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Comparative study between the Passive House Standard in warm climates and Nearly Zero Energy Buildings under Spanish Technical Building Code in a dwelling design in Seville, Spain

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ABSTRACT

The Passive House Standard is based on the reduction of energy demand and consumption. In Spain, this Passive House concept has become the preferred alternative for achieving nearly Zero Energy Buildings. The necessary criteria were incorporated into Spain's 2019 Technical Building Code, which considers the passive design of buildings. In fact, it is possible that the design of many Spanish buildings complying with the basic criteria of passive architecture and the current regulatory framework, meet the requirements of the Passive House. On the other hand, the adaptation of the standard to different climates is very general and wide- ranging. The inflexibility of certain criteria brings into question the effectiveness of the certification in warm climates such as in the south of Spain or Southern Europe.

This study compares the application of basic Passive House standards with Spain's current building regulations to achieve nZEB in a project which applies passive design strategies to a single-family dwelling in Seville, Spain. The results show that the current national regulations render unnecessary the application and/or certification of the Passive House standard as a guarantee of energy efficiency and offer a better solution in terms of building sustainability for a warm climate.

1. Introduction

The Energy Performance of Buildings Directive 2010/31/EU [1] introduced the concept of nearly Zero-Energy Buildings (nZEB) in order to promote buildings that are more efficient at fulfilling the current minimum energy performance requirements. The definition and requirements must be included in the national plan of each EU Member, including a numerical indicator of primary energy use expressed in kWh/m^2 per year.

The first Spanish National Plan [2] derived from this directive, defined the nZEB as one that reached class A in the Energy Efficiency Rating Scheme, as the primary energy consumption of class A buildings is 70 % lower than buildings fulfilling the minimum energy requirements of the Spanish Technical Building Code (hereinafter CTE) approved in 2006 [3]. The update of the CTE in 2013 [4] was more demanding in regards to the minimum energy requirements but the 2014 [5] and 2017 [6] national plans did not include an update in the definition of nZEB. However, they did highlight that the update of the CTE was a step forward to reaching nZEB.

The December 2019 update of the CTE [7] introduced a fixed, quantitative threshold to define what Spain classifies as a nZEB and the 2020 National Plan [8] includes measures focused on reaching a high energy efficient and decarbonized building stock before 2050 in line with the Directive 2018/844/EU [9].

An increased wareness of achieving low energy buildings gave rise to several Green Building Rating Systems and Sustainability assessment methods for buildings that include an assessment of energy efficiency. The main Green Building Rating Systems and Sustainability assessment methods for buildings known in Spain are LEED [10], BREEAM [11], and VERDE [12]. Additionally, there are other construction standards such as Passive House (hereinafter PH) [13], Effinergie [14], Casaclima [15] and Minergie-ECO [16]. Among them, the Passive House standard is one of the most internationally recognised [17] and promoted as a guarantee of

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nZEB in Spain, despite not being rigourously implemented as an official certification.

1.1. The Passive House standard

The PH methodology sets out guidelines for achieving ultra-low energy buildings and the voluntary certification of those that meet its criteria. Until very recently, these guidelines had been one step ahead of energy efficiency regulations in some countries, such as Spain, and were considered a benchmark for high energy efficient buildings [17]. Authors such as Colclough et al. [18] recognise the methodological value of this standard in the reduction of energy consumption in different climates and highlight the main strategy of the PH system which is based on controlling the envelope with high levels of insulation and airtightness. This strategy is currently being adapted [18] through a number of codes and regulations at both national and European levels.

For a building to be considered a Passive House, it must meet the following criteria [13]:

1. The space Heating Energy Demand is not to exceed 15 kWh/m^{2}year or 10 W/m^2 (peak demand).
2. The Primary Renewable Energy Demand must not exceed 60 kWh/m^{2}year for Passive House Classic certification.
3. The Airtightness must be verified with an onsite pressure test giving a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50).
4. Thermal comfort must be met for all living areas during winter as well as in summer, with no>10 % of the hours in a given year over 25 °C.

For achieving these criteria, the standard proposes an intelligent building design, incorporating passive strategies to control the heat balance, and the implementation of the 5 Passive House principles:

1. High Thermal insulation
2. High insulated windows
3. Heat recovery ventilation
4. Airtightness of the building
5. Absence of thermal bridges

This method requires exhaustive control both of the building design, carried out by a certified Passive House Designer and verified through Passive House's own software (Passive House Planning Package – PHPP) and of the building execution, including several controls by accredited Passive House certifiers.

The obligation to apply nZEB energy efficiency concepts to European public buildings from 2018, and to all buildings from 2020 [1] led to a 2015 update of the general PH standards in place since 1991 (Table 1) so as not to lag behind the nZEBs [18].

1.2. Adaptation of the Passive House standard to warm climates

The Passive House began as a building concept which provided high thermal comfort levels with low energy consumption in the context of Central European homes. The standard is now widely accepted in Central European countries [19], particularly in Germany, the country where it was conceived (505 certified homes), and France (311 certified homes). However, in countries such as Spain, the number of PH certified homes remains very low (101 certified homes) [20]. Of the 101 certified homes in Spain, 3.9 % are in Andalusia, an area classified by Köppen as a warm climate [21,22], while the remaining homes are located in a temperate-warm climate, proving that the number of certified homes decreases dramatically in warm climates. This same trend can been seen in Portugal, the south of Italy and Greece [20].

Table 1
Passive House requirements. 1991 and 2015 versions. Source: the authors, from PH standard.

	1991	2015
Heating Energy Demand	≤15 kWh/m^2	≤15 kWh/m^2 or Peak demand ≤ 10 W/m^2
Cooling Energy Demand	≤15 kWh/m^2	≤15 kWh/m^2 and dehumidification or Peak demand ≤ 10 W/m^2
Airtightness [1]	0.60 h^{-1} n_{50}	0.60 h^{-1} n_{50}
Primary Energy Demand	Non-renewable Energy Demand: ≤120 kWh/m^{2}year Covers heating, cooling, DHW and electrical consumption	Renewable Energy Demand: ≤60/45/30 kWh/m^{2}year for Classic/Plus/Premium certification Maximum deviation: ± 15 kWh/m^{2}year Renewable energy generated onsite: ≥ 60/120 kWh/m^{2}year for Plus/Premium certification Covers heating, cooling, dehumidification, DHW, lighting, auxiliary electricity and electrical appliances
Outdoor Air rate	≥30 m^3/h person (Residential buildings)	≥30 m^3/h person (Residential buildings)
Heat recovery unit	Compulsory/Needed	Compulsory/Needed

[1]verified with an onsite blower door test.

Central European climate conditions, with harsher winters than the south of Europe (which suffers harsher summers) define the Passive House standard, which is based on passive heating strategies.

In Southern European climates, which have higher levels of solar radiation and less severe winters, it may be simpler to reduce heating demand [23]. However, these buildings have a higher cooling demand which means habitability and comfort conditions are linked to passive cooling strategies such as natural cross-ventilation, night ventilation, night radiative cooling or evaporative cooling [24].

While the basic principles of the Passive House standard are general and can be applied across all countries [25]], numerous studies highlight the need to adapt the criteria of the standard to other climate conditions [18] where there is overheating as a result of high levels of insulation, high levels of humidity and poor interior air quality as a result of airtightness and a lack of air renewal. Some of the basic principles of Passive House in its original environment such as mechanical heat recovery ventilation and thermally broken triple glazed windows can be detrimental strategies in warm climates [26] which has a negative effect on its implementation in other climates.

As a consequence, the Passive House standard has been modified to adapt to temperate and warm climates within the framework of the Passive-On Project [23]. It was considered that the unique qualities of climate conditions should be taken into account and as a result, that passive strategies depend on climate zones [17,25]. It was concluded that certain passive strategies could be implemented in the design of buildings in warm climates, adapting the concept of the passive home to these climates. These strategies include:

- Natural, mainly night time, ventilation to dissipate internal and solar gains.
- High thermal inertia which helps avoid overheating and decreases cooling demand.
- Use of solar shading such as awnings, blinds or overhangs, which help with solar control.

Passive strategies gain importance when adapting to different climates so that glazing quality, insulation levels and installations depend on the climate but also on the building form and orientation [19]. As a result, in warm climates, night ventilation can be fundamental for avoiding overheating [27].

These strategies should be implemented as a priority [28] alongside the 5 principles of the Passive House (insulation and airtightness of the envelope). Furthermore, the project showed that low demand for heating can be achieved using air extraction systems without using heat recovery [23,29].

Table 2 shows the adaptation of Central European (cold climate) PH criteria to the warm and temperate climates characteristic of the south of Europe [30]:

As can be observed, criteria for new buildings in warm climates contemplate the justification for indirect heating and cooling energy demand as well as the non-compulsory usage of a heat recovery unit in the air extraction system.

Nevertheless, one of the PH standard's weak points is the lack of rigourous adaptation to the diversity of climate zones with no reference to regional micro and macro climate conditions [31].

1.3. Implementation of the Passive House standard in Spain

Prior to the 2019 update of the Spanish Technical Building Code [7], the absence of a definition for nZEB based on quantitative criteria meant that the PH standard was seen as the only alternative for achieving nZEB in Spain.

New build homes achieving Class A energy ratings in Spain, possibly meet all or at least some of the PH criteria, yet never get certified. This could be for a number of reasons: additional cost, difficulty of design or execution, demands of an external certification, lack of adaptation to the diversity of climate zones.

Table 2
Adaptation of Passive House criteria to warm climates. Source: the authors, from PH standard.

	Passive House 2015	Adaptation to Warm climates
Heating Energy Demand	$\leq$15 kWh/m^2 or Peak demand $\leq$ 10 W/m^2	$\leq$15 kWh/m^2 Indirectly: Winter thermal comfort according to EN 15251. $T_{indoor} \geq 20$ °C
Cooling Energy Demand	$\leq$15 kWh/m^2 and dehumidification or Peak demand $\leq$ 10 W/m^2	$\leq$15 kWh/m^2 and dehumidification Indirectly: Summer thermal comfort according to EN 15251. $T_{indoor} \leq 26$ °C during > 10 % summer hours Overheating: less than5% summer hours $dT_{in\text{-}out} \leq 6$ °C if T_{out} > 32 °C
Airtightness [1]	0.60 h^{-1} n_{50}	0.60 h^{-1} n_{50}
Outdoor Air rate	$\geq$30 m^3/h person (Residential buildings)	$\geq$30 m^3/h person (Residential buildings)
Heat recovery unit	Compulsory/Needed	Not strictly necessary
Primary Energy Demand	Renewable Energy Demand: $\leq$60/45/30 kWh/m^{2}year for Classic/Plus/Premium certification Maximum deviation: ± 15 kWh/m^{2}yearRenewable energy generated onsite: $\geq$ 60/120 kWh/m^{2}year for Plus/ Premium certification Covers heating, cooling, dehumidification, DHW, lighting, auxiliary electricity and electrical appliances	Non-renewable Energy Demand: $\leq$120 kWh/m^{2}yearCovers heating, cooling, DHW, lighting and electrical appliances

[1]verified with an onsite blower door test.

With regards to additional costs, adopting the PH standard has implications on the cost of the home [18]. However, this increase is not comparable to that of the rest of Europe: additional costs are around 2.85 % in Seville and 10 % in France [23]. This range reflects the differences in construction costs, traditions and thermal regulations between countries. The initial return on investment period also differs between countries: from 19 years in countries such as the United Kingdom, France or Germany to 4 years in the south of Spain.

As the number of countries in which the PH standard has been implemented increases, costs have decreased. In Central Europe costs have been reduced from an intial 12 % to the current 3–5 % which reduces amortisation to 10 years [32].

This additional cost is usually reflected in the design and construction of the envelope, which requires greater insulation and thermal breaks of both facings and glazing [18] than traditional construction. In Spain, traditional construction methods do not make use of triple glazing. Nevertheless, some authors point out that the additional cost associated with complying to the PH standard is the minumum in terms of cost-effectiveness necessary to meet the expectations and restrictions of nZEB buildings [18].

Considering the increased energy efficiency demands of the updated CTE, the aim of this study is to verify whether applying the PH standard in warm climates offers a competitive advantage with regards to the improvement of energy behaviour, building and economic sustainablility, compared to compliance with current Spanish regulations through passive design criteria.

2. Materials and methods

This study evaluates the use of passive strategies in the design process of a dwelling in the south of Spain, a warm interior climate, as a necessary method to achieve the nZEB requirements set out in the 2019 CTE. It also compares the energy behaviour of the dwelling with the requirements set out by the PH standard for certification.

2.1. Case study description and location

The case study is a terraced single-family dwelling on a 210 m^2 plot of mostly flat land. The dwelling is NE-SW facing and has a front and back patio. Other adjoining dwellings sit to the left and right hand side.

The two-storey plus basement building has a living-dining area, kitchen, three bedrooms and two bathrooms on the ground and first floor, as shown in Fig. 1. The basement is an open plan space with a small bathroom and storeroom. The indoor courtyard and back patio provide natural lighting and ventilation. Neither the basement space nor its entrance hall are considered in the energy evaluation. The useful and built areas are found in Table 3.

In order to define the climatic zones for energy assessment purposes, the HE Energy Saving Basic Document of the Spanish Technical Building Code (hereinafter CTE DB HE) [33] classifies each location based on the severity of its winters and summers (Fig. 2). Winter severity ranges from A to E, plus α for the Canary Islands, and summer severity ranges from 1 to 4, with α and A being the lowest winter severity and 1 the lowest summer severity.

The building is located in Gines (37°23' N, 6°04' W), in the province of Seville, an inner province of Andalusia, in the South of Spain. According to the CTE DB HE, Gines is a B4 climatic zone, which supposes mild winters and warm summers, reaching the maximum Spanish summer severity, and has a Mediterranean cli-

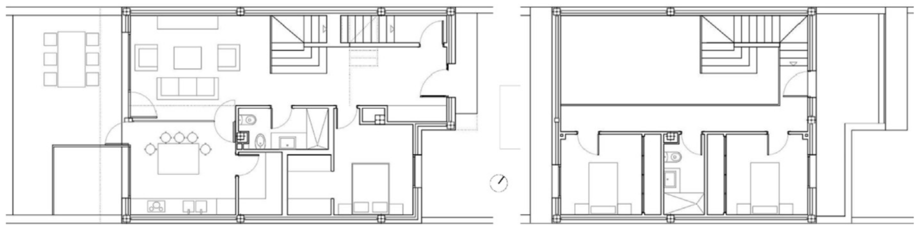


Fig. 1. Ground (left) and First (right) Floors. Source: the authors.

Table 3
Table of surface areas. Source: the authors.

	Built Area (m^2)	Useful area (m^2)
Ground floor	89.45	66.90
First floor	47.95	42.93
TOTAL Assessed	137.40	109.83

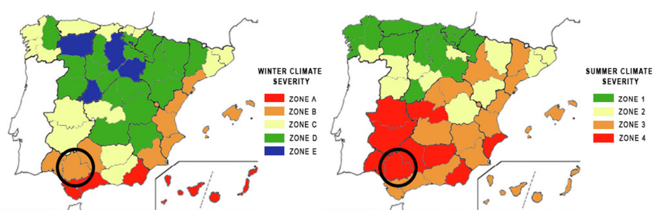


Fig. 2. Spanish winter (left) and summer (right) severity climatic zoning. The circle highlights the province where the case study is located. Source: Spanish Technical Building Code (CTE DB HE).

mate [21,22], characterized by extremely hot, dry summers and mild, partially wet winters.

The average annual temperature is 18.0 °C reaching a maximum absolute temperature of 46.6 °C in July and a minimum absolute temperature of −5.5 °C in February. The average maximum temperature during summer is higher than 25.0 °C and the average minimum temperature during winter is lower than 10.0 °C with an average relative humidity higher than 70 %.

2.2. Methodology

Taking into account the importance of including passive strategies in building design [28] to achieve nZEB and, in order to evaluate the level to which compliance with the CTE also meets the PH standard requirements, the following methodology has been used:

1. Correlation of pH standard criteria with CTE requirements.
   PH criteria have been reviewed for warm climates and the equivalent have been sought in the CTE, especially in the demands related to obtaining nZEB.
2. Passive Design of the Dwelling
   Both location and setting conditions, and urban planning restrictions have been taken into account so that passive strategies can be incorporated into the dwelling design.
3. Energy evaluation and compliance with mandatory regulations.
   Once compliance with mandatory regulations has been guaranteed, energy evaluation and certification is carried out on the building with the Spanish government's officially recognised calculation programmes.
4. Compliance with PH standard for warm climates and comparison with the CTE.
   The "regulation" dwelling is checked to see if it complies with the PH standard and which level of pH certification it would achieve. Differences with the CTE are detected during this process.
5. Comparative economic study of compliance with CTE and PH standard for warm climates.
   An economic study is carried out to obtain the additional costs incurred through certifying PH voluntarily and in addition to complying with current mandatory regulations, which is seen as the reference cost.

3. Results

3.1. PH criteria and regulatory demands for achieving nZEB in Spain

The requirements of the PH standard for warm climates relate to heating and cooling demand, airtightness of the envelope and primary energy consumption, as well as interior comfort conditions.

Under Spanish code, these questions and the requirements to achieve nZEB are set out in the regulatory documents for Environmental Health [34] and Energy Saving [33]:

1. CTE-DB-HE Energy Saving

The demands related to the requirements of the PH standard are: HE-0 for the limiting of energy consumption, in which the requirements of energy consumption in buildings are defined as almost zero (nZEB); HE-1 regarding conditions for the control of energy demand, in which the thermal and airtight properties of the thermal envelope are specified; HE-2 regarding conditions for thermal installations; and HE-4 regarding the minimum contribution of renewable energy to cover demand for domestic hot water.

2. CTE-DB-HS Health

This document sets out the demands to ensure minimum standards of health, such as providing adequate interior air (HS-3). This demand is related to the PH standard and establishes the minimum flow of outdoor air which must enter a dwelling.

3. R.D. 235/2013 Standard [35]: Energy Certification

This document is for the regulatory adoption of methodology for the calculation of energy efficiency in buildings (Directive 2002/91/EC [36] modified by Directive 2010/31/EU [1]) to offer the user objective information about CO_2 emissions. This information is displayed as a scale on an Energy Efficiency label in which class A corresponds to the most energy efficient buildings.

The scale reflects compliance with the minimum requirements of energy efficiency set out in the CTE-DB-H. To be considered nZEB, as set out in the Energy Efficiency and Saving Plan 2011–2020 [2], a building must be classified A on the primary non-renewable energy consumption indicator, the limit values of which are set out in the CTE-DB-HE-0 document [33].

Below, the PH standard requirements for warm climates are compared with mandatory regulation requirements for the climate zone in which the case study is located (Fig. 3).

Table 4 summarises how the PH standard requirements for warm climates correlate with Spanish regulations for the B4 climate zone and residential use.

3.1.1. Heating and cooling demand

The PH standard establishes that demand for heating and cooling should be equal to or lower than 15 kWh/m^2/year, and additionally, considers the contribution of dehumidification on the demand for cooling where necessary. Furthermore, for a warm climate, it sets out some indirect criteria for interior comfort in line with regulation UNE-EN 16798–1 [37] (Table 4).

The determinations related to heating and cooling demand can be found in CTE-DB-HE-1 [33] which establishes the thermal characteristics of the building envelope (thermal transmittance, permeability, solar control) to reduce energy demand. In contrast to the earlier version, the 2019 update does not establish limit values for heating and cooling demand, but instead establishes a global coefficient for heat transmission through the building's thermal envelope (K_{lim}) which depends on its compactness V/A [m^3/m^2]. As the compactess of the case study is 1.44, the global coefficient limit Klim is 0.6 W/m^{2}K.

On the other hand, regulation calculations related to the UNE-EN 16798–1 [37] standard can be found in the CTE-DB-HE-2 document [33], which coincides with the Code for Thermal Installations in Buildings [38]. This document sets out the ranges of temperature and relative humidity which must be reached both in winter and summer for certain clothing and activity conditions.

To achieve a low energy demand, the regulations nevertheless establish the following requirements:

3.1.1.1. Thermal transmittance of the thermal envelope. The CTE-DB-HE-1 document [33] sets the thermal transmittance limit (W/m^{2}K) of the building elements of the thermal envelope, as can be seen in Table 5:

3.1.1.2. Solar control of the thermal enclosure. The CTE-DB-HE-1 document [33] also introduces the concept of "solar control of the thermal envelope" as a strategy for controlling cooling demand. This is the relation between solar gains in the month of July in the openings in the thermal envelope with mobile solar shading activated (including awnings and blinds), and the useable areas included. The limit value set for residential buildings is 2 kWh/m^2 per month.

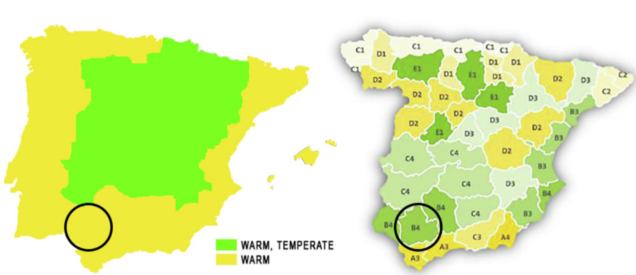


Fig. 3. Climatic classification of Spain: PH (left), CTE DB HE (right) 1. The black circle highlights the province where the case study is located. Source: the authors.

Table 4
Passive House requirements for warm climate and their correlation with Spanish regulations. Source: the authors

	PH Warm	CTE Document	CTE requirements
Heating Energy Demand	≤15 kWh/m^2 Indirectly: Winter thermal comfort according to EN 15251. T_{indoor} ≥ 20 °C	DB-HE-1: Conditions for controlling energy demand	Requirements depend on the climatic zone and use. For B4 climatic zone and residential use: U-values thresholds: Façades and floors (air): 0.56 W/m^{2}K Roofs: 0.44 W/m^{2}K Windows: 2.3 W/m^{2}K Vertical Partitions: 1.20 W/m^{2}K Horizontal Partitions: 1.55 W/m^{2}K Partitions dif. Use: 1.10 W/m^{2}K Dividing wall: 0.75 W/m^{2}K Global envelope U-value depends on the compactness (V/A) Case study U_{thr}: 0.60 W/m^{2}K Max Solar radiation on windows during July: 2 kWh/m^2 month
Cooling Energy Demand	≤15 kWh/m^2 and dehumidification Indirectly: Summer thermal comfort according to EN 15251. T_{indoor} ≤ 26 °C during > 10 % summer hours Overheating: <5% summer hours dT_{in-out} ≤ 6 °C if T_{out} > 32 °C		
Airtightness	0.60 h^{-1} n_{50} Verified by a blower-door test		For windows(air permeability): $Q_{100,lim}$ ≤ 27 m^3/h m^2 Blower-door test if Sup_{us} ≥ 120 m^2
Outdoor Air rate	≥30 m^3/h person (Residential buildings)	DB-HS-3: Indoor air quality	Outdoor air flow depends on the type of indoor space. Ranges between 6 and 33 l/s
Heat recovery unit	Not strictly necessary	DB-HE-2: Thermal installations conditions	Mandatory if the outflow rate is higher than 0.50 m^3/s
Primary Energy Demand	Non-renewable Energy Demand: ≤120 kWh/m^{2}year Covers heating, cooling, DHW, lighting and electrical appliances	DB-HE-0: Limitation of energy consumption DB-HE-4: Minimum contribution of renewable energy to cover energy demand	Requirements depend on the climatic zone, usable area, and use. For B4 climatic zone and residential use: Max Non-renewable Primary energy consumption: 28 kWh/m^{2}year Max Total Primary Energy Consumption: 56 kWh/m^{2}year Renewable energy contribution for DWH: 60 %

Table 5
Thermal transmittance limit. Source: the authors, from CTE

Element	U-limit CTE 2019	U-recommended CTE 2019
External walls and floors	0.56	0.38
External Roofs	0.44	0.33
Elements in contact with the ground or non-habitable spaces	0.75	0.69
Windows and Openings (frame + glazing)	2.30	2.00

3.1.2. Airtightness of the envelope and air renewal

The PH standard establishes that the building envelope should be completely airtight and that air renewal with 50 Pa (n50) differential pressure must be less than 0.60 h^{-1} and verified by a blower-door test. It also establishes that outdoor air flow should be provided equal to or>30 m^3/h per person.

The envelope's airtightness is controlled in the CTE-DB-HE-1 document [33], although this only states a limit value of air renewal of 50 Pa (n50) if the total useable area is greater that 120 m^2. As the case study house has a total useable area lower than this, there are no specific demands on the airtightness of the thermal envelope.

The outdoor air flow requirement is correlated in the CTE-DB-HS-3 document [34] in which the minimum ventilation flows are set out. Impulse and extraction flows will be at least those obtained in the following table (Table 6) of the CTE:

As well as this direct correlation with the PH standard determinations, the CTE-DB-HE-1 document [33] establishes specific values for air opening permeability (glazing-framework, the airtightness of the join between frame and opaque support is not specified), which depends on the climate severity in winter and is established for 100 Pa pressure. For winter climate severity B (case study) the air permeability (Q_{lim}) of the window product must be $\leq$ 27 m^3/hm^2, which corresponds to Class 2.

3.1.3. Heat recovery and other conditions of the thermal installations

The PH standard adapted for warm climates considers that air extraction heat recovery, which is one of its 5 pillars, is not strictly necessary [17][23]. This determination is correlated in document CTE-DB-HE-2 [33].

Spanish code considers both the incorporation of units that allow free outdoor air cooling and air extraction heat recovery in the section related to energy recovery. The former strategy is compulsory if nominal cooling power is equal or>70 kW while the latter is compulsory if expulsion flow is>0.50 m^3/s. Minimum performance of the heat recovery unit must be between 50 % and 75 % and maximum loss between 180 Pa and 260 Pa depending on the explusion flow: from 0.50 m^3/s to over 12 m^3/s.

As well as establishing the minimum ventilation flow, the CTE-DB-HS-3 document [34] establishes whether general ventilation is hybrid or mechanical, allowing for the incorporation of energy recovery units. However, there are no indications related to the thermal treatment of ventilation air.

3.1.4. Primary energy consumption

The PH Standard for warm climates limits the consumption of primary energy to 120 kWh/m^2 per year for heating, cooling, DHW, domestic appliances and lighting. The correlation of this limit value is found in document CTE-DB-HE-0 [33] which establishes the limit values for primary non-renewable energy consumption (Cep,nren) and total primary energy consumption (Cep, tot = renewable energy + non-renewable energy). These limit values depend on the winter climate severity and the type of intervention. The values established in the latest update of the HE require a 50 % decrease compared to previous versions which is a determining factor for achieving nZEB.

For a new residential build in a Class B winter climate severity zone, the limit values are Cep,nren $\leq$ 28 kWh/m^2 per year and Cep, tot $\leq$ 56 kWh/m^2 per year. As can be observed, the limit value of primary energy consumption is a 53 % reduction on that demanded by the PH standard, which does not establish limits on primary non-renewable energy.

On the other hand, with regard to primary energy, those provisions are found in Spanish code.

3.1.4.1. Minimum contribution of renewable energy to cover demand for domestic hot water. The CTE-DB-HE-4 document [33] establishes the percentage of domestic hot water demand that must be covered by energy from renewable sources, allowing for renewable cogeneration or connection to an urban heating system.

The new 2019 version establishes coverage of at least 70 % of annual hot water energy demand from renewable sources, and only 60 % if hot water demand is lower than 5000 l per day, as is the case study (112 l/day). This contribution is obtained from monthly demand and contributes to the global balance of primary energy and non-renewable primary energy consumption.

3.2. Passive design strategies in warm climates

The European Directive 2010/31/UE [1] expresses that the measures to improve the energy performance of the buildings should take into account climatic and local conditions as buildings have an impact on long-term energy consumption. The achievement of the requirements of the Spanish Technical Building Code related to the energy demand and the nZEB, accredited by the energy qualification of the building, requires a strong commitment to implementing building passive strategies that consider and take advantage of the local climate and characteristics of the building location.

In order to achieve nearly zero-energy buildings, it is essential to implement passive strategies which consider and take advantage of the local climate and characteristics of the building location. Thus, passive design of buildings is a determining factor for the achievement of the parameters established by the PH standard, yet it is not exclusive to this standard. The fundamental passive building strategies [41], based on the building orientation, compactness, solar admittance control, quality of the thermal envelope, airtightness, natural ventilation design and other singular aspects, are also considered by the Passive House standard [42], and have been a part of the architectural discipline from its origin [43], when

Table 6
Minimum ventilation flow (l/s). Source: the authors, from CTE

Type of dwelling	Dry spaces			Wet spaces	
	Main bedroom	Rest of bedrooms	Living and dining rooms	Minimum in total	Minimum per wet space
0 or 1 bedrooms	8	–	6	12	6
2 bedrooms	8	4	8	24	7
3 or more bedrooms	8	4	10	33	8

there were no active systems to compensate the defective passive indoor conditioning.

Although selecting the adequate passive strategy depends on climatic and functional factors, several authors have proven certain strategies suitable for warm climates with high solar radiation levels [41,44,45], such as solar admission control (solar shading), energy flow control (thermal insulation, thermal inertia, solar reflective materials) or natural ventilation strategies (cross-ventilation, night or early morning ventilation).

The design process is based on passive bioclimatic strategies for warm climates with the aim of minimizing demand and energy consumption. Some accredited tools and previous research on bioclimatic design for warm climates [46 47] have been used in order to make specific decisions. The adopted constructive solutions within the case study are based on the vernacular passive strategies for warm climates [48] adapted to the specific climatic conditions of the building location. These have subsequently been tested and anlysed using the official building energy evaluation tools, mandatory for the accreditation of the building energy label in Spain [49].

Baruch Givoni psychrometric charts [50,51], were used to ascertain the main passive strategies that must be used in each moment of the year and time of day (Fig. 4). These are: solar gain in winter, solar shading in summer, the use of thermal inertia, night-time convection cooling in summer and selected cross ventilation.

3.2.1. Solar gains in winter and solar shading in summer: Opening dimensions and solar shading based on orientation.

The NE-SW orientation conditioned the location of useful areas of the dwelling and the corresponding design of the two façades. In this lattitude, a window-to-floor ratio of 10 % in each espace guarantee the achievement of minimum Daylight Factor. The excessive daylight illuminance provoking glare can be blocked by using curtains and blinds. This practice results in achieving a 12.41 % window-to-wall-ratio (WWR) for the NE façade and 34 % WWR for the SW façade, and there are no skylights (Fig. 5).

All openings have solar shading which were dimensionated acording to use and orientation, given that the SW orientation (rear facade) at that latitude, recieves high solar radiation, mainly in the afternoon which is favourable in winter for its solar gains (Fig. 6). There are no adjoining or facing volumes which can provide the building with shade.

From the sunlight study of the main (NE) and rear (SW) façades and the rooms, the overhangs dimensions are ascertained. For

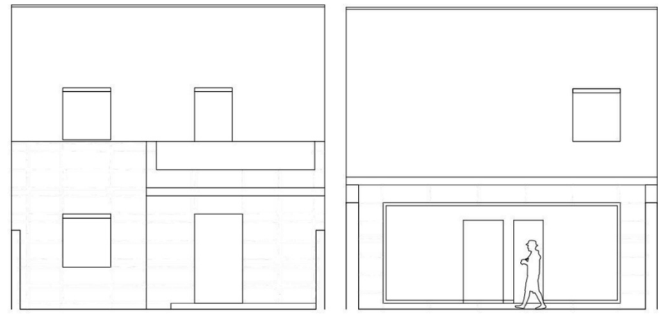


Fig. 5. Windows and openings: a) Main façade (NE), b) Rear façade (SW). Source: the authors.

example, the bedroom windows are almost square in proportion and have a 40 cm overhang to protect against the rain and avoid direct solar radiation from midday (local solar time) to half evening from mid-February to mid-November, for the SW facing window (Fig. 7), allowing the entrance of solar radiation during all the solar exposition hours from mid-November to mid-February. They are complemented by a rolling blind system for solar shading and daylight illuminance control which will be used when is needed, mostly from late spring to early autum at the hours not covered by the overhang.

In the large SW facing opening on the ground floor, the rolling blind system is substituted by an awning to avoid elements which prevent exterior vision and natural light gains. As the awning is a mobile textile element, solar shading can be adapted throughout the year (Fig. 8) acording to the need of entrance of solar radiation during winter and avoidance of it from late-spring to early-autum, and daylight illuminance needs.

3.2.2. Quality of the envelope

Passive strategies which take advantage of the local climate conditions for interior thermal conditioning are not effective if the thermal envelope does not preserve active and passive efforts to achieve interior comfort conditions. The key elements in this sense will be the amount of surface area which accumulate and transfers heat, controlled through compactness, the thermal inertia, the thermal transmittance and the airtightness of its elements, and the solar control of the enclosure.

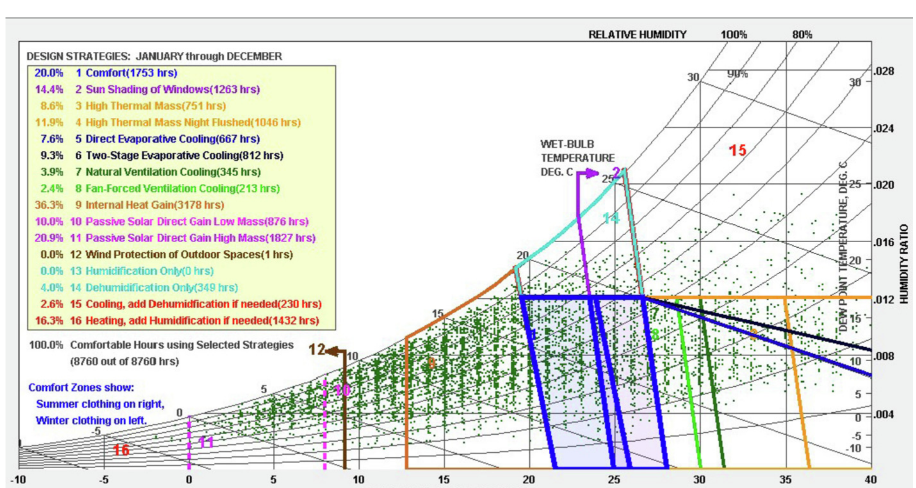


Fig. 4. Psychrometric chart with design strategies for the climate of Seville. Source: the authors.

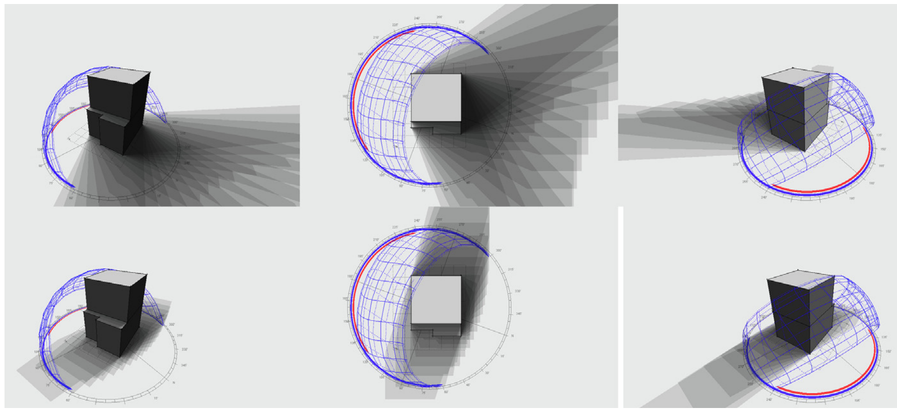


Fig. 6. Sunlight exposure from 9am to 5 pm at winter and summer solstice: main façade, top and rear façade perspectives. Source: the authors.

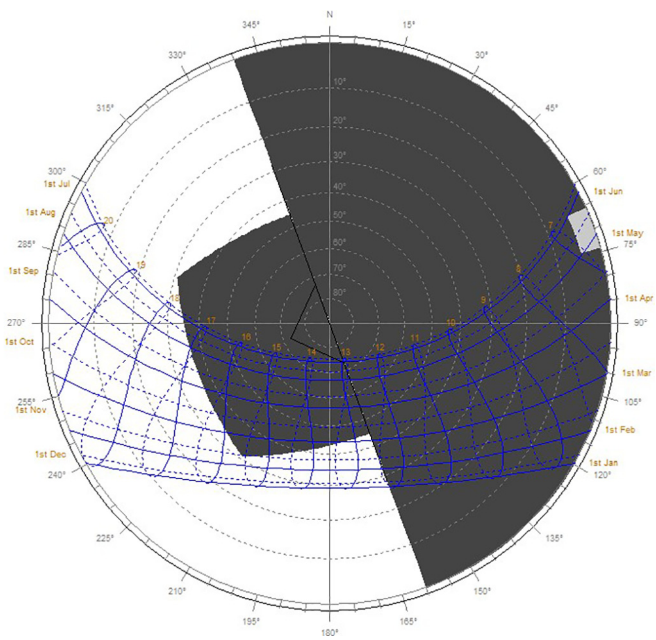


Fig. 7. Southwest window overhang design: shading mask. Source: the authors.

3.2.2.1. Building compactness. The mandatory document "DB-HE-1: Conditions for controlling energy demand" limits the global envelope U-value based on the building use and compactness (V/A), which is defined as the relationship between the volumen enclosed in the thermal envelope and the area of the thermal envelope. If the envelope of the building was the thermal envelope, the compactness defined in the Spanish standard would be the inverse of the Shape Factor of the building. In climates such as the Mediterranean with high solar radiation levels hot and dry during summers [52], building compactness is traditionally used [48] to avoid solar overexposure, and is therefore an adequate strategy for the Sevillian case [47].

To achieve the greatest compactness possible (Volume/∑Area envelope), the building is designed in cuboid form, with the exception of the front volume on the ground floor. The total surface area of the thermal envelope is 258 m^2, the enclosed volume 371.53 m^3 therefore a compactness of 1.44 m^3/m^2 is obtained.

3.2.2.2. Envelope construction system: thermal inertia and thermal transmitance. To use thermal inertia as a passive strategy, high density building solutions have been designed for the facades and adjoining walls based on traditional Southern Spain and Mediteranean climate ceramic construction methods. The building solutions for the opaque elements are not only designed to incorporate thermal inertia in the building but must also have a thermal transmittance lower than the limit value (section 3.1.1).

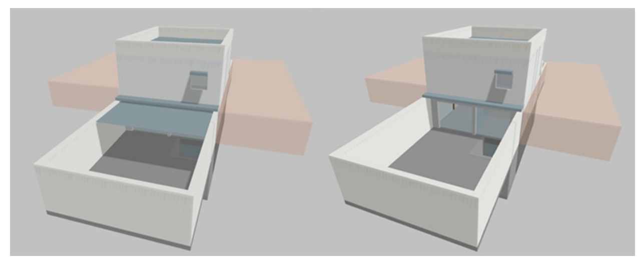


Fig. 8. Temporary solar shading system or awning on the Southwest façade: winter (right) and summer (left) position. Simulation of the thermal impact by means of CypeTherm software (Cype 2020). Source: the authors.

The following table (Table 7) shows the building composition of the solutions, indicating the thickness of layers and the properties of the materials necessary to obtain thermal transmittance, thermal mass, cushioning and divergence. The composition of the solutions gives a thermal transmittance of 0.29 W/m^2K for the façades and adjoining walls and 0.28 W/m^2K for the roof.

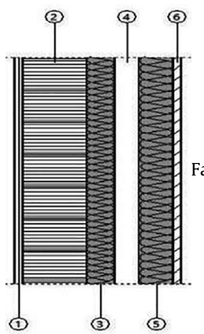
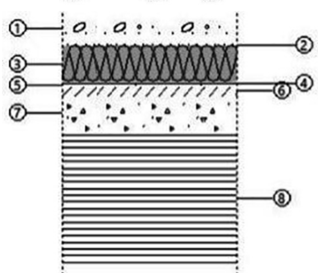
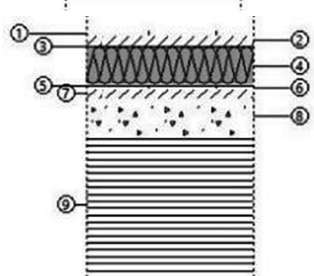
To reduce thermal bridges, junctions between building elements are studied so that insulation is continuous and there are no breaks (Fig. 9), which corresponds to the PH standard pencil rule.

For this project, the free tool THERM was used to study thermal bridges, particularly around openings, in the search for uninterrupted insulation as well as the correct reception of carpentry in line with UNE 85219:2016 [53] standard. The constructive resolution of thermal bridges of the structure (columns, beams and lintels) have been resolved by means of an external thermoacoustic insulation of lime mortar with 0.042 W / m.k and a thickness of 2.5 cm.

With regards to the thermal properties of the openings: orientation, surface and space served by each opening as well as exterior noise levels have been taken into consideration before choosing the quality of the glazing and frame. To minimise air and noise filtrations a casement window system was chosen over sliding panes for its greater airtightness.

The chosen frame is aluminium with thermal breakage, 1.3 W/m^2K thermal transmittance and class 4 air permeability (UNE-EN 12207:2017 [54]), which carries two types of glazing (G1 and G2) that respond to the thermal insulation, solar control and

Table 7
Characteristics of the building solutions of the envelope. Source: the authors

Constructive section	Layers	Thickness (cm)	Conductivity (W/mK)	Density (kg/m^3)	U W/m^{2}K	Thermal capacity (J/m^{2}K)
 Façade	1. Waterproof lime plaster	1.50	1.30	1900	0.29	19025.4
	2. Half foot of perforated brick	11.50	0.667	1140		
	3. Rock wool	5.00	0.0375	40		
	4. Non-ventilated air gap	4.50	0.45/λ	1		
	5. Rock wool	6.00	0.0375	40		
	6. Gypsum board panel	1.50	0.25	825		
 Non-trafficable roof	1. Gravel	7.00	2	1450	0.28	133802.9
	2. Geotextile cover	0.20	0.05	120		
	3. Extruded polystyrene (XPS)	8.00	0.04	37.5		
	4. Geotextile cover	0.20	0.05	120		
	5. Bituminous cover	0.50	0.23	1100		
	6. Cement mortar	2.00	1.3	1900		
	7. Lightweight concrete	8.00	1.35	1900		
	8. Concrete floor-slab with Expanded polystyrene (EPS) boxes	30.00	0.667	1470		
 Trafficable roof	1. Ceramic tiles	1.00	1	2000	0.28	59426.87
	2. Cement mortar	2.00	1.3	1900		
	3. Geotextile cover	0.20	0.05	120		
	4. Extruded polystyrene (XPS)	8.00	0.04	37.5		
	5. Geotextile cover	0.20	0.05	120		
	6. Bituminous cover	0.50	0.23	1100		
	7. Cement mortar	2.00	1.3	1900		
	8. Lightweight concrete	8.00	1.35	1900		
	9. Concrete floor-slab with Expanded polystyrene (EPS) boxes	30.00	0.667	1470		

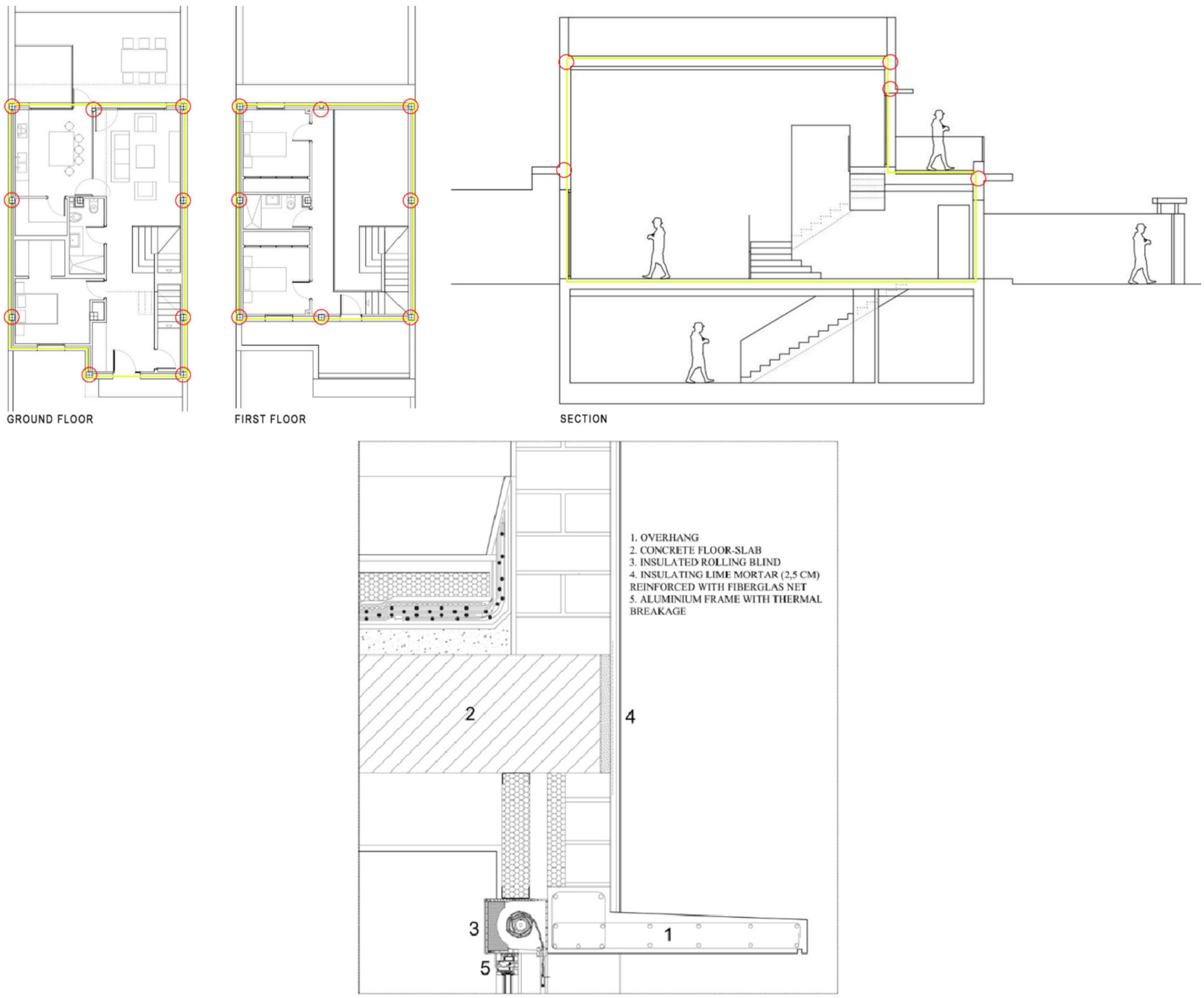


Fig. 9. a) Insulation continuity in the envelope to avoid thermal bridges. Circles represent the presence of thermal bridges. b) Constructive detail solving thermal bridges of structure and openings. Solar shading systems in openings (overhang and rolling blind). Source: the authors.

Table 8
Properties of the groups of glazing. Source: the authors

Group Orientation	Glazing	Gap	Composition Out/Gap/In	Ug (W/m^{2}K)	SHGC	Acoustic Attn (dB)
G1 NE	Laminated	100 % air	6*/16/6	1.3	0.424	30 (-1;-5)
G2 SO	Laminated	100 % air	4 + 4*/16/4 + 4	1.3	0.407	44 (-1;-7)

* Position of the low emissive layer

Table 9
Openings. Source: the authors

Facade	Gap	Frame %	Glass %	Solar shading	Distance overhang-lintel (m)	Overhang depth (m)	Setback (m)
NE	Bedroom	20	80	Roller blind + overhang	0.00	0.55	0.15
	Hall	20	80	Roller blind + overhang	0.50	1.10	–
	Bedroom	20	80	Roller blind + overhang	0.00	0.55	0.15
	Door	20	80	Roller blind + overhang	0.50	0.55	0.15
SW	Living room, Kitchen	20	80	Awning (Tent) + overhang	0.50	1.10	–
	Bedroom	20	80	Roller blind + overhang	0.00	0.55	0.15

acoustic insulation needs of the interior spaces and their orientation. G1 corresponds to the glazing of bedroom windows and other NE facing openings while G2 corresponds to the glazing in the SW facing living room and kitchen (Table 8).

The transmittance values, solar factor and permeability offered by these openings (Table 9) are superior to those strictly established by the code as they are considered determining elements in the correct energy behaviour and permeability of the building.

Table 10
Minimum Ventilation airflow (m^3/h). Source: the authors

Space	Admission	Space	Extraction
Main bedroom	32.4	Kitchen	39.6
Bedroom 1	18	Bathroom 1	39.6
Bedroom 2	18	Bathroom 2	39.6
Living room	50.4		
Total	118.8	Total	118.8

3.2.2.3. Other envelope improvements. As well as the previously mentioned elements, and with the aim of improving the vertical closings, a handcrafted lime mortar was chosen for the exterior finish due to its high level of reflection (85 %) and additional impermeability and transpirability properties to reduce condensation. Given its elastic properties, it adapts better, with less cracking, to dilatation caused by the strong sunlight typical of warm climates.

As well as its light-reflecting qualities, it is a porous material which absorbs and retains atmospheric CO_2, carbonising over time and strengthening walls by creating an impermeable screen against gases and exterior humidity. It is also fungicidal and bactericide [55].

Due to the differing heights with neighbouring proprerties, the same mortar was applied to adjoining walls, which are treated in the same way as façades.

3.2.3. Night flushing in summer and selective cross ventilation

The prescriptive minimum outdoor airflow of the CTE-DB-HS-3 document [34] is based on a limitation of CO_2 concentration within each space. These minimum values influence opening sizes, so achieving higher opening sizes ensures indoor air quality.

To comply with ventilation demands (section 3.1.2) a hybrid ventilation sytem is used. This system includes sensors which allow it to operate when natural conditions do not guarantee the prescriptive minimum airflow rate, so it takes advantage of the natural conditions when they are favourable and functions mechanically, with extractors in humid spaces, when necessary. One of the disadvantages of this system is the loss of energy from air extraction and the possible creation of bothersome air currents.

The dominant winds in Seville are, in their majority, southwesterly in summer and northeasterly in winter. To take advantage of these so that the system works naturally and to avoid overheating [56], the façade openings are placed facing each other to promote natural cross ventilation while the creation of a double height space (living room) and the placing of openings lead to a chimney effect. Window openings are manual and depend on the user. However, in Southern Spain there is a strong traditional energy habit of early morning window opening during winter and of night ventilation during summer, in order to promote cross-ventilation to combat the high temperatures reached on Sevillian summer nights.

In the building energy labelling tool the prescriptive outdoor airflow is an input in the form of ventilation air change (ach^{-1}). The standardised user profile for residential buildings considers manual window opening in order to provide summer night ventilation.

3.3. Energy evaluation of the case study and compliance with the regulations (CTE and energy certification)

3.3.1. Heating and cooling demand

To calculate the heating and cooling energy demand, the simplified procedure for new build energy certification CE3X v.2.3 [57] is used alongside the verification plug-in for the demands outlined in CTE-DB-HE-0 and CTE-DB-HE-1. The CE3x tool is an official software used in Spain to achieve the energy label of the building and to certify the requirements of the Energy Demand and Energy Consumption limitations of the Spanish Technical Building Code. The simplified procedure for residential buildings, compares the parametric data introduced with those compiled in a database of energy simulations using the official general procedure for residential building energy labelling in Spain (CALENER VyP) which uses the S3PAS calculation engine. The plugin follows the standard ISO 13,790 "Building energy efficiency. Heating and cooling energy consumption calculation procedure" for the estimation of the energy consumption of the building.

To determine the energy demand, it is necessary to include the value of interior air renewal due to airflow, as well as the geometric and building conditions. The minimum airflow is set out in CTE-DB-HS-3 [34] depending on the number of bedrooms in the dwelling. This project has three bedrooms and two bathrooms, so admission and extraction airflow after the balance of admission and extraction are as follows (Table 10):

Thus, considering a minimum airflow of 118.80 m^3/h and the dwelling's interior volume of 371.53 m^3, 0.32 h^{-1} interior air renewal is obtained.

On the other hand, CTE-DB-HE-1 [33] limits the overall coefficient of heat transmission through the building's thermal envelope (K_{lim}) and the solar control value. The value of K_{lim} obtained based on compactness V/A [m^3/m^2] is 0.36 W/m^2K and is therefore below the limit value of 0.58.

The solar control demand is achieved as a result of the solar shading employed on openings such as manual blinds, fixed concrete overhangs, carpentry overhangs and mobile textile elements or awnings.

This document states that windows must have Class 2 air permeability ($Q_{100,\ lim} \leq 27\ m^3/h\ m^2$) and the project has used Class 4 ($Q_{100,\ lim} \leq 3\ m^3/h\ m^2$) as well as studying the layers of materials of the building solutions to provide continuous insulation and airtightness of the thermal envelope.

With the data regarding geometrics, building conditions of the enclosure, ventilation and airtightness of the enclosure, a heating demand of 11.56 kWh/m^2 per year and a cooling demand of 12.57 kWh/m^2 per year are obtained.

3.3.2. Primary energy consumption and energy rating

Through the energy certification programme, total primary energy consumption, non-renewable primary energy consumption,

Table 11
HVAC and DHW systems. Characteristics. Source: the authors

HVAC EQUIPMENT	Rated Power	sEER	sCOP	Characteristics
Multizone Heat Pump: Ground Floor	10 kW	6.3	4.2	Aerothermal and renewable
Single zone Heat Pump: First Floor	2x3 kW	6.7	4.0	Aerothermal and renewable
DHW EQUIPMENT	**Rated Power**	**Medium Load**	**Efficiency**	
Electric Water Heater (100 l)	1.5 kW	0.2	86 %	
RENEWABLE ENERGY EQUIPMENT	**DHW Demand Covered**	**Generated Energy**		**Configuration**
Solar Thermal Panels + heat exchanger tank (200 l)	60 %			Thermosiphon
Photovoltaic Panels		974 kWh/year		

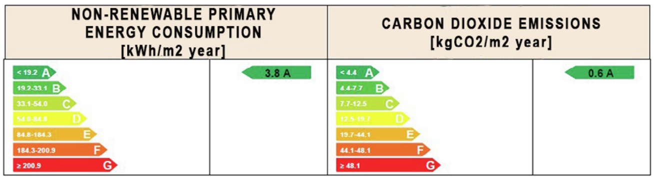


Fig. 10. Energy Rating Indicators. Left: Non-renewable primary energy consumption (kWh/m^2 per year)/Right: Carbon dioxide emissions (kgCO_2/m^2 per year). Source: the authors.

Table 12
Requirements and compliance. Source: the authors

	CTE 2019	PH warm 2007	Project
Total Primary Energy Consumption [kWh/m^2 year]	≤56	≤120	46.00
Non-Renewable Primary Energy Consumption [kWh/m^2year]	≤28	–	3.80
Renewable Energy Contribution DHW [%]	60	–	60
Heating Energy Demand [kWh/m^2]	–	≤15	11.56
Cooling Energy Demand [kWh/m^2]	–	≤15	12.57
Global envelope U-value [W/m^2K]	0.58	–	0.36
U-value walls [W/m^2K]	0.56	–	0.29
U-value roofs [W/m^2K]	0.44	–	0.28
U-value window [W/m^2K]	2.30	–	1.30
Q solar [kWh/m^2 month]	2.00	–	2.00
Airtightness [h^{-1}]	–	0.60	to be tested
Airtightness windows [m^3/h·m^2]	≤ 27	–	≤ 3
Outdoor Air rate [m^3/h]	118.80		118.80
Outdoor Air rate [m^3/h·pers]		≥30	29.70
Heat recovery unit	outflow rate > 0.50 m^3/s	Not strictly necessary	Not included

and CO_2 emissions associated with energy consumption of the thermal installations can be obtained.

To rate the project, it must first comply with the demands related to thermal installations and the contribution made by renewable energy sources as set out in documents CTE-DB-HE-2 (RITE [38]) and CTE-DB-HE-4 [33] respectively.

The dwelling's heating and cooling system is based on a direct expansion system with heat pump (Table 11). A multizone unit is installed to provide heating and cooling to the living room and ground floor bedroom and single zone units are installed in the first floor bedrooms.

In line with CTE-DB-HE-4, 60 % of the energy necessary to supply the demand for domestic hot water must come from renewable sources.

To cover the demand for 60 °C DHW (112 l/day, 22.19 kWh/m^2 per year) a solar energy system composed of solar panels and a 200 l heat exchanger tank is used. This is installed at a higher level to take advantage of the thermosyphon effect. The support boiler is a 100 l, 1.5 kW electric water heater with a 0.86 UEF performance.

As well as these regulation demands, a photovoltaic solar energy system has been included, although until now it has not been a requirement of the CTE. This allows electricity to be generated from a renewable energy source, reducing the building's CO_2 emissions, and covers 90 % of the heating and cooling consumption, according with the specific study provided by the engineering consultancy. This measure was included in response to the recent approval in Spain of the home consumption directive RD 244/2019, which has had great acceptance in a country such as Spain where the sun is an exceptional source of energy.

With the data from thermal installations and the contribution of renewable energy, the results obtained are total primary energy consumption (Cep,tot) of 46 kWh/m^2 per year, of which 3.8 kWh/m^2 per year is non-renewable primary energy consumption (Cep, nren). Both values are below their corresponding limit values of Cep,tot ≤ 56 kWh/m^2 per year and Cep,nren ≤ 28 kWh/m^2 per year and therefore meet regulation requirements.

At this point some aspects should be highlighted:

1. Final energy consumption is due mainly to the DHW system (10.32 kWh/m^2 per year).
2. DHW demand accounts for 47.9 % of the building's energy demand, compared to 24.9 % heating demand and 27.1 % cooling demand.
3. Renewable energy sources cover 60 % of the energy demand for DHW (thermal solar energy) and 90 % of electrical energy consumed by heat pumps (home consumption photovoltaic generation).

Finally, the energy rating of the building at project stage is Class A, as required by current regulation for new builds in Spain. Without the installation of photovoltaic panels, which are not mandatory, the renewable contribution to heating and cooling would rely solely on the aerothermal energy of the heat pumps (approximately 30 % contribution at each service), thus obtaining Class B grade.

It can therefore be observed that the building complies with current regulatory demands in Spain (Fig. 10).

3.4. Verifying Passive House standard criteria for warm climates

According to the Passivhaus Institute, to achieve certification, it is necessary to employ the 5 PH principles and comply with the limit values of energy demand and consumption.

As shown in the previous sections, passive strategies were incorporated into the dwelling design in order to also meet the regulation demands. As a result, opaque building solutions have been designed to reduce thermal transmittance and incorporate thermal mass, opening solutions and solar shading have been chosen and designed to provide airtightness, solar control and low thermal transmittance, and joins have been studied to give contiunuous thermal insulation and eliminate thermal bridges.

The incorporation at the project stage of warm climate passive design strategies which meet the regulations, leads us to believe that PH standard criteria can also be met:

1. Both the heating demand (11.56 kWh/m^2 per year) and the cooling demand (12.57 kWh/m^2 per year) are lower than the PH standard demand, in which the maximum limit is 15 kWh/m^2 per year for each demand.
2. Total primary energy consumption (46 kWh/m^2 per year) is considerably lower than the 120 KWh/m^2 per year limit set by PH, although this consumption does not include domestic appliances or lighting.
3. Airtightness of the envelope at 50 Pa pressure is not limited in living spaces of less than 120 m^2, with PH setting the value limit at 0.6.

From the airflow calculation, it is ascertained that the dwelling has an air renewal value of 0.32 h^{-1}. Considering that the dwelling will be occupied by 4 people, regulation airflow calculations allow for 29.7 m^3/h per person, while PH sets a minimum ratio of 30 m^3/h per person, so the airflow must be increased in order to meet the requirements of the standard.

There are some PH principles which have not been applied: envelope airtightness is not a code requirement, and due to the

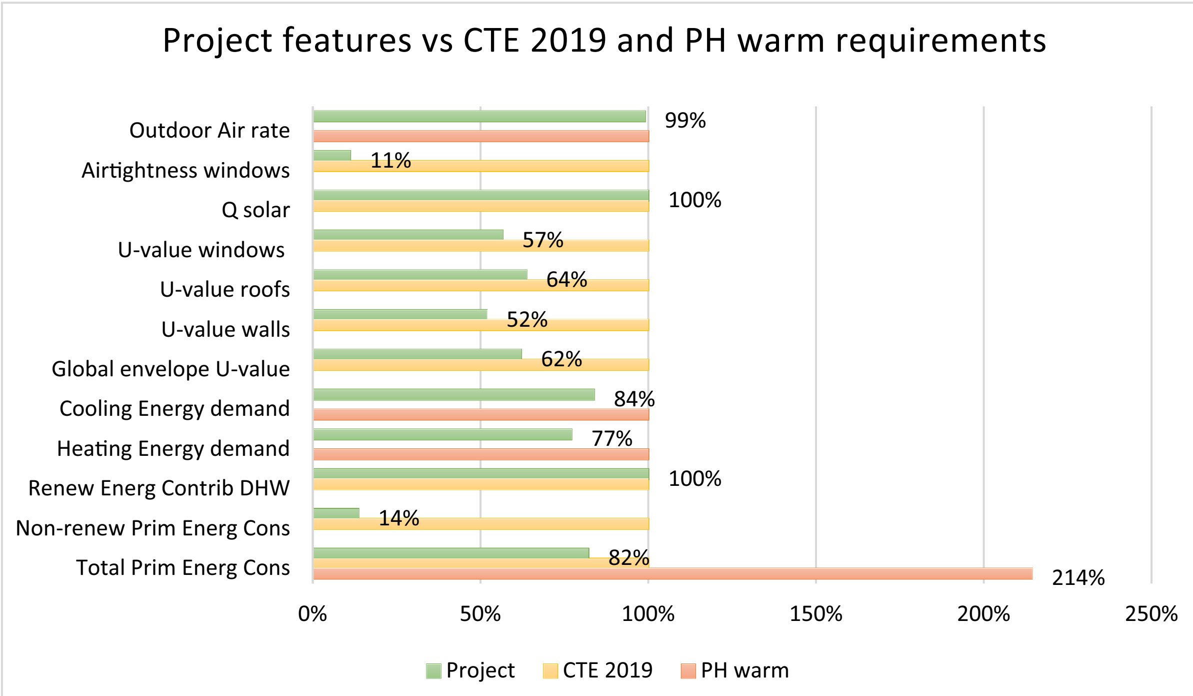


Fig. 11. Requirements of CTE 2019 and PH warm climate vs relative Project achievement. Source: the authors.

configuration of the ventilation system, a heat recovery unit has not been incorporated. This, however, is a requirement of the PH standard although not strictly necessary in the adaptation to warm climates.

While the airtightness of the envelope is checked when building work is completed, the incorporation of a heat recovery unit is not contemplated as the local climate conditions and the strategy to take advantage of dominant winds gives rise to an interior comfort with very low energy consumption both in air conditioning/heating and ventilation (Table 12) (Fig. 11).

Table 13
Extracosts. Differential investments. Source: the authors

	CTE 2019 (B4)	PH STANDARD (Warm climate)
CONSTRUCTION COSTS		**+ 58.00 €/m²**
Insulation and thermal bridges		+2,382.00€
Carpentry		+5,587.00€
HVAC and DHW EQUIMPENT	**7,150.00€**	**6,100.00€**
Heat pump, aerothermal and renewable	6,500.00€	
Electric water heater 100 l DHW	310.00€	
Hybrid ventilation system	340.00€	
Heat recovery system		6,100.00€
RENEWABLE ENERGY EQUIPMENT	**6,000.00€**	
Solar Thermal	1,000.00€	
Photovoltaic	5,000.00€	
ADDITIONAL CERTIFICATION		**3,465.00€**
Phase I: Architectural project energy consulting (PHPP)		1,125.00€
Phase II: Assistance to execution of works and Blower Door test		2,340.00€
EXTRA INVESTMENT*	**13,150.00€**	**17,194.20€**
TOTAL CONSTRUCTION COST	935.70€/m²	965.14€/m²

* Extra investment considers that implementing the heat recovery unit (full mechanic ventilation system) substitutes the hybrid ventilation system in the CTE project.

3.5. Comparative economic study

To comply with the regulatory demands of the CTE and obtain a Class A energy rating, the material cost of building this dwelling, without including the costs related to HVAC, DWH and renewable energy equipment, was 840€/m^2. Labour costs must be added to this sum, which we have considered similar in both cases, due to the rigorous study of the project with different tools such as THERM [58] to analyse thermal bridges in the CTE and the PHPP programme in the case of the PH which will lead to later control at the construction phase.

The construction solutions adopted in the project consider insulation thicknesses greater than those stricty required to accomplish the Spanish regulation - those recommended by CTE for climate B, giving transmittance values similar to those demanded by the PH for warm climates (U = 0.29 W/m^{2}K). The optimization of insulation and reduction of thermal bridges to also fulfil the PH requirements represents an investment of 2382.00€. However, the biggest difference in construction costs between both standards is due to the incorporation of certified components, such as the opening carpentry. In this case, the installation of pH certified windows for warm climates [18], is considered an extra cost as the triple glazing (Uw = 1.0 W/m^{2}K) and Class 4 airtighness are not a necessary requirement for Spanish Code. The higher quality of the carpentry increases its price, but also its certification as a PH component. The improvement of the carpentry represents an investment of 5587.00€, so the construction costs of the case study to accomplish both standards increases to 898.00 €/m^2, of which nearly 30 % is due to insulation and thermal briges and 70 % to PH carpentry.

Apart from the certified components, the main difference in economic cost is found in the economic investment in HVAC, DHW and renewable energy equipment. In the "code" dwelling, aerothermal energy has been chosen for heating and air conditioning, the hybrid ventilation system and the DHW boiler, resulting in an investment of 7150.00€ compared to the €6100.00 cost of the certified Heat Recovery Unit contemplated in the PH project to accomplish with one of its basic pillars, although this is not strictly necessary for warm climates.

The "code" case also incorporates sources of renewable energy in order to achieve a Class A energy certification: thermal solar energy for the obligatory renewable contribution to DHW; and photovoltaic solar energy which, although it is not currently obligatory, is a determining factor for achieving a Class A rating. The PH certification does not have any concrete requirements regarding renewable energy. The investment in Renewable energy equipment is 6000.00€.

On other hand, to achieve PH certification, a Certified Passive House Designer (external consultant) must study whether the project meets the PH criteria using the Passive House Planning Package (PHPP). This external consultant must also advise and assist execution of works to guarantee airtightness of the building (with the blower door test), insulation and optimisation of thermal bridges. In this case study, these actions pose an additional 3465.00€ in costs. In the case of the CTE code, meeting the requirements and supervising the works to guarantee the requirements specified in the project is part of the job of the project management team, according to Spanish law.

The result can be seen in Table 13, where it can be observed that the additional cost for obtaining the PH certificate for the dwelling would be 3 % and could even reach 4 % if the thermal solar panels are replaced with photovoltaic ones.

While this does not represent a large increase in budget, the developer in this case was not willing to assume the additional cost as they deemed it uneccesary to carry out an extra consultancy further to the project management team already hired for the project and execution of the works for a certification that offers few further benefits. On the other hand, the installation of renewable energy receives fiscal benefits from the local council, as well as a reduction in electricity tariffs due to home consumption. This can be important for the final cost of the investment.

Despite what some authors such as Clogough indicate, in reference to the cost of the PH standard being the minimum possible to reach nZEB, it is evident that the lower cost is not necessarily using the standard, as the conditions of the Spanish code already make a considerable advance comparable to the standard with an estimated 3 % lower cost.

From an energy and health perspective, the high demands of the current Spanish regulation standard mean that it is now necessary to bear higher building costs than before. With time, these will become more normalized and aligned with the PH certification.

As a result, users and developers will come to understand that these costs are not exceptional but regulatory and that they provide comfort and lower energy consumption. In their interest, they can also take advantage of the tax allowances set out in various local bylaws for those buildings which meet the sustainability requirements without the need for PH certification.

4. Discussion

The adaptation of the Passive House standard to warm climates establishes certain requirements for Heating and Cooling Energy Demand, Airtightness, Outdoor Air Rate, Heat Recovery of the Exhaust Ventilation Airflow and Primary Energy Demand. On the other hand, the last update of the Spanish Technical Building Code requires certain achievements for a new residential building to get the construction license. Some of these requirements are related to those requirements of the PH for warm climates.

Meanwhile some requirements of the Spanish Technical Building Code are mandatory and the result of their fulfillment are the requirements of the PH for warm climates, such as controlling the energy demand or limiting the energy consumption. Other requirements are not mandatory or their implementation is mandatory if the new building fulfills some features such as climatic zone, building use or useful area, the envelope's airtightness or the incorporation of a heat recovery unit.

When analysing and comparing the demands of the CTE with the requirements for PH standard certification for warm climates (Fig. 11,Table 4), it is observed that the primary energy consumption is limited to a fixed value in PH, while in the CTE it depends on the climate zone.

The adaptation of the Passive House for warm climates considers two climatic classifications for Spain: warm and warm-temperate (Fig. 3), while the Spanish Technical Building Code considers several climatic classifications, adjusting their requirements to the climatic zone of the new building. It stands out that the PH standard, when adapted to other climates, does not take microclimate zones into consideration [31], instead applying the same criteria to large geographical areas. This difference results in higher efforts of those buildings within the same Passive House climatic classification but with more relaxed requirements for the Spanish Technical Building Code [33] to fulfill the requirements of the PH adaptation, reinforcing one of the criticisms of the standard [18 31].

While the thermal issues are relatively similar, the big difference between both standards can be seen in the way that airflow is regulated or limited within the dwelling (airtightness of the envelope, outdoor airflow and heat extraction recovery). Both standards require airtightness to be verified with a Blower door test, but in the CTE it is only necessary for surface areas of over 120 m^2. In smaller areas it is limited by window permeability.

On the other hand, outdoor airflow is calculated in PH with an overall criteria for the whole dwelling, while in the CTE minimum outdoor airflows are specified for each room type and occupation. With regards to heat extraction recovery, althought it is one of the 5 basic Passive House pillars, it is only mandatory in the CTE if a certain level of airflow extraction is reached. Nevertheless the Passiv-On project showed that low demand for heating can be achieved using air extraction systems without using heat recovery [29].

Regarding the energy demand, the PH standard sets limit values for heating and cooling demand, which in the case of the CTE are regulated through limiting the thermal behaviour of the building elements and a global coefficient for the thermal envelope.

The incorporation of renewable energy to cover DHW demand is mandatory in the CTE, but it is not considered in the PH standard for warm climates. Nevertheless, the option to incorporate renewable energy helps to obtain a Class A energy rating. However, the standard has recently introduced new levels of pH certification based on the renewable energy contribution in its buildings. Furthermore, the recent approval of the home consumption electricity directive (RD 244/2019 [59]) may lead to these requirements being incorporated into the CTE, encouraging the use of photovoltaic panels as a renewable energy source in private residental properties which has not been the case up until now.

Finally, the PH consumption limit is for total primary energy and includes air conditioning and heating, DHW, domestic appliances and lighting consumption. The CTE consumption limit, while also being for total primary energy, additionally establishes a consumption limit for primary non-renewable energy and only includes heating, cooling and DHW consumption in residential buildings. This difference between the scope of the primary energy consumption in both systems makes their comparison difficult.

The achievement of the requirements of the Spanish Technical Building Code related to the energy demand and energy consumption, accredited by the energy rating of the building, requires a firm commitment to implementing: a) passive building strategies, with the compactness and high relevance of the design of thermal bridges and the solar shading being mandatory, b) energy efficient thermal systems, including ventilation, with a full mechanical ventilation for residential buildings not being mandatory, and c) renewable energy systems, mandatory for domestic hot water.

The passive strategies are aligned to the adaptation of the Passive House to warm climates and are implemented as priority [17,25,28]. In this context, one of the most important passive strategies in the climate of the case study is the cross-ventilation of the indoor spaces [24] and its adequate management throughout building openings [47,48].

The achievement of the Spanish Technical Building Code requires an investment in energy efficient HVAC and DHW equipment as well as in Renewable energy equipment that are not required in the PH standard for warm climates.However, the fulfillment of the PH standard requirements for warm climates results in an increase in the budget [18], due to the improvement of the thermal envelope and the thermal characteristics of the carpentry, the incorporation of a full mechanical ventilation system in order to implement a heat recovery unit, the architectural project energy consultancy and the assistance to execution works and Blower Door test to fulfill the Passive House requirements.

Although the PH standard recommends the use of certified components, whose specifications and parameters can be introduced directly into the PHPP for energy evaluation, offering a high level of certainty, their use can go against the objectives of nZEB for minimising energy consumption and even the very energy embedded in the construction materials.

The majority of window products certified by PH contain elements, such as spacers in the carpentry, made from high environmental impact insulating materials and plastics. They also use triple glazing, when a low emission double glazing would be sufficient for warm climates [17]. The presence of high environmental impact materials and the overuse of material have negative repercussions both on the energy within the products and the circularity of these products.

20 % of the economic increase in the budget to fulfill both standards is due to technical consulting and assistance carried out by accredited PH employees whose functions could be carried out by the building works technical direction. Furthermore, the Spanish Technical Building Code deems the improvement of the envelope, carpentry and the heat recovery system as unneccesary.

Having demonstrated that a Spanish nZEB accomplishes the energy demanda and primary energy consumption requirements of the PH for warm climates, nowadays the PH standard is not the only alternative for achieving nZEB in Spain, as seen previously.

5. Conclusions

While the PH certification is mandatory in some German cities because it ensures a certain level of energy efficiency, compliance with the latest update to the Spanish CTE, with an increase in demands, raises the question as to the role that the PH standard plays in Spain.

After comparing the specifications of the CTE and PH, it is observed that the health and energy-saving requirements of the mandatory Spanish regulations (CTE) are equal to, or even more restrictive than the PH standard. The biggest difference is found in the treatment of the building ventilation and airtightness.

Adaptation to the PH standard to warm climates contemplates natural ventilation as a fundamental passive strategy for introducing outdoor air into near-comfort conditions despite the fact that it is not permitted in its original plan, developed for the Central European context [17]. The adaptation considers that an excessively insulated building in a warm climate, can become overheated in summer, or even during intermediate seasons [61].

Nevertheless, the PH standard does not allow for ventilation of homes with manual opening of windows, but imposes a completely mechanical system, which goes against the housing traditions of the Mediterranean culture, in which the user opens the windows and uses solar shadings to make the most of the mild exterior climate during the majority of the year. Insulating the dwelling and trying to create an artificial interior climate is countercultural.

In the PH certification, as well as controlling and advising at the design stage of the building, controlling the execution of works is essential to ensure a very low energy demand. Nevertheless, this control, both in the definition of construction details to avoid thermal bridges and in the exhaustive control of the construction works, can be carried out by technicians using free validated tools such as the THERM program [58] and with tests during the works such as thermographic analysis, Blower door airtightness tests, or air quality measurements which guarantee the correct execution of the design. This procedure is enhanced if an exhaustive control of the indicators found on the energy certificate is carried out by the competent authorities to reflect the veracity of the values obtained.

In a warm climate such as Seville (Andalusia), utilisation of solar energy is a determining factor in energy behaviour as it reduces energy consumption considerably and brings it in line with the near Zero Energy Building requisite for 2020, which proposes the incorporation of renewable energy production systems.

The combination of thermal solar, photovoltaic solar and aerothermal energy obtains a Class A energy rating without a heat exchanger and reinforces the idea that these are not an adequate or obligatory resource for a warm climate [25]. Aerothermy is a suitable solution for warm climates due to the relatively reduced difference in outdoor air temperatures and the set temperature [17].

With regards to the financial evaluation, it is observed that the added cost of obtaining the PH certification for a single family home in Seville, in addition to compliance with the CTE, would suppose a 3 % increase or even 4 % if we choose photovoltaic over thermal solar panels. This difference stems from the need for an additional external consultancy and the incorporation of certified windows which may be the reason why there are so few certifications in the South of Spain.

Finally, after analysing the case study, we can conclude that the application of the PH standard does not result in a competitive advantage in terms of improvement in energy behaviour and building sustainability in a warm climate when compared to the application of passive design criteria based on compliance with current Spanish regulations. The PH standard certification is therefore unnecessary to guarantee higher energy efficiency in Spain.

Author contributions

The four authors developed the research and collaborated to produce this paper and all authors have read and agreed to the published version of the manuscript.

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