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Relationship between shape and energy performance of buildings under long-term climate change

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A R T I C L E I N F O

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A B S T R A C T

The Mediterranean basin is projected to experience the most significant effects of global warming in Europe. As climate change intensifies, resulting in hotter and lengthier summers, there will be a substantial rise in the demand for cooling systems. This study investigates the influence of the surface-to-volume ratio (S/V) in mitigating the impact of climate change on energy performance in Italian buildings, highlighting its often-overlooked status in current research and methodologies. Three different S/V ratio are considered to evaluate the building thermal performance ($EP_{tot,nd}$) in compliance with the main Italian energy policies (issued in 2005, 2015, 2020) and three different representative Concentration Pathway (RCP) scenarios. The investigation encompasses all national climate zones in Italy. Results vary in relation to national climate zone (from A to F) and standards considered. When comparing $EP_{tot,nd}$ values in 2030 to the ones of 2050 and 2070, hot regions (Zones A, B and C) show an increase in $EP_{tot,nd}$, reaching a maximum of 20 %, with minimal differences in almost every scenario. The climate zone D displays a varied behavior in $EP_{tot,nd}$ demand, with a trend of reduction for smaller S/V ratios. In climatic zone E, the $EP_{tot,nd}$ demand varies; if there is an increase compared to 2030, it is slight (up to 10 %), and this increase is further mitigated with a low S/V ratio. The cold climate zone F shows a slight reduction in the demand for $EP_{tot,nd}$ in 2050 and 2070, compared to the values required in 2030.

Nomenclature

Ar	Argon -
Bsh	Hot semi-arid climate -
BSk	Cold semi-arid climate -
Cfa	Humid subtropical climate -
Cfb	Temperate oceanic climate -
Cfc	Subpolar oceanic climate -
Csa	Hot-summer Mediterranean climate -
Csb	Warm-summer Mediterranean climate -
d	Day -
D	Total number of days -
D.D.	Degree Days -

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Dfb	Warm-summer humid continental climate	-
Dfc	Subarctic climate	-
$EP_{c,nd}$	Cooling thermal performance index	kWh/m^2
$EP_{h,nd}$	Heating thermal performance index	kWh/m^2
EPS	Expanded polystyrene	-
$EP_{tot,nd}$	Total thermal performance index	kWh/m^2
h	Number of hours	-
HDD	Heating Degree Days	$^\circ$ C
IPCC	Intergovernmental Panel on Climate Change	-
Kr	Krypton	-
PVC	Polyvinyl chloride	-
R	Resistence	m^2K/W
RCP	Representative Concentration Pathway	-
S/V	Surface-to-volume building ratio	-
t	Thickness	cm
$T_{b,hs}$	Indoor temperature	$^\circ$C
$T_{e,h}$	External temperature	$^\circ$C
U_{lim}	Thermal transmittance limits	W/m^2K
U_{set}	Stationary thermal transmittance	W/m^2K
λ	Thermal conductivity	W/mK
ρ	Density	Kg/m^3

1. Introduction

The building sector constitutes over a third of global energy consumption, with many existing structures recognized for their high energy demands [1,2]. Buildings worldwide consume 40 % of energy and contribute 30 % of greenhouse gas emissions, with a significant environmental impact [3]. Efforts to enhance energy efficiency in buildings remain crucial, given their consumption of about a third of the world's primary energy resources.

Climate change, driven by human-induced greenhouse gas emissions, demands urgent global action, including emission reduction, enhanced energy efficiency, and sustainable practices. Buildings play a pivotal role in emissions and should prioritize energy efficiency through incentives, certifications, and sustainable standards to combat climate change, lower energy expenses, and foster sustainability [4–6].

Considering that buildings act as interface between the external and internal environments, providing safety and comfort to occupants, it is evident that climate change will significantly and deeply affect this sector [7], determining a higher demand for cooling and reduced need for heating [8]. The Mediterranean basin is projected to experience the most significant effects of global warming in Europe [9].

As climate change intensifies, resulting in hotter and lengthier summers, there will be a substantial rise in the demand for cooling systems, especially in densely populated areas [10]. Regrettably, despite evidence of climate change impact on buildings and energy systems [11], many energy analyses continue to prioritize current climate conditions, disregarding future climate scenarios.

1.1. The state of the arts

Achieving energy efficiency and thermal comfort in buildings largely depends on the design of an optimal building envelope [12]. Retrofitting buildings with energy-efficient techniques can offer significant benefits, including reducing heating demand and overall energy consumption while maintaining acceptable indoor climatic conditions [13]. A reduction in the stationary thermal transmittance U value of a building envelope does not always correspond to a decrease in energy performance, especially when taking into account prevailing or future climatic conditions [14,15].

Goia [16] emphasizes that Window-to-Wall Ratio (WWR) is a key factor that affects building resilience, suggesting increasing transparency in colder climates, contrary to traditional guidelines favoring smaller windows. This recommendation, considering all energy uses, aligns with findings showing north-facing facades tend to benefit from higher optimal WWR values. Chen et al. [17] underline the need for adaptable energy conservation models due to diverse regional climates and evolving energy standards, emphasizing the importance of exploring the relationship between climate change and urban building energy consumption.

Previous studies [18,19] have shown that building shape exerts a substantial influence on heating and cooling energy costs. In accordance with the observations of Monteiro et al. [20], building configuration can serve as a passive approach to cope with increased heating demand or to mitigate high cooling demand. In their research, Geraldi et al. [21] incorporate building shape as a variable in building energy benchmarking models. The classification of various building forms within the building stock has the potential to improve understanding of how the building envelope influences energy performance. Haseeb et al. evaluated a ten-story high-rise building and identified a T-shaped configuration at a 285° rotation angle as the most energy-efficient design, offering valuable guidance for future energy-conscious buildings in Kirkuk, Iraq [22]. Hachem et al. [23] explored the solar potential of different designs for two-story single-family houses in a mid-latitude climate, examining seven configurations (square, rectangular, trapezoidal, L-shaped, U-shaped, H-shaped, and T-shaped) to analyze their impact on shading and optimize solar exposure and energy efficiency.

Kocagil et al. [24] examined the impact of building shape and settlement structure on heating and cooling loads in traditional houses within a representative city in Turkey's hot-dry climate zone. By analyzing the design parameters, the study reveals the correlation between building form, settlement structure, and energy loads.

AlAnzi et al. [25] evaluated the impact of building shape on energy efficiency in Kuwaiti buildings. Through a comprehensive parametric analysis, it is found that building shape predominantly affects total energy consumption through three key factors: compactness, window-to-wall aspect ratio, and glazing type based on solar thermal gain coefficient.

1.2. Problem statement

This study emphasizes the crucial link between climate conditions and building performance, highlighting the oversight of climate change implications in setting building standards. It addresses the lack of research on the influence of climate change on building shapes, particularly focusing on the surface-to-volume ratio in Italian buildings, underlining its often-overlooked significance. By evaluating the impact of this ratio on residential buildings across varying Italian regulations and climate zones, this research aims to identify which form ratios better adapt to climate change. Additionally, it examines the effects of different regulatory constraints and future climate scenarios, using forecasted data up to 2070 based on Representative Concentration Pathways (RCPs) for climate zones in Italy.

2. Methodology

Seventeen Italian locations, belonging to distinct climatic zones, were selected. The identification of the locations was based on both national classifications and the Köppen-Geiger classification zones. In designing the envelope of the buildings under examination, three different Italian regulatory limits were considered, according to Legislative Decree 192/2005 (L.D. 192/2005), Ministerial Decree of June 26, 2015 (M.D. June 26, 2015), and Ministerial Decree of August 6, 2020 (M.D. August 06, 2020). Additionally, the envelope performance was calculated considering thermal performance indices for the years 2030, 2050, and 2070, each with respect to three different RCP scenarios (2.6, 4.5, and 8.5). The S/V values, used as the basis for the construction of the buildings in question, were taken from the Ministerial Decree of June 26, 2015 (D.M. June 26, 2015).

2.1. Geographical-climatic Italian description

In Italy, the distinction of climate zones relies on HDD, as defined by UNI EN ISO 15927–6:2008 [26], which calculates the sum of positive differences between indoor (set at 20 °C) and outdoor temperatures (only if positive) over the entire year. HDD can be calculated using the following formula [27]:

$$HDD = \sum_{d=1}^{D} \left(\frac{1}{24} \sum_{h=1}^{24} \left(T_{b,hs} - T_{e,h} \right)^{+} \right)_{d} \tag{1}$$

where

$T_{b,hs}$ is the indoor temperature

$T_{e,h}$ is the extHernal temperature

d is the day

D is the total number of days.

Italy is divided into six climatic zones, denoted by the letters A to F, as shown in Table 1.

2.2. The Italian regulatory context

This research deepened the impact of three key Italian regulatory limits on building design: Legislative Decree 192/2005 (D.L. 192/2005) [28], the Ministerial Decree of June 26, 2015 (D.M. June 26, 2015) [29], and the 7Ministerial Decree of August 6, 2020 (D.M. August 06, 2020) [30]. These regulations imposed the limits on the stationary thermal transmittance depending to each national climate zone.

Legislative Decree 192/2005, effective from January 1, 2006, mandated the verification of thermal transmittance limits for new buildings across all uses, excluding horizontal elements and industrial building windows. Although the decree introduced additional transmittance limits for tax renovation deductions, they were not mandatory and were not considered.

The Ministerial Decree of June 26, 2015 introduced the concept of a 'reference building,' mirroring the geometry, orientation,

Table 1
Italian climate zones and relative Heating Degree Days value.

Italian climate zones	Heating Degree Days
A	HDD ≤600
B	600< HDD ≤900
C	900< HDD ≤1400
D	1400< HDD ≤2100
E	2100< HDD ≤3000
F	HDD >3000

thermal characteristics, and energy parameters of the building under consideration. The transmittance limits for the reference building aligned with those effective from January 1, 2019, for public buildings and from January 1, 2021, for residential buildings.

The most recent decree, M.D. August 06, 2020, specified limit values for tax renovation deductions in residential buildings, exhibiting a notable reduction in comparison with L.D. 192/2005 and M.D. June 26, 2015. Table 2 shows the thermal transmittance limits (U_{lim}) imposed by the three different regulations for each climate zone.

As stated by Congedo et al., strategic envelope design can effectively regulate internal temperatures in Mediterranean buildings without relying on cooling systems [31].

2.3. Characteristics of the selected cities

This work centers its attention on the choice of Italian locations that encompass the full range of climate zones found in Italy. This selection considers both the national climate classification and the Köppen-Geiger climate classification [32,33]. The selected locations are reported in Fig. 1.

Seventeen locations were selected to represent a comprehensive range of both Köppen-Geiger and national climates in Italy. The first choice was on provincial capitals; in cases where a specific climate type did not include a provincial capital, alternative cities within that climate zone were chosen. The analyses of the external temperatures are conducted based on the projected RCP scenarios for the years 2030, 2050, and 2070. This study considers three IPCC RCP scenarios for the 21st century: RCP2.6 (ambitious emission reductions), RCP4.5 (intermediate stabilization), and RCP8.5 (high-emission). While initial differences (until about 2050) between scenarios may be small, they become more pronounced over time, leading to varying impacts and consequences in the latter half of the century, according to the IPCC [34].

Climate data are sourced from Meteonorm [35,36] which is a climate database widely employed in literature [34]. Meteonorm files compile data from several meteorological stations all over the world, encompassing monthly averages of eight key parameters: ambient air temperature, precipitation and precipitation days, humidity, wind speed and direction, sunshine duration, global irradiance [37]. Climate data were exported for three distinct timeframes (2030, 2050, and 2070) and three Representative Concentration Pathway (RCP) scenarios (2.6, 4.5, and 8.5).

The Supplementary Data 01 presents monthly temperature data for the years 2030, 2050, and 2070, encompassing all selected locations. Between 2030 and 2070, there is a notable increase in monthly average temperatures, particularly evident under RCP 8.5. Maximum temperatures experience a more significant rise than minimum temperatures in most locations, with RCP 8.5 demonstrating the widest variation. The transition from climate zone A to E witnesses a substantial temperature increase, and Zones F and E exhibit the most prominent temperature differences between 2030 and 2070, particularly pronounced under RCP 8.5.

2.4. Description three reference buildings

This section defines the characteristics of the reference building. Even though it is widely known that each locality has its own traditional architecture, the comparison would be less effective if a differentiation between various types of structures were be considered. For this reason, for each location it was chosen the same building model, characterized by reinforced concrete insulated walls. This prototype can be considered a common choice for designers in many Italian climate zones, thanks to its capability to face difficult weather conditions and offer a secure and comfortable environment for residents at a minimal construction expense. The analysis concentrates on the building envelope in absence of air conditioning. The characteristic of the envelope satisfies energy regulations of each Italian climate zone. Though the outcomes pertain to this building type, its simplicity enables cross-comparisons with numerous other structures within the region. The resultant trends can function as a standard of comparison for analogous forms of

Table 2
Thermal transmittance limits imposed by the three different regulations.

Climate Zones	Regulations	U_{lim} [W/m^{2}K]			
		Wall	Roof	Floor	Window
A	L.D. 192/2005	0.85	0.80	0.80	5.50
	M.D. 2015	0.43	0.35	0.44	3.00
	M.D. 2020	0.38	0.27	0.40	2.60
B	L.D. 192/2005	0.64	0.60	0.60	4.00
	M.D. 2015	0.43	0.35	0.44	3.00
	M.D. 2020	0.38	0.27	0.40	2.60
C	L.D. 192/2005	0.57	0.55	0.55	3.30
	M.D. 2015	0.34	0.33	0.38	2.20
	M.D. 2020	0.30	0.27	0.30	1.75
D	L.D. 192/2005	0.50	0.46	0.46	3.10
	M.D. 2015	0.29	0.26	0.29	1.80
	M.D. 2020	0.26	0.22	0.28	1.67
E	L.D. 192/2005	0.46	0.43	0.43	2.80
	M.D. 2015	0.26	0.22	0.26	1.40
	M.D. 2020	0.23	0.20	0.25	1.30
F	L.D. 192/2005	0.44	0.41	0.41	2.40
	M.D. 2015	0.24	0.20	0.24	1.10
	M.D. 2020	0.22	0.19	0.23	1.00

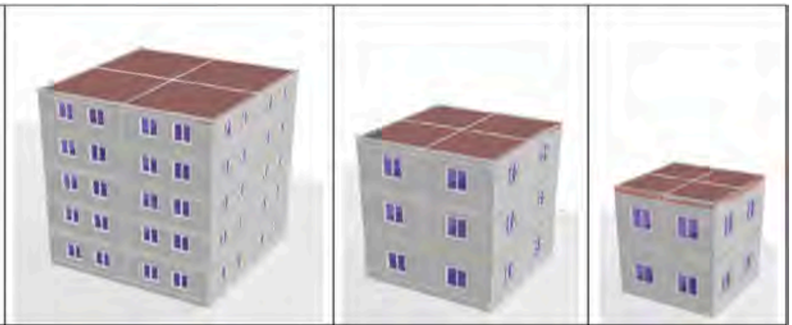
Fig. 1. Mapping of the selected locations.

construction.

As shown in Fig. 2, three cubic-shaped reference buildings with different surface-to-volume ratios were analysed. The construction of the study's buildings adhered to values ensuring surface-to-volume (S/V) ratios closely aligned with those specified in the national Ministerial Decree of June 26, 2015.

The materials of which the envelope is composed are the same for all three buildings. Table 3 presents the thermal characteristics of each layer. The provided information includes the thickness (t), thermal conductivity (λ), and density (ρ) of each layer within the opaque envelope. To achieve the required transmittance values specified by the three regulatory limits, only the insulation thickness (EPS) has been adjusted. The range of thickness variations (d) is indicated in yellow. The thermal transmittance of the floor on the ground has been calculated using the analytical method suggested by the UNI 11300–1:2014 [38]. In particular, the floor is built directly on a gravel soil of thermal conductivity of 2 W/mK.

The insulation thickness of the opaque envelope, the characteristics of the windows, and consequently the stationary thermal transmittance (U_{set}), are determined for each climate zone in order to closely align with the thermal transmittance limits (U_{lim}) imposed by the three regulations (reported in Table 2) for each respective climate zone, as detailed in Table 4. The window design



S/V	≃0.35	≃0.55	≃0.75
Heat loss surface S [m^2]	1622.04	662.12	338.97
Heated gross volume V [m^3]	4632	1237.36	468.73
Heated usable floor area [m^2]	1264.05	294.03	95.22
Total external height [m]	17	11	8
Net internal floor height [m]	2.8	3	3.25
Gross floor width [m]	17	11	8
Gross floor length [m]	17	11	8
Gross floor area [m^2]	289	121	64
Number of Floors	5	3	2

Fig. 2. Representation of the three reference buildings.

Table 3
Thermal characteristics of opaque envelope.

Layers (from inside to outside)		t [cm]	λ [W/mK]	ρ [Kg/m^3]	R [m^{2}K/W]
Roof	*Internal thermal resistance*				0.1
	Plaster	1	0.700	1400	
	Floor block with *in-situ* lightning elements	26	0.743	1800	
	Vapour barrier	0.05	0.400	360	
	Expanded polystyrene (EPS)	2–16	0.033	24	
	Bituminous waterproofing membrane	0.5	0.170	1200	
	Concrete	10	0.940	1800	
	Cement-mortar substrate	1	1.400	2000	
	Ceramic-porcelain tiles	1	1.300	2300	
	Outside thermal resistance				0.04
External walls	*Internal thermal resistance*				0.13
	Plaster	1	0.700	1400	
	Brick blocks	25	0.400	1000	
	Expanded polystyrene (EPS)	2–13	0.033	24	
	Plaster	1	0.900	1800	
	Outside thermal resistance				0.04
Floor on the ground	*Internal thermal resistance*				0.17
	Tiles	1	1.000	2300	
	Cement mortar	1	1.400	2000	
	Concrete slab	8	1.060	1700	
	Vapour barrier	0.05	0.400	360	
	Expanded polystyrene (EPS)	1–8	0.033	24	
	Bituminous waterproofing membrane	0.5	0.170	1200	
	Reinforced concrete	8	1.910	2400	
	Under-floor cavity with ventilated interspace	20	1.390	1200	
	Lean concrete	8	1.000	2200	
	Coarse gravel without clay	15	1.200	1700	

aligns with Article 5 of the Italian Ministerial Decree of 1975, ensuring adequate natural lighting for rooms in dwellings except for specific areas like bathrooms and corridors. Window size of each living space complies to maintain an average daylight factor of at least 2%, with the operable window area set at a minimum of 1/8 of the floor area for the entire building. The study focused on design elements, excluding manual operations like opening and closing blinds, which are individual preferences. Automatic closure of blinds at night for 12 h followed guidelines recommended by UNI TS 11300-1 [38] for residential buildings, implemented uniformly across all locations. Table 4 summarizes the characteristics of the windows used.

Table 5 reports a summary of the specifications for the transparent envelope, in terms of.

- cavity gas options: Argon (Ar) or Krypton (Kr)
- glass stratigraphy: single (1), double (2), or triple (3) glazing
- number of air chambers in the frame
- variations in glass coating (normal or Low-e), "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 calculation of the free internal gains and thermal performance indices are carried out according to UNI TS 11300-1 [38]. Energy analyses are conducted utilizing the certified software simulation tool Termolog 13 [39]. This software is widely employed in the realm of research [40,41], and it is widely used by Italian designers for conducting thermal certifications and energy performance assessments of buildings [42,43]. The Italian Thermo-technical Committee (CTI) acknowledges and officially certifies the utilization of this software.

Table 4
Characteristics of the windows.

Windows per floor	S/V	Number
	0.75	8
	0.55	8
	0.35	16
Windows dimensions	Width [cm]	Lenght [cm]
	150	160
Frame	Type	Thickness [cm]
	PVC	6
Vertical partition [cm]	10	
Shutters	Pastel-colored	
	Exterior	
Blinds	Automatic	
	Alluminum	
	Night closure: 8 p.m.- 8 a.m.	

Table 5
Envelope settings for each climate zone and regulation.

Climate Zones	Regulations	Insulation thickness set [cm]			Features of windows set				U_{set} [W/m^{2}K]			
		Wall	Roof	Floor	Cavity gas	N. of Glass	N. chambers	Coating	Wall	Roof	Floor	Window
A	L.D. 192/2005	2	2	1	–	1	2	normal	0.701	0.785	0.466	5.014
	M.D. 2015	5	8	2	Ar	2	2	normal	0.428	0.323	0.406	2.782
	M.D. 2020	6	10	3	Ar	2	6	normal	0.379	0.270	0.359	2.534
B	L.D. 192/2005	3	4	2	Ar	2	2	normal	0.578	0.532	0.406	2.782
	M.D. 2015	5	8	2	Ar	2	2	normal	0.428	0.323	0.406	2.782
	M.D. 2020	6	10	3	Ar	2	6	normal	0.379	0.270	0.359	2.534
C	L.D. 192/2005	4	4	2	Ar	2	2	normal	0.492	0.532	0.406	2.782
	M.D. 2015	7	8	3	Ar	2	2	low-e 1	0.340	0.323	0.359	1.825
	M.D. 2020	9	10	5	Ar	2	2	low-e 2	0.282	0.270	0.289	1.727
D	L.D. 192/2005	4	5	2	Ar	2	2	normal	0.492	0.458	0.406	2.782
	M.D. 2015	9	11	5	Ar	2	3	low e 1	0.282	0.250	0.289	1.783
	M.D. 2020	10	13	6	Ar	2	5	low e 1	0.260	0.217	0.266	1.584
E	L.D. 192/2005	5	6	2	Ar	2	2	normal	0.428	0.402	0.406	2.782
	M.D. 2015	11	13	7	Ar	3	6	low-e 1	0.241	0.217	0.246	1.319
	M.D. 2020	12	15	7	Ar	3	3	low-e 2	0.224	0.192	0.246	1.287
F	L.D. 192/2005	5	6	2	Ar	2	2	low-e 1	0.428	0.402	0.406	1.825
	M.D. 2015	12	15	8	Kr	3	6	low-e 1	0.224	0.192	0.229	1.054
	M.D. 2020	13	16	8	Kr	3	6	low-e 2	0.210	0.181	0.229	0.843

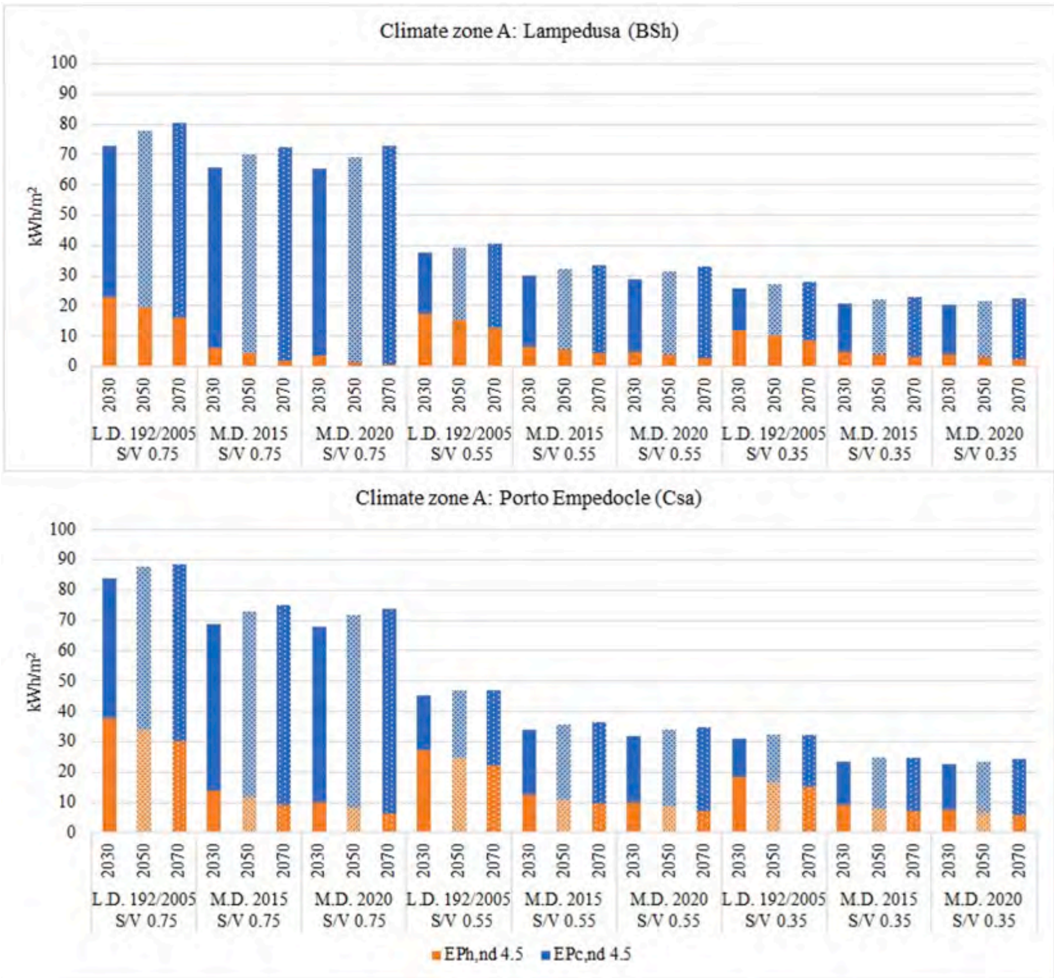


Fig. 3. Thermal performance indices for climate zone A.

The evaluation of building performance, under various conditions and climatic scenarios, has been conducted based on thermal performance indices [kWh/m^2], namely.

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

3. Results and discussions

This section illustrates, through stacked column charts, the results of the simulations for all climate zones, considering the intermediate stabilization scenario RCP 4.5. The complete results, relative to all scenarios, are reported in Supplementary Data 02 and discussed in Overall considerations (subparagraph 3.7).

3.1. Climate zone A

Fig. 3 illustrates the thermal performance indices for the climate zone A. The obtained graphs reveal the following trends.

- for Lampedusa, buildings constructed under the L.D. 192/2005 show a reduction of approximately 47 % in $EP_{h,nd}$ between S/V of 0.75 and 0.35 for all years, while the ones constructed under M.D. June 26, 2015 and M.D. August 06, 2020 result in an increase in $EP_{h,nd}$ for all year. Porto Empedocle experiences consistent reductions in $EP_{h,nd}$ for all years and all regulations, between the S/V of 0.75 and 0.35. The greatest decrease occurring in the L.D. 192/2005 regulation in 2030, representing a 51.75 % reduction between the S/V of 0.75 and 0.35. The variations between S/V ratio of 0.55 and S/V ratio of 0.35 are less pronounced for both locations.
- Significant reductions in $EP_{c,nd}$ values are observed for both locations when comparing S/V of 0.75 and 0.35 across all three regulations, with the most substantial reductions of 72.19 % in Lampedusa, for buildings constructed under the M.D. August 06, 2020 in 2070, and of 73 % in Porto Empedocle, for buildings constructed under the M.D. June 26, 2015 in 2030. The differences between the S/V ratios of 0.55 and 0.35 are less conspicuous.
- Significant reductions in $EP_{tot,nd}$ value are observed for both locations when comparing S/V ratios of 0.75 and 0.35 across all three regulations and for each year.

3.2. Climate zone B

Fig. 4 illustrates the thermal performance indices for climate zone B. The obtained graphs reveal the following trends.

- regarding the $EP_{h,nd}$, the values obtained for buildings with S/V of 0.35 are lower than those obtained for buildings with S/V of 0.75 for all three regulations and across all three years. The most significant variation is observed in the case of the L.D. 192/2005 in the year 2030 (42.59 %).
- significant reductions in $EP_{c,nd}$ value are observed when comparing S/V of 0.35 with the other ones, across all three regulations, with the most substantial reductions of approximately 72 % for buildings constructed under the M.D. August 06, 2020 in 2070.
- Significant reductions in $EP_{tot,nd}$ values are observed when comparing S/V of 0.75 and 0.35 across all three regulations and for each year.

3.3. Climate zone C

Fig. 5 displays the thermal performance indices for the climate zone C. The analysis results in graphs that reveal the following

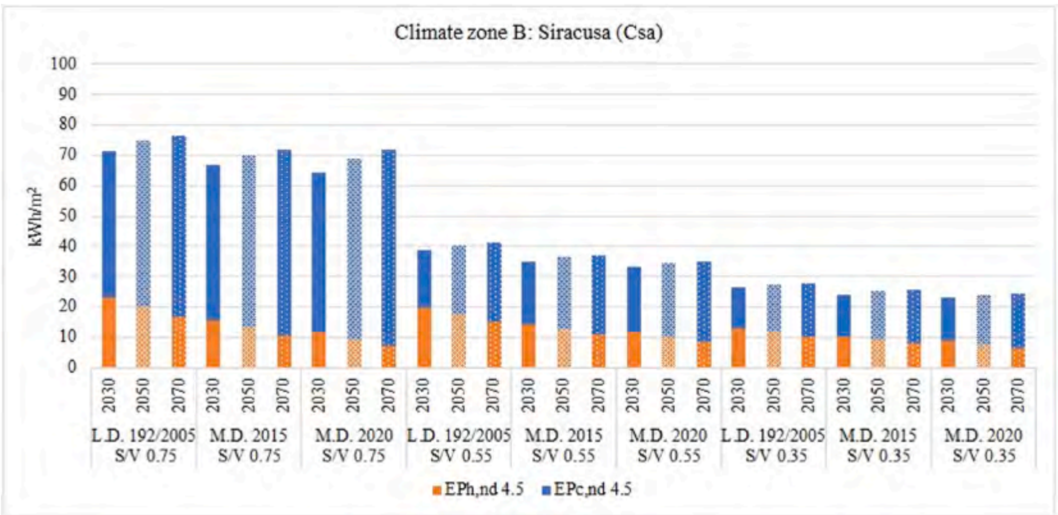


Fig. 4. Thermal performance indices for climate zone B.

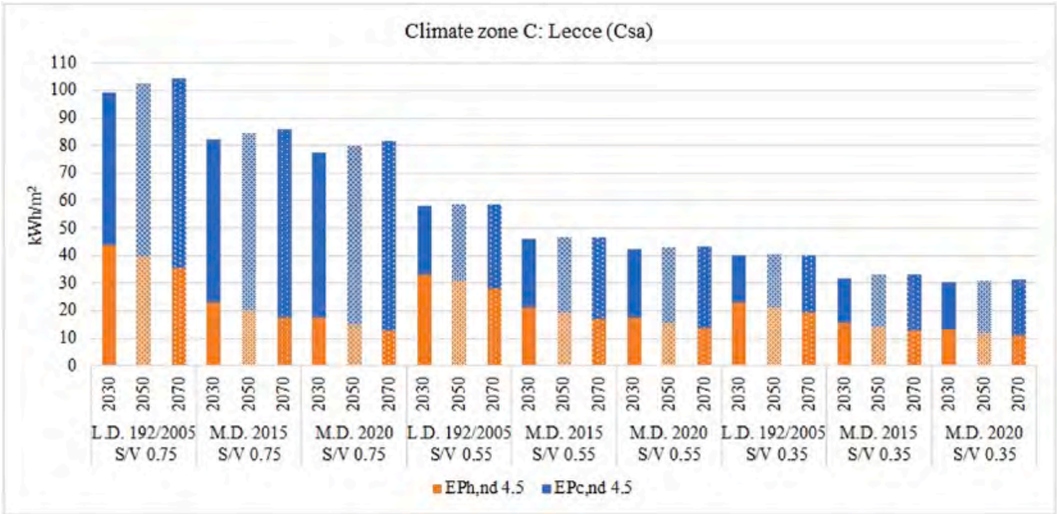


Fig. 5. Thermal performance indices for climate zone C.

trends.

- Regarding $EP_{h,nd}$, when comparing the values obtained with S/V of 0.75 and S/V of 0.35, a reduction is observed for all cases. The most substantial reduction is obtained for the L.D. 192/2005 case in the year 2030 (47.24 %).
- Similarly, the $EP_{c,nd}$ also tends to decrease when comparing the results obtained with S/V of 0.75 and S/V ratio of 0.35 for all three regulations. The most significant reduction (71.56 %) is observed in the comparison between the S/V values of 0.75 and 0.35 for the M.D. August 06, 2020 in the year 2030.
- significant reductions in $EP_{tot,nd}$ value are observed when comparing S/V ratios of 0.75 and 0.35 across all three regulations and for each year.

3.4. Climate zone D

Fig. 6 exhibits the thermal performance indices for locations within climate zone D. The obtained graphs reveal the following trends.

- when comparing the values obtained with S/V ratios of 0.75 and 0.35, considering the three regulations and the three years (2030, 2050, 2070), a reduction in the $EP_{h,nd}$ value is observed for all cities. Particularly, the most noticeable reduction is obtained for the L.D. 192/2005 in 2030, with reductions of 48.76 % for Foggia, 49.25 % for Pescara, 49.60 % for Farindola, 45.38 % for Roma, and 50.18 % for Roma.
- When comparing the values obtained with S/V ratios of 0.75 and 0.35, considering the three regulations and the three years (2030, 2050, 2070), a reduction in the $EP_{c,nd}$ value is observed for all cities. The most pronounced reduction is obtained for the year 2030, considering the M.D. August 06, 2020 regulation (72.78 % for Foggia, 75.88 % for Pescara, 72.45 % for Farindola, 71.70 % for Roma, 79.92 % for Stazzema).
- Significant reductions in $EP_{tot,nd}$ are observed when comparing S/V of 0.75 and 0.35 across all three regulations and for each year.

3.5. Climate zone E

Fig. 7 presents the thermal performance indices for locations within climate zone E. The obtained graphs reveal the following trends.

- regarding the $EP_{h,nd}$, when considering the values with S/V of 0.75 and 0.35, a significant reduction in its value is observed. The most pronounced reduction is obtained for the year 2030, considering the L.D. 192/2005 for all cities considered (50.65 % for Ferrara, 48.54 % for L'Aquila, 49.49 % for Arezzo, 51.40 % for Lagonegro).
- For the $EP_{c,nd}$ as well, considering the values with S/V of 0.75 and 0.35, a significant reduction in its value is obtained for all regulations. For Ferrara, the greatest reduction is obtained in the year 2030, considering a building constructed according to the M. D. June 26, 2015 regulation. For L'Aquila and Arezzo, the highest values are achieved for the M.D. August 06, 2020 regulation in the year 2030 (with values of 72.50 % and 74.72 % respectively). For Lagonegro, the most substantial reduction is obtained for the year 2030, considering the L.D. 192/2005 regulation (88.97 %).

3.6. Climate zone F

Fig. 8 displays the thermal performance indices for locations within climate zone F. The obtained graphs reveal the following trends.

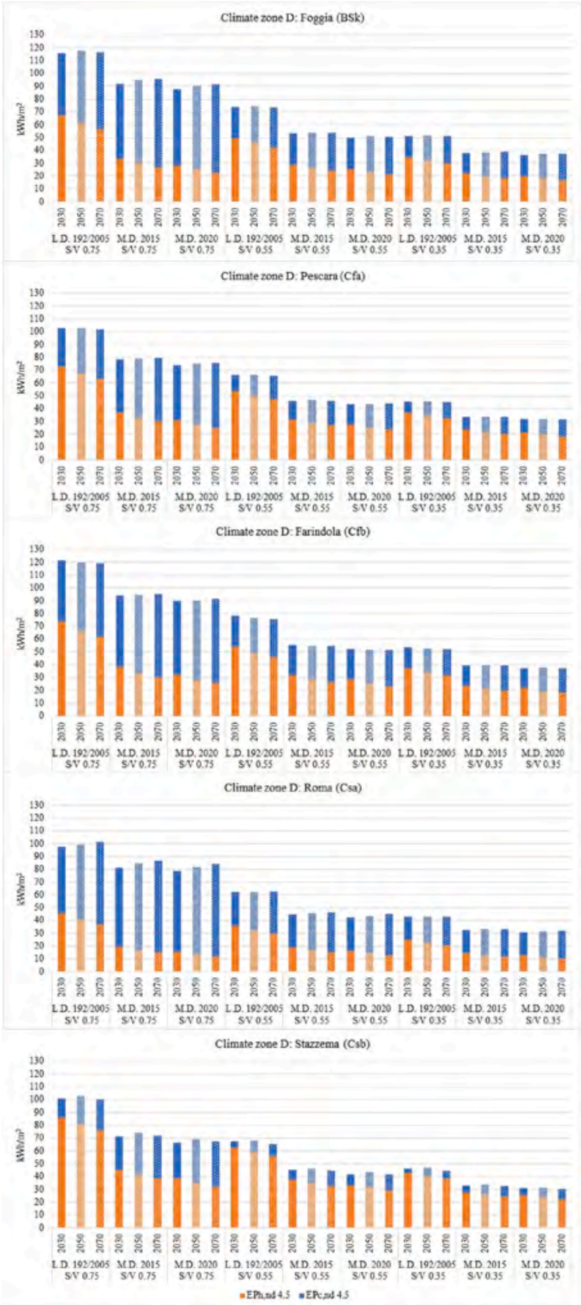


Fig. 6. Thermal performance indices for climate zone D.

- In relation to $EP_{h,nd}$, a substantial reduction is observed when comparing S/V of 0.75 and 0.35. The most significant decrease is obtained for the year 2030, adhering to the L.D. 192/2005 regulation, for all cities considered (48.06 % for Belluno, 50.85 % for Fenestrelle, 51.92 % for Asiago, 50.59 % for Tarvisio).
- For the $EP_{c,nd}$ as well, considering the values with S/V of 0.75 and 0.35, a significant reduction in its value is obtained for all regulations. For Belluno and Fenestrelle, the most substantial reduction is observed in 2030, considering buildings constructed according to the M.D. August 06, 2020 (78.47 % and 91.11 % respectively). For Asiago, the highest values are obtained for the M.D. June 26, 2015 in 2030. For Tarvisio, the most substantial reduction is obtained in 2030, adhering to the L.D. 192/2005 regulation (88.67 %).
- Significant reductions in $EP_{tot,nd}$ value are observed when comparing S/V of 0.75 and 0.35 across all three regulations and for each year.

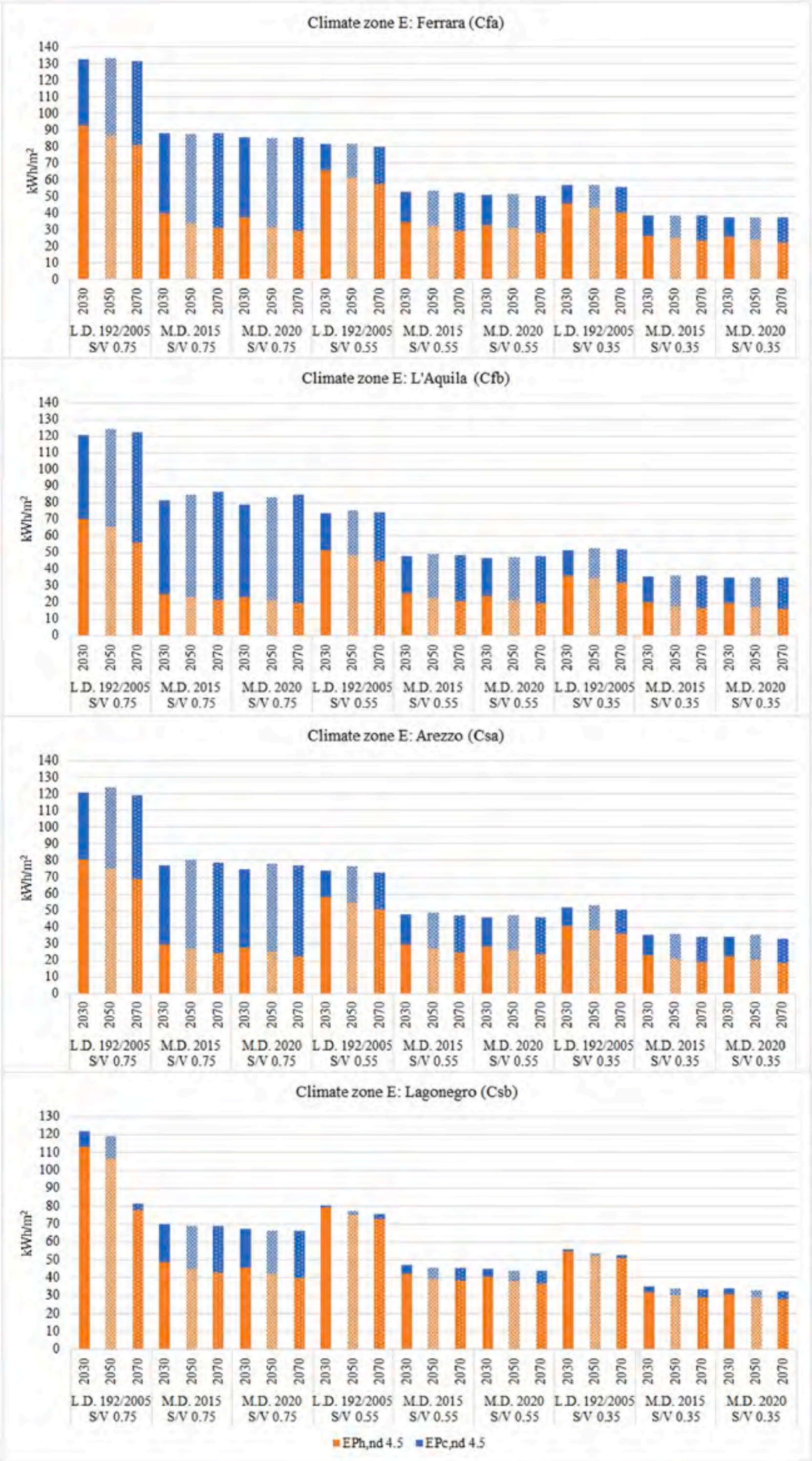


Fig. 7. Thermal performance indices for climate zone E.

3.7. Overall considerations

Tables 6–9 show the percentage variation in $EP_{tot,nd}$ from 2030 to 2050 and 2070 for all RCP scenarios and regulations, considering the effect of different S/V values. Results are grouped according to the Koppen-Geiger climate classification. Positive values represent

Fig. 8. Thermal performance indices for climate zone F.

an increase of $EP_{tot,nd}$ over the years. In light orange is indicated a slight increase (between 0 and 10 %), in orange is indicated a large increase (i.e. greater than 10 %). In light green is indicated a slight decrease (between 0 and -10 %), in green is indicated a large decrease (i.e. less than −10 %).

Table 6
Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zones Csa and Csb.

Italian climate zone	Koppen climate classification	City	S/V	Regulations	RCP 2.6		RCP 4.5		RCP 8.5	
					ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070
A	Csa	Porto Empedocle	0.75	L.D. 2005	4%	2%	4%	5%	5%	13%
				M.D. 2015	3%	4%	6%	9%	7%	19%
				M.D. 2020	4%	4%	6%	9%	12%	25%
			0.55	L.D. 2005	1%	1%	4%	4%	4%	12%
				M.D. 2015	2%	3%	5%	7%	6%	16%
				M.D. 2020	3%	4%	6%	8%	7%	17%
			0.35	L.D. 2005	1%	1%	4%	4%	4%	11%
				M.D. 2015	2%	3%	5%	6%	5%	17%
				M.D. 2020	3%	3%	5%	9%	5%	18%
B	Csa	Syracuse	0.75	L.D. 2005	2%	5%	5%	7%	8%	14%
				M.D. 2015	3%	6%	5%	8%	8%	19%
				M.D. 2020	3%	6%	7%	11%	12%	21%
			0.55	L.D. 2005	1%	5%	4%	6%	9%	12%
				M.D. 2015	5%	9%	4%	5%	7%	11%
				M.D. 2020	2%	6%	4%	6%	7%	13%
			0.35	L.D. 2005	1%	5%	3%	4%	7%	11%
				M.D. 2015	2%	5%	6%	7%	-9%	13%
				M.D. 2020	4%	7%	4%	6%	-7%	12%
C	Csa	Lecce	0.75	L.D. 2005	5%	2%	3%	5%	9%	13%
				M.D. 2015	4%	2%	3%	4%	7%	10%
				M.D. 2020	4%	2%	3%	5%	7%	12%
			0.55	L.D. 2005	3%	0%	1%	0%	4%	7%
				M.D. 2015	3%	1%	2%	2%	5%	8%
				M.D. 2020	3%	1%	2%	2%	5%	12%
			0.35	L.D. 2005	3%	0%	1%	0%	4%	8%
				M.D. 2015	3%	3%	3%	4%	7%	10%
				M.D. 2020	5%	3%	2%	2%	5%	8%
D	Csa	Rome	0.75	L.D. 2005	-1%	-1%	2%	4%	3%	12%
				M.D. 2015	1%	1%	4%	7%	7%	16%
				M.D. 2020	1%	1%	4%	7%	7%	17%
			0.55	L.D. 2005	-2%	-2%	1%	1%	2%	6%
				M.D. 2015	-1%	-1%	2%	3%	4%	13%
				M.D. 2020	0%	0%	2%	6%	5%	14%
			0.35	L.D. 2005	-2%	-2%	0%	1%	2%	7%
				M.D. 2015	1%	1%	2%	3%	4%	9%
				M.D. 2020	-1%	-1%	2%	3%	4%	11%
E	Csa	Arezzo	0.75	L.D. 2005	-8%	-5%	3%	-1%	-1%	-1%
				M.D. 2015	-6%	-4%	5%	3%	2%	11%
				M.D. 2020	-6%	-4%	5%	3%	3%	11%
			0.55	L.D. 2005	-8%	-4%	3%	-2%	-1%	0%
				M.D. 2015	-8%	-6%	2%	-1%	0%	3%
				M.D. 2020	-7%	-5%	2%	-1%	1%	3%
			0.35	L.D. 2005	-8%	-5%	2%	-2%	-1%	-1%
				M.D. 2015	-7%	-5%	3%	-3%	-3%	-1%
				M.D. 2020	-7%	-5%	3%	-3%	-3%	0%
D	Csb	Stazzema	0.75	L.D. 2005	0%	-1%	2%	-1%	-2%	3%
				M.D. 2015	1%	0%	4%	1%	-1%	7%
				M.D. 2020	2%	0%	4%	2%	0%	10%
			0.55	L.D. 2005	-1%	-1%	0%	-3%	-4%	-1%
				M.D. 2015	0%	-1%	2%	-2%	-3%	3%
				M.D. 2020	0%	-1%	4%	0%	-1%	5%
			0.35	L.D. 2005	0%	-1%	1%	-3%	-4%	0%
				M.D. 2015	0%	-1%	2%	-2%	-3%	2%
				M.D. 2020	1%	-1%	2%	-2%	-3%	3%
E	Csb	Lagonegro	0.75	L.D. 2005	-1%	-4%	-2%	-33%	0%	-1%
				M.D. 2015	0%	-3%	-2%	-1%	3%	3%
				M.D. 2020	0%	-3%	-2%	-1%	3%	4%
			0.55	L.D. 2005	-2%	-4%	-4%	-6%	-3%	-7%
				M.D. 2015	-1%	-4%	-3%	-4%	1%	-1%
				M.D. 2020	-1%	-4%	-3%	-3%	1%	0%
			0.35	L.D. 2005	-2%	-4%	-4%	-6%	-3%	-7%
				M.D. 2015	-1%	-3%	-2%	-4%	0%	-2%
				M.D. 2020	-1%	-3%	-2%	-3%	0%	-2%

In general, it is observed that buildings with an S/V ratio of 0.35 compared to other S/V ratios show less variation in $EP_{tot,nd}$ over time. Buildings with lower S/V ratios are less affected by climate change.

In accordance with Italian classification, climate zones A and B show an increasing trend of $EP_{tot,nd}$, particularly for an S/V ratio of 0.75 where the highest increments are recorded. In these climatic zones, buildings with an S/V of 0.35, constructed according to LD 192/2005, are more resilient to climate change. In climate zones C and D, a complex pattern is shown. In general, that buildings with

Table 7
Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zones BSh and BSk.

Italian climate zone	Koppen climate classification	City	S/V	Regulations	RCP 2.6		RCP 4.5		RCP 8.5	
					ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070
A	BSh	Lampedusa	0.75	L.D. 2005	3%	3%	7%	9%	9%	18%
				M.D. 2015	4%	4%	7%	9%	9%	19%
				M.D. 2020	4%	4%	6%	10%	10%	21%
			0.55	L.D. 2005	2%	2%	4%	7%	7%	16%
				M.D. 2015	4%	4%	7%	10%	10%	20%
				M.D. 2020	4%	4%	8%	12%	11%	20%
			0.35	L.D. 2005	2%	2%	5%	7%	7%	15%
				M.D. 2015	3%	4%	7%	10%	9%	19%
				M.D. 2020	4%	4%	7%	10%	10%	20%
D	BSk	Foggia	0.75	L.D. 2005	1%	4%	1%	1%	5%	8%
				M.D. 2015	2%	5%	3%	4%	7%	12%
				M.D. 2020	3%	4%	3%	5%	8%	13%
			0.55	L.D. 2005	1%	3%	1%	-1%	4%	4%
				M.D. 2015	3%	5%	2%	1%	5%	7%
				M.D. 2020	1%	4%	2%	2%	6%	11%
			0.35	L.D. 2005	1%	3%	1%	0%	4%	4%
				M.D. 2015	3%	5%	1%	3%	5%	9%
				M.D. 2020	1%	4%	3%	3%	7%	9%

S/V of 0.35 coherent with L.D. 192/2005 present the best behaviour. In climate zones E and F, there is a notable improvement for all the scenarios considered, offering a significant chance of advancement and, as a result, leading to a reduction in $EP_{tot,nd}$.

Considering the Koppen-Geiger classification, BSh zone has the largest increases in $EP_{tot,nd}$ compared to 2030 over the years. In particular, there are increases of well over 10 % for the RCP 8.5 scenario. The BSk zone also shows increases in $EP_{tot,nd}$ for most scenarios, but there is a smaller percentage change than that shown for the BSh climate zone. For the Csa climate zone, an increase in $EP_{tot,nd}$ is noted for all scenarios. the only exceptions to this behavior are the cities of Rome and Arezzo, which show reductions in $EP_{tot,nd}$. In particular, Arezzo shows the greatest reduction for the S/V ratio 0.35. Porto Empedocle and Syracuse present a deteriorations in EP for S/V 0.75. Cfa and Cfb show a mixed trend. The largest increases occur for S/V ratio 0.75. Cfc presents a decrease in Cfc values for almost all scenarios considered. The lowest values are reached considering L.D. 192/2005 with S/V ratio 0.35. Considering climate zones Dfb and Dfc, a decrease in $EP_{tot,nd}$ values is evident. For S/V equal to 0.35 there are the greatest reductions in $EP_{tot,nd}$ especially considering buildings constructed according to M.D. August 06, 2020. Dfc shows few exceptions to this decreasing trend for S/V values of 0.75.

In consideration of climatic zones A through F, distinct trends emerge regarding the influence of the Surface-to-Volume (S/V) ratio and adherence to regulatory frameworks on $EP_{tot,nd}$ variations. Notably, in zone A, minor $EP_{tot,nd}$ variations are evident in structures with an S/V ratio of 0.35, constructed in accordance with the L.D. 192/2005 regulation. Similarly, in zone B, the least $EP_{tot,nd}$ variation is observed in buildings with S/V ratios of 0.55 and 0.35, conforming to the M.D. August 26, 2015 and L.D. 192/2005 regulations, respectively. Zone C exhibits analogous $EP_{tot,nd}$ variations for S/V ratios of 0.55 under L.D. 192/2005 and 0.35 conforming to both L.D. 192/2005 and M.D. August 26, 2020 regulations. Considering the cost-effectiveness, construction in compliance with L.D. 192/2005 emerges as a prudent choice for designers. Furthermore, in zones D and E, the minor $EP_{tot,nd}$ variations are apparent in structures featuring S/V ratios of 0.75 and 0.35, respectively, conforming to the L.D. 192/2005 regulation. Zone F showcases minor $EP_{tot,nd}$ variations with an S/V ratio of 0.35, aligning with the L.D. 192/2005 regulation. This analysis underscores the impracticality of pursuing hyper-insulation in buildings. While seemingly beneficial for climate resilience, such an approach often proves costly and fails to ensure effective adaptation to climatic shifts.

4. Conclusions

This research emphasizes the crucial role of building envelope design in achieving energy efficiency, particularly under the influence of climate change. It highlights that a reduction in the steady-state thermal transmittance value (U) of the building envelope might not necessarily result in a decrease in energy performance, especially when considering future climatic conditions.

The study investigates the often-ignored surface-to-volume ratio (S/V) in Italian buildings, assessing its impact on the resilience of buildings constructed according to three different Italian regulations, which have progressively imposed lower U-values over time. The analysis encompasses all climatic locations in Italy, falling under both national and international Köppen-Geiger climate classification.

Three distinct Italian regulatory standards were considered: Legislative Decree 192/2005 (L.D. 192/2005), Ministerial Decree of June 26, 2015 (M.D. June 26, 2015), and Ministerial Decree of August 6, 2020 (M.D. August 06, 2020). Additionally, the assessment of envelope performance involved the calculation of thermal performance indices for the years 2030, 2050, and 2070, relative to three different RCP scenarios (2.6, 4.5, and 8.5).

The study, aiming for effective comparisons across diverse locations, opted for a consistent building model across locations with reinforced concrete insulated walls. This model, resilient to harsh weather conditions and cost-effective, is a common choice for

Table 8
Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zones Cfa, Cfb and Cfc.

Italian climate zone	Koppen climate classification	City	S/V	Regulations	RCP 2.6		RCP 4.5		RCP 8.5	
					ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070
D	Cfa	Pescara	0.75	L.D. 2005	-2%	-3%	0%	-1%	2%	6%
				M.D. 2015	1%	0%	1%	2%	4%	12%
				M.D. 2020	0%	-1%	1%	2%	5%	14%
			0.55	L.D. 2005	-3%	-3%	0%	0%	2%	5%
				M.D. 2015	-2%	-2%	0%	0%	2%	7%
				M.D. 2020	-2%	-2%	0%	1%	3%	9%
			0.35	L.D. 2005	-2%	-3%	0%	-1%	1%	5%
				M.D. 2015	-2%	-2%	0%	-1%	2%	6%
				M.D. 2020	-2%	-2%	0%	-1%	2%	8%
E	Cfa	Ferrara	0.75	L.D. 2005	-5%	-4%	1%	-1%	1%	1%
				M.D. 2015	-5%	-5%	-1%	0%	1%	5%
				M.D. 2020	-3%	-3%	-1%	0%	4%	8%
			0.55	L.D. 2005	-5%	-5%	0%	-2%	0%	-2%
				M.D. 2015	-5%	-4%	1%	-1%	0%	-1%
				M.D. 2020	-4%	-4%	1%	-1%	0%	-1%
			0.35	L.D. 2005	-5%	-4%	0%	-2%	0%	-2%
				M.D. 2015	-5%	-4%	0%	1%	2%	1%
				M.D. 2020	-5%	-4%	1%	1%	2%	1%
D	Cfb	Farindola	0.75	L.D. 2005	-1%	2%	-1%	-2%	9%	9%
				M.D. 2015	1%	3%	0%	1%	10%	13%
				M.D. 2020	1%	4%	1%	2%	11%	13%
			0.55	L.D. 2005	-1%	2%	-2%	-3%	8%	5%
				M.D. 2015	0%	3%	-1%	-1%	9%	9%
				M.D. 2020	0%	3%	-1%	-1%	9%	11%
			0.35	L.D. 2005	-1%	2%	-2%	-3%	8%	5%
				M.D. 2015	0%	3%	0%	0%	10%	8%
				M.D. 2020	1%	4%	0%	0%	10%	9%
E	Cfb	L'Aquila	0.75	L.D. 2005	-3%	-2%	3%	1%	4%	7%
				M.D. 2015	-1%	0%	5%	7%	8%	15%
				M.D. 2020	-1%	0%	5%	7%	10%	15%
			0.55	L.D. 2005	-4%	-2%	2%	0%	4%	2%
				M.D. 2015	-4%	-1%	2%	1%	3%	10%
				M.D. 2020	-4%	-1%	2%	3%	4%	10%
			0.35	L.D. 2005	-4%	-2%	2%	2%	4%	1%
				M.D. 2015	-3%	-2%	1%	1%	5%	7%
				M.D. 2020	-5%	-3%	1%	1%	5%	7%
F	Cfb	Belluno	0.75	L.D. 2005	-1%	-3%	2%	1%	-2%	3%
				M.D. 2015	1%	-1%	3%	1%	-1%	7%
				M.D. 2020	-2%	-4%	0%	2%	0%	8%
			0.55	L.D. 2005	-1%	-3%	2%	0%	-3%	-2%
				M.D. 2015	0%	-2%	2%	1%	-1%	2%
				M.D. 2020	-1%	-3%	2%	2%	-2%	2%
			0.35	L.D. 2005	-1%	-3%	1%	0%	-3%	-2%
				M.D. 2015	-1%	-3%	2%	1%	-2%	2%
				M.D. 2020	-1%	-3%	2%	1%	-2%	2%
F	Cfc	Fenestrelle	0.75	L.D. 2005	-1%	-2%	-4%	-4%	-5%	-7%
				M.D. 2015	0%	-1%	-2%	-1%	-2%	-2%
				M.D. 2020	0%	-1%	-2%	0%	-1%	2%
			0.55	L.D. 2005	-1%	-3%	2%	0%	-3%	-2%
				M.D. 2015	-1%	-2%	-3%	-4%	-5%	-8%
				M.D. 2020	-1%	-2%	-3%	-4%	-4%	-6%
			0.35	L.D. 2005	-2%	-2%	-4%	-6%	-7%	-12%
				M.D. 2015	-1%	-2%	-3%	-3%	-3%	-8%
				M.D. 2020	-1%	-2%	-3%	-3%	-3%	-7%

designers across many Italian climate zones, ensuring a secure and comfortable living environment. Focusing on the building envelope without air conditioning, it is designed to meet energy regulation limits for each climate zone. The simplicity of the building type allows for broad comparisons with other regional structures, offering trends that can serve as a benchmark for similar constructions.

Three cubic-shaped reference buildings, each with distinct surface-to-volume ratios, are used in the analysis. These structures align closely with the S/V ratios specified in the national Ministerial Decree of June 26, 2015.

Table 9
Percentage variations of $EP_{tot,nd}$ from 2020 to 2030, 2050 and 2070 for zone Dfb and Dfc.

Italian climate zone	Koppen climate classification	City	S/V	Regulations	RCP 2.6		RCP 4.5		RCP 8.5	
					ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070	ΔE_{ptot} 2030-2050	ΔE_{ptot} 2030-2070
F	Dfb	Asiago	0.75	L.D. 2005	-2%	-3%	-5%	-6%	-5%	-10%
				M.D. 2015	0%	-2%	-3%	-3%	-1%	-2%
				M.D. 2020	0%	-2%	-2%	-2%	-1%	-2%
			0.55	L.D. 2005	-2%	-3%	-4%	-6%	-6%	-12%
				M.D. 2015	-2%	-3%	-5%	-7%	-6%	-9%
				M.D. 2020	-2%	-3%	-5%	-6%	-6%	-9%
			0.35	L.D. 2005	-2%	-3%	-4%	-6%	-6%	-12%
				M.D. 2015	-2%	-3%	-4%	-6%	-5%	-10%
				M.D. 2020	-2%	-3%	-4%	-6%	-5%	-10%
F	Dfc	Tarvisio	0.75	L.D. 2005	-1%	-1%	-2%	-5%	-1%	-3%
				M.D. 2015	0%	1%	1%	-1%	3%	6%
				M.D. 2020	1%	1%	-1%	-2%	2%	5%
			0.55	L.D. 2005	-1%	-2%	-4%	-8%	-4%	-7%
				M.D. 2015	-1%	-1%	-3%	-5%	-1%	-2%
				M.D. 2020	-1%	-1%	-2%	-5%	-1%	-2%
			0.35	L.D. 2005	-2%	-2%	-3%	-7%	-4%	-7%
				M.D. 2015	-1%	-1%	-3%	-5%	-2%	-3%
				M.D. 2020	-1%	-1%	-2%	-6%	-2%	-3%

The evaluation of building performance under diverse conditions and climatic scenarios was carried out using thermal performance indices.

The findings display variations across national climate zones (ranging from A to F) and the considered standards. When comparing $EP_{tot,nd}$ values between 2030, 2050, and 2070, hot regions (Zones A, B, and C) demonstrate an increase in $EP_{tot,nd}$, reaching up to a maximum of 20 %, with minimal differences across most scenarios. Zone D showcases diverse $EP_{tot,nd}$ behaviours, indicating a tendency for reduction with smaller S/V ratios.

In climatic zone E, the $EP_{tot,nd}$ demand fluctuates; any increase compared to 2030 is slight (up to 10 %), which is further mitigated with a lower S/V ratio. The cold climate zone F presents a slight decrease in $EP_{tot,nd}$ demand in 2050 and 2070 compared to the demands in 2030.

Summarizing, the U value represents the rate of heat transfer through a building element. A lower U value indicates better insulation. Changing the U value can directly impact energy efficiency. The S/V ratio influences the amount of surface area exposed to external conditions relative to the internal volume. It affects the overall heat gain or loss. High S/V ratios may lead to more significant thermal losses. A change in one factor could potentially compensate for the other. For instance, increasing insulation (lowering U value) might compensate for a higher S/V ratio, reducing overall heat loss. It is necessary to adapt regulations to consider both U-values and S/V ratios to comprehensively address energy efficiency according to the climatic zone.

In conclusion, a holistic approach that considers U values, S/V ratios, and urban form is crucial for effective energy-efficient building design and urban planning. Recommendations for policymakers and designers should focus on creating a balance between insulation, form, and urban development to achieve sustainable and energy-efficient built environments under climate changes.

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CRediT authorship contribution statement

Cristina Baglivo: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation. **Paola Maria Albanese:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Paolo Maria Congedo:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2024.108544.

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