

Article

A Comparative Analysis of Energy Performance in Heating Consumption for Different Building Envelope Materials and Designs: A Case Study

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Abstract

The EU has established various general objectives aimed at energy sustainability, developing a broad regulatory framework linked to the various sectors that account for a significant share of global energy demand. Within this regulatory framework, strategic guidelines have been established through which the general objectives can be achieved. Numerous studies have been published related to the analysis of new materials and/or construction solutions for the thermal envelopes of buildings aimed at minimizing their energy demand. In the research presented here, an exhaustive analysis is conducted of these studies and of the technical characteristics of the materials and/or construction solutions identified. A method is developed, including standard calculation models, that is applied to all the technical solutions identified in the literature. Based on this, multiple simulations are carried out to evaluate energy demand and CO₂ emissions for heating in different building types located in cold climate zones. From the results obtained, the performance of the different technical solutions was compared according to building type and climate zone. The results show appreciable differences in energy performance among the various construction solutions, even when they use the same reference material. This disparity in results varies depending on the type of housing and the climate zone. The results are of interest for the establishment of strategies in nearly zero-energy building planning.

Keywords: nearly zero energy buildings; energy efficiency; building thermal envelope; energy planning

Academic Editors: Magdalena Grudzińska and Jing Zhao

Received: 26 March 2026

Revised: 21 April 2026

Accepted: 28 April 2026

Published: 29 April 2026

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1. Introduction

Energy use in buildings amounted to more than 120 exajoules (EJ) in 2023, equivalent to approximately 30% of global final energy consumption [1]. By 2050, it is projected to increase to 153 EJ in the Stated Policies Scenario (STEPS) but fall to 92 EJ in the Net Zero Emissions (NZE) scenario. A notable increase in the share of electricity consumption by this sector is expected globally over the coming decades, primarily due to increased cooling and appliance use. This will position it as the largest electricity-consuming sector by 2035 in the STEPS.

Energy efficiency and electrification are the two primary drivers of decarbonization in the NZE scenario [2]. Ibrahim et al. [3] reported on the advantages of implementing strategies based on the concept of so-called nearly zero energy buildings (NZEBs) with a view to reducing primary energy demand, arguing that these should be incentivized in energy policies. In their conclusions, they emphasized the technical feasibility and environmental impact of implementing NZEB strategies, as well as the need for research focused on case studies that evaluate the effectiveness of different designs in reducing energy demand in buildings.

The European Union (EU) has acknowledged the problem of slow electrification and low renewable energy penetration in heating [4]. The EU set the target of NZE by 2050 through the 2021 European Climate Law [5], establishing various objectives within the framework of the pathway towards a zero-emission building stock by 2050 through the Energy Performance of Buildings Directive (EPBD) 2024/1275 [6]. As recorded in the EPBD, Member States must guarantee that, by 2030, the average primary energy use of the total residential building stock, in kWh/(m²·year), is reduced by at least 16% relative to 2020 levels. To this end, the EPBD requires renovation in line with the ‘energy efficiency first’ (EE1ST) principle. According to Commission Recommendation 2021/1749 [7], this means Member States will have to prioritize energy efficiency improvements in policy, planning, and investment decisions when energy demand or supply is affected. In the building sector specifically, the EE1ST principle should be implemented in both renovation projects and new construction. Improving the performance of the building envelope is one of the measures by which the reduction in the overall energy demand of the building can be maximized [7]. It is recommended to carry out this measure before others, such as replacing the heating system.

The EPBD calls for integrated national energy and climate plans to include specific policies and measures to achieve the target of NZE by 2050 and to promote, for example, the energy efficiency of buildings. In Spain, heating is the most energy-intensive use in households, accounting for 39.3% of consumption in 2022 [8]. For this reason, Spain’s National Energy and Climate Plan [9] includes among its main objectives the prioritization of measures that target the building’s thermal envelope in order to reduce final energy demand for heating and cooling. Different factors, such as the efficiency of thermal technologies or usage habits, have a decisive influence on energy demand and intensity in the residential sector.

Various studies have focused on improving the design characteristics of the building envelope to reduce its heating energy demand. Iturriaga et al. [10] developed a model to optimize the energy renovation of buildings and applied it to a case study of a residential multi-family building in Bilbao (Northern Spain). For the analysis, the authors considered different energy-saving measures. The measures specifically proposed for the building envelope, which is made of hollow bricks, are based on providing it with a greater thickness of expanded polystyrene (EPS) insulation. As a result, they determined that the optimal design for the zero energy building case, based on 8 cm insulation for the façades and 14 cm for the roof, achieves a 27.9% reduction in heating load. In no case was improvement of the windows selected, as it would require a high investment in relation to the potential heating savings. Applying this method to other building types and climate zones would further demonstrate its high potential for energy planning.

In [11], the energy retrofit of the main façades and roof of an existing multi-family building in Montcada i Reixac, Barcelona (Spain), was monitored and assessed. Most notable among the measures implemented was the replacement of the building’s façade, with the addition of an external insulation layer of EPS foam. As a result, its thermal transmittance decreased from 1.89 to 0.489 W/m²·K. However, the authors concluded that the energy retrofit did not significantly reduce energy consumption or increase indoor

thermal comfort and deduced that energy performance was affected by negative thermal breaks created by the existing exterior openings.

Goenaga-Pérez et al. [12] evaluated the minimum requirements set by Spanish regulations in terms of cost-effective solutions. They used a new apartment building with 22 dwellings on eight floors, located in Ermua, Bilbao (Spain), climate zone C, as a reference building representative of new multi-family buildings in Spain. The authors concluded that equipping the building with optimized energy systems, such as heat pumps, PV panels, or solar thermal collectors, was more effective at reducing annual costs and primary energy consumption than passive solutions, as thermal demand is significantly reduced if the thermal transmittance of the envelope elements does not exceed the maximum established in subsection HE1 of the Spanish Technical Building Code (TBC) [13]. However, following the EE1ST principle, improving the envelope elements should be prioritized over other active measures [7], so special attention should be given to measures adopted to achieve an optimal envelope transmittance value. Furthermore, in some situations, whether due to inefficient building energy systems or particular operational specificities, the minimum equivalent uniform annual cost is obtained when a comprehensive energy renovation of the building envelope is considered [14].

The thermal transmittance (U-value) of the building envelope is a key parameter as it can directly affect the operational energy consumption of buildings [15]. In this regard, various studies on its influence on building design [16,17] and energy consumption [18] can be found in the scientific literature. Fernandes et al. [17] evaluated the impact of the U-value on building design in sixteen non-island locations in the Mediterranean region. In [18], the authors found that the effect of thermal mass on the building's energy consumption varies depending on the U-value chosen, and therefore its levels should be selected in relation to the thermal transmittance value. As in previous studies, the Evolutionary Program for the Space Allocation Problem (EPSAP) algorithm was also used to determine the ideal U-value range for future climates in Brazil [19] and Iran [20].

Among the most commonly studied measures in the reviewed scientific publications are certain passive and active solutions for buildings located in specific climate zones. These include improving the thermal insulation of the building envelope or installing energy supply systems, as well as determining U-values that optimize the building's energy performance. As previously mentioned, in addition to determining the optimal U-values for a building's envelope, it is also necessary to identify the construction solutions and/or design materials that best suit the conditions to which the building is exposed.

In this paper, a method is developed to conduct a detailed comparative analysis of effects on primary energy demand and CO₂ emissions for heating of a wide variety of materials (concrete, brick, timber, or composites) and building envelope design typologies, obtained following an extensive review of the literature. Based on the technical characteristics of each, the method—which incorporates standard calculation models—is applied, and multiple simulations are run for various single-family-home (SFH) types and cold climatic conditions. From the results obtained, it is possible to analyze, evaluate, and compare the performance and/or adaptability of the different thermal envelope construction solutions. The results and the conclusions derived from them are of interest in the strategic planning of NZEBs.

2. Materials and Methods

For this study, an extensive review of the literature was conducted to collect thermal transmittance values for different building envelope typologies, with the aim of comparing primary energy consumption for heating. Section 2.1 presents the 33 different building envelope typologies selected for a comparative analysis after the literature review. This analysis is conducted for a specific case study, defined in Section 2.2, which considers

three SFH types located in two distinct climate zones. Section 2.3 explains the methodology followed in the simulations conducted to compare energy consumption with the different types of building envelopes. Finally, Section 2.4 sets out the economic analysis method that was followed. Figure 1 offers a schematic representation of the method developed for the present study.

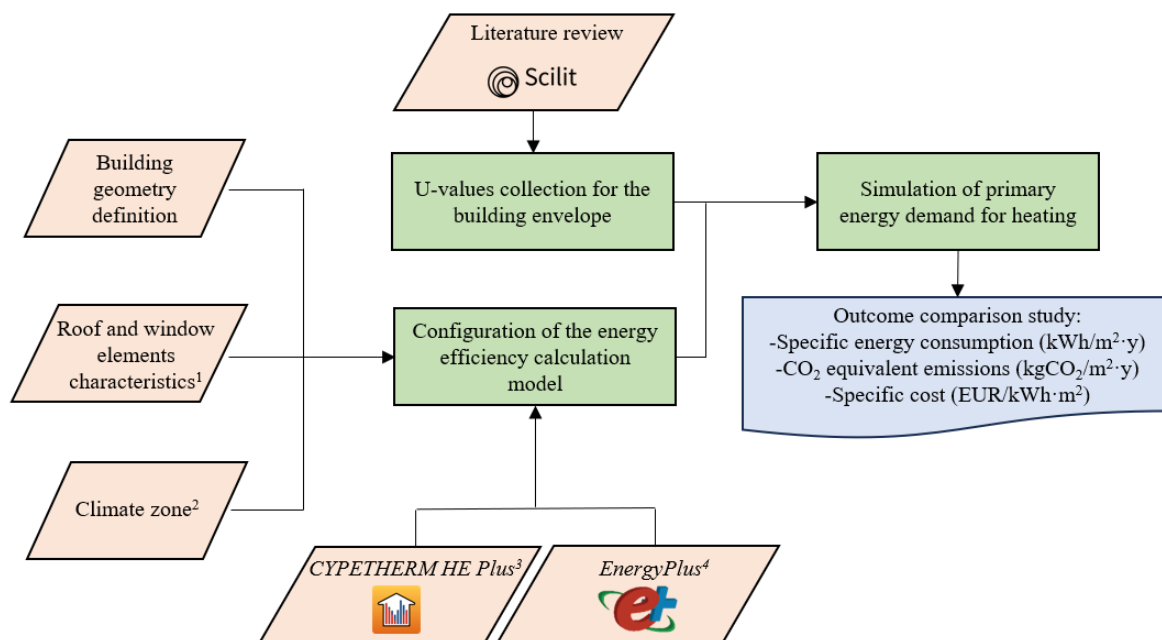


Figure 1. Method developed. ¹ Spanish Technical Building Code [21]. ² Climate zone data [22]. ³ See [23]. ⁴ See [24].

2.1. Search for and Selection of Building Materials

Different types of construction materials were considered for the building envelope, whose thermal transmittance values were previously measured both in situ and in the laboratory using common methods such as the heat flow meter (HFM), the hot box test (HBT), the simple hot box (SHB), quantitative infrared thermography (QIRT), and the calibrated hot box (CHB) [25]. These methods ensure the accurate measurement of thermal transmittance, which has significant implications for building energy efficiency [26].

The search strategy for construction materials was carried out in the Scilit database [27], using the advanced search field “Common Fields [Title, Abstract, Keyword].” The search string was structured using the following combination of terms and operators: (“envelope”) AND (“U-value” OR “thermal transmittance”) AND (“measurement”) AND (“laboratory” OR “in situ”) AND (“heat flow meter” OR “hot box test” OR “simple hot box” OR “quantitative infrared thermography” OR “calibrated hot box”). This combination allowed the research studies to be narrowed down to those which focused on measuring the thermal transmittance of the envelope and the most relevant experimental methods, both in the laboratory and under real conditions.

Once the studies that met the established inclusion criteria for the search had been identified and collected, they were classified according to the main material of the building envelope. More specifically, four types of building envelope were considered: concrete envelope (CE), brick envelope (BE), timber envelope (TE), and composite building envelope (CBE). Tables 1–4 show the measured U-values for each of the building envelope types selected for the analysis in this paper. Their specific construction details, as well as the method used to measure their U-value, can be found in the corresponding references

indicated in the tables. Figure 2 shows the number of building envelope assemblies selected for analysis by measurement type and method.

Although the U-values were obtained using different methods, they are considered, in general terms, comparable for the purposes of this study. However, it should be noted that differences in boundary conditions, such as the temperature difference between the interior and exterior, air speed, and solar radiation, can lead to some variability in the results. These conditions can also be consulted in the references indicated in the tables.

Table 1. Identification, description and thermal transmittance of the concrete envelopes (CEs).

Identification	Description	Measurement Type	Measurement Method	Transmittance (W/m ² ·K)	Ref.
CE-1	Cavity envelope	In situ	HFM	0.26	[28]
CE-2	Concrete block envelope	In situ	SHB-HFM	1.26	[29]
CE-3	Reinforced CE	In situ	HFM	0.23	[30]
CE-4	Hollow concrete blocks	In situ	HFM	2.1	[31]
CE-5	Lightweight CE	In situ	HFM	1.782	[32]
CE-6	Thin precast CE	Laboratory	HBT	0.555	[33]
CE-7	CE with internal polyisocyanurate insulation	In situ	HFM	0.148	[34]
CE-8	Autoclaved concrete block envelope	Laboratory	HBT	1.23	[35]

Table 2. Identification, description and thermal transmittance of the brick envelopes (BEs).

Identification	Description	Measurement Type	Measurement Method	Transmittance (W/m ² ·K)	Ref.
BE-1	Clay BE	Laboratory	CHB	0.304	[36]
BE-2	BEs	In situ	QIRT	0.285	[37]
BE-3	Perforated BE	In situ	QIRT	1.51	[38]
BE-4	Ceramic BE	In situ	HFM	0.97	[39]
BE-5	Lightweight clay BE	N/A	N/A	0.62	[40]
BE-6	Fired-clay BE	In situ	HFM	1.32	[41]
BE-7	Hollow BE	Laboratory	CHB	1.24	[42]
BE-8	Tuff BE	In situ	HFM	0.75	[43]
BE-9	Solid BE with gypsum plaster	In situ	QIRT	1.57	[44]
BE-10	Silica BE	In situ	QIRT	0.229	[45]

Table 3. Identification, description and thermal transmittance of the timber envelopes (TEs).

Identification	Description	Measurement Type	Measurement Method	Transmittance (W/m ² ·K)	Ref.
TE-1	Light timber external envelope	In situ	QIRT	0.38	[37]
TE-2	Cross-laminated TE	In situ	QIRT	0.194	[37]
TE-3	Type of light TE with wooden fiber insulation	In situ	QIRT	0.16	[46]
TE-4	Timber frame envelope with wheat chaff insulation	Laboratory	HBT	0.307	[47]
TE-5	Wood panel envelope	In situ	HFM	0.174	[48]
TE-6	Modular plywood panel envelope	In situ	HFM	0.201	[48]
TE-7	Cross-laminated TE	Laboratory	HBT	0.199	[49]
TE-8	TE	In situ	HFM	0.6	[50]
TE-9	Four-layered spruce wood envelope	Laboratory	HBT	0.375	[51]

Table 4. Identification, description and thermal transmittance of the composite building envelopes (CBEs).

Identification	Description	Measurement Type	Measurement Method	Transmittance (W/m ² ·K)	Ref.
CBE-1	Envelope with cork insulation between bio-composite structural profiles	In situ	HFM	0.27	[52]
CBE-2	Ultra-low carbon steel sandwich panel with wood fiber insulation	In situ	N/A	0.38	[53]
CBE-3	Double skin ultra-low carbon sandwich panel with wood fiber insulation and planks	In situ	N/A	0.3	[53]
CBE-4	Multi-sheet straw bale envelope with a timber frame	Laboratory	HBT	0.154	[54]
CBE-5	Sandwich panel with polyurethane insulation	N/A	N/A	0.51	[55]
CBE-6	Light-gauge steel-framed straw envelope	Laboratory	CHB	0.661	[56]

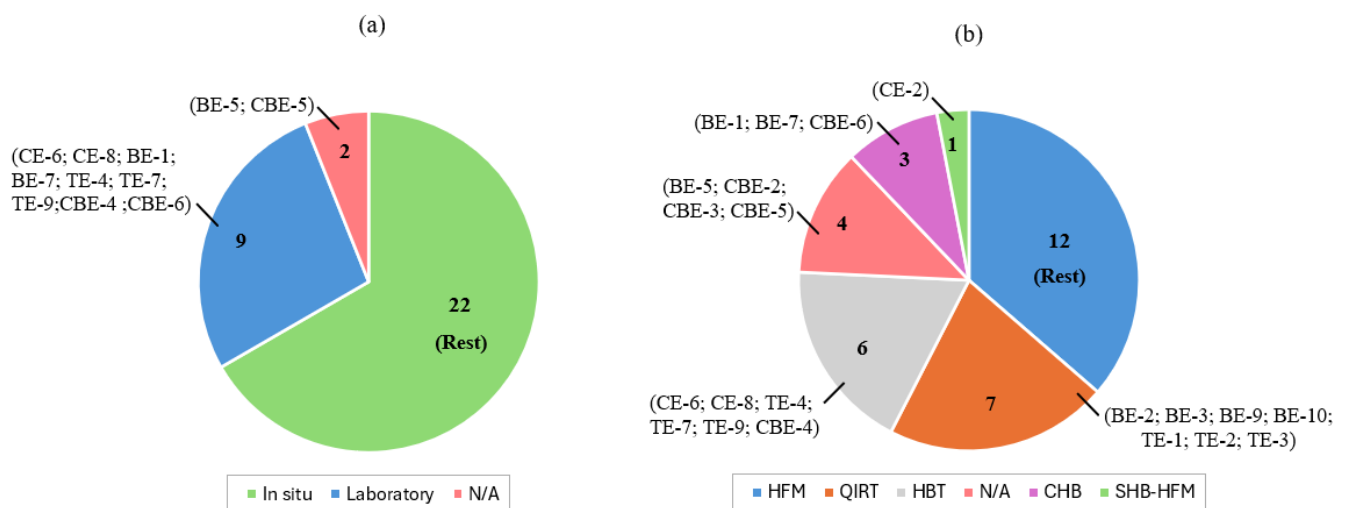


Figure 2. Number of selected building envelopes according to measurement type (a) and measurement method (b).

2.2. Case Study

2.2.1. Climate Zones

Outdoor climate and local characteristics need to be considered in order to boost the energy efficiency of buildings [6]. Appendix B of the Spanish TBC [13] includes the reference climatic conditions assigned to the different climatic zones, which are organized using codes that combine an alphabetical term and a numerical value. The alphabetical term ranges from A to E, while the numerical value varies from 1 to 4, reflecting a progressive increase in the intensity of winter and summer climatic conditions, respectively. These conditions are of fundamental importance to determine the energy consumption of buildings.

For the specific case of the territories in the Canary Islands, cold climate zones A2 and C2 were considered so that the comparative analysis would encompass territories with mild and medium-to-high winter climate severity.

The Government of Spain provides, in [22], various files containing hourly average values of various climatological parameters for a representative year in the different climate zones. The specific data for the climate zones studied in this paper can be found in files zonaA2c.met and zonaC2c.met. Figure 3 shows the monthly mean values of the climatological parameters in climate zones A2 and C2, respectively [22].

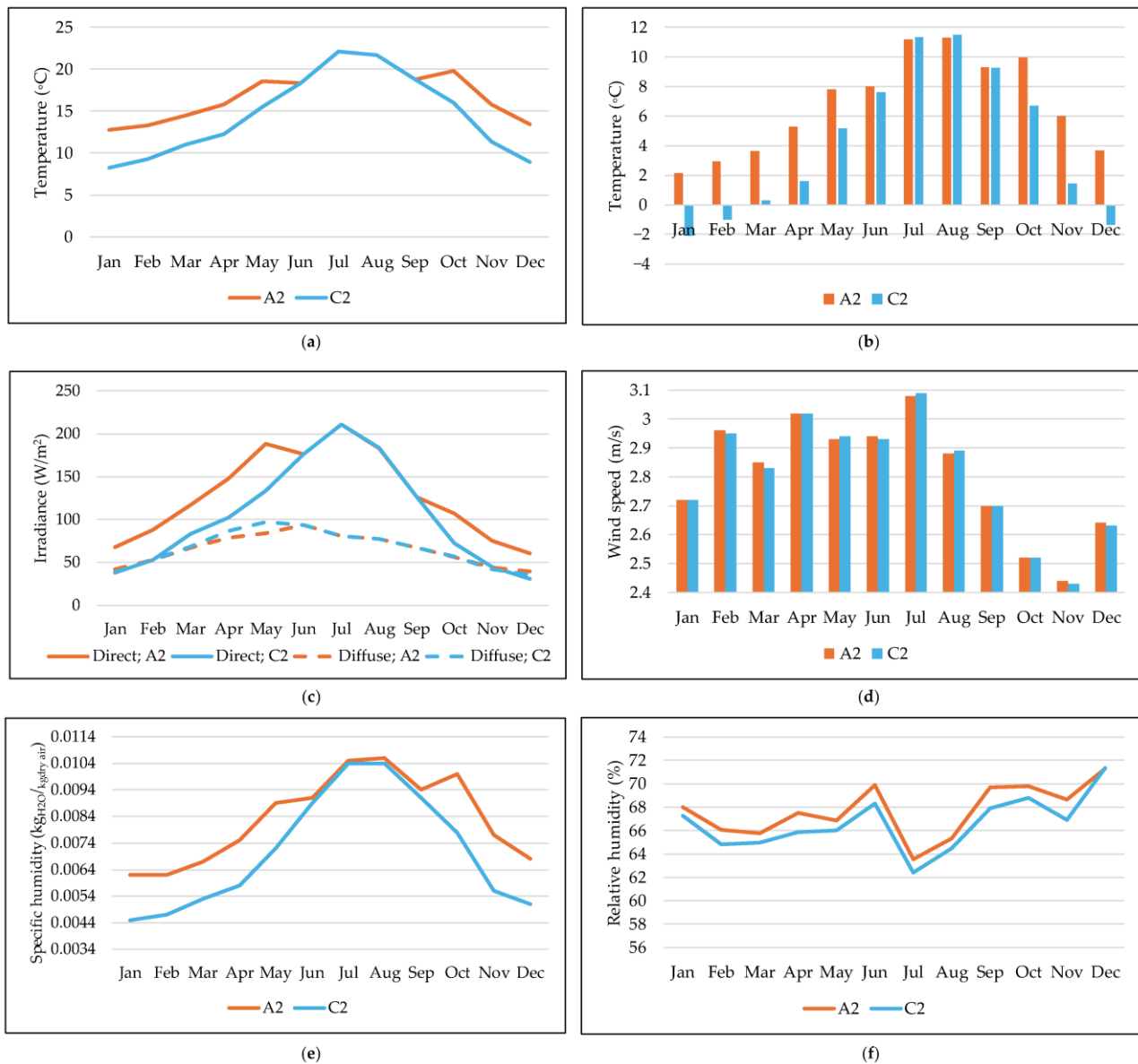


Figure 3. Monthly average values of (a) Dry temperature; (b) effective sky temperature; (c) direct and diffuse solar irradiance; (d) wind speed; (e) specific humidity; (f) specific humidity, in climate zones A2 and C2.

2.2.2. Characterization of the Dwellings

Three typical SFH typologies are considered, differentiated according to their spatial arrangement relative to other buildings [57]: an SFH attached on two side façades (SFH-1), an SFH attached on one side façade (SFH-2), and a detached or unattached SFH (SFH-3). In this way, the simulations analyze the sensitivity of the energy consumption of an SFH to its spatial arrangement relative to others in a differentiated manner. Figure 4 shows the three SFH typologies modelled for the study presented in this paper.

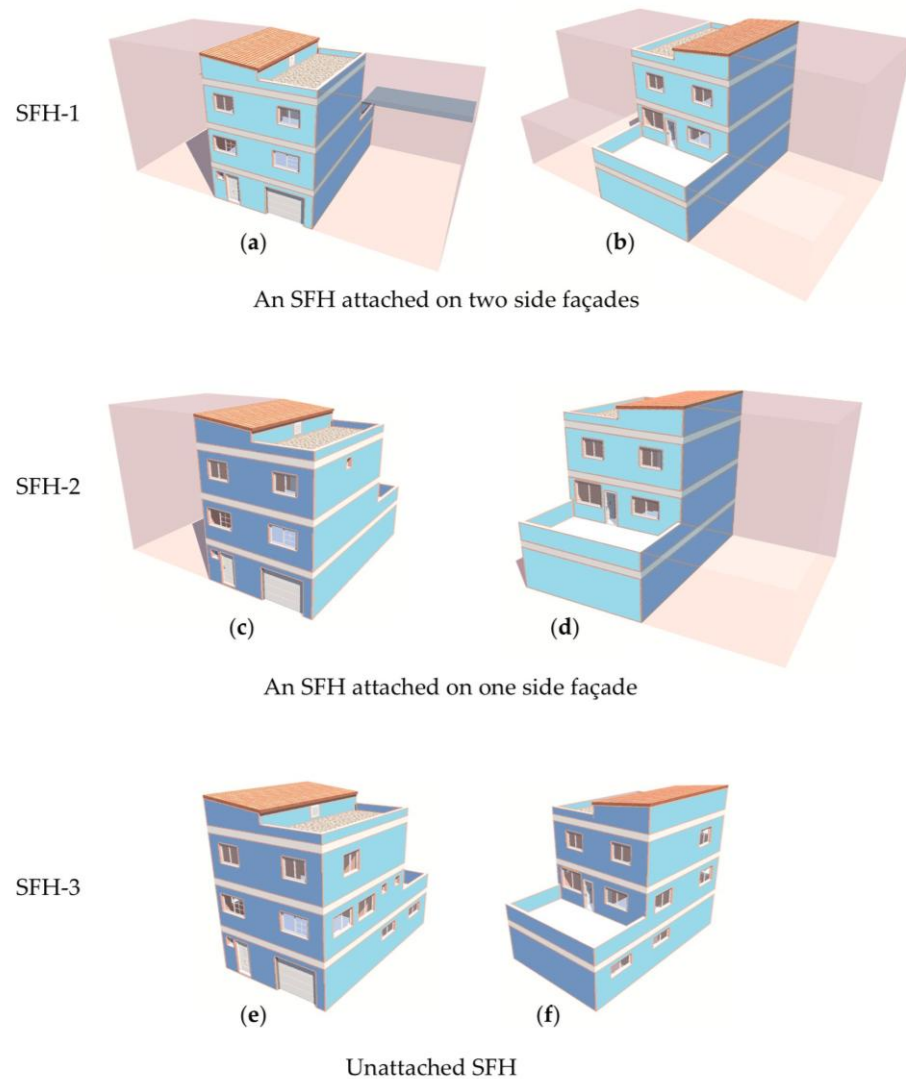


Figure 4. (a) Main façade of SFH-1; (b) Rear façade of SFH-1; (c) Main façade of SFH-2; (d) Rear façade of SFH-2; (e) Main façade of SFH-3; (f) Rear façade of SFH-3.

Described below are the characteristics of the design factors that remain constant for all energy simulations of the different SFH types considered in this study. The SFH roof has a thermal transmittance of $1.73 \text{ W/m}^2\cdot\text{K}$ and consists of several layers of clay, mortar, bitumen, and gypsum plaster, as well as a one-way slab with a depth of 30 cm and a 10 cm-thick concrete layer. The pavement in contact with the ground is a concrete slab with peripheral insulation and has a thermal transmittance of $0.6 \text{ W/m}^2\cdot\text{K}$. As for the window elements, 4 mm-thick glass with a solar factor of 85% is used, with thermal transmittances of 5.7 and $6.9 \text{ W/m}^2\cdot\text{K}$ in vertical and horizontal positions, respectively, and a frame with a thermal transmittance of $2.2 \text{ W/m}^2\cdot\text{K}$, an absorptivity of 0.75, and an air permeability of $50 \text{ m}^3/\text{h}\cdot\text{m}^2$. The total areas of the main and rear façades of the three types of SFHs are 62.38 and 62.71 m^2 , respectively, with window-to-wall ratios (WWRs) of 16% and 15.6% [57]. The area of the right facade of SFH-2 and SFH-3 is 86.11 m^2 , while the WWRs are 0.6% and 10.8%, respectively. The left facade of SFH-3 is 94.95 m^2 , with a WWR of 9.3%.

The construction material used for the building façade is the design factor that will be varied in the different simulations to quantify its effect on primary energy demand for heating.

2.3. Simulations

The characteristics of the SFH design factors, as well as their location relative to other buildings, were used for the energy modelling and simulation employing the EnergyPlus calculation engine [24] through CYPETHERM HE Plus v2024 software [23]. The latter is recognized by the Government of Spain for regulatory compliance with the basic energy-saving requirements defined in the Spanish TBC [13]. This software program is accredited by the Government of Spain to obtain the energy certification of a building [58]. The spaces in the thermal model will have, in each simulation, the operational conditions and usage profiles corresponding to private residential use, as defined in Annex D of [13]. In this way, the heating setpoint temperature is defined by means of an hourly profile [23]. Specifically, the lower setpoint temperature is 17 °C between 23:00 and 6:59 and 20 °C between 7:00 and 22:59 throughout the year except for the summer period (June to September), for which the lower setpoint temperature is not defined. The upper setpoint temperature is only defined for the summer period, namely 27 °C between 23:00 and 6:59 and 25 °C for the rest of the day. Based on these hourly setpoint regimes, the program calculates the percentage of time outside the specified temperature range, and verifies, for each simulation, that these do not exceed 4% of the total occupancy time, a criterion required by the TBC to ensure indoor thermal comfort. For the purpose of calculating energy demand, the model takes into account the thermal loads (in W/m²) generated hourly inside the building, including those from sensible and latent occupancy, lighting, and equipment. Additionally, the model considers both the ventilation and the unwanted air infiltrations caused by the opening of windows [59]. The ventilation and infiltration rates are handled by the program as a number of air changes per hour. In [59], the hourly values of the internal loads are published. The occupancy loads are differentiated based on whether the day is a weekday, Saturday, or holiday, while the ventilation and infiltration rates vary depending on whether it is summer or winter.

In the simulations, thermal bridges are considered to ensure accuracy in the calculations of energy demand. More specifically, the program has been instructed to assign the corresponding thermal transmittance coefficient from the Thermal Bridges Atlas [60] of the Spanish TBC to each type of junction. One of the effects of thermal bridges is the increased risk of surface condensation formation on the interior face of the structural element. In this regard, the program only allows the performance of energy simulations that meet the conditions established in the TBC [23]. In this way, it is ensured that the condensation does not significantly affect the thermal performance of the envelope.

It should also be noted that the thermal gains due to solar radiation transmitted to the building through the openings are also taken into account in the energy simulations.

Before executing the simulations, accredited CYPETHERM HE Plus v2024 software verifies that the building model is correct, analyzing all the definitions made in the project [23]. If there are incorrect or incompatible definitions, the standard calculation model will not execute the energy simulations. In this sense, the building model is validated, while, on the other hand, the energy simulations are validated since the developed method uses already accredited standard calculation models.

Each configuration was simulated for eight orientations of the building's main façade, from north (0°) to northwest (315°). As a result of the simulations, the primary energy demand for heating per unit area and year was obtained. This last parameter was then compared for each of the building envelopes selected for the study. Likewise, the equivalent CO₂ emissions per unit area and per year were also obtained. These were calculated based on the tested emission factors set out in [61], which are determined according to the electricity generation structure by type of plant and fuel. For the particular case of the Canary Islands, the emission factor considered by the program amounts to 0.776 kg CO₂/kWh of final energy.

2.4. Analysis of Economic Aspects

In addition to directly influencing the energy efficiency of the building and the thermal comfort of the user, the envelope constitutes a significant part of the lifecycle cost (LCC) [62], as it is a main structural layer very prone to defects. In this regard, an additional analysis of economic aspects is included in the case study of this paper with the aim of identifying low-carbon solutions that also have low economic costs. The CYPE construction price generator [63] was used to obtain the reference price adjusted to the specific installation conditions of each envelope type. The generator determines the price based on the cost of materials, equipment and machinery, labor, and supplementary direct costs.

The LCC of the envelope includes the initial investment and the ongoing expenses such as repair and maintenance costs. In this study, the specific cost of energy savings (SCES), Equation (1), is calculated as the ratio between the total cost and the energy savings achieved per unit of envelope surface area, which allows determination of the economic effort required per reduced kWh for the different construction solutions:

$$\text{SCES} = \frac{\text{CAPEX} \times \text{CRF} + \text{OPEX}}{\text{PES}} \quad (1)$$

where

- CAPEX: capital expenditure per unit area (in EUR/m²);
- CRF: capital recovery factor, Equation (2);
- OPEX: operating expenditure per unit area (in EUR/m²-year);
- PES: primary energy saving (in kWh/m²-year).

$$\text{CRF} = \frac{d(1 + d)^n}{(1 + d)^n - 1} \quad (2)$$

where

- d: discount rate;
- n: useful life of the building envelope (in years).

In this study, a discount rate of 2.5% is assumed, taking into account its evolution in the EU over the past three years [64]. Regarding the lifespan of building envelopes, 50 years is considered for CEs [65], 80 years for BEs [66], 75 years for TEs [67], and 60 years for CBEs [66]. An OPEX of 2 EUR/m²-year is considered for CEs and BEs [68], 8 EUR/m²-year for TEs [62], and 7 EUR/m²-year for CBEs.

3. Results and Discussion

In the context of energy simulations, an example simulation was first conducted as a function of the orientation of the main façade of the buildings (Figure 5). In this simulation example, a baseline façade was considered, consisting of a 1.5 cm-thick layer of cement mortar, a 20 cm-thick cinder block layer, and a 1.5 cm-thick layer of gypsum plaster. The thermal transmittance of this façade is 1.81 W/m²-K. It can be observed that, in general, the highest primary energy consumption for heating was obtained with the northeast orientation. This is because, among other factors, it: (i) receives less solar radiation during the day; and (ii) it is more affected by the cool, humid air carried by winds characteristic of the climate zones under study, since its orientation aligns with the prevailing wind direction. In this regard, and to avoid repetition in the analysis, the results and discussion of the comparative study presented below correspond to simulations conducted for that specific orientation.

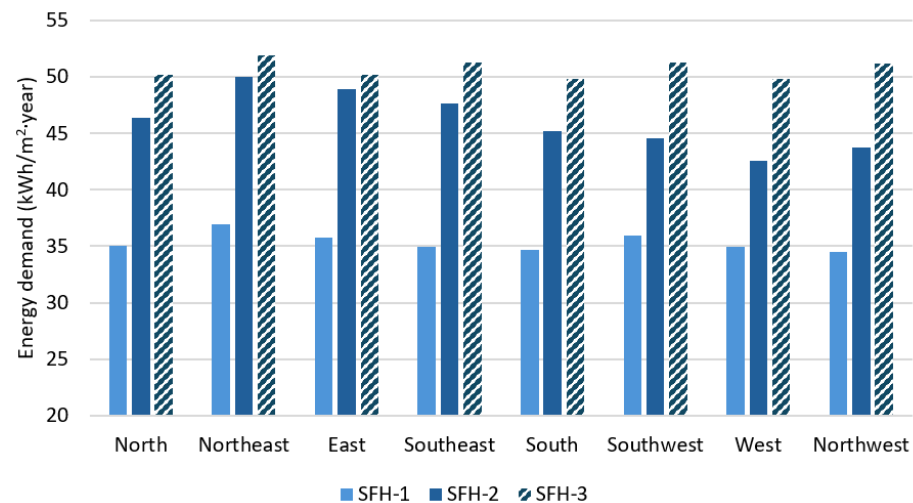


Figure 5. Primary energy demand of heating by main façade orientation and dwelling type in climate zone A2.

Figures 6 and 7 show the results for primary energy demand for heating for the different types of building envelope, broken down by housing type and climate zones A2 and C2, respectively. The figures show the results for the two housing types, SFH-1 and SFH-3, which exhibited the lowest and highest dispersions of results for each material, respectively, although Table 5 presents the relative results for all types, including SFH-2. In the figures, for each of the four material categories (CE, BE, TE, and CBE), the construction solutions that maximize and minimize demand are indicated, as well as those that mark the median demand value. Except for the TE category, which includes an odd number of construction solutions and therefore the median demand coincides with that of solution TE-6, the remaining categories each have two solutions that mark the median. Table 5 shows the relative variation in primary energy demand for heating, for the construction solutions that maximize and minimize energy demand, as well as for those that represent the median demand in each category, relative to the demand resulting from the baseline case.

The hollow concrete block envelope, CE-4, was found to be the least energy-efficient as it was the only one that increased heating energy demand by at least 5% compared to the baseline case for all three SFH types and both climate zones considered (see Table 5). The relative increase in demand was greater in climate zone A2 than in C2 (e.g., almost 10% for the case of SFH-3 located in climate zone A2).

A concrete envelope with internal polyisocyanurate (PIR) insulation, CE-7, is the envelope type that achieved the greatest reduction in primary energy demand for heating relative to the baseline case. Specifically, a relative reduction of more than 56.06% was obtained for an SFH-3 located in climate zone A2. Similar relative reductions were achieved with a type of light timber envelope, TE-3, and a multi-sheet straw bale envelope with a timber frame, CBE-4, both exceeding 55.5%, also for the SFH-3 located in climate zone A2. In climate zone C2, these three envelope types obtained an approximate relative reduction of 42% for the SFH-3.

Of the four building envelope categories studied, CE exhibited the widest range of primary energy demand for heating across its various construction solutions, since, as mentioned above, the highest and lowest resulting demands were obtained with envelopes CE-4 and CE-7, respectively. The energy demand ranges obtained for the TE and CBE categories were narrower, but the least energy-efficient materials in both—TE-8 and CBE-6—still exhibited consumption below the median for the CE and BE categories, remaining below 35 kWh/m²-year and 30 kWh/m²-year for SFH-3 and SFH-1, respectively,

in climate zone A2, and below 125 kWh/m²-year and 100 kWh/m²-year for both SFH types in climate zone C2.

In summary, Figures 6 and 7 and the results presented in Table 5 show that, regardless of the climate zone and housing type, all construction solutions—except for CE-4—reduced the primary energy demand compared to the baseline case. The greatest reductions in demand were achieved with construction solutions CE-7 and CBE-4. In all cases, the degree of reduction achieved was greater for climate zone A2. In other words, the performance of interventions carried out on the building envelope is influenced by the specific climate zone where the building is situated. Nonetheless, the appreciable disparity in the behavior of the results according to material type, housing type, and climate zone should be highlighted. It is observed that, for the different housing types and climate zones, the range of variation in the results for the various construction solutions using CE-type material is much greater than for the others, and that this disparity also depends on the type of housing considered. In this case, it is observed to be highest for the SFH-3 housing type.

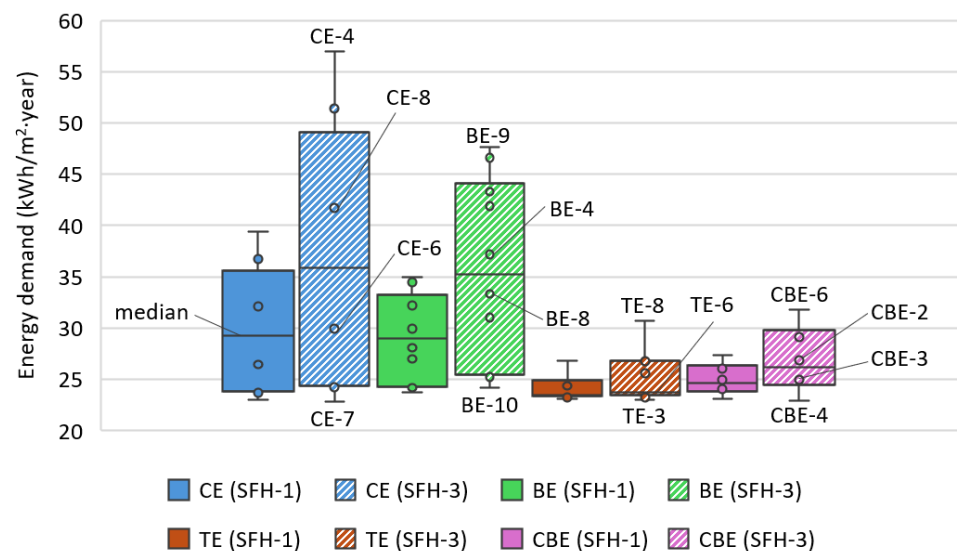


Figure 6. Primary energy demand for heating in SFH-1 and SFH-3 for different building envelope types in climate zone A2. The circles correspond to the different construction solutions.

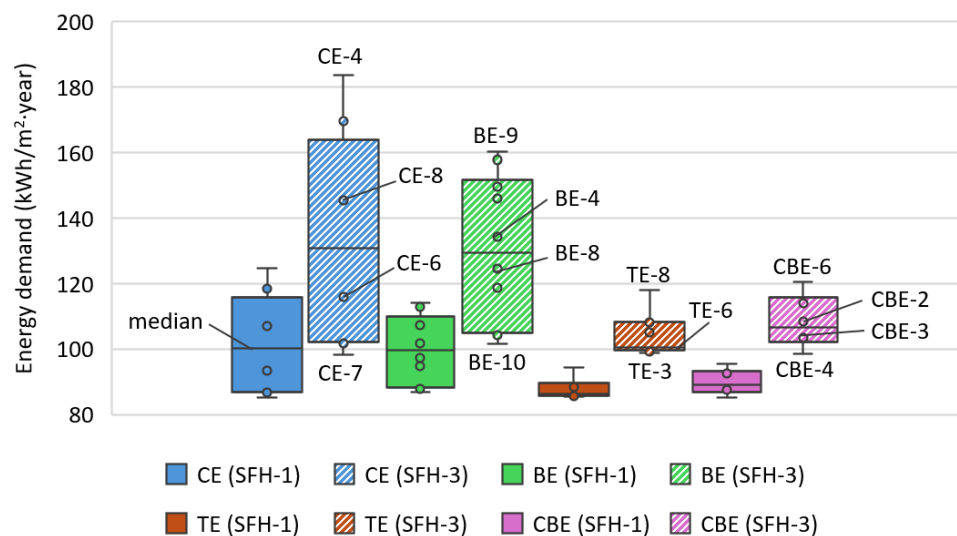


Figure 7. Primary energy demand for heating in SFH-1 and SFH-3 for different building envelope types in climate zone C2. The circles correspond to the different construction solutions.

Table 5. Relative variation in primary energy demand with respect to the resulting demand for the baseline façade case. The solutions that maximize and minimize demand are shown, as well as those that correspond to the median demand in each category.

Home Type	SFH-1		SFH-3		SFH-3	
Climate Zone	A2	C2	A2	C2	A2	C2
Baseline case ¹	36.9	118.8	50.0	148.3	51.9	170.6
CE-4	+6.74%	+5.06%	+8.91%	+7.06%	+9.74%	+7.65%
CE-8	-13.03%	-9.85%	-17.49%	-13.54%	-19.59%	-14.68%
CE-6	-28.37%	-21.41%	-37.96%	-29.52%	-42.34%	-32.01%
CE-7	-37.62%	-28.39%	-50.31%	-39.16%	-56.06%	-42.45%
BE-9	-5.31%	-4.02%	-7.17%	-5.49%	-8.13%	-5.95%
BE-4	-18.94%	-14.30%	-25.37%	-19.70%	-28.35%	-21.35%
BE-8	-23.94%	-18.07%	-32.05%	-24.90%	-35.77%	-27.00%
BE-10	-35.78%	-27.00%	-47.85%	-37.24%	-53.33%	-40.38%
TE-8	-27.35%	-20.64%	-36.60%	-28.46%	-40.83%	-30.85%
TE-6	-36.41%	-27.48%	-48.70%	-37.90%	-54.28%	-41.09%
TE-3	-37.35%	-28.18%	-49.95%	-38.87%	-55.66%	-42.15%
CBE-6	-25.96%	-19.60%	-34.75%	-27.01%	-38.77%	-29.29%
CBE-2	-32.35%	-24.41%	-43.27%	-33.66%	-48.24%	-36.50%
CBE-3	-34.16%	-25.78%	-45.70%	-35.56%	-50.94%	-38.55%
CBE-4	-37.48%	-28.28%	-50.13%	-39.01%	-55.86%	-42.30%

¹ Primary energy demand for heating (in kWh/(m²-year)) for the baseline case with a façade U-value of 1.81 W/m²-K.

Figure 8 shows the primary energy demand for cooling in SFH-3 for the CE category in climate zones A2 and C2. Unlike the primary energy demand for heating, the gradient of the energy demand for cooling among the different envelope typologies is significantly lower. This is clearly observed for the CE typology, where the heating demand in climate zone A2 differs by up to 149.8% between the different construction solutions, while for cooling, the variation is only 16.4%. Moreover, for the cold climate conditions studied, the cooling demand in absolute terms is significantly lower than that of heating. For this reason, the comparative analysis mainly focuses on the heating demand.

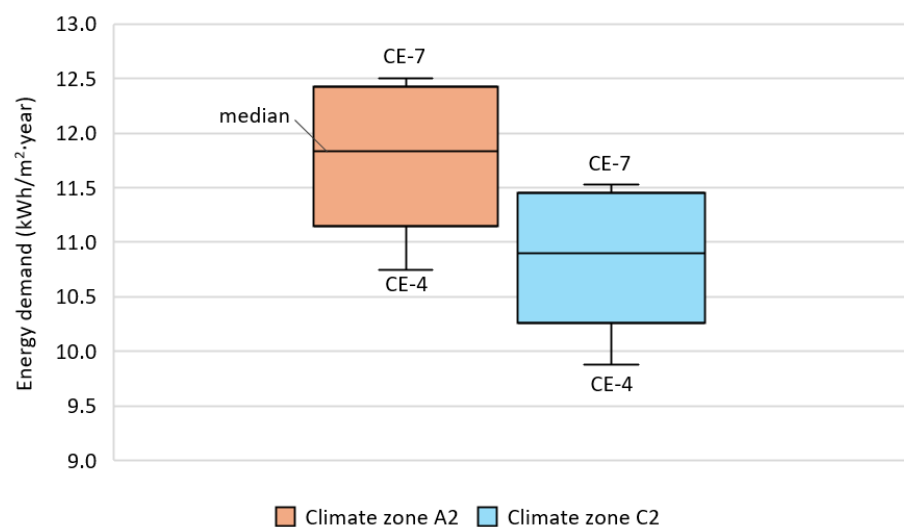


Figure 8. Primary energy demand for cooling in SFH-3 for the CE category in climate zones A2 and C2.

Table 6 shows the results obtained for the construction solutions with the highest and lowest annual CO₂ emissions, broken down by the four material categories, housing type, and climate zone. Emissions are minimized with the CE-7 envelope type, resulting in values below 5 kg CO₂/(m²-year) for SFH-1 and SFH-3 located in climate zone A2. Conversely, emissions are maximized with the CE-4 building envelope, exceeding 11 kg CO₂/(m²-year) for SFH-2 and SFH-3. The same holds true in climate zone C2, where minimum emissions are achieved with CE-7, falling below 20 kg CO₂/(m²-year) for SFH-1 and SFH-2, while maximum emissions exceed 33 kg CO₂/(m²-year) for SFH-2 and SFH-3 with the CE-4 building envelope.

Table 6. Annual CO₂ emissions (in kg CO₂/(m²-year)).

Home Type	SFH-1		SFH-3		SFH-3	
Climate Zone	A2	C2	A2	C2	A2	C2
Baseline case	7.82	25.16	10.59	31.40	10.98	36.14
CE-4	8.35	26.44	11.53	33.62	12.05	38.91
CE-7	4.88	18.01	5.26	19.10	4.83	20.78
BE-9	7.40	24.15	9.83	29.67	10.09	33.99
BE-10	5.02	18.36	5.52	19.70	5.13	21.53
TE-8	5.68	19.96	6.72	22.46	6.50	24.98
TE-3	4.90	18.06	5.30	19.19	4.88	20.89
CBE-6	5.79	20.23	6.91	22.91	6.73	25.55
CBE-4	4.89	18.04	5.28	19.14	4.85	20.84

Figure 9 shows the resulting SCES from the different construction solutions for the particular case of SFH-3 located in climate zone C2. It follows that, while technical solutions such as TE-3 and CBE-4 reduce the building’s energy demand and emissions to a greater extent than BE-10, the latter has a much lower economic cost than the former, resulting in a lower economic effort per kWh reduction. For all simulations conducted in the case study, the CE-7 typology requires the lowest economic effort to reduce heating energy demand. The maximum economic effort is presented by the BE-9 type, even though its absolute initial investment is very low (see Table 7).

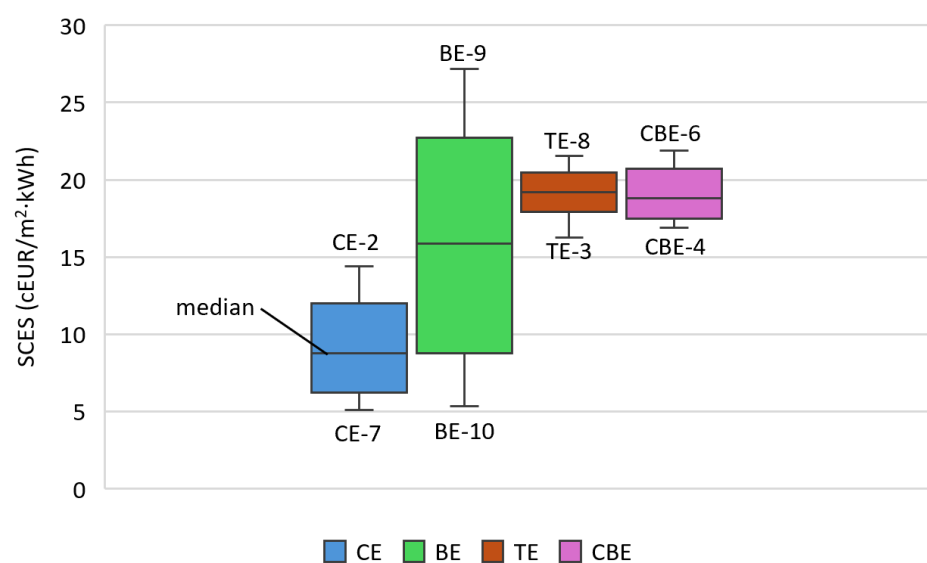


Figure 9. SCES for different building envelope types for SFH-3 in climate zone C2.

Table 7. CAPEX per unit area of the different types of envelope and their respective reference code in the CYPE price generator.

Envelope Type	CAPEX (EUR/m ²)	CYPE Reference Code
CE-2	48.38	FFZ020 + NKF011
CE-7	40.05	FFZ020
BE-10	57.58	FFX010
BE-9	26.15	FFN020
TE-3	124.24	FAZ012 + NVP020
TE-8	112.88	FAZ012
CBE-4	160.35	EMN010
CBE-6	121.57	EMN010 + EAT020

Finally, the comparative study of the wide range of construction solutions identified in the scientific literature (see Tables 1–4) shows that, while the vast majority of these improve the building's energy efficiency compared to the reference case design, they do not all perform equally, with their behavior depending on the building type and climate zone. While the energy performance does not differ much for different materials within the same category, as is the case for TEs and CBEs, it does vary significantly for the categories of CEs and BEs, mainly due to the wider range of U-values measured by other authors. On the other hand, the sensitivity of the cooling energy demand to different types of envelopes is much lower. The housing stock in the EU is notable for its relatively high average age, between 40 and 60 years. About 75% of the homes were built before 1990 [69]. Spain is one of the countries within the EU with a housing stock of a lower average age due to the significant construction boom that occurred in the country between 1997 and 2008. Even so, practically 78% of its homes were built before 2003 [70]. The 33 selected and compared construction solutions cover the period between 2003 and 2025, so the conclusions obtained in the comparative analysis conducted in this study are applicable to a large part of the current housing stock. Additionally, in the process of optimizing the appropriate construction solution, the specific costs of each one must be taken into account. In this sense, after considering the initial investment, the ongoing expenses, the useful life, and the energy savings achieved, it is found that the CE-7 and BE-10 solutions would require the least economic effort. However, given the significant energy savings achieved by other solutions such as TE-3 and CBE-4, their economic effort is lower than that of other types with a smaller initial investment like BE-9.

4. Conclusions

In the present study, research was conducted within the framework of the NZEB objective. After an exhaustive review of the scientific literature, the technical characteristics of 33 building envelope construction solutions aimed at reducing energy demand were analyzed. These were grouped according to the primary material of each (Concrete—CE; Brick—BE; Timber—TE; and Composite—CBE). The technical characteristics of all these construction solutions were incorporated into a common model developed in this paper, which covers different building types and climate zones, and with which multiple simulations were carried out to evaluate their performance. Finally, the results obtained for heating energy demand (kWh/m²-year) and greenhouse gas emissions (kg CO₂/m²-year) were compared.

The results of the various simulations and comparative analyses indicate that the performance of construction solutions is, generally speaking, influenced by the type of housing in which they are used as well as the climatic conditions of the area where the building is located. It is also worth noting that the dispersion of results for the different construction solutions varies depending on their primary material. Thus, for the eight

construction solutions evaluated with CE-type materials and the ten evaluated with BE, the results for heating energy demand differ by as much as 149.8% and 96.9%, respectively, while for the nine construction solutions evaluated with TE-type materials and the six with CBE, the maximum variation among the results is approximately 33.5% and 38.7%, respectively. From this general conclusion, it follows that it is very important in the technical optimization process of the building envelope to take into account the type of building, the site's climatic conditions, and the potential variations in results that may exist among different construction solutions, even when they use the same reference material.

The four best-performing construction solutions for each reference material type across all simulations conducted considering the different building types and climate zones were as follows: CE-7, BE-10, TE-3, and CBE-4. With these, energy demand reductions of up to 56.06%, 53.33%, 55.66%, and 55.86%, respectively, were achieved compared to the baseline case envelope.

A comparative analysis was also conducted based on the specific costs (€/kWh) for each construction solution. Not all the most energy-efficient solutions were those with the lowest cost. Therefore, in the process of optimizing the thermal envelope, it is necessary to determine the specific cost for each technical solution. For example, in the case study, and specifically for the four abovementioned construction solutions, while TE-3 and CBE-4 offered better energy performance than BE-10, the latter, considering its construction cost, had a lower final specific cost than the former two, making it therefore preferable in the technical-economic optimization process.

The results and conclusions of the work carried out are considered to be of general interest for energy planning in any region or country, as well as a reference for specific regulatory frameworks in the construction sector. This sector accounts for a significant share of global energy demand.

As a future line of research, we propose delving deeper into the comparative analysis of the building envelope, incorporating other construction aspects such as glazing and window shading, for hot-climate conditions. This would allow for the selection of integrated solutions that prevent the increase in energy consumption associated with over-heating and, at the same time, ensure interior thermal comfort.

Author Contributions: Conceptualization, S.V.-M.; Methodology, F.E.-G. and S.V.-M.; Software, F.E.-G.; Validation, S.V.-M.; Formal analysis, S.V.-M.; Investigation, F.E.-G., F.M.-M. and S.V.-M.; Data curation, F.E.-G. and F.M.-M.; Writing—original draft, F.E.-G., F.M.-M. and S.V.-M.; Writing—review and editing, S.V.-M.; Supervision, S.V.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by the ERDF funds through the INTERREG MAC 2021–2027 program in the RESMAC project (1/MAC/2/2.2/0011) The project was developed within the framework of the agreement (code: C2025/16) between the University of Las Palmas de Gran Canaria and the company BLUENEWABLE, S.L (S.C. Tenerife, Spain). F. Montesdeoca-Martínez is a recipient of a pre-doctoral grant (FPU2023/00357) from the Ministry of Science, Innovation and Universities of the Government of Spain. No funding sources had any influence on the study design; the collection, analysis, or interpretation of the data; manuscript preparation; or the decision to submit for publication.

Data Availability Statement: Data available on request due to restrictions.

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

Abbreviations

The following abbreviations are used in this manuscript:

BE	Brick envelope
CBE	Composite building envelope
CE	Concrete envelope
CHB	Calibrated hot box
CRF	Capital recovery factor
EPBD	Energy Performance of Building Directive
EPS	Expanded polystyrene
EPSAP	Evolutionary Program for the Space Allocation Problem
HBT	Hot box test
HFM	Heat flow meter
LCC	Lifecycle cost
NZE	Net Zero Emissions
NZEB	Nearly zero energy building
PES	Primary energy saving
PIR	Polyisocyanurate
QIRT	Quantitative infrared thermography
SCES	Specific cost of energy savings
SFH	Single-family home
SHB	Simple hot box
STEPS	Stated Policies Scenario
TBC	Technical Building Code
TE	Timber envelope
WWR	Window-to-wall ratio

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