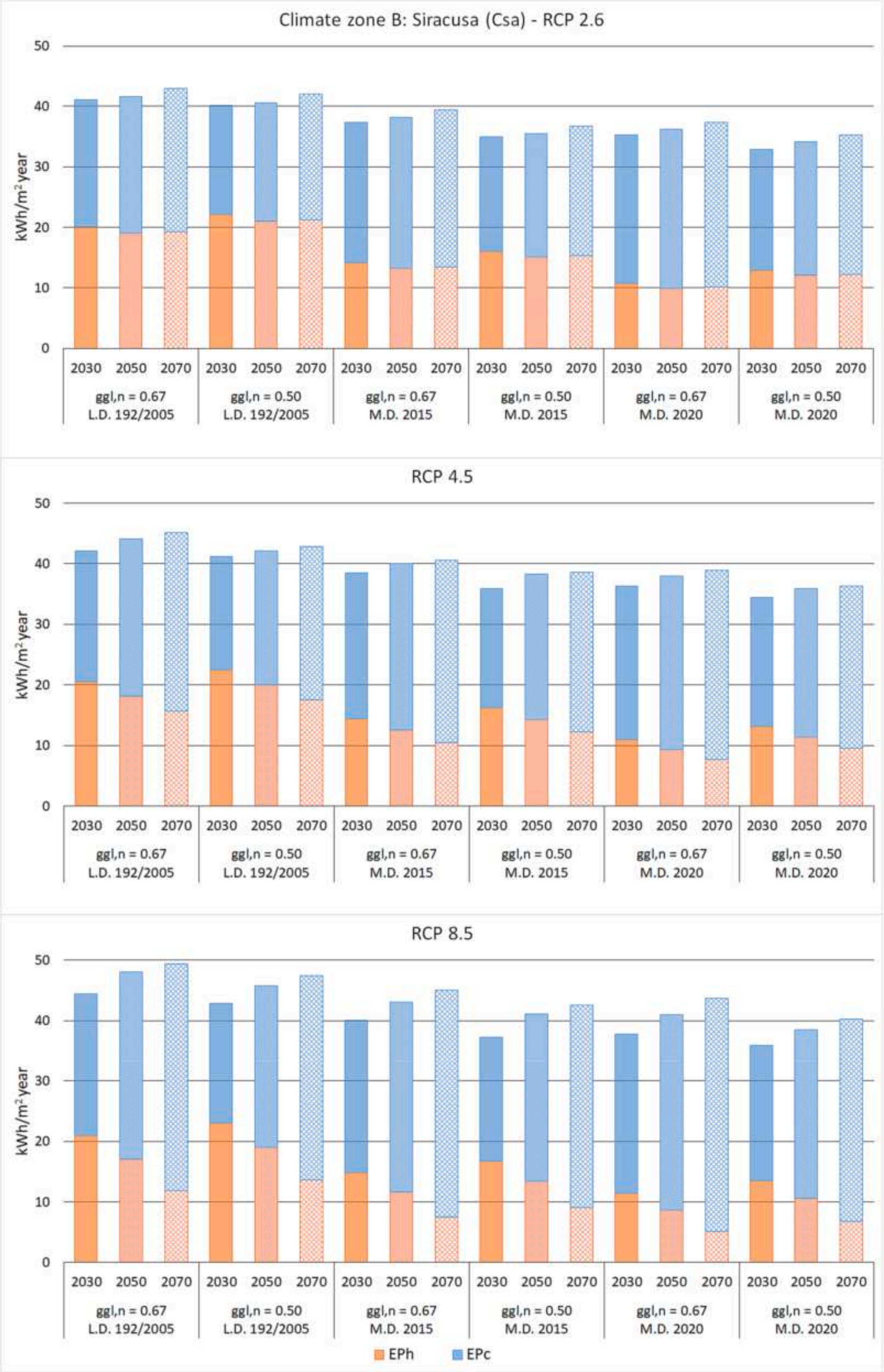


Fig. 5. Trends of the thermal performance indices over the years in climate zone B.

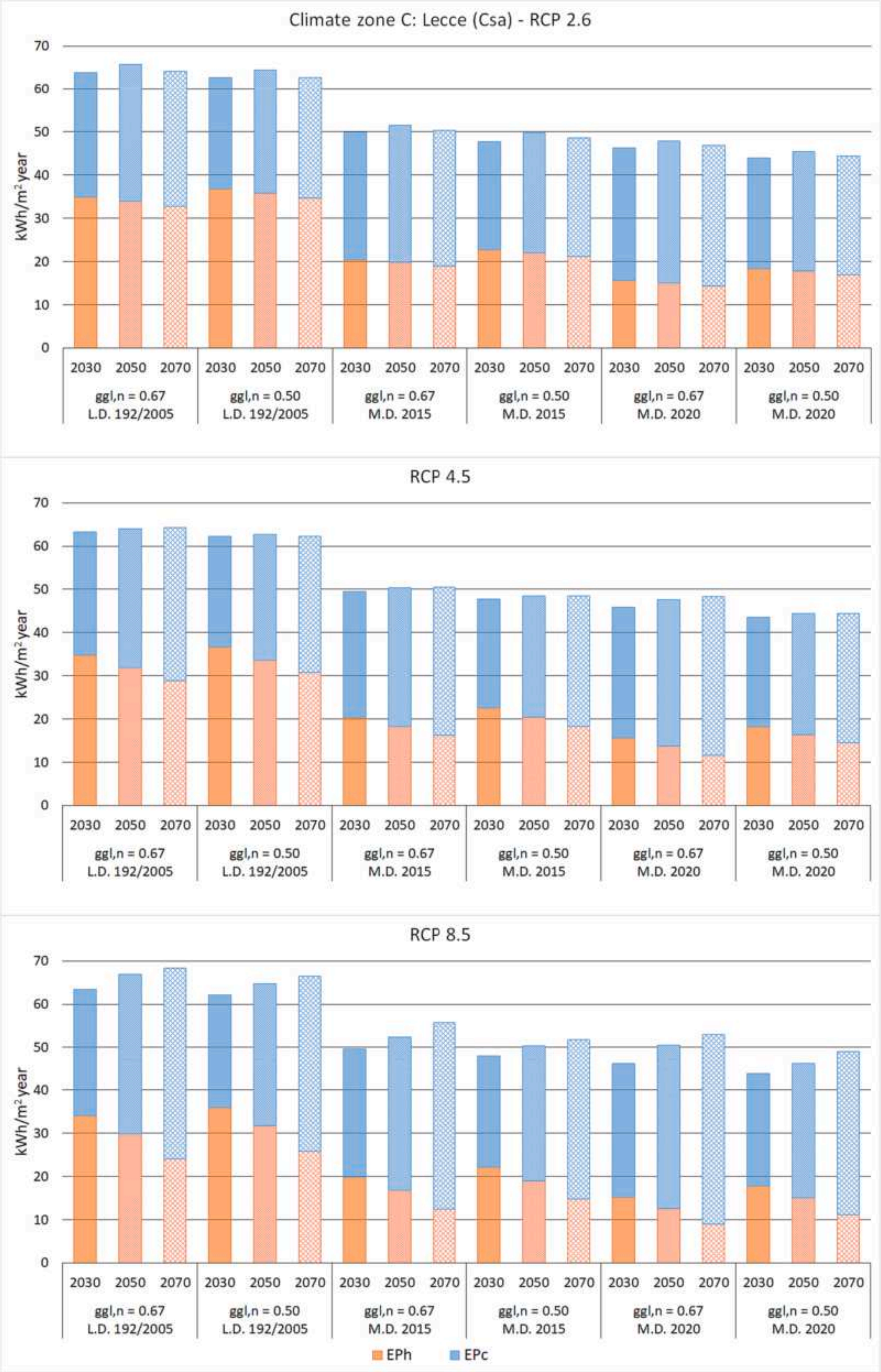


Fig. 6. Trends of the thermal performance indices over the years in climate zone C.

Fig. 7 presents the temporal trends of the thermal performance indices for the location of Rome.

3.6. Building thermal performances in climate zone E

From the analysis of the graphs obtained for the three Representative Concentration Pathways (RCPs), clear trends emerge for $EP_{h,nd}$, $EP_{c,nd}$, and EPtot, which are consistent across all cities within the considered climate zone. These trends are summarized in the following bullet points:

1) **Reduction in $EP_{h,nd}$ for all three RCP scenarios considered, more evident reduction observed for buildings constructed under L. D. 192/2005 standard.** The consistent decrease in $EP_{h,nd}$ between 2030 and 2050, and between 2030 and 2070, holds more significance in instances where $g_{gl,n}$ is set at 0.67, especially within the context of the L.D. 192/2005 regulation. This greater relevance of the reduction in $EP_{h,nd}$ highlights a distinct impact of $g_{gl,n}$ set at 0.67.
2) **$EP_{c,nd}$ nearly constant for RCP 2.6, increase of $EP_{c,nd}$ in other RCP scenarios.** $EP_{c,nd}$ demonstrates a more diverse behavior compared to EPh. It remains nearly constant between 2030 and 2050 and between 2030 and 2070 in the RCP 2.6 scenario, with a slight and almost negligible increase, showing the highest values by 2050 regardless of the $g_{gl,n}$ value considered. In contrast, for other RCP scenarios, there is an increase in $EP_{c,nd}$ between 2030 and 2050 and between 2030 and 2070. This rise is more noticeable for $g_{gl,n}$ values set at 0.67.
3) **Decrease in $EP_{tot,nd}$ in RCP 2.6 scenario, decrease for other scenarios.** Between 2030 and 2050, as well as between 2030 and 2070, $EP_{tot,nd}$ decreases regardless of the $g_{gl,n}$ value or the regulation under consideration for RCP 2.6 scenario. However, for other RCP scenarios, there is an increase specifically for $g_{gl,n}$ set at 0.67, notably observed within the frameworks of the 2015 and 2020 regulations.

Fig. 8 presents the temporal trends of the thermal performance indices for the location of Ferrara.

3.7. Building thermal performances in climate zone F

From the analysis of the graphs obtained for the three Representative Concentration Pathways (RCPs), clear trends emerge for $EP_{h,nd}$, $EP_{c,nd}$, and EPtot, which are consistent across all cities within the considered climate zone. These trends can be summarized in the following bullet points:

1) **Reduction in $EP_{h,nd}$ for all three RCP scenarios considered, more evident reduction observed for $g_{gl,n}$ 0.67.** $EP_{h,nd}$ decreases between 2030 and 2050 and 2030–2070 irrespective of $g_{gl,n}$ value or the regulation under consideration, with the most significant decrease observed with $g_{gl,n}$ 0.67.
2) **Increase in $EP_{c,nd}$ close to zero, slight increase with $g_{gl,n}$ 0.67.** The $EP_{c,nd}$ values are consistently close to zero, with a slight increase observed when comparing values between 2030, 2050, and 2070 within the same building regulation. The most significant variations occur when considering $g_{gl,n}$ 0.67.
3) **Slight decrease in $EP_{tot,nd}$ across all considered scenarios.** $EP_{tot,nd}$ tends to decrease slightly comparing values between 2030, 2050, and 2070 within the same building regulation.

Fig. 9 presents the temporal trends of the thermal performance indices for the location of Asiago.

3.8. Overall considerations

Tables 7-10 present the percentage changes in $EP_{tot,nd}$ from 2020 to 2030, 2050, and 2070 for all scenarios, grouping the results by different Koppen zones. Positive values indicate an increase of $EP_{tot,nd}$ over the years. Light orange cells indicate a small increase (between 0 and 10 %), and orange cells with orange lettering indicate a large increase (i.e. greater than 10 %). Light green cells indicate a small decrease (between 0 and −10 %), and green cells with green lettering indicate a large decrease (i.e. less than −10 %).

In general, it is observed that buildings designed in compliance with LD 192/2005 compared with the other regulations exhibit a smaller variation of $EP_{tot,nd}$ over time. Due to climate change, the heightened insulation in warm regions has contributed to a rise in annual global consumption. Looking ahead, a reduction in transmission limits is anticipated to have adverse consequences.

Particularly, by the analysis of the Italian climate classification, emerges that in hot regions, like Zone A and Zone B, it becomes apparent that opting for a $g_{gl,n}$ value of 0.5 has a greater impact on buildings constructed under LD 192/2005, enabling the mitigation of the effects of climate change. In Climate Zone D different behaviors are notable. Generally, buildings designed under LD 192/2005 regulations exhibit a more uniform trend. In Climate Zones E and F, the situation markedly improves, providing a more substantial opportunity for improvement and, consequently, resulting in a decrease in $EP_{tot,nd}$.

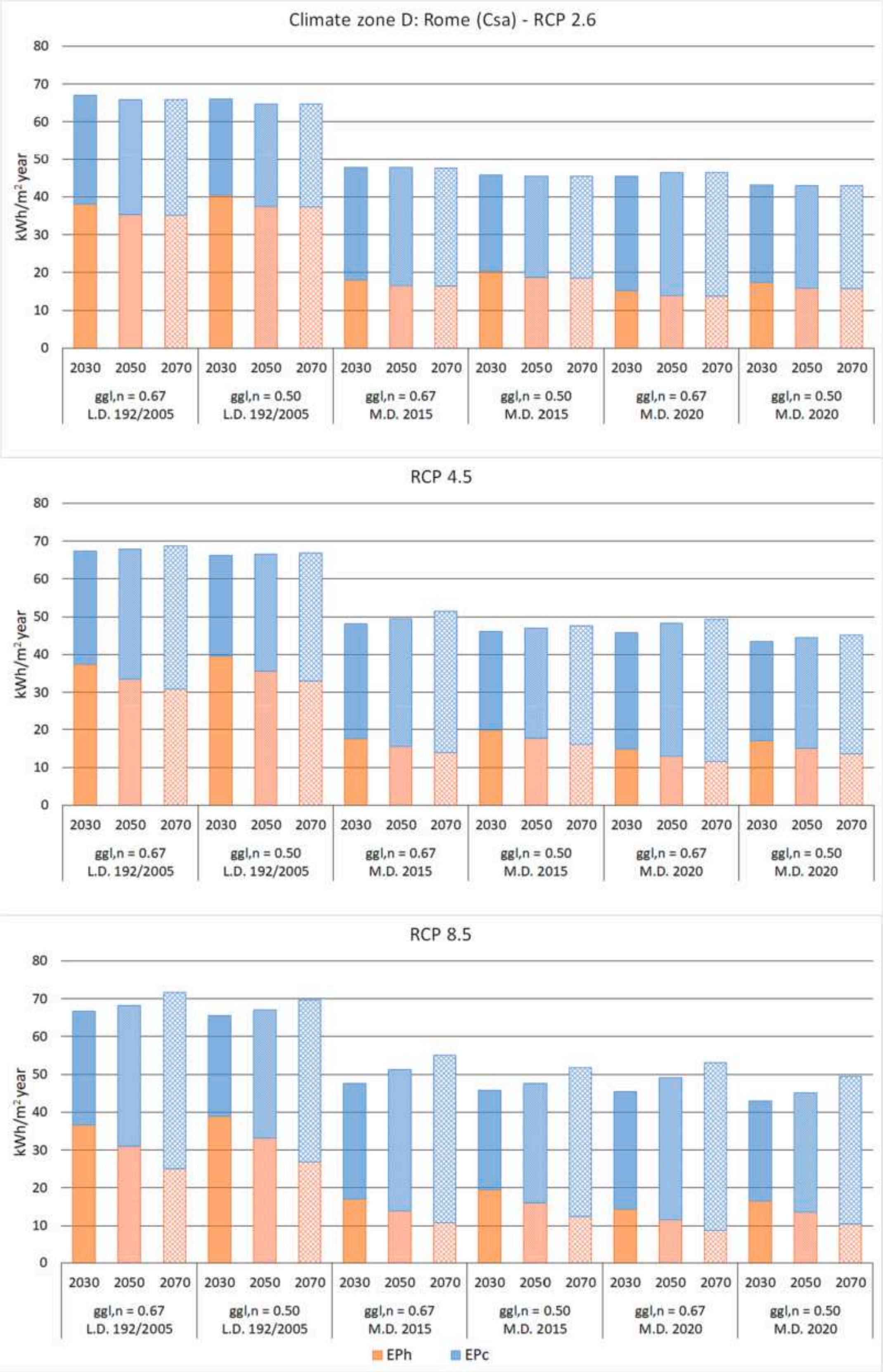
An analysis of the Koppen climate classification shows that the BSh zone sees the greatest increase in $EP_{tot,nd}$ over the years in all scenarios; it is the zone in which the increase exceeds 10 % at most. In the BSk zone, increases in $EP_{tot,nd}$ are present in all scenarios, but the amount of values greater than 10 % is smaller than in BSh.

In climate Csa, the increase in $EP_{tot,nd}$ occurs in all scenarios, the trend is rather similar in all cities, except for Porto Empedocle, which shows more marked worsening. Csb, Cfa, Cfb show a mixed trend. Csb, Cfa, and Cfb show values between −10 and 10 % for L.D. 192/2005, the increases rise with subsequent decrees, due to higher outside temperatures. Cfc shows decreased $EP_{tot,nd}$, it is the only area that shows decreases in all scenarios. Dfb shows mixed behaviour of $EP_{tot,nd}$, but with values between −10 and 10 %. An increase of $EP_{tot,nd}$, is evident with 0.50 $g_{gl,n}$ decrease with 0.67 $g_{gl,n}$. Dfc shows all decreases of $EP_{tot,nd}$ apart from a few small increases.

4. Conclusions

The article proposes an exhaustive analysis of the regulations on energy efficiency in buildings in Italy, focusing in particular on L.D. 192/2005, M.D. 26/06/2015, and M.D. 06/08/2020, in response to the challenges imposed by climate change. The research deals with the effectiveness of these regulations in improving the resilience of building envelopes in facing climate change. To this end, a newly constructed multi-family residential building was tested in 17 locations belonging to different climate zones, considering two main classifications: the national climate (A, B, C, D, E, F) and the related Köppen-Geiger (BSh, Csa, BSk, Cfa, Cfb, Csb, Cfc, Dfb, Dfc). The design of the building envelope met the transmittance limits specified for each zone by the three regulations. The research emphasizes the importance of the total solar energy transmissivity for the normal impact of the glazing system on the building's energy performance, highlighting its role in managing thermal gains/losses, energy consumption, and thermal comfort. Windows with the appropriate transmissivity of solar energy can reduce the need for mechanical heating/cooling, leading to lower energy consumption and reduced greenhouse gas emissions.

In climate zone A, the change in $g_{gl,n}$ affects buildings according to M.D. 192/2005 the most; going from $g_{gl,n}$ 0.67 to 0.50 through retrofitting measures can increase resilience at lower costs. For buildings in compliance with M.D. 26/06/2015, changing $g_{gl,n}$ results in a significant reduction of $EP_{tot,nd}$, while for those compliant with M.D. 06/08/2020 the changes are negligible. In climate zone B, it becomes evident that the change in $g_{gl,n}$ has a more pronounced effect on buildings that comply with M.D. 06/08/2020, especially considering the RCP 8.5 scenario. Implementing retrofitting interventions to go from 0.67 to 0.50 $g_{gl,n}$ can


Climate zone D: Rome (Csa) - RCP 2.6

RCP 4.5

RCP 8.5

Fig. 7. Trends of the thermal performance indices over the years in climate zone D.

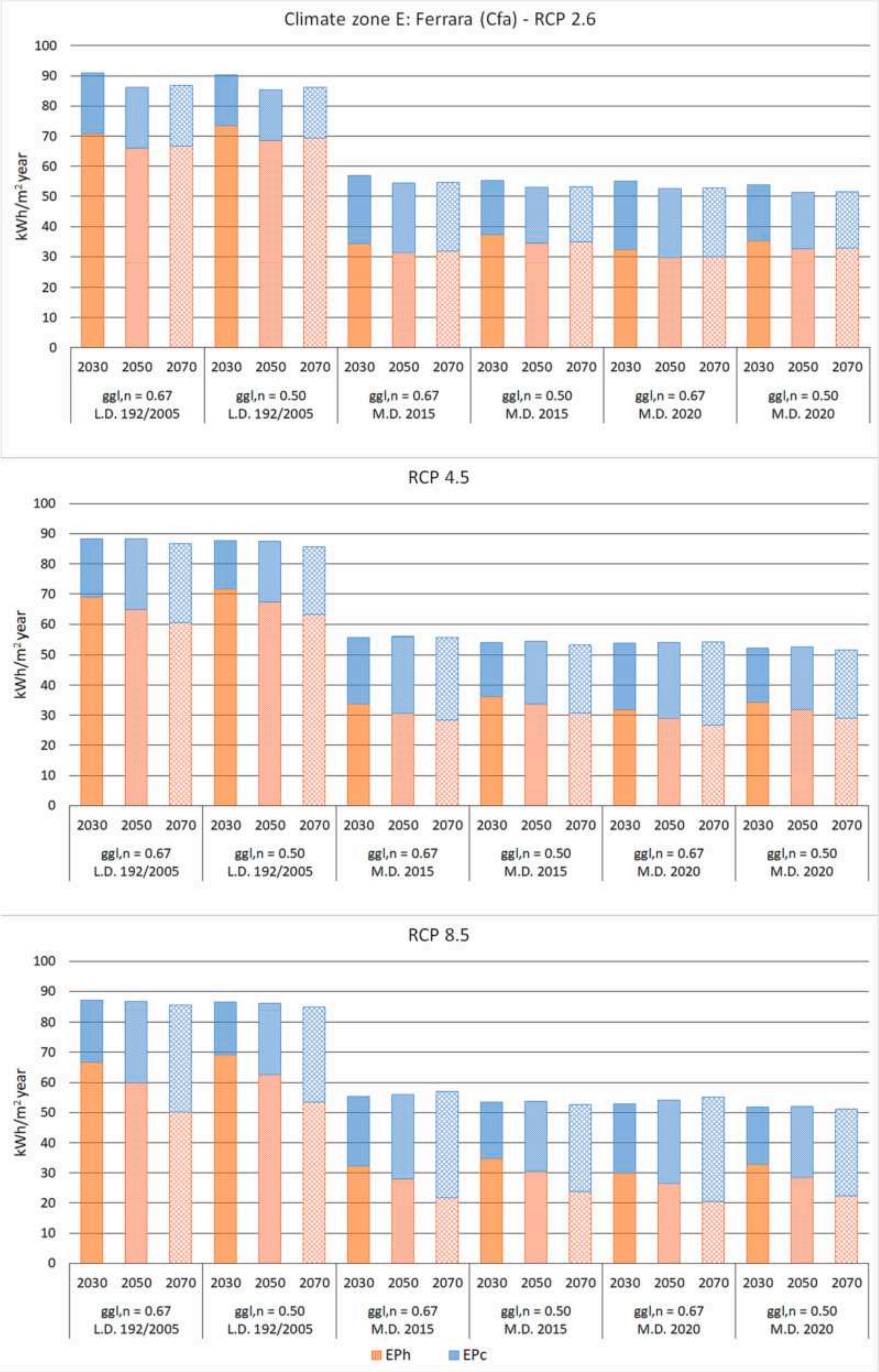


Fig. 8. Trends of the thermal performance indices over the years in climate zone E.

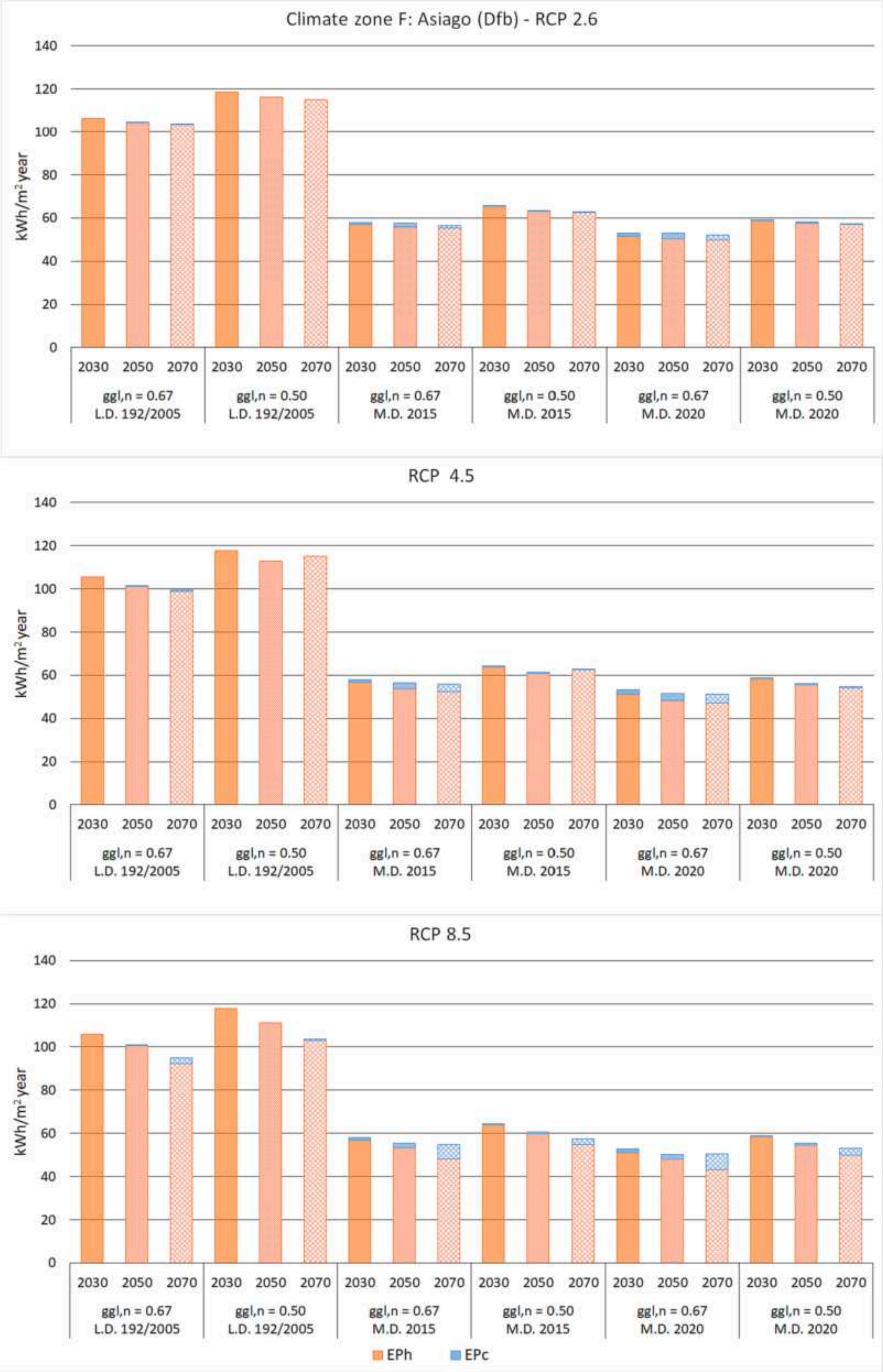


Fig. 9. Trends of the thermal performance indices over the years in climate zone F.

Table 7

Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zone BSh and BSk.

Italian zone	Koppen zone	City	Regulation	Year	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
					$g_{gl,n}$ 0.5			$g_{gl,n}$ 0.67		
A	BSh	Lampedusa	L.D. 192/2005	2030	6%	4%	8%	**12%**	10%	**14%**
				2050	8%	8%	**15%**	**15%**	**16%**	**25%**
				2070	8%	**11%**	**28%**	**15%**	**22%**	**40%**
			M.D. 26/6/2015	2030	**12%**	**10%**	**15%**	6%	5%	9%
				2050	**16%**	**18%**	**27%**	**10%**	**13%**	**21%**
				2070	**17%**	**23%**	**45%**	**11%**	**19%**	**37%**
			M.D. 6/8/2020	2030	**24%**	**22%**	**27%**	9%	7%	**12%**
				2050	**30%**	**32%**	**41%**	**14%**	**16%**	**24%**
				2070	**30%**	**38%**	**59%**	**14%**	**21%**	**40%**
D	BSk	Foggia	L.D. 192/2005	2030	4%	5%	2%	3%	4%	1%
				2050	5%	6%	6%	4%	5%	6%
				2070	7%	4%	6%	6%	4%	7%
			M.D. 26/6/2015	2030	3%	4%	2%	4%	5%	2%
				2050	5%	7%	8%	5%	7%	8%
				2070	8%	7%	**10%**	8%	7%	**15%**
			M.D. 6/8/2020	2030	5%	7%	4%	4%	5%	3%
				2050	7%	9%	**10%**	6%	7%	9%
				2070	10%	9%	**13%**	8%	**11%**	**16%**

be beneficial, allowing buildings to enhance resilience at a lower cost than alternative interventions. Intervening on $g_{gl,n}$ for buildings compliant with M.D. 26/06/2015 also results in a reduction of $EP_{tot,nd}$. Furthermore, it is advantageous to intervene on $g_{gl,n}$ in the RCP 8.5 scenario for buildings constructed according to L.D. 192/2005. In climate zone C, it is evident that the change in $g_{gl,n}$ has a comparable impact on all three standards.

In particular, when $g_{gl,n}$ is set to 0.50, the value of $EP_{c,nd}$ is lower than when it is set to 0.67. In contrast, for $EP_{h,tot}$, when $g_{gl,n}$ is set to 0.50, higher values are obtained than when it is set to 0.67. This observation applies to all three RCP scenarios. The effect of the variation of $g_{gl,n}$ is not significant for buildings with an envelope complying with L.D. 192/2005, but is more pronounced for buildings constructed according to M.D. 06/08/2020, especially considering the RCP 8.5 scenario. In climate zone D, it is observed that the influence of the variation of $g_{gl,n}$ is more pronounced in scenarios where buildings comply with M.D. 06/08/2020 and M.D. 26/06/2015. Implementing retrofitting measures to change $g_{gl,n}$ from 0.67 to 0.50 offers distinct benefits, enhancing the resilience of buildings with relatively lower costs than other interventions. Conversely, intervening on $g_{gl,n}$ for buildings complying with L.D. 192/2005 may result in minimal changes, making such interventions less significant. However, if the building under consideration is mainly used during winter, the benefits associated with interventions on $g_{gl,n}$ decrease. In climate zone E, it is not advisable to modify $g_{gl,n}$ to increase the resilience of the building. Such interventions result in minimal reductions in $EP_{tot,nd}$ and, in addition, lead to an undesirable increase in $EP_{h,nd}$ values. In climate zone F, interventions in $g_{gl,n}$ do not contribute to the resilience of the building, as they lead to an increase in both $EP_{h,nd}$ and $EP_{tot,nd}$ values between the scenario with $g_{gl,n}$ equal to 0.67 and that with $g_{gl,n}$ equal to 0.50.

Analysing climate change from 2020 to 2030, 2050, and 2070, it can be seen that the BSh zone shows the greatest increase in $EP_{tot,nd}$ over the years in all scenarios, exceeding 10 % in most cases. In the BSk zone, increases in $EP_{tot,nd}$ are present in all scenarios, but to a lesser extent than in BSh. In the Csa climate, increases in Ep are present in all scenarios, with a rather similar trend in all cities, except for Porto Empedocle, which shows a more marked worsening. Csb, Cfa, and Cfb show a mixed trend. Csb, Cfa, and Cfb show values between −10 and 10 % for L.D. 192/2005, with increases with subsequent decrees, due to the increase in outdoor temperature. Cfc shows only decreases in $EP_{tot,nd}$ and is the only area that shows decreases in all scenarios. Dfb shows a mixed behaviour of $EP_{tot,nd}$, but with values between −10 and 10 %. An increase in $EP_{tot,nd}$ is evident with $g_{gl,n}$ at 0.50, a decrease with $g_{gl,n}$ at 0.67. Dfc shows only decreases in $EP_{tot,nd}$, except for some small increases. In general, it is observed that buildings designed in accordance with L.D. 192/2005, compared to other regulations, show a smaller variation of $EP_{tot,nd}$ over time. Due to climate change, increased insulation in warm areas has contributed to an increase in overall annual consumption. Looking to the future, a reduction in transmission limits is expected to have adverse consequences. Variations in the results indicate how a building's energy performance is affected by climate scenarios and envelope standards. The results indicate that the resilience of the envelope to climate change shows a gradual dependence on the transmissivity of its components.

However, there does not seem to be a specific combination of values that ensures consistent performance as climatic conditions change. Consequently, effective regulatory planning must include a thorough assessment of future climatic conditions. The research suggests the importance of building envelope regulations in mitigating the impact of climate change on energy demand under different scenarios. The results seem valuable for making informed decisions regarding building design and energy efficiency measures to optimise energy performance under changing climate conditions.

The complex dynamics between buildings and climates require a multifaceted approach based on customised energy uses and climate considerations. Specific retrofitting or envelope improvements can be explored to achieve more substantial resilience improvements. With the continuous development in the field of climate-resilient buildings, future developments could focus on the integration of advanced materials and technologies as well as the implementation of data-driven strategies with innovative design techniques to optimise energy efficiency and improve the overall performance of buildings for dynamic adaptation to changing climatic conditions.

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CRediT authorship contribution statement

Paolo Maria Congedo: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original

Table 8

Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zones Csa and Csb.

Italian zone	Koppen zone	City	Regulation	Year	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
					$g_{gl,n}$ 0.5			$g_{gl,n}$ 0.67		
A	Csa	Porto Empedocle	L.D. 192/2005	2030	1%	3%	6%	5%	7%	**10%**
				2050	2%	7%	7%	7%	**13%**	**17%**
				2070	2%	6%	**18%**	7%	**14%**	**25%**
			M.D. 26/6/2015	2030	6%	8%	**12%**	2%	4%	7%
				2050	9%	**14%**	**18%**	4%	**10%**	**15%**
				2070	9%	**15%**	**29%**	5%	**12%**	**25%**
			M.D. 6/8/2020	2030	**14%**	**16%**	**20%**	3%	5%	8%
				2050	**17%**	**22%**	**28%**	6%	**11%**	**15%**
				2070	**18%**	**25%**	**43%**	6%	**13%**	**29%**
B	Csa	Siracusa	L.D. 192/2005	2030	-2%	1%	5%	-2%	0%	6%
				2050	-1%	3%	**12%**	-1%	5%	**14%**
				2070	3%	5%	**16%**	2%	7%	**18%**
			M.D. 26/6/2015	2030	-1%	1%	6%	0%	3%	8%
				2050	0%	8%	**16%**	2%	8%	**16%**
				2070	4%	9%	**20%**	6%	9%	**21%**
			M.D. 6/8/2020	2030	1%	6%	**10%**	0%	3%	7%
				2050	5%	**10%**	**19%**	2%	7%	**16%**
				2070	8%	**12%**	**24%**	5%	10%	**23%**
C	Csa	Lecce	L.D. 192/2005	2030	2%	2%	2%	3%	2%	2%
				2050	5%	2%	6%	6%	3%	8%
				2070	2%	2%	9%	3%	3%	**10%**
			M.D. 26/6/2015	2030	3%	3%	4%	4%	3%	3%
				2050	8%	5%	9%	7%	5%	9%
				2070	5%	5%	**12%**	5%	5%	**16%**
			M.D. 6/8/2020	2030	4%	3%	3%	5%	4%	4%
				2050	7%	4%	9%	9%	8%	**14%**
				2070	5%	5%	**16%**	6%	10%	**20%**
D	Csa	Rome	L.D. 192/2005	2030	4%	4%	3%	3%	3%	2%
				2050	2%	4%	5%	1%	4%	4%
				2070	1%	5%	9%	1%	5%	10%
				2030	4%	5%	4%	4%	5%	4%
			M.D. 26/6/2015	2050	4%	7%	8%	4%	8%	**12%**
				2070	4%	8%	**18%**	4%	**12%**	**20%**
			M.D. 6/8/2020	2030	4%	5%	4%	5%	6%	5%
				2050	4%	7%	9%	7%	**12%**	**14%**
				2070	4%	9%	**19%**	7%	**14%**	**23%**
E	Csa	Arezzo	L.D. 192/2005	2030	8%	2%	2%	**11%**	4%	5%
				2050	-1%	6%	2%	2%	7%	3%
				2070	2%	1%	2%	5%	2%	3%
			M.D. 26/6/2015	2030	9%	3%	3%	**10%**	4%	5%
				2050	0%	6%	3%	2%	8%	4%
				2070	3%	2%	6%	5%	3%	9%
			M.D. 6/8/2020	2030	9%	3%	3%	**11%**	5%	5%
				2050	0%	6%	3%	3%	9%	3%
				2070	3%	3%	6%	6%	2%	10%
D	Csb	Stazzema	L.D. 192/2005	2030	4%	2%	4%	4%	2%	3%
				2050	4%	3%	-1%	4%	3%	-1%
				2070	3%	-1%	2%	3%	0%	2%
			M.D. 26/6/2015	2030	3%	2%	4%	1%	-1%	0%
				2050	3%	3%	-1%	1%	3%	-1%
				2070	2%	-1%	6%	0%	-1%	5%
			M.D. 6/8/2020	2030	3%	1%	3%	0%	-1%	2%
				2050	3%	3%	1%	3%	3%	0%
				2070	2%	1%	7%	1%	0%	6%
E	Csb	Lagonegro	L.D. 192/2005	2030	-2%	0%	-3%	-2%	1%	-3%
				2050	-1%	-3%	-3%	-2%	-3%	-4%
				2070	-3%	-5%	-8%	-4%	-5%	-6%
			M.D. 26/6/2015	2030	1%	4%	0%	1%	4%	0%
				2050	2%	1%	1%	1%	0%	3%
				2070	0%	-2%	2%	-1%	1%	6%
			M.D. 6/8/2020	2030	0%	3%	0%	2%	4%	-1%
				2050	1%	0%	-1%	1%	1%	4%
				2070	-1%	-3%	1%	-1%	2%	6%

Table 9
Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zones Cfa, Cfb and Cfc.

Italian zone	Koppen zone	City	Regulation	Year	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
					$g_{gl,n}$ 0.5			$g_{gl,n}$ 0.67		
D	Cfa	Pescara	L.D. 192/2005	2030	3%	0%	-1%	3%	0%	-1%
				2050	0%	-1%	-1%	1%	1%	1%
				2070	0%	-2%	3%	1%	0%	4%
			M.D. 26/6/2015	2030	6%	2%	1%	4%	1%	0%
				2050	3%	3%	3%	2%	2%	3%
				2070	3%	2%	9%	2%	2%	9%
			M.D. 6/8/2020	2030	4%	1%	-1%	5%	2%	1%
				2050	2%	1%	2%	4%	3%	4%
				2070	1%	1%	8%	3%	3%	**11%**
E	Cfa	Ferrara	L.D. 192/2005	2030	4%	1%	0%	3%	0%	-2%
				2050	-1%	1%	-1%	-3%	0%	-2%
				2070	-1%	-1%	-2%	-2%	-2%	-4%
			M.D. 26/6/2015	2030	3%	1%	0%	3%	1%	0%
				2050	-1%	2%	0%	-2%	1%	1%
				2070	0%	0%	-2%	-1%	0%	3%
			M.D. 6/8/2020	2030	4%	1%	0%	3%	1%	-1%
				2050	-1%	2%	1%	-2%	1%	1%
				2070	0%	0%	-1%	-1%	2%	3%
D	Cfb	Farindola	L.D. 192/2005	2030	3%	6%	0%	1%	4%	-1%
				2050	1%	3%	8%	0%	2%	7%
				2070	5%	2%	4%	4%	1%	5%
			M.D. 26/6/2015	2030	2%	6%	0%	3%	6%	0%
				2050	2%	4%	9%	3%	5%	**10%**
				2070	5%	4%	8%	6%	5%	**12%**
			M.D. 6/8/2020	2030	3%	6%	1%	3%	6%	1%
				2050	3%	5%	**10%**	3%	6%	**13%**
				2070	6%	5%	**12%**	6%	8%	**13%**
E	Cfb	L'Aquila	L.D. 192/2005	2030	1%	0%	-2%	2%	1%	-1%
				2050	-3%	2%	2%	-2%	3%	3%
				2070	-1%	0%	0%	0%	2%	1%
			M.D. 26/6/2015	2030	3%	1%	0%	2%	1%	-1%
				2050	-2%	3%	3%	-2%	6%	7%
				2070	0%	-3%	10%	1%	7%	**12%**
			M.D. 6/8/2020	2030	3%	2%	1%	3%	3%	0%
				2050	-1%	3%	4%	2%	7%	9%
				2070	0%	2%	**11%**	3%	9%	**15%**
F	Cfb	Belluno	L.D. 192/2005	2030	-3%	-4%	-3%	0%	-2%	-1%
				2050	-4%	-2%	-5%	-2%	0%	-4%
				2070	-6%	-3%	-9%	-4%	-2%	-1%
			M.D. 26/6/2015	2030	0%	0%	0%	2%	1%	2%
				2050	1%	2%	-1%	2%	4%	0%
				2070	-2%	2%	2%	-1%	2%	4%
			M.D. 6/8/2020	2030	2%	1%	1%	**14%**	**13%**	**13%**
				2050	1%	3%	-1%	**13%**	**15%**	**12%**
				2070	-1%	1%	2%	**10%**	**16%**	**18%**
F	Cfc	Fenestrelle	L.D. 192/2005	2030	-6%	-6%	-6%	-7%	-7%	-7%
				2050	-7%	**-11%**	**-13%**	-9%	**-11%**	**-12%**
				2070	-8%	**-12%**	**-18%**	-9%	**-12%**	**-19%**
			M.D. 26/6/2015	2030	-5%	-4%	-4%	-4%	-4%	-4%
				2050	-5%	-8%	-9%	-5%	-6%	-8%
				2070	-6%	-8%	**-12%**	-6%	-6%	**-10%**
			M.D. 6/8/2020	2030	-4%	-4%	-4%	-5%	-4%	-4%
				2050	-5%	-7%	-8%	-5%	-6%	-6%
				2070	-6%	-8%	**-11%**	-6%	-5%	-9%

draft, Writing – review & editing, Visualization, Supervision. **Paola Maria Albanese:** Formal analysis, Investigation, Data curation, Writing – original draft. **Delia D'Agostino:** Formal analysis, Resources, Visualization, Writing – original draft, Writing – review & editing. **Cristina Baglivo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 10
Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zones Dfb and Dfc.

Italian zone	Koppen zone	City	Regulation	Year	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
					$g_{gl,n}$ 0.5			$g_{gl,n}$ 0.67		
F	Dfb	Asiago	L.D. 192/2005	2030	7%	6%	6%	2%	1%	1%
				2050	5%	2%	0%	0%	-3%	-3%
				2070	4%	4%	-7%	-1%	-5%	-9%
			M.D. 26/6/2015	2030	9%	7%	7%	1%	1%	1%
				2050	6%	2%	1%	1%	-2%	-3%
				2070	4%	4%	-4%	-1%	-3%	-4%
			M.D. 6/8/2020	2030	8%	7%	7%	1%	1%	1%
				2050	6%	2%	1%	1%	-2%	-4%
				2070	4%	0%	-3%	-1%	-2%	-4%
F	Dfc	Tarvisio	L.D. 192/2005	2030	-5%	-4%	-4%	-4%	-3%	-5%
				2050	-7%	-8%	-10%	-6%	-7%	-9%
				2070	-7%	**-12%**	**-14%**	-6%	**-11%**	-10%
			M.D. 26/6/2015	2030	-3%	-1%	-4%	-1%	1%	-2%
				2050	-4%	4%	-4%	-1%	-1%	-2%
				2070	-4%	-6%	-5%	-1%	-4%	-1%
			M.D. 6/8/2020	2030	-2%	0%	-2%	-1%	1%	-1%
				2050	-3%	-2%	-3%	-1%	0%	-1%
				2070	-3%	-5%	-4%	-2%	-3%	-1%

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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