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Influence of Balcony Thermal Bridges on Energy Efficiency of Dwellings in a Warm Semi-Arid Dry Mediterranean Climate

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Abstract: Thermal bridges significantly influence the energy performance of buildings. However, their impact varies depending on the type of thermal bridge, climate conditions, construction methodologies, and geometric characteristics of the building. On the Spanish Mediterranean coast, buildings with large balconies are predominant. Nevertheless, the Spanish energy efficiency regulations do not adequately specify the thermal bridges at the junctions of balconies with facades, leading to a lack of consideration for their influence in the majority of architectural projects. The objective of this study is to qualitatively and quantitatively assess the impact of such thermal bridges on the energy efficiency of buildings in a dry Mediterranean climate (BShs) within a warm semi-arid climate (BSh). As a case study, the influence of this thermal bridge is analyzed in two residential buildings located on the Mediterranean coast of southeastern Spain. The study also examines the modification of various construction parameters of this thermal bridge and determines the optimal design parameters to reduce its thermal transmittance. The results demonstrate that the energy needs caused by thermal bridges account for approximately 40% of the total annual energy needs of the studied residential buildings. Balcony thermal bridges account for 25% to 40% of the energy needs caused by all thermal bridges. The lack of differentiation in Spanish standards between balcony–facade and facade–slab edge junctions causes an imprecision in calculations equivalent to 12% of the total annual energy needs of dwellings. The novelty of this research lies in highlighting that current regulations and calculation programs need improvement to better characterize balcony thermal bridges and enhance the accuracy of building energy efficiency calculations.

Keywords: balcony thermal bridges; energy efficiency; hygrothermal performance; indoor thermal comfort; sustainable rehabilitation; warm semi-arid dry Mediterranean climate

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1. Introduction

The Spanish energy-saving regulations [1,2], in accordance with European regulations [3,4], primarily emphasize five aspects: reducing the thermal transmittance of opaque enclosures and thermal bridges, reducing the thermal transmittance of glazing, controlling solar gains through glass, regulating air renewal through ventilation, and minimizing air infiltrations. The improvement of construction materials and products has allowed enhancing all these parameters. However, reducing thermal bridges is the most challenging aspect to address because it involves modifying the typical construction techniques in Spain. As some research highlights, the percentage impact of thermal bridges on the building's energy needs increases with the improvement of its thermal insulation [5]. Therefore, the increase in regulatory insulation requirements for enclosures also raises the percentage of thermal bridges in the total heat loss of the house, emphasizing the importance of their control and reduction [6].

In cold European regions, regulations require the elimination of thermal bridges due to high thermal losses and the risk of condensation, mold growth, and deterioration of building elements. In temperate and warm Mediterranean climates, correcting thermal bridges is not mandatory by regulations because condensation issues typically do not occur due to thermal bridges. However, despite the milder severity of the Mediterranean climate not making the elimination of thermal bridges essential, their influence on the energy needs of buildings is still significant [7]. Numerous studies suggest that thermal bridges in residential buildings significantly increase heating and cooling loads, though results vary depending on the climate and calculation methods [8,9]. Some estimates indicate that thermal bridges can contribute up to 20% of the total energy consumption of a home, with variations depending on climate types [10]. Other studies specify that in mild Mediterranean climates, thermal bridges may cause up to 25% of heating needs but only 3.5% of cooling needs, averaging around 8.5% annually. Therefore, cost-benefit analyses from these studies argue that the savings achieved by reducing thermal bridges in warm climates are insufficient to recover the additional construction costs incurred to eliminate them [11].

According to Spanish and European regulations, thermal bridges are areas in the building enclosure where thermal resistance is significantly lower compared to the rest of the enclosure due to materials with higher thermal conductivity, changes in enclosure thickness, or differences between internal and external areas [12,13]. The regulations consider the following thermal bridges: the facade–slab front encounter, the facade–pillar encounter, the facade–roof encounter, the facade–lower slab encounter exposed to outdoor air, the facade–ground encounter in contact with the ground, the outlines of window and door openings, and the corners [12]. Thermal bridges are calculated according to European regulations [13–16] and are measured by their linear thermal transmittance. Spanish regulations and official calculation programs [17–20] include the mentioned list of thermal bridges with their specific characteristics for calculating the building's energy needs.

However, the list of thermal bridges considered by the regulations and calculation programs does not include a very common type of thermal bridge on the Spanish Mediterranean coast: the encounters of balconies with facades. Along the Mediterranean coast of Spain, since the tourist boom of the 1960s and 1970s, there are numerous tourist apartment buildings with large balconies [21], providing spacious outdoor areas to enjoy the warm and sunny climate of the Mediterranean coast [22] and protecting the windows from the intense solar radiation of this geographic area [23–25]. These beachfront buildings were traditionally used as second homes only in the summer [26], but this architectural style has become widespread and is now applied to most residential buildings in the BShs climate [27]. Therefore, this architectural typology is very common on the Mediterranean coast, increasing the prevalence of facade–balcony encounters. This type of thermal bridge has specific construction and geometric characteristics. A balcony is an extension of the structure's slab that protrudes from the facade plane, interrupting the thermal envelope, and the construction solution to avoid the thermal bridge is complex. However, regulations and calculation programs do not differentiate between facade–balcony encounters and facade–slab front encounters, considering them the same type of thermal bridge even though they have different thermal transmittances. Additionally, the thermal bridge catalog in the regulations simplifies some construction parameters that influence the linear thermal transmittance of thermal bridges. Therefore, it is advisable to study and analyze in detail the thermal behavior of these two types of thermal bridges and their influence on the overall calculation of thermal gains and losses in buildings in this climate.

Numerous studies in colder countries highlight that balcony slabs are one of the thermal bridges that have a significant negative impact on the energy efficiency of buildings [28–31]. They affect thermal comfort [32,33] and contribute to increased condensation issues [34,35]. Their geometry and surface make them heat exchangers [36]. There are various studies emphasizing the advantages of using thermal break elements in cantilevered slabs of structures to reduce thermal bridging in balconies and overhangs [37]. These construction solutions can reduce the linear thermal transmittance of thermal bridges by more than 60% [38] and decrease heating consumption by 5% to 13% and cooling consumption by 1% [39]. However, other research limits the impact of thermal break disruptions in balconies on the overall thermal and energy performance of the building, demonstrating that their effect on annual energy consumption is relatively small [40].

In the southeastern part of Spain, these construction solutions are not employed due to their high cost. There are other more economical construction alternatives, such as thermally insulating balcony slabs from below and above. However, analyses conducted by some research studies demonstrate that balcony thermal insulation is also not economically efficient in mild climates [41].

Other construction systems with many years of application in Central Europe, such as External Thermal Insulation Systems (ETICS), are now being widely implemented on the Spanish Mediterranean coast. Their widespread adoption is primarily due to their advantages in reducing thermal bridges on facades [42,43]. There are even studies demonstrating the benefits of using insulated cornices and moldings to complete all the distinctive junctions of the exterior thermal envelope of facades with ETICSs [44]. However, thermal bridges on balconies are challenging to avoid because the ETICS is interrupted by the structure. This limits its advantages, as shown by research in other climatic zones [45]. Other studies conducted in Mediterranean climates have demonstrated that insulating from the interior has a higher cost/benefit ratio than the ETICS [46]. They also caution against the lack of optimization and cost-effectiveness of using exterior insulation with excessive thickness in mild climates [47]. However, these studies do not specify the parameters influencing the energy needs of homes in the BShs climate based on the construction system employed.

Given the lack of conclusive data and specific results for the characteristics of the BShs climate and the imprecision of Spanish regulations regarding thermal bridges on balconies, studies are needed to analyze their influence on the energy needs of buildings on the Spanish Mediterranean coast.

This work comparatively analyzes the influence of different thermal bridges in a group of recently constructed residential buildings on the Mediterranean coast of southeastern Spain to determine which thermal bridges are more predominant using thermographic images. Subsequently, it conducts a detailed analysis of the thermal bridges on balconies and slab fronts in two buildings, qualitatively and quantitatively determining their influence on energy efficiency. The study also assesses whether Spanish energy-saving regulations adequately consider these thermal bridges. To achieve this, the study employs a combination of field measurements and computer simulations. Detailed thermographic photographs were taken to qualitatively assess the thermal bridges. A thermal transmittance flowmeter was used to quantify the thermal transmittances of the facades and thermal bridges. The impact of the analyzed thermal bridges on the total annual energy needs of the inspected dwellings was evaluated through computer simulations. Finally, it conducts a detailed study to determine the influence of modifying various construction and geometric parameters of these thermal bridges to identify optimal construction solutions using computer simulations. This work considers the most common construction solutions currently used in buildings on the Spanish Mediterranean coast, with conventional ceramic brick envelopes, laminated plaster beaches, and insulation such as rock wool and expanded or extruded polystyrene. Therefore, more efficient thermal insulation materials or more innovative building solutions with phase change materials [48,49] are not considered.

The objective is to qualitatively and quantitatively determine the influence of thermal bridges at the facades' encounters with balconies on the energy efficiency of buildings in a dry Mediterranean climate (BShs) within a warm semi-arid climate (BSh). The novelty of this study lies in demonstrating that current regulations and calculation programs need improvement to characterize these thermal bridges more accurately and enhance the precision of energy efficiency calculations. The work complements and refines the typological database of thermal bridges contemplated by regulations and evaluates and determines optimal design parameters to reduce the linear thermal transmittance of the most predominant thermal bridges.

2. Materials and Methods

2.1. Methodology

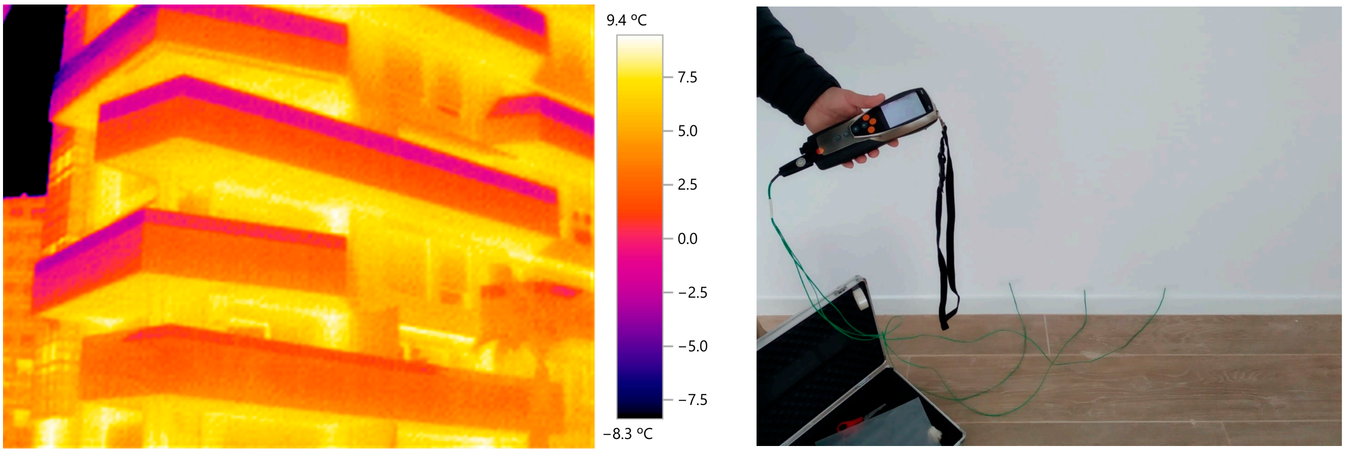
The methodology consisted of three phases. First, a comparative analysis was conducted on the majority of buildings constructed in Alicante in the last two years using thermal images to identify the most significant and common types of thermal bridges in this geographic area. Subsequently, two representative buildings were selected, CS1 (case study 1) and CS2 (case study 2), for a qualitative and quantitative analysis of the chosen thermal bridges through thermal imaging and on-site measurements. The influence of the selected thermal bridges on the total energy needs of the two studied buildings was quantified using computer simulations. Finally, various modifications to the construction and geometric parameters of the selected thermal bridges were studied, and their impact on the energy efficiency of the building was calculated through computer simulations. This methodology allowed for the identification of the most significant thermal bridges in residential buildings in this geographic area, quantifying their influence on the energy needs of the homes and determining optimal construction solutions to reduce thermal gains and losses, thereby improving the energy efficiency of the buildings.

Phase 1. Twenty-six buildings constructed between 2018 and 2022 were selected based on the database of the Architects' Association of Alicante. Thermal images of their facades were taken to differentiate qualitatively the zones of the building envelope with varying thermal insulation and to detect thermal bridges based on temperature differences on the surfaces of the facades [50].

The thermal bridges considered by the regulations were identified, related to the complete or partial penetration of construction elements with different thermal conductivity or changes in the thickness of the enclosure. Thermal bridges related to differences between the internal and external areas of the enclosure at corners were not considered because they are not associated with the employed construction systems and cannot be detected thermographically.

The percentage of the facade surface occupied by each type of thermal bridge was measured. Additionally, the thermal difference between the average surface temperature of each type of thermal bridge and the average temperature of the rest of the facade was measured. With these data, the Thermal Bridge Wall Ratio (THBWR) was calculated for each thermal bridge. This index indicates the proportion between the surface area multiplied by the temperature difference for each thermal bridge and the total sum of surface areas and average temperatures for all thermal bridges. This process established a classification of the most representative and common thermal bridges in the studied buildings. In this classification, the connections of balconies with facades were differentiated from the rest of the connections at slab edges due to their specific construction and geometric characteristics.

Phase 2. Two representative buildings were selected, CS1 (case study 1) and CS2 (case study 2), to qualitatively and quantitatively analyze the most significant thermal bridges. Detailed thermographic photographs were taken to qualitatively study the selected thermal bridges (Figure 1a). The purpose of conducting thermographic images is to obtain approximate information about the temperatures of the exterior surfaces of the different areas of the facade. This allows us to detect which areas of the facade experience greater energy loss from the interior to the exterior of the building in winter and, thus, which areas of the enclosure have higher thermal transmittance. On-site measurements were taken to quantify thermal transmittances of the facades and thermal bridges by using a thermal transmittance flowmeter (Figure 1b). The purpose of using the thermal transmittance flowmeter is to approximately quantify the thermal transmittance per unit area of the enclosure, thereby allowing us to approximately estimate the linear thermal transmittance in the thermal bridges. This method allowed for more precise on-site quantification of the heat flow in different areas of the enclosures of each of the two analyzed dwellings.



(**a**) (**b**)

Figure 1. On-site measurements of the studied building enclosures: (**a**) thermographic photograph; (**b**) thermal transmittance measurement.

Next, the influence of the analyzed thermal bridges on the total annual energy needs of the two examined dwellings was quantified through computer simulations. To achieve this, the energy needs of each dwelling were calculated, taking into account the actual thermal transmittance data of the building enclosures obtained from on-site measurements. The total annual energy needs caused by the linear thermal transmittance of all thermal bridges regulated by standards were independently calculated. Additionally, the total annual energy needs caused by the thermal transmittance of opaque enclosures, the thermal transmittance of glazing, solar radiation through glass, air exchanges through ventilation, and air infiltrations were also computed. Subsequently, the proportion of thermal gains and losses caused by all regulated thermal bridges that constitute the connections of balconies and the remaining floor slab edges on the facades was determined. Firstly, the total thermal gains and losses caused by all thermal bridges were calculated. Then, the gains and losses were recalculated by eliminating the thermal bridges in the floor slab edges of the facades, and the results were compared. Finally, the gains and losses were recalculated by only eliminating the thermal bridges in the connections of balconies and facades.

Phase 3. Computer simulations were used to evaluate the thermal effect of the modification of various geometrical and constructive parameters of the analyzed thermal bridges in the two selected buildings, CS1 and CS2. Before calculating the new proposals, we proceeded to adjust and validate the calculations made with the energy simulation tool. For this purpose, computer simulations were compared with actual measurements obtained from the electricity consumption records of the dwellings studied. The annual energy needs were calculated by computer simulation comparing the results obtained with the actual measurements.

Thermal bridges at balcony and slab-front junctions in the two buildings studied were specifically analyzed. It was calculated how the modification of the thermal insulation of these thermal bridges influences their linear thermal transmittance and the total energy needs of the dwellings.

Thermal insulation improvement can be achieved by increasing its thickness, reducing its thermal conductivity, or combining both solutions. In this study, it was decided to modify the insulation thickness for easier comparison of changes in construction parameters. The thermal insulation of the facades, floors, and ceilings was modified with different insulation thicknesses. This methodology allowed for quantifying the impact of the thermal insulation improvement on the reduction in the total energy needs of the dwellings and determining optimal construction solutions. Four different options were calculated for the two selected buildings, CS1 (case study 1) and CS2 (case study 2), with the current characteristics, with less insulation and with more insulation (Table 1).

Table 1. Summary of thermal insulation characteristics of the thermal bridges of the four calculated options in the two selected buildings: case study 1 (CS1), case study 2 (CS2).

Isolation Situation	Option 1 Very Low Isolation	Option 2 Low Isolation	Option 3 Current Features	Option 4 More Isolated
	CS1/CS2	CS1/CS2	CS1/CS2	CS1/CS2
False ceiling indoor dwelling	-/-	30 mm MW (0.035 W/m·K)/20 mm XPS (0.034 W/m·K)	60 mm MW (0.035 W/m·K)/40 mm XPS (0.034 W/m·K)	90 mm MW (0.035 W/m·K)/60 mm XPS (0.034 W/m·K)
Indoor floor dwellings	-/-	20 mm EPS (0.030 W/m·K)/-	40 mm EPS (0.030 W/m·K)/-	60mm EPS (0.030 W/m·K)/-
External insulation (ETICS) slab front (alternative solution only in dwelling 2)	-/-	-/20 mm EPS (0.032 W/m·K)	-/40 mm EPS (0.032 W/m·K)	-/60mm EPS (0.032 W/m·K)

The methodology used is shown in a flow chart below (Figure 2).

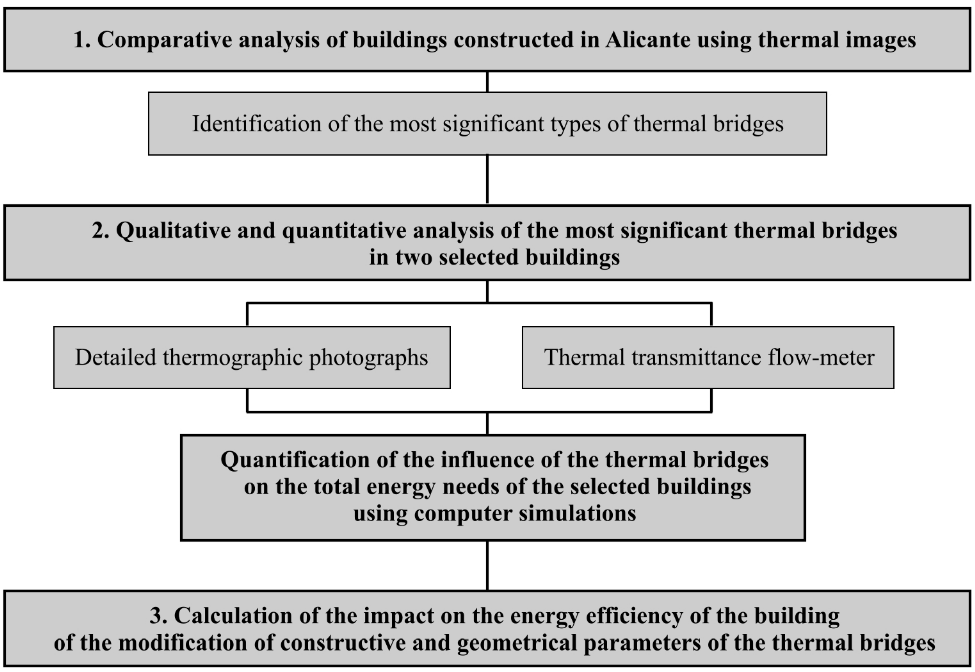
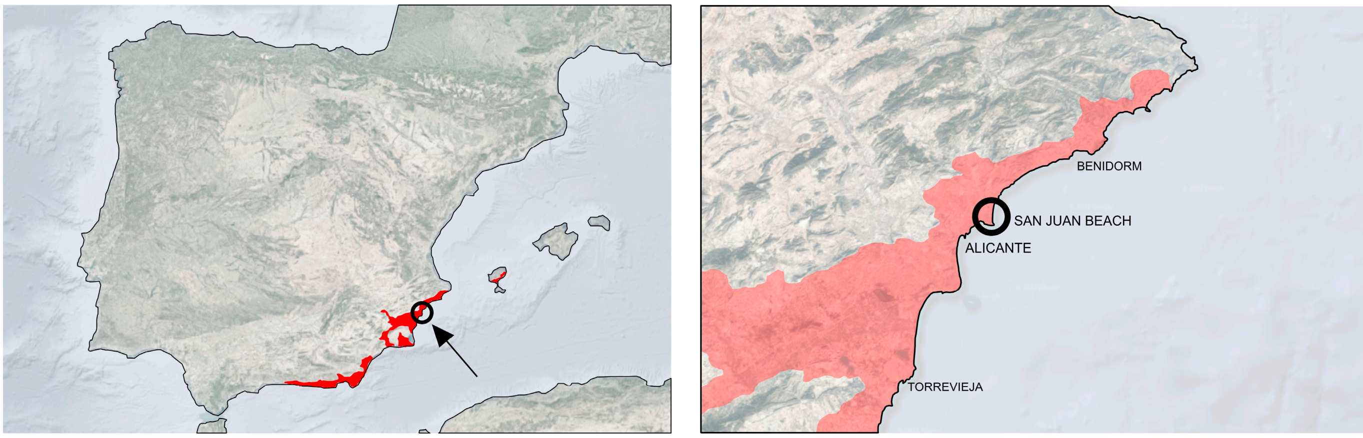


Figure 2. General flow chart of the method.

2.2. Case Studies

The buildings in the case study are located in Playa de San Juan, Alicante (Spain). The area has a dry Mediterranean climate (BShs) within the warm semi-arid climate zone (BSh) according to the Köppen-Geiger climate classification [51] (Figure 3) and a B4 climate according to Spanish legislation [52]. This climate experiences lower annual temperature fluctuations compared to most climates due to the Mediterranean Sea breeze acting as a thermoregulator. As a result, winters are mild, and summers are not excessively hot, with an average winter temperature of around 18 °C and a summer temperature of approximately 27 °C. This climate is characterized by high radiation all year round.



(**a**) (**b**)

Figure 3. (**a**) Geographical area of BShs climate in Spain (red); (**b**) building location.

Two residential buildings were studied. The case study buildings were selected among the last residential buildings constructed in this city. Their construction finished in 2022. The architectural typology of the buildings and their dimensions, as well as the typologies of the dwellings and their dimensions, are very common in current buildings in this geographic area. The first selected building is a nine-story structure with a rectangular plan geometry measuring 60 m in length and 20 m in width. The second selected building is a four-story structure with a rectangular plan geometry measuring 55 m in length and 16 m in width. Both buildings receive ample sunlight and are surrounded by residential structures with numerous landscaped areas. The analyzed dwellings feature a living area of approximately 90 m^2. Each dwelling includes a living-dining room, a kitchen, three bedrooms, two bathrooms, and spacious exterior balconies on their facades (Figure 4).

(**a**) (**b**)

Figure 4. (**a**) Case study buildings: (**a**) external image of building 1; (**b**) external image of building 2.

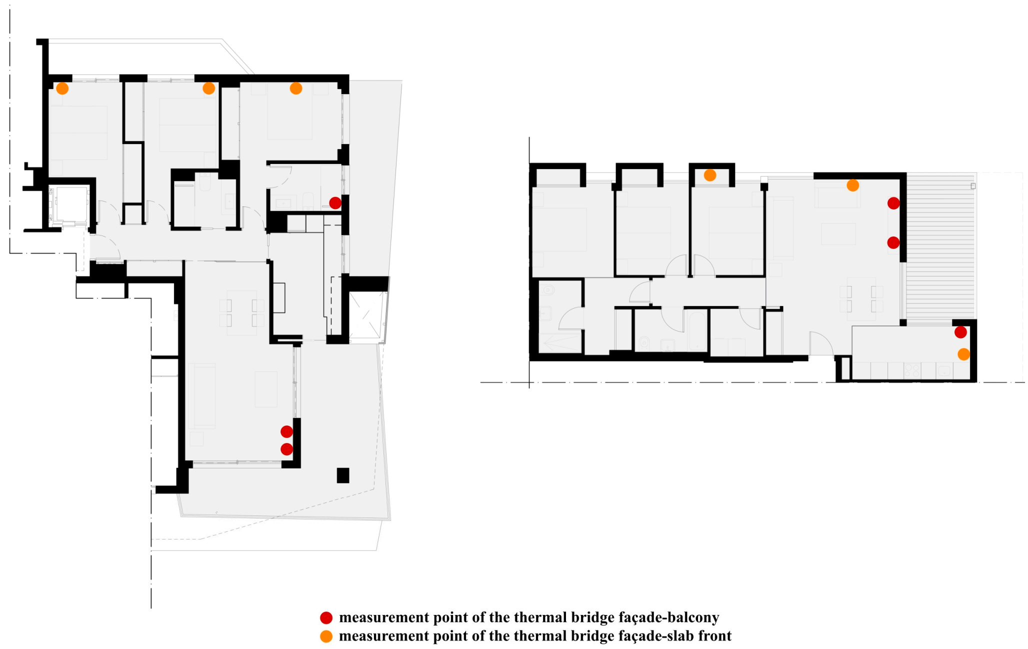
These buildings were chosen because they were recently constructed and comply with the latest energy efficiency standards. Additionally, they feature architectural and construction typologies that are very common in this geographic area. Both buildings have spacious balconies, and each is executed using one of the two most common construction techniques in Spain currently. The first one has facades made of exposed brick, thermally insulated from the inside with additional cladding. The second one has facades with a continuous External Thermal Insulation System (ETICS). This allows for the analysis of thermal bridges, considering current standards, architectural typologies, and the most common construction techniques in this area. Consequently, these results and conclusions can be extrapolated to the majority of new residential buildings in the coastal areas of Southern Spain and Europe.

2.3. Methodological Details and Tools

The thermographic measurements of the 26 studied buildings were conducted in winter (January and February 2023), between 23:00 h and 02:00 h. The goal was to avoid distortion of the temperature reflected from solar radiation and to maintain a thermal difference of around 15 °C between the interior of the dwellings and the exterior temperature, aiming to minimize the margin of error of the equipment. Mean outdoor temperatures were between 6 and 10 °C during the measurements. Occupied dwellings were assumed to have indoor temperatures between 21 and 25 °C at the time.

Both the thermographic measurements and the in situ thermal transmittance measurements of the two selected buildings were carried out during the night, between 23:00 h and 02:00 h, in the coldest week of the year, with heating active inside the dwellings. Mean outdoor temperatures were between 6 and 7 °C, and indoor temperatures were between 21 and 23 °C. The objective was to achieve the maximum thermal difference between the interior and exterior, ensuring the highest precision in the measurements. The thermographic measurements considered the average emissivity of the building materials of the facades, around 0.90. The humidity and outside temperatures were also measured. Measuring instruments were to be switched on five minutes before taking the measurements to allow the sensors to acclimatize to the indoor and outdoor environment.

On-site measurements with the thermal transmittance flowmeter were taken from the interior of the dwellings. Three types of thermal transmittance measurements were taken for each of the two analyzed dwellings. Measurements were conducted in the center of each facade section to determine the average thermal transmittance of the facade. Measurements were also taken in areas of the facade close to the junction with the floor slab edge, and measurements were taken in areas of the facade near the junction with the balconies. Measurements were taken at different points of the facade–slab and facade–balcony junctions to verify that windows and other thermal bridges (columns, jambs, corners, etc.) had no influence (Figures 5–7).



(**a**) (**b**)

Figure 5. Drawings of the two analyzed dwellings indicating the measurement points: (**a**) case study 1 (brick facade with interior insulation and cladding); (**b**) case study 2 (facade with ETICS).

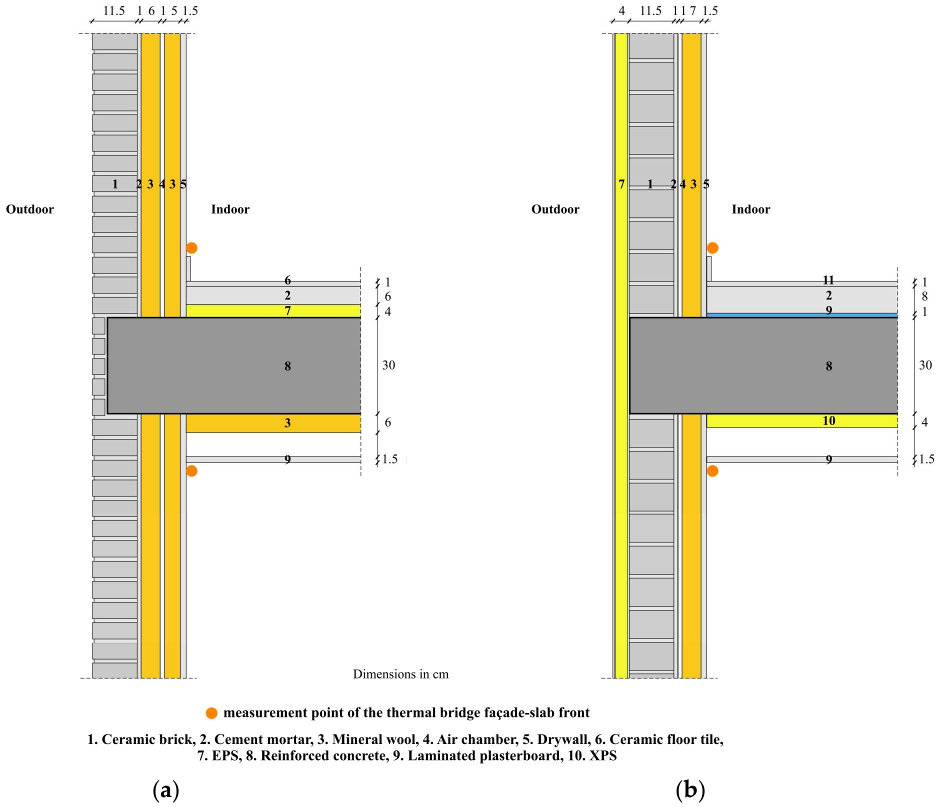


Figure 6. Drawings of the facade–slab junction indicating the measurement points: (**a**) case study 1 (brick facade with interior insulation and cladding); (**b**) case study 2 (facade with ETICS).

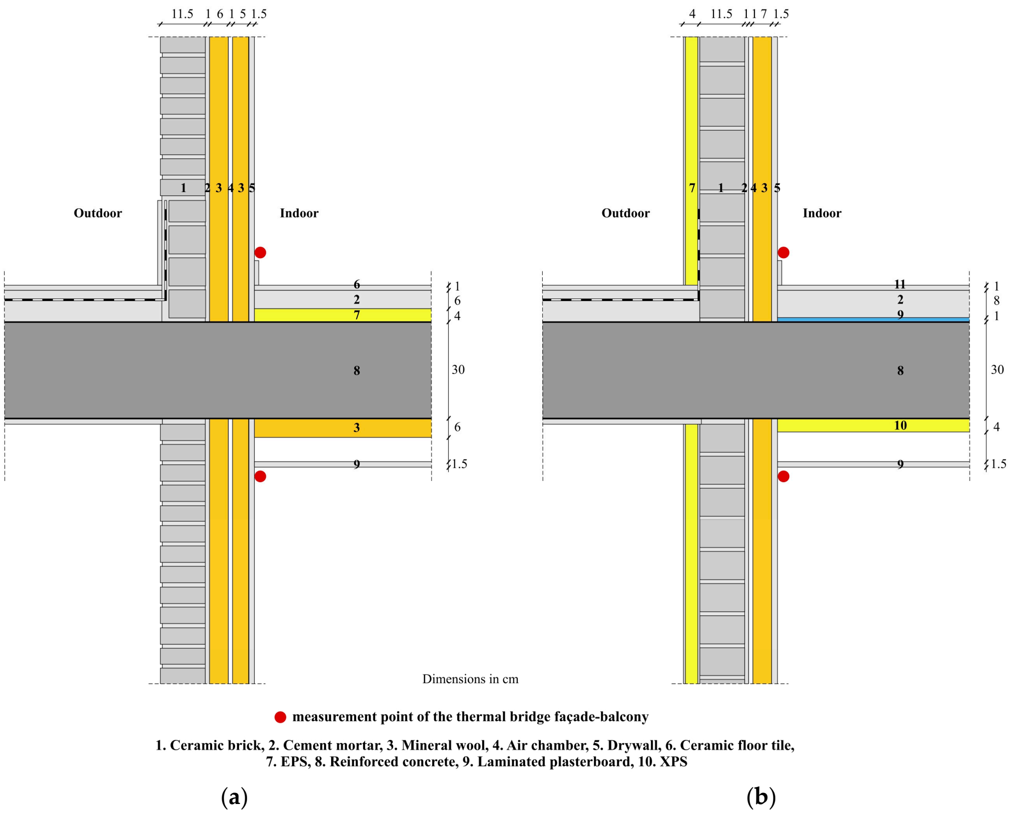


Figure 7. Drawings of the facade–balcony junction indicating the measurement points: (**a**) case study 1 (brick facade with interior insulation and cladding); (**b**) case study 2 (facade with ETICS).

The thermographic evaluation was carried out by using a Testo 868 camera (Testo SE & Co. KGaA, Titisee, Germany). The measurements of thermal transmittance, humidity, and dry bulb temperature were carried out using a Testo 435-2 multifunctional instrument (Testo SE & Co. KGaA, Titisee, Germany) calibrated to standard settings (Figure 8 and Table 2).

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 8. Instruments and measuring equipment used: (**a**) Testo 868 thermal imaging camera; (**b**) thermal transmittance flowmeter Testo 435-2; (**c**) humidity/temperature probe with wireless handle; (**d**) surface probe; (**e**) hot wire probe.

Table 2. Summary of measuring instruments and their characteristics.

	Model	Measuring Range	Accuracy
Thermographic camera	Testo 868	−15–+50 °C +10–+95% HR	±2 °C/ ±2% ±2% HR
Thermal transmittance flowmeter	Testo 435-2	−20–+50 °C	-
Humidity/temperature probe	Testo	−20–+70 °C +10–+100% HR	±0.3 °C ±2% HR
Surface probe	Testo	−20–+70 °C	±0.1 °C
Hot wire probe	Testo	−20–+70 °C	±0.3 °C ±0.3 m/s

A Líder-Calener Unified Tool [17] (version 2.0.2253.1167) was used because it is the official software of the Spanish Government for modeling and assessing the energy of buildings in Spain for the verification of compliance with the Spanish Technical Building Code (Royal Decree 732/2019) and Spanish and European energy certification standards (Royal Decree 390/2021 and Directive (EU) 2018/844). This software uses the calculation procedure included in the UNE-EN ISO 52000-1:2019 standard [53]. Although the official software was less capable of calculating and analyzing the results than other calculation programs, it allowed a better verification of the energy performance of the building in accordance with the established regulatory requirements. Moreover, this aspect is fundamental in order to be able to consider possible energy improvements that have to be made. The software program Cypetherm Bridges [54] (version v2022.e, Cype Ingenieros S.A., Alicante, Spain) was also used. This software determines the thermal transmittance in linear thermal bridges through the resolution and post-processing of a two-dimensional heat transfer analysis model using finite element methods in accordance with the European standard UNE-EN ISO 10211 [13]. Only heat exchange by conduction was considered in the analyses.

The computer calculations considered the thermal properties of the building envelope obtained from field measurements. The computer model for the calculation of the building's energy needs considered its location, dimensions, orientation, geometry, glazing position, and thermal envelope design features. The calculation method used considered the thermal transmission of the enclosure, the transmission of solar radiation through translucent surfaces using a correction factor for the solar radiation coefficient, the air transmission, and the gains and losses due to air transmission, according to current standards. The virtual simulation of the hygrothermal performance considered outdoor temperature and relative humidity data recorded on the same day as the field measurement campaign (Table 3).

Table 3. Summary of thermal properties of the building facades according to on-site measurements: case study 1 (CS1), case study 2 (CS2).

Thermal Properties	**Thickness (cm)**	**U ($W/m^2{\cdot}K$)**	**g**	**Absorptivity**	**Air Permeability $m^3/h{\cdot}m^2$**
	CS1/CS2	**CS1/CS2**	**CS1/CS2**	**CS1(CS2**	**CS1/CS2**
Opaque facade enclosure	25/25	U = 0.36/0.37			
Glass (80% of the window)	2.0/2.2	Ug = 2.421/2.368	0.58/0.60		
Frames (20% of the window)	7.0/7.0	Uf = 2.534/2.475		0.75/0.75	27.00/27.00
Floor	40.0/45.0	U = 0.85/0.90			
Roof	40.0/45.0	U = 0.85/0.78			
Air change rates by natural ventilation = 0.55 ren/h					
Frame air permeability = 27.00 $m^3/h{\cdot}m^2$					

The calculations took into account parameters such as occupancy, air conditioning performance, usage plans and calendars, target temperatures, legally mandated supply air updates, and internal lighting loads (Table 4).

Table 4. Parameters considered in the computer simulation calculations: case study 1 (CS1), case study 2 (CS2).

Parameter	**Values**			**Applicable Regulation**
	CS1/CS2			
Occupation	People/m^2 0.05/0.05	Metabolic rate 1	Schedule Activated 24/7	DB-HE Application Guide 2019 [55]
Cooling equipment Heating equipment	Cop 4/4.2 3.5/3.6	Months 6/7/8/9 1/2/3/4/5/10/11/12	Schedule 0:00–24:00 27 °C 0:00–24:00 19 °C	DB-HE Annex D Operational conditions and use profiles [56]
Mechanical ventilation Natural nocturnal ventilation	Air renewals/hour 0.55/0.52 4.0 (summer)		Schedule Activated 24/7 0:00–08:00 100%	DB-HS3 [56]
Internal lightning loads	Average illumination 200 lux/200 lux	Power 2 W/m^2	0:00–07:00 10% 07:00–19:00 30% 19:00–23:00 100% 23:00–24:00 50%	Royal Decree 486/1997 Annex IV [57]

The calculations by finite element simulations considered the thicknesses and material properties of the different layers of the facade, floors, and roofs of the two dwellings (Table 5).

Table 5. Parameters considered in the computer calculations by finite element simulations: case study 1 (CS1), case study 2 (CS2).

Construction Element	Layer	Thickness (cm)	Linear Thermal Conductivity (W/m·K)	Thermal Resistance (m^2·K/W)
CS1				
Facade:				
	Ceramic brick	11.5	$\lambda = 0.991$	
	Cement mortar	1.0	$\lambda = 0.550$	
	Mineral wool	6.0	$\lambda = 0.035$	
	Air chamber	1.0		R = 0.15
	Rock wool	5.0	$\lambda = 0.035$	
	Drywall	1.5	$\lambda = 0.250$	
Indoor floor:				
	Ceramic floor tile	1.0	$\lambda = 2.300$	
	Cement mortar	6.0	$\lambda = 0.550$	
	EPS	4.0	$\lambda = 0.030$	
Structural slab:	Reinforced concrete	30.0	$\lambda = 1.838$	
Indoor false ceiling:				
	Mineral wool	6.0	$\lambda = 0.035$	
	Laminated plasterboard	1.5	$\lambda = 0.250$	
CS2				
Facade:				
	EPS	4.0	$\lambda = 0.032$	
	Ceramic brick	11.5	$\lambda = 0.991$	
	Cement mortar	1.0	$\lambda = 0.550$	
	Air chamber	1.0		R = 0.15
	Mineral wool	7.0	$\lambda = 0.035$	
	Drywall	1.5	$\lambda = 0.250$	
Indoor floor:				
	Laminated wood flooring	1.0	$\lambda = 2.300$	
	Cement mortar	8.0	$\lambda = 0.550$	
	Acoustic foil	1.0	$\lambda = 0.050$	
Structural slab:	Reinforced concrete	30.0	$\lambda = 1.838$	
Indoor false ceiling:				
	XPS	4.0	$\lambda = 0.034$	
	Laminated plasterboard	1.5	$\lambda = 0.250$	

3. Results

First, this section identifies the most representative thermal bridges of the facades of buildings constructed in recent years through the thermographic study carried out. Second, the results of the qualitative and quantitative analysis of the thermal bridges in the two studied buildings through on-site measurements are shown. Subsequently, the impact of the analyzed thermal bridges on the total annual energy requirements of the dwellings was determined using computer simulations. Third, this section illustrates the effects of modifying various construction and geometric parameters of the analyzed thermal bridges on the overall energy consumption of the dwellings.

3.1. Thermographic Study of the Facades of Buildings Constructed in Recent Years

The thermographic study of the analyzed facades allowed for the identification of the most representative thermal bridges. Balcony junctions with facades and slab edges on the facades constitute the type of thermal bridge with the highest proportion of surface area. These thermal bridges collectively account for an average of 44% of the surface area of all detected thermal bridges in the studied buildings. When analyzed separately, balcony junctions with facades represent 24% of the surface area with an average thermal difference of 1.4 °C. Facade slab edges represent 20% with an average thermal difference of 1.2 °C.

Integrated pillars in facades account for 18%, with an average thermal difference of 0.9 °C. Window sills represent 9% of the surface area with an average thermal difference of 0.7 °C. Roof–facade junctions make up 7%, with an average thermal difference of 1.3 °C. Cantilever junctions with facades have a 5% surface area proportion and an average thermal difference of 1.6 °C. The remaining thermal bridge types specified by regulations each represent less than 5% (Figure 9).

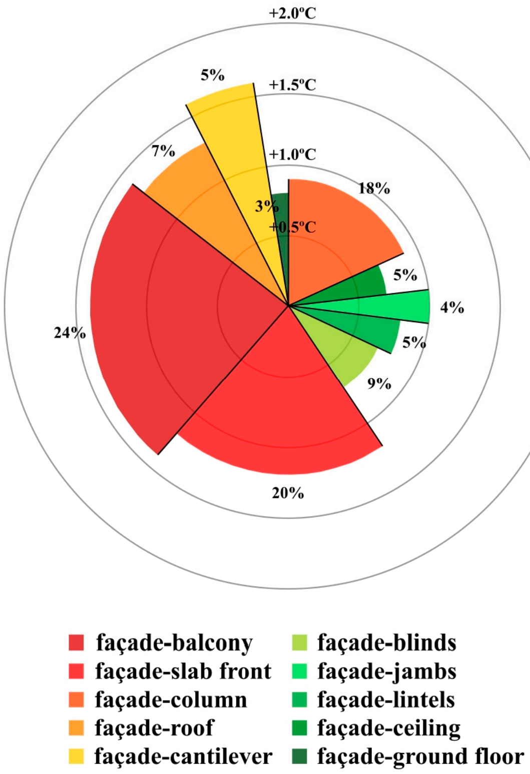


Figure 9. The percentage of facade surface occupied by each type of thermal bridging, and the thermal difference between the average surface temperature of the facade surface of each type of thermal bridging and the average surface temperature of the rest of the facade.

Next, the Thermal Bridge Wall Ratio (THBWR) of each thermal bridge was considered. This index indicates the proportion between the surface multiplied by the average temperature difference of each thermal bridge ($S_n \cdot \Delta T_n$) and the total sum of surfaces and average temperature differences of all thermal bridges ($\Sigma\, S_{(1,2,\ldots n,\ldots 10)} \cdot \Delta T_{(1,2,\ldots n,\ldots 10)}$). The average temperature difference of each thermal bridge was calculated by comparing the average surface temperature of each thermal bridge and the average surface temperature of the facade. The facade–balcony thermal bridge area was calculated by multiplying the thickness of the slab by the length of the balconies. The facade–floor thermal bridge area was calculated by multiplying the thickness of the slab by the length of the facade–floor junctions. The junctions of balconies with facades and the slab edges on the facades have a THBWR of 0.523, meaning they account for more than 50% of the total thermal differences caused by all thermal bridges. When analyzed separately, the junctions of balconies with facades have a THBWR of 0.305, and the slab edges have a THBWR of 0.218. Integrated pillars on the facades have a THBWR of 0.162. Roof-to-facade connections have a THBWR of 0.083. Cantilever junctions with facades have a THBWR of 0.073. Copings have a THBWR of 0.057. The remaining types of thermal bridges established by the regulations each have a THBWR of less than 0.05 (Figure 10).

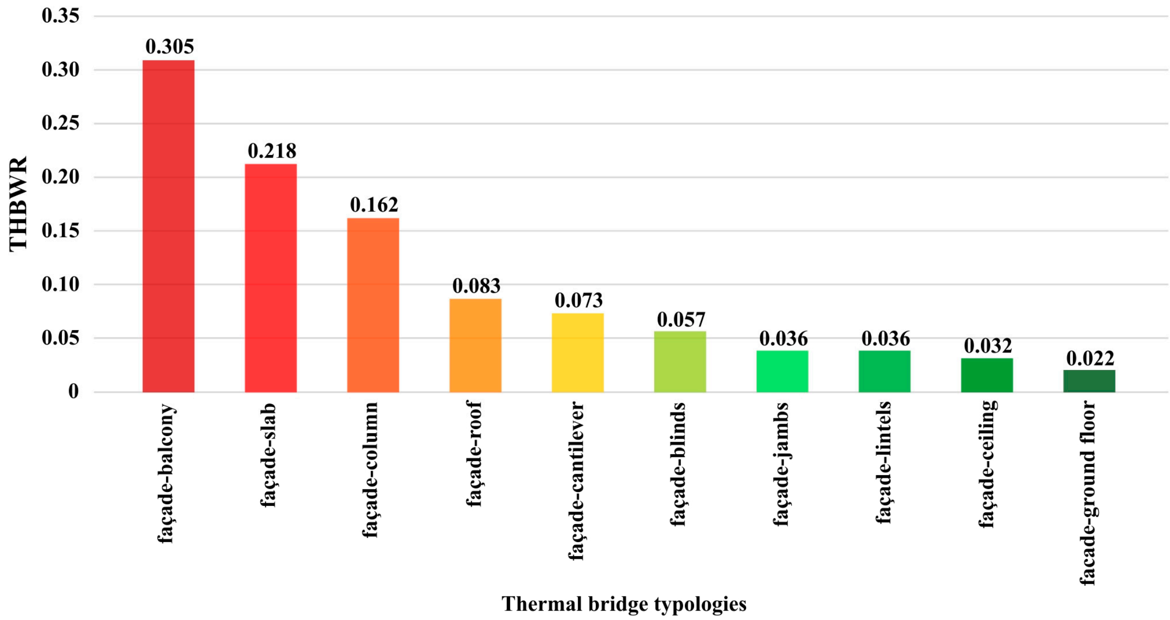


Figure 10. Thermal Bridge Wall Ratio Classification of the thermal bridges identified in the buildings studied depending on the Thermal Bridge Wall Ratio.

3.2. Influence of the Thermal Bridges Analyzed on the Total Annual Energy Needs of Studied Dwellings

The detailed thermographic study of the buildings in the two analyzed dwellings confirmed that the slab edges and the junctions of balconies with facades are the most influential types of thermal bridges in both buildings. Differences were also observed between them based on the construction typology of the facade: a brick-faced facade with interior cladding and insulation (case study 1) and a facade with External Thermal Insulation System (ETICS) (case study 2) (Figures 6, 7 and 11).

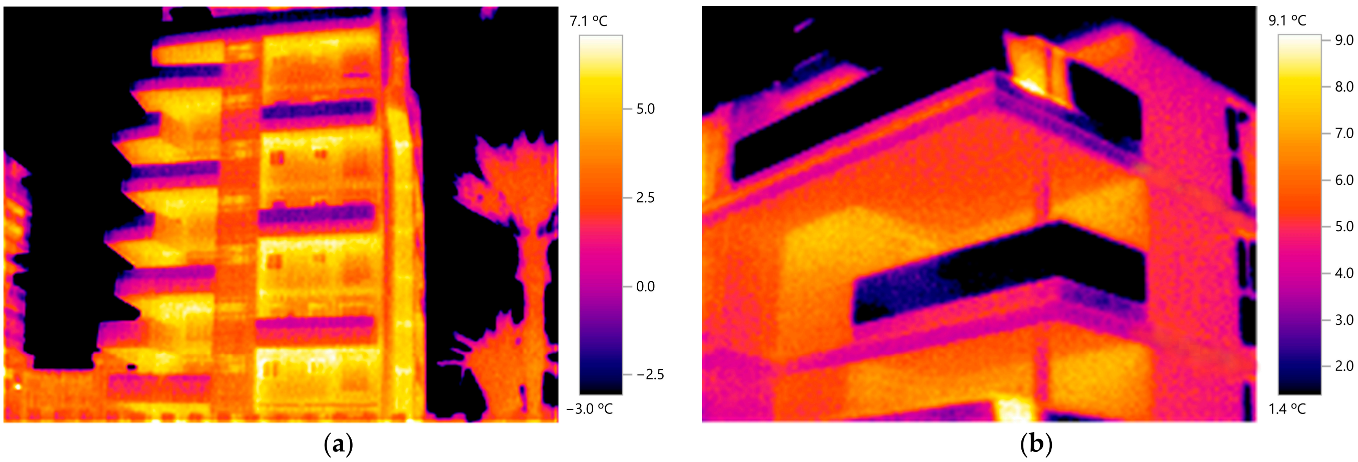
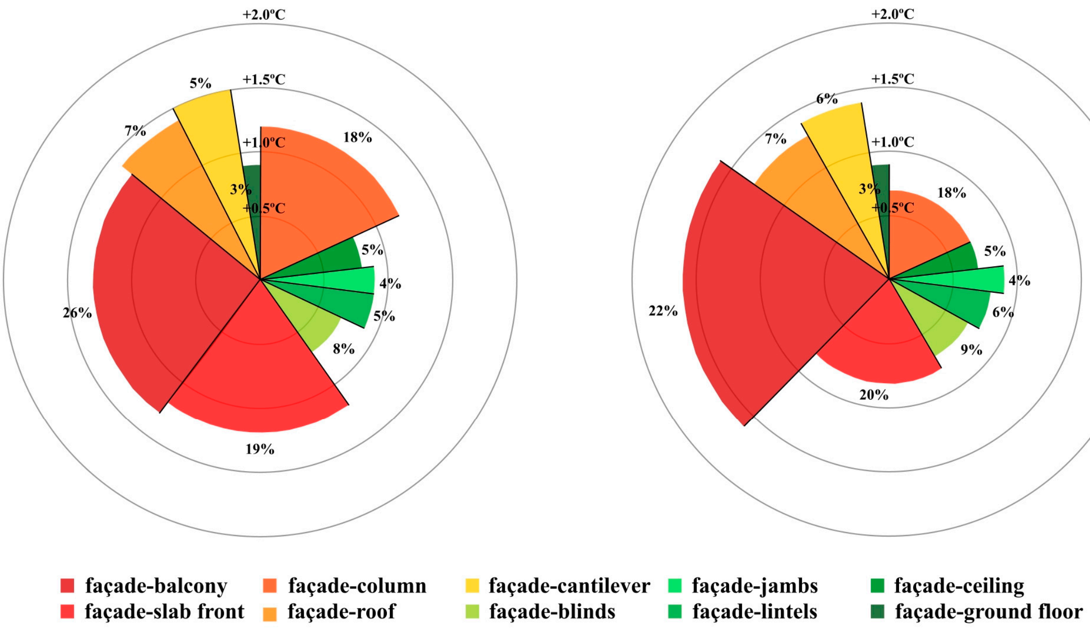


Figure 11. A thermographic image of the facades of the two buildings analyzed in detail: (**a**) case study 1 (brick facade with interior insulation and cladding); (**b**) case study 2 (facade with ETICS).

These two types of thermal bridges constitute 45% of the total thermal bridge surface area in the building of dwelling 1 (case study 1) and 42% in the building of dwelling 2 (case study 2). Specifically, the junctions of balconies with facades account for a surface proportion of 26% and an average thermal difference of 1.3 °C in building 1 and 22% with 1.6 °C in building 2. The slab edges on the facades represent 19% with an average thermal difference of 1.2 °C in building 1 and 20% with 0.8 °C in building 2 (Figure 12).



(**a**) (**b**)

Figure 12. The percentage of facade area occupied by each type of thermal bridging, and the thermal difference between the average facade surface temperature of each type of thermal bridging and the average surface temperature of the rest of the facade: (**a**) study case 1; (**b**) study case 2.

On-site measurements using a heat flux meter confirm significant differences between the average thermal transmittance of the facade and the thermal transmittance of the facade areas near the slab edges and the junctions with balconies (Figures 5–7). Substantial variations are also evident based on the construction typology of the facade. The average thermal transmittance on the facade of building 1 is 0.27 $W/m^2{\cdot}K$, near the slab edge is 1.10 $W/m^2{\cdot}K$, and near the balcony junction is 1.22 $W/m^2{\cdot}K$. In building 2, the average thermal transmittance on the facade is 0.27 $W/m^2{\cdot}K$, near the slab edge is 0.74 $W/m^2{\cdot}K$, and near the balcony junction is 1.51 $W/m^2{\cdot}K$ (Table 4). From the surface thermal transmittance obtained from the on-site measurements, the linear thermal transmittance of the thermal bridge can be estimated considering the total thickness of the floor slab with the ceiling and the flooring. Subsequently, the linear thermal transmittances of the analyzed thermal bridges were calculated using finite element simulations considering the thicknesses and material properties of the different layers of the facade, floors, and ceilings of the two dwellings (Table 5). The linear thermal transmittance of the facade–slab edge junction is 0.477 $W/m{\cdot}K$ in case study 1 (Figure 13a) and 0.320 $W/m{\cdot}K$ in case study 2 (Figure 13b).

The statistical analysis for the validation of the energy model considered 504 thermal transmittance values obtained from on-site measurements inside the two analyzed dwellings, distributed over six measuring points in each dwelling. The actual measurements were compared with the results of the computer simulations for the same constructive solutions. The obtained Mean Bias Error (MBE) was 1.62. The Normalized Mean Bias Error (NMBE) was 4.95%. This value is less than the $\pm$10% upper limit set by ASHRAE Guideline 14 in the hourly calibration criteria. The Root Mean Square Error (RMSE) was 3.86. And the Coefficient of the Variant of Root Mean Square Error (CV(RMSE)) was 8.23%. This value is lower than the 30% upper limit set by ASHRAE Guide 14. This allows validation of the calculation procedure used.

Subsequently, the annual energy needs of the two studied dwellings were calculated considering the thermal transmittance data of the enclosures obtained in situ and confirmed by computer simulations.

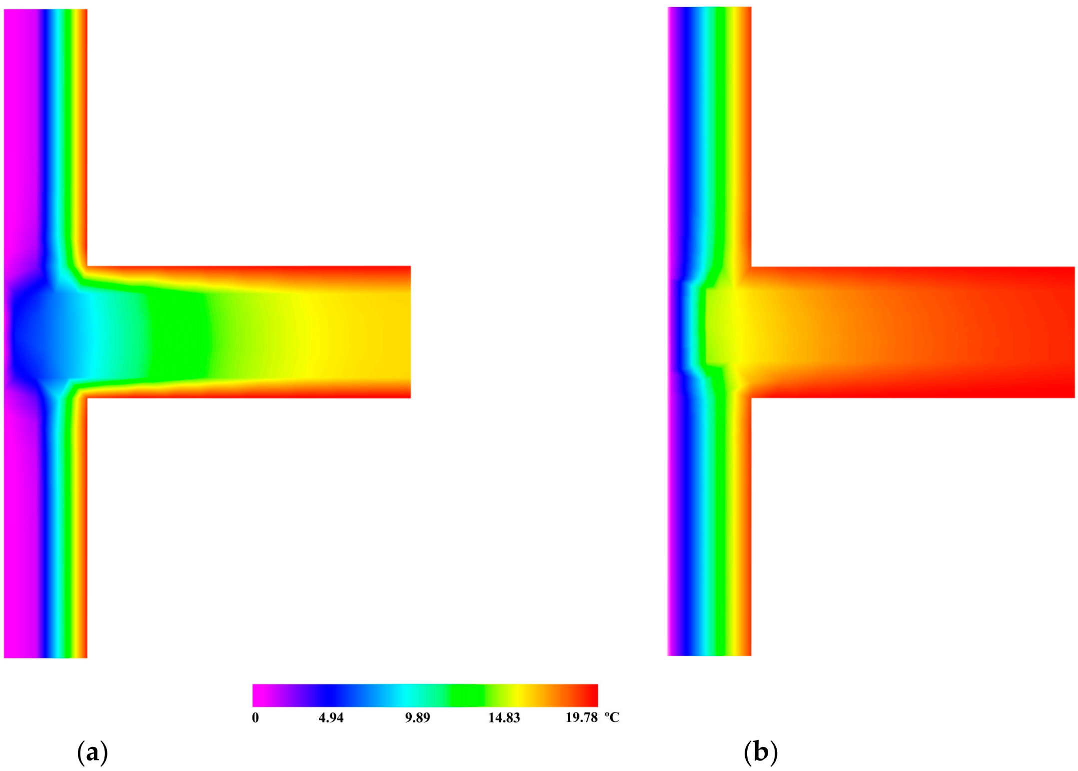


Figure 13. Analysis of the linear thermal transmittance by computer simulation according to UNE EN-ISO 10211 of the thermal bridge facade-floor slab front: (**a**) case study 1; (**b**) case study 2.

The linear thermal transmittance of the facade–balcony junction is 0.529 W/m·K in case study 1 (Figure 14a) and 0.653 W/m·K in case study 2 (Figure 14b).

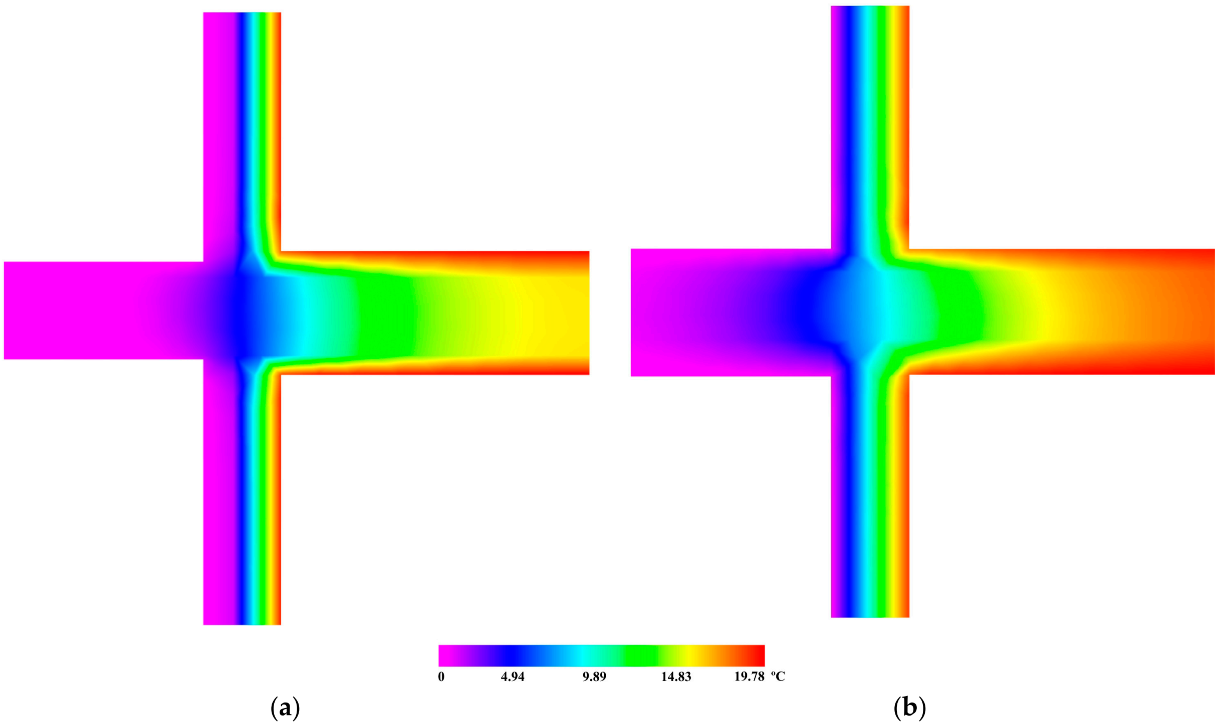


Figure 14. Analysis of the linear thermal transmittance by computer simulation according to UNE EN-ISO 10211 of the thermal bridge facade-balcony: (**a**) case study 1; (**b**) case study 2.

Initially, energy needs were calculated without distinguishing between the thermal bridges of the facade slab edge and facade balcony, following standard procedures. Subsequently, the calculation was repeated, differentiating between these two types of thermal bridges.

The results indicate that the annual energy needs (heating + cooling) caused by the thermal bridges in dwelling 1 are equivalent to 40.8% of the total energy needs if the thermal bridges of the facade slab edge and facade balcony are not differentiated, and 44.3% if they are distinguished (Figure 15). The annual energy needs in dwelling 1 are 20.6 kWh/m^2·year without distinguishing the thermal bridges and 21.9 kWh/m^2·year when considering the thermal bridges of the facade slab edge and facade balcony separately. The difference is 1.3 kWh/m^2·year, which represents 6.3% of the total annual energy needs of the dwelling and entails a 15.5% difference in the calculation of the energy needs of the thermal bridges.

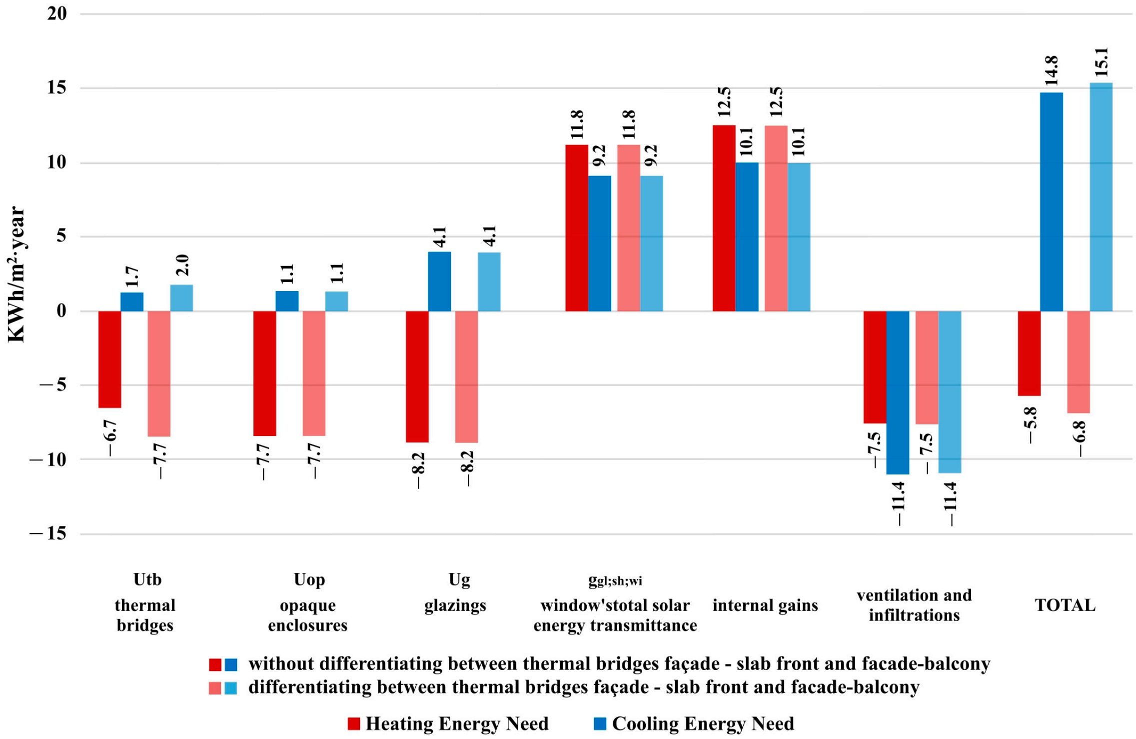


Figure 15. Total annual energy needs of dwelling 1 according to the type of thermal bridge.

Meanwhile, the annual energy needs (heating + cooling) caused by the thermal bridges in dwelling 2 are equivalent to 29.7% of the total energy needs if the thermal bridges are not differentiated, and 37.4% if they are distinguished (Figure 16). The annual energy needs in dwelling 2 are 15.5 kWh/m^2·year without distinguishing the thermal bridges and 17.4 kWh/m^2·year when considering the thermal bridges separately. The difference is 1.9 kWh/m^2·year, which represents 12.3% of the total annual energy needs of the dwelling and entails a 41.3% difference in the calculation of the energy needs of the thermal bridges.

Subsequently, the annual energy needs specifically caused by the thermal bridges of the facade slab edge and facade balcony were calculated. The results show that the combined contribution of these two types of thermal bridges accounts for 41.2% of the annual energy needs caused by all thermal bridges in case study 1 and 52.3% in case study 2. Specifically, the junctions of balconies with facades contribute to 25.8% of the energy needs in case 1 and 38.5% in case 2, while the slab edges on the facades contribute to 15.4% in case 1 and 13.8% in case 2 (Figure 17).

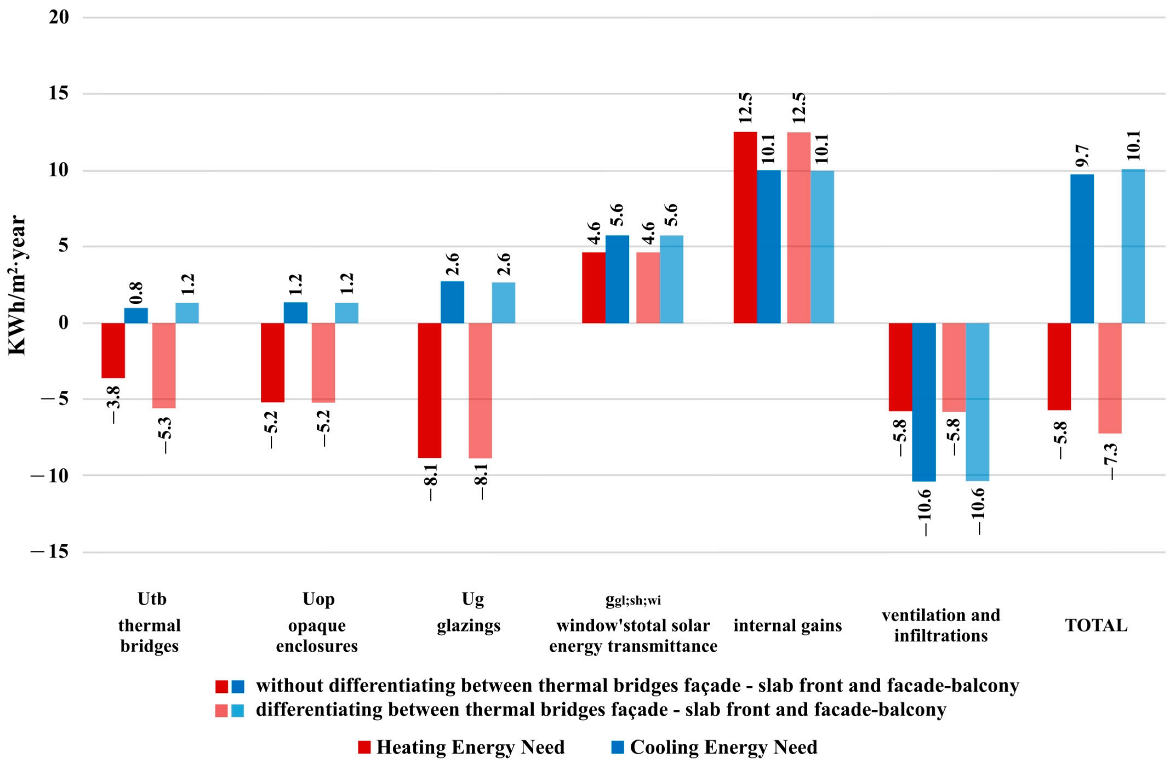


Figure 16. Total annual energy needs of dwelling 2 according to the type of thermal bridge.

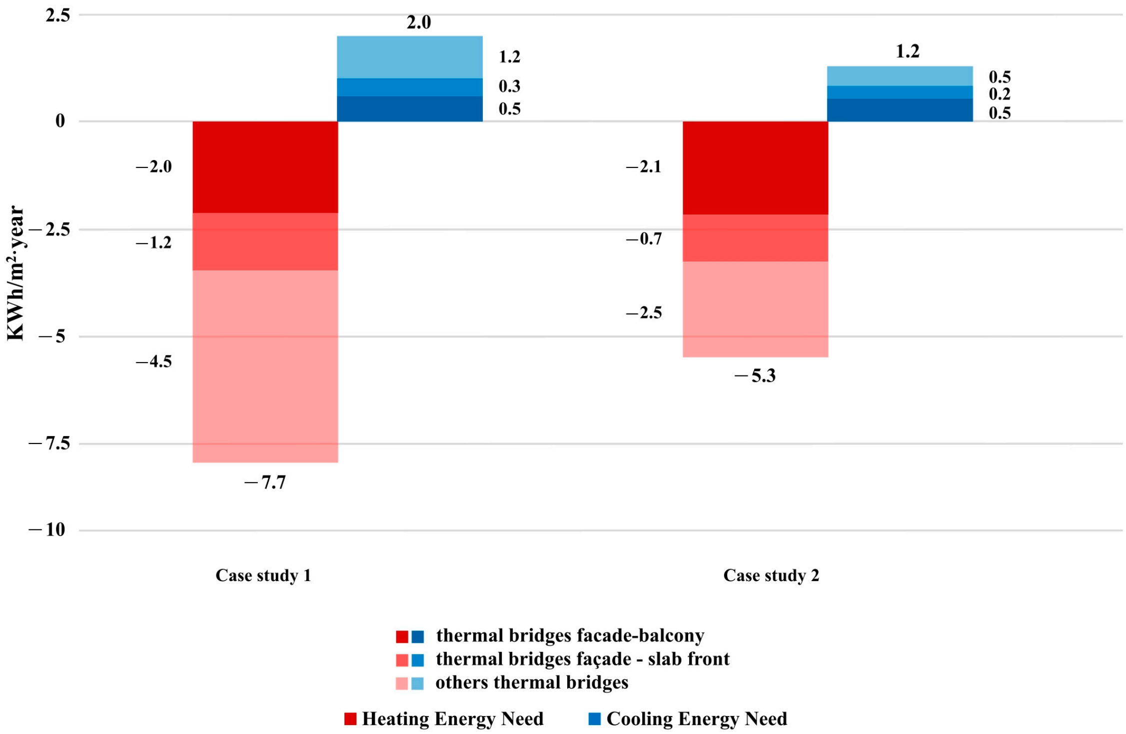


Figure 17. Total annual energy needs according to the type of thermal bridge in each dwelling surveyed.

3.3. Influence of Modification of Construction Parameters on Thermal Bridges

The results indicate that improving the thermal insulation of thermal bridges significantly reduces their linear thermal transmittance in case 1 but only marginally in case 2. Additionally, enhancing the insulation of thermal bridges does not result in a directly proportional reduction in the linear thermal transmittance of the thermal bridge. The reduction becomes negligible for higher insulation thicknesses.

In the balcony–facade junctions, the thermal transmittance of this thermal bridge can be reduced by increasing the thermal insulation of indoor floors and ceilings near the balcony. Insulating floors and ceilings in the proximity of the balcony–facade junctions of dwelling 1 (Figure 7a) reduces the linear thermal transmittance of the thermal bridge by 34.7%; doubling the insulation reduces the transmittance by 45.3%, and tripling it reduces the transmittance by 51.4%. On the other hand, insulating ceilings near the balcony–facade junctions of dwelling 2 (Figure 7b) reduces the linear thermal transmittance by 14.8%; doubling the insulation reduces the transmittance by 20.1%, and tripling it reduces the transmittance by 23.8% (Figure 18).

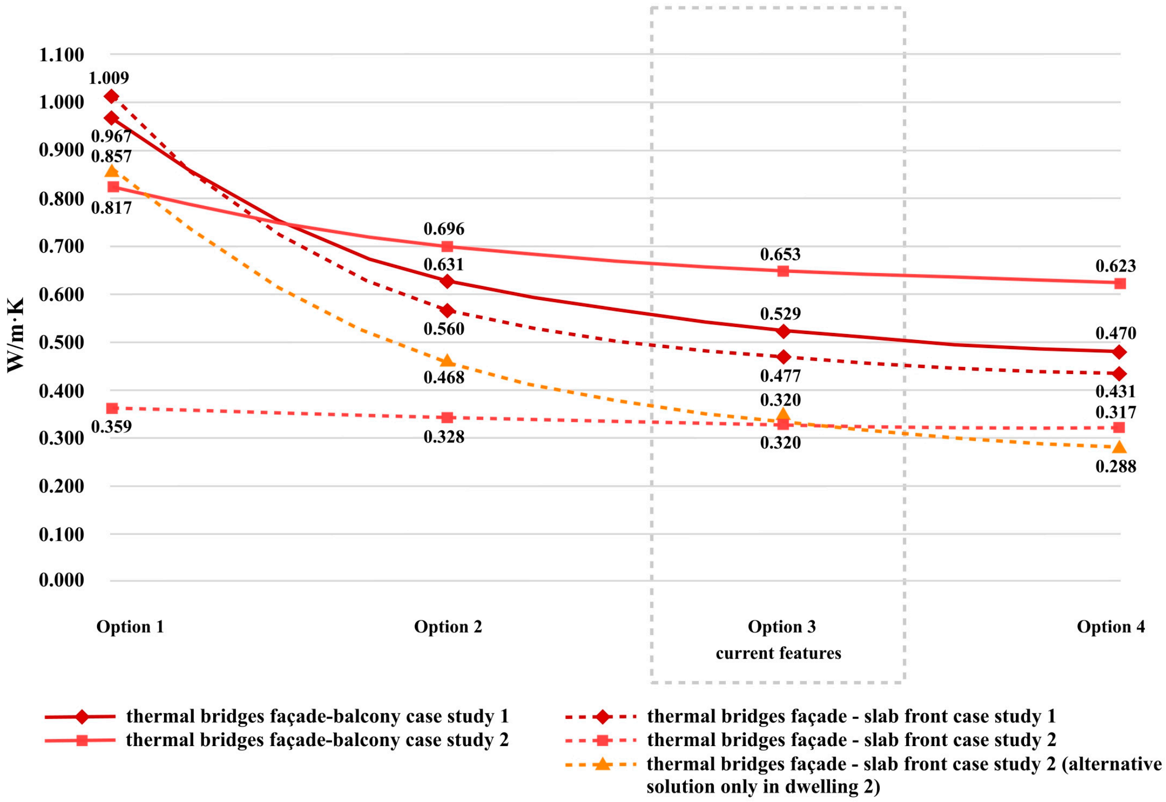


Figure 18. The linear thermal transmittance depending on the type of thermal bridge and the thickness of the thermal bridge insulation.

In the slab edge junctions, insulating the floors and ceilings indoors near the facade of dwelling 1 (Figure 6a) reduces the linear thermal transmittance of the thermal bridge by 44.5%; doubling the insulation reduces the transmittance by 52.7%, and tripling it reduces the transmittance by 57.3%. Conversely, insulating the ceilings near the facade of dwelling 2 (Figure 6b) reduces the linear thermal transmittance by 8.6%; doubling the insulation reduces the transmittance by 10.9%, and tripling it reduces the transmittance by 11.7%. Instead of increasing the insulation of internal ceilings, the external thermal insulation can be increased at the slab faces (alternative solution only in dwelling 2). This second option reduces the linear thermal transmittance of the thermal bridge much more. The ETICS exterior insulation of the slab edge junctions in dwelling 2 reduces the linear thermal transmittance of the thermal bridge by 45.4%; doubling the insulation reduces the transmittance by 62.7%, and tripling it reduces the transmittance by 66.4%.

The energy needs calculations for the dwellings show that insulating floors and ceilings near the junctions of the facade slab edge and facade balcony in dwelling 1 reduces the total annual energy needs by 9.6%; doubling the insulation reduces the energy needs by 12.4%, and tripling it reduces the energy needs by 15.6%. On the other hand, insulating floors and ceilings near the junctions of the facade slab edge and facade balcony in dwelling 2 reduces the total annual energy needs by 2.9%, doubling the insulation reduces the energy needs by 4.6%, and tripling it reduces the energy needs by 5.1% (Figure 19). Additionally, in facades with External Thermal Insulation Systems (ETICS), doubling the exterior thermal insulation at the junctions of the facade slab edge in dwelling 2 reduces the total annual energy needs by 5.1%, and tripling it reduces the energy needs by 6.2% (Figure 18).

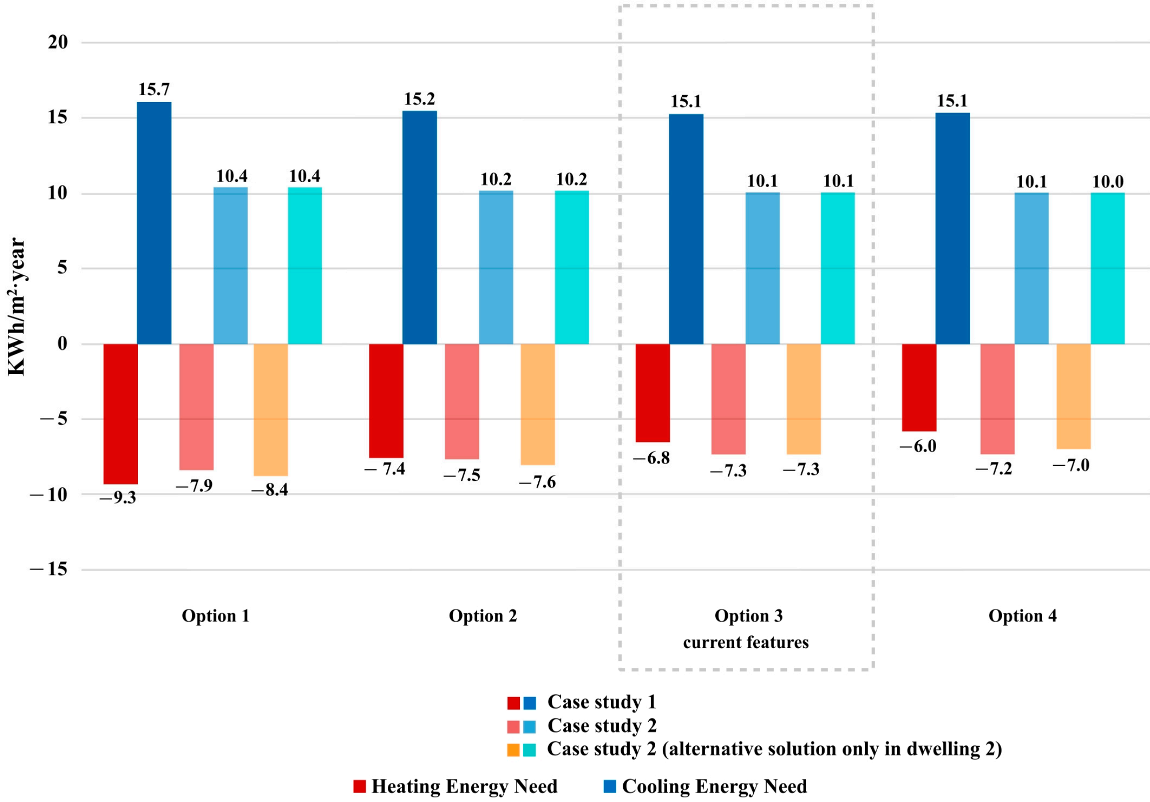


Figure 19. Total annual energy needs according to the thickness of the thermal bridge insulation.

4. Discussion

4.1. Constructive Study of the Current Facades

The analysis of the obtained results highlights that the most representative thermal bridges are the slab edge junctions on the facades, constituting an average of 44% of the total thermal bridge surface area and a Thermal Bridge Wall Ratio (THBWR) of 0.523. Although Spanish regulations consider the slab edge junctions as a single type of thermal bridge, within this category, it is advisable to differentiate balcony–facade junctions from the rest of the slab edge junctions because they exhibit different thermographic measurements. The slab edge junctions on facades have higher thermal differences concerning the average surface temperature of the rest of the facade. However, the balcony–facade junctions have a larger transmission surface area. All this demonstrates that these two thermal bridges have different thermal behaviors due to significantly different construction and geometric characteristics.

In the facade–slab edge junctions, there are layers of the vertical facade cladding that cover the front of the structure. However, in the balcony–facade junction, the structural slab extends through the facade toward the exterior with layers covering the slab both below (ceiling of the overhang) and above (balcony floor). Due to these differences in construction, geometry, and thermal properties, it would be advisable to consider the balcony–facade junction as a specific type of thermal bridge. Furthermore, each of these two types of thermal bridges has a sufficiently representative THBWR. The balcony–facade junctions have a THBWR of 0.218, while the rest of the slab edge junctions have a THBWR of 0.305. Other types of thermal bridges have much lower THBWR. However, Spanish regulations do not identify the balcony–facade junctions as separate and independent thermal bridges. This reduces the precision of the calculation of the building's energy needs and complicates the specific treatment of this type of thermal bridge in building projects. This issue is particularly significant in the region of the Spanish Mediterranean coast and the BShs climate, where buildings often feature numerous balconies.

4.2. Influence of the Thermal Bridges Analyzed on the Total Annual Energy Needs of Studied Dwellings

The detailed thermographic study of the two buildings demonstrated that the balcony–facade junctions and facade–slab edge junctions are the most influential types of thermal bridges in this building type, constituting more than 40% of the total thermal bridge surface area. The results showed that exterior surfaces in balcony–facade junctions have a higher thermal difference from the average facade temperature compared to facade–slab edge junctions. Additionally, the facade–slab edge junctions exhibit significantly lower thermal differences when an Exterior Thermal Insulation System (ETICS) is utilized, whereas the thermal difference in balcony–facade junctions remains similar in both buildings.

These findings align with the results obtained from in situ measurements of the thermal transmittance of different areas on the facades. The analysis of measurements reveals thermal transmittance differences greater than 0.83 $W/m^2{\cdot}K$ near the facade slab edge in case study 1, compared to only 0.47 $W/m^2{\cdot}K$ in case study 2. Similarly, thermal transmittance differences are 0.95 $W/m^2{\cdot}K$ near balcony–facade junctions in case study 1 and 1.24 $W/m^2{\cdot}K$ in case study 2. These results are consistent with computer simulation outcomes, which indicate a 50% higher linear thermal transmittance of facade–slab edge junctions in case study 1 and a 23% higher transmittance of balcony–facade junctions in case study 2.

These differences stem from the lack of sufficient thermal insulation in facade–slab edge junctions in brick facades with interior insulation, whereas in the ETICS, they have an appropriate layer of external insulation. However, in balcony–facade junctions, the structural slab extends through the facade to the exterior in both studied buildings, interrupting the thermal envelope insulation in both cases. Additionally, in case study 2, the dwelling lacks thermal insulation in the floor, making the thermal bridge on the balcony worse than in case study 1, which has thermal insulation in the floor.

Due to these construction and thermal differences, it would be advisable to consider balcony–facade junctions as a specific type of thermal bridge, distinct from facade–slab edge junctions. Computer calculations demonstrated that thermal bridges account for over 40% of the total annual energy needs in dwelling 1 and around 30% in dwelling 2. Thermal losses and gains through thermal bridges are comparable to those produced by all other opaque enclosure surfaces in the dwelling. This is due to the increased requirements of current energy efficiency regulations, which have improved insulation in facades. However, as buildings enhance the insulation of their facades, the lack of insulation in unique junctions between different construction systems, such as thermal bridges, becomes more evident. The analysis of results indicates that minimizing thermal bridges would almost eliminate the heating energy needs in dwelling 1 and significantly reduce it in dwelling 2.

Furthermore, the results also demonstrated that the total energy needs of the dwellings change substantially when differentiating and correctly specifying facade–slab edge junctions and balcony–facade junctions. Distinguishing these two thermal bridges increases the energy needs related to all thermal bridges by 15.5% in dwelling 1 and the total annual energy needs by 6.3%. In the case of dwelling 2, the energy needs related to all thermal bridges increased by 41.3%, and the total annual energy needs of the dwelling increased by 12.3%. This implies that the current regulations and official calculation programs, by not considering the qualitative and quantitative differences between these two thermal bridges, result in a high degree of inaccuracy in the calculation of thermal bridges and the energy needs of buildings. This situation is particularly critical in the region of the Spanish Mediterranean coast and the BShs climate, where the surface and length of balconies are often much greater than in other Spanish and European geographical areas.

Finally, computer simulations also demonstrated that facade–slab edge junctions and balcony–facade junctions are the most decisive thermal bridges in the analyzed buildings. These two thermal bridges constitute 41.2% of the annual energy needs caused by all thermal bridges in case study 1 and 52.3% in case study 2. The comparative analysis of results also confirms that balcony–facade junctions cause much more energy needs than facade–slab edge junctions, especially in case study 2, where facade–slab edge junctions are well-insulated thanks to the ETICS. These data are consistent with the results obtained in the detailed thermographic study of the two buildings and in the in situ measurements of the thermal transmittance of different areas on the facades. These findings further highlight the severity of the regulation's failure to consider the construction and thermal specificities of balcony–facade junctions.

4.3. Influence of Modification of Construction Parameters on Thermal Bridges

The analysis of the results demonstrates that improving the insulation of thermal bridges does not result in a directly proportional reduction in the linear thermal transmittance of the thermal bridges. In fact, the reduction becomes negligible for very high thermal insulation thicknesses. This is because the linear thermal transmittance value of the thermal bridge is also influenced by the difference between the exterior surface of the facade and the intrados of the facade. The value cannot approach zero because there is a heat flow transmitted through the thickness of the facade slab edge or the balcony, which adds to the energy transmitted through the rest of the facade (Figure 13).

Enhancing the thermal insulation of floors and interior ceilings near facade slab edges and balconies significantly reduces the linear thermal transmittance of thermal bridges in the brick facade with interior insulation (case study 1) but has a minimal impact on the facade with an Exterior Thermal Insulation System (ETICS) (case study 2). This is because facades with ETICSs have facade slab edge thermal bridges that are well-insulated from the exterior, and consequently, their thermal transmittances are already small and challenging to improve by insulating from the interior. In facades with ETICSs, increasing the exterior insulation on facade slab edges does reduce the thermal transmittance of that thermal bridge significantly. On the other hand, in balcony–facade junctions, the thermal transmittance of the thermal bridge in the ETICS facade of case study 2 has very high values. This is due to the interruption of the ETICS, creating significant thermal bridges because the dwellings lack interior insulation for floors. In balcony–facade junctions, the only solution is to insulate the floors and interior ceilings or use costly construction systems with thermal breakers for balconies and cantilevers (thermal separation of cantilevered reinforced concrete slabs).

Consequently, improving the insulation of thermal bridges does not result in a directly proportional reduction in the energy needs of dwellings, with improvements becoming negligible for high thermal insulation thicknesses (Figure 14). This is because the energy needs also include factors such as thermal gains and losses from all opaque enclosures, internal gains, ventilation air exchanges, and air infiltrations.

Enhancing the thermal insulation of thermal bridges significantly reduces the energy needs in the brick facade with interior insulation (case study 1) but has a minimal effect on the facade with the ETICS (case study 2). This is because facades with ETICSs have facade slab edge thermal bridges that are well-insulated from the exterior, and consequently, their thermal transmittances are already small and difficult to improve. However, in balconies, the ETICS is interrupted, creating significant thermal bridges because the dwellings lack interior insulation for floors.

In conclusion, Figures 13 and 14 indicate that optimal construction solutions are those that greatly reduce the thermal transmittance of thermal bridges and the energy needs of dwellings without excessively increasing their thermal insulation.

Furthermore, in facades with ETICSs, it is better to increase the exterior thermal insulation on facade slab edges than to insulate floors and interior ceilings. However, to reduce the energy needs, it is essential to also reduce the thermal bridge in balcony–facade junctions by insulating floors and interior ceilings of dwellings in areas near balconies or by using thermal breakers in cantilevered slab structures.

Moreover, the regulations also do not consider that ETICSs are often combined with interior claddings for thermal-acoustic insulation, reducing the thickness of the ETICS as less thermal insulation is needed (Figures 6b and 7b). This results in a greater thermal bridge in facade slab edges and balconies than the regulations state because the exterior thermal insulation is continuous, but the interior insulation is interrupted.

The study has some limitations. Official regulations and calculation programs do not sufficiently include the effect of thermal radiation on balcony surfaces. In architectural typologies with deep and elongated balconies, balcony surfaces can influence thermal gains and losses as radiators. In the summer, the high solar radiation of the BShs climate can cause balcony surfaces to absorb a lot of radiation and transmit heat to the interior during peak sunlight hours. Additionally, it would be advisable to complete calculations with more combinations of construction solutions, combining ETICSs and interior thermal-acoustic insulations, using different insulation thicknesses in floors and ceilings and studying more housing typologies with varying sizes and orientations.

5. Conclusions

(1) This work demonstrates that the energy needs caused by thermal bridges account for approximately 40% of the total annual energy needs of the studied residential buildings, constructed under the current Spanish energy efficiency regulations. The annual energy needs (heating + cooling) caused by thermal bridges are slightly higher than 40% in buildings with a brick facade with interior cladding with insulation and slightly less than 40% in buildings with an Exterior Thermal Insulation System (ETICS).

(2) Balcony–facade and facade–slab edge junctions are the most predominant thermal bridges in the analyzed buildings. The sum of these two thermal bridges constitutes, on average, 44% of the total thermal bridge surface area and has a Thermal Bridge Wall Ratio (THBWR) of 0.523. They represent more than 40% of the annual energy needs caused by all thermal bridges in the studied building with interior insulation and over 50% in the building with the ETICS. Balcony thermal bridges account for between 25% and 40% of the energy needs produced by all thermal bridges, while facade–slab edge junctions contribute around 15%.

(3) The constructive, geometric, and thermal behavior characteristics of balcony–facade and facade–slab edge junctions are very different. The linear thermal transmittance of the balcony–facade junction is higher than that of the facade–slab edge junction. Consequently, balcony–facade junctions cause much more energy needs than slab edge junctions, especially in buildings with ETICSs. However, current Spanish energy efficiency regulations and official calculation programs do not identify the balcony–facade junction as a separate and independent thermal bridge but consider it the same as slab edge junctions.

(4) The lack of differentiation in Spanish regulations between balcony–facade and facade–slab edge junctions results in a very high lack of precision in the calculation of thermal bridges and energy needs for buildings. Correctly specifying these two thermal bridges increases the energy needs of thermal bridges by up to 41.3% and the total annual energy needs of dwellings by up to 12.3%. The lack of precision in regulations leads to inaccurate energy needs calculations, especially in regions of the Spanish Mediterranean coast and the BShs climate, where the surface and length of balconies are often much larger than in other Spanish and European regions.

(5) Improving the insulation of thermal bridges does not result in a directly proportional reduction in the linear thermal transmittance of thermal bridges or the total energy needs of the dwelling, with the reduction becoming negligible for very high thermal insulation thicknesses. Therefore, optimal construction solutions are those that greatly reduce the

thermal transmittance of thermal bridges and the energy needs of the dwelling without excessively increasing its thermal insulation.

(6) Enhancing the insulation of thermal bridges reduces the total annual energy needs of buildings with a brick facade and interior insulation by up to 15% and up to 6% in buildings with ETICSs.

(7) In facades with ETICSs, it is better to increase the exterior thermal insulation on slab edges than to insulate floors and interior ceilings. However, an ETICS significantly reduces the thermal transmittance of slab edge junctions in facades, while barely affecting the thermal transmittance of balcony–facade junctions. Therefore, to reduce the energy needs, it is necessary to also reduce the thermal bridge in balcony–facade junctions by insulating floors and interior ceilings or using thermal breakers in the structure.

(8) This study highlights the need to modify current energy efficiency regulations and official calculation programs in Spain to incorporate balcony–facade junctions as a separate and specific thermal bridge. It also underscores the need to promote new construction solutions that reduce thermal bridges in balcony–facade junctions.

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