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Optimization of Architectural Thermal Envelope Parameters in Modern Single-Family House Typologies in Southeastern Spain to Improve Energy Efficiency in a Dry Mediterranean Climate

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Abstract: The increasing regulatory requirements for energy efficiency in Europe imply a significant increase in insulation and solar control of buildings, especially in hot and semi-arid climates with high annual insolation such as the Spanish Mediterranean southeast. The consequences in architectural design to optimize compliance with the new technical and regulatory requirements of nearly zero-energy buildings are high. This paper analyzes the energy performance of a modern single-family house on the Spanish Mediterranean coast. The objective is to determine which design parameters most influence the energy improvement of this case study in order to establish design strategies that can be generalized to other new construction or energy retrofit projects, taking into account the specific characteristics of the warm and semi-arid Mediterranean climate. The scientific novelty of the work is to demonstrate that the design criteria of most modern single-family houses built or rehabilitated in the Spanish Mediterranean in the last decade comply with the energy efficiency requirements of Directive 2010/31/EU but are not specifically adapted and optimized for the special characteristics of the dry Mediterranean climate. This is the case of the house studied in this paper. The methodology used consisted of a systematized study of the main construction and geometric parameters that most influence the thermal calculation of this project: the thermal insulation thickness, thermal transmittance of the glazing, solar control of the glazing, total solar energy transmittance of the glazing with the movable shading device activated, size of glazing and the size of façade overhangs. The results obtained show that the use of mobile solar protection devices in summer, such as awnings or blinds, reduces the cooling need in summer up to 44% and the overall annual energy need (Cooling + Heating) up to 20%. This implementation is more efficient than increasing the thermal insulation of facades and glazing, reducing the size of windows or increasing overhangs. The most optimal solution is the simultaneous modification of several parameters. This reduces both heating need in winter and cooling need in summer, achieving an overall reduction in an annual need of 48%. This multiple solution improves the annual energy performance of the house much more than any solution consisting of modifying a single individual parameter. The results determine trends, explanations and deductions that can be extrapolated to other projects.

Keywords: energy efficiency; nearly zero energy buildings; sustainable rehabilitation; warm semi-arid dry Mediterranean climate; interior comfort; intervention compatibility

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1. Introduction

The increasing regulatory requirements for energy efficiency in Europe, derived from the European Directive 2010/31/EU [1] on the energy performance of buildings and subsequently from Directive (EU) 2018/844 [2] and transposed into national regulations such as the Basic Document DB-HE on "Energy Saving" of the Technical Building Code in Spain by Royal Decree 732/2019 [3] and Royal Decree 390/2021 on the certification of the energy performance of buildings [4], represent a significant increase in thermal insulation and a significant increase in the solar control requirements of buildings [5,6]. The energy saving requirements of these mandatory European and Spanish regulations are equal to or even more restrictive than the Passive House Standard, as some studies have shown [7]. This situation is especially aggravating in hot semi-arid climates with high annual insolation. Moreover, the dry Mediterranean climate of southeastern Spain is a clear example. In fact, several studies conclude that designing Passive Houses in Southwest Europe is more difficult than in Central Europe due to the hot summers, which require additional measures to avoid overheating [8]. All of these considerations have important implications in the architectural design for optimized compliance with the new technical and regulatory requirements of nearly zero energy buildings (NZEB) [9] and for reducing the significant contribution of greenhouse gases from buildings [10].

The design and construction of nearly zero energy buildings make it necessary to propose more efficient architectural designs that avoid energy need. Equipped with efficient air conditioning systems to save energy consumption and complemented by the use of renewable energies to offset such consumption. This includes following low-energy passive design strategies such as those proposed in the Kyoto Pyramid [11], with the aim of reducing energy consumption and CO_2 emissions based on higher construction quality resulting in greater comfort and quality of life for users and taking into account thermal and lighting conditions [12] based on the maxim that the cheapest energy is the energy that is not consumed.

However, to reduce the energy need of residential buildings in hot semi-arid climates, it is not enough to reduce thermal transmittance through their envelopes by increasing thermal insulation and implementing the advantages of eliminating thermal bridges in the facades [13,14] by means of continuous thermal envelopes [15], nor is it feasible to take advantage of the benefits of traditional passive energy control strategies typical of Mediterranean vernacular architecture. They are not sufficiently covered either by the current Spanish or European building energy certification regulations, nor do official computer programa [16] facilitate their modeling. Many scientific studies have defended the application or reinterpretation of traditional bioclimatic designs [17]. Other studies have analyzed the advantages of natural cross ventilation in buildings as an energy saving strategy [18], being especially advantageous in climatic zones with moderate summers and mild winters such as this one [19] as a method of dissipating excess energy accumulated inside dwellings in summer. For economic and architectural design reasons, the benefits of the application of integrated adaptive envelope systems (AES) [20] or double-skin ventilated façades [21] with their advantages over single-skin façades [22] cannot be generalized in residential buildings either.

Due to all these limitations, in the dry Mediterranean climate, it is essential to provide buildings with solar shading elements that reduce the high incidence of sunlight gradually depending on the time of year. These solutions make it possible to take advantage of the benefits of solar radiation control through mobile and adaptable solar shading systems throughout the year [23], and preferably external to glazing due to their better thermal performance in this climate compared to internal solar shading devices [24]. The objective is the design of energy-efficient buildings based primarily on the application of passive strategies and that the use of active air-conditioning systems should be reduced to what is strictly necessary [25]. All these technical aspects have repercussions on the modification of the construction systems used, with important implications for the architectural design itself, in order to optimize compliance with the significant increase in technical and regulatory requirements for energy efficiency in buildings [26].

It is, therefore, relevant to analyze which technical and regulatory aspects most influence and condition the energy performance of buildings and, on this basis, to investigate which technical and architectural solutions are the most optimal considering the advantages of better adapting new architectural projects to the characteristics of different existing climates [27,28], since it has been proven that in places with substantially different climatic conditions, such as the Mediterranean, the design and construction criteria for energy efficient houses are very different from the standard procedures in Northern European countries [29].

Although there is a lot of research on the energy efficiency of buildings according to the new nearly zero energy building regulations in Europe, there are few studies that analyze how to optimize the parameters of the building envelope that most influence the correct energy performance of buildings located specifically in warm semi-arid dry Mediterranean climate zones (BShs) in the Köppen Geiger climate classification [30]. Existing studies analyze projects located in countries not constrained by the limitations of European and Spanish regulations, which influences the design variables used and the results obtained [31,32]. The dry Mediterranean climate, characterized by dry and hot summers, has warmer winter temperatures than the typical Mediterranean climate. With less rainfall and high insolation throughout the year, it is a very specific exception in Europe that is located exclusively in the provinces of Alicante, Murcia and Almeria in Saoutheastern Spain, which requires particular considerations in architectural design that are very different from the rest of the European climates.

This article presents the study carried out in a house on the Mediterranean coast of southeastern Spain that analyzed a combination of different architectural design strategies to optimize the energy performance of the building for its energy retrofit as a nearly zero energy building. The study takes advantage of multi-criteria methodologies based on energy simulations [33] and simplifying the multi-criteria decision making (MCDM) process [34,35] specifically considered to select the most optimal combination of solutions for the specificities of the hot semi-arid dry Mediterranean climate of Southeastern Spain.

The study focused on geometric and constructive architectural design parameters based on passive energy efficiency measures to analyze the effectiveness of passive design aspects in achieving nearly zero energy buildings. The aim is to identify formal and technical aspects that, from the initial conception of the project, have the greatest influence on the energy performance of the building in this type of climate. For this reason, this study does not include other variables based on active systems, such as the use of renewable energies through thermal panels and photovoltaic panels, which are highly efficient in this geographical area thanks to the high annual sunshine and which have been experiencing great technological advances and interesting possibilities for architectural integration in recent years [36].

Apart from that, current Spanish building energy efficiency regulations condition the possible solutions to be adopted but do not consider the thermal benefits of several bioclimatic design strategies [37]. Therefore, other possible passive cooling measures that could significantly minimize the need for mechanical cooling [38], such as natural cross ventilation [39] or evaporative cooling methods [40], which have been used for many years in vernacular architecture in this region and in similar climates [41], have not been analyzed. These types of solutions would offer proven benefits in energy impact [42] and on the thermal comfort of users [43] and indoor air quality of residential buildings [44].

For the selection of the modified constructive and geometric parameters and the combination of values used, the criteria of constructive coherence and economic feasibility were taken into account in addition to the multiplicity of feasible combinations of constructive solutions and the optimization of their energy performance depending on different environmental, energy, economic and design variables, which prevent a single most effective solution [45], especially in case of energy retrofitting of an existing building where the multi-criteria evaluation methodology ends up being substantially altered by the requirements of the owner–users [46].

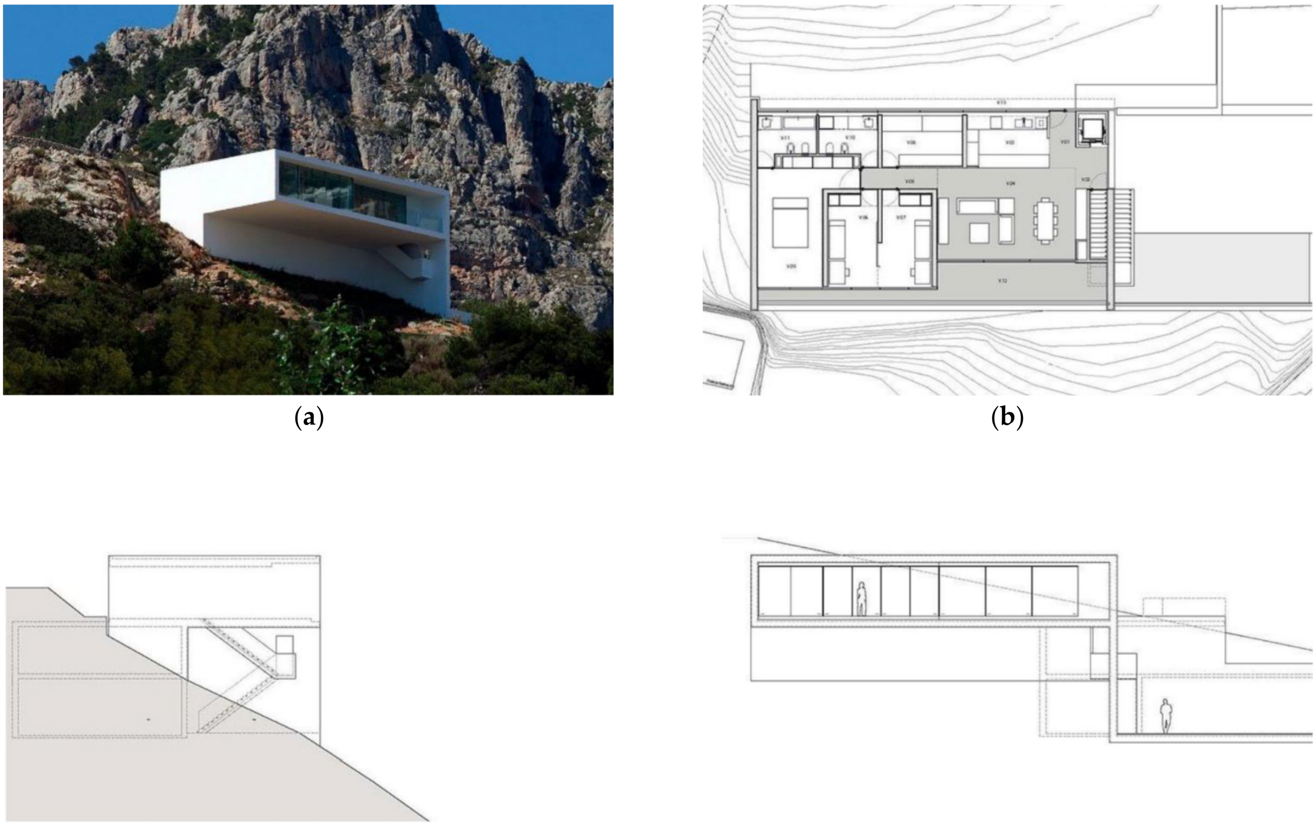
This article analyzes, as a case study, the energy performance of one of the most singular works of the architect Fran Silvestre, designed on the Spanish Mediterranean coast, with the aim of analyzing and assessing the architectural design criteria that most influence the energy efficiency of modern single-family dwellings in a warm climate. This type of housing is increasingly demanded by foreign inhabitants and increasingly awarded in architecture exhibitions.

The methodology employed consisted of a systematized study of the main geometric and construction parameters that most influence the thermal calculation of this project.

The usefulness of the study is to quantitatively evaluate and optimize the most relevant architectural design parameters for improving the energy efficiency of single-family houses located specifically in a dry Mediterranean climate, achieving more sustainable rehabilitation methodologies that adapt the house to the climate, thus also contributing to improving the interior comfort of users and achieving greater compatibility of the intervention with the existing building.

2. Materials and Methods

The case study selected is the "Cliff House" designed in 2012 in the town of Calpe (Spain) by the famous Spanish architect Fran Silvestre, a project of recognized prestige that is a representative example of the most contemporary trends in Spanish Mediterranean architecture [47]. It is situated on a mountainside overlooking the sea, and its main façade faces southeast, where most of the rooms are located. It is a house with a living-dining room, kitchen, 4 bedrooms and two bathrooms, with a total built area of 240 m^2 and 200 m^2 of usable area (Figure 1).



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

(**c**) (**d**)

Figure 1. House under study: (**a**) external image; (**b**) floor plan; (**c**) southwest elevation; (**d**) southeast elevation.

This house was selected because it is a well-known and influential example of modern Mediterranean tourist housing, and its main formal criteria (minimalist forms with flat roofs and large glazing for natural lighting) have ended up influencing and being common to most tourist single-family houses built on the Spanish coast in the last decade.

The predominance of this type of architectural design on the Alicante coast can be seen in the architecture exhibitions of the Alicante Architects' Association in recent years. [48–50] (Figure 2). In fact, after statistically analyzing a sample of 100 randomly selected single-family houses from the projects approved in the last ten years at the Alicante Architects' Association [51], it can be seen that more than 85% of the houses had flat roofs, and 50% had large south-facing glazing.

Figure 2. Selected houses in the architecture exhibitions of the Alicante Architects' Association in the last 15 years.

In addition, a project was selected for which its formal synthesis and orientation help to better analyze the influence of the modification of the construction and geometric parameters analyzed in this research study on the energy performance of the house. Taking into account the results of this work, another study is being developed by focusing on other typologies of traditional Mediterranean architecture in Spain. These other types of houses, although not very common in the projects of recent years, are very abundant in the large pre-1990s building stock and are in need of energy rehabilitation.

The methodology used consisted of a systematized and organized study of the main construction and geometric parameters that most influence the thermal calculation of this project, with a comparative analysis of the influence that the modification of each of these parameters has on the energy efficiency of the building, taking into consideration the specific characteristics of the dry Mediterranean climate.

To this end, six construction and geometric parameters were analyzed and modified gradually and sequentially (Figure 3), carrying out a sufficient sample of calculations to allow the preparation of comparative graphs used to analyze the trend, coherence and causes of the results obtained. The modified construction parameters were as follows: the thermal insulation thickness of the opaque enclosures, the thermal transmittance of the glazing (Ug), solar control of the glazing (g) and total solar energy transmittance of the glazing with the movable shading device activated ($g_{gl;sh;wi}$). The geometrical parameters that were modified were as follows: the size of the glazing by modifying the size ratio between glass and opaque enclosures, and the size of the façade overhangs that act as fixed solar protection for the glazing.

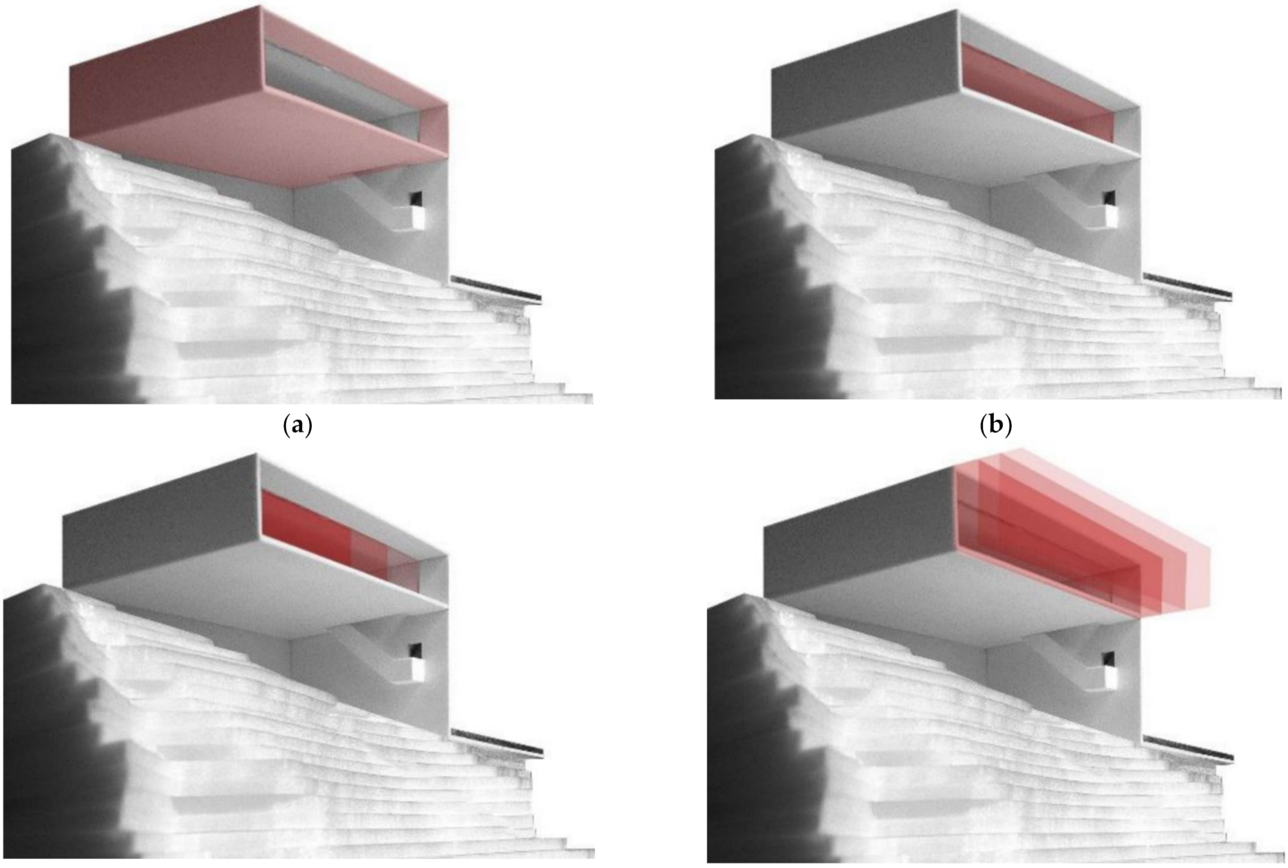
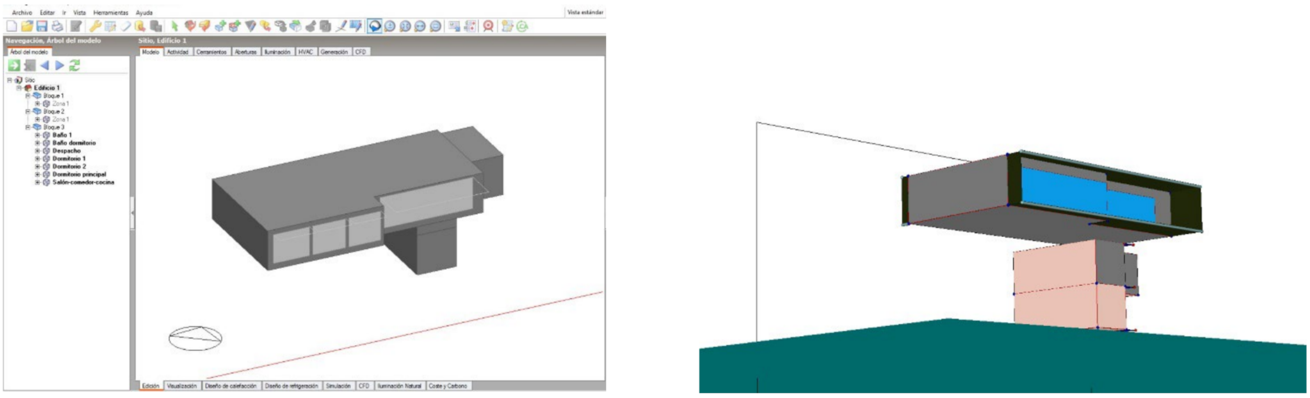

(**a**) (**b**) (**c**) (**d**)

Figure 3. Constructive and geometrical parameters to be studied: (**a**) modification of insulation of opaque enclosures; (**b**) modification of thermal transmittance of the glazing (Ug), solar control of the glazing (g) and total solar energy transmittance of the glazing with the movable shading device activated ($g_{gl;sh;wi}$); (**c**) modification of the size of the glazing by modifying the size ratio between glass and opaque enclosures; (**d**) modification of size of the façade overhangs that act as fixed solar protection for the glazing.

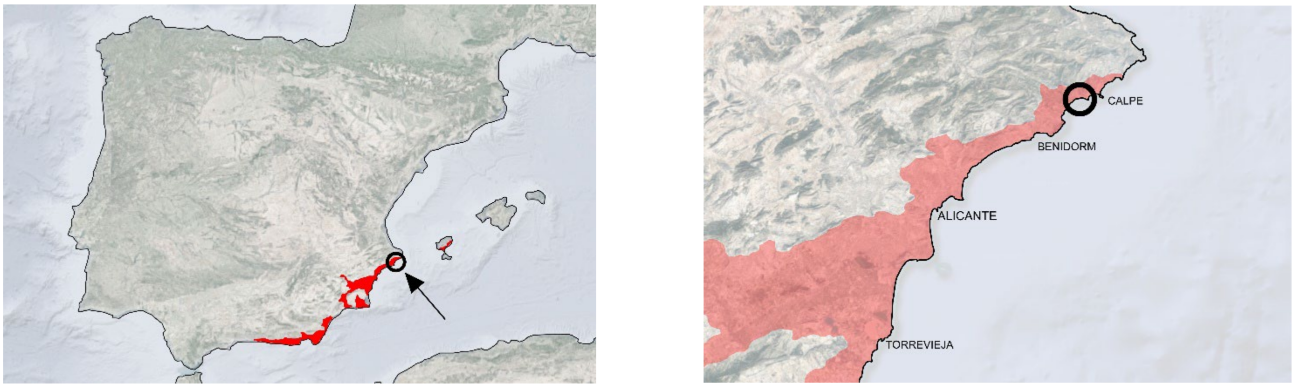
For the modeling and calculation of the energy performance of the dwelling, Design Builder software [52] (version v6.1.8.021) was used for its capacity and accuracy by using the EnergyPlus calculation engine to calculate and analyze individually the thermal loads that affect the energy performance of the house. This software is also very useful for calculating and visualizing the monthly evolution of heating and cooling needs (Figure 4a). In addition, Líder-Calener Unified Tool [53] (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). Although the official software was less capable of calculating and analyzing the results, they allow 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 (Figure 4b).



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

Figure 4. (**a**) Modeled in the software "Design Builder"; (**b**) modeled in the software "Herramienta Unificada LIDER-CALENER".

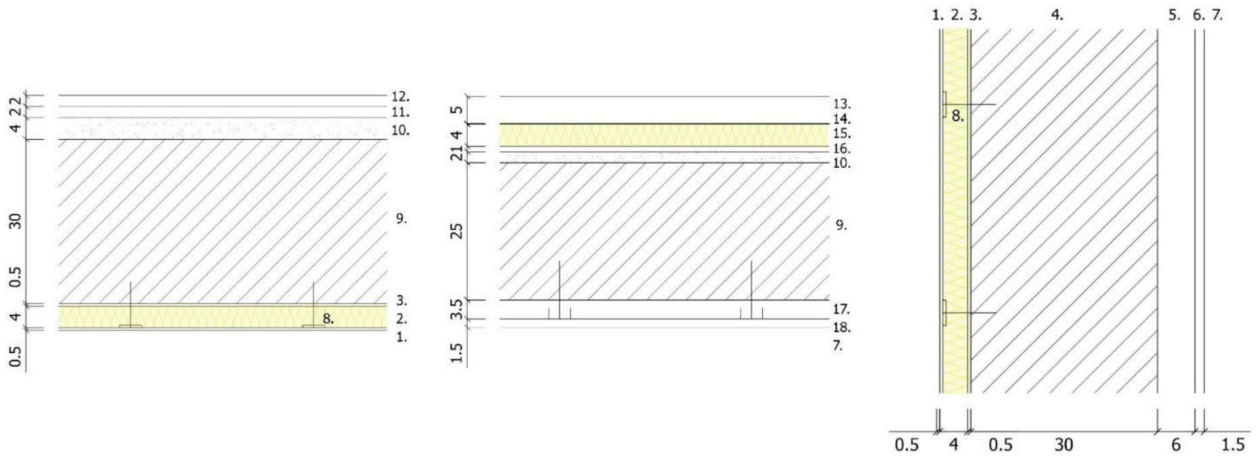
For energy calculation, the specific climatic characteristics of the climate zone have been taken into account in terms of where the building is located: between the tourist towns of Calpe and Altea (Spain) and 59 meters above sea level. This geographical area corresponds to B4 climate according to Spanish legislation [54] and climate BShs (dry Mediterranean climate within a warm semi-arid climate) according to the Köppen climate classification [55]. This type of climate is strongly influenced by the Mediterranean because the sea breeze tempers the sensation of heat, with very mild temperatures in winter and warm in summer, and with an average annual temperature of 18.3 °C and tropical nights in summer with minimum temperatures above 22 °C. Rainfall is less than 500 mm concentrated mainly in autumn and with markedly dry summers. This highlights the great insolation with more than 3000 h of sunshine per year and high average annual relative humidity (Figure 5).



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

Figure 5. (**a**) BShs climate zone according to the Köppen–Geiger Climate Classification for the Iberian Peninsula, the Balearic Islands and the Canary Islands of the Agencia Estatal de Meteorología del Ministerio para la Transición Ecológica del Gobierno de España; (**b**) location of the house and BShs climate zone (red) (own elaboration).

The computer model of the existing dwelling took into account its orientation; geometry; glazing arrangement and size; and the constructive compositions of each of the elements of the architectural envelope (Figure 6 and Table 1).



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

Figure 6. Current constructive compositions of the house: (**a**) construction section of the lower slab; (**b**) construction section of the roof; (**c**) constructive section of the façade wall. Materials: 1. reinforced mortar; 2. expanded polystyrene (EPS) type 3; 3. bonding mortar; 4. reinforced concrete wall; 5. ceramic brick; 6. gypsum plaster; 7. plastic paint; 8. anchoring elements; 9. reinforced concrete slab; 10. self levelling mortar; 11. bonding mortar; 12. natural stone (white marble); 13. gravel Ø2–3 mm; 14. geotextile film; 15. extruded polystyrene (XPS); 16. polyester film; 17. air chamber; 18. plasterboard cladding; 19. Ug = 2.80 W/m^2·K; 20. g = 0.78; 21. $g_{gl;sh;wi}$ = 0.51; 22. Uf = 3.5 W/m^2·K (dimensions in cm).

Table 1. Summary of construction composition of the thermal envelope of the original house.

Composition of the Thermal Envelope of the Original House	Thickness (cm)	Thermal Conductivity (W/m·K)	Thermal Resistance (m^2·K/W)	U (W/m^2·K)	g
Roof:				0.53	
Gravel Ø2–3 mm					
Geotextile film	0.15	0.050			
Extruded polystyrene (XPS)	4.0	0.034			
Polyester film 1.5 mm	0.15	0.23			
Self levelling mortar	2.0	0.55			
Reinforced concrete slab	25	2.30			
Air chamber	3.5		0.31		
Plasterboard cladding	1.5	0.25			
Walls:				0.65	
Reinforced mortar	0.5	0.55			
Expanded polystyrene (EPS) type 3	4.0	0.038			
Bonding mortar	0.5	0.55			
Reinforced concrete wall	30	2.30			
Ceramic brick	7	0.432			
Gypsum plaster	1.5	0.57			
Lower slab:				0.66	
Natural stone (white marble)	2.0	3.50			
Bonding mortar	2.0	0.55			
Self levelling mortar	4.0	0.55			
Reinforced concrete slab	30	2.30			
Bonding mortar	0.5	0.55			
Expanded polystyrene (EPS) type 3	4.0	0.038			
Reinforced mortar	0.5	0.55			
Window				Uw = 2.87	
Glass (90.5% of the window)				Ug = 2.80	g = 0.78
Frame (9.5% of the winwow)				Uf = 3.50	

Frame absorptivity = 0.40; Frame air permeability = 9.00 m^3/h·m^2 (at 100 Pa).

For the modeling of the alterations of the different construction and geometric parameters modified for the proposed comparative study, the parameters have been systematically and sequentially appproahced to introduce individual and progressive variations in each of the selected parameters, calculating their impact on the energy performance of the house by quantifying the differences produced in the thermal needs in summer and winter (Figures 7 and 8 and Table 2).

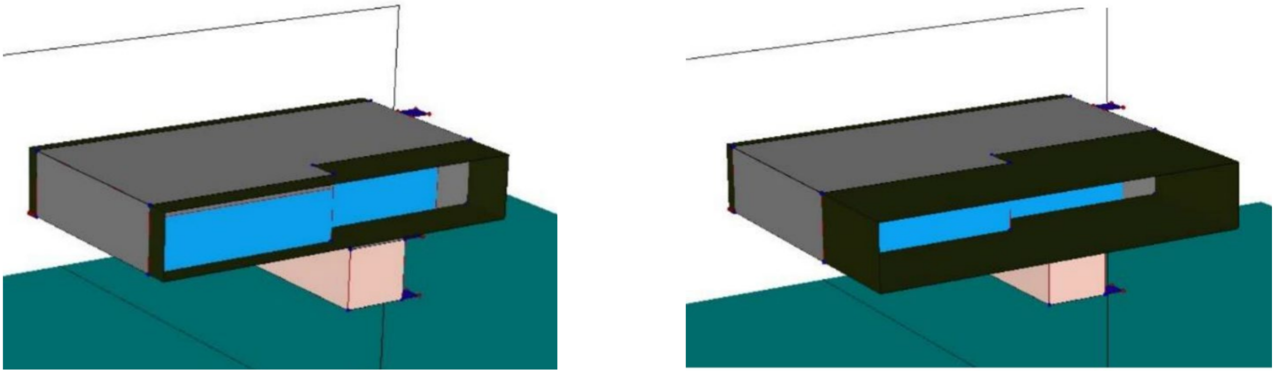

(**a**) (**b**)

Figure 7. Entry of the modified geometric data into in the software "Herramienta Unificada LIDER-CALENER": (**a**) original house with 2 m overhang on the façade; (**b**) modified house with 5 m overhang on the façade.

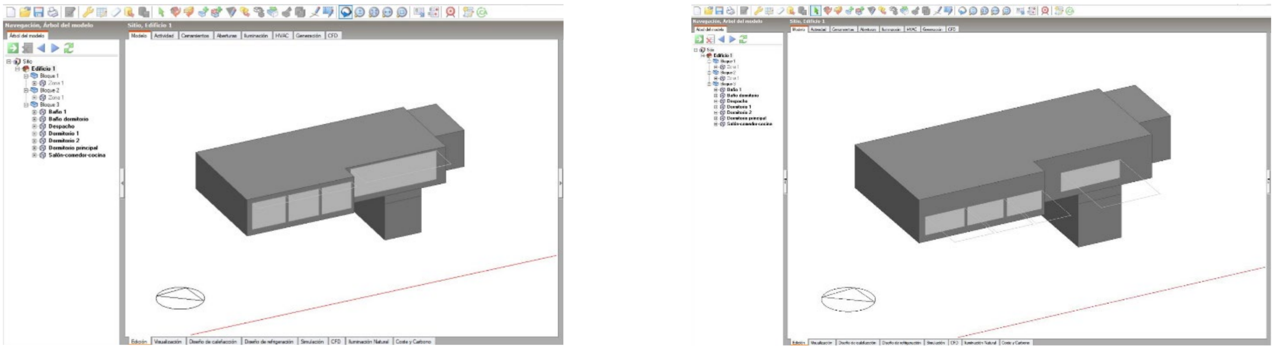

(**a**) (**b**)

Figure 8. Entry of the modified geometric data into in the software "Design Builder": (**a**) original house; (**b**) modified house with 70% of windows compared to the original house.

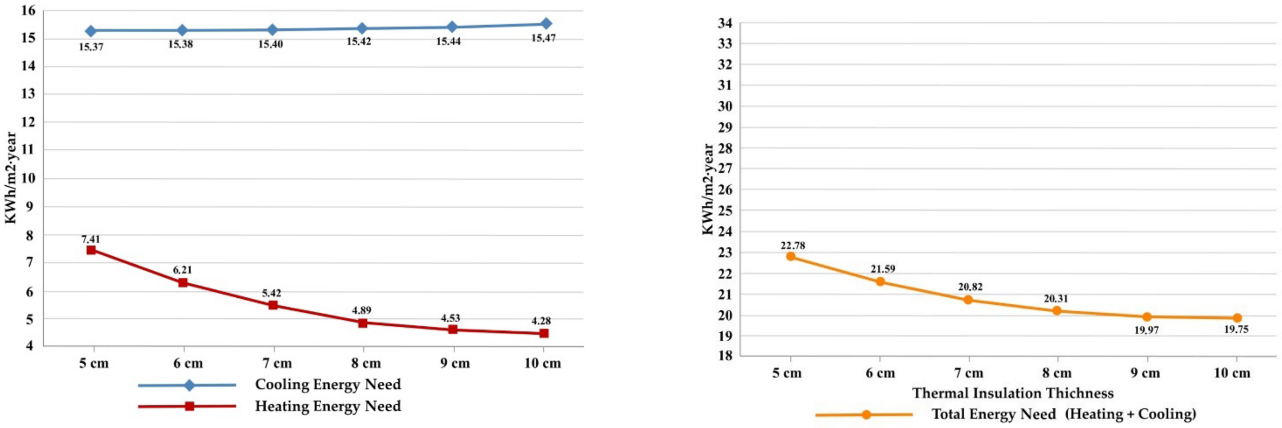
Table 2. Summary of construction and geometrical characteristics of the original house and proposed modifications.

	Thermal Insulation Thickness (cm)	Ug (W/m^2·K)	g	$g_{gl;sh;wi}$	Percentage of Windows (% with Respect to the Original House)	Façade Cantilever (m)
original house	5	2.80	0.78	0.51	100	2
modification 1	6	2.40	0.68	0.36	90	3
modification 2	7	2.00	0.58	0.28	80	4
modification 3	8	1.60	0.48	0.20	70	5
modification 4	9	1.20	0.38	0.14	60	6
modification 5	10	0.80	0.28	0.05	50	7

Indicators and parameters of CTE DB-HE: Ug (W/m^2·K): thermal transmittance of glass; g: solar factor of glass; $g_{gl;sh;wi}$: total solar energy transmittance of the glazing with the movable shading device activated.

3. Results

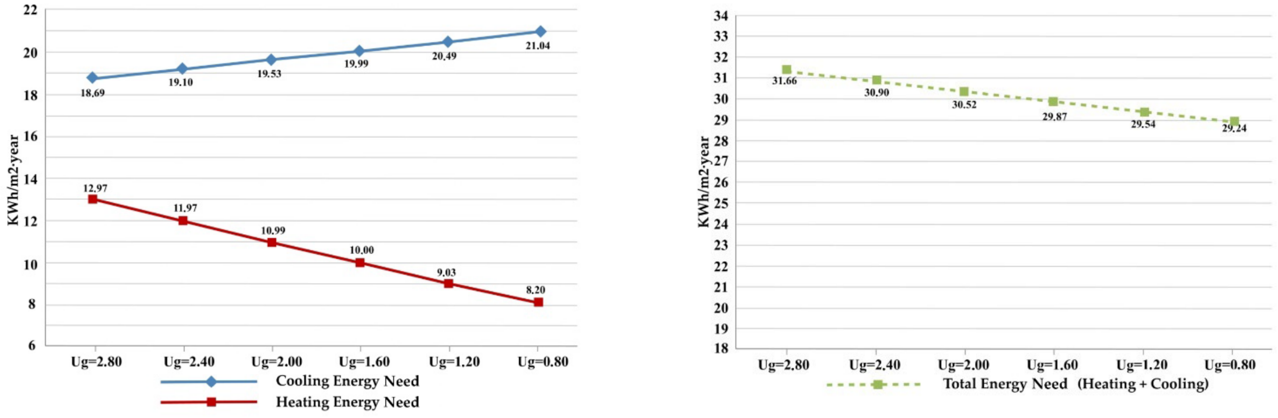
The outcomes obtained show that increasing the thermal insulation of opaque façades up to 10 cm thickness reduces heating needs in winter by up to 42%. For thicker insulation thicknesses, the reduction in heating need becomes lower until it becomes negligible. However, the results also show that, with increasing insulation, cooling needs in summer are not reduced but increases slightly (Figure 9a). On the other hand, the overall annual energy need (Heating + Cooling) is only reduced by 13% (Figure 9b).



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

Figure 9. Modification of thermal insulation thichness of opaque enclosures: (**a**) cooling and heating energy needs; (**b**) total energy need.

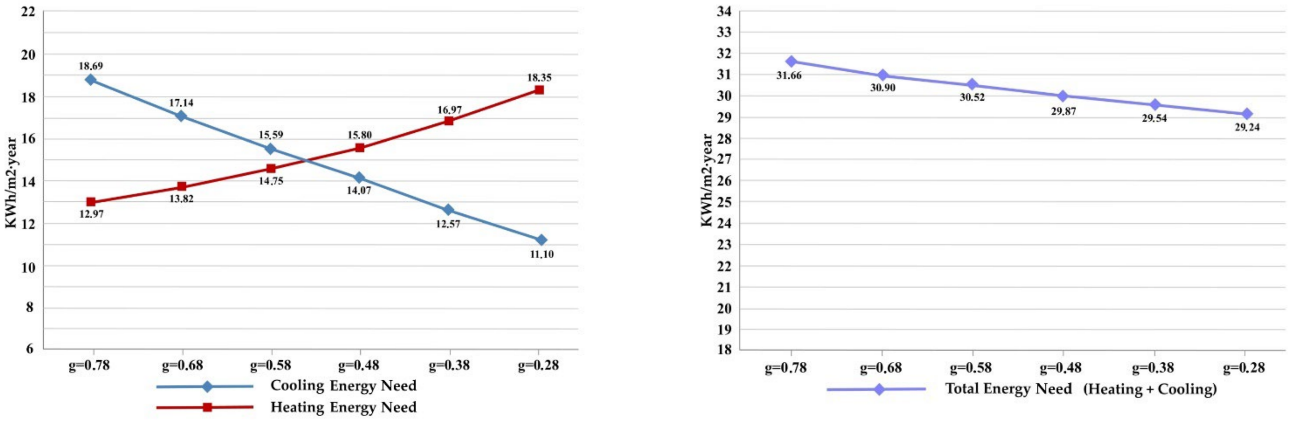
The results obtained show that improving the thermal insulation of glazing produces a directly proportional decrease in winter heating needs of up to 37%, but linearly increases summer cooling needs by up to 13% (Figure 10a). As a consequence, the overall annual need (Heating + Cooling) is only reduced by 8% (Figure 10b).



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

Figure 10. Modification of thermal transmittance of glazing (Ug): (**a**) cooling and heating energy needs; (**b**) total energy need.

On another note, reducing the solar factor (g) of glazing by using solar control glazing reduces cooling needs in summer by up to 41%, but increases heating needs in winter by the same proportion to 41% (Figure 11a). The overall annual need (Cooling + Heating) is reduced by 8% (Figure 11b) because, as the cooling need is proportionally higher than the heating need, the cooling savings are greater than the increase in heating expenditure.



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

Figure 11. Modification of solar control of the glazing (g): (**a**) cooling and heating energy needs; (**b**) total energy need.

In addition, the reduction in the solar factor of the glazing is insufficient to meet the solar control parameter limit of the Spanish regulations in this climate zone (qsol; jul), unless very low solar factor glazing values ($g < 0.28$) are used, which are very expensive and have lower light transmission (Figure 12).

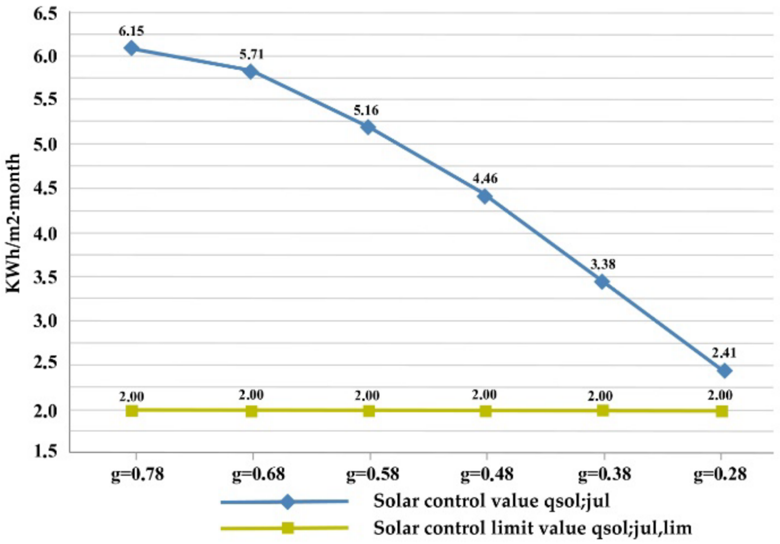
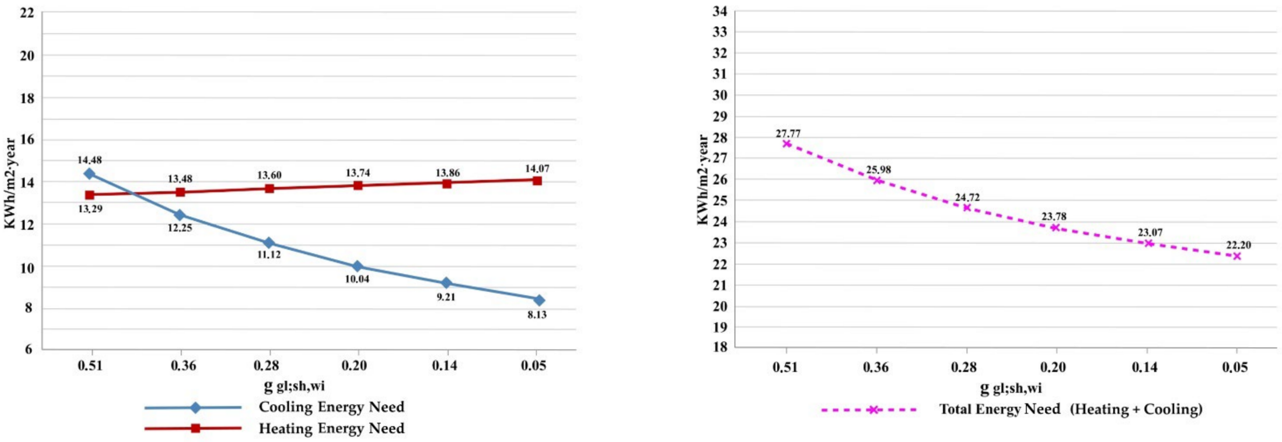


Figure 12. Influence of solar control of the glazing (g) on the solar control value qsol;jul.

The use of movable solar shading devices in the summer, such as awnings or blinds, decreases cooling needs by up to 44% and hardly increases heating needs (Figure 13a). As a result, the overall annual energy need (Cooling + Heating) is reduced by 20% (Figure 13b).

Furthermore, the use of movable shading devices allows solar gains in the summer to be reduced by up to 90%, meeting the solar control parameter limit of Spanish regulations in this climate zone (Figure 14).

With regard to the modification of the geometrical parameters of the building, calculations show that reducing the window area by up to 50% reduces cooling needs by up to 42%, but this decrease is increasingly negligible. On the contrary, reducing the window size results in an increase in winter heating needs of up to 35% (Figure 15a). Consequently, the overall annual need (Cooling + Heating) is reduced by only up to 7%. Furthermore, decreasing the window size by more than 30% increases the overall annual need again (Figures 15b and 16–19).



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

Figure 13. Modification of total solar energy transmittance of the glazing with the movable shading device activated ($g_{gl;sh;wi}$): (**a**) cooling and heating energy needs; (**b**) total energy need.

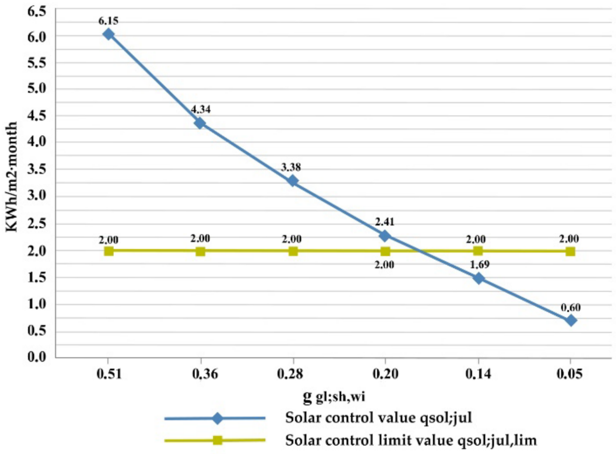
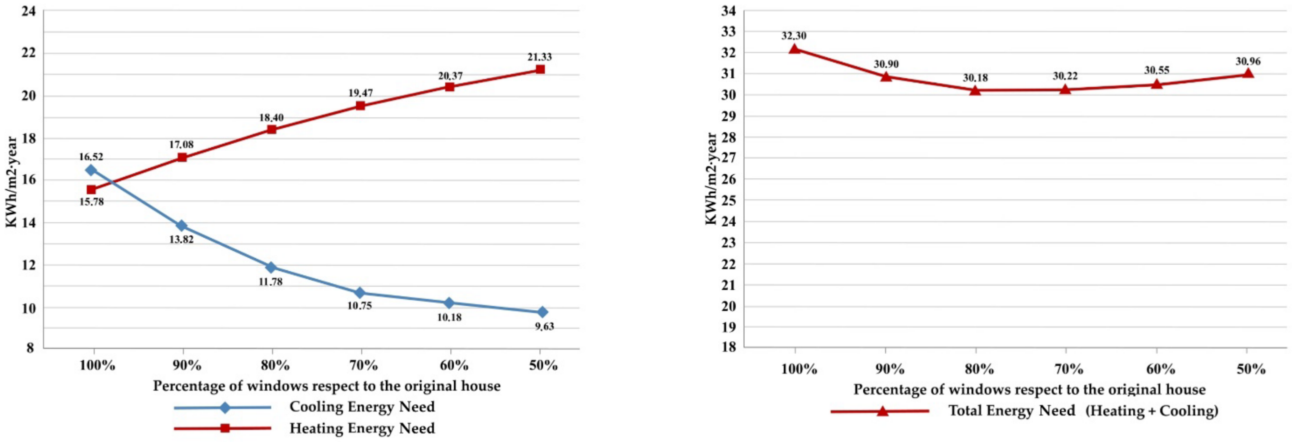


Figure 14. Influence of total solar energy transmittance of the glazing with the movable shading device activated ($g_{gl;sh;wi}$) on the solar control value qsol;jul.



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

Figure 15. Modification of size of the glazing by modifying the size ratio between glass and opaque enclosures: (**a**) cooling and heating energy needs; (**b**) total energy need.

Figure 16. Analysis of energy gains and losses in the original house using the software "Design Builder" (yellow column: solar gains of glass).

Figure 17. Analysis of energy gains and losses in the modified house using the software "Design Builder" (yellow column: solar gains of glass).

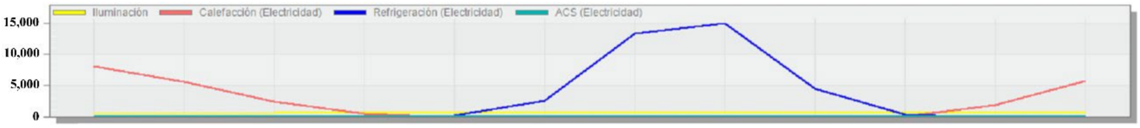


Figure 18. Analysis of the evolution of heating and cooling energy needs over the year in the original house using the software "Design Builder".

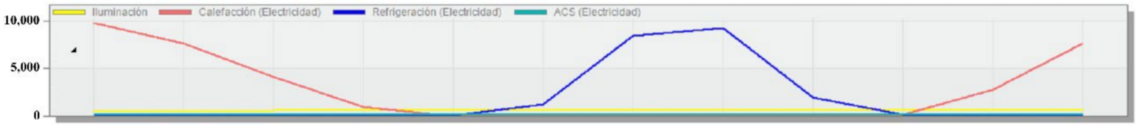


Figure 19. Analysis of the evolution of heating and cooling energy needs over the year in the modified house using the software "Design Builder".

The reduction in glazing reduces solar gains in the summer but is insufficient to meet the solar control parameter limit of the Spanish regulations in this climate zone (Figure 20).

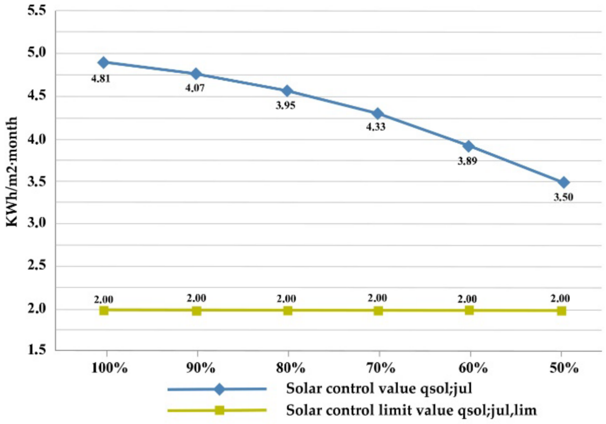
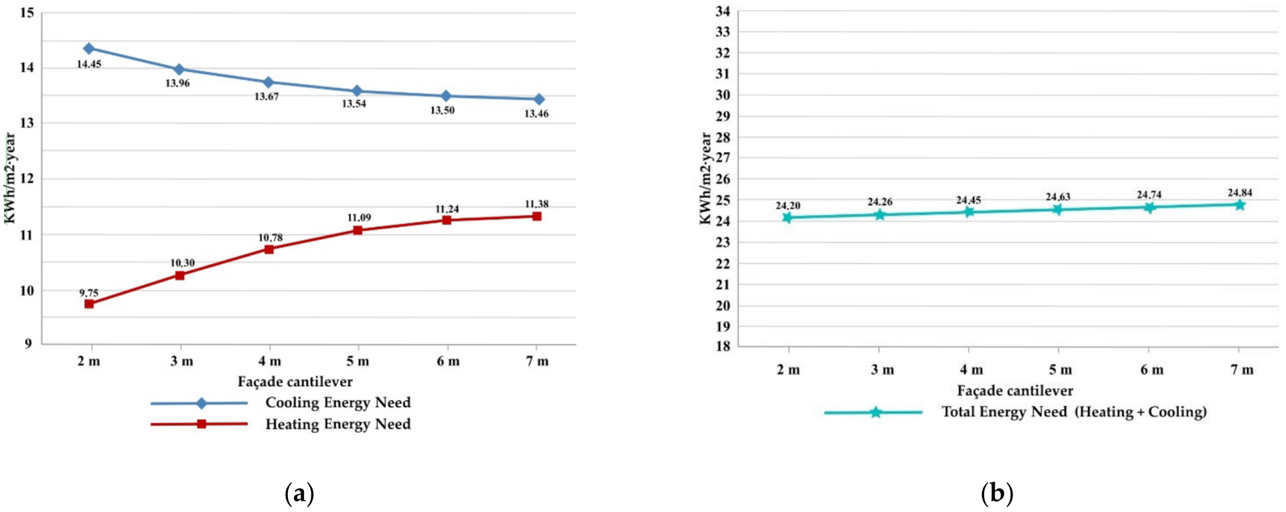


Figure 20. Influence of size of the glazing by modifying the size ratio between glass and opaque enclosures on the solar control value qsol;jul.

In relation to the geometric modification of the façade overhang, increasing the overhang to 4 meters decreases summer cooling needs by up to 5%, but this decrease becomes less and less important until it is almost negligible (Figure 21a). In contrast, heating needs in the winter increase proportionally more, so the overall annual need and annual energy consumption of air conditioning installations increases (Figures 21b and 22–25).



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

Figure 21. Modification of size of the façade cantilever that act as fixed solar protection for the glazing: (**a**) cooling and heating energy needs; (**b**) total energy need.

Figure 22. Analysis of energy gains and losses in the original house using the software "Design Builder" (yellow column: solar gains of glass).

Figure 23. Analysis of energy gains and losses in the modified house using the software "Design Builder" (yellow column: solar gains of glass).

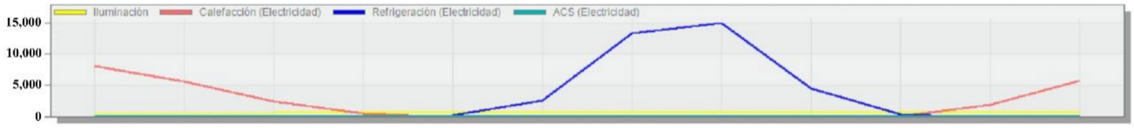


Figure 24. Analysis of the evolution of heating and cooling energy need over the year in the original house using the software "Design Builder".

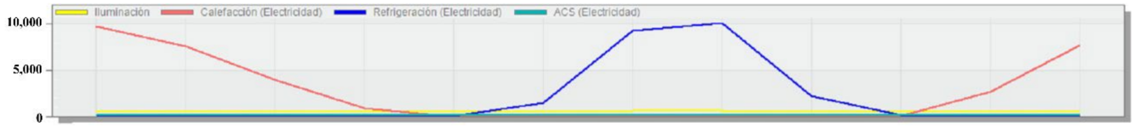


Figure 25. Analysis of the evolution of heating and cooling energy need over the year in the modified house using the software "Design Builder".

In addition, despite a reduction of up to 9% of solar gains in the month of highest insolation, the modifications to the overhangs are clearly insufficient to achieve compliance with the limit values of the solar control parameter established by Spanish regulations for this climate zone (Figure 26).

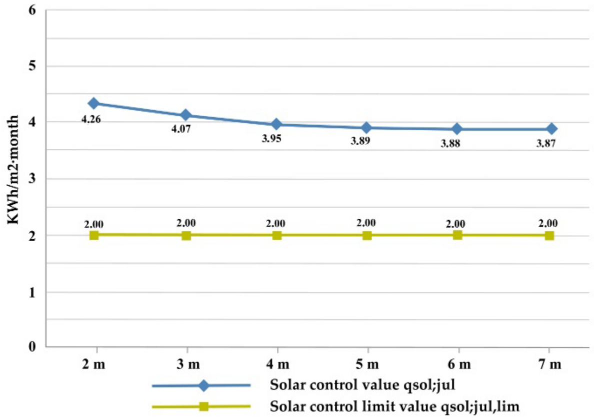


Figure 26. Influence of size of the façade cantilever that act as fixed solar protection for the glazing on the solar control value qsol; jul.

Finally, several combinatorics were calculated by focusing only on altering the parameters for which its modification has been most beneficial in the overall annual need. Therefore, the size of the original cantilever of the project was kept constant, and the size of the windows was kept constant but reduced to 70% as this was the most optimal solution according to the results obtained previously.

The outcomes show that the simultaneous modification of the selected parameters allows a reduction in both winter heating needs by up to 49% and summer cooling needs by up to 48%. As a result, the overall annual need (Cooling + Heating) is reduced by up to 48%, improving the annual energy performance of the house much more than any of the calculated solutions that modified the parameters individually (Figure 27).

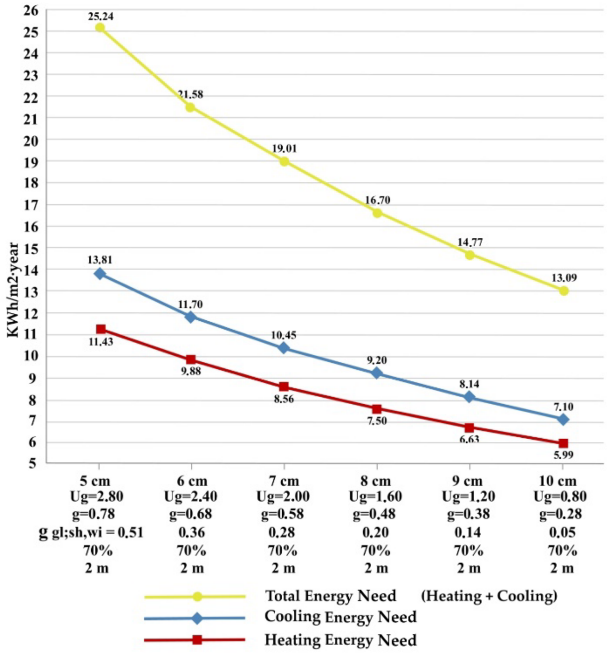


Figure 27. Influence of the combination of construction and geometrical parameters on total energy need.

Lastly, the energy consumption of air-conditioning systems was calculated by considering the nominal power ratings and nominal and seasonal coefficient of performance and energy efficiency ratio of the air-conditioning equipment. The current installations of the house were considered because the improvement of the air-conditioning equipment was not the subject of this work. The air-conditioning system consists of a heat pump with a rated cooling output of 10.20 KW, an energy efficiency ratio of 3.24, seasonal energy efficiency ratio of 4.92, a rated heating capacity of 11.25 KW, a coefficient of performance of 3.41 and a seasonal coefficient of performance of 3.21. The house also has an aerothermal system for domestic hot water with a renewable energy coverage of 82.50%.

The calculations of the original house and the modified house have considered an indoor operating temperature between 21 and 23 °C in the winter and between 23 and 25 °C in the summer, in accordance with the Spanish thermal regulation for buildings [56,57]. Relative indoor humidities of 40–50% in the winter and 45–60% in the summer, and all other aspects in accordance with the regulations, have also been considered.

The calculated total annual primary energy consumption of the current building was 44.30 kWh/m^2·year, with 9.46 in heating consumption, 21.80 in cooling, 9.63 in domestic hot water and 3.41 in ventilation. The calculated total annual non-renewable primary energy consumption was 27.50 kWh/m^2·year, with 5.82 in heating consumption, 16.62 in cooling, 2.46 in domestic hot water and 2.60 in ventilation. However, the theoretical consumption calculated with the computer tools does not logically coincide with the actual energy consumption of the house, as it is a holiday home used only on weekends and holidays. In fact, the actual consumption is only 15 kWh/m^2·year, with an annual expenditure of approximately EUR 600. This expenditure corresponds to a total energy cost of approximately EUR 0.20/kWh. which includes the cost of the energy consumed plus the proportional charges for the contracted energy and taxes.

The total annual primary energy consumption of the current house calculated using the computer tools complies with the Spanish nearly zero energy buildings standard but without the proposed improvement measures, the house does not comply with the solar control parameter limit of the Spanish regulations.

The results show that the energy performance of the house can be greatly improved. The energy improvement proposals put forward in this study would reduce the theoretical total annual primary energy consumption to 29.10 kWh/m^2·year, with 6.23 in heating consumption, 14.26 in cooling, 6.32 in domestic hot water and 2.29 in ventilation. The total annual non-renewable primary energy consumption would reduce to 17.90 kWh/m^2·year, with 3.76 in heating consumption, 10.81 in cooling, 1.59 in domestic hot water and 1.74 in ventilation.

These calculations represent a saving of approximately 34% in the primary energy consumption and 35% in the non-renewable primary energy consumption of the dwelling.

4. Discussion

The analysis of the results obtained shows that increasing the thermal insulation of the opaque enclosures reduces the heating need in winter considerably (−42%), although it slightly increases the cooling need in the summer due to the fact that the greenhouse effect inside the house also increases slightly (Figure 9a). However, this reduction in heating expenditure represents little saving in total annual expenditure (−13%) (Figure 9b). This is because cooling expenditure is proportionally much higher than heating expenditure due to being in a warm climate with mild winters. In addition, the results show that further increasing the insulation thickness above 10–12 cm in facades and roofs hardly improves the energy performance of the house. This is explained by the fact that the dry Mediterranean climate is characterized by mild winters with a few very cold days; therefore, excessively insulated houses are not needed.

Regarding the improvement of the glazing characteristics, the comparative analysis of the results shows that the reduction in thermal transmittance and the solar factor of the glazing reduces the total annual energy need only slightly (−8%) (Figures 10b and 11b). There are two reasons for this. On the one hand, the dry Mediterranean climate is characterized by many sunny days throughout the year. This means that increased glass insulation reduces heating needs in the winter but increases the greenhouse effect in the summer by making it more difficult to release the heat from solar radiation that accumulates inside the house, which increases cooling costs (Figure 10a). On the other hand, reducing the solar factor of glazing reduces solar gains and cooling needs in the summer but increases heating costs in the winter by preventing free heat gains from solar radiation in the colder months (Figure 11a).

With regard to the reduction in glazing size, the comparative analysis of the results shows that reducing the percentage of windows slightly reduces the total annual need (Figure 15b) because it improves the cooling need in summer and still allows thermal gains from solar radiation in winter to be used. However, if the window size is reduced too much, the total annual need starts to worsen because the increase in heating expenditure in winter is greater than the cooling savings in summer (Figure 15a), because the heat gains from solar radiation through the windows are wasted for many months of the year.

Regarding the modification of overhangs, calculations show that increasing the size of the overhangs does not improve the total annual need (Figure 21b) because it reduces the cooling need in summer but significantly increases the heating need in winter as a result of reduced heat gains due to the lower incidence of solar radiation through the glazing (Figure 21a). In addition, the solar control caused by the overhang on the glazing is almost negligible when the overhang is very large (>4 m) as the sun no longer shines on the glass.

The comparative analysis of the results obtained for the individually modified variables shows that the incorporation of movable shading devices for solar control leads to the greatest improvement in the annual energy performance of the house (Figure 13b), because it substantially reduces the cooling need in summer but hardly increases the heating need in winter (Figure 13a). This is because movable shading devices allow the control of excessive solar radiation in summers when deployed, but they also allow thermal gains from solar radiation in winters when folded. This is explained by the important influence of high annual insolation during all months of the year, including winter, which characterizes the warm semi-arid climate, which has a strong influence on the energy performance of the house.

These mobile shading devices are passive systems that can be adapted to different sun protection needs throughout the year. They can be traditional elements such as blinds, awnings, louvres or deciduous vegetation. However, they can also be increasingly advanced mobile systems such as bioclimatic pergolas and variable geometry or stationary louvres capable of reducing the penetration of solar radiation into the interior of the house in the warmer months and allowing the heat of solar radiation to pass through in winter. These industrialized solutions can even incorporate photovoltaic modules for electricity production [58], and their potential and relevance in climates with high insolation, such as the dry Mediterranean climate, form the basis for further research. Curtains or blinds inside the house can also be considered as mobile solar shading devices, but their effectiveness in reducing thermal gains from solar radiation is much lower [59–61]. The results obtained on the influence of mobile shadowing devices have similarities with other scientific publications in other geographical areas [62]. However, the calculations made in this study are focused on the dry Mediterranean climate, which allows obtaining more specific results and conclusions for this climate zone.

Finally, the study shows that the best results are obtained by modifying several of the parameters considered simultaneously and in a balanced manner (Figure 27). To achieve this, it is necessary to increase the insulation of the enclosures and glazing while improving the solar control of the glazing and also applying movable shading devices. With this solution, the results are better because the heating need in winter is reduced by increasing insulation and also taking advantage of the heat gains from solar radiation, but excessive solar radiation in summer is avoided with the movable shading devices.

However, the size of the overhangs is kept fixed because it does not lead to a clear improvement in energy performance, as demonstrated in this study. The size of the windows is also kept fixed because, as the calculations have shown, changing the glazing can lead to better or worse results depending on the proportion of glazing in relation to the geometry of the house, and a suitable solution for this variable cannot be generalized to other houses.

Despite the great improvement obtained in the energy efficiency of the case study, the results achieved are less optimal than other research works related to other geographical areas that apply multi-objective optimization analysis [63,64]. These works combine energy calculation simulation software with computer optimization tools, using algorithms instead of parametric studies [65–67]. Therefore, the results and conclusions of this paper are useful for further research by applying automated optimization methods in dry Mediterranean climates.

Apart from that, the factors analyzed in this case study show the dependence on the use of efficient air conditioning systems. This dependence in Mediterranean climate in other types of housing with social character is practically unaffordable due to the socioeconomic situation of their owners [68]. Because of that, a correct study of the solar protection parameters and the increase in the insulation of the enclosures and glazing will reduce cooling and heating needs and, consequently, the operating hours of air-conditioning equipment and their energy and economic costs.

5. Conclusions

The study carried out shows the convenience of adopting design and energy rehabilitation criteria adapted to the specific climate of the area, in this case the dry Mediterranean climate, given that the modification of each construction and geometric parameter affects the energy performance of the house in very different ways depending on the climatic characteristics.

This work demonstrates that, in the case of a dry Mediterranean climate, it is necessary to simultaneously improve the thermal insulation of the façades and the solar control of the glazing. If only the insulation of the façades is improved, the greenhouse effect and cooling costs are increased by making it more difficult to dissipate the heat introduced by radiation through the glazing due to the high annual insolation in this type of climate.

The analysis of the results obtained shows that, in this type of warm semi-arid climate, flexible solutions that allow incident radiation on the façade glazing to be adjusted according to the time of year and weather conditions, such as blinds, awnings, shutters, louvres, deciduous vegetation, etc., are much more optimal. Due to the specificities of this climate characterized by many sunny days throughout the year, this type of solution makes it possible to use the heat from solar radiation in winter to minimize heating costs, to protect the glazing from excessive solar radiation in summer to reduce cooling costs and to maintain the greatest number of hours of comfort without the need for air-conditioning during the spring and autumn months.

The study shows that the adoption of permanent architectural solutions such as increasing overhangs or reducing the size of windows reduces cooling needs in summer but increases heating need in winter by wasting heat from solar radiation in cold weather.

The study is very conclusive and shows that the best option for improving the energy efficiency of buildings is to combine the increased insulation of the thermal envelope and the use of mobile solar shading devices, taking into account the specific characteristics of the dry Mediterranean climate that is characterized by mild winters and hot summers with high sunshine throughout the year. The improvement achieved with this solution is a reduction in cooling and heating requirements, which reduces the operating needs of air-conditioning systems and their energy consumption.

This developed research study verifies that the most efficient architecture is not that which uses digital tools to seek compliance through the use of more equipment, as if a house was a living machine. The most efficient architecture is that which arranges and balances the rational use of openings, envelopes and solar protection with the support of air conditioning systems. There is nothing more efficient than eliminating consumption.

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visualization, A.L.-P.; supervision, C.P.-C., Á.B.G.-A. and A.G.-G.; project administration, C.P.-C. and Á.B.G.-A. All authors have read and agreed to the published version of the manuscript.

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