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Optimization of energy consumption in residential housing within the framework of energy sustainability strategies. A case study in the Canary Islands

Francisco Espino-González [a], MaríaEugenia Armas-Cabrera [b], Fernando Montesdeoca-Martínez [a], Sergio Velázquez-Medina [c,*]

[a] *Doctoral School of the University of Las Palmas de Gran Canaria, Campus de Tafira s/n, 35017, Las Palmas de Gran Canaria, Canary Islands, Spain*
[b] *Department of Architectural Construction, University of Las Palmas de Gran Canaria, Campus de Tafira s/n, 35017, Las Palmas de Gran Canaria, Canary Islands, Spain*
[c] *Department of Electronics and Automatics Engineering, University of Las Palmas de Gran Canaria, Campus de Tafira s/n, 35017, Las Palmas de Gran Canaria, Canary Islands, Spain*

A R T I C L E I N F O

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Climate conditions

A B S T R A C T

Given that the energy consumption of buildings equates to practically 40 % of the total energy demand of any electrical system, research studies on reducing such energy consumption are of paramount importance. This problem is accentuated in isolated weak electrical systems, like those found in many island territories, where there are significant limitations on the management of energy generation and demand. The objective of the present work is to identify the relationship between the energy consumption of residential housing and its thermal envelope characteristics within the framework of energy sustainability strategies. For this purpose, multiple solutions were compared based on combinations of values associated to different types of residential building, a wide range of thermal transmittance values based on the application of different materials and/or envelope designs, and different climate zones. It is concluded that the energy consumption of these buildings can be significantly reduced by optimizing the technical characteristics of the thermal envelope, adapting it the surrounding climate conditions. For the case study, the specific energy saving can be as high as 51.4 kWh/m^2·year. Bearing in mind the housing stock in the study area, the total energy saving is equivalent to 9.17 % of its current energy demand. The results and conclusions obtained can be used in the development of planning strategies for new housing and/or the optimization of energy consumption in already existing housing stock.

1. Introduction

Through its Directive 2023/1791 [1], the European Union (EU) unifies different regulatory documents on energy efficiency and establishes a common framework for its promotion with the goal of contributing to the application of Regulation (EU) 2021/1119 [2] and the energy supply security of Member States through the reduction of external energy dependency. The Directive also establishes the collective goal of reducing final energy consumption in the EU by at least 11.7 % by 2030. For this purpose, the Directive

* Corresponding author.
E-mail address: sergio.velazquezmedina@ulpgc.es (S. Velázquez-Medina).

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encourages Member States to establish building energy efficiency improvement strategies, among other aspects.

Buildings are responsible for 40 % and 36 % of energy consumption and greenhouse gas (GHG) emissions, respectively, in the EU [3]. Strategies to mitigate climate change and energy poverty must therefore include actions to reduce energy consumption and CO_2 emissions in the construction sector [4–6]. Such actions are fundamental for the attainment of more energy efficient buildings, as stated in Directive 2010/31/EU [7], amended by Directive 2018/844/EU [8], of the European Parliament and Council. The latter Directive established a green and decarbonized time horizon of 2050 for so-called nearly zero-energy buildings (nZEBs) and, among other objectives, an 80–95 % reduction of GHG emissions in the EU compared to 1990. Recently, the European Council launched its "Fit for 55" package of proposals [3], which incorporates stricter rules, including a zero-emissions requirement, for new buildings by 2030 and for already existing buildings by 2050 through renovation work.

Maduta et al. [9] undertook an analysis of the strategic objectives established in European legislation on the energy efficiency of buildings and their degree of implementation in the different member states. They found that while over 75 % of Member States had implemented heating and cooling system inspection schemes, few had actually assessed their impacts. They concluded that efforts needed to be intensified, especially in renovation rates, to achieve the aim of zero-emission buildings. Chen Y. et al. [10], in their study on multiple urban building types in China, underlined the importance of the impact of climate change on their energy consumption. Spain, through its Integrated National Energy and Climate Plan (PNIEC by its initials in Spanish) [11], has set the target of a highly energy efficient and decarbonized residential and non-residential building stock by 2050. Within the framework of the strategies established in the PNIEC, it is proposed to improve building energy efficiency through optimization of the thermal envelope of 1,200, 000 residential properties and renovation of the heating and domestic hot water insulation of 300,000 properties over the course of the 2020–2030 decade.

The construction sector is one of the most cost-effective in terms of energy use reduction [12–14]. A growing number of studies are being conducted on so-called dynamic thermal insulation technologies, which can be classified into passive, hybrid, active and non-specified systems [15]. Given the importance of insulation in building energy consumption [16], numerous scientific works have undertaken specific works based on these technologies. Fernando D. et al. [17] reviewed the performance of different façade systems. They concluded that, in the design process, architects, engineers, and builders need to consider sustainable façade systems that enable high energy efficiency and fewer environmental impacts. In Ref. [18], the authors describe the growing development of new plant-based concretes and their use for building insulation, with particular emphasis on a new concrete made of Typha with a cementitious matrix. Pedone et al. [19], developed a predictive model for the estimation of building energy consumption, simulating a practical case study in constructions designed for educational activities. In their conclusions, they highlighted the importance of the shape factor, the ratio between the building's envelope area and its volume, and the thermal properties of the building envelope in its energy consumption. Liu et al. [20] studied a novel composite concrete containing phase change material (PCM) as a potential strategy for mitigating building energy consumption. They concluded that for optimal results it is important to appropriately select the PCM, as their effectiveness depends on the climate zone where they are implemented. In Ref. [21], the authors showed that natural ventilation is a viable technique to facilitate the charging and discharging cycle of PCM and offer a practical, sustainable, and cost-effective solution with eco-friendly and energy-efficient outcomes.

Wan et al. [22] developed a mathematical model for the simulation of an adaptive building roof, which can be considered a passive system as it is based on the combination of optical properties to achieve variable transparency with shape stabilization through PCMs whose properties can adapt to the outside temperature. Sommese F. et al. [23] undertook a review of different smart materials and their potential application as biomimetic solutions in environmentally adaptive building envelopes. They concluded that the application of these materials is still limited in current architecture and that further research studies are required to analyse in greater detail their benefits in sustainability buildings.

Koenders et al. [24] analysed the operation of a novel hybrid system, and in Ref. [25] an opaque and ventilated dynamic façade was assessed as an active heat insulation system using computational fluid dynamics simulations. Kishore et al. [26] examined a novel design of a wall comprised of a layer of PCM between two layers of dynamic insulation materials, which can be considered a non-specified dynamic thermal insulation system.

Nanofluids, which are fluids to which nanoparticles have been added, are another emerging technology that can be included among the non-specified systems. Experimental studies have been undertaken comparing the thermal conductivity of different nanofluids by, for example, Wu et al. [27], although such studies require further validation.

Despite the rapid growth in research into these emerging technologies, optimizing the thermal insulation of building envelope elements continues to be a fundamental strategy before other more complex ones should be considered [15,28]. Optimizing insulation by limiting the heat transfer coefficient of a building is essential for the attainment of a compromise solution between heat comfort, construction cost and energy consumption [29]. In their study, Kistelegdi et al. [30] justified the primordial importance of design techniques, and especially building shape optimization, in building comfort and energy efficiency.

The following can be concluded from the extensive analysis of the literature that has been conducted: (1) The importance of building energy consumption in the total energy demand of any country/region; (2) The design characteristics of the thermal envelope and climate conditions of the area play a fundamental role in the aim of achieving nZEBs; (3) Heating and cooling energy consumption has the greatest weight in the total energy consumption of buildings; (4) The construction industry is working hard on the development of new materials and/or technical solutions to improve envelope insulation; (5) The different countries/regions need to establish strategies to achieve the minimization of energy consumption in existing and new buildings.

Optimizing the energy efficiency of buildings with the aim of reducing energy consumption is a strategy that can be even more beneficial in territories with vulnerable electrical systems that are additionally highly dependent on fossil fuels. A clear example of this can be found in the Canary Archipelago (Spain) and its seven major islands, each with its own small, isolated and weakly meshed electrical system [31,32]. Currently, 80.17 % of the archipelago's electricity demand is met by fossil fuels [33]. Tenerife and Gran Canaria are the two most populated islands, with 42.7 % and 39.2 %, respectively, of the total population of the archipelago [34]. The Government of Spain, through the aforementioned PNIEC [11], established among its objectives a reduction in primary energy consumption by 2030 of 39.6 % compared to the envisaged value according to the current trend. However, given the complications that arise as a result of the insular nature of the territory and the specific characteristics of the electrical systems of the archipelago's islands, this goal was subsequently adjusted to 27 % [35] through the application of realistically feasible measures.

The islands are an interesting case study because they have, due in principle to their volcanic nature and variable orography, many different microclimates which result in significant climate diversity in small surface area extensions depending on the altitude and orientation of the area in question [36,37]. For this reason, in this type of island territory the different climate zones need to be very precisely analysed to examine their effect on the primary energy demand of buildings and to optimize their energy consumption.

1.1. Aims and original contribution of the study

The extensive analysis of the literature that was undertaken revealed that, in general terms, the studies tend to analyse a specific material for the envelope of buildings based on its thermal characteristics and for specific climate characteristics. We consider that research studies are required which compare different materials and/or technical solutions for the envelope with different thermal characteristics, as well as their effect in different climate zones. In this way, an analysis can be made of the relative improvement that these provide in building energy sustainability terms. In this regard, to cover the gap that we have detected, the objective of the present work is to identify the relationship between the energy consumption of buildings (in kWh/m^2 of primary energy), specifically cooling and heating energy consumption, and the thermal characteristics of their envelope. For this purpose, multiple results were compared based on combinations of values associated to.

(1) Different types of single-family dwellings with different geographical orientations.
(2) A wide range of thermal transmittance values based on the application of different materials and/or envelope design.
(3) Different climate zones.

For this, we used the building energy simulation program "EnergyPlus" [38].

In addition, in the framework of energy sustainability policies, an analysis is undertaken of the impact of the results obtained on the improvement in the energy demand of the housing stock of the Canary Archipelago, with an assessment of the reduction in primary energy needs and, in consequence, the amount of CO_2 emissions avoided.

The results can serve as a guideline to define strategies for the optimization of energy consumption in the residential building sector, in this way reducing the load for weak, island-based electrical systems. Such strategies could be incorporated in future energy plans.

2. Materials and methods

2.1. Climate zones

According to EU Directive 2010/31 [7], the promotion of the energy efficiency of buildings should take into account external climate conditions and local particularities. An important aspect to determine the energy demand of buildings is knowledge of the climate zone associated to the area where the building is situated. For the particular case of Spain, diverse climate zones have been identified for the purpose of energy demand calculations [39]. A reference climate can therefore be defined according to external temperature and solar radiation conditions [40]. Each climate zone is identified by a letter and number. The letter and number describe winter and summer climate severity, respectively. The letters range from A to E for winter climates and the numbers from 1 to 4 for summer climates, in both cases from lower to greater severity.

In the case of the Canary Archipelago territories, a total of four different climate zones have been identified: A2, B2, C2, and one that is exclusive to the archipelago, α3. In the latter climate zone, the severity of climate conditions in winter is practically negligible

Table 1
MEAN monthly climate data of climate zone A2 in the canary archipelago.

Month	Dry temperature (°C)	Effective sky temperature (°C)	Direct solar irradiance (W/m^2)	Diffuse solar irradiance (W/m^2)	Specific humidity ($kg_{H2O}/kg_{dry\ air}$)	Relative humidity (%)	Wind speed (m/s)	Prevailing wind direction
January	12.78	2.14	67.38	42.07	0.0062	67.99	2.72	NE
February	13.28	2.93	88.12	52.78	0.0062	66.09	2.96	NE
March	14.48	3.63	116.88	66.66	0.0067	65.78	2.85	NE
April	15.80	5.27	147.50	78.43	0.0075	67.51	3.02	NE
May	18.60	7.81	188.19	84.00	0.0089	66.85	2.93	NE
June	18.33	7.99	175.97	93.75	0.0091	69.89	2.94	NE
July	22.13	11.17	210.90	80.48	0.0105	63.57	3.08	NE
August	21.71	11.32	183.25	77.11	0.0106	65.31	2.88	N
September	18.74	9.28	126.11	67.31	0.0094	69.67	2.70	NE
October	19.81	9.96	107.31	56.00	0.0100	69.79	2.52	NE
November	15.82	5.99	75.23	44.09	0.0077	68.67	2.44	NE
December	13.42	3.66	60.26	39.12	0.0068	71.28	2.64	NE

and for this reason it was not included in the present study.

The climatological parameters considered for the differentiation of climate zones, and their characteristic values, are defined in the Technical Building Code (TBC), drawn up by the Government of Spain. In Ref. [39], the mean hourly values can be consulted that are characteristic of a representative year of each climate zone. These data are provided in files with the extension ".met". Each ".met" file contains the characteristic data of the following meteorological parameters: dry temperature (°C), effective sky temperature (°C), direct solar irradiance on a horizontal surface (W/m^2), diffuse solar irradiance on a horizontal surface (W/m^2), specific humidity ($kg_{H2O}/kg_{dry\text{-}air}$), relative humidity, wind speed (m/s), and wind direction. The specific data for the three climates considered in the present paper (A2, B2, C2) are found in the files zonaA2c.met, zonaB2c.met and zonaC2c.met, and can be consulted in Ref. [41]. On this basis, the average monthly values of the different climatological parameters were calculated for each of the climate zones studied (see Tables 1–3).

The reference climates established in the TBC define the external conditions which the buildings in question are subject to for the different parameters over the 8760 h of a typical year. These are used to calculate the energy demand of the building. The determining parameters of the behaviour of the reference climate are dry temperature (°C), direct solar irradiance on a horizontal plane (W/m^2) and diffuse solar irradiance on a horizontal plane (W/m^2) [40].

Considering the data of all the climatological parameters and the geographic conditions of each Spanish region, a climate zone is assigned in the TBC to each territory according to its altitude. The altitude-climate zone relationship differs in each region (see Appendix B in Ref. [37]). The distribution of climate zones by altitude for the particular case of the Canary Archipelago is shown in Table 4.

In this way, a specific climate zone is associated to each municipality in the archipelago according to its mean altitude.

2.2. Dwelling types used in the simulations

A total of three single-family dwelling types were used, differentiated according to their orientation or situation in relation to other buildings.

- H1: Single-family mid-terraced dwelling (Fig. 1(a) and (b))
- H2: Single-family semi-detached dwelling (Fig. 1(c) and (d))
- H3: Single-family detached dwelling (Fig. 1(e) and (f))

In this regard, it was therefore possible to analyse separately the effect of the position of certain single-family dwellings with respect to others and its repercussions in terms of energy demand.

The influence of the climate characteristics on energy consumption for these types of single-family dwelling is much more notable than in the case of, for example, flat dwellings in multi-storey buildings as the former are more exposed, through their construction envelopes, to variations in climate conditions.

2.3. Type of climate and housing stock associated to each municipality in the archipelago

The corresponding climate zone was associated to each municipality in the archipelago based on its climate characteristics and using the mean climate data shown in Tables 1–3 (see Fig. 2).

According to Ref. [34], 77.8 % of single-family dwellings in the archipelago were constructed before 2002. The housing stock of the islands can therefore be considered old and in need of major energy efficiency improvement.

Through [42], information was obtained, for each municipality, on the number of dwellings by mean surface area in the following ranges: <30 m^2, 30–45 m^2, 46–60 m^2, 61–75 m^2, 76–90 m^2, 91–105 m^2, 106–120 m^2, 121–150 m^2, 151–180 m^2 and >180 m^2. The mean weighted surface area of dwellings was then calculated for each municipality. The information obtained from Ref. [42] was for all types of dwelling, not just the single-family dwellings considered in the present paper. For the purposes of this study, the number of single-family dwellings for each municipality was estimated as 30 %, 70 % and 80 % of the total given in Ref. [42] for climate zones A2, B2 and C2, respectively. This estimation was based on the good correlation between climate zone and family housing construction type

Table 2
MEAN monthly climate data of climate zone B2 IN the canary archipelago.

Month	Dry temperature (°C)	Effective sky temperature (°C)	Direct solar irradiance (W/m^2)	Diffuse solar irradiance (W/m^2)	Specific humidity ($kg_{H2O}/kg_{dry\ air}$)	Relative humidity (%)	Wind speed (m/s)	Prevailing wind direction
January	10.88	0.47	59.40	40.09	0.0054	67.15	2.72	NE
February	11.68	1.15	79.32	53.22	0.0055	65.07	2.96	NE
March	13.28	2.79	107.87	67.81	0.0061	64.91	2.83	NE
April	14.82	4.40	136.80	81.12	0.0069	65.80	3.01	NE
May	18.10	7.26	172.61	88.71	0.0085	66.14	2.95	NE
June	18.33	7.70	175.96	93.76	0.0089	68.32	2.94	NE
July	22.13	10.99	210.88	80.47	0.0104	62.43	3.09	NE
August	21.72	11.42	183.24	77.10	0.0104	64.51	2.89	N
September	18.74	8.99	126.11	67.32	0.0091	67.90	2.70	NE
October	18.81	9.27	96.53	56.67	0.0093	68.85	2.51	NE
November	14.04	4.11	67.12	42.81	0.0066	67.22	2.44	NE
December	11.42	1.38	51.30	37.53	0.0059	70.95	2.63	NE

Table 3
MEAN monthly climate data of climate zone C2 IN the canary archipelago.

Month	Dry temperature (°C)	Effective sky temperature (°C)	Direct solar irradiance (W/m^2)	Diffuse solar irradiance (W/m^2)	Specific humidity ($kg_{H2O}/kg_{dry\ air}$)	Relative humidity (%)	Wind speed (m/s)	Prevailing wind direction
January	8.27	−2.09	37.66	38.62	0.0045	67.26	2.72	NE
February	9.28	−1.01	52.96	52.66	0.0047	64.84	2.95	NE
March	10.98	0.31	83.28	68.08	0.0053	64.96	2.83	NE
April	12.25	1.60	101.95	86.95	0.0058	65.86	3.02	NE
May	15.50	5.17	133.30	97.08	0.0072	66.00	2.94	NE
June	18.34	7.61	175.97	93.73	0.0089	68.31	2.93	NE
July	22.13	11.36	210.90	80.47	0.0104	62.42	3.09	NE
August	21.72	11.49	183.26	77.10	0.0104	64.48	2.89	N
September	18.74	9.25	126.12	67.31	0.0091	67.90	2.70	NE
October	16.01	6.70	72.65	56.68	0.0078	68.82	2.52	NE
November	11.38	1.45	44.30	42.17	0.0056	66.93	2.43	NE
December	8.93	−1.36	30.91	35.26	0.0051	71.35	2.63	NE

Table 4
CLIMATE zone associated to height in the canary archipelago.

Climate zone	Altitude (m)
α3[a]	<350
A2	<750
B2	<1000
C2	≥1000

[a] Not studied in this paper.

(flat dwellings in multi-storey buildings vs. single-family dwellings) in the housing stock of the archipelago.

Fig. 2 shows for each municipality considered its corresponding climate zone and number of dwellings.

The total number of single-family dwellings and their distribution by type (H1, H2 or H3) and climate zone was estimated (see Table 5). This distribution was carried out bearing in mind that, for the case of the Canary Archipelago, the proportion of type H3 buildings rises with the altitude of the municipality in which they are found.

2.4. *Types of façade used in the simulations*

The façade, or vertical wall comprising the envelope, is the main limit that controls the flow of mass and energy between the outside and inside of the building [25]. For the purposes of the present study, simulations were performed with 5 different façade types.

- F1: Basic façade. Comprising a 1.5 cm layer of mortar, a layer of 20 cm thick cinder blocks and a 1.5 cm thick plaster finish layer.
- F2: Façade with ETICS/SATE system. Comprising a layer of 20 cm thick cinder blocks, a 1.5 cm thick plaster finish layer and a 2 cm thick insulating layer of expanded polystyrene between two 1.5 cm thick layers of mortar.
- F3: Ventilated façade. Comprising a 1 cm thick ceramic tile, a 10 cm air chamber, a 4 cm thick insulating layer of expanded polystyrene, a 1.5 cm layer of mortar, a layer of 20 cm thick volcanic charcoal-based cinder blocks and a 1.5 cm thick plaster finish layer.
- F4: Ventilated façade. As façade F3, but with 8 cm thickness of the insulating layer of expanded polystyrene.
- F5: Ventilated façade. As façade F3, but with 12 cm thickness of the insulating layer of expanded polystyrene.

Table 6 shows the thermal transmittance values for each façade type.

2.5. *Roof types used in the simulations*

Five different roof types were considered with the following characteristics.

- R1: Basic roof. Comprising diverse layers of clay, mortar, bitumen and plaster, in addition to a 30 cm thick unidirectional roof slab and a 10 cm thick layer of concrete.
- R2: Non-ventilated roof. Similar to R1, but with a 2 cm thick insulating layer of expanded polystyrene.
- R3: Ventilated roof T1. Similar to R2, but with a 15 cm thick ventilated air chamber between a 3 cm thick layer of limestone tiles and a 4 cm thick insulating layer of expanded polystyrene.
- R4: Ventilated roof T2. As R3, but with an 8 cm thick insulating layer of expanded polystyrene.
- R5: Ventilated roof T3. As R3, but with a 12 cm thick insulating layer of expanded polystyrene.

Table 7 shows the thermal transmission coefficients of each roof type.

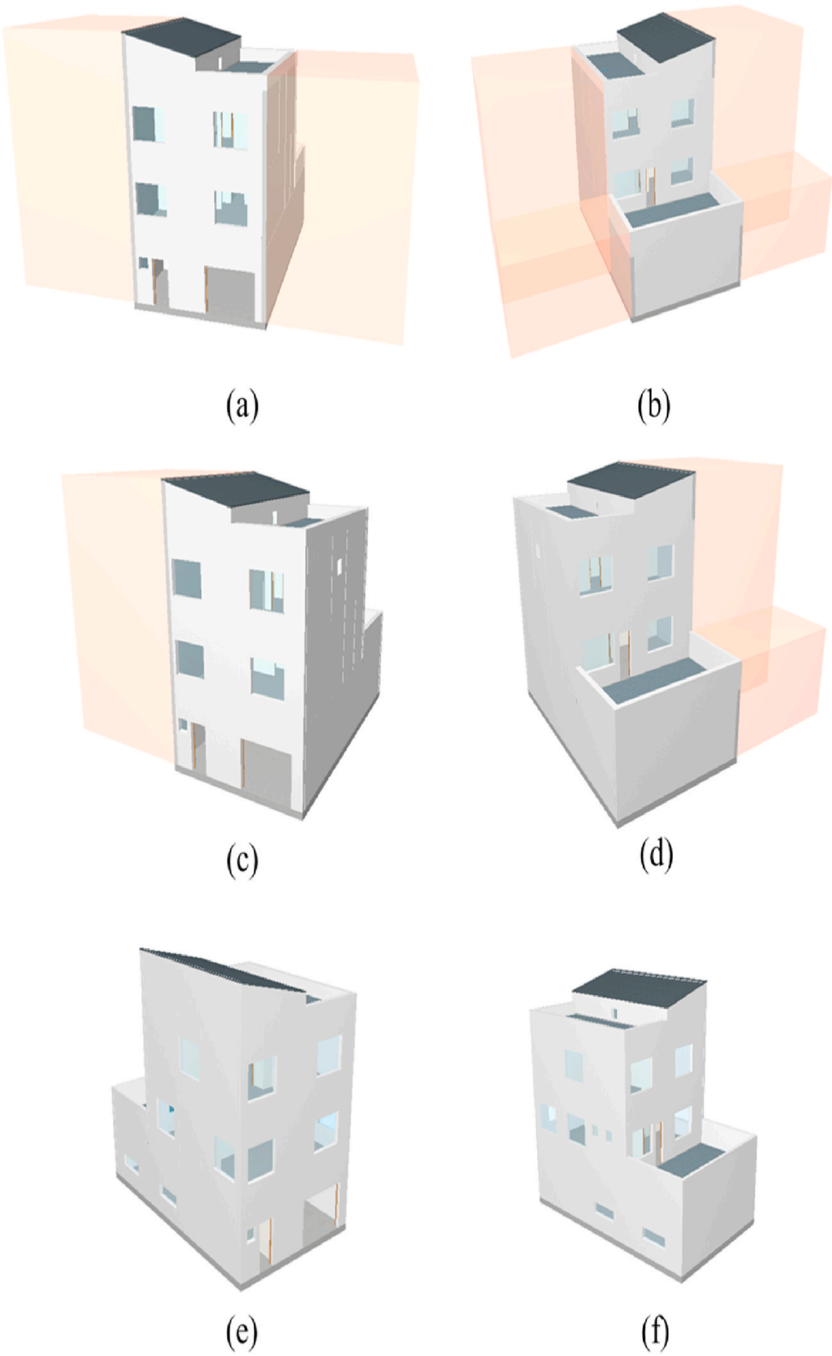

Fig. 1. (a) Front of dwelling H1; (b) Back of dwelling H1; (c) Front of dwelling H2; (d) Back of dwelling H2; (e) Front of dwelling H3; (f) Back of dwelling H3.

2.6. Other parameters considered in the simulations of the buildings

- Orientation: As well its geometry, construction and use, a building's orientation is extremely important with respect to its energy consumption. Its orientation impacts on the heat gains/losses generated by solar radiation when traversing the envelope elements. For this reason, management of its orientation is considered a passive energy consumption reduction technique [43]. Table 8 shows the alternative orientations of the main (front) façade (see Fig. 1) considered in the different simulations.
- Window elements. For the analysis of heat gains/losses, these elements were subdivided into 'glazing' and 'frame'. For the purposes of the present study, these elements were kept constant for all the simulations and were as follows:

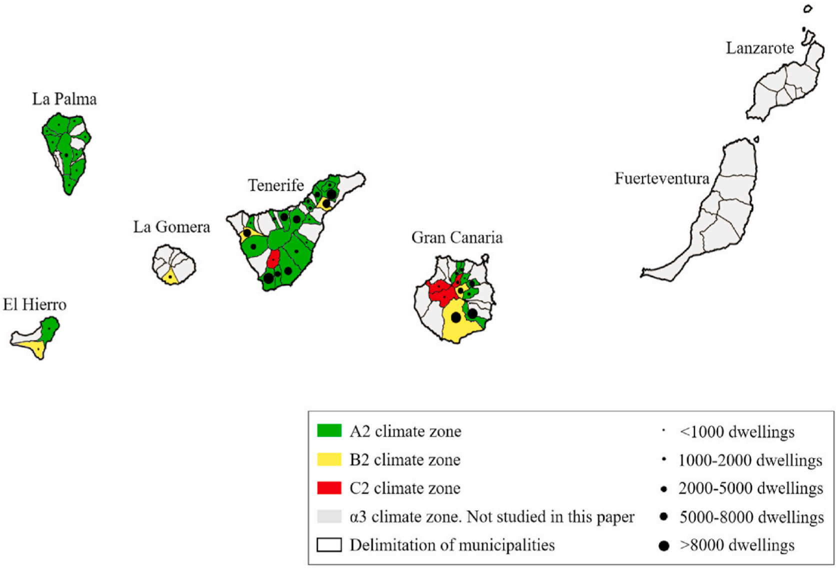

Fig. 2. Climate zone associated to each municipality in the Canary Archipelago and number of dwellings.

Table 5
DISTRIBUTION and total number of dwelling types by climate zone.

Climate zone	Dwelling type H1	Dwelling type H2	Dwelling type H3
A2	35 % (32,366)	15 % (13,870)	50 % (46,234)
B2	15 % (5411)	5 % (1804)	80 % (28,858)
C2	15 % (534)	5 % (178)	80 % (2847)

Note: total number of dwellings for each type is shown in brackets.

Table 6
THERMAL transmittance of each façade type.

Type of façade	Thermal transmittance (in $W/m^2·K$)
F1	1.81
F2	0.91
F3	0.55
F4	0.34
F5	0.25

Table 7
THERMAL transmission coefficients of each roof type.

Roof type	Thermal transmission (in $W/m^2·K$)
R1	1.73
R2	0.82
R3	0.55
R4	0.35
R5	0.25

Glazing: Thickness of 4 mm, solar factor of 85 % and thermal transmittances of 5.7 and 6.9 $W/m^2·K$ in vertical and horizontal position, respectively.

Frame: Thermal transmittance of 2.2 $W/m^2·K$, absorptivity of 0.75 and air permeability of 50 $m^3/h·m^2$.

Table 9 shows the surface area occupied by the windows by façade and single-family dwelling type.

- Shading elements. In view of the characteristics of the climate zones studied in the present paper, no shading element was incorporated in the simulations that were performed.

Table 8
ORIENTATIONS.

Orientation	Angle	Coding
N	0°	O1
NE	45°	O2
E	90°	O3
SE	135°	O4
S	180°	O5
SW	225°	O6
W	270°	O7
NW	315°	O8

Table 9
TOTAL SURFACE AREAS OF THE WINDOWS BY FAÇADE AND TYPE OF FAMILY DWELLING (in m^2).

	Front façade	Rear façade	Right-hand side façade	Left-hand side façade	TOTAL
Dwelling type H1	9.76	9.76	0.25	0.00	19.77
Dwelling type H2	9.76	9.76	0.55	0.00	20.07
Dwelling type H3	9.76	9.76	7.57	7.32	34.41

2.7. Software used

The CYPETHERM HE Plus v2022 software was used for the simulations. This programme has been authorized for the issuing of building energy efficiency certificates in Spain and the basic energy saving documents HE 0 and HE 1 of the Spanish TBC [44]. The programme can perform energy simulations of building models through the EnergyPlus calculation engine [38] developed by the United States Department of Energy. The results that are given include, among others, the total equivalent primary energy demand and CO_2 emissions, differentiated by consumption installation (heating, cooling, domestic hot water, …), as detailed in Annex I of Directive 2010/31/EU [7], amended by Directive 2018/844 [8]. On the basis of the aforementioned Directives, the Government of Spain issued a document containing the corresponding weighting factors to calculate the energy performance of buildings (EPB) [45].

2.8. Method followed in the simulation process

Firstly, with the aim of analysing the influence of the technical characteristics of the façade on primary energy consumption and CO_2 equivalent emissions, an initial round of simulations was performed maintaining the basic roof type R1 constant and varying the type of façade (from F1 to F5). These simulations were carried out for each dwelling type, climate zone and front façade orientation. This first round of simulations resulted in a total of 360 simulations, 45 for each of the 8 orientations considered for the front façade.

Subsequently, with the aim of analysing the influence of the roof, further simulations were performed maintaining the basic façade type F1 and varying the roof type (from R2 to R5). As in the first round, the simulations were differentiated for each dwelling type, climate zone and front façade orientation. In this case, the number of simulations was 288, 36 for each orientation, making a grand total of 648 simulations (360 + 288).

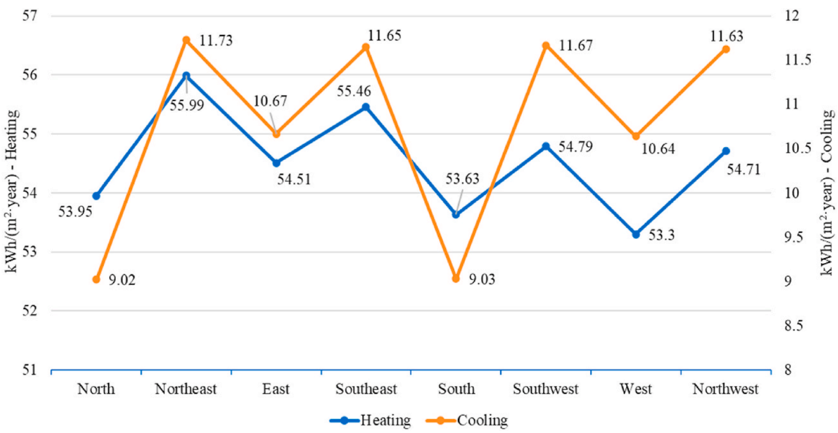

Fig. 3. Energy consumption of a single-family dwelling according to the orientation of its front façade. The example shown is the case of dwelling type H3, climate zone B2, façade type F3 and roof type R1.

3. Results and discussion

3.1. Results of the simulations

Fig. 3 shows the primary energy demand in heating and cooling for a simulation example in type H3 dwellings (detached) according to the orientation of the front façade. As can be seen in Table 9, the surface area of the windows for the front and rear façades is the same regardless of whether the front façade faces north or south. For this reason, the cooling energy consumption in summer and the heating consumption in winter are very similar for the two orientations. With respect to the other orientations, the windows are exposed for more hours during the day to solar irradiation, the key climate parameter in heat gain. For this reason, cooling energy consumption in these other orientations is higher than when the buildings are facing north or south. This same effect is also responsible for greater heating requirements in winter periods.

It was found that these results were generalized for the different dwelling types and climate zones. Therefore, for the purposes of the present paper, the results obtained in the simulations made with the O2 orientation will be shown and discussed.

3.2. Simulations with modification of transmittance in façades

Figs. 4–6 show the sensitivity of primary energy demand in heating and cooling to variations in the thermal transmittance of the façades of the envelope for the different dwelling types and climate zones studied. In principle, thermal transmittance variation was found to have practically no effect on the cooling energy demand. In addition, in all cases, the cooling demand is considerably lower than the heating demand. There can also be seen, in all the simulations, an important reduction in heating energy consumption as the thermal transmittance decreases. In addition, for all climate zones, heating demand is notably higher in H3 (detached) than H1 (mid-terraced) dwelling types. This question should be taken into consideration when planning single-family dwellings to minimize overall energy demand.

The degree of the decrease in energy demand with transmittance varies. In the first section of transmittance values (1.81–0.91), with an approximate reduction of 50 %, a maximum relative decrease in primary energy consumption of 30.4 % can be observed (see in Fig. 4 the results for dwelling type H3), whereas for the transmittance values between 0.55 and 0.25, also equivalent to a decrease of approximately 50 %, for the same simulation a lower energy consumption relative decrease is obtained of 17.4 %. If the final section of transmittance values from 0.34 to 0.25 is considered, the relative decrease obtained is 6.1 %. This suggests that beyond these latter values the economic investment in terms of façade modification to reduce thermal transmittance and, with it, energy consumption may not be economically justifiable.

Table 10 provides a summary of the results for energy saving in heating and cooling with respect to the demand obtained for the case simulated with the baseline façade (F1).

In absolute terms, it should be noticed that the reduction in energy consumption depends on both the type of dwelling and the climate zone where the building is located and is much more sensitive in the zones with more severe winter climate zones. For example, in climate zone C2, in the section of transmittances between 1.81 and 0.91 $W/m^2{\cdot}K$, a maximum energy consumption reduction of 38.3 $kWh/m^2{\cdot}year$ is obtained for H3 type dwellings, whereas the corresponding value for climate zone A2 is 15.8 $kWh/m^2{\cdot}year$. This result should also be taken into account when focusing efforts on planning strategies.

A similar analysis to that for primary energy consumption was made for CO_2 emissions ($kg/m^2{\cdot}year$). In this case, for the purposes of the present paper, the results obtained for climate zone A2 are considered (see Fig. 7).

3.3. Simulations with modification of roof transmittance

In this case, the simulations were performed modifying roof thermal transmittance and maintaining constant the façade type F1. Fig. 8 shows the results for climate zone B2 and for the different dwelling types. Unlike the façade results that were obtained, the sensitivity of primary energy demand in heating to roof thermal transmittance variation was practically negligible. The same conclusion was obtained for the other two studied climate zones.

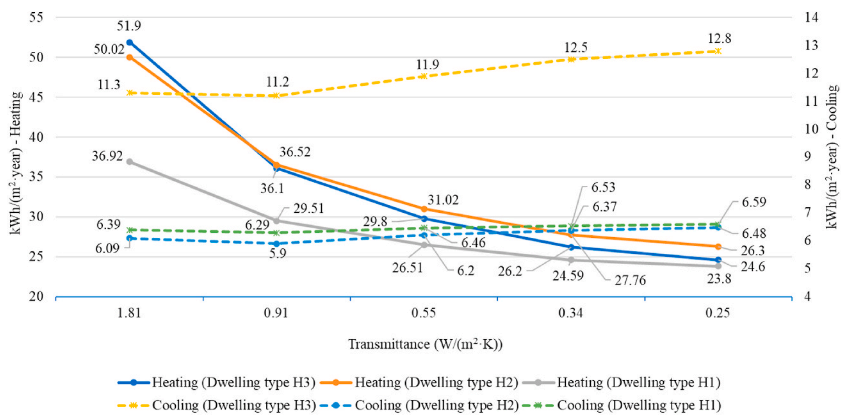

Fig. 4. Sensitivity of primary energy demand in heating and cooling according to façade thermal transmittance and dwelling type. *Climate zone A2.*

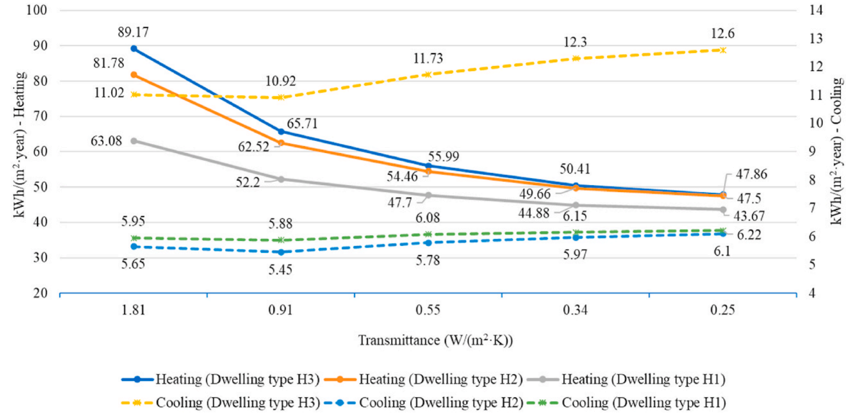

Fig. 5. Sensitivity of primary energy demand in heating and cooling according to façade thermal transmittance and dwelling type. *Climate zone B2.*

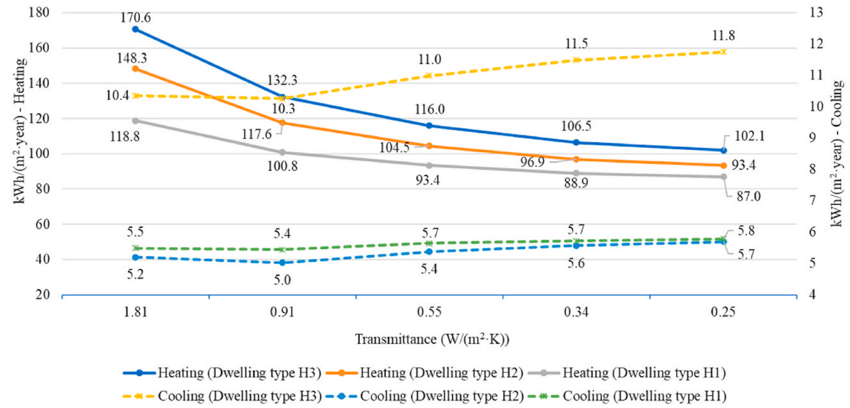

Fig. 6. Sensitivity of primary energy demand in heating and cooling according to façade thermal transmittance and dwelling type. *Climate zone C2*

In summary, for the simulations that were performed it can be deduced that: i) for all cases, energy demand in cooling is negligible compared to in heating; ii) the reduction in energy demand in heating is much more sensitive to modification of the façade than the roof; ii) the energy demand in H1 dwelling type constructions is significantly lower than in H2 or H3 types. These results should be considered key when making technical decisions in the adoption of new constructions or modifying already existing single-family dwellings to minimize their energy consumption. Considerably higher energy savings can be obtained with small modifications to the technical characteristics of the façades compared to roof-based modifications.

3.4. Analysis of the potential annual energy saving and reduction in CO_2 emissions through thermal envelope improvements

As commented on previously, the single-family dwelling housing stock in the Canary Archipelago is quite old, generally presenting the equivalent to type F1 façades. The Government of Spain's TBC [39] has established maximum and guideline values for the façades of new family housing constructions differentiated by climate zones (see Table 11).

In this regard, for the purposes of the present study, an estimation was made of the potential energy saving for the different islands' electrical systems that would be obtained in heating, as well as the consequent reduction in CO_2, if modifications were made to the thermal envelope of already existing single-family dwellings such that a thermal transmittance is obtained equal to the guideline value proposed by the Spanish TBC.

The improvement of the thermal transmittance of the envelope through modification of type F1 façades to another with a transmittance equal to the guideline TBC value is equivalent to a reduction in specific energy consumption, Δ *SEC,* in heating (see Figs. 4–6 and Table 10). Through Eq. (1), the annual primary energy savings (PES) was calculated by climate zone and dwelling type.

$$PES = \Delta SEC \cdot A \cdot n \tag{1}$$

where:

PES = annual primary energy saving (in kWh/year)

ΔSEC = equivalent reduction of specific energy consumption (in $kWh/m^2 \cdot year$)

A = average surface area of the dwellings

n = number of dwellings by type and climate zone.

Table 10
VARIATION IN ENERGY CONSUMPTION (in kWh/m^2·year) WITH RESPECT TO THE RESULTS OBTAINED WITH THE THERMAL TRANSMITTANCE OF THE BASELINE FAÇADE (F1), DIFFERENTIATED BY CLIMATE ZONE AND TYPE OF SINGLE-FAMILY DWELLING. Note: Values shown are heating/cooling). A negative value represents a reduction in energy consumption compared to the baseline case.

	CLIMATE ZONE		
THERMAL TRANSMITTANCE	A2	B2	C2
1.81		Baseline cases	
	-7.41 / -0.10	-10.88 / -0.07	-17.97 / -0.05
	-13.50 / -0.19	-19.26 / -0.20	-30.70 / -0.17
0.91	-15.80 / -0.10	-23.46 / -0.10	-38.31 / -0.09
	-10.41 / 0.07	-15.38 / 0.13	-25.43 / 0.16
	-19.00 / 0.11	-27.32 / 0.13	-43.73 / 0.18
0.55	-22.10 / 0.60	-33.18 / 0.71	-54.65 / 0.64
	-12.33 / 0.14	-18.20 / 0.20	-29.87 / 0.23
	-22.26 / 0.28	-32.12 / 0.32	-51.41 / 0.37
0.34	-25.70 / 1.20	-38.76 / 1.28	-64.17 / 1.14
	-13.12 / 0.2	-19.41 / 0.27	-31.86 / 0.30
	-23.72 / 0.39	-34.28 / 0.45	-54.91 / 0.49
0.25	-27.30 / 1.50	-41.31 / 1.58	-68.59 / 1.40

Results for dwelling type H1
Results for dwelling type H2
Results for dwelling type H3

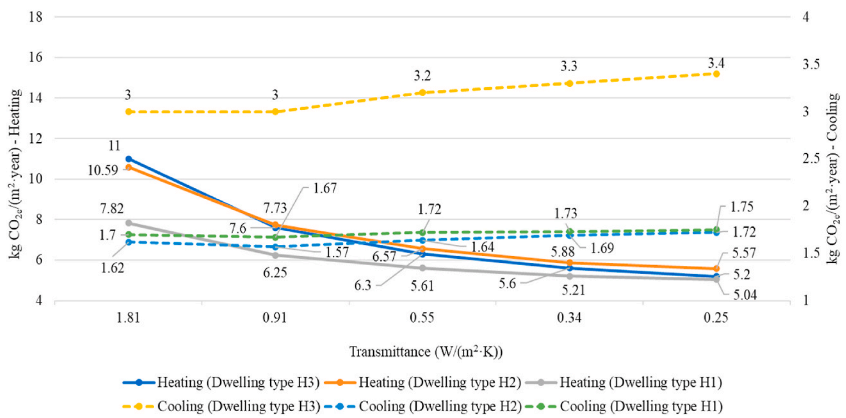

Fig. 7. CO_2 emissions by façade thermal transmittance and dwelling type. *Climate zone A2.*

Using the methodology explained above, and considering the distribution of climate zones and the number of dwellings in each island (see Fig. 2), it was found that the total annual energy saving in heating amounts to 290.36 GWh/year. Bearing in mind the technology of the electrical energy generation systems in the archipelago, the conversion factor tCO_2/MWh is equal to 0.575 [33] and, therefore, the equivalent emissions reduction in heating is 166.96 $ktCO_2$/year. As can be observed from the results obtained for the

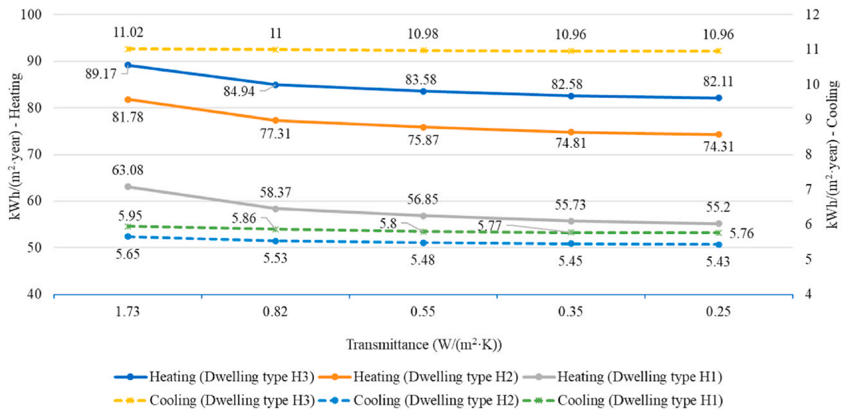

Fig. 8. Sensitivity of primary energy demand in heating and cooling according to roof thermal transmittance and dwelling type. *Climate zone B2.*

Table 11
Spanish TBC maximum and guideline thermal transmittance values of façades or walls in contact with the outside air [39].

	A	B	C
Maximum TBC value	0.70	0.56	0.49
Guideline TBC value	0.50	0.38	0.29

variations in energy consumption in cooling through envelope optimization (Figs. 4–6), these are very small compared to those in heating for the studied climate zones. Following an analogous method to that used for heating, the variation in energy consumption in cooling was estimated, with the result showing an increase in total energy demand of 7.22 GWh, equivalent to additional emissions of 4.15 $ktCO_2$/year. Combining the heating and cooling results, the resulting net total saving is 283.14 GWh, equivalent to 162.81 $ktCO_2$/year.

Table 12 shows the results obtained for the different islands in terms of estimated annual energy saving after thermal envelope optimization and the consequent reduction in CO_2 emissions.

Considering the energy demand of the housing sector in the Canary Archipelago, calculated on the basis of the last official published data in Refs. [33,46], this energy saving is equivalent to 9.17 % of the current electrical energy consumption in the housing sector.

4. Conclusions

A study has been presented on primary energy demand optimization in the heating and cooling systems of single-family dwellings in reference to the technical configuration of the building's envelope. A case study was carried out in the Canary Archipelago for different dwelling types, with different thermal characteristics of the envelope and located in different climate zones. In the characteristics of the studied climate zones, winter conditions were considerably more severe than summer ones. Energy consumption in cooling was therefore negligible in comparison to that for heating in the simulations performed. It was also found that modification of the thermal transmittance of façades had a bigger effect on specific energy savings compared to corresponding modifications to the roofs of the buildings. For example, for an H3 type dwelling located in climate zone B2, the maximum energy saving after roof modification was 7.05 kWh/m^2·year, whereas façade modification resulted in a maximum energy saving of 41.3 kWh/m^2·year.

The islands that make up the archipelago are small in size, with territorial limitations, and have isolated, non-interconnected electrical systems with limited capacity for the management of electrical energy generation and demand.

The results obtained with respect to heating energy consumption reveal that.

Table 12
RESULTS of the analysis of potential energy saving by island.

Island	Number of single-family dwellings	Net primary energy saving (GWh/year)	Emissions reduction ($ktCO_2$/year)
Tenerife	82,624	159.43	91.56
Gran Canaria	41,673	108.38	62.42
La Palma	5067	8.74	5.03
El Hierro	1586	3.42	1.97
La Gomera	1152	3.17	1.83
Total	132,102	283.14	162.81

i) It is highly sensitive to modifications in the transmittance of the thermal envelope. The results obtained in the simulations performed in the present study show that the energy saving with respect to the baseline façade type can reach as high as 51.4 kWh/m^2.year
ii) This sensitivity varies depending on the transmittance range considered, reaching a minimum value beyond which the heating energy demand remains practically constant. For a reduction of transmittance values from 1.81 to 0.91, equivalent to a decrease of approximately 50 %, a maximum relative decrease in primary energy consumption of 30.4 % was obtained, whereas for a reduction from 0.55 to 0.25, also equivalent to a decrease of approximately 50 %, a lower energy consumption relative decrease of 17.4 % was obtained. This conclusion is key in building design as the relative improvement that a new material and/or technical solution may provide for the envelope may not make economic sense in terms of the building's energy sustainability.
iii) This sensitivity is also dependant on the climate characteristics of the zone and the building type. It was found that sensitivity is greater in the zones with more severe winter climate zones. For example, in climate zone C2, in the section of transmittances between 1.81 and 0.91 $W/m^2 \cdot K$, a maximum energy consumption reduction of 38.3 $kWh/m^2 \cdot$year was obtained for H3 type dwellings, whereas the corresponding value for climate zone A2 was 15.8 $kWh/m^2 \cdot$year.

An estimation was also made of the energy saving after optimization of the thermal envelope. For this, the general technical characteristics of the thermal envelope of dwellings already present in the study area were taken into account. Calculation was then made of the energy saving that could be obtained if measures were adopted to meet the technical conditions for the envelope currently demanded for new constructions in the Technical Building Code drawn up by the Government of Spain. The specific energy saving (in $kWh/m^2 \cdot$year) for each type of dwelling and each climate zone was calculated. Considering the average surface area of the dwellings and their number by type and climate zone, it was found that the potential energy saving in the study area could be as high as 283.14 GWh/year, equivalent to an emissions reduction of 162.81 $ktCO_2$/year. This saving could equate to up to 9.17 % of the current energy demand of the housing sector in the archipelago, in this way reducing the load on the islands' weak electrical systems.

The results and conclusions obtained can be used in the development of planning strategies for new housing and/or improvements to the already existing housing stock within the framework of the goals established in the different EU Directives concerning energy efficiency in general and especially in the housing sector.

In future research studies, the authors plan to study the potential corresponding energy saving in warmer climates with more severe summer conditions and where the energy consumption in cooling is more pronounced. The effect of other construction-related aspects, such as the window openings, could be analysed. For this, the technical characteristics of the glass and frame, as well as the effects of different shading elements, would have to be taken into consideration.

CRediT authorship contribution statement

Francisco Espino-González: Writing – original draft, Software, Methodology, Investigation, Data curation. **MaríaEugenia Armas-Cabrera:** Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Fernando Montesdeoca-Martínez:** Writing – original draft, Investigation, Data curation. **Sergio Velázquez-Medina:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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