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Towards nearly zero-energy buildings in Mediterranean countries: Fifteen years of implementing the Energy Performance of Buildings Directive in Spain (2006–2020)

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ABSTRACT

The regulations regarding energy savings in buildings in Spain have evolved in parallel with the Energy Performance of Buildings Directive (EPBD). In addition to the requirements that must be met by both new and renovated buildings, the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) compiles the requirements necessary to achieve nearly zero-energy buildings (NZEBs). The objective of this work is to analyse the evolution of the CTE-DB-HE in detail for both the residential and non-residential sectors, highlighting the major novel aspects and changes introduced during the last 15 years. To illustrate these changes, several case studies are examined to verify the implications of applying the CTE-DB-HE to the building sector. This work then explores the direction of this sector in the near future, given that NZEBs are already a reality in Spain, and it discusses how progress is being made towards achieving the 2030–2050 objectives for the European building stock. The most recent CTE-DB-HE presents both challenges and opportunities to carry out ambitious energy renovation in the Spanish building sector.

1. Introduction

The building sector of the European Union (EU) is responsible for 40% of the EU's total energy consumption [1] and 36% of its total CO_2 emissions [2]. In addition to being the largest energy-consuming sector in Europe, approximately 35% of these buildings are over 50 years old, almost 75% of the building stock is energy inefficient, and only approximately 1% of the building stock is renovated annually [3]. Therefore, the EU established a legislative framework composed of the Energy Performance of Buildings Directive (EPBD) 2010 [1], which consolidated the EPBD 2002 [4], and the Energy Efficiency Directive 2012 [5]. In addition, the EU established that all new buildings must be nearly zero-energy buildings (NZEBs) from 31 December 2020 onward, and all new public buildings must be NZEBs from 31 December 2018 onward [1]. The current EPBD 2018 [2] amends the EPBD 2010 [1] and the Energy Efficiency Directive 2012 [5], and as one of its main new features, it implements a long-term strategy geared towards a highly energy-efficient and decarbonised building stock by 2050.

Mediterranean countries should take advantage of the challenges and opportunities presented by the EPBD, particularly in executing the regulations regarding NZEBs and addressing the energy renovation of their existing building stock [6]. It is necessary to progressively coordinate the different national laws enacted to implement the EPBD to ensure that the energy demands of buildings located in similar climate zones but in different countries are the same [7]. This issue is addressed by the Concerted Action EPBD [8], which addresses the EPBD and contributes to reducing energy use in European buildings through the exchange of knowledge and best practices in the field of energy efficiency and energy savings among all EU Member States, plus Norway. The Concerted Action EPBD [8] enhances the sharing of information and experiences from the national adoption and implementation of this important European legislation.

The impact of EPBD implementation on Portuguese, Spanish, Italian, Greek and Cypriot legislation was studied in Refs. [9–14], respectively. Other studies have investigated the incorporation of the EPBD into the national legislation of non-member countries, such as Turkey [15], Serbia [16] and Chile [17].

Studies on the design of NZEBs using optimal cost methods have been performed across Europe [18] and the Mediterranean [19], as well as in Portugal [20], France [21], Italy [22,23], Croatia [24] and Greece [25]. Additionally, studies that applied optimal cost methods in energy renovation to achieve NZEBs have been conducted in Portugal [26],

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Spain [27–29], France [30,31] and Italy [32–36].

The average final energy consumption (FEC) for the normalised climate of the building sector in Mediterranean countries and the EU28 [37], broken down into residential and non-residential sectors, is shown in Fig. 1. During the 2011–2014 period, the average FEC of the EU28 residential sector was 179.59 kWh/m^2·year, with 67.17% corresponding to space heating; that for EU28 Mediterranean countries was 143.01 kWh/m^2·year, with 50.55% corresponding to space heating. For the 2011–2013 period, the average FEC of the EU28 non-residential sector was 250.82 kWh/m^2·year, with 48.85% corresponding to space heating, while that of the non-residential sector of the EU28 Mediterranean countries was 347.90 kWh/m^2·year, with 34.85% corresponding to space heating.

The FEC of the Spanish residential sector during the 1991–2013 period was analysed and studied in Ref. [38], and its evolution in the building sector between 2000 and 2018 [39] is shown in Fig. 2. The FEC in the Spanish building sector increased by 36.89% from 18.74 Mtoe in 2000 to 25.65 Mtoe in 2018. In 2018, electric energy, natural gas, petroleum products, renewable energy, and coal and non-renewable urban solid waste accounted for 50.20%, 21.75%, 16.04%, 11.73%, and 0.28% of FEC, respectively [40,41]. In 2018, the residential and non-residential sectors accounted for 17.14% and 12.43% of total FEC, respectively [39], and commercial and office buildings were responsible for 71.36% of non-residential sector FEC [41].

In Spain, initially, the EPBD 2002 [4] was transposed into national legislation through the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) 2009 [42–44]. Subsequently, the EPBD 2010 [1] was transposed through the CTE-DB-HE 2013 [45–47] in the first phase and through the new CTE-DB-HE 2019 [48] in the second phase. The new CTE-DB-HE 2019 [48] includes the following six basic requirements: (a) a limitation on energy consumption (CTE-DB-HE0 2019); (b) conditions for controlling energy demand (CTE-DB-HE1 2019); (c) the performance of thermal installations (CTE-DB-HE2 2019), developed in the Regulations for Thermal Installations in Buildings [49]; (d) conditions for lighting installations (CTE-DB-HE3 2019); (e) the minimum renewable energy contribution to meet domestic hot water (DHW) demand (CTE-DB-HE4 2019); and (f) the minimum generation of electrical energy (CTE-DB-HE5 2019). Since 2017, buildings that meet the new building requirements of the current CTE-DB-HE have been

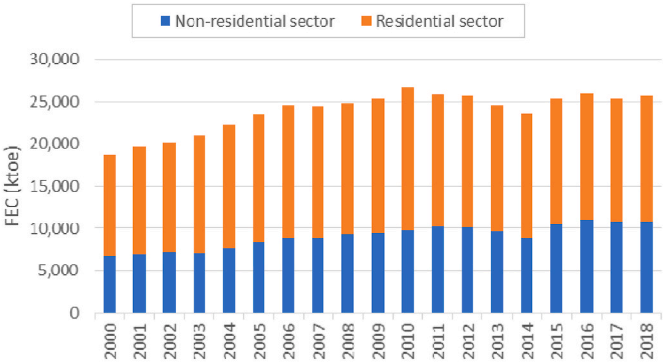

Fig. 2. Evolution of FEC in the Spanish building sector from 2000 to 2018 (in ktoe) [39].

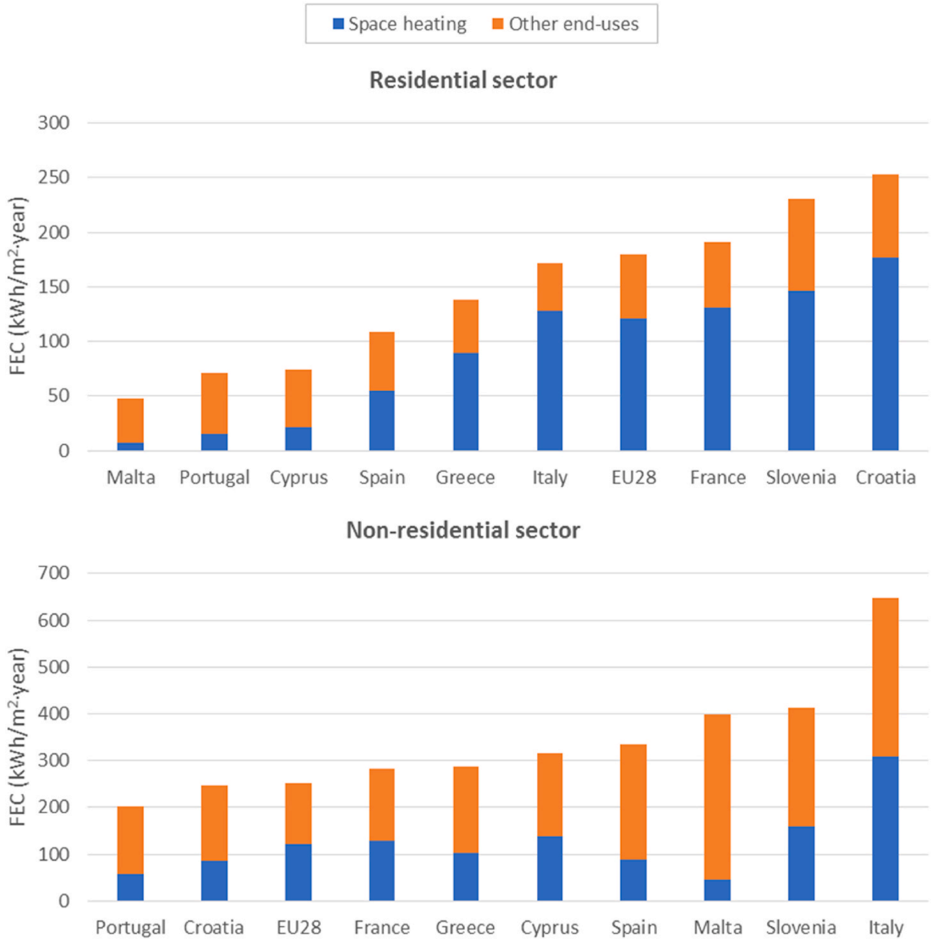

Fig. 1. Average FEC for the normalised climate in the EU28 Mediterranean countries and the EU28 (in kWh/m^2·year) for the residential and non-residential sectors [37].

defined as NZEBs [47,48]. Therefore, first-generation NZEBs are nearly zero energy according to the CTE-DB-HE 2013 [45–47], and second-generation NZEBs are nearly zero energy according to the CTE-DB-HE 2019 [48].

The evolution of the building regulations in Spain from regulations prior to the CTE-DB-HE [50], through the CTE-DB-HE 2009 [42–44], and to the CTE-DB-HE 2013 [45–47], as well as the different proposals for achieving NZEBs, was studied for residential buildings in Refs. [51, 52] and for non-residential buildings in Ref. [53]. For residential buildings [51,52], were updated by Ref. [10], which analysed the evolution from the Basic Building Norm on Thermal Conditions in Buildings [54] to the CTE-DB-HE 2018 project [55], which was the antecedent of the new CTE-DB-HE 2019 [48].

The objective of this work is to explore in depth the evolution of the CTE-DB-HE in the building sector in Spain over the last 15 years, highlighting the new features and differences in the new CTE-DB-HE 2019 [48], both for the residential sector and for the non-residential sector. To that end, this research is conducted as follows: (a) the requirements outlined in the CTE-DB-HE and any modifications over the past 15 years are studied; (b) the implications of these changes are scrutinised through case studies focusing on both the residential and non-residential sectors; and (c) the main indicators for evaluating the energy saving requirements for the building sector and the implications for the future are presented.

2. Methodology

2.1. Climate zones and solar climate zones

According to the CTE-DB-HE 2019 [48], in Spain, there are 15 climate zones based on winter climate severity and summer climate severity: α3, A2, A3, A4, B2, B3, B4, C1, C2, C3, C4, D1, D2, D3 and E1 (Fig. 3). The letter indicates the level of winter climate severity, with winter climate zone α representing the lowest heating energy demand and winter climate zone E representing the highest heating energy demand. The number indicates the level of summer climate severity, with summer climate zone 1 representing the lowest cooling energy demand and summer climate zone 4 representing the highest cooling energy demand. The climate zone assignment method used is identical to that in the CTE-DB-HE 2013 [45–47], but notably, it varies from the method employed by the CTE-DB-HE 2009 [42–44], as reflected in Refs. [10,56, 57]. According to the CTE-DB-HE 2009 [42–44], the level of winter climate severity is obtained from the winter degree-days with a base temperature of 20 °C and the global radiation accumulated or from the winter degree-days with a base temperature of 20 °C and the ratio between the number of sunlight hours and the maximum number of sunlight hours, with both methods using the corresponding values for the months of December to February. The level of summer climate severity is obtained from the summer degree-days with a base temperature of 20 °C and the global radiation accumulated or from the summer degree-days with a base temperature of 20 °C and the ratio between the number of sunlight hours and the maximum number of sunlight hours, with both methods using the corresponding values for the months of June to September. In contrast, according to the Descriptive Document on Reference Climates [58], for the CTE-DB-HE 2013 [45–47] and CTE-DB-HE 2019 [48], the level of winter climate severity is obtained from the winter degree-days with a base temperature of 20 °C and the ratio between the number of sunlight hours and the maximum number of sunlight hours, using the corresponding values for the months of October to May. The level of summer climate severity is obtained from the summer degree-days with a base temperature of 20 °C, using the corresponding values for the months of June to September.

The solar climate zones were defined as a function of the mean annual global solar irradiance on a horizontal surface. There are five solar climate zones: I, II, III, IV and V. Solar climate zone I receives the least solar radiation, while solar climate zone V receives the most solar radiation (Fig. 3) [42–47].

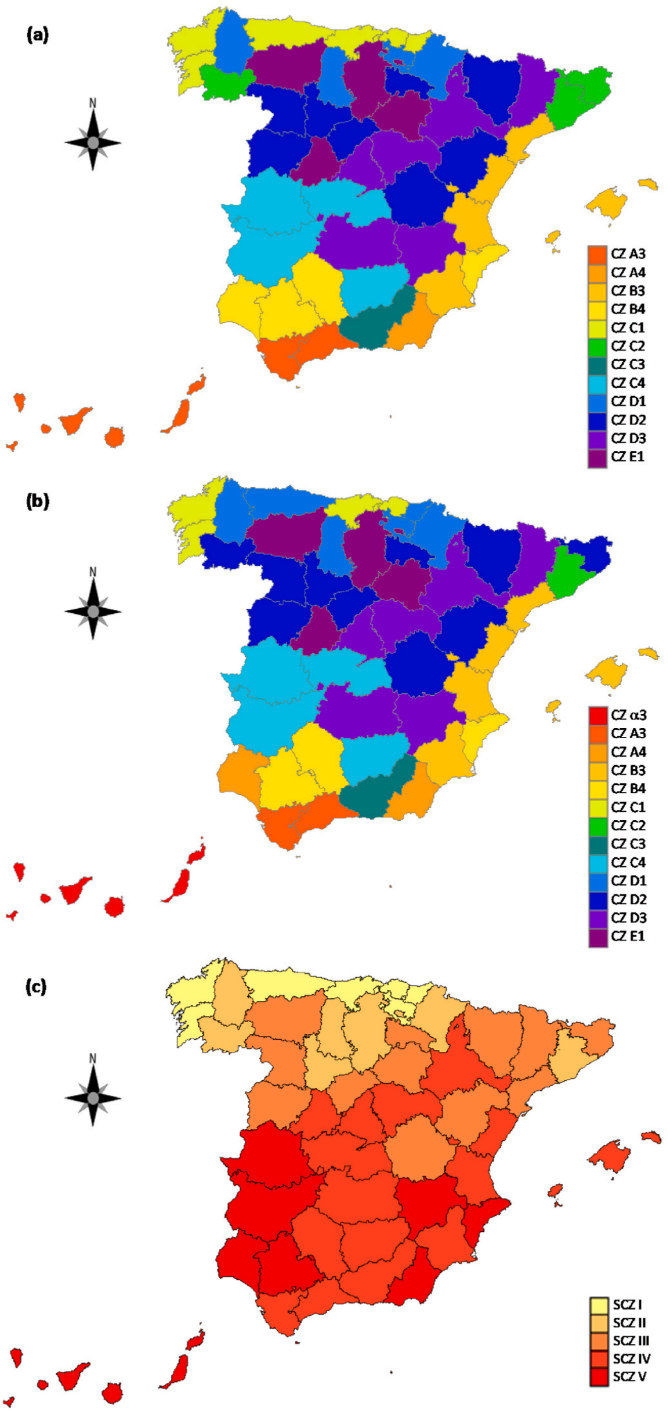

Fig. 3. Evolution of the climate zoning of all Spanish provincial capitals and autonomous cities: (a) climate zones (CZs) according to the CTE-DB-HE 2009 [42–44]; (b) climate zones (CZs) according to the CTE-DB-HE 2013 [45–47] and CTE-DB-HE 2019 [48]; and (c) solar climate zones (SCZs) according to the CTE-DB-HE 2009 [42–44] and CTE-DB-HE 2013 [45–47].

2.2. Contribution of renewable energy sources

The CTE-DB-HE4 [42–48] has always had a minimum renewable energy contribution to meet part of the annual DHW energy demand and for the heating of indoor swimming pools in both residential and non-residential buildings, both new and renovated. Both the CTE-DB-HE4 2009 [42–44] and CTE-DB-HE4 2013 [45–47] prioritised achieving this minimum renewable energy contribution through thermal solar systems, although they allowed the partial or total replacement of these thermal solar systems with alternative renewable energy installations, cogeneration processes or waste energy sources from the installation of heat recovery systems unrelated to the thermal installation of the building, carried out either in the building itself or through a connection to an urban air conditioning network.

Fig. 4 shows the required minimum renewable energy contribution to meet part of the annual DHW energy demand established by the CTE-DB-HE4 2009 [42–44], CTE-DB-HE4 2013 [45–47] and CTE-DB-HE4 2019 [48], depending on the DHW demand and the solar climate zone. In addition, the CTE-DB-HE4 2009 [42–44] makes distinctions based on whether the contributing energy source is (a) diesel, propane, natural gas or other or (b) electrical (Joule effect). In addition, Fig. 4 shows the required minimum renewable energy contribution to meet part of the annual energy demand for the heating of indoor swimming pools set by the CTE-DB-HE4 2009 [42–44], CTE-DB-HE4 2013 [45–47] and CTE-DB-HE4 2019 [48].

To comply with the CTE-DB-HE4 2009 [42–44], CTE-DB-HE4 2013 [45–47] and CTE-DB-HE4 2019 [48], the DHW demand in residential and non-residential buildings is calculated based on the DHW demand at a reference temperature of 60 °C, as indicated in Table A1, at an occupancy at least equal to the minimum established in Table A2 for residential buildings and, for multi-family housing, a centralisation factor, as indicated in Table A3.

For buildings that consume relatively large amounts of electricity, the CTE-DB-HE5 [42–48] has always required renewable resources to be incorporated into their electrical generation system for self-consumption or grid supply, focusing on non-residential buildings, both new and renovated, with both the CTE-DB-HE5 2009 [42–44] and CTE-DB-HE5 2013 [45–47] prioritising photovoltaic solar systems. Thus, the non-residential buildings listed in Table 1 must comply with

Fig. 4. Required minimum renewable energy contribution (in %) to meet part of the annual energy demand for DHW by DHW demand (in l/day) and for each solar climate zone and to meet part of the annual energy demand for the heating of indoor swimming pools by solar climate zone according to each CTE-DB-HE4 [42–48].

Table 1

Types of buildings, with their corresponding built surfaces, to which each CTE-DB-HE5 [42–48] was applied.

Building use type	CTE-DB-HE5 2009 [42–44]	CTE-DB-HE5 2013 [45–47]	CTE-DB-HE5 2019 [48]
Hypermarkets (NRB1)	5000 m^2	5000 m^2	3000 m^2
Shopping plazas and leisure centres (NRB2)	3000 m^2	5000 m^2	3000 m^2
Storage and distribution warehouses (NRB3)	10,000 m^2	5000 m^2	3000 m^2
Administrative (NRB4)	4000 m^2	–	3000 m^2
Hotels and hostels (NRB5)	100 beds	–	3000 m^2
Covered sports facilities	–	5000 m^2	3000 m^2
Hospitals, clinics, and isolated residences (NRB6)	100 beds (except isolated residences)	5000 m^2	3000 m^2
Convention centres (NRB7)	10,000 m^2	5000 m^2	3000 m^2
Other	–	–	3000 m^2

the CTE-DB-HE5 2009 [42–44], CTE-DB-HE5 2013 [45–47] and CTE-DB-HE5 2019 [48] when their built surface exceeds the value indicated in Table 1.

The minimum mandatory power is calculated by Eq. (1), Eq. (2) and Eq. (3) according to the CTE-DB-HE5 2009 [42–44], CTE-DB-HE5 2013 [45–47] and CTE-DB-HE5 2019, respectively [48]:

$$P_{min2009} = C \cdot (A \cdot S_{built} + B) \tag{1}$$

$$P_{min2013} = C \cdot (0.002 \cdot S_{built} \text{ - } 5) \tag{2}$$

$$P_{min2019} = 0.01 \cdot S_{builtw} \tag{3}$$

here $P_{min2009}$ is the minimum peak power (in kWp); $P_{min2013}$ is the minimum nominal power (in kW); $P_{min2019}$ is the minimum installed power (in kW); A and B are the coefficients defined in Table A4 as a function of the building use type; C is the coefficient defined in Table A5 as a function of the solar climate zone; and S_{built} is the built surface of the building (in m^2).

The CTE-DB-HE5 2009 [42–44] established that the minimum peak power to be installed should be 6.25 kWp and that the inverter should have a minimum power of 5 kW because it is mandatory that the inverter power be at least 80% of the real peak power of the photovoltaic generator. The CTE-DB-HE5 2013 [45–47] established that the minimum peak power of the generator should be at least equal to the nominal power of the inverter and that the mandatory maximum installed power in all cases be 100 kW. In addition, to estimate the production of the photovoltaic solar system, the production ratios by solar climate zone in Table A5 are considered. Finally, the CTE-DB-HE5 2019 [48] stipulated that the mandatory installed power must not be less than 30 kW or greater than 100 kW; the installed power limit, $P_{lim2019}$ (in kW), is calculated using Eq. (4):

$$P_{lim2019} = 0.05 \cdot S_{roofw} \tag{4}$$

here S_{roof} is the built surface of the roof of the building (in m^2).

2.3. Energy efficiency of lighting installations

The CTE-DB-HE3 [42–48] requires that non-residential buildings provide adequate lighting to meet the needs of their users and that they are energy-efficient, with a control system that makes it possible to adjust the lighting to the actual occupancy of the zone and a regulation system that optimises the use of natural light, in zones that meet certain conditions.

In each zone, the value for the energy efficiency of the installation (VEEI) must not exceed the corresponding limit value ($VEEI_{lim}$) established for each CTE-DB-HE3 [42–48], as shown in Table 2. The CTE-DB-HE3 2009 [42–44] distinguished between (a) non-representative zones or spaces in which the design criterion, the image or the mood to be transmitted to the user through lighting is secondary to other criteria such as the lighting level, visual comfort,

Table 2

VEEI limit by zone for each CTE-DB-HE3 [42–48].

Use of the space	CTE-DB-HE3 2009 [42–44]	CTE-DB-HE3 2013 [45–47] and CTE-DB-HE3 2019 [48]
Administrative in general	3.50 (group 1) 6.00 (group 2)	3.00
Transport station platforms	3.50 (group 1)	3.00
Convention and exhibition halls	3.50 (group 1)	3.00
Diagnostic rooms	3.50 (group 1)	3.50
Classrooms and laboratories	4.00 (group 1)	3.50
Hospital rooms	4.50 (group 1)	4.00
Interior spaces not described in the corresponding list	4.50 (group 1) 10.00 (group 2)	4.00
Common areas	4.50 (group 1) 10.00 (group 2)	4.00
Warehouses, archives, technical rooms and kitchens	5.00 (group 1)	4.00
Car parks	5.00 (group 1)	4.00
Sports spaces	5.00 (group 1)	4.00
Transport stations	6.00 (group 2)	5.00
Supermarkets, hypermarkets and department stores	6.00 (group 2)	5.00
Libraries, museums and art galleries	6.00 (group 2)	5.00
Common areas in residential buildings	7.50 (group 2)	–
Common areas in non-residential buildings	–	6.00
Shopping centres (excluding stores)	8.00 (group 2)	6.00
Hospitality and catering	10.00 (group 2)	8.00
Religious in general	10.00 (group 2)	8.00
Function rooms, auditoriums, multipurpose and convention rooms, entertainment and showrooms, meeting rooms and conference rooms	10.00 (group 2)	8.00
Stores and small businesses	10.00 (group 2)	8.00
Hotel rooms, hostels, etc.	12.00 (group 2)	10.00
Premises with lighting levels greater than 600 lux	–	2.50

Table 3
Maximum power to be installed per lighted surface (in W/m^2) according to use and E_m (in lux).

Use	E_m	Maximum power	
		CTE-DB-HE3 2013 [45–47]	CTE-DB-HE3 2019 [48]
Car park	–	5.00	5.00
Administrative	≤ 600	12.00	10.00
	> 600	25.00	25.00
Commercial	≤ 600	15.00	10.00
	> 600	25.00	25.00
Education	≤ 600	15.00	10.00
	> 600	25.00	25.00
Hospitality	≤ 600	15.00	10.00
	> 600	25.00	25.00
Restoration	≤ 600	18.00	10.00
	> 600	25.00	25.00
Auditoriums, theatres and cinemas	≤ 600	15.00	10.00
	> 600	25.00	25.00
Public residential	≤ 600	12.00	10.00
	> 600	25.00	25.00
Other	≤ 600	10.00	10.00
	> 600	25.00	25.00

Table 4
$NRPEC_{base}$, $CF_{NRPEC,surf}$, HED_{base} and $CF_{HED,surf}$ by winter climate zone [45–47].

	Winter climate zone					
	α	A	B	C	D	E
$NRPEC_{base}$ (kWh/m^2·year)	40	40[a]	45[a]	50[a]	60	70
$CF_{NRPEC,surf}$ (kWh/year)	1000	1000	1000	1500	3000	4000
HED_{base} (kWh/m^2·year)	15	15	15	20	27	40
$CF_{HED,surf}$ (kWh/year)	0	0	0	1000	2000	3000

[a] These values are multiplied by 1.20 for non-mainland territories (the Canary Islands, the Balearic Islands, Ceuta and Melilla).

safety and energy efficiency (group 1) and (b) representative zones or spaces where the design criterion, image or the mood that the user wants to achieve with lighting is emphasised over the energy efficiency criteria (group 2).

The energy efficiency of a lighting installation in a zone is determined by the VEEI (in W/m^2 per 100 lux) using Eq. (5):

$$VEEI = 100 \cdot P_{light} / (S_{light} \cdot E_m) \tag{5}$$

Where P_{light} is the lighting power used by the luminaires, including auxiliary equipment (in W), S_{light} is the lighted surface (in m^2), and E_m is the average maintained horizontal illuminance (in lux).

The total power of luminaires and auxiliary equipment per lighted surface must not exceed the maximum value established by the CTE-DB-HE3 2013 [45–47] and CTE-DB-HE 2019 [48], as outlined in Table 3; this requirement is not applicable to the CTE-DB-HE 2009 [42–44].

Finally, each CTE-DB-HE3 [42–48] requires the lighting installations in each zone to have a control and regulation system that includes a manual on-and-off system external to the electrical panel and a centralised lighting control system in each electrical panel. In zones of sporadic use, the centralised lighting switch in each electrical panel can be replaced by an on-and-off control through an automated sensor system or a timed push-button system. In addition, each CTE-DB-HE3 [42–48] requires the installation of natural light systems that automatically and proportionally regulate the contribution of natural light, the level of illumination of the luminaires located in the vicinity of windows and the level of illumination of windows located under skylights when a series of conditions is met.

2.4. Limitation on energy consumption and conditions for controlling energy demand

The non-renewable primary energy consumption (NRPEC) in new buildings, both residential and non-residential, was limited by the CTE-DB-HE0 2013 [45–47], depending on the climate zone of the location of the building and its intended use. Subsequently, the CTE-DB-HE0 2019 [48] strengthened the requirements of the CTE-DB-HE0 2013 [45–47] and expanded their scope, limiting both NRPEC and total primary energy consumption (TPEC) as a function of the climate zone of the location of the building and whether it was a residential or non-residential building and distinguishing between new and renovated residential buildings.

The CTE-DB-HE0 2013 [45–47] required the NRPEC for heating, cooling and DHW services of new residential buildings to not exceed a limit value, $NRPEC_{lim}$ (in kWh/m^2·year), according to its winter climate zone and its habitable surface, S_{hab}, (in m^2):

$$NRPEC_{lim} = NRPEC_{base} + CF_{NRPEC,surf} \big/ S_{hab} \tag{6}$$

where $NRPEC_{base}$ is the base value of NRPEC dependent on the winter climate zone corresponding to the location of the building (in kWh/

Table 5
Limit values of NRPEC and TPEC (both in kWh/m^2·year) for residential and non-residential buildings according to whether the buildings are new or renovated by winter climate zone (WCZ) [48].

		WCZ α	WCZ A	WCZ B	WCZ C	WCZ D	WCZ E
NRPEC limit	New residential building$^{(1)}$	20	25	28	32	38	43
	Renovated residential building$^{(1)}$	40	50	55	65	70	80
	New or renovated non-residential building$^{(2)}$	$70 + 8 \cdot C_{FI}$	$55 + 8 \cdot C_{FI}$	$50 + 8 \cdot C_{FI}$	$35 + 8 \cdot C_{FI}$	$20 + 8 \cdot C_{FI}$	$10 + 8 \cdot C_{FI}$
TPEC limit	New residential building$^{(3)}$	40	50	56	64	76	86
	Renovated residential building$^{(3)}$	55	75	80	90	105	115
	New or renovated non-residential building$^{(2)}$	$165 + 9 \cdot C_{FI}$	$155 + 9 \cdot C_{FI}$	$150 + 9 \cdot C_{FI}$	$140 + 9 \cdot C_{FI}$	$130 + 9 \cdot C_{FI}$	$120 + 9 \cdot C_{FI}$

C_{FI} is the average internal load (in W/m^2).
(1) These values are multiplied by 1.25 for non-mainland territories (the Canary Islands, the Balearic Islands, Ceuta and Melilla).
(2) These values are multiplied by 1.40 for non-mainland territories.
(3) These values are multiplied by 1.15 for non-mainland territories.

m^2·year) and $CF_{NRPEC,surf}$ is the surface correction factor of the NRPEC (in kWh/year), both defined in Table 4.

In contrast, CTE-DB-HE0 2013 [45–47] stipulates that the energy rating for the indicator of NRPEC for heating, cooling, DHW and lighting services of a new non-residential building should have an efficiency equal to or greater than that of class B, according to the basic procedure for the certification of the energy performance of buildings [59,60]. Hence, the percentage of savings of the NRPEC of the target building, with respect to its corresponding reference building, should be greater than 35% in new non-residential buildings [61]. The reference building is derived from the target building (same shape and size, same interior zoning, same use of each space of the building and same surrounding obstacles), replacing the different elements of its thermal envelope with others with the respective thermal transmittance limits and modified solar limit factors needed to comply with the CTE-DB-HE1 2009 [42–44], in the case of a new building, or the CTE-DB-HE1 2013 [45–47], in the case of a renovated building.

Currently, the CTE-DB-HE0 2019 [48] mandates a limitation on both the NRPEC and the TPEC of the spaces contained within the thermal envelope of the building, depending on whether it is considered residential or non-residential, according to the winter climate zone (Table 5). In addition, for residential buildings, the CTE-DB-HE0 2019 [48] differentiates between new and renovated buildings, while in the case of non-residential buildings, the average internal load of the building is the relevant factor. The internal load is the set of general stresses inside the building that are fundamentally due to the energy contributions of the internal sources corresponding to occupancy, lighting and equipment, where the average internal load is the average value during a typical week. The internal load levels are as follows: low when the average internal load is less than 6 W/m^2; medium when it is equal to or greater than 6 W/m^2 and less than 9 W/m^2; high when it is equal to or greater than 9 W/m^2 and less than 12 W/m^2; and very high when it is equal to or greater than 12 W/m^2. Both NRPEC and TPEC encompass the corresponding consumption associated with heating, cooling, DHW, ventilation, humidity control services and, in the case of non-residential buildings, lighting services.

The CTE-DB-HE1 2009 [42–44] limited both the heating energy demand and cooling energy demand of residential and non-residential buildings according to the climate zone of the buildings' location and the internal load of their spaces (low or high). The heating and cooling energy demands of the target building must be lower than those of the corresponding reference building. In addition, the CTE-DB-HE1 2009 [42–44] established a thermal transmittance limit and a maximum thermal transmittance value for each element of the thermal envelope and a limit to the air permeability of openings; it also stipulated that there should be no possibility of surface or interstitial condensation being produced in the thermal envelope of the building.

The CTE-DB-HE1 2013 [45–47] continued to restrict both the heating and cooling energy demands, increasing these requirements and clearly differentiating between new and renovated buildings. Renovated buildings, both residential and non-residential, should not exceed the energy demands of the corresponding reference building according to the climate zone of their location and their internal load; that is, they must comply with the CTE-DB-HE1 2009 [42–44]. However, the requirements of the CTE-DB-HE1 2013 [45–47] for new residential buildings and new non-residential buildings were different:

(a) In new residential buildings, the limit allowed for heating energy demand, HED_{lim} (in kWh/m^2·year), is based on their winter climate zone and habitable surface, and the limit allowed for cooling energy demand, CED_{lim} (in kWh/m^2·year), is based on their summer climate zone:

$$HED_{lim} = HED_{base} + CF_{HED,surf} \Big/ S_{hab} \tag{7}$$

$$CED_{lim} = \begin{cases} 15 & \text{if summer climate zone is } 1,\ 2 \text{ or } 3 \\ 20 & \text{if summer climate zone is } 4 \end{cases} \tag{8}$$

where HED_{base} is the base value of heating energy demand dependent on the winter climate zone corresponding to the location of the building (in kWh/m^2·year) and $CF_{HED,surf}$ is the surface correction factor of the heating energy demand (in kWh/year); both are defined in Table 4.

(b) Considering a ventilation rate of 0.8 air changes/hour during the occupancy period for both the target building and the reference building, new non-residential buildings should achieve the following energy savings over the corresponding reference buildings in terms of heating and cooling: at least 25% for buildings with low, medium and high internal source loads in summer climate zones 1 and 2 and for buildings with low internal source loads in summer climate zones 3 and 4; 20% for buildings with medium internal source loads in summer climate zones 3 and 4; 15% for buildings with high internal source loads in summer climate zones 3 and 4; 10% for buildings with very high internal source loads in summer climate zones 1 and 2; and 0% for buildings with very high internal source loads in summer climate zones 3 and 4. In addition, for both new and renovated residential and non-residential buildings, the CTE-DB-HE1 2013 [45–47] stated a maximum thermal transmittance for each element of the thermal envelope, thermal transmittance limits for the interior partitions and limits on the air permeability of openings. Furthermore, it stipulated that there should be no possibility of surface or interstitial condensation being produced in the thermal envelope of the building.

Instead of restricting energy demand like the CTE-DB-HE1 2009 [42–44] and CTE-DB-HE1 2013 [45–47], the CTE-DB-HE1 2019 [48] introduced requirements for controlling energy demand, acting on the thermal envelope of the building. These requirements are as follows:

(a) The thermal transmittance of the elements of the thermal envelope of the building should not exceed the limit values according to the winter climate zone where the building is located.
(b) The coefficient of global heat transfer through the thermal envelope of the building must not exceed a limit that is a function of the building use type (residential or non-residential, differentiating between new and renovated in the case of the former but not in the case of the latter), building compactness, and the winter climate zone of the building's location (Fig. 5).
(c) The solar control parameter should not exceed the limit value according to the building use type (whether it is new or renovated).
(d) The air permeability of the openings of the thermal envelope of the building should not exceed a limit set according to the winter climate zone where the building is located.
(e) The air change ratio with a differential pressure of 50 Pa for new residential buildings should not exceed a limit value as a function of building compactness (Fig. 6).
(f) The thermal transmittances of the interior partitions of the building should not exceed the limits set according to the units of use that they delimit and the winter climate zone where the building is located.

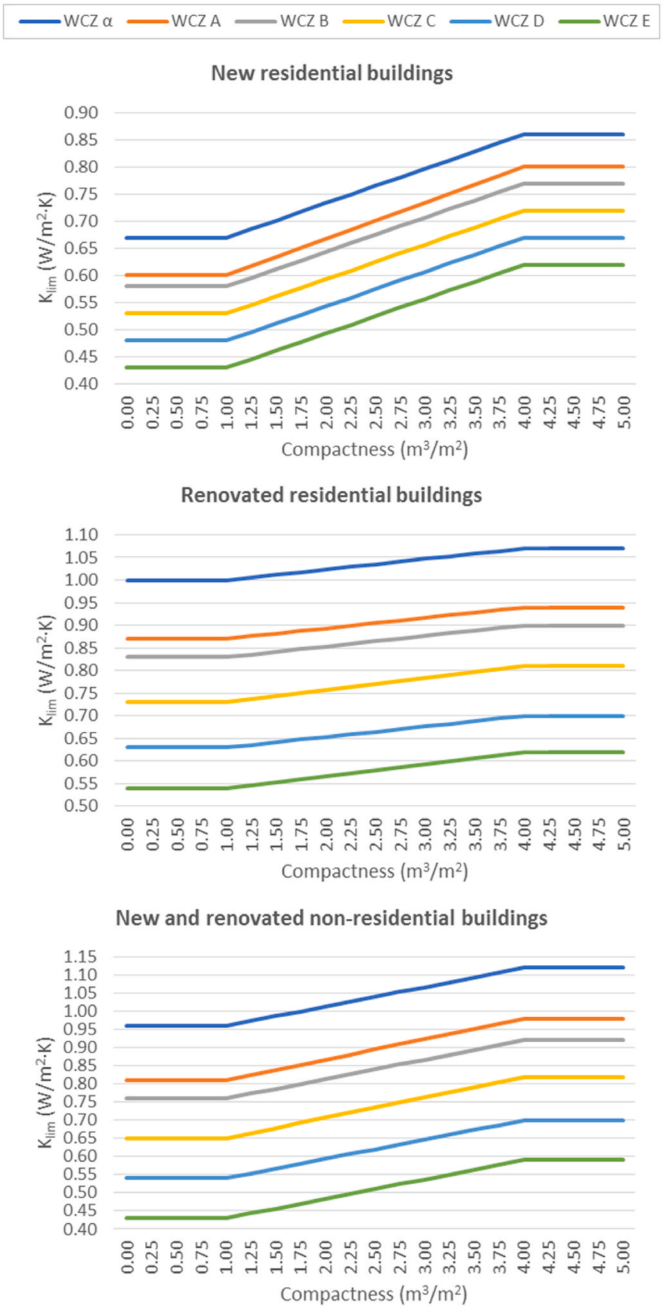

Fig. 5. Limit values for the coefficient of global heat transfer through the thermal envelope, K_{lim} (in $W/m^2 \cdot K$), as a function of building compactness (in m^3/m^2) by winter climate zone (WCZ) according to the CTE-DB-HE1 2019 [48] for residential and non-residential buildings.

(g) There should be no surface condensation or interstitial condensation.

The recommended thermal transmittances are collected for the different elements of the thermal envelope of the building according to the CTE-DB-HE1 2009 [42–44], CTE-DB-HE1 2013 [45–47] and CTE-DB-HE1 2019 [48] for residential and non-residential buildings, as shown in Table B1. For both residential and non-residential buildings, Table B2 shows the thermal transmittance limits allowed for interior partitions.

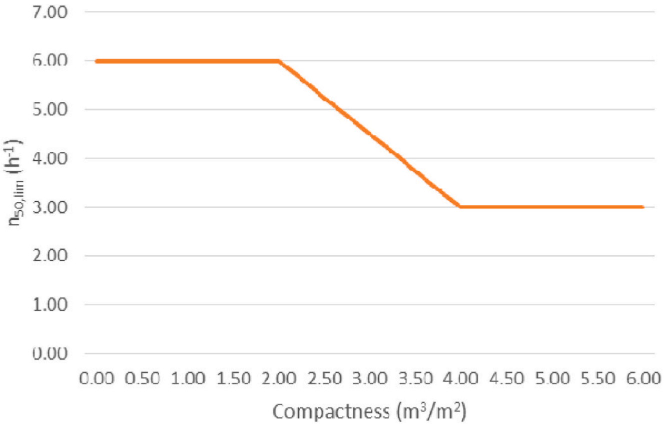

Fig. 6. Limit values for the air change ratio with a differential pressure of 50 Pa, $n_{50,lim}$ (in h^{-1}), as a function of building compactness (in m^3/m^2) according to the CTE-DB-HE1 2019 [48] for new residential buildings.

With the CTE-DB-HE1 2019 [48], the openings of the thermal envelope for winter climate zones α, A and B must be at least class 2, and the openings of the thermal envelope for winter climate zones C, D and E must be at least class 3. All these classes are defined according to UNE-EN 12207:2017 [62], where in class 1, the corresponding thermal envelope openings required by both the CTE-DB-HE1 2009 [42–44] and CTE-DB-HE1 2013 [45–47] are improved.

The solar control parameter should not exceed 2.00 kWh/m^2·month for residential buildings and 4.00 kWh/m^2·month for non-residential buildings.

Verification of compliance with the CTE-DB-HE0 2013 [45–47] should be performed with HULC 2017 [63], and verification of compliance with the CTE-DB-HE0 2019 [48] should be performed with HULC 2020 (software under testing) [64]. Both HULC 2017 [63] and HULC 2020 (software under testing) [64] use the conversion factors from final energy to non-renewable primary energy, total primary energy and CO_2 emissions from Ref. [65].

2.5. *Buildings and case studies*

2.5.1. *Buildings studied*

The residential building studied was used in Refs. [10,51,52]. It has a ground floor and five levels, with a total living area of 2216.57 m^2. There are four types of dwellings on each level: three types have three bedrooms, and one type has four bedrooms. The base is square and has an area of 484.00 m^2, and the height of each floor is 3.00 m. The main entrance and a car parking space are on the ground floor. The roof is hipped and has a height of 2.00 m. Fig. 7 presents a 3D view of the residential building studied.

The non-residential building studied is an educational building that was used in Ref. [53]. It has a ground floor and two levels, with a total surface area of 4595.60 m^2: 1363.90 m^2 on the ground floor and 1615.85 m^2 on the first and second floors. The height of each floor is 3.50 m, and the roof is flat. It has a capacity for 1000 students and a staff of 65 people, including teachers, administrators and others. Fig. 7 depicts a 3D view of the non-residential building studied.

2.5.2. *Contribution of renewable energy sources*

To illustrate the evolution of the contributions from renewable energy sources in buildings, each CTE-DB-HE4 [42–48] is applied, both in the residential building studied and in the non-residential building

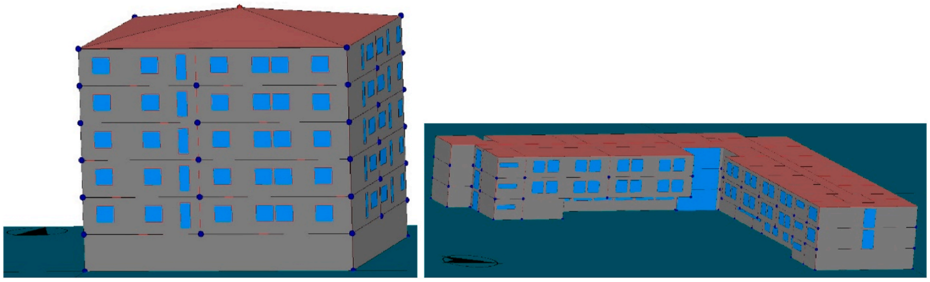

Fig. 7. 3D view of the residential building studied (left) and the non-residential building studied (right).

studied. Where mandatory, each CTE-DB-HE5 [42–48] is applied to different types of non-residential buildings. The buildings are located in cities that are representative of the five solar climate zones: Bilbao (solar climate zone I), Barcelona (solar climate zone II), Logroño (solar climate zone III), Madrid (solar climate zone IV) and Sevilla (solar climate zone V).

For each CTE-DB-HE4 [42–48], the FEC, NRPEC, TPEC and CO_2 emissions from providing DHW are evaluated for the following cases:

- Case TRE1: a natural gas boiler with a performance of 0.92.
- Case TRE2: a thermal solar system that meets the required minimum renewable energy contribution, supported by a natural gas boiler with a performance of 0.92.
- Case TRE3: a biomass boiler with a performance of 0.85.
- Case TRE4: an electrically driven heat pump with a seasonal coefficient of performance ($SCOP_{DHW}$) of 2.50.
- Case TRE5: an electrically driven heat pump with a $SCOP_{DHW}$ of 3.33.

According to Directive 2009/28/EC [66] and Decision 2013/114/EU [67], the energy generated by electrically driven heat pumps can be considered renewable energy when the $SCOP_{DHW}$ is equal to or greater than 2.50. When the $SCOP_{DHW}$ is 2.50, a renewable energy contribution to DHW of 60% is achieved, and when the $SCOP_{DHW}$ is 3.33, a renewable energy contribution to DHW of 70% is achieved.

Furthermore, both the minimum and maximum installed power of the required photovoltaic solar systems and their estimated electrical energy production for different types of non-residential buildings in different solar climate zones are evaluated for the following cases:

- Case PVS1: meets the requirements of the CTE-DB-HE5 2009 [42–44].
- Case PVS2: meets the requirements of the CTE-DB-HE5 2013 [45–47].
- Case PVS3: meets the requirements of the CTE-DB-HE5 2019 [48], considering a one-to-one ratio for the built surface of the building and the built surface of the roof.

Moreover, the possibilities for the CTE-DB-HE5 2019 [48] are specifically examined, evaluating the minimum, limit, and maximum installed power of electrical generation systems from required renewable sources, as well as their electrical energy production, considering different ratios between the built surface of the building and the built surface of the roof for the following cases:

- Case ERE1: a non-residential building with a daily use period of 8 h.
- Case ERE2: a non-residential building with a daily use period of 12 h.
- Case ERE3: a non-residential building with a daily use period of 16 h.
- Case ERE4: a non-residential building with a daily use period of 24 h.

2.5.3. *Energy efficiency of lighting installations*

To demonstrate the implications of the CTE-DB-HE3 [42–48], E_m is evaluated (in lux) with different VEEIs (in W/m^2 per 100 lux) and different total powers for the luminaires and auxiliary equipment per lighted surface (in W/m^2).

2.5.4. *Conditions for controlling energy demand*

To analyse the evolution of the CTE-DB-HE1 [42–48] in the residential building sector, all required parameters to control energy demand are assessed according to the CTE-DB-HE1 2019 [48] for the residential building studied in the following cases:

- Case RTE1: the use of the thermal transmittance limits of the CTE-DB-HE1 2009 [42–44] and the default thermal bridges established by HULC [63,64].
- Case RTE2: the use of the orientation thermal transmittances of the CTE-DB-HE1 2013 [45–47] and the default thermal bridges established by HULC [63,64].
- Case RTE3: the use of the orientation thermal transmittances of the CTE-DB-HE1 2019 [48] and the corresponding thermal bridges that allow isolation continuity in and between the components of the thermal envelope according to Supporting Document 3 [68] and HULC [63,64].
- Case RTE4: the use of the required thermal transmittances to meet the CTE-DB-HE1 2019 [48] and the corresponding thermal bridges that allow isolation continuity in and between the components of the thermal envelope according to Supporting Document 3 [68] and HULC [63,64].

For a similar analysis of the evolution of the CTE-DB-HE1 [42–48] in the non-residential building sector, all required parameters to control energy demand are evaluated according to the CTE-DB-HE1 2019 [48] for the non-residential building studied in the following cases:

- Case NRTE1: the use of the thermal transmittance limits of the CTE-DB-HE1 2009 [42–44] and the default thermal bridges established by HULC [63,64].
- Case NRTE2: the use of the CTE-DB-HE1 2009 thermal transmittances of the reference building [42–44], without exceeding the maximum thermal transmittances of the CTE-DB-HE1 2013 [45–47], and the default thermal bridges established by HULC [63,64].
- Case NRTE3: the use of thermal transmittances that reduce the global heat transfer coefficient by 25% with respect to that of the corresponding reference building (case NRTE1) to meet the CTE-DB-HE1

2013 [45–47] in cases with lower internal source loads and the default thermal bridges established by HULC [63,64].

- Case NRTE4: the use of the thermal transmittance limits of CTE-DB-HE1 2019 [48] and the corresponding thermal bridges that allow continued isolation in and between the components of the thermal envelope according to Supporting Document 3 [68] and HULC [63,64].
- Case NRTE5: the use of thermal transmittances to meet the CTE-DB-HE1 2019 [48] and the corresponding thermal bridges that allow continued isolation in and between the components of the thermal envelope according to Supporting Document 3 [68] and HULC [63,64].

2.5.5. *Limitation on energy consumption*

To verify the limits required by the CTE-DB-HE0 2019 [48], the TPEC limit and the NRPEC limit for the heating, cooling ventilation and humidity control services of the residential and non-residential buildings studied, including both new and renovated buildings, are determined for each of the winter climate zones for the following cases of DHW service:

- Case DHWS1: a thermal solar system that meets the required minimum renewable energy contribution according to the CTE-DB-HE4 2019 [48], supported by a natural gas boiler with a performance of 0.92.
- Case DHWS2: a biomass boiler with a performance of 0.85.
- Case DHWS3: an electrically driven heat pump with a $SCOP_{DHW}$ of 2.50.

For the DHW service, the minimum average annual temperature of cold tap water for each winter climate zone is considered according to HULC [63,64].

In addition, for the non-residential building studied, the following is considered:

- The average internal loads are 6 W/m^2 and 9 W/m^2, and the occupancy periods are 12 h and 16 h.
- The total power of the luminaires and auxiliary equipment per lighted surface is 5 W/m^2, and the number of annual hours is indicated for the occupancy period, according to CE3X [69], for the lighting service.
- The installation of a photovoltaic solar system with the minimum installed power according to the CTE-DB-HE5 2019 [48] is assumed, and the production ratio by solar climate zone is assumed to be the lowest ratio of the solar climate zone of each winter climate zone according to the CTE-DB-HE5 2013 [45–47].

2.6. *The future of the building sector in 2030 and 2050*

The CTE-DB-HE 2019 [48] primarily focused on heating, cooling and DHW services for the residential sector. Given that heating and DHW energy consumption account for approximately 60% of the total [40] and that cooling energy consumption represents approximately 1% of the total [40], it was decided to consider scenarios focused on heating and DHW. Hence, to evaluate the energy and environmental impact of implementing the CTE-DB-HE 2019 [48] in the Spanish residential sector during the 2020–2050 period, the following two scenarios were established:

(a) Scenario RBS1: New and renovated homes meet the requirements of the CTE-DB-HE 2019 [48] for new and renovated buildings, respectively.
(b) Scenario RBS2: Both new and renovated homes meet the requirements of the CTE-DB-HE 2019 [48] for new buildings.

In both scenarios, both renovated and new home heating energy needs are met with electrically driven heat pumps with a $SCOP_{heating}$ of 2.50, and DHW energy needs are met with electrically driven heat pumps with a $SCOP_{DHW}$ of 2.50.

The number of homes was estimated by province from 2020 to 2050 based on the number of homes by province for 2019 [70] in the 2020–2035 household projections by Autonomous Community [71] and considering that the variation in homes by Autonomous Community between 2035 and 2050 will be the same as that between 2020 and 2035. The estimated annual number of new homes (new construction with and without demolition) and renovated homes from 2020 to 2050 was obtained from Ref. [72] (Fig. 8). Furthermore, the number of homes by province was grouped by winter climate zone according to the CTE-DB-HE 2019 [48], given that all homes in each province are in the same winter climate zone as the capital of the province. Fig. 9 shows the evolution of the number of homes by winter climate zone in the

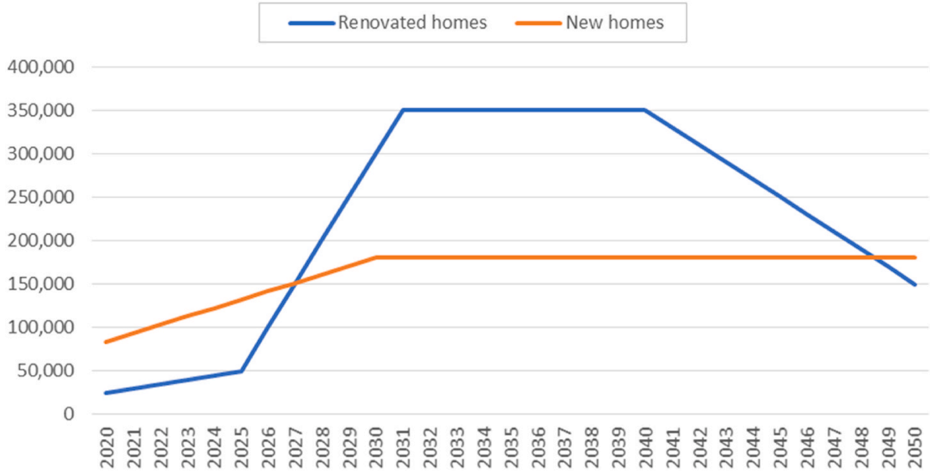

Fig. 8. Annual number of new and renovated homes from 2020 to 2050.

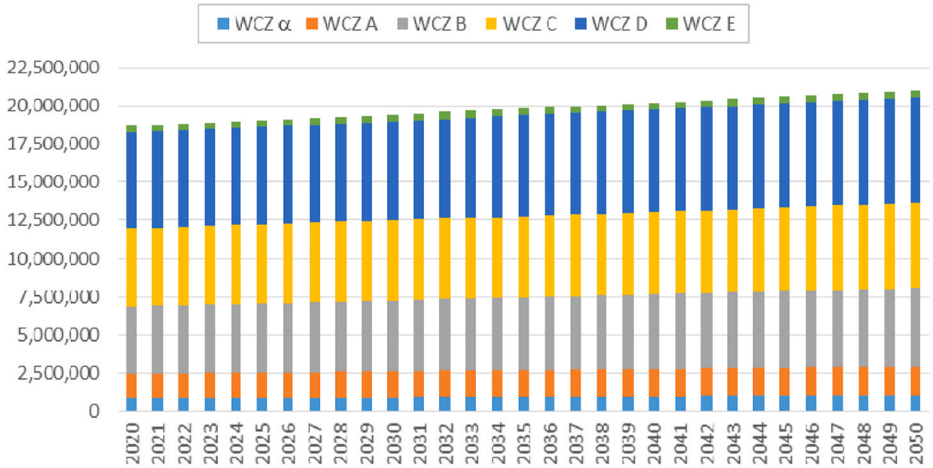

Fig. 9. Evolution of the number of homes by winter climate zone (WCZ) from 2020 to 2050.

Table 6

FEC of homes for heating and DHW by winter climate zone (WCZ) (in kWh/m^2·year).

Service	Homes	WCZ α	WCZ A	WZC B	WCZ C	WCZ D	WCZ E
Heating	Existing [40, 50]	0	18.32	26.74	46.41	57.28	97.34
	Renovated [10]	0	6.81	9.17	24.23	26.59	31.62
	New [10]	0	0.78	1.74	7.66	10.29	12.74
DHW	Existing [40]	17.93	17.93	17.93	17.93	17.93	17.93
	Renovated and new [10]	6.60	6.60	6.60	6.60	6.60	6.60

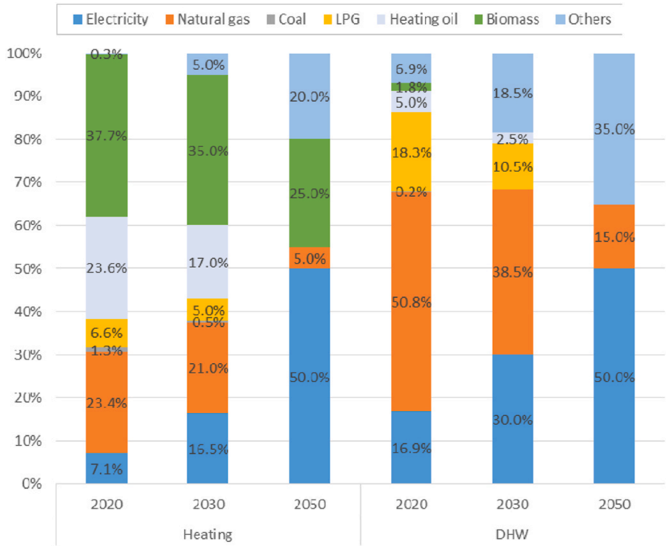

Fig. 10. FEC for heating and DHW by source in 2020, 2030 and 2050 (in %). Note: LPG is liquefied petroleum gas.

2020–2050 period. The average surface area of homes is 95.16 m^2 based on data obtained from Ref. [70].

The energy consumption of homes between 2010 and 2018 [40] was used to estimate the energy consumption of existing homes for heating and DHW in 2020. The heating energy consumption of existing homes by winter climate zone is related to the national average heating energy demand by winter climate zone found in Ref. [50]. The values for the heating energy demand of new and renovated homes for each winter climate zone are the corresponding heating limit values of [10] to comply with the CTE-DB-HE 2019 [48]. The FEC of existing, renovated and new homes for heating and DHW by winter climate zone is shown in Table 6.

Table 7

Conversion factors from final energy (FE) to non-renewable primary energy (NRPE), total primary energy (TPE) and CO_2 emissions for electricity, heating and DHW in 2020, 2030 and 2050.

Energy source	Year	NRPE conversion factor (kWh_{NRPE}/kWh_{FE})	TPE conversion factor (kWh_{TPE}/kWh_{FE})	CO_2 emissions conversion factor (kg CO_2/kWh_{FE})
Electricity	2020	2.007	2.403	0.357
	2030	0.699	1.756	0.095
	2050	0.000	1.444	0.000
Heating	2020	0.825	1.246	0.187
	2030	0.661	1.247	0.143
	2050	0.081	1.260	0.017
DHW	2020	1.227	1.385	0.252
	2030	0.823	1.328	0.160
	2050	0.179	1.251	0.038

To evaluate NRPEC, TPEC and CO_2 emissions, the conversion factors of [65] were used for all energy sources in 2020, 2030 and 2050, except for those corresponding to electricity, which were used only for 2020. These conversion factors for electricity in 2030 and 2050 were evaluated using the methodology of [65] and taking into account the objectives of electricity production by source of [73] (74% of total electricity generation from renewable energy in 2030 and 100% by 2050). Once all the conversion factors for all sources were obtained, it was possible to assess the conversion factors of the set of all homes for heating and DHW using the corresponding 2018 breakdowns of FEC by source from Ref. [40] for 2020 and those from Ref. [72] for 2030 and 2050 (Fig. 10). The conversion factors used are presented in Table 7.

The Institute for Energy Diversification and Saving [41] provides the FEC of the non-residential building sector by source but not by service. The energy performance certificates of non-residential buildings reveal that approximately 50% of energy consumption is dedicated to heating and DHW services; the other 50% is dedicated to cooling and lighting services [74]. Therefore, it can be assumed that all final thermal energy consumption is used for heating and DHW and that the amount of final electrical energy consumption dedicated to heating, cooling, DHW and lighting equals the final thermal energy consumption, with the remaining final electrical energy consumption going to all other electrical appliances. Moreover, with the application of the CTE-DB-HE 2019 [48] to the energy renovation of non-residential buildings, savings of at least 50% are achieved in the FEC associated with heating,

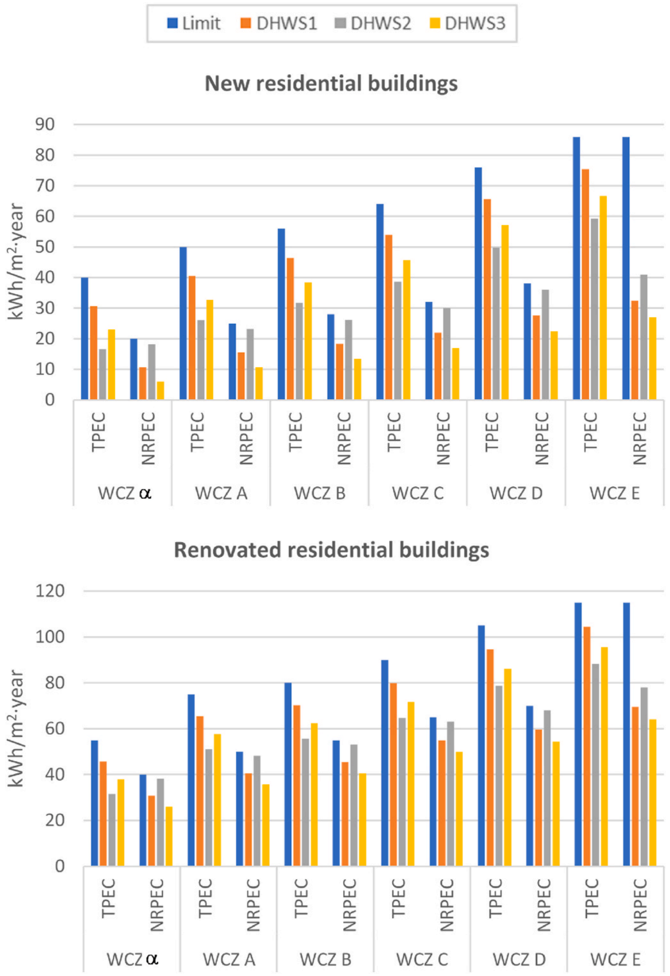

Fig. 11. Maximum possible TPEC and NRPEC for all services except DHW and the corresponding limit values (in kWh/m^2·year) of each of the case studies for residential buildings by winter climate zone (WCZ).

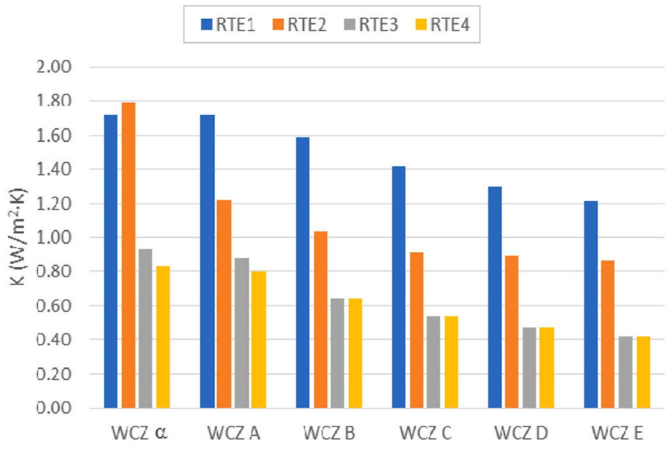

Fig. 12. Coefficient of global heat transfer through the thermal envelope, K (in W/m^2·K), for the case studies of residential buildings by winter climate zone (WCZ).

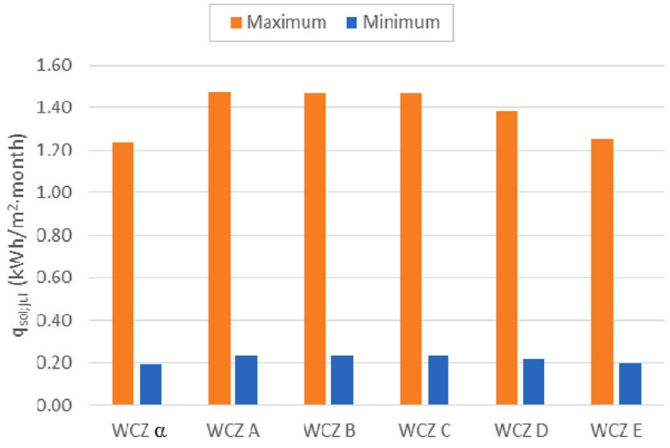

Fig. 13. Maximum and minimum solar control parameters, $q_{sol;jul}$ (in kWh/m^2·month), for the residential building studied by winter climate zone (WCZ).

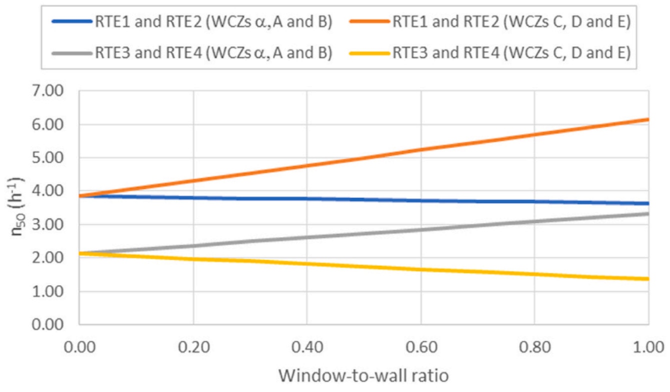

Fig. 14. Air change ratio with a differential pressure of 50 Pa, n_{50} (in h^{-1}), as a function of the window-to-wall ratio for the case studies of residential buildings by winter climate zone (WCZ).

cooling, DHW, and lighting. Scenario NRBS, in which, annually, a set of non-residential buildings responsible for 3% of total FEC undergoes energy renovation to comply with the CTE-DB-HE 2019, is established [48].

The FEC of non-residential buildings remained essentially constant from 2010 to 2018 [39]. Therefore, the FEC in 2020 is the same as that in 2018, as is the distribution between the final thermal and electrical energy consumption. Finally, to evaluate the NRPEC, TPEC and CO$_2$ emissions of the non-residential sector in 2020, 2030 and 2050, the 2018 breakdown of FEC by energy source from Ref. [41], the conversion factors for all energy sources (except electricity) from Ref. [65] and the conversion factors for electricity are all taken into account and listed in Table 7.

3. Results and discussion

3.1. Residential sector

The maximum possible TPEC and the maximum possible NRPEC for the heating, cooling, ventilation and humidity control services of the residential building studied are evaluated for each winter climate zone using the different systems proposed for the DHW service. Fig. 11 shows

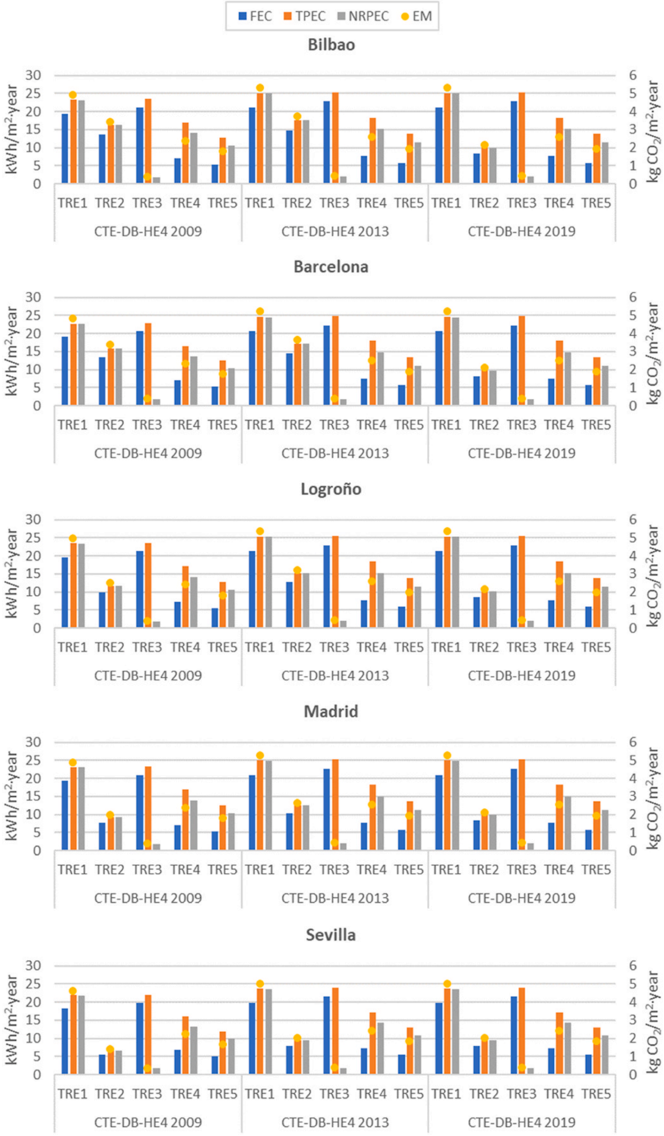

Fig. 15. For DHW, FEC, TPEC, and NRPEC (in kWh/m^2·year) and CO$_2$ emissions, EM (in kg CO$_2$/m^2·year), of the case studies of residential buildings in the selected cities.

the results for a new building and those for a renovated building, accompanied by the corresponding TPEC limit values and NRPEC limit values. The highest ratio between the maximum possible TPEC for the services described above and the corresponding TPEC limit occurs in case DHWS1; the lowest ratio occurs in case DHWS2. The highest ratio between the maximum possible NRPEC for the services described above and the corresponding NRPEC limit occurs in case DHWS2; the lowest ratio occurs in case DHWS3.

Fig. 12 shows the values of the coefficient of global heat transfer through the thermal envelope of the residential building studied for each of the cases and each winter climate zone. In case RTE4, reductions in the global heat transfer coefficient of 51.40%, 53.46%, 59.64%, 62.06%, 63.62% and 65.11% in winter climate zones α, A, B, C, D and E, respectively, compared to those of case RTE1, are achieved. Additionally, reductions of 53.46%, 34.45%, 38.08%, 40.67%, 47.12% and 51.23% in winter climate zones α, A, B, C, D and E, respectively, compared to those of case RTE2, are achieved. In case RTE4, it is necessary to reduce the orientation thermal transmittances of case RTE3 for winter climate zones α and A by 10.15% and 8.76%, respectively.

The maximum solar control parameter for the residential building studied is evaluated for the case in which black exterior rolling shutters and openings with single-pane glass are used, and the minimum solar control parameter is evaluated for the case in which white exterior rolling shutters and openings with double or triple glazed glass are used. Furthermore, for the different winter climate zones, the average maximum solar radiation in July for each orientation of the building is established for each climate zone. Fig. 13 shows that in all the winter climate zones, both the maximum and minimum solar control parameters are below the required limit value of 2.00 kWh/m^2·month.

For the residential building studied, the air change ratio with a differential pressure of 50 Pa should not exceed 3.00 h^{-1}. Fig. 14 shows how the air change ratio varies with the window-to-wall ratio considering the maximum permeability values for the required classes [62] according to the case study and the winter climate zone. Fig. 14 indicates that this requirement is met in cases RTE3 and RTE4 for winter climate zones C, D and E for all window-to-wall ratios and for winter climate zones α, A and B when the window-to-wall ratio is less than 72.87%.

For DHW, FEC, NRPEC, TPEC and CO$_2$ emissions are evaluated by applying the different CTE-DB-HE4 [42–48] to each case study for residential buildings in the selected cities (Fig. 15).

Finally, the evolution of FEC for the heating and DHW services of the residential sector from 2020 to 2050 is outlined, as seen in scenario RBS1 (Fig. 16) and scenario RBS2 (Fig. 17). For these scenarios, in 2020, 2030 and 2050, the main energy and environmental parameters (Table 8) and the corresponding FEC by winter climate zone (Table 9)

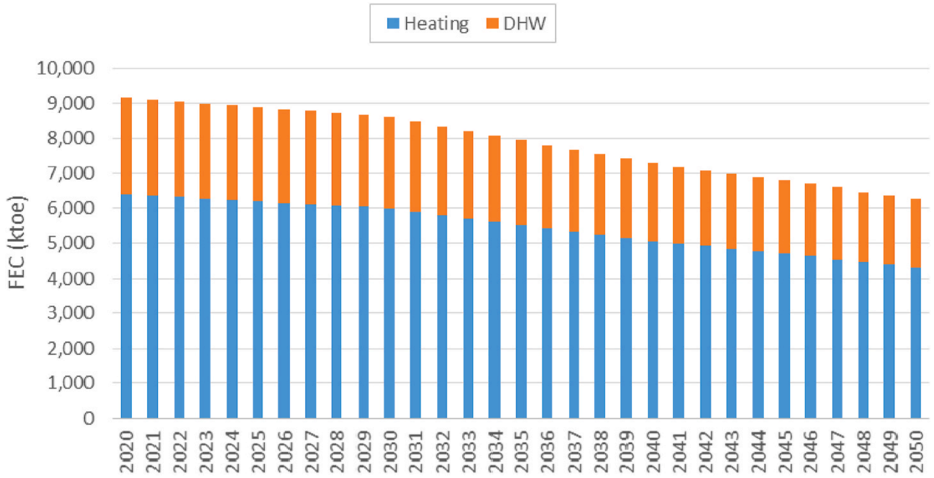

Fig. 16. FEC of the residential sector for heating and DHW in scenario RBS1 from 2020 to 2050 (in ktoe).

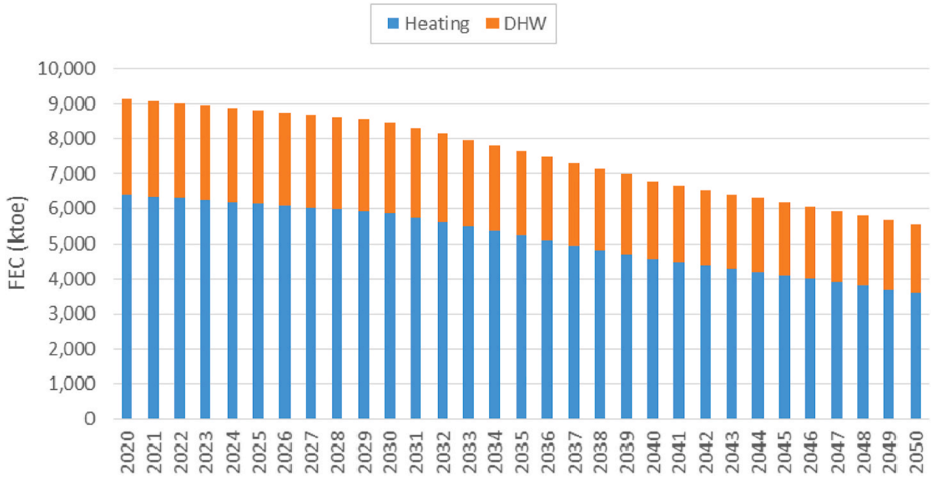

Fig. 17. FEC of the residential sector for heating and DHW in scenario RBS2 from 2020 to 2050 (in ktoe).

Table 8

Main energy and environmental parameters of each residential scenario in 2020, 2030 and 2050.

Scenario	Parameter	2020	2030	2050
RBS1	FEC (ktoe)	9147	8607	6286
	NRPEC (ktoe)	8645	6111	698
	TPEC (ktoe)	11,775	10,942	7904
	CO$_2$ emissions (kt CO$_2$)	21,982	14,803	1720
RBS2	FEC (ktoe)	9144	8480	5556
	NRPEC (ktoe)	8643	6028	639
	TPEC (ktoe)	11,771	10,784	6984
	CO$_2$ emissions (kt CO$_2$)	21,976	14,593	1575

Table 9

FEC of each residential scenario by winter climate zone (WCZ) in 2020, 2030 and 2050 (in ktoe).

Scenario	WCZ	2020	2030	2050
RBS1	α	125	123	98
	A	475	451	327
	B	1607	1529	1104
	C	2671	2510	1861
	D	3843	3620	2667
	E	427	375	229
RBS2	α	125	123	98
	A	475	445	296
	B	1606	1511	997
	C	2670	2465	1606
	D	3842	3565	2352
	E	426	371	207

are also obtained. Compared to 2020, scenario RBS1 achieves savings in FEC of 5.90% by 2030 and 31.28% by 2050; it achieves savings in NRPEC of 29.30% by 2030 and 91.92% by 2050; it achieves savings in TPEC of 7.08% by 2030 and 32.87% by 2050; and it achieves CO$_2$ emissions reductions of 32.66% by 2030 and 92.18% by 2050 (Table 8). Compared to 2020, scenario RBS2 achieves savings in FEC of 7.26% by 2030 and 39.24% by 2050; it achieves savings in NRPEC of 30.26% by 2030 and 92.60% by 2050; it achieves savings in TPEC of 8.39% by 2030 and 40.67% by 2050; and it achieves CO$_2$ emissions reductions of 33.60% by 2030 and 92.83% by 2050 (Table 8). Performing energy renovations so that all buildings comply with CTE-DB-HE 2019 [48] standards for a new building rather than for a renovated building implies additional savings in FEC and in TPEC of 7.96% and 7.80%, respectively, in 2050 compared to 2020, while the savings in NRPEC and CO$_2$ emissions reductions amount to less than 1%.

3.2. Non-residential sector

The maximum possible TPEC and the maximum possible NRPEC for heating, cooling, ventilation and humidity control services are evaluated for the non-residential building studied given the proposed DHW service system and the winter climate zone. Fig. 18 shows the results for the proposed average internal loads and occupancy periods of 12 h and 16 h, accompanied by the corresponding TPEC and NRPEC limits. The greatest ratio for the services listed above between the maximum possible TPEC and the TPEC limit and that between the maximum possible NRPEC and the NRPEC limit occur under the shortest occupancy period and the highest average internal load.

Fig. 19 shows the values of the coefficient of global heat transfer through the thermal envelope of the non-residential building studied for each case examined and each winter climate zone. In case NRTE5, compared to case NRTE1, reductions in the global heat transfer coefficient of 30.43%, 40.08%, 38.48%, 40.10%, 43.72% and 50.33% in winter climate zones α, A, B, C, D and E, respectively, are achieved. Compared to case NRTE4, reductions of 8.51%, 9.08%, 1.71%, 7.20%, 8.51% and 21.23% in winter climate zones α, A, B, C, D and E, respectively, are achieved.

The maximum and minimum solar control parameters for the non-residential buildings studied are evaluated using the same conditions applied for the residential buildings studied for all winter climate zones. Fig. 20 shows that in all winter climate zones, both the maximum and minimum solar parameters are below the required limit value of 4.00 kWh/m^2·month.

E$_m$ (in lux), given different VEEIs (in W/m^2 per 100 lux), and different total lighting and auxiliary equipment powers per lighted surface (in W/m^2), are evaluated for the non-residential buildings studied (Fig. 21).

For DHW, FEC, NRPEC, TPEC and CO$_2$ emissions are evaluated by applying the different CTE-DB-HE4 [42–48] for each case study for non-residential buildings in the selected cities (Fig. 22).

The minimum installed power of the required photovoltaic solar systems (Fig. 23) and their estimated electrical energy production

Fig. 18. Maximum possible TPEC and maximum possible NRPEC for heating, cooling, ventilation and humidity control services and the corresponding limit values for TPEC and NRPEC (in kWh/m^2·year) for the proposed average internal loads, C_{FI}, and occupancy periods for the non-residential buildings studied by DHW system and winter climate zone (WCZ).

(Fig. 24) are evaluated for the different types of non-residential buildings in different solar climate zones for the different cases. According to the CTE-DB-HE5 2013 [45–47] and CTE-DB-HE5 2019 [48], the maximum installed power of the photovoltaic solar systems is 100 kW in all solar climate zones, and their estimated annual electrical energy production is 132.20, 136.20, 149.20, 163.20 and 175.30 MWh in solar climate zones I, II, III, IV and V, respectively. To verify the possibilities of the CTE-DB-HE5 2019 [48], the minimum, limit and maximum power and electrical energy production of electrical generation systems from

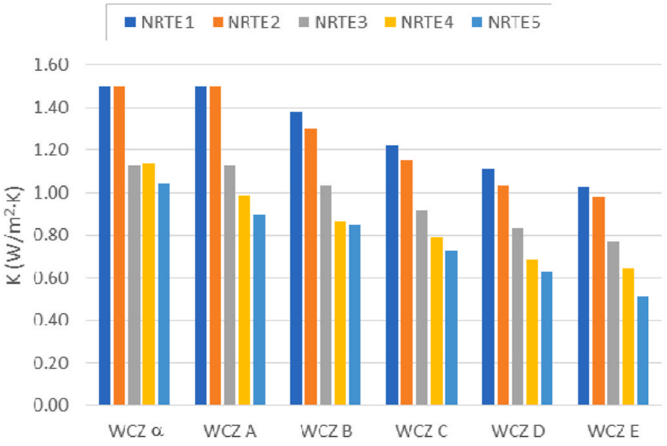

Fig. 19. Coefficient of global heat transfer through the thermal envelope, K (in W/m^2·K), of the case studies for non-residential buildings by winter climate zone (WCZ).

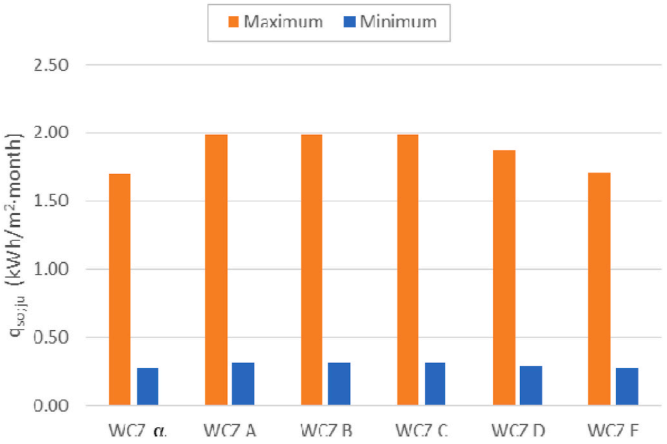

Fig. 20. Maximum and minimum solar control parameters (in kWh/m^2·month) for the non-residential buildings studied by winter climate zone (WCZ).

the required renewable sources are assessed for the different case studies considering different ratios between the built surface of the building and the built surface of the roof (Fig. 25).

Finally, the evolution of the FEC of the non-residential sector from 2020 to 2050 is established and broken down into thermal and electrical energy in scenario NRBS (Fig. 26), as well as the main energy and environmental parameters in 2020, 2030, and 2050 (Table 10). Compared to 2020, scenario NRBS achieves savings in FEC of 12.17% by 2030 and 36.52% by 2050; it achieves savings in NRPEC of 53.67% by 2030 and 84.59% by 2050; it achieves savings in TPEC of 29.50% by 2030 and 54.98% by 2050; and it achieves CO_2 emissions reductions of 56.84% by 2030 and 82.58% by 2050. Regarding the evolution of the sector, by carrying out the minimum actions in energy renovation and assuming that FEC remains constant from 2020 to 2050, by 2050, scenario NRBS will achieve savings in FEC of 36.52%, savings in NRPEC of 45.00%, savings in TPEC of 35.88% and CO_2 emissions reductions of 45.00%.

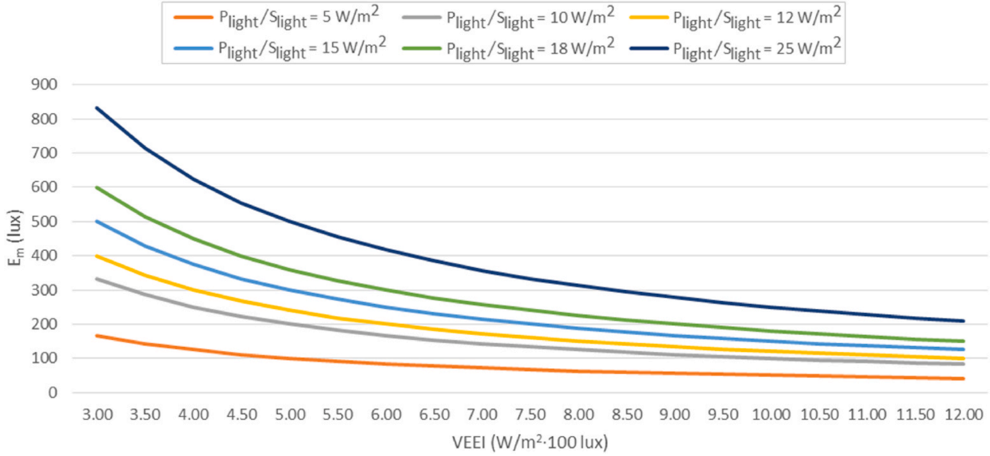

Fig. 21. E_m (in lux), given different VEEIs (in W/m² per 100 lux), and different total lighting and auxiliary equipment powers per lighted surface, P_{light}/S_{light} (in W/m²).

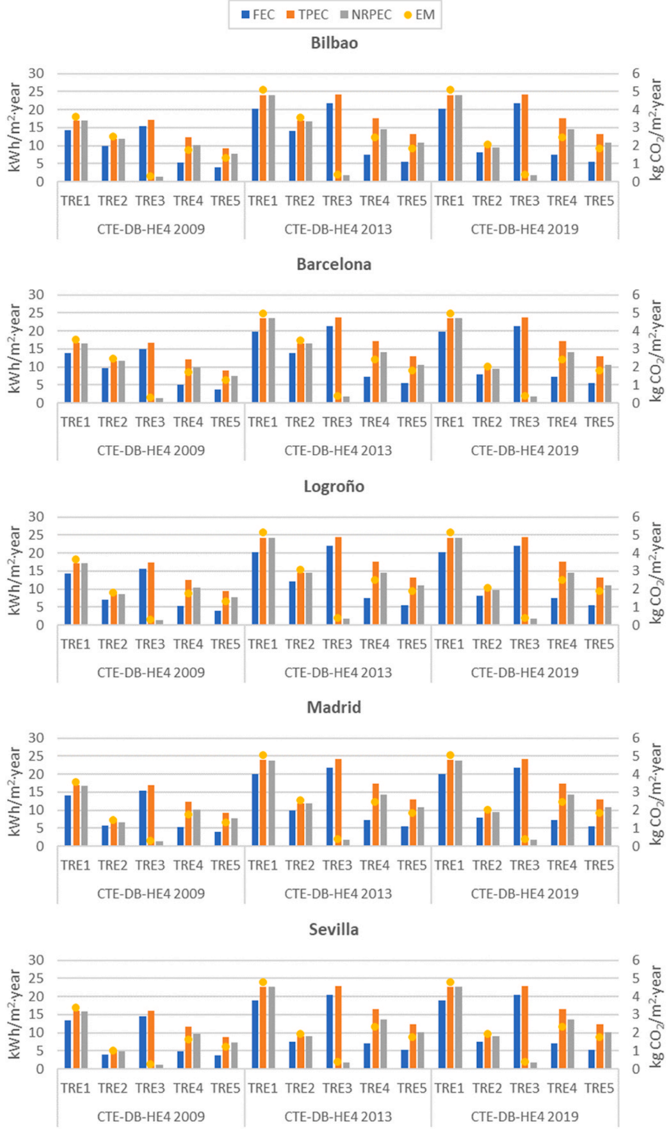

Fig. 22. For DHW, FEC, TPEC, and NRPEC (in kWh/m²·year) and CO_2 emissions, EM (in kg CO_2/m²·year), for the case studies of non-residential buildings in the selected cities.

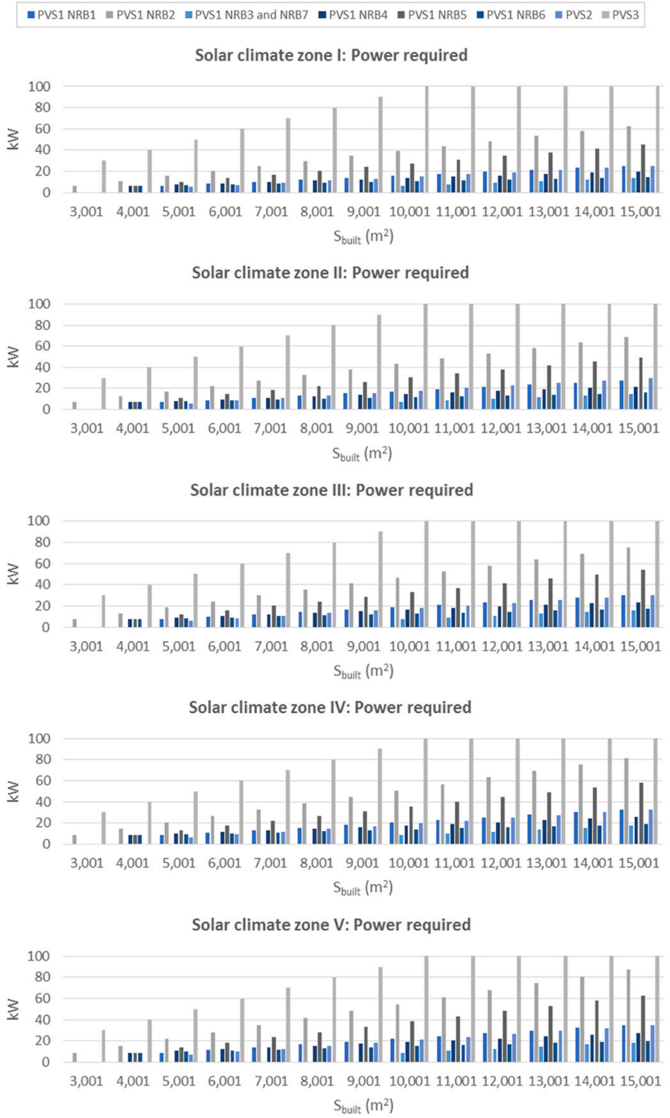

Fig. 23. Minimum installed power values of the required photovoltaic solar systems (in kW) for different types of non-residential buildings and their built surface (in m²) in different solar climate zones for the different cases.

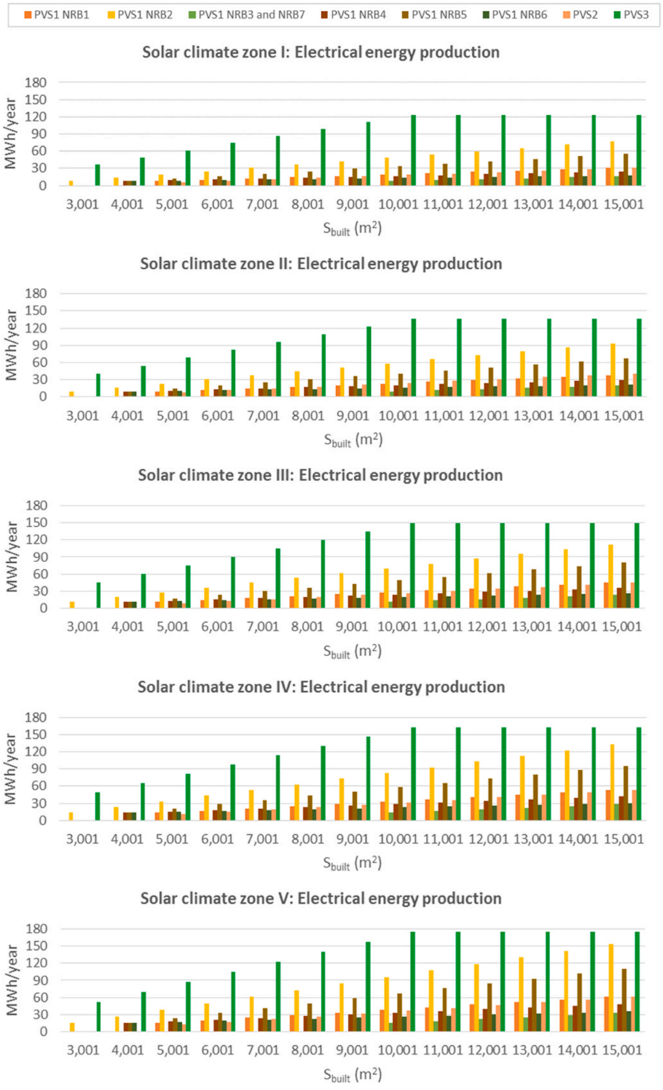

Fig. 24. Minimum estimated electrical energy production by the required photovoltaic solar systems (in MWh/year) for different types of non-residential buildings and their built surface (in m^2) in different solar climate zones for the different cases.

3.3. Indicators of the building sector

The CTE-DB-HE 2019 [48] redefined NZEBs and ensured considerable energy savings compared to the previous CTE-DB-HE [42–47] for both new and renovated buildings, thus contributing to achieving highly energy-efficient and low-carbon buildings for the 2030–2050 period. Table 11 presents the evolution of the requirements related to the CTE-DB-HE [42–48] over the 15 years of EPBD implementation, as well as its key indicators for the building sector. As Table 11 reveals, energy demand for heating and cooling is controlled through limitations to the thermal envelope of buildings, notably reducing such demand and adding new parameters to consider. The reduction in these energy demands, together with the greater use of renewable energies and improvements in the energy efficiency of thermal and lighting installations, implies a substantial reduction in energy consumption. In addition, by limiting both NRPEC and TPEC, the requirements for the building sector have been homogenised, thus presenting these parameters for the non-residential sector more clearly. Regarding the use of renewable energies, the requirement of a renewable energy contribution to DHW and/or indoor swimming pools for all of Spain has been implemented, and demand for the generation of electrical energy from renewable energy has been expanded to a greater number of buildings.

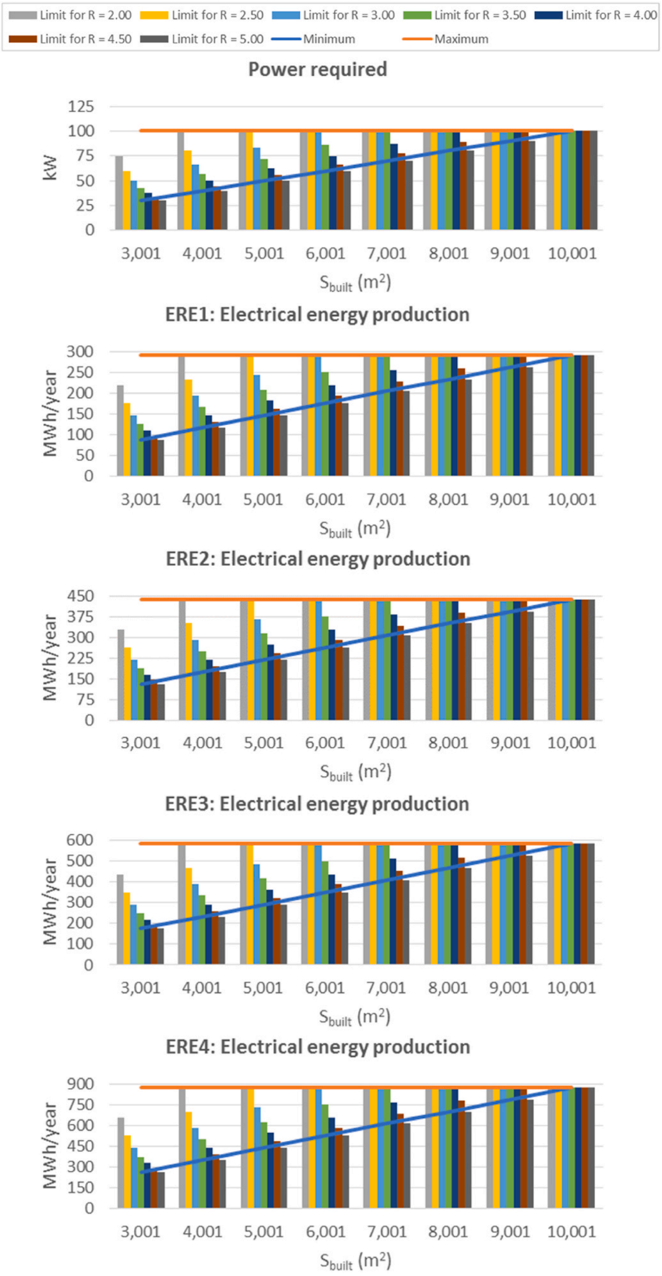

Fig. 25. Minimum, limit and maximum powers (in kW) of electrical generation systems from the required renewable sources and their electrical energy production (in MWh/year) considering different ratios of S_{built} to S_{roof} (R) for non-residential buildings and different case studies.

The exploitation of renewable energy sources is a key strategic factor in achieving NZEBs. Therefore, in addition to the traditional use of thermal and photovoltaic solar systems, different Mediterranean

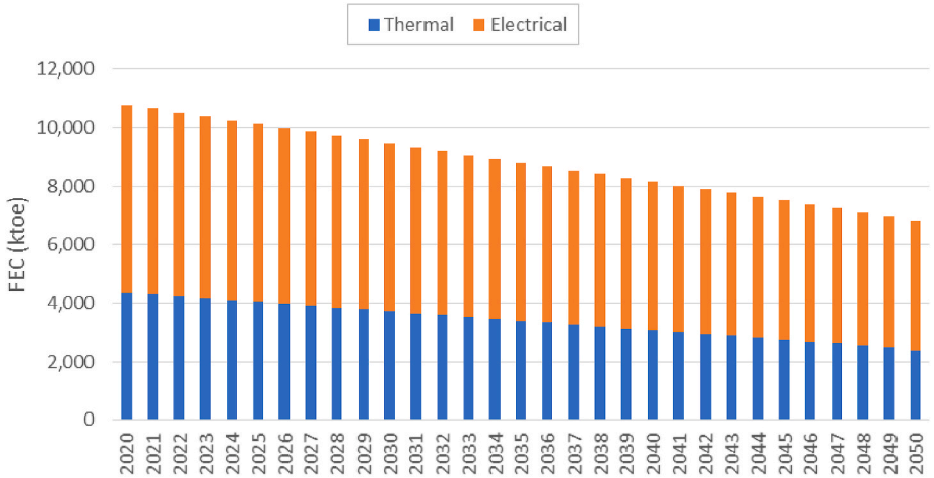

Fig. 26. FEC of the non-residential sector for thermal and electrical energy in scenario NRBS from 2020 to 2050 (in ktoe).

Table 10
Main energy and environmental parameters for scenario NRBS in 2020, 2030 and 2050.

Parameter	2020	2030	2050
FEC (ktoe)	10,782	9470	6845
NRPEC (ktoe)	17,866	8277	2754
TPEC (ktoe)	20,615	14,534	9281
CO_2 emissions (kt CO_2)	38,921	16,799	6778

countries, such as Italy [75] and Spain [10], are promoting the implementation of heat pumps, which are considered renewable, to meet the minimum requirements for the integration of renewable energy sources in buildings. In Greece, to replace electrical water heaters for DHW production, solar thermal water heating systems with electrical boosting are the best option for cold climate zones, and solar photovoltaics/thermal water heating systems with electrical boosting are the best option for temperate climate zones [76]. Using models that scale from NZEBs to nearly zero-energy cities, it has been confirmed that

Table 11
Evolution of the indicators of the requirements related to the CTE-DB-HE [42–48].

CTE-DB-HE 2009 [42–44]	CTE-DB-HE 2013 [45–47]	CTE-DB-HE 2019 [48]
	CTE-DB-HE0: Limitation on energy consumption • NRPEC (residential buildings) • NRPEC rating (non-residential buildings)	**CTE-DB-HE0: Limitation on energy consumption** • NRPEC • TPEC
CTE-DB-HE1: Limitation on energy demand • Percentage of joint energy demand (heating and cooling) of the target building with respect to its reference building • Thermal transmittances for different elements of the thermal envelope • Air permeability of openings • Superficial condensation • Interstitial condensation	**CTE-DB-HE1: Limitation on energy demand** • Heating energy demand (residential buildings) • Cooling energy demand (residential buildings) • Percentage of joint energy demand (heating and cooling) of the target building with respect to its reference building (non-residential buildings) • Thermal transmittances for different elements of the thermal envelope • Thermal transmittances for interior partitions • Air permeability of openings • Superficial condensation • Interstitial condensation	**CTE-DB-HE1: Conditions for controlling energy demand** • Thermal transmittances for different elements of the thermal envelope • Thermal transmittances for interior partitions • Coefficient of global heat transfer through the thermal envelope of the building • Solar control parameter • Air permeability of openings • Air change ratio (residential buildings) • Superficial condensation • Interstitial condensation
CTE-DB-HE3: Energy efficiency of lighting installations (non-residential buildings) • Energy efficiency value of the installation • Control and regulation systems • Natural lighting systems	**CTE-DB-HE3: Energy efficiency of lighting installations** (non-residential buildings) • Energy efficiency value of the installation • Installed power • Control and regulation systems • Natural lighting systems	**CTE-DB-HE3: Conditions for lighting installations** (non-residential buildings) • Energy efficiency value of the installation • Installed power • Control and regulation systems • Natural lighting systems
CTE-DB-HE4: Minimum solar contribution to meeting DHW demand • Contribution by the thermal solar energy support system to meeting DHW needs	**CTE-DB-HE4: Minimum solar contribution to meeting DHW demand** • Contribution by the thermal solar energy support system or by alternative installations to meeting DHW needs	**CTE-DB-HE4: Minimum renewable energy contribution to meeting DHW demand** • Renewable energy contribution to meeting DHW needs
CTE-DB-HE5: Minimum contribution of photovoltaic electrical energy (non-residential buildings) • Installed power of solar photovoltaic systems	**CTE-DB-HE5: Minimum contribution of photovoltaic electrical energy** (non-residential buildings) • Installed power of solar photovoltaic systems	**CTE-DB-HE5: Minimum generation of electrical energy** (non-residential buildings) • Installed power in electrical power generation systems from renewable sources

photovoltaics for own consumption and the local markets of prosumers help reduce primary energy consumption and CO_2 emissions in Mediterranean countries [77]. Hence, it is reasonable to assume that in the future, the implementation of photovoltaic solar systems in the residential sector will be required, as is the case in the non-residential sector.

4. Conclusions

In this work, a detailed analysis of EPBD implementation in Spain over the last 15 years was carried out, covering both renovated and new buildings. The main requirements and indicators established in the different modifications and updates made to the CTE-DB-HE were taken into account, and the evolution of the requirements for buildings to be considered NZEBs was studied. Comparing the initial and current requirements, this study highlights the following:

- NRPEC was not explicitly limited until the CTE-DB-HE0 2013 [45–47]; this limitation was expanded to TPEC with the CTE-DB-HE0 2019 [48] and significantly reduced these types of consumption.
- The CTE-DB-HE1 evolved from limiting the heating and cooling energy demands of a building as a function of those of the corresponding reference building to establishing a series of conditions for controlling these demands, highlighting the global heat transfer coefficient.
- The CTE-DB-HE3 increased the requirements for lighting installations, reducing the VEEIs by zone and the total installed power per unit of lighted area in different non-residential buildings.
- The CTE-DB-HE4 evolved from requiring a renewable energy contribution to meet part of the energy demand for DHW, depending on DHW demand and the solar climate zone, to establishing a minimum of 70% for the entire country by default or 60% if the demand is less than 5000 l/day.
- The CTE-DB-HE5 focused on requiring a renewable energy contribution to meet part of the electrical needs of non-residential buildings, evolving from being applicable only to certain types of buildings to applying to all non-residential buildings larger than 3000 m^2.

To illustrate the gradual strengthening of the different requirements and their implications, several case studies were developed that focused on a multi-family residential building and an educational building. This work serves as a reference for verifying the evolution experienced by the building sector and shows the direction in which that sector is heading in the near future. In addition, the great advances experienced by second-generation NZEBs compared to first-generation NZEBs are evident, and progress towards meeting the objectives for the 2030–2050 European building stock is elucidated. Finally, the requirements of the CTE-DB-HE 2019 [48] present challenges and opportunities for ambitious energy renovation in the Spanish building sector.

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.

Appendix A

Table A.1. Reference DHW demands at a temperature of 60 °C according to the building type and the CTE-DB-HE4 [42–48].

Building type	CTE-DB-HE4 2009 [42–44]	CTE-DB-HE4 2013 and CTE-DB-HE4 2019 [45–48]
Single-family housing	30 l/person·day	28 l/person·day
Multifamily housing	22 l/person·day	28 l/person·day
Hospitals and clinics	55 l/bed·day	55 l/person·day
Outpatient and health centres	–	41 l/person·day
Hotel, 5-star	–	69 l/person·day
Hotel, 4-star	70 l/bed·day	55 l/person·day
Hotel, 3-star	55 l/bed·day	41 l/person·day
Hotel/budget hotel, 2-star	40 l/bed·day	34 l/person·day
Camping	40 l/site·day	21 l/person·day
Budget hotel/pension, 1-star	35 l/bed·day	28 l/person·day
Residence (elderly, students, etc.)	55 l/bed·day	41 l/person·day
Prison	–	28 l/person·day
Hostel	–	24 l/person·day
Locker rooms/showers	15 l/times used·day	21 l/person·day
Schools without showers	3 l/student·day	4 l/person·day
Schools with showers	3 l/student·day	21 l/person·day
Barracks	20 l/person·day	28 l/person·day
Factories and workshops	15 l/person·day	21 l/person·day
Administrative/offices	3 l/person·day	2 l/person·day
Gyms	From 20 to 25 l/user·day	21 l/person·day
Laundries	From 3 to 5 l/kg of clothing·day	–
Restaurants	From 5 to 10 l/meal·day	8 l/person·day
Cafeterias	1 l/lunch·day	1 l/person·day

Table A.2. Minimum occupancy established (number of people) by each CTE-DB-HE4 [42–48].

Number of bedrooms	CTE-DB-HE4 2009 [42–44]	CTE-DB-HE4 2013 [45–47] and CTE-DB-HE4 2019 [48]
1	1.5	1.5
2	3	3
3	4	4
4	6	5
5	7	6
6	8	6

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(*continued*)

Number of bedrooms	CTE-DB-HE4 2009 [42–44]	CTE-DB-HE4 2013 [45–47] and CTE-DB-HE4 2019 [48]
7	9	7
≥ 7	Number of bedrooms	7

Table A.3. Centralisation factor for multi-family residential buildings by each CTE-DB-HE4 [42–48].

Number of dwellings (N)	CTE-DB-HE4 2009 [42–44]	CTE-DB-HE4 2013 [45–47] and CTE-DB-HE4 2019 [48]
$N \leq 3$	1.00	1.00
$4 \leq N \leq 10$	1.00	0.95
$11 \leq N \leq 20$	1.00	0.90
$21 \leq N \leq 50$	1.00	0.85
$51 \leq N \leq 75$	1.00	0.80
$76 \leq N \leq 100$	1.00	0.75
$N \geq 101$	1.00	0.70

Table A.4. Coefficients A and B as a function of the building use type [42–44].

Building use type	A	B
Hypermarkets (NRB1)	0.001875	−3.13
Shopping plazas and leisure centres (NRB2)	0.004688	−7.81
Warehouses (NRB3)	0.001406	−7.81
Administrative (NRB4)	0.001223	1.36
Hotels and hostels (NRB5)	0.003516	−7.81
Hospitals and private clinics (NRB6)	0.000740	3.29
Convention centres (NRB7)	0.001406	−7.81

Table A.5. Climate coefficient C [42–47] and annual reference equivalent hours [45–47] by solar climate zone.

Solar climate zone	C	Annual reference equivalent hours
I	1.00	1232
II	1.10	1362
III	1.20	1492
IV	1.30	1632
V	1.40	1753

Appendix B

Table B.1. Recommended thermal transmittances (in W/m^2·K) for different elements of the thermal envelope of buildings according to each CTE-DB-HE1 [42–48] and by winter climate zone (WCZ).

	WCZ	Residential buildings						Non-residential buildings					
		U_M	U_S	U_C	U_T	U_{MD}	U_H	U_M	U_S	U_C	U_T	U_{MD}	U_H
CTE-DB-HE1 2009 [42–44]	α	0.94	0.53	0.50	0.94	1.22	3.40–5.70	0.94	0.53	0.50	0.94	1.22	3.40–5.70
	A	0.94	0.53	0.50	0.94	1.22	3.40–5.70	0.94	0.53	0.50	0.94	1.22	3.40–5.70
	B	0.82	0.52	0.45	0.82	1.07	2.70–5.70	0.82	0.52	0.45	0.82	1.07	2.70–5.70
	C	0.73	0.50	0.41	0.73	1.00	2.20–4.40	0.73	0.50	0.41	0.73	1.00	2.20–4.40
	D	0.66	0.49	0.38	0.66	1.00	1.90–3.50	0.66	0.49	0.38	0.66	1.00	1.90–3.50
	E	0.57	0.48	0.35	0.57	1.00	1.90–3.10	0.57	0.48	0.35	0.57	1.00	1.90–3.10
CTE-DB-HE1 2013 [45–47]	α	0.94	0.53	0.50	0.94	1.35	4.70–5.70	0.94	0.53	0.50	0.94	0.94	3.40–5.70
	A	0.50	0.53	0.47	0.50	1.25	1.80–3.50	0.94	0.53	0.50	0.94	0.94	3.40–5.70
	B	0.38	0.46	0.33	0.38	1.10	1.40–2.70	0.82	0.52	0.45	0.82	0.82	2.70–4.20
	C	0.29	0.36	0.23	0.29	0.95	1.20–2.10	0.73	0.50	0.41	0.73	0.73	2.20–3.10
	D	0.27	0.34	0.22	0.27	0.85	1.20–2.10	0.60	0.40	0.38	0.60	0.60	1.90–2.70
	E	0.25	0.31	0.19	0.25	0.70	1.20–2.00	0.55	0.35	0.35	0.55	0.55	1.90–2.50
CTE-DB-HE1 2019 [48]	α	0.56	0.56	0.50	0.80	0.80	2.70	0.80	0.80	0.55	0.90	0.90	3.20
	A	0.50	0.50	0.44	0.80	0.80	2.70	0.70	0.70	0.50	0.80	0.80	2.70
	B	0.38	0.38	0.33	0.69	0.69	2.00	0.56	0.56	0.44	0.75	0.75	2.30
	C	0.29	0.29	0.23	0.48	0.48	2.00	0.49	0.49	0.40	0.70	0.70	2.10
	D	0.27	0.27	0.22	0.48	0.48	1.60	0.41	0.41	0.35	0.65	0.65	1.80
	E	0.23	0.23	0.19	0.48	0.48	1.50	0.37	0.37	0.33	0.59	0.59	1.80

Note: U_M is the thermal transmittance of façade walls; U_S is the thermal transmittance of floors in contact with air; U_C is the thermal transmittance of roofs; U_T is the thermal transmittance of elements in contact with the ground; U_{MD} is the thermal transmittance of dividing walls; and U_H is the thermal transmittance of openings.

Table B.2. Thermal transmittance limits (in W/m^2·K) for interior partitions according to the CTE-DB-HE1 2013 [45–47] and CTE-DB-HE1 2019 [48] by winter climate zone (WZC).

	WCZ α	WCZ A	WCZ B	WCZ C	WCZ D	WCZ E
Horizontal interior partitions that delimit units of the same use	1.90	1.80	1.55	1.35	1.20	1.00
Vertical interior partitions that delimit units of the same use	1.40	1.40	1.20	1.20	1.20	1.00
Horizontal and vertical interior partitions that delimit units of different uses	1.35	1.25	1.10	0.95	0.85	0.70

CrediT author statement

Luis M. López-Ochoa: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Jesús Las-Heras-Casas:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Writing – review & editing. **Pablo Olasolo-Alonso:** Formal analysis, Investigation, Visualization, Writing – review & editing. **Luis M. López-González:** Project administration, Resources, Supervision, Writing – review & editing.

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