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A Comparative Analysis of the International Regulation of Thermal Properties in Building Envelope

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Received: 17 September 2019; Accepted: 4 October 2019; Published: 10 October 2019

Abstract: To achieve the goals of reducing building energy consumption, regulations are being designed to guarantee the appropriate energy performance of buildings. Both European and South American countries establish requirements of thermal properties of building envelope according to the climate zone, thus implying notable differences in climate classifications and technical requirements. This research provides a general view of advantages and limitations between the different state regulations of three South American countries (Argentina, Brazil, and Chile) and three European countries (Spain, Portugal, and France). A total of 792 simulations were conducted with Energy Plus by considering 12 different dwelling typologies in 66 climate zones. Building envelopes were adapted to the regulations of the various countries. Results showed tendencies of performance clearly different between the South American and the European countries, with the latter being those with the lowest energy demands. The cluster analysis of distributions of energy demand revealed that buildings located in similar climates but in different countries present very different energy performances. This research opens up the discussion on the development of more demanding policies related to thermal properties of buildings. Also, the analysis at a continental scale could reduce the differences between countries and guarantee a more sustainable life for the building stock.

Keywords: thermal transmittance; energy demand; international regulation; building; South America; Europa; cluster analysis

1. Introduction

As a result of the oil crisis of the 1970s, concerns regarding the effects of climate change on the planet exponentially increased. High energy consumption, greenhouse gas emissions (GHG), and climate change nowadays constitute the main concerns of society. A greater requirement in the energy performance has been reflected in many sectors, including the building sector, as most existing buildings present bad energy behavior [1,2]. In quantified data, the building sector is responsible for 30% of the energy consumption worldwide [3], generating 40% of GHG emissions [4,5] In addition, the use of fossil sources to produce energy aggravates this situation—most of the energy consumed in 2018 was produced by fossil sources [6].

To reduce the progressive degradation generated by climate change, a total of 195 countries were committed to significantly reduce GHG emissions in the 2015 Paris Climate Conference, thus leading to ambitious objectives by 2050, both at continental [7] and state [8–10] scales. Most programs establish a demanding goal of reducing building energy consumption by more than 90% [8–10].

To achieve such a goal, countries are designing regulations that establish limitations in the properties of buildings to guarantee their appropriate energy performance. Among the characteristics of buildings, setpoint temperatures [11], compactness [12], bioclimatic strategies [13], efficient installations [14], and thermal properties of envelopes [15,16] are those most influencing the energy performance, as the main type of consumption is the use of heating, ventilation and air conditioning (HVAC) systems [17]. It is therefore essential for countries to ensure an acceptable energy performance of buildings through their regulations, and they should pay special attention to the limitation of residential building energy consumption [18]. Even though there are several research studies analyzing the possibilities of modifying setpoint temperatures and compactness, thermal characteristics of building envelope are some of the main regulatory instruments, as establishing limitations in their properties is very easy, and they are directly related to the building energy demand due to heat losses and gains through them [19–22].

As for the European Union, most countries have widely developed since 1991 in relation to energy efficiency agreements [23]. Regarding the energy efficiency of buildings, the European Union has the Directive 2010/31/UE [5] as regulatory framework, which establishes the objective of guaranteeing the energy efficiency of European buildings. Through such a directive, each country of the European Union has developed different regulations on energy efficiency and adapted to them. The directive therefore does not establish specific technical objectives or demands for buildings. Among the highlights of the directive 2010/31/UE is the obligation that all new buildings from 31 December 2020 should be nearly zero energy buildings (nZEB). Consequently, European countries are reviewing their technical regulations [24] with the added difficulty that, in the warmest regions, guaranteeing an acceptable performance in summer seasons is something of a challenge [25].

Regarding South American countries, there are research studies proving that they are primarily the countries with high energy consumption, with a rising trend in recent years [26] as the economy of these countries progressively increases [27,28]. Therefore, the adoption of proposals to reach categories of nZEB in their building stock would be promising, although reality shows that there is a lack of measures focused on this objective [29,30]. Nevertheless, South American countries are more and more aware of the energy saving, as reflected by their regulations [31]. Many of them signed the 2015 Paris Climate Conference, and they are committed to reducing between 20 and 40% of the GHG emissions to the atmosphere [32].

Most regulations from European and South American countries, however, establish requirements of thermal properties of building envelope according to the climate zone [33]. These regulations present notable differences in climate classifications and technical requirements of thermal properties of building envelope to ensure an appropriate energy performance. This research, therefore, provides a general view of the existing advantages and limitations between the various state regulations and analyzes the possible differences between both continents. For this purpose, three South American countries and three European countries were analyzed. The South American countries selected were Argentina, Brazil, and Chile, and the reasons are as follows: they are those with the greatest surface of territory, they have a consolidated regulation on energy efficiency, and they have the greatest electricity consumption per capita in recent years [34]. The Spanish countries selected were Spain, Portugal, and France, and the reasons are as follows: their geographic proximity allows similarity patterns to be established in their climate conditions, the difficulties of implementing nZEB policies in these regions [24], and they have regulations on energy efficiency of the envelope with similar characteristics. A total of 792 simulations were carried out with EnergyPlus and were useful to adequately understand the performance the built building stock could provide according to the regulations of each country. Simulations were conducted in cities located in different climate regions of each country. Also, the properties of the envelope were adapted to the limit values established for each region. The analysis was based on the comparison of energy demand (i.e., the useful energy that HVAC systems would have to provide optimal thermal comfort conditions).

2. Thermal Regulation of Building Envelope

2.1. France

In France, the regulation establishing the different requirements that buildings must fulfill is the *Code de la construction et de l'habitation* [35]. Basic requirements related to buildings are established in this regulation, such as the structure safety or the energy efficiency. As for the latter, the limit values established in the regulation are continuously updated. Regarding the thermophysical properties, the levels of thermal and energy performance, which the article R 131-28 of the Code should reach, were updated in the decree *Arrêté du 22 mars 2017* [36]. In this decree, limit values of thermophysical properties of opaque elements and windows were updated (see Tables 1 and 2). It is worth stressing that limit values of thermophysical properties for opaque elements are more demanding beginning 1 January 2023 (see Table 3). Unlike other regulations, the variable used in opaque elements to establish limitations is the thermal resistance. These values are applied to new or existing buildings, with some exceptions:

- Buildings and parts of buildings where energy is not used to regulate the internal temperature;
- Temporary constructions for a use period of less than or equal to two years;
- Independent buildings with a surface area less than 50 m^2;
- Buildings for agricultural or industrial use that only need a small amount of energy for heating, warm water, or cooling;
- Religious buildings;
- Historical buildings.

Table 1. Minimum thermal resistance values of the opaque elements of the building envelope (French regulation).

Element	Minimum Thermal Resistance ($m^2 \cdot K \cdot W^{-1}$)		
	Thermal Zone		
	H1a, H1b, H1c	H2a, H2b, H2c, H2d, and H3 at an Altitude Greater than 800 m	H3 at an Altitude Lower than 800 m
Walls	2.9	2.9	2.2
Walls in contact with unheated air or space	2	2	2
Horizontal roofs	3.3	3.3	3.3
Inclined roofs	4.4	4.3	4
Floors in contact with unheated air or space	2.7	2.7	2.1
Walls	2.9	2.9	2.2

Table 2. Maximum thermal transmittance values of glazed building elements (French regulation).

Type of Window	Maximum Thermal Transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
Windows of surface greater than 0.5 m^2, French windows, double windows	1.9
Front door of the single-family house, which opens to the exterior	2.0
Canopy	2.5
Veranda	2.5

Table 3. Minimum thermal resistance values of the opaque elements of the building envelope from 1 January 2023 (French regulation).

Element	Minimum Thermal Resistance ($m^2 \cdot K \cdot W^{-1}$)		
	Thermal Zone		
	H1a, H1b, and H1c	H2a, H2b, H2c, H2d, and H3 At an Altitude Greater than 800 m	H3 At an Altitude Lower than 800 m
Walls	3.2	3.2	2.2
Walls in contact with unheated air or space	2.5	2.5	2.5
Horizontal roofs	4.5	4.3	4
Inclined roofs	5.2	4.5	4
Floors in contact with unheated air or space	3	3	2.1

As can be seen, the limitations of the thermophysical properties of the envelope depend on the climate zone of the building. The climate classification is regulated in the decree *Arrêté du 26 octobre 2010* [37]. In this decree, climate is divided into three zones for winter (H1, H2, and H3) and four for summer (a, b, c, and d). A total of eight different climate zones are obtained from the combinations (see Figure 1).

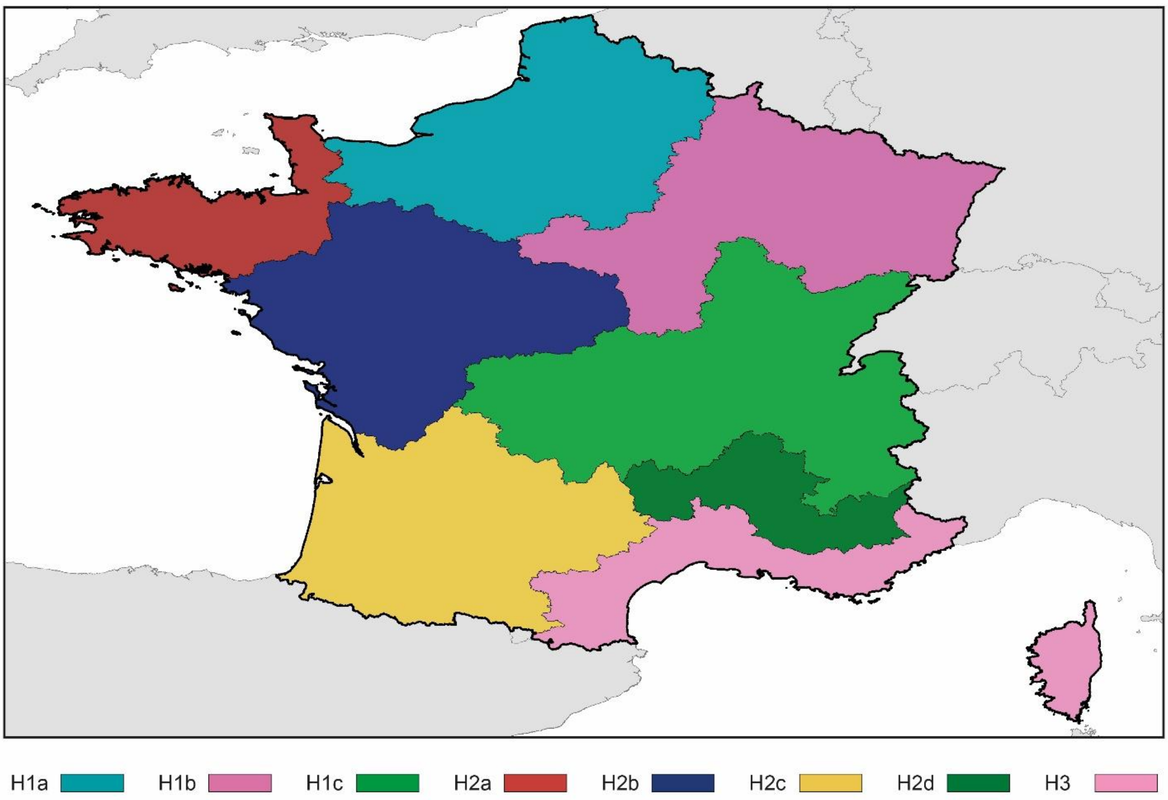

Figure 1. Climate classification in France.

2.2. Portugal.

In Portugal, the energy regulation of buildings is developed in the decree-law 118/2013 [38]. This decree-law was the transposition of the Directive 2010/31/UE in Portugal [39]. Recently, some articles of this regulation were modified in the decree-law 251/2015 [40]. Its application scope is as follows:

1. New buildings;
2. Greater intervention; in this aspect, the Portuguese regulation distinguishes two assumptions: (a) when the cost of intervention works in the building is greater than 25% of the total value of the building (not including the value of ground), and (b) when there is an extension of the building with a cost greater than 25% of the total value of the building.

Regarding the thermophysical properties of the envelope, the regulation *Portaria 379-A/2015* establishes the limit values for envelope elements. Since 31 December 2015, the thermophysical properties of opaque and glazed elements of the envelope have been regulated with the limit values provided in Table I.05B of the regulation *Portaria 379-A/2015* (see Table 4). Such limit values are established for the climate classification set up in Portugal. As can be seen, limit values are established according to the climate zone of the building. The climate classification of Portugal is included in the decree-law 80/2006 [41], where three climate zones are established by each type of season (see Figure 2): three in winter (I1, I2, and I3) and three in summer (V1, V2, and V3). Each city of Portugal belongs to a different summer and winter climate zone. Each index is classified according to both the heating degrees for the winter index and the external temperature in the summer index. The numeric indicator determines the severity of each climate, and those with the greatest value are the most severe. Like other regulations as in Spain, limit values for the thermophysical properties of buildings built in their territory are distinguished from those of buildings built in insular territories.

2.3. Spain

The regulation on energy efficiency of buildings in Spain started in 1979 through the royal decree 2429/79 (also known as NBE-CT-79 [42]). A climate classification of the country in five different regions was established in this decree, as well as the different limit values of thermal transmittance. This regulation was in force until 2006, when the royal decree 314/2006 came into force [43]. This last royal decree is divided into several standards, including the document of energy saving (also known as CTE-DB-HE). In both the version from 2006 and the subsequent reviews in 2013 and 2019, climates of the country are classified according to the climate severity in winter and summer, which is calculated depending on the heating and the cooling degree-days. The classification is carried out by distinguishing five zones for winter (A, B, C, D, and E) and four zones for summer (1, 2, 3, and 4); zones with a higher letter (e.g., E in winter) or a higher number (e.g., 4 in summer) are the most severe. A total of 12 different climate zones are obtained from the combinations of classifications of winter and summer (see Figure 3).

Table 4. Maximum thermal transmittance values of the opaque and the glazed elements of the building envelope (Portuguese regulation).

Element	Maximum Thermal Transmittance ($W·m^{-2}·K^{-1}$)					
	Continental Portugal			Autonomous Regions		
	Climate Zone			Climate Zone		
	I1	I2	I3	I1	I2	I3
Walls	0.50	0.40	0.35	0.70	0.60	0.45
Roofs	0.40	0.35	0.30	0.45	0.40	0.35
Windows	2.80	2.40	2.20	2.80	2.40	2.20

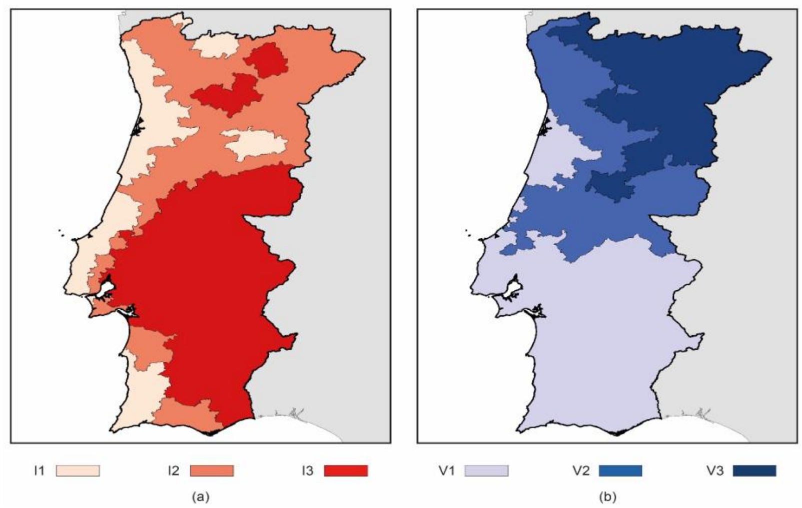

Figure 2. Climate classification in Portugal: (**a**) winter classification and (**b**) summer classification.

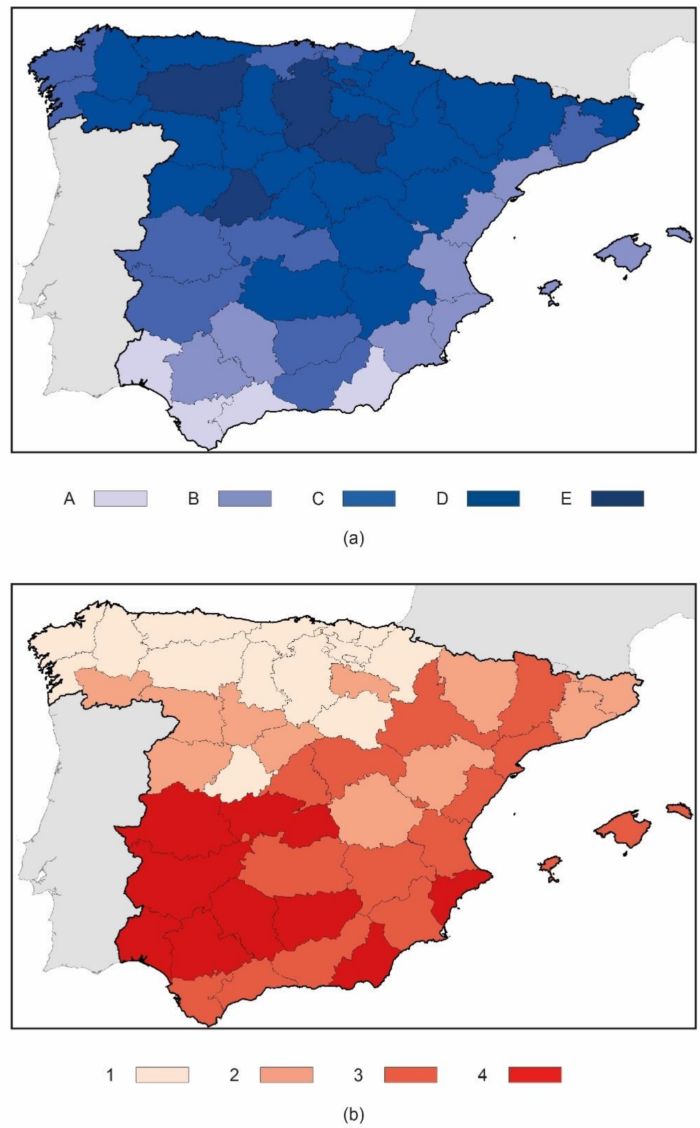

Figure 3. Climate classification in Spain: (**a**) classification of climate severity in winter and (**b**) classification of climate severity in summer.

The CTE-DB-HE also establishes the limit values of thermal transmittance of envelope elements (see Table 5), which are assigned according to the winter climate zone of the building. These limitations are applied to new buildings and to interventions in existing buildings.

Table 5. Maximum thermal transmittance values of the opaque and the glazed elements of the building envelope (Spanish regulation).

Element	Maximum Thermal Transmittance ($W \cdot m^{-2} \cdot K^{-1}$)				
	Winter Climate Zone				
	A	B	C	D	E
Wall	1.25	1.00	0.75	0.60	0.55
Elements in contact with the ground	1.25	1.00	0.75	0.60	0.55
Roof	0.80	0.65	0.50	0.40	0.35
Floor in contact with air	0.80	0.65	0.50	0.40	0.35
Window	5.70	4.20	3.10	2.70	2.50

2.4. Chile

Chile was one of the first South American countries with a wide development on energy efficiency of buildings. The climate zone of Chile was approved in 1976 through the standard NCh 1079 [44]. This standard, reviewed in 2008, establishes the climate classification in nine different zones (see Figure 4). These climates have notable differences between them. The topography of Chile significantly influences the climate characteristics of the various regions (rainfalls, temperatures, solar radiation, etc.), as many research studies reflect [45–48]. Therefore, there are different microclimates as the altitude oscillates between 0–6000 mamsl [49]. Regarding the climate classification, distinctions are not made according to the climate severities of winter and summer (as in other countries) but according to the bioclimatic characteristics of each region. For this reason, the nomenclature of zones varies: An (the Andean and the upper pre-Andean border in the Chilean highlands), CI (the central valley between the NL zone and the pre-Andea of Andes), CL (coastal zone from Mount Aconcagua to the Bío-Bío valley), ND (region between the Costa and the Los Andes mountain ranges), NL (coastal zone between the border with Perú and the northern limit of La Ligua), NVT (northern region between the coastal zone and the Los Andes valley and between Pueblo Hundido and the valley of Aconcagua river), SE (region in the south from Chiloé to Tierra del Fuego), SI (region in the south from Bío-Bío to the Reloncaví inlet), and SL (coastal zone from Bío-Bío to Chiloé and Puerto Montt).

The NCh 1079 [44] also establishes the thermal requirements of the building envelope (see Table 6). As for the limitation of the thermophysical properties of windows, it is worth stressing that the limitation is associated with the maximum surface percentage allowed according to both the type of window and the climate zone of the building.

Table 6. Maximum thermal transmittance values of the opaque and the glazed elements of the building envelope (Chilean regulation).

Element	Maximum Thermal Transmittance ($W \cdot m^{-2} \cdot K^{-1}$)								
	Climate Zone								
	An	CI	CL	ND	NL	NVT	SE	SI	SL
Wall	0.30	0.60	0.80	0.50	2.00	0.80	0.40	0.50	0.60
Roof	0.25	0.50	0.60	0.40	0.80	0.60	0.25	0.30	0.40
Floor in contact with air	0.40	0.80	1.20	0.70	3.00	1.20	0.50	0.70	0.80
Window	2.40	3.00	3.00	3.00	5.80	3.00	2.40	3.00	3.00

An (the Andean and the upper pre-Andean border in the Chilean highlands), CI (the central valley between the NL zone and the pre-Andea of Andes), CL (coastal zone from Mount Aconcagua to the Bío-Bío valley), ND (region between the Costa and the Los Andes mountain ranges), NL (coastal zone between the border with Perú and the northern limit of La Ligua), NVT (northern region between the coastal zone and the Los Andes valley and between Pueblo Hundido and the valley of Aconcagua river), SE (region in the south from Chiloé to Tierra del Fuego), SI (region in the south from Bío-Bío to the Reloncaví inlet), and SL (coastal zone from Bío-Bío to Chiloé and Puerto Montt).

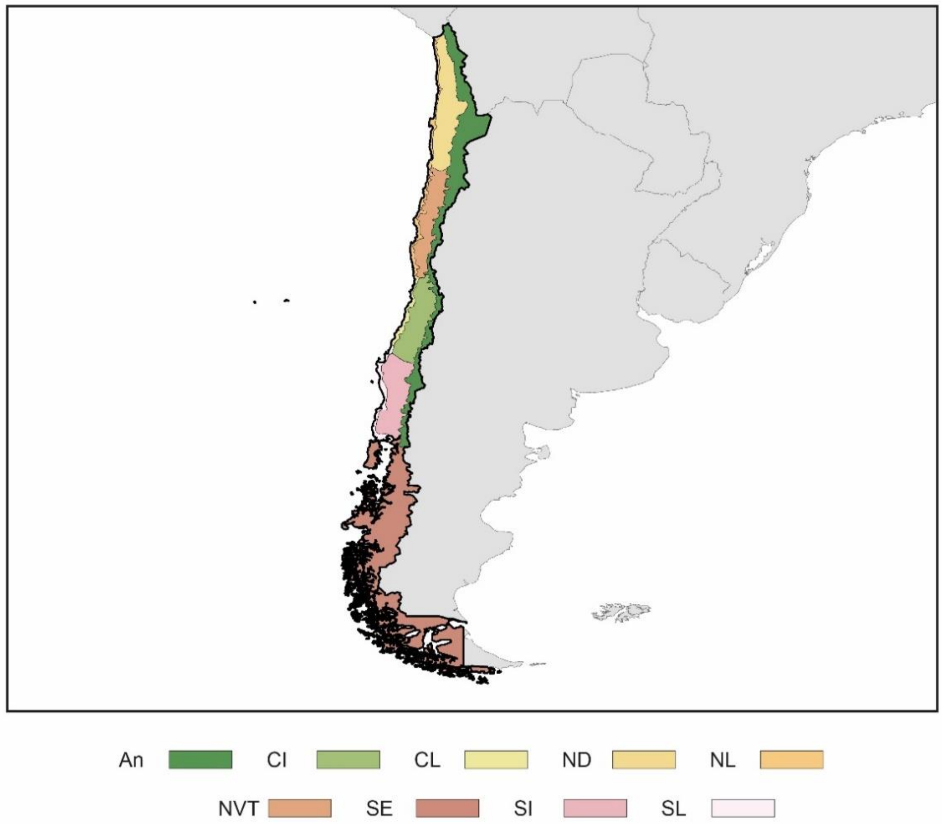

Figure 4. Climate classification in Chile.

2.5. Argentina

Together with Chile, Argentina was one of the first South American countries with a regulatory development on energy efficiency of buildings. In this regard, one of the first standards marking the energy beginnings of the country was the standard IRAM 11603 in 1981 [50]. This standard made a bioclimatic classification of the country in six different zones (see Figure 5). The classification was made by naming zone I as the hottest zone and zone VI as the coldest. In a review conducted in 2012, a total of four subcategories were distinguished in zones I–IV according to the bioclimatic characteristics of each zone: a (zones with thermal amplitudes greater than 14 °C), b (zones with thermal amplitudes lower than 14 °C), c (zones of transition from zones with greater thermal amplitudes to others with lower thermal ranges), and d (coastal zones with low amplitudes throughout the year). In addition, the IRAM 11603 provides general guidelines related to the design of the envelope as well as the evaluation of favorable orientations and the compliance of minimum sunlight in buildings for dwelling purposes.

However, the subsequent development of IRAM 11605 [51] established more restrictive limitations on the thermal properties of opaque elements. The standard establishes limit values for the thermal transmittance of walls and ceilings according to three comfort levels: A (recommended), B (medium), and C (minimum). Also, distinctions are made in the limit values of thermal transmittance for the seasons of summer and winter (see Tables 7 and 8). In the distinction of thermal transmittance of winter, limit values are not assigned according to the climate zone but to the external temperature of the design established in the IRAM 11603 for different cities. For a certain building, the lowest values of both tables are assigned. These limit values were adopted as compulsory in the decree 1030/10 [52].

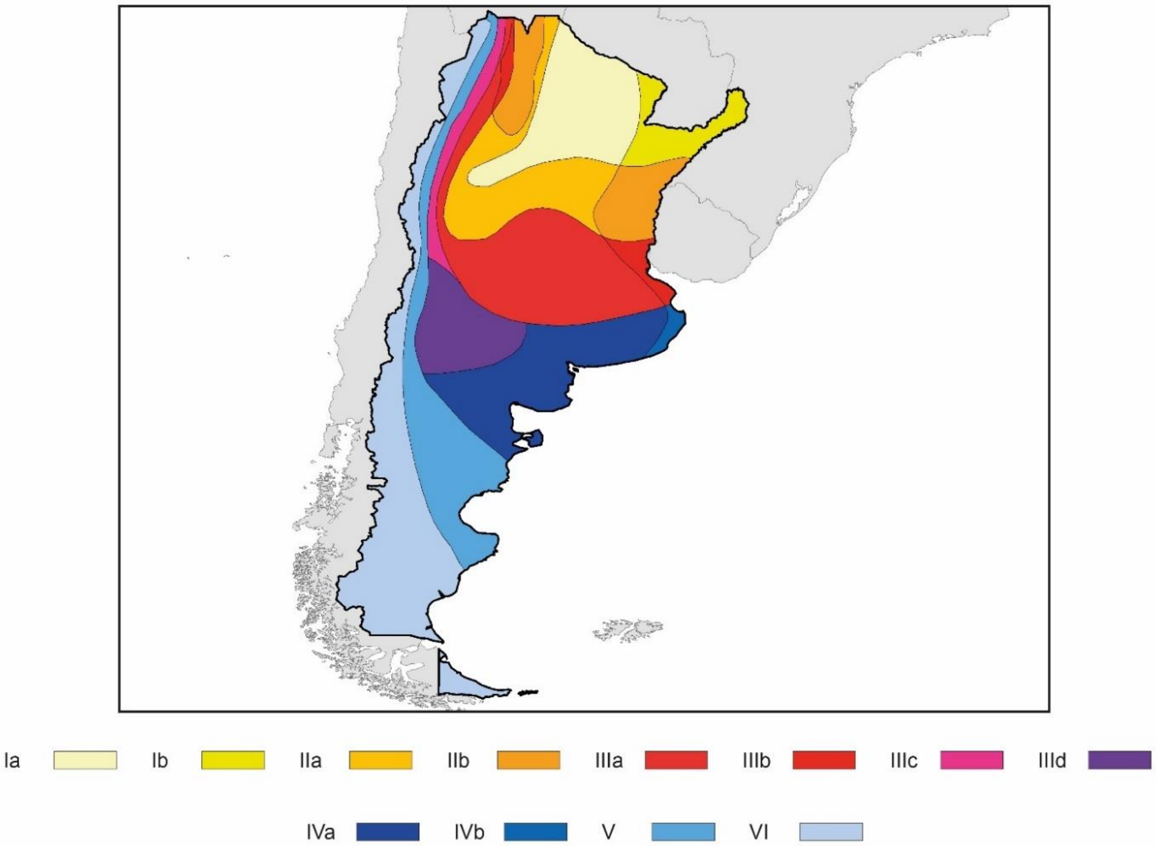

Figure 5. Climate classification in Argentina.

Table 7. Maximum values of thermal transmittance of winter of opaque elements of the building envelope (Argentinian regulation).

Design External Temperature [°C]	Maximum Thermal Transmittance (W·m^{-2}·K^{-1})					
	Level A		Level B		Level C	
	Wall	Roof	Wall	Roof	Wall	Roof
−15	0.23	0.20	0.60	0.52	1.01	1.00
−14	0.23	0.20	0.61	0.53	1.04	1.00
−13	0.24	0.21	0.63	0.55	1.08	1.00
−12	0.25	0.21	0.65	0.56	1.11	1.00
−11	0.25	0.22	0.67	0.58	1.15	1.00
−10	0.26	0.23	0.69	0.60	1.19	1.00
−9	0.27	0.23	0.72	0.61	1.23	1.00
−8	0.28	0.24	0.74	0.63	1.28	1.00
−7	0.29	0.25	0.77	0.65	1.33	1.00
−6	0.30	0.26	0.80	0.67	1.39	1.00
−5	0.31	0.27	0.83	0.69	1.45	1.00
−4	0.32	0.28	0.87	0.72	1.52	1.00
−3	0.33	0.29	0.91	0.74	1.59	1.00
−2	0.35	0.30	0.95	0.77	1.67	1.00
−1	0.36	0.31	0.99	0.80	1.75	1.00
≥0	0.38	0.32	1.00	0.83	1.85	1.00

A (recommended), B (medium), and C (minimum).

Table 8. Maximum values of thermal transmittance of summer of opaque elements of the building envelope (Argentinian regulation).

Climate Zone	Maximum Thermal Transmittance ($W{\cdot}m^{-2}{\cdot}K^{-1}$)					
	Level A		Level B		Level C	
	Wall	Ceiling	Wall	Ceiling	Wall	Ceiling
I and II	0.45	0.18	1.10	0.45	1.80	0.72
III and IV	0.50	0.19	1.25	0.48	2.00	0.76

Regarding the thermal characteristics of windows, the standard IRAM 11507-4 [53] establishes the limit values of thermal transmittance of windows for various categories (see Table 9). As for these categories, the decree 1030/10 [52] establishes that buildings up to 10 m height should have windows of category K5, and for buildings of greater size, the minimum category is K4.

Table 9. Maximum values of thermal transmittance of summer of glazed elements of the building envelope (Argentinian regulation).

Category	Maximum Thermal Transmittance ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
K1	<1.0
K2	$1.0 \leq$ U-value ≤ 1.5
K3	$1.5 <$ U-value ≤ 2.0
K4	$2.0 <$ U-value ≤ 3.0

2.6. Brazil

In Brazil, the first regulatory development on the energy efficiency of buildings took place in 2005 through the NBR 15220 [54], in which the technical characteristics of social housing were established. These characteristics were assigned differently in the country through a climate classification in eight various zones (see Figure 6). Later, in 2008 and in the version reviewed in 2013, the standard NBR 15575 [55] established the thermal characteristics that buildings should have. In particular, limitations are established in the thermophysical properties of walls and roofs, distinguishing different limit values according to the climate zone (see Table 10).

Table 10. Maximum values of thermal transmittance of winter of opaque elements of the building envelope (Brazilian regulation).

Element	Subcategory	Maximum Thermal Transmittance ($W{\cdot}m^{-2}{\cdot}K^{-1}$)				
		Climate Zone				
		Zones 1–2	Zones 3–6		Zones 7 and 8	
			$\alpha \leq 0.6$	$\alpha > 0.6$	$\alpha \leq 0.4$	$\alpha > 0.4$
Wall	–	2.5	3.7	2.5	–	–
Roof	Minimum	2.3	2.3	1.5	2.3 *	1.5 *
	Medium	1.5	1.5	1.0	1.5 *	1.0 *
	Maximum	1.0	1.0	0.5	1.0 *	0.5 *

* Values for roofs without ventilation. As for roofs with ventilation, limit values should be multiplied by the following factor: $FV = 1.17 - 1.07\, h^{-1.04}$, with h being the height of the air gap of the roof.

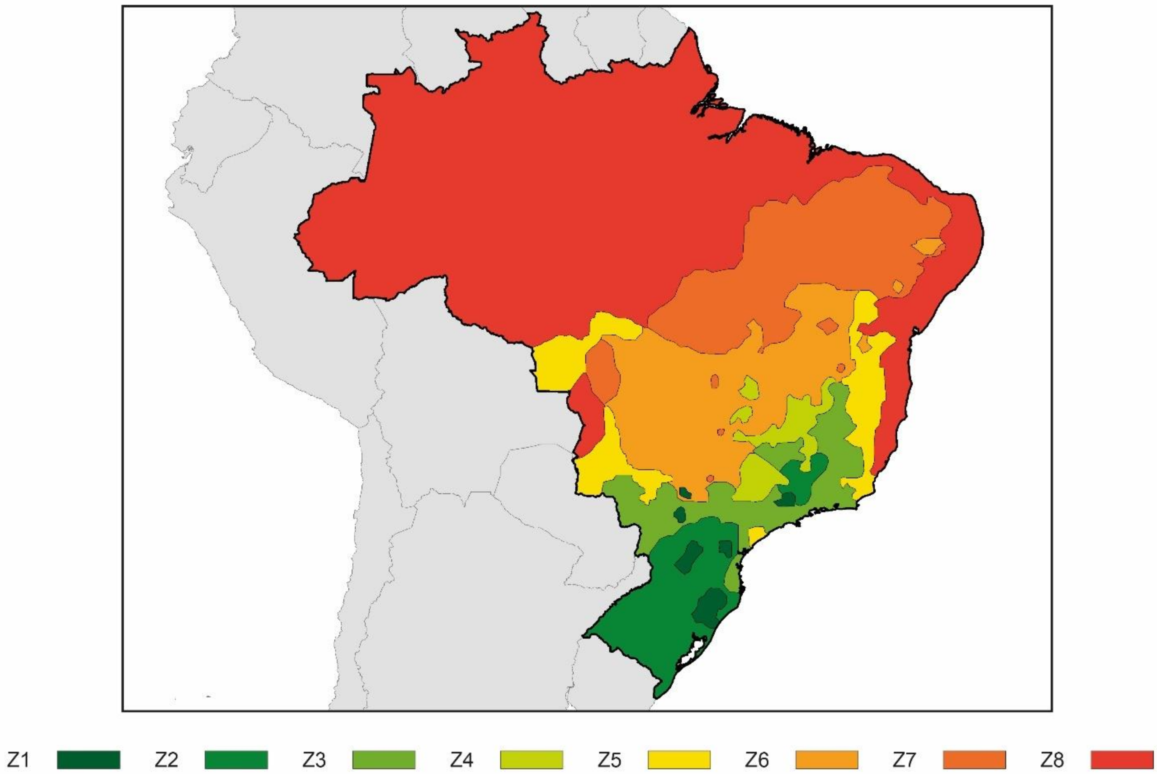

Figure 6. Climate classification in Brazil.

The standard makes a distinction according to a subcategory similar to the Argentinian regulation: minimum, medium, and maximum. This subcategory is determined based on the minimum temperature differential in winter between the internal and the external temperature as well as on the maximum temperature differential in summer. The subcategory of the building leads to the variation of the thermal transmittance of the roof. Also, the absorptivity for walls and ceilings vary the limit values of thermal transmittance. This value of absorptivity is obtained from the values established by the NBR 15220 for wall surface materials. Finally, it is worth highlighting that the NBR 15575 does not establish limitations for the thermal transmittance of walls in the climate zones 7 and 8, and that there are not limitations in the thermal properties of windows.

3. Methodology

The flowchart of the research procedure consisted of designing a set of building models and their evaluation of the useful energy demand obtained according to the thermal requirements of the envelope in each climatic zone (see Figure 7). For this purpose, models were simulated in the different climatic zones, and their envelopes were configured according to each regulation. Finally, a cluster analysis was carried out to assess the similarity between the climatic zones.

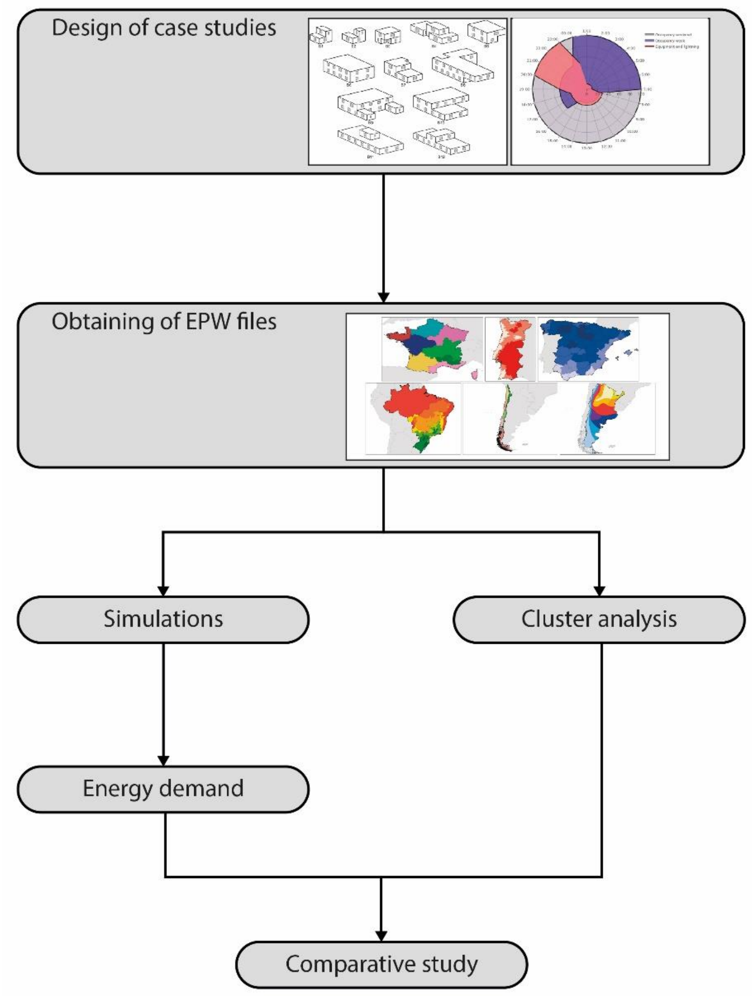

Figure 7. Flowchart of the procedure followed in this study.

3.1. Case Study

The results of this study were based on simulations carried out with Energy Plus. The energy demand was calculated by Energy Plus with dynamic hourly simulation. A total of 12 different building typologies were modeled for accurate knowledge (see Figure 8). Consequently, as 12 typologies were used, and there are 66 climate zones and regulations of the various countries (including the new regulation of France from 2023), a total of 792 different simulations were conducted. Models were designed to include different building typologies, from single-family dwellings to multi-family buildings. These models were based on other existing research studies on the subject matter [56–59]. Moreover, these designs were made to be similar to buildings of the countries analyzed. A limitation of two floors was established due to the variations presented by some regulations in the thermal properties according to the number of floors (e.g., Argentina in the thermal transmittance of windows). The percentage of glazed surface was 15% in all the opaque surfaces of the models.

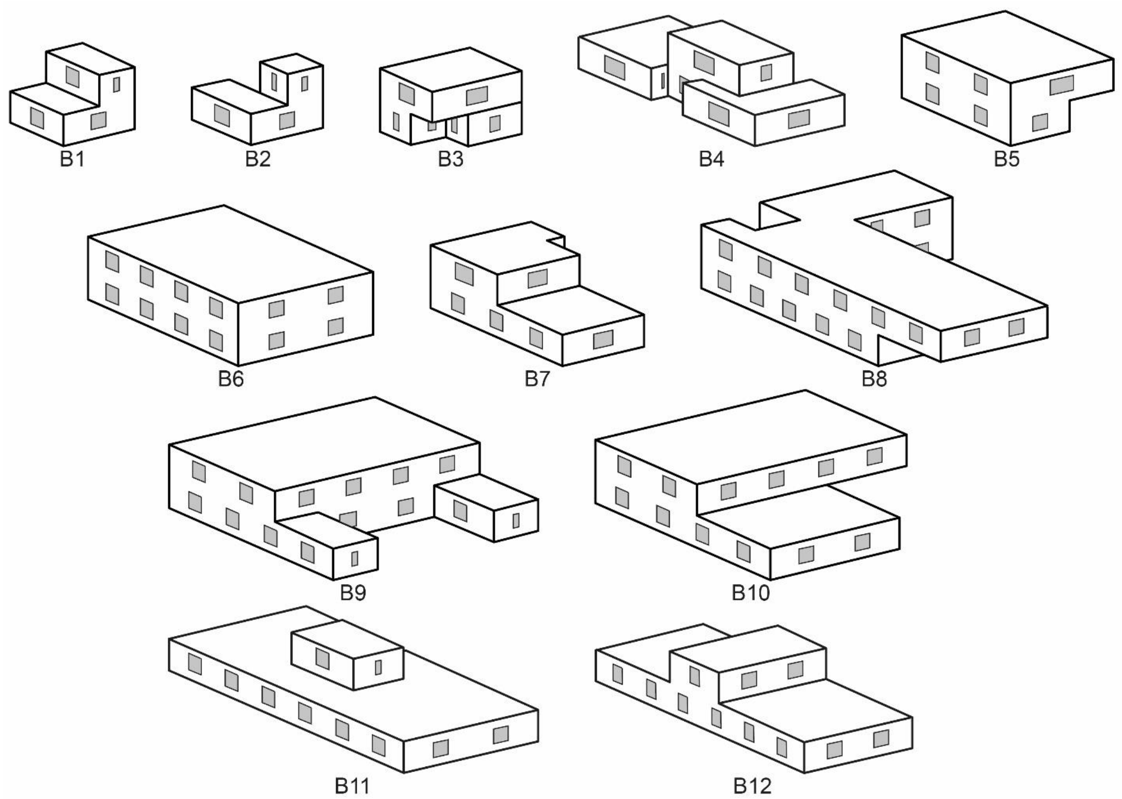

Figure 8. Models of the buildings used in the simulation process.

The thermal properties of each envelope elements were adapted according to the requirements established in the regulations described in Section 2. Table 11 indicates the standards used to establish the thermal properties of envelope elements. It is worth stressing that some countries do not establish limitations in some envelope elements. For example, values related to windows are not established in Brazil. For this case, a thermal transmittance of 5.7 (W·m^{-2}·K^{-1}) was considered for the windows designed in all climate zones of Brazil, as it is representative of the type of window most used in the country [60]. As for countries that do not establish limit values of thermal transmittance of floors in contact with the air, and similar to what the Spanish regulation establishes, the limit value for roofs was the same for floors. Regarding France, which establishes limit values of thermal resistance, the limit value of thermal transmittance was obtained through the inverse of such values. Regarding the thermal transmittance of the floor in contact with the ground, it does not vary between the different climate zones, as only the Spanish regulation establishes some limit values. For this reason, a configuration of floor with a thermal resistance of 1.9 m^2·K·W^{-1} was assigned to guarantee the compliance of the Spanish regulation in all climate zones. Window shading systems were not considered due to the differences in the typical window shading styles of each country (e.g., blinds in Spain or shutters in France).

Table 11. Standards used for the limit values of the thermal properties of the envelope.

Country	Wall	Roof	Floor	Window
Argentina	IRAM 11605	IRAM 11605	–	IRAM 11507-4
Brazil	NBR 15575	NBR 15575	–	–
Chile	NCh 1079	NCh 1079	NCh 1079	NCh 1079
France	Arrêté du 22 mars 2017	Arrêté du 22 mars 2017	Arrêté du 22 mars 2017	Arrêté du 22 mars 2017
Spain	CTE-DB-HE	CTE-DB-HE	CTE-DB-HE	CTE-DB-HE
Portugal	Portaria 379-A/2015	Portaria 379-A/2015	–	Portaria 379-A/2015

A general usage and load profile was used for all climate zones, thus making representative comparisons between the climate zones. Figure 9 shows the profiles used. The sensible load in weekends corresponding to 100% of occupancy was 2.15 W·m^{-2}, and the latent load was 1.36 W·m^{-2}. During the week, the sensible and the latent occupancy loads varied from 100% at night up to 0.54 W·m^{-2} and 0.34 W·m^{-2} (period between 08:00 to 15:00) and up to 1.08 W·m^{-2} and 0.68 W·m^{-2} (period between 16:00 to 23:00), respectively. The lighting and the equipment load varied throughout the day, being 100% (4.40 W·m^{-2}) from 20:00–23:00. The number of air changes per hour was 0.69. All the models had a conventional natural gas boiler for heating with a coefficient of performance (COP) of 0.92 and a heat pump for cooling with an energy efficiency ratio (EER) of 2.00. Setpoint temperatures varied depending on the time of day (see Table 12). As the variations of latitude between South America and Europe cause a change in the winter and the summer months of the year, constant upper and lower limits were considered during all months of the year. Two aspects were therefore met: (i) the profile was valid both for South American and European countries, and it could also be used in climate regions with lower thermal oscillations throughout the year, such as some zones of Brazil; and (ii) the profile met those isolated cooling energy demands that could take place in winter seasons, such as in Spain (as some studies report) [61].

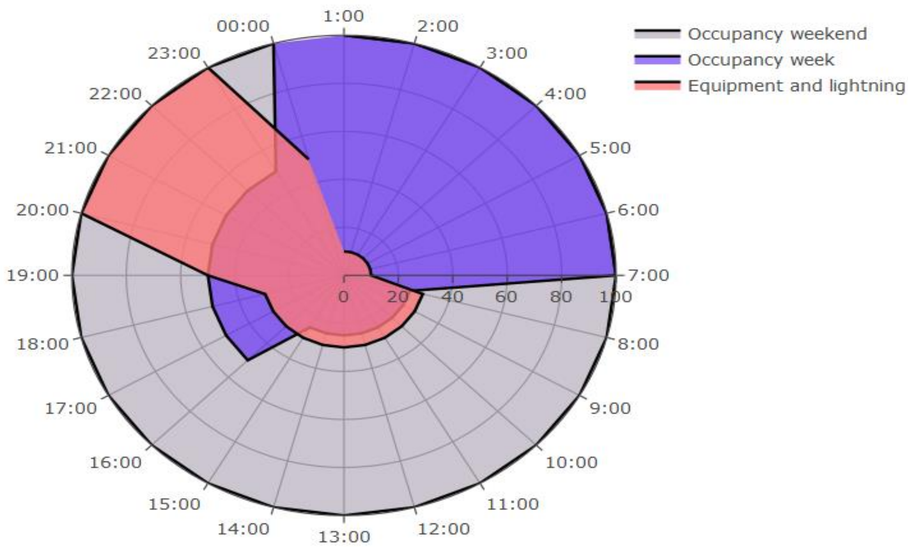

Figure 9. Radar chart with the hourly profiles of occupancy, equipment, and lightning.

Table 12. Setpoint temperatures used in each model.

Limit	Setpoint Temperature [°C]								
	January–May			June–September			October–December		
	00:00–07:00	08:00–15:00	16:00–23:00	00:00–07:00	08:00–15:00	16:00–23:00	00:00–07:00	08:00–15:00	16:00–23:00
Upper limit	27	–	25	27	–	25	27	–	25
Lower limit	17	–	20	17	–	20	17	–	20

3.2. Climate Data and Cities Analyzed

Climate data were required for the energy analysis of the limit values of regulations to conduct simulations in Energy Plus. Such climate data were obtained with the METEONORM software. This tool is constituted by 8325 weather stations located all over the world and conducts interpolations between the different seasons to obtain hourly climate data in any location. The temperature period considered for generating EnergyPlus Weather (EPW) files was 2000–2009, and the period of radiation was 1991–2010.

Annex A includes a list of the cities considered for each climate zone. Cities were selected by using the different lists of cities associated with each climate zone indicated in the regulation of each country (see Appendix A). It is worth stressing two aspects: (i) as for the zone H3 of the French regulation, the city of Nîmes was used, as it is at an altitude lower than 800 m, and the values of the thermophysical properties were different than those of the other zones (if the city selected for the zone H3 had an altitude higher than 800 m, then the limit values were the same as for zone H2); and (ii) small overseas territories were not considered in the analysis (except Majorca in the case of Spain due to its proximity and its similarity with the near zones of the country).

3.3. Cluster Analysis

Finally, a comparative analysis between the results obtained among the climate zones presenting similarities was conducted. For this purpose, an independent cluster analysis was carried out for the climate zones of South America and Europe. A cluster analysis is a multivariant statistical technique that classifies a set of objects—similar objects are in the same conglomeration, and far objects are in different groups, giving as a result homogeneous *k*-groups [62]. The Ward method was used [63], which belongs to the agglomerative hierarchical methods, and the Euclidean distance was used as a distance measure [see Equation (1)]. The variables considered for each climate zone were the heating degrees-hours for base temperature of 20 and cooling degrees-hours for base temperature of 25.

$$d\left(x_i, x_j\right) = \left[\sum_{r=1}^{p}\left(x_{ir} - x_{jr}\right)^2\right]^{1/2} \quad (1)$$

where x_i and x_j are two individuals, and p is the number of variables considered.

4. Results and Discussion

Firstly, the mean percentage contribution of each type of energy demand (heating and cooling) was analyzed in the different zones. This step was made before analyzing each climate zone in detail, as the aim was for the discussion to be based on the total energy demand to simplify its interpretation. Figure 10 represents the percentage contributions of each type of energy demand. Results highlighted the heterogeneity of the climate zones and the thermophysical characteristics analyzed in the various countries. The greatest contribution of energy demand was due to heating in most climate zones—countries such as Chile and France as well as certain climate zones of Argentina (IIa, IIb, IIIa, IIIb, IVa, IVb, IVc, IVd, V, and VI), Brazil (Z1 and Z2), Spain (A3, C1, C2, C3, D1, D2, D3, and E1), and Portugal (I1V2, I1V3, I2V1, I2V2, I2V3, I3V1, I3V2, and I3V3) presented percentages greater than 75%. However, there were some zones where the contribution of the cooling energy demand was the most important type of energy demand (greater than 50%): (i) zones Ia and Ib in Argentina; (ii) zones between Z3 and Z8 in Brazil; (iii) zone I1V1 in Portugal; and (iv) zones A4, B3, and B4 in Spain. Among these zones, it is worth stressing the high contribution of cooling energy demand in zones of Brazil due to their location in latitude near the equator, which implies that the thermal oscillation between the different seasons is low and temperatures are warmer.

If these percentage values of cooling and heating are compared with the limit values regulated by the countries analyzed, three different tendencies are found: (i) Spain and Portugal establish fewer demanding requirements in the thermal transmittance of the building envelope elements located in zones with a greater cooling demand than in colder zones. As for Spain, the limit of thermal transmittance of walls goes from 1.25 and 1.0 $W{\cdot}m^{-2}{\cdot}K^{-1}$) in the climate zones of winter A and B, respectively, to 0.75 in the winter climate zone C; (ii) in Brazil, limit values of thermal transmittance are established between zones 3 and 6 and are similar to those of the coldest zones of the country (zones 1 and 2). Also, the regulation does not consider limit values for zones 7 and 8 (it is worth remembering that the case studies with the same limitations in zones 3 and 6 were analyzed in this study). This aspect reflects the little adaptation presented by these limit values according to the characteristics of each climate zone of Brazil with the same limitations in buildings located in warm and cold regions; and (iii) Argentina establishes a different criterion of regulation according to the severity in summer.

As previously seen, the main limitation is established by the mean design temperature in winter, as lower thermal transmittance values are usually established. However, as for roofs, the characteristics of summer may demand lower values. In this regard, both zones with a greater cooling energy demand (Ia and Ib) correspond to zones in which the lowest thermal transmittance value of roofs in summer is established (it would be 0.18 $W \cdot m^{-2} \cdot K^{-1}$ for a level A), and this value increases in those zones with a lower cooling energy demand (e.g., zones IIIa and IVb), thus reflecting the climate adaptation presented by the limit values of Argentina.

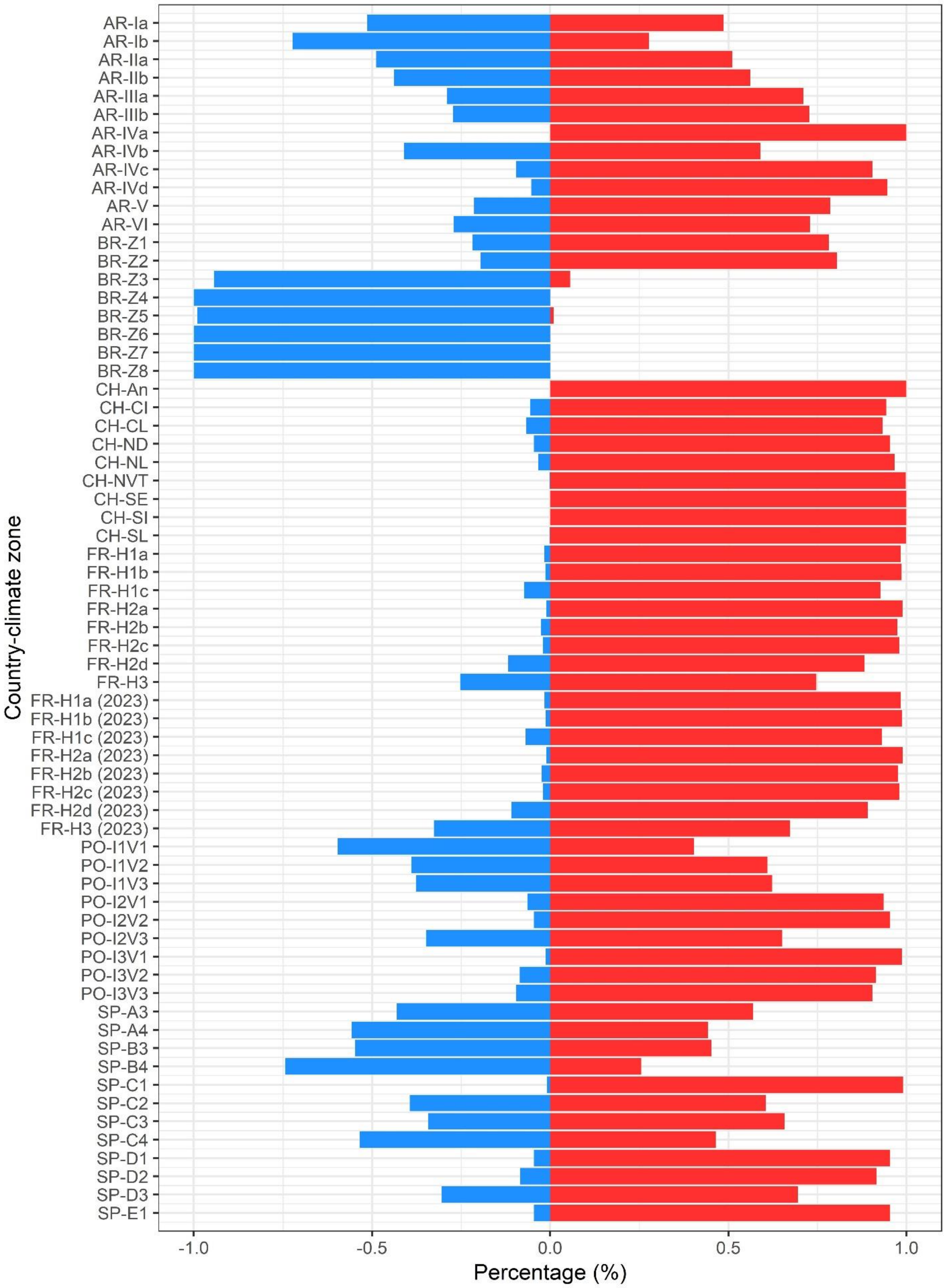

Figure 10. Mean percentage contribution of cooling (blue) and heating (red) energy demand in the 12 case studies in each climate zone.

After analyzing the percentage contribution of each case study in the various climate zones, the results of the total energy demand obtained by each case study were analyzed. It is worth remembering that the case studies presented different characteristics of orientation and design, which varied the total energy demand of each. The aim was to analyze the effect of the thermal limitations on statal regulations with different designs of buildings.

As for France, there were two limit values: (i) limit values for buildings designed and built before 1 January 2023 (see Table 13); and (ii) limit values for buildings designed and built after 1 January 2023 (see Table 14). This variation of limit values only took place in the opaque envelope elements. Regarding the results obtained, the zone and the configuration presenting the lowest total energy demand was zone H2a, with a percentage reduction between 7.08 and 23.41%. The next two zones with a lower total energy demand were zone H3 (with a percentage reduction between 7.09 and 16.91%) and zone H1a (with a deviation percentage between 1.89 and 10.50%), thus showing the favorable conditions of summer classification of type a of the French regulation, as they were those with the lowest energy demand. Regarding the zones with a greater total energy demand, zones with a summer classification of type c (H1c and H2c) were those obtaining the highest total energy demand values.

Table 13. Results of the total energy demand in the climate zones of France.

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
H1a	234.2	100.6	185.4	378.3	376.7	340.8	1090.9	738.7	890.9	873.6	704.6	560.5
H1b	254.7	109.3	204.7	419.6	421.3	378.5	1225.6	830.0	1001.3	984.3	789.6	626.3
H1c	263.6	114.2	207.6	426.2	420.0	384.1	1217.3	821.2	986.0	959.8	773.3	621.7
H2a	200.5	80.5	153.7	321.8	325.5	288.5	960.6	645.2	776.8	768.6	619.1	485.8
H2b	240.6	101.3	188.0	385.0	384.7	346.7	1117.4	754.1	908.3	891.4	716.3	570.2
H2c	250.7	105.0	197.0	409.0	412.1	367.6	1207.1	812.3	977.3	963.6	773.5	611.2
H2d	245.6	104.7	192.1	393.0	384.6	353.5	1108.1	742.4	889.4	868.4	697.5	562.7
H3	219.5	106.8	186.3	344.7	367.0	324.6	990.3	636.1	754.2	735.7	591.0	489.2

Table 14. Results of the total energy demand in the climate zones of France (2023).

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
H1a	224.9	93.7	174.1	352.5	351.9	318.8	1026.7	699.2	840.3	815.3	653.4	521.5
H1b	244.7	101.9	192.4	391.7	394.5	354.7	1156.3	787.4	946.7	921.2	734.2	584.4
H1c	253.5	106.3	195.5	397.7	393.7	359.5	1147.5	777.8	930.6	900.8	719.1	577.7
H2a	191.8	74.5	143.5	298.6	303.2	268.9	902.6	609.9	731.7	716.1	573.2	451.0
H2b	231.2	94.5	176.6	358.8	359.6	324.6	1052.6	714.2	857.2	832.5	664.6	530.8
H2c	240.4	97.1	184.5	379.8	384.1	342.8	1134.9	768.1	920.6	898.2	716.1	567.5
H2d	236.1	98.7	182.3	368.0	361.3	332.8	1044.8	706.4	842.5	812.7	647.5	526.3
H3	219.0	106.3	160.8	351.4	315.4	316.0	957.5	608.1	713.6	690.6	550.8	464.9

The same tendency was found with the limit values for 2023—zones of type a of summer had the lowest values, and those of type c had the highest. The new limit values, however, influenced the total energy demand (see Figure 11). The percentage reduction was similar between the different zones, with average values between 5.34 and 6.50%. However, the values of percentage reduction presented a slight variation in zone H3. The values of percentage reduction were between 0.25 and 14.06%, whereas in the other zones, there was a greater concentration of such values of percentage reduction (between 7.47 and 3.88%). The reason could be the difference presented by the new limit values of the zone H3 in comparison with the other zones. As seen in Section 2, limit values of thermal resistance in 2023 for zones H3 at an altitude lower than 800 m are 2.2 (m^2K)/W in walls. However, this limit value is the same as that used in current limit values, whereas in the other zones, there is an increase of 0.3 $m^2 \cdot K \cdot W^{-1}$ in the limit values of thermal resistance of walls. This difference could lead to changes in the tendency of percentage reduction of zone H3 with the other zones. Anyway, the improvement of new limit values will improve the energy performance of buildings, although this improvement could be insufficient if compared with the results obtained in other regulations.

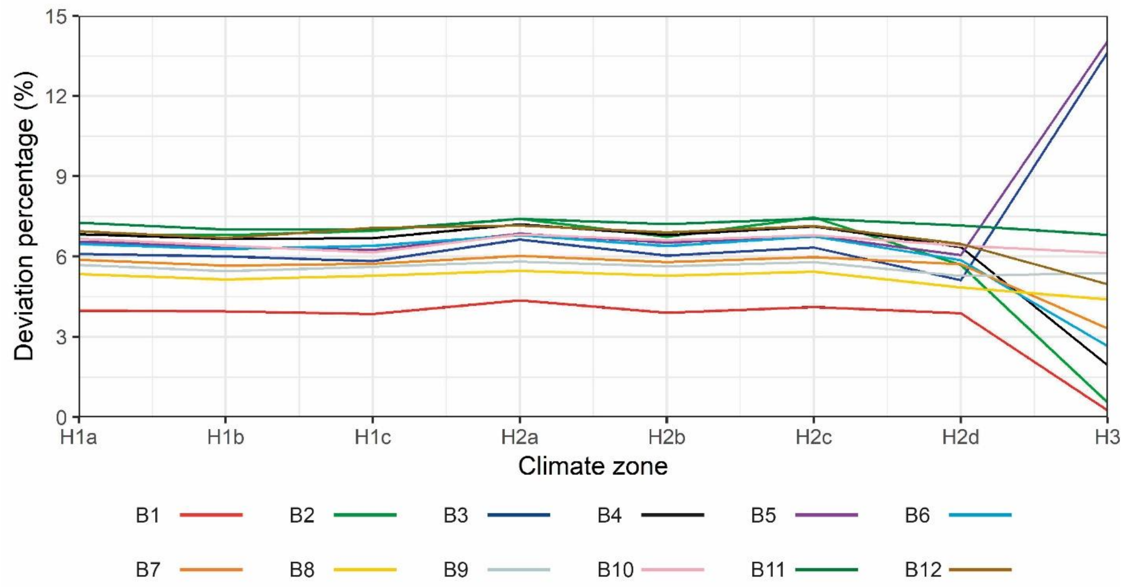

Figure 11. Percentage reduction of the total energy demand in the case studies analyzed with the new limit values for 2023 in France.

The results obtained in Portugal showed a better energy performance than that of France. In the climate zone where the lowest values were obtained (zone I2V1), the values of total energy demand oscillated between 44 and 469.1 kW·h·m^{-2} (see Table 15), whereas in the French zone H2a, they oscillated between 74.5 and 902.6 kW·h·m^{-2}. Comparing the results obtained in the different Portuguese climate zones, zone I2V1 presented average percentage reductions between 10.02 and 57.85% in the total energy demand with respect to the other zones. It is worth stressing that zone I2V2 also presented a lower total energy demand. If the limit value is more restrictive as the winter classification increases (i.e., a more restrictive value in zone I3 than in zone I1), these results highlight how some of these values adjust to the climate characteristics of each region. However, two aspects reflecting a certain limitation of the Portuguese regulation were found: (i) the values of total energy demand in the coldest regions (I3) were higher than those of the other winter climate zones, thus showing that the limit values for such zones need to be reviewed to guarantee that there is not a considerable energy difference between the buildings of the different zones; and (ii) in regions with the same winter climate classification, summer climate zones of type 3 presented a greater energy demand than zones 1 and 2 (e.g., zone I2V3 in comparison with zones I2V1 and I2V2), thus also reflecting the need to establish new limitations in the thermophysical properties according to the summer climate zone, which could be related to the thermophysical properties of windows (e.g., solar factor).

Table 15. Results of the total energy demand in the climate zones of Portugal.

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
I1V1	137.0	64.1	109.6	232.6	204.3	205.2	528.7	364.9	427.0	395.2	322.9	I1V1
I1V2	123.7	61.1	93.9	198.0	177.6	172.8	490.0	322.5	377.6	360.1	297.0	I1V2
I1V3	171.7	83.1	137.2	286.2	266.5	251.6	740.1	489.8	574.0	550.9	455.7	I1V3
I2V1	110.3	44.0	75.2	163.0	157.5	141.7	469.1	305.1	366.1	363.9	305.7	I2V1
I2V2	123.3	49.1	86.0	186.3	181.5	162.4	542.0	353.5	424.5	422.4	352.4	I2V2
I2V3	173.0	82.0	133.0	289.0	273.0	255.7	783.0	511.9	608.3	577.6	471.4	I2V3
I3V1	230.8	92.9	181.0	376.0	382.2	336.9	1147.7	770.0	928.8	914.9	735.7	I3V1
I3V2	191.5	78.1	139.7	291.9	283.6	259.7	832.2	557.3	667.0	648.7	533.2	I3V2
I3V3	187.0	74.7	133.2	285.1	278.3	250.7	822.9	545.8	652.9	639.3	524.3	I3V3

As for Spain, the results obtained were different and were characterized by a greater total energy demand despite the proximity and the possible similarity between the climate characteristics of Spain and Portugal. The lowest total energy demand was associated with zone C1, with a total energy demand oscillating between 66.9 and 677.6 kW·h·m^{-2} (see Table 16). The comparison with the other climate zones shows the huge difference with this climate zone, with a deviation percentage oscillating between 23 and 47.52%. The energy performance presented by the remaining zones was therefore higher than that of zone C1, thus showing a limitation of the limit values established by the CTE-DB-HE for the thermophysical properties of the envelope. The zones presenting a greater total energy demand were both cold (D2, D3, and E1) and warm (B3 and B4), and the latter associated the maximum values of energy demand in the 12 case studies (with values of total energy demand of up to 1306.4 kWh/m^2).

Table 16. Results of the total energy demand in the climate zones of Spain.

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
A3	203.4	121.5	194.9	387.6	322.4	327.8	862.6	553.4	657.5	624.7	556.1	463.3
A4	187.1	107.1	169.4	338.3	304.6	294.8	834.8	545.2	642.7	606.4	513.5	438.3
B3	289.3	178.4	291.6	576.2	513.8	509.8	1306.4	906.6	1050.1	972.2	797.7	790.9
B4	252.0	157.7	250.5	498.3	444.6	442.4	1219.6	813.4	968.2	881.1	723.8	639.7
C1	144.6	66.9	117.1	240.9	236.8	209.4	677.6	434.9	529.1	532.1	438.2	345.2
C2	239.5	144.8	228.6	414.0	394.3	415.6	1034.5	648.8	858.9	799.7	613.6	526.5
C3	246.9	133.4	220.2	448.6	423.9	395.3	1179.4	767.2	913.3	879.9	718.5	597.3
C4	237.0	133.3	206.7	436.9	405.5	387.8	1124.8	744.5	896.7	816.2	667.0	582.7
D1	200.7	89.2	164.7	336.0	339.2	296.4	984.1	641.9	779.0	778.3	625.2	492.8
D2	273.5	129.8	226.9	457.7	445.6	404.7	1265.6	829.0	1000.0	978.9	794.2	643.2
D3	253.4	130.2	234.7	461.1	430.3	411.8	1212.7	800.0	958.1	910.4	729.8	621.9
E1	276.6	128.2	226.0	459.3	448.3	405.6	1285.7	844.5	1018.3	997.1	811.0	650.4

Regarding the South American countries, three different behaviors were found, as Figure 10 shows: Brazil with a climate with a predominance of cooling energy demand, Argentina with a variable climate with a predominance of cooling or heating depending on the region, and Chile with a predominance of cold climates. In the case of the latter, Section 2 includes that NCh 1079 was the regulation establishing limit values for all climate zones. Despite this detailed regulation, the results obtained of total energy demand showed that there are notable differences between zones. The climate zone that presented the lowest total energy demand was the zone ND, with a percentage reduction between 29.07 and 79.95% (see Table 17). Thus, there was a huge deviation percentage between this zone and the others, as the remaining zones (except zone NL) had differences greater than 68%. The zone ND is characterized by establishing more restrictive values for the thermal transmittance of the envelope together with zones An and SE. Nevertheless, values of the NCh 1079 require review. Zones with more demanding limitations for the thermal transmittance should also be reviewed. The highest values of energy demand were obtained in zones An and SE, reaching maximum values of 1994.0 and 2246.5 kW·h·m^{-2}, respectively.

Table 17. Results of the total energy demand in the climate zones of Chile.

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
An	241.0	146.5	313.4	633.8	693.7	591.0	1994.0	1377.1	1684.7	1675.3	1270.0	998.9
CI	164.2	126.6	239.7	505.4	507.6	464.8	1468.5	1021.4	1230.2	1200.1	951.0	758.1
CL	178.4	139.4	263.2	536.2	542.2	493.6	1543.3	1063.1	1281.2	1257.4	986.0	793.6
ND	39.1	37.2	61.8	158.3	158.0	142.5	470.3	331.2	401.7	407.7	330.0	242.5
NL	60.5	53.4	97.0	219.2	240.9	197.2	674.3	440.4	535.7	579.8	424.0	323.3
NVT	145.8	112.9	225.7	485.2	516.4	447.9	1480.0	1011.2	1231.9	1254.6	964.0	751.3
SE	278.1	190.0	373.8	760.8	776.0	701.8	2246.5	1587.2	1911.2	1832.9	1438.6	1158.8
SI	231.7	157.6	316.2	645.9	672.3	598.5	1938.5	1350.0	1629.6	1588.2	1235.6	980.4
SL	182.4	129.2	259.8	538.2	563.4	498.1	1626.7	1124.1	1361.2	1346.3	1039.3	825.5

There was an improvement in the values of the total energy demand in the climate zones of Argentina. The values of total energy demand presented a maximum of 1680.4 kW·h·m^{-2} (see Table 18), thus meaning a reduction of 25.2% with respect to the maximum value of Chile recorded in the zone SE. Among the zones and the configurations with the best energy performance, the zone IVa was the most efficient. Limitations of IRAM 11605 and IRAM 11507-4 caused the percentage reduction of the case studies in this zone to oscillate between 36.39 and 65.0%. As the limit values established for the zone IVa were the same as those of the remaining zones III and IV (because the external temperature of design was the same), the best energy performance of the case studies was due to the climate of zone IVa. This aspect therefore shows that the detailed climate classification established by the standard IRAM 11603 does not present the same level of detail in the limit values of IRAM 11605, thus causing differences in the energy demand between the various zones. This would also be a reason why, in some cases, the energy demand obtained was lower in the coldest zones (V and VI) than in zones III and IV.

Table 18. Results of the total energy demand in the climate zones of Argentina.

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
Ia	159.2	96.4	179.4	328.7	322.8	311.4	926.4	652.3	763.0	685.3	685.3	685.3
Ib	182.3	97.6	178.3	308.5	299.6	294.1	844.2	586.8	679.6	600.1	600.1	600.1
IIa	148.1	97.5	180.8	338.6	335.0	318.9	957.8	672.4	789.1	715.6	715.6	715.6
IIb	153.3	99.6	185.0	343.3	339.7	325.3	977.5	693.6	814.3	733.7	733.7	733.7
IIIa	156.3	107.0	202.7	386.4	381.0	363.9	1104.5	789.1	932.7	848.8	848.8	848.8
IIIb	153.6	108.7	205.2	400.7	398.8	376.1	1158.1	827.5	979.4	898.3	702.8	582.5
IVa	61.2	37.4	84.1	190.3	208.8	176.5	640.2	461.6	568.4	544.5	425.7	318.3
IVb	150.6	96.2	179.5	338.3	332.9	319.0	961.1	681.2	800.9	724.8	557.2	473.6
IVc	207.2	149.5	285.7	580.3	571.7	538.5	1680.4	1205.3	1440.8	1330.2	1058.1	864.1
IVd	180.2	132.0	258.9	537.4	532.0	498.8	1584.2	1142.4	1365.1	1263.2	1009.2	815.1
V	153.9	107.7	204.4	406.7	401.3	379.8	1172.0	835.1	989.8	920.2	728.4	597.9
VI	130.9	93.2	176.0	358.3	356.4	333.7	1041.2	738.1	877.1	815.1	640.6	523.3

Finally, Brazil was the country associated with the greatest energy consumption. As Figure 10 shows, most climate zones are characterized by a greater cooling energy demand. Also, those zones with a greater percentage contribution of heating (Z1 and Z2) corresponded to zones with a low total energy demand (see Table 19). However, in zones with a greater contribution in the cooling energy demand, the values obtained were high. Values of total energy demand of 20183.4 and 34938.0 kW·h·m^{-2} were obtained in Z7 and Z8, respectively, mainly due to the limit values established by the standard NBR 15575. This standard establishes similar limit values for the different climate zones, being characterized by the values of thermal transmittance of walls between 3.7 and 2.5 W·m^{-2}·K. Likewise, the Brazilian regulation does not establish limit values for the thermophysical properties of windows, thus leading to the high energy demand obtained in the case studies between zones Z3 and Z8. This aspect is in accordance with the low energy label, which is obtained by most social housing built in the country according to the NBR 15575 [64].

Table 19. Results of the total energy demand in the climate zones of Brazil.

Zone	Total Energy Demand (kW·h·m^{-2})											
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
Z1	213.4	172.3	285.8	569.8	534.0	509.5	1456.1	1001.3	1204.4	1115.2	919.4	769.7
Z2	116.9	87.3	141.2	291.8	267.6	259.3	748.8	516.3	622.6	574.6	473.5	395.5
Z3	438.7	681.7	989.7	1537.5	1455.7	1589.6	3250.5	2070.5	2764.9	2008.6	986.4	1615.8
Z4	201.8	142.8	187.4	357.3	253.3	300.0	665.2	471.8	533.1	391.4	430.4	389.0
Z5	436.7	387.0	819.9	1245.2	1235.3	1364.6	3010.2	2001.0	2285.5	1412.8	848.7	1299.4
Z6	231.6	156.4	209.2	391.1	285.9	335.3	748.2	528.9	594.6	451.3	487.7	436.0
Z7	1994.7	2987.3	4398.9	10,341.6	8220.0	9776.0	20,183.4	17,717.2	17,725.9	13,019.7	8757.2	11,402.0
Z8	2614.7	3955.4	6484.0	12,161.2	12,993.1	9177.9	34,938.0	20,351.4	21,385.1	20,295.6	16,138.6	11,287.9

The values of the total energy demand between the regulation and the climate zones of the countries presented different tendencies (see Figure 12). The energy performance of the buildings built according to the Brazilian regulation is associated with a high energy impact in comparison with other countries. Consequently, new technical requirements need to be established in the thermal properties of the envelope with the objective of guaranteeing development and update of its efficient building stock with a low environmental impact. Regarding the other countries, Chile presents high values of total energy demand in some climate zones (e.g., SE and SI). There is also a notable difference in the tendencies of energy demand between the South American and the European countries analyzed; the latter were characterized by obtaining the lowest values of energy demand, whereas in the former, only some zones (e.g., ND in Chile and IVa in Argentina) obtained similar values. Despite the need to improve the European regulations, its wide development and update in recent years [23] has led to higher adjustment of thermal parameters of the envelope in different climate regions compared to the South American countries. This is shown, for example, in the case of Spain, with four modifications in the energy regulation of buildings since 1979 (NBE-CT-79 (1979), CTE-DB-HE 2006 (2006), CTE-DB-HE 2013 (2013), and CTE-DB-HE 2019 (2019)).

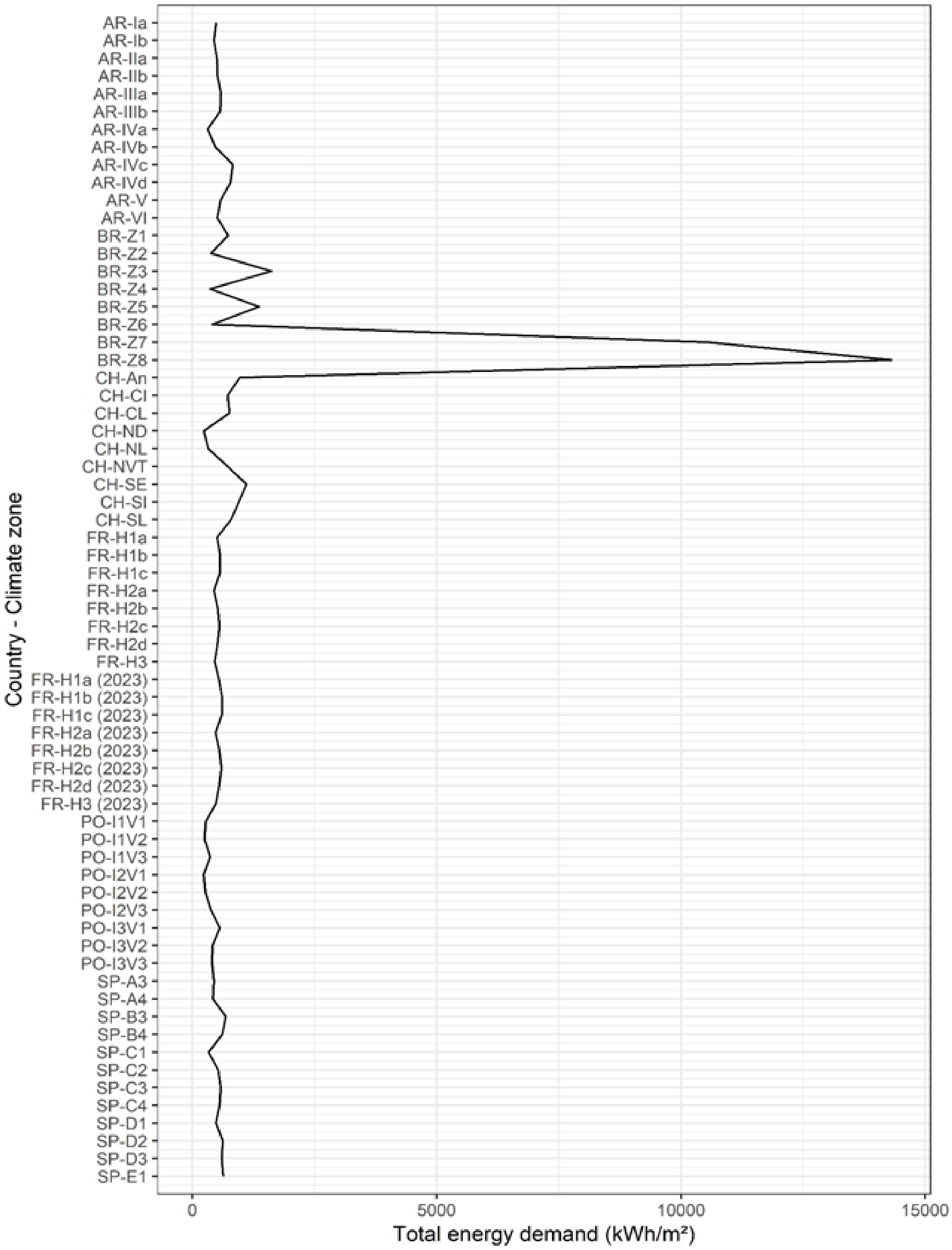

Figure 12. Linear tendency of the total average energy demand of the 12 models analyzed in the different climate zones and according to the limitations of each state regulation.

Finally, cluster analysis was conducted. Figure 13 shows the clustering of the climate zones of South America, and Figure 14 shows the clustering of the climate zones of Europe. A total of 13 clusters were obtained in South America, of which five were not grouped with any other climate zone, whereas 12 clusters were obtained in Europe with only two individual clusters. From the groups obtained based on the heating and the cooling degree-days, the variations presented by the case studies simulated in the same groups were compared. Figure 15 shows the box plots of the total energy demand of the zones studied in South America and Figure 16 shows those of Europe.

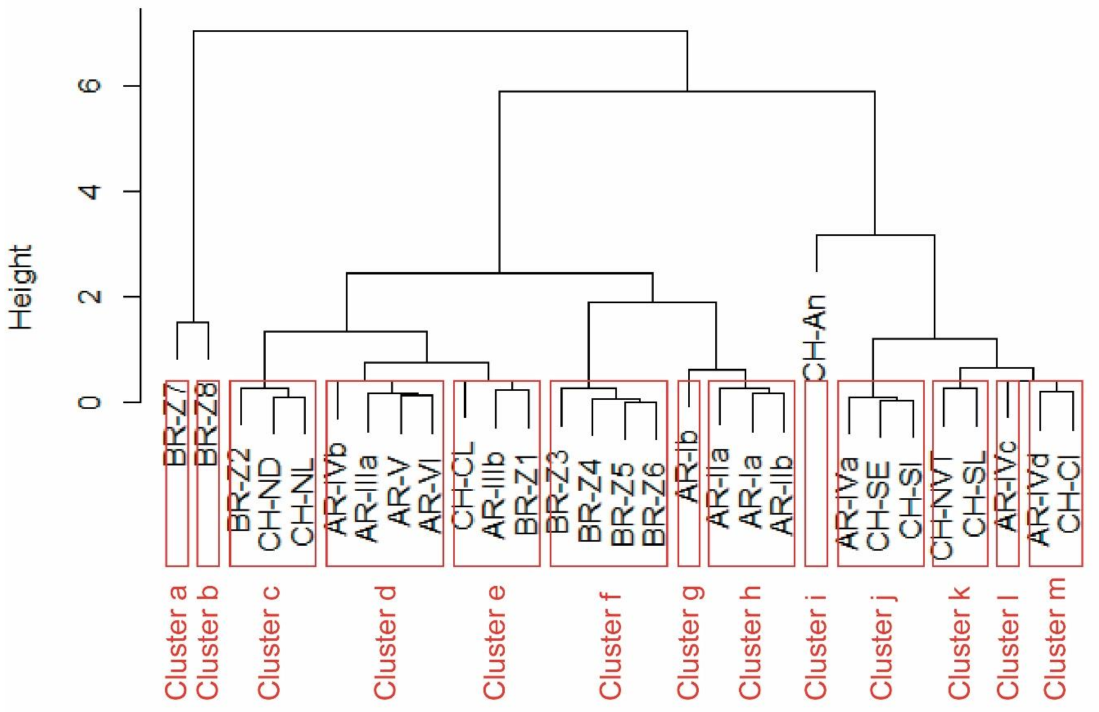

Figure 13. Clustering dendrogram of the climate zones of Argentina, Chile, and Brazil.

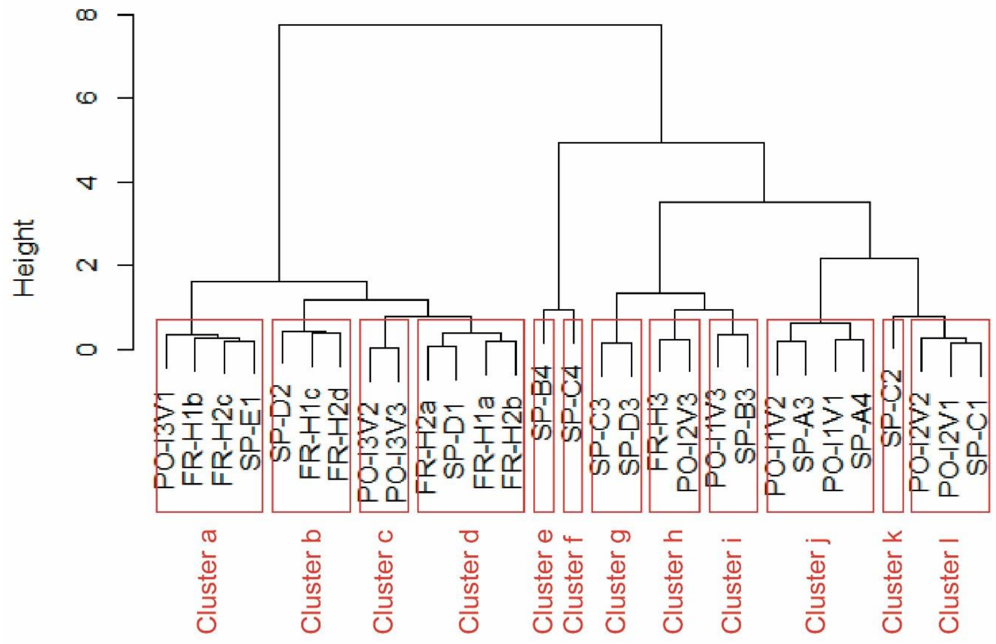

Figure 14. Clustering dendrogram of the climate zones of France, Portugal, and Spain.

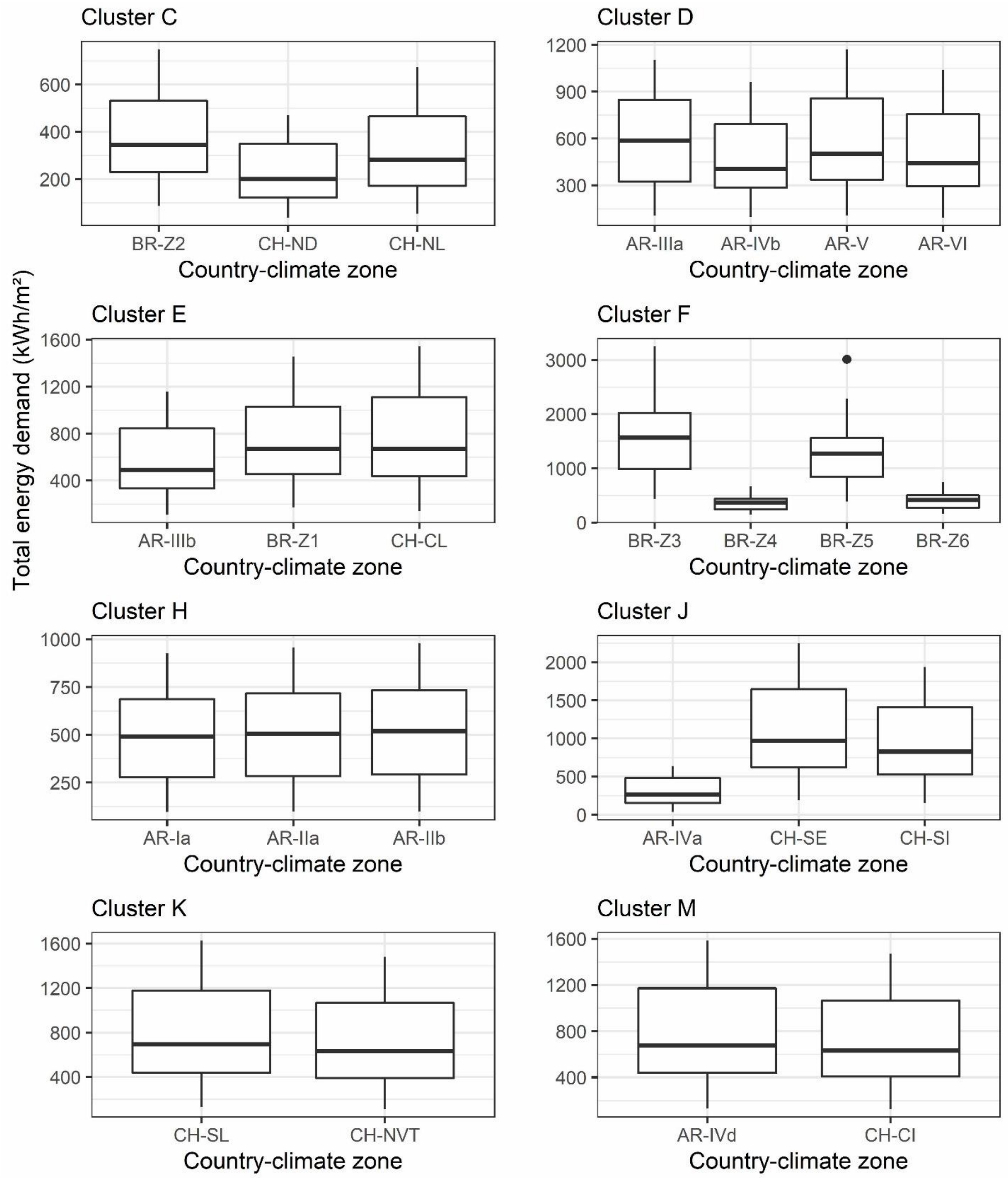

Figure 15. Distribution of the total energy demand between the climate zones grouped in the cluster analysis of South America.

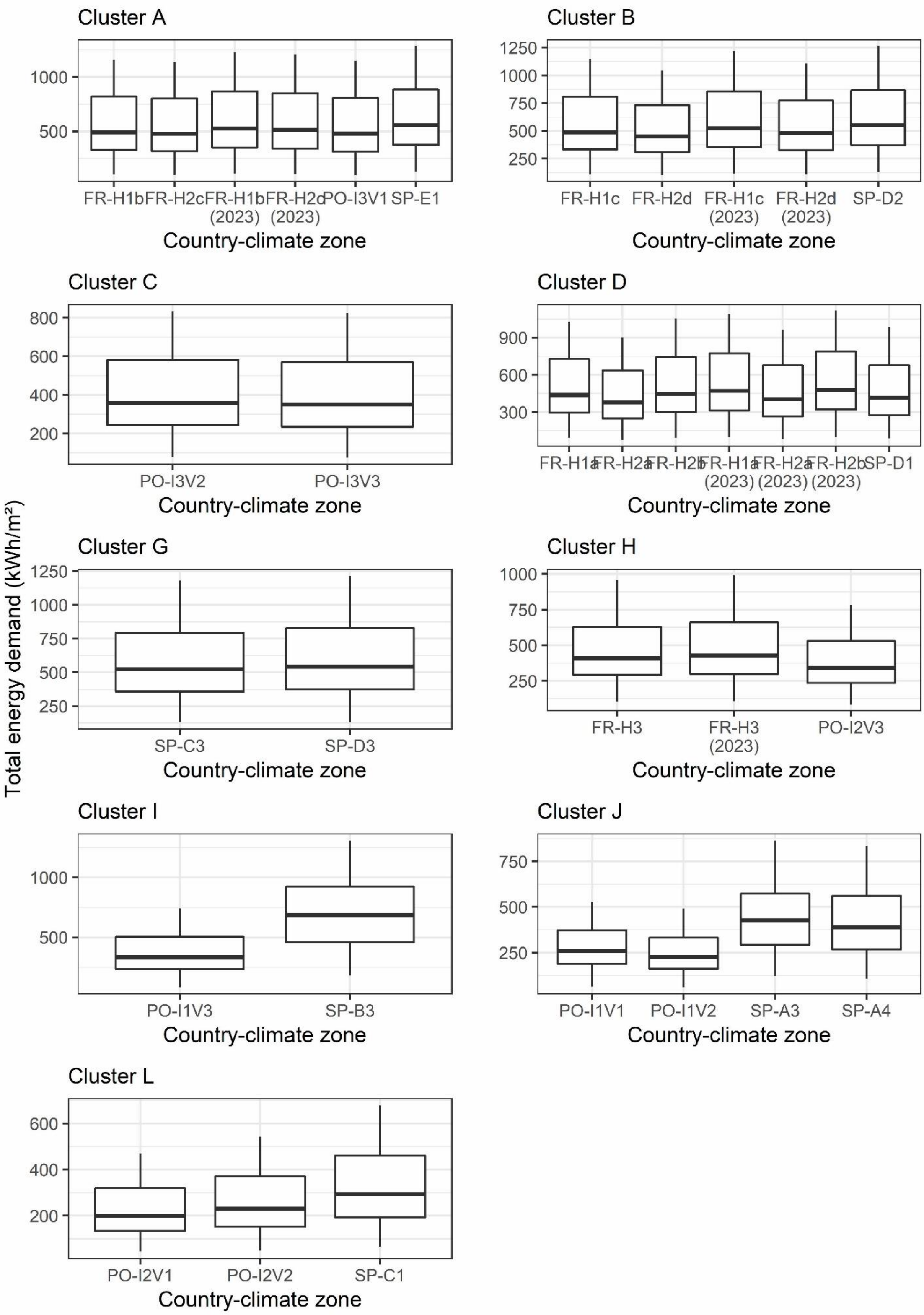

Figure 16. Distribution of the total energy demand between the climate zones grouped in the cluster analysis of Europe.

As for the groups between different South American countries, there were differences in data distributions. In cluster J, the total energy demand in the zone IVa was lower than in zones CH-SE and CH-SI. Also, in some clusters grouping zones of the same country, such as cluster F, there were great differences in the results of total energy demand between zones. In Europe, there were similarities between the climate zones of Spain and Portugal, where the existing difference in the energy demand obtained in the case studies can be seen. The results showed that the Portuguese regulation generated a better energy performance than the Spanish regulation. These results reiterate the need for a general review of the thermal properties established in the regulations of the different countries and the use of new thermal variables, such as the periodic variables of UNE-EN ISO 13786 [65]. In this regard, the Italian regulation establishes limit values for the periodic thermal transmittance of walls and roofs through the *Decreto Interministeriale 26 giugno 2015* [66].

Also, the similarity relationships found through the cluster analysis between the regions of the countries suggest the possibility of establishing a community framework that regulates both the climate classification between different countries and the requirements for buildings. As a result, a new bioclimatic classification for all South American countries could be developed to establish reference values between different countries and to reduce the inequalities between the energy performance of the buildings built in different regions. In addition, this new regulatory framework should consider the possible limitations presented by each country (e.g., economic limitations) to allow a sustainable development of the building stock.

5. Conclusions

This study analyzed the regulatory framework of the properties of the building envelope in countries of South America and Europe. Particularly, regulations on energy efficiency of buildings of Argentina, Brazil, Chile, France, Portugal, and Spain were analyzed. Comparisons were conducted with 12 simulated case studies, which were configured with the thermal demands for envelopes established by each country for their climate zones.

Results showed different tendencies between the regulation and the climate zones of the various countries. One of the most important aspects is the high energy demand of buildings built according to the limit values established in the Brazilian regulation. In addition, tendencies of performance clearly different between the South American and the European countries were found, with the latter being those with the lowest energy demands. A detailed analysis conducted by the technical bodies of the South American countries to improve the energy performance of their buildings would reduce these differences. This aspect should be understood as a process of constant evolution similar to what happened in the European countries, which have updated their energy regulations over the years. Nevertheless, there were differences in the energy performance of the buildings located in different climate regions of the European countries, thus leading to the need to review the limit values established by the state regulations of the European countries to guarantee the removal of the existing energy differences between the buildings built in different regions of the same country. In this sense, one of the highlights in the regulations of the various countries is that establishing limitations according to summer climate conditions is not considered. This aspect becomes important in countries such as Spain, where the main energy contribution in some of its climate zones is due to cooling.

The cluster analysis conducted between the different climate zones was also useful to highlight similarity patterns between various regions of the same continent. The subsequent analysis of the distributions of energy demand revealed that buildings located in similar climates but in different countries present energy performances significantly different, thus leading to the same problem reflected between the energy differences in buildings of the same country. As occurs at a country scale, the development of regulations limiting the differences of energy performance between regions should be guaranteed at a continental scale. Climate analysis between countries to establish a valid climate classification for a whole continent, the proposal of new limit values, and even the use of other variables such as periodic thermal transmittance should be aspects to be reviewed by the leaders of countries.

To conclude, the contribution of this research to the energy saving of buildings is that limitations were found in the regulations of their envelopes. The efforts made by the governments of the countries analyzed to establish controls in the thermal parameters of the building envelopes to ensure an acceptable energy performance were highlighted. However, based on the results of this research, differences were found in the energy demand, thereby opening the discussion on the need for new criteria when establishing these policies at a state level. The development of more demanding policies related to the thermal properties of buildings and the analysis at a continental level could reduce the differences between countries and guarantee a more sustainable life for the building stock.

6. Limitations and Future Work

Further steps of this research will be focused on the energy analysis of actual buildings built in accordance with the regulations of the various countries. One of the limitations of this study is that the energy analysis was carried out with simulations. Although EnergyPlus has a good performance in the results obtained in many studies, the use of actual data would allow the existing discussion between the differences in the regulations of buildings to be deeply analyzed.

Moreover, new possibilities in the thermal properties of different countries and the possibilities of using global criteria of climate classification to establish policies at a continental scale should be analyzed. In this sense, the control of the thermal mass, the periodic thermal properties, the solar factor, etc., could constitute new possibilities of thermal regulation.

Author Contributions: All the authors contributed equally to this work. All the authors participated in preparing the research from the beginning to end, such as establishing the research design, method, and analysis. All the authors discussed and finalized the analysis results to prepare the manuscript in accordance with the research progress. All the authors have read and approved the final manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to acknowledge "Erasmus+ traineeship" for financing the international mobility of David Bienvenido-Huertas at the Universidade do Algarve.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of cities used for each climate zone.

Country	City	Climate Zone (Winter)	Climate Zone (Summer)	Latitude	Longitude	Altitude
Argentina	Vera	Ia	–	−29.466667	−60.216667	48
	Empedrado	Ib	–	−27.954262	−58.808912	56
	Arauco	IIa	–	−28.568333	−66.801389	768
	Concordia	IIb	–	−31.392222	−58.016944	21
	San Lorenzo	IIIa	–	−32.75	−60.733333	40
	Buenos Aires	IIIb	–	−34.599722	−58.381944	25
	Cochinoca	IVa	–	−22.745	−65.896667	3552
	Rivadavia	IVb	–	−31.3242	−61.0511	33
	Picún Leufú	IVc	–	−39.52351	−69.27966	411
	Balcarce	IVd	–	−37.846412	−58.255625	97
	Escalante	V	–	−33.171111	−62.768889	118
	Tinogasta	VI	–	−28.066667	−67.566667	1204
Brazil	Caixas do Sul	Z1	–	−29.167778	−51.178889	817
	Ponta Grossa	Z2	–	−25,095	−50.161944	975
	Florianópolis	Z3	–	−27.593281	−48.553047	0
	Brasilia	Z4	–	−15.793889	−47.882778	1171
	Santos	Z5	–	−23.960833	−46.333889	2
	Goiânia	Z6	–	−16.678889	−49.253889	749
	Picos	Z7	–	−8.086944	−42.051944	292
	Belém	Z8	–	−1.455833	−48.503889	10
Chile	San Pedro de Atacama	An	–	−22.9108	−68.2001	2408
	Santiago	CI	–	−33.45	−70.666667	520
	Valparaiso	CL	–	−33.045944	−71.616361	10
	Calama	ND	–	−22.4624	−68.9272	2400
	Antofagasta	NL	–	−23.6464	−70,398	40
	Vicuña	NVT	–	−30.016667	−70.7	650
	Cochrane	SE	–	−47.266667	−72.55	2
	Lautaro	SI	–	−38.529167	−72,435	217
	Concepción	SL	–	−36.833333	−73.05	12

Table A1. *Cont.*

Country	City	Climate Zone (Winter)	Climate Zone (Summer)	Latitude	Longitude	Altitude
France	Paris	H1	a	48.856944	2.351389	33
	Orleans	H1	b	47.902222	1.904167	116
	Grenoble	H1	c	45.186944	5.726389	212
	Vannes	H2	a	47.655	−2.761667	22
	Bourges	H2	b	47.083611	2.395556	153
	Rodez	H2	c	44.35	2.574167	572
	Privas	H2	d	44.735	4.599167	322
	Nimes	H3	–	43.836944	4.36	39
Portugal	Lagos	I1	V1	37.1	−8.666667	10
	Setúbal	I1	V2	38.524306	−8.892611	40
	Évora	I1	V3	38.5725	−7.907222	295
	Porto	I2	V1	41.149472	−8.610778	104
	Braga	I2	V2	41.533333	−8.416667	215
	Castelo Branco	I2	V3	39.823	−7.493139	319
	Guarda	I3	V1	40.536389	−7.268333	1056
	Vila Real	I3	V2	41.30021	−7.73985	420
	Lamego	I3	V3	41.083333	−7.866667	493
Spain	Cádiz	A3	3	36.516667	−6.283333	13
	Almería	A4	4	36.833333	−2.45	16
	Mallorca	B3	3	39.566667	2.649722	24
	Sevilla	B4	4	37.383333	−5.983333	11
	A Coruña	C1	1	43.366667	−8.383333	21
	Barcelona	C2	2	41.3825	2.176944	13
	Granada	C3	3	37.178056	−3.600833	684
	Badajoz	C4	4	38.880278	−6.975278	182
	Lugo	D1	1	43.011667	−7.557222	462
	Salamanca	D2	2	40.965	−5.663889	798
	Madrid	D3	3	40.418889	−3.691944	657
	Ávila	E1	1	40.654347	−4.696222	1131

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