Energy 276 (2023) 127539

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Towards nearly zero-energy residential buildings in Mediterranean countries: The implementation of the Energy Performance of Buildings Directive 2018 in Spain

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ARTICLE INFO

Handling Editor: X Zhao

Keywords:
Energy Performance of Buildings Directive (EPBD)
Nearly zero-energy buildings (NZEBs)
Energy savings
Residential sector
Spain

ABSTRACT

The new Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) provides the necessary requirements to achieve nearly zero-energy buildings (NZEBs) and promotes the use of renewable energies in the Spanish building sector. In addition, the new CTE-DB-HE, transposition of the Energy Performance of Buildings Directive 2018, introduces specific requirements for the implementation of electric vehicle charging infrastructures in building car parks. The objective of this study is to analyse the energy and environmental impacts of the application of the new CTE-DB-HE in the residential sector. Different multi-family buildings in the most representative cities that meet the requirements for new and renovated buildings and use different heating and domestic hot water systems, as well as photovoltaic solar systems, are studied. The results are compared with those obtained by applying the previous regulations. Compared to the previous NZEBs, the new NZEBs achieve reductions by at least 46% in non-renewable primary energy consumption and 13% in total primary energy consumption. In addition, the changes introduced are shown to have helped prompt significant progress in the achievement of a highly energy-efficient and decarbonized building stock, achieving a reduction by at least 19% by 2050 in the main energy and environmental indicators.

1. Introduction

The building sector is responsible for 40% of total energy consumption [1] and 36% of total CO_2 emissions [2] in the European Union (EU). This sector is essential to achieve the energy and environmental objectives of the EU, as well as the building and renovation objectives established in the European Green Deal [3]. For this reason and to promote building energy performance, improve the existing building stock and achieve a highly energy-efficient and decarbonized building stock by 2050, the Energy Performance of Buildings Directive (EPBD) 2018 was created [2]. The EPBD 2018 [2] amended the EPBD 2010 [1], which consolidated the EPBD 2002 [4] and the Energy Efficiency Directive 2012 [5].

The EPBD 2010 [1] instructed the EU Member States to define nearly zero-energy buildings (NZEBs) and established that all new buildings must be NZEBs. A framework for the cost-optimal design of NZEBs was studied in representative European climates in Ref. [6]. In the Mediterranean climate zone, the reference values applicable to the energy performance of NZEBs for new single-family houses are 0–15 $kWh/m^2 \cdot year$ of net primary energy, with 50–65 $kWh/m^2 \cdot year$ of primary energy use covered by 50 $kWh/m^2 \cdot year$ from renewable energy sources in situ [7]. Numerous studies on how to achieve NZEBs have been carried out in the Mediterranean environment, highlighting Refs. [8,9] in Portugal, Ref. [10] in Portugal and Spain, Refs. [11,12] in Spain, Refs. [13,14] in France, Refs. [15–18] in Italy, Refs. [19–21] in Greece and Ref. [22] in Cyprus. In addition, the implementation of NZEBs in

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https://doi.org/10.1016/j.energy.2023.127539
Received 7 November 2022; Received in revised form 8 February 2023; Accepted 14 April 2023
Available online 16 April 2023

southern European countries, as well as the challenges and opportunities they face, were studied in Ref. [23]. Moreover, numerous studies have evaluated the impact of the implementation of the EPBD 2010 [1] on different national legislation in countries with a Mediterranean climate, both within the EU, such as Ref. [24] in Portugal, Refs. [25,26] in Spain, Ref. [27] in Italy, Ref. [28] in Greece and Ref. [29] in Cyprus, and outside the EU, such as Ref. [30] in Turkey, Ref. [31] in Serbia and Refs. [32,33] in Chile.

The EPBD 2018 [2] urged EU Member States to establish a long-term strategy to support the renovation of their national building stocks. An in-depth analysis of the current European regulatory framework regarding the energy performance of buildings was proposed, and the economic strategies adopted to economically support the transition to the zero-energy building stock were highlighted. Furthermore, how the new Italian funding programme could increase the diffusion of energy efficiency interventions was shown in Ref. [34]. The EPBD 2018 [2] promoted electromobility. Significant potential was found for residential electric vehicle charging flexibility when private parking spaces have a charge point, as electric vehicle charging is a main source of flexible electricity use in multi-family buildings in Ref. [35]. The EPBD 2018 [2] introduced the smart readiness indicator to evaluate the capabilities of buildings to adapt their operation to the needs of their occupants and the network while also improving their energy efficiency and overall performance. The retrofitting cost towards building smartification and the smart readiness indicator score with which to achieve NZEBs and even positive energy buildings were evaluated for different residential building renovation scenarios in five EU countries in Ref. [36]. In addition, the EPBD 2018 [2] introduced a voluntary system of building renovation passports to complement the energy performance certificates and provide a long-term and phased roadmap for building renovation. The potential of and barriers to current initiatives on building renovation passports implemented in Flanders, France and Germany were studied in Ref. [37]. The integration of existing instruments for building conservation, renovation and heritage protection in Spain was proposed in Ref. [38].

In the specific case of Spain, the EPBD 2002 [4] was transposed into national law through the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE), CTE-DB-HE 2009 [39–41]. Subsequently, the EPBD 2010 [1] was transposed into Spanish law through the CTE-DB-HE 2013 [42–44] in the first phase and through the CTE-DB-HE 2019 [45] in the second phase. These updates to the CTE-DB-HE [42–45] were needed because the EPBD 2010 [1] established the obligation to review and update the minimum energy performance requirements periodically to adapt them to the technical advances of the construction sector. In parallel to the revision of these minimum values, the definition of NZEB was also updated. The first-generation NZEB defines buildings that met the regulatory requirements established for new buildings in the different sections of the CTE-DB-HE 2013 [42–44], while the second-generation NZEB defines a building, new or existing, that meets the regulatory requirements established for new buildings in the CTE-DB-HE 2019 [45] with regard to the limitation on energy consumption for new buildings. It should be noted that compared to first-generation NZEBs, second-generation NZEBs reduce the non-renewable primary energy consumption by approximately 40% and, for the first time, limit the total primary energy consumption. Ref. [10] highlighted the impact of the achievement of NZEBs through energy renovation by applying the CTE-DB-HE 2019 [45] to a multi-family building built between 1961 and 1980. Ref. [25] demonstrated the impact of the evolution of the CTE-DB-HE [39–45] in the building sector, as well as its implications for the future of this sector. Ref. [26] discussed the impact of the evolution of the CTE-DB-HE [39–45] on a single-family house in Andalucía (Spain). The EPBD 2018 [2] was transposed into Spanish law through the new CTE-DB-HE 2022 [45,46], which maintained the definition of the NZEB established in the CTE-DB-HE 2019 [45]. A literature review of the subject revealed a gap in knowledge given this recent transposition into Spanish law. Overall, the main objective of this work is to analyse the energy and environmental impacts of the application of the CTE-DB-HE 2022 [45,46] to both present and future residential sectors. This study proceeds as follows: (a) presentation of the main novelties of the CTE-DB-HE 2022 [45, 46] with respect to the CTE-DB-HE 2019 [45]; (b) analysis of the implications of compliance with the CTE-DB-HE 2022 [45,46] through case studies of multi-family buildings, both new and renovated, in the most representative cities of the six winter climate zones (WCZs) that use different heating and domestic hot water (DHW) systems, as well as photovoltaic solar systems; (c) study of the evolution of the main indicators to evaluate energy-saving requirements in the residential sector; and (d) evaluation of the impact achieved through the CTE-DB-HE 2022 [45,46] with respect to both previous regulations for energy saving in buildings and those for future residential building stock in 2030 and 2050.

2. Materials and methods

2.1. Main novelties of the new CTE-DB-HE 2022

The requirements of the new CTE-DB-HE 2022 [45,46] are as follows:

(a) Limitation on energy consumption (CTE-DB-HE0).
(b) Conditions for controlling energy demand (CTE-DB-HE1).
(c) Conditions for thermal installations (CTE-DB-HE2).
(d) Conditions for lighting installations (CTE-DB-HE3).
(e) Minimum renewable energy contribution to meet DHW demand (CTE-DB-HE4).
(f) Minimum generation of electrical energy from renewable energy sources (CTE-DB-HE5).
(g) Minimum provisions for electric vehicle charging infrastructure (CTE-DB-HE6).

The CTE-DB-HE 2022 [45,46] maintains the same definition of NZEBs as the CTE-DB-HE 2019 [45]. As its main novelties, the CTE-DB-HE 2022 [45,46] substantially modifies the CTE-DB-HE5 and creates the new CTE-DB-HE6.

2.1.1. Minimum generation of electrical energy from renewable energy sources

Both the CTE-DB-HE5 2022 [45,46] and the CTE-DB-HE5 2019 [45] require that buildings must have electricity generation systems from renewable energy sources for their own use or supply to the grid.

The CTE-DB-HE5 2022 [45,46] is applicable to both residential and non-residential buildings in the following cases: (a) newly constructed buildings with a built surface greater than 1000 m^2; (b) extensions of existing buildings with an increase in the built surface of more than 1000 m^2; and (c) existing buildings that will be or have been completely renovated or in which there is a change in characteristic use with a built surface greater than 1000 m^2. Compared to the CTE-DB-HE5 2019 [45], the CTE-DB-HE5 2022 [45,46] broadens its application to residential buildings and reduces the built surface by 2000 m^2 in each case (new buildings and expansion, reform or change of use in existing buildings) with respect to previous requirements for non-residential buildings. Both the CTE-DB-HE5 2022 [45,46] and the CTE-DB-HE5 2019 [45] consider the built surface to include the surface of the parking areas inside the building but to exclude the common outdoor areas.

According to the CTE-DB-HE5 2019 [45], the minimum power to be installed ($P_{min\ 2019}$) and the limit power to be installed ($P_{lim\ 2019}$), both in kW, are obtained with Equations (1) and (2), respectively:

$$P_{min\ 2019} = 0.01 \bullet S_{built} \tag{1}$$

$$P_{lim\ 2019} = 0.05 \bullet S_{roof} \tag{2}$$

where S_{built} is the built surface of the building, in m^2, and S_{roof} is the built surface of the roof of the building, in m^2.

Regardless of Equations (1) and (2), the mandatory power to be installed cannot be less than 30 kW or greater than 100 kW.

According to the CTE-DB-HE5 2022 [45,46], the minimum power to be installed ($P_{min\ 2022}$) is obtained with Equation (3) and corresponds to the lowest power to be installed resulting from applying both Equation (4) (P_1) and Equation (5) (P_2), all of them in kW:

$$P_{min\ 2022} = min(P_1, P_2) \tag{3}$$

$$P_1 = F_{pr;el} \bullet S_{built} \tag{4}$$

$$P_2 = 0.1 \bullet \left(0.5 \bullet S'_{roof} - S_{occupied\ roof}\right) \tag{5}$$

where $F_{pr;el}$ is the electrical production factor and takes a value of 0.005 kW/m^2 for residential buildings and 0.010 kW/m^2 for non-residential buildings; S'_{roof} is the roof surface that is not passable or accessible only for conservation, in m^2; and $S_{occupied\ roof}$ is the roof surface that is not passable or accessible only for conservation occupied by thermal solar collectors, in m^2.

It should be noted that, in contrast to the CTE-DB-HE5 2019 [45], the CTE-DB-HE5 2022 [45,46] only establishes the minimum power to be installed and eliminates the maximum mandatory power to be installed.

2.1.2. Minimum provisions for electric vehicle charging infrastructure

The new CTE-DB-HE6 2022 [45,46] establishes that buildings must have a minimum infrastructure that allows for the charging of electric vehicles and complies with the Low Voltage Electrotechnical Regulation [47] and, specifically, with its Complementary Technical Instruction ITC-BT-52 “Special purpose facilities. Infrastructure for charging electric vehicles” [48].

The new CTE-DB-HE6 2022 [45,46] is applicable to new buildings with parking (interior or exterior attached to the building) or existing buildings to which any of the following apply: changes of use; expansions in which the surface or volume built is increased by more than 10% and more than 50 m^2 of expanded useful surface; reforms in which the parking lot is altered and in which more than 25% of the thermal envelope is renovated; or interventions in the electrical installation of the building or parking lot that affect more than 50% of the installed power. The following building scenarios are excluded from this application: non-residential buildings with less than or equal to 10 parking spaces; those interventions whose cost for meeting this requirement exceeds 7% of the overall cost of intervention (cost of material execution) in residential or non-residential buildings with less than or equal to 20 parking spaces; and officially protected buildings.

The new CTE-DB-HE6 2022 [45,46] requires the installation of cable conduction systems that allow future supply to charging stations for 100% of the parking spaces in residential buildings and for at least 20% of the parking spaces in non-residential buildings. To allow the calculation of these charging stations for the purposes of compliance with the requirement, in general, a charging station will be installed for every 40 parking spaces, or fraction, in non-residential buildings and for every 20 parking spaces, or fraction, in non-residential buildings owned by public administrations. Finally, if car parks have accessible parking spaces, a charging station will be installed for every 5 accessible parking spaces. These last charging stations can be considered to meet this requirement.

2.1.3. Limitation on energy consumption

In its revisions to the CTE-DB-HE0 2019 [45], the CTE-DB-HE0 2022 [45,46] highlights in its calculation procedure that:

(a) The calculation of the energy balance necessary for its verification is performed according to UNE-EN ISO 52000–1:2019 [49], cancelling the export factor.

(b) For the purposes of allocation to the different services, the distribution of the electrical energy produced in situ, in each time interval, is performed proportionally to the electrical energy consumption of the services considered.

(c) For undefined aspects, the calculation of the different energy parameters will be performed according to Ref. [50].

2.1.4. Conditions for controlling energy demand

Compared to the CTE-DB-HE1 2019 [45], the CTE-DB-HE1 2022 [45,46] includes that, for both new and renovated buildings, it is not necessary to meet the requirement relative to the coefficient of global heat transfer through the thermal envelope of the building when the energy demand for heating is less than 15 kWh/m^2·year and the energy demand for cooling is less than 15 kWh/m^2·year.

2.2. Study residential building

The study residential building consists of a ground floor and five additional floors, with a square base of 484.00 m^2 and floor height of 3.00 m. The total living area of the building is 2216.57 m^2, with four types of dwellings in each floor: Dwelling type A is 100.05 m^2 and has three bedrooms; dwelling type B is 101.93 m^2 and has three bedrooms; dwelling type C is 137.64 m^2 and has four bedrooms; and dwelling type D is 103.69 m^2 and has three bedrooms. On the ground floor are the main entrance and the car parking space. The roof is hipped and has a height of 2.00 m. The thermal envelope of the building delimits floors 1–5 and the roof space, resulting in a compactness of 4.19 m^3/m^2. The study building is presented in Fig. 1. The study building was used to study the evolution of the implementation of the EPBD 2002 [4] and the EPBD 2010 [1] in the Spanish residential sector in Refs. [25,51–53], and is, therefore, validated in those research works.

Given that the requirements to achieve a residential NZEB are a function of the WCZ in which the building is located [45,46], it was decided to locate study buildings in the most representative cities of each of the different WCZs (Fig. 2): Las Palmas de Gran Canaria (WCZ α), Málaga (WCZ A), Sevilla (WCZ B), Barcelona (WCZ C), Madrid (WCZ D) and León (WCZ E). The WCZ α has the lowest winter climate severity and, therefore, the lowest energy demand for heating, while the WCZ E presents the highest winter climate severity and, therefore, the highest energy demand for heating [54].

2.3. Case studies

The impact of the application of the CTE-DB-HE 2022 [45,46] was analysed for the study building in each of the representative cities for three different heating and DHW systems, resulting in the cases described in Table 1. Both new and renovated buildings meet the corresponding specific requirements of the CTE-DB-HE 2022 [45,46].

For both new and renovated buildings to meet the corresponding specific requirements of the CTE-DB-HE 2022 [45,46], the following design criteria were established for the different case studies:

- The values for the thermal transmittance of opaque enclosures were adjusted to the corresponding recommended values in Annex E of the CTE-DB-HE 2022 [45,46] for new buildings, while the values for opaque enclosures were adjusted to the corresponding limit values established in the CTE-DB-HE1 2022 [45,46] for renovated buildings. The values for the thermal transmittance of interior partitions were adjusted to the corresponding limit values established in the CTE-DB-HE1 2022 [45,46] for both new and renovated buildings. To compare the impact of the CTE-DB-HE 2022 [45,46] with all the previous CTE-DB-HE [39–45], the compositions of opaque enclosures and interior partitions of the study building have been extracted from Ref. [51] for Madrid and León, and from Ref. [52] for Las Palmas, Málaga, Sevilla and Barcelona. In addition, it was necessary to determine the thickness of thermal insulation to achieve

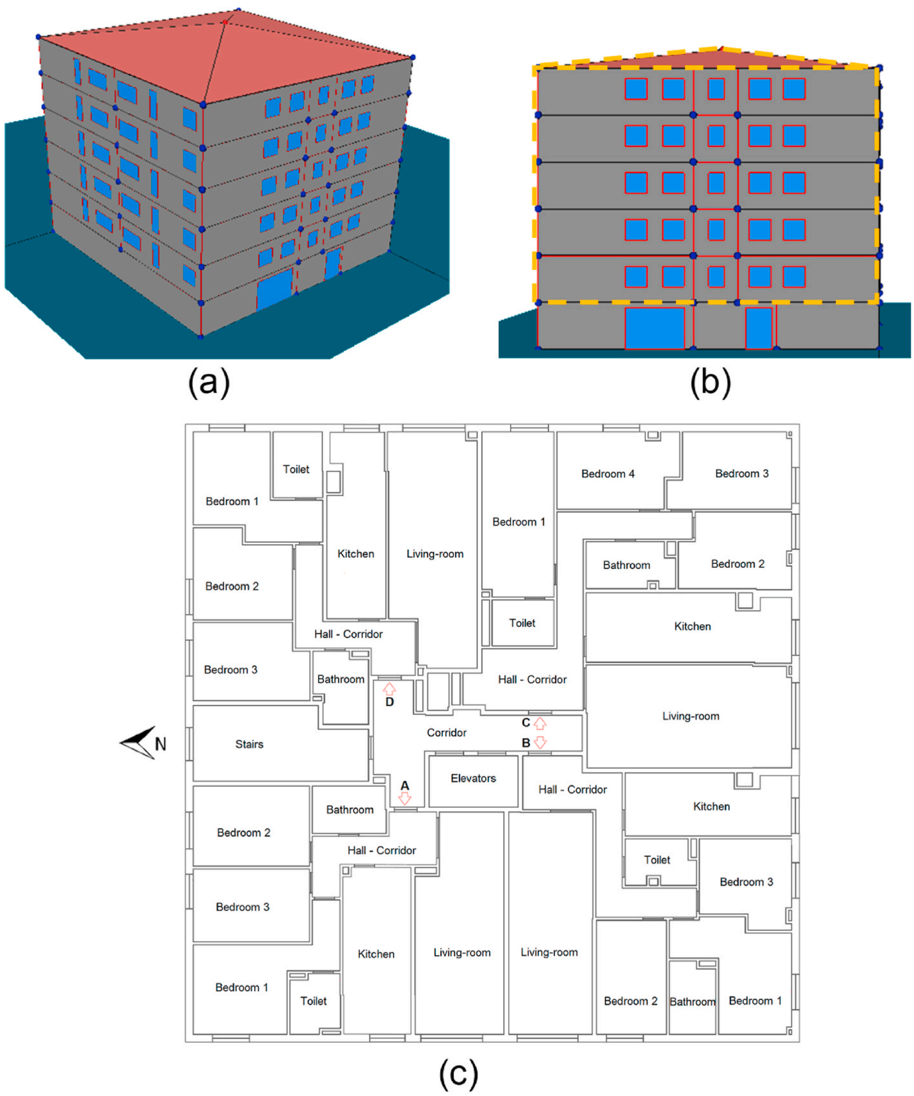

Fig. 1. Study residential building: (a) 3D model; (b) delimitation of the thermal envelope (north orientation); and (c) floorplan of the four dwelling types.

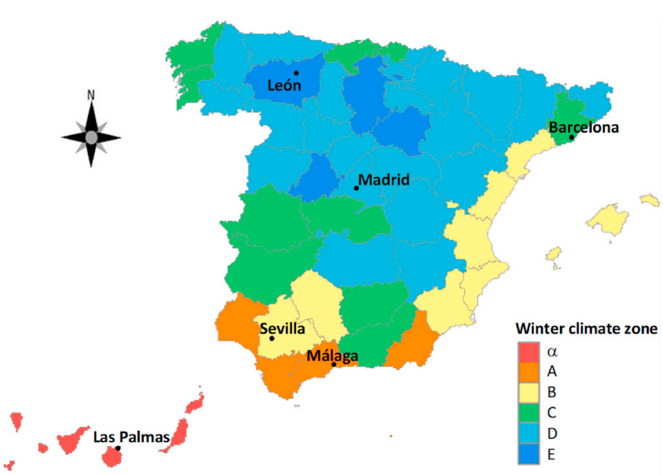

Fig. 2. WCZs of all provincial capitals of Spain according to the CTE-DB-HE 2022 [45,46].

Table 1
Case studies.

Case	Building type	Heating and DHW system	Seasonal performance	Thermal solar support system for DHW
1	New	Natural gas boiler	$\eta = 0.92$	Yes
2	New	Biomass boiler	$\eta = 0.85$	No
3	New	Electric heat pump	$SCOP_{heat} = 3.52$ $SCOP_{DHW} = 2.50$	No
4	Renovated	Natural gas boiler	$\eta = 0.92$	Yes
5	Renovated	Biomass boiler	$\eta = 0.85$	No
6	Renovated	Electric heat pump	$SCOP_{heat} = 3.52$ $SCOP_{DHW} = 2.50$	No

Note: η is seasonal performance; $SCOP_{heat}$ is seasonal coefficient of performance for heating; and $SCOP_{DHW}$ is seasonal coefficient of performance for DHW.

the different values of thermal transmittance required for both new and renovated buildings.

- To comply with the CTE-DB-HE1 2022 [45,46], the values for the thermal transmittance of the different elements of the thermal envelope and of the interior partitions do not exceed their corresponding limit values.

- The thermal bridges allow the continuity of the thermal insulation in and between the different elements of the thermal envelope, with their values indicated in Supporting Document 3 [55].
- There is no interstitial or surface condensation in the opaque enclosures of the thermal envelope in contact with the outside air, as required by the CTE-DB-HE1 2022 [45,46].
- The air permeability of the thermal envelope openings is class 2 (less than or equal to 27 $m^3/h{\cdot}m^2$) for Las Palmas, Málaga and Sevilla, and is class 3 (less than or equal to 9 $m^3/h{\cdot}m^2$) for Barcelona, Madrid and León, thus complying with the CTE-DB-HE1 2022 [45,46].
- The energy needs for cooling are met by the reference system defined in the CTE-DB-HE0 2022 [45,46], that is, an electrical system with a seasonal energy efficiency ratio of 2.52.
- The ventilation system was sized and selected to meet the indoor air quality requirement of the Basic Document on Health of the Technical Building Code (CTE-DB-HS3), CTE-DB-HS3 2022 [39–41, 44–46]. The ventilation flow of the study building is 660.00 l/s, applying the CTE-DB-HS3 2022 [39–41,44–46] requirement, and the electrical power consumed by the required exclusive ventilation equipment is 873.28 W.
- To comply with the CTE-DB-HE2 2022 [45,46], all the thermal installations in the building are appropriate for achieving the thermal well-being of its occupants in compliance with the Regulations for Thermal Installations in Buildings [56].
- To comply with the CTE-DB-HE3 2022 [45,46], the average horizontal illuminance does not exceed 250 lux in common areas or 100 lux in car parks. In addition, both control and regulation systems and the required natural light utilization systems have been installed.
- To meet the new requirement that modifies the CTE-DB-HE5 2022 [45,46], the power of the photovoltaic solar system to be installed is 14.52 kW.
- To meet the new requirement introduced by the CTE-DB-HE6 2022 [45,46], cable management systems must be installed that allow future supply to charging stations for all parking spaces in compliance with Refs. [47,48].

The thermal transmittance of the different elements of the thermal envelope and the necessary thermal insulation thickness of the opaque enclosures for each case study and city are presented in Table 2. The compositions of the opaque enclosures of the thermal envelope for each representative city are presented in Appendix A (Tables A1-A3). The composition and the main characteristics of the openings of the thermal envelope for each representative city are presented in Table 3. Finally, in Table 4, the main requirements for verification of compliance with the CTE-DB-HE 2022 [45,46] for new and renovated buildings are compiled for all representative cities.

2.4. Energy simulation of the study buildings

For the energy simulation of the different case studies, the LIDER-CALENER Unified Tool (HULC) [57] was used. HULC [57] is the official tool offered by the Ministry of Transport, Mobility and Urban Agenda and by the Institute for Energy Diversification and Saving for verification of buildings' compliance with the CTE-DB-HE 2022 [45,46] and energy performance certification.

Table 3
Composition and main characteristics of the openings for each representative city.

		Las Palmas and Málaga	Sevilla and Barcelona	Madrid and León
Glass	Type	Double-pane	Low-emissive double-pane 1	Low-emissive double-pane 2
	U	2.80	1.90	1.60
	g	0.75	0.70	0.70
Frame	Type	Medium-high density wood	Two-chamber PVC	Three-chamber PVC
	U	2.20	2.20	1.80
	α	0.70	0.70	0.70
Blind	$g_{gl;sh;wi}$	0.08	0.05	0.08

$g_{gl;sh;wi}$ is total solar energy transmittance of the glazing with the mobile shading device activated for the month of July for openings.

In the present research, using HULC [57], the following actions were performed:

- Evaluation of the energy impact: energy demands, final energy consumption, non-renewable primary energy consumption, renewable primary energy consumption and total primary energy consumption, both by service and overall.
- Environmental impact assessment: CO_2 emissions, both by service and overall.
- Verification of compliance with the CTE-DB-HE 2022 [45,46]: CTE-DB-HE0, CTE-DB-HE1, CTE-DB-HE4 and CTE-DB-HE5 requirements.
- Energy performance certification: rating in non-renewable primary energy consumption and rating in CO_2 emissions.

To evaluate non-renewable primary energy consumption, renewable primary energy consumption and total primary energy consumption, as well as CO_2 emissions, HULC [57] uses Ref. [58]. The calculation methodology used by HULC [57] to evaluate the renewable energy contribution to meet DHW demand is established in UNE-EN ISO 52000–1:2019 [49] and explained in the Application Guide of the CTE-DB-HE [59]. In addition, the final energy consumption for DHW associated to the ambient energy captured by the heat pump is evaluated as indicated in Directive 2009/28/EC [60] and Decision 2013/114/EU [61] for electrically driven renewable heat pumps.

The monthly values of thermal energy produced by thermal solar systems were obtained through the f-chart method [62] and the monthly values of electrical energy produced by the photovoltaic solar systems were obtained through Abbreviated Residential Energy Rating Method (CERMA) application [63]. CERMA [63] is an application for the energy

Table 2
Thermal insulation thickness of the opaque enclosures (t), in m, and thermal transmittance of the different elements of the thermal envelope (U), in $W/m^2{\cdot}K$, for new and renovated buildings in each representative city.

		Las Palmas		Málaga		Sevilla		Barcelona		Madrid		León	
		t	U	t	U	t	U	t	U	t	U	t	U
New	Roof	0.044	0.50	0.052	0.44	0.074	0.33	0.110	0.23	0.100	0.22	0.122	0.19
	Walls	0.042	0.56	0.048	0.50	0.067	0.38	0.092	0.29	0.098	0.27	0.115	0.23
	First floor framework	0.021	0.79	0.021	0.79	0.026	0.69	0.044	0.48	0.048	0.48	0.049	0.48
	Openings	–	2.65	–	2.65	–	1.98	–	1.98	–	1.65	–	1.65
Renovated	Roof	0.039	0.55	0.044	0.50	0.052	0.44	0.059	0.40	0.043	0.35	0.049	0.33
	Walls	0.025	0.80	0.031	0.69	0.042	0.56	0.049	0.49	0.058	0.41	0.066	0.37
	First floor framework	0.017	0.89	0.021	0.79	0.023	0.75	0.026	0.69	0.032	0.65	0.037	0.59
	Openings	–	2.65	–	2.65	–	1.98	–	1.98	–	1.65	–	1.65

Table 4
Main requirements to verify compliance with the CTE-DB-HE 2022 [45,46] for new and renovated buildings in all representative cities.

Requirement		Las Palmas		Málaga		Sevilla		Barcelona		Madrid		León	
		New	Renovated	New	Renovated	New	Renovated	New	Renovated	New	Renovated	New	Renovated
CTE-DB-HE1 2022 [45,46]	Coefficient limit of global heat transfer through the thermal envelope of the building [(a)] ($W/m^2·K$)	0.86	1.07	0.80	0.94	0.77	0.90	0.72	0.81	0.67	0.70	0.62	0.62
	Energy demand limit for heating [(b)] ($kWh/m^2·year$)	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
	Energy demand limit for cooling [(c)] ($kWh/m^2·year$)	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
	Solar control parameter limit ($kWh/m^2·month$)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Air change ratio limit with a differential pressure of 50 Pa (h^{-1})	3.00	N/A	3.00	N/A	3.00	N/A	3.00	N/A	3.00	N/A	3.00	N/A
CTE-DB-HE4 2022 [45,46]	Minimum renewable energy contribution to meet DHW demand (–)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
CTE-DB-HE5 2022 [45,46]	Minimum installed power in electrical power generation systems from renewable energy sources (kW)	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52
CTE-DB-HE0 2022 [45,46]	Non-renewable primary energy consumption limit ($kWh/m^2·year$)	25.00	50.00	25.00	50.00	28.00	55.00	32.00	65.00	38.00	70.00	43.00	80.00
	Total primary energy consumption limit ($kWh/m^2·year$)	46.00	63.25	50.00	75.00	56.00	80.00	64.00	90.00	76.00	105.00	86.00	115.00
	Maximum number of hours outside the setpoint (h)	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00	350.00

Notes: Non-compliance with requirement [(a)] can be compensated for by meeting requirements [(b)] and [(c)]. N/A is not applicable.

performance certification of residential buildings, which allows the verification of compliance with the CTE-DB-HE 2019 [45] and is recognized by the Ministry for the Ecological Transition and Demographic Challenge and by the Ministry of Transport, Mobility and Urban Agenda.

3. Results and discussion

3.1. Energy and environmental impact of the CTE-DB-HE 2022

The main parameters for the verification of compliance with the CTE-DB-HE 2022 [45,46], the energy impact, the environmental impact and the ratings of the energy performance certificates were evaluated for each representative city and case study. The results obtained are presented in Table 6.

Regarding compliance with the CTE-DB-HE 2022 [45,46], it was verified that, to comply with the CTE-DB-HE1 2022 [45,46] and the CTE-DB-HE0 2022 [45,46], the limit values of Table 4 must not be exceeded. Moreover, to meet the requirements of the CTE-DB-HE4 2022 [45,46] and the CTE-DB-HE5 2022 [45,46], the minimum values of Table 4 must be reached or exceeded. Cases 1–3 meet the CTE-DB-HE 2022 [45,46] requirements for new buildings, and cases 4–6 meet the CTE-DB-HE 2022 [45,46] requirements for renovated buildings (Table 6).

The new and renovated buildings in Las Palmas and Málaga comply with the CTE-DB-HE1 2022 [45,46], since although their coefficients of global heat transfer through the thermal envelope of the building exceed the established limit values, their energy demands for both heating and cooling do not exceed 15.00 $kWh/m^2·year$ (Tables 4 and 6). In addition, the energy demand for heating is less than 15.00 $kWh/m^2·year$, and the energy demand for cooling is less than 15.00 $kWh/m^2·year$ in all cases and in all representative cities, except in Sevilla, where the energy demands for cooling of new and renovated buildings exceed 15.00 $kWh/m^2·year$ by 2.89 $kWh/m^2·year$ and 3.04 $kWh/m^2·year$, respectively (Table 6).

For all the different systems used, the minimum renewable energy contribution to meet DHW demand of 0.60 required by the CTE-DB-HE4 2022 [45,46] has been exceeded (Tables 4 and 6).

NZEBs are achieved in all cases, for both new and renovated buildings, as neither the limit values of non-renewable primary energy consumption nor the limit values of total primary energy consumption required for new buildings in the corresponding WCZs are exceeded (Tables 4 and 6). In addition, in all cases, the buildings are not outside the setpoint at any time, thus complying with the CTE-DB-HE0 2022 [45,46].

The maximum energy efficiency ratings (class A) for both non-renewable primary energy consumption and CO_2 emissions are achieved in all cases in Barcelona, Madrid and León, as well as in cases 2 and 5 in Málaga and cases 1–3, 5 and 6 in Sevilla (Table 6). The best ratings in Las Palmas are achieved in cases 2 and 5, obtaining class B in non-renewable primary energy consumption and class A in CO_2 emissions, similar to those obtained in cases 3 and 6 in Málaga and in case 4 in Sevilla (Table 6).

3.2. Evolution of regulations for energy saving in buildings

López-Ochoa et al. [25] analysed the impact of the evolution of the CTE-DB-HE [39–45] in the Spanish residential sector. Table 7 presents the evolution of the indicators considered by the main energy-saving requirements for residential buildings from the NBE-CT-79 [64] to the CTE-DB-HE 2022 [45,46] with the different transpositions of the EPBD [1,2,4]. From Table 7, the evolution can be summarized as follows:

- The CTE-DB-HE 2013 [42–44], the CTE-DB-HE 2019 [45] and the CTE-DB-HE 2022 [45,46] require the limitation on energy consumption. In contrast, the CTE-DB-HE 2013 [42–44] only limits the

Table 6
Main parameters for the verification of compliance with the CTE-DB-HE 2022 [45,46], the energy impact, the environmental impact and the ratings of the energy performance certificates for each representative city and case study.

City	Case	K (W/ $m^2 \cdot K$)	$q_{sol;jul}$ (kWh/ $m^2 \cdot$month)	n_{50} (h^{-1})	ED_{heat} (kWh/ $m^2 \cdot$year)	ED_{cool} (kWh/ $m^2 \cdot$year)	ED_{DHW} (kWh/ $m^2 \cdot$year)	FEC_{heat} (kWh/ $m^2 \cdot$year)	FEC_{cool} (kWh/ $m^2 \cdot$year)	FEC_{DHW} (kWh/ $m^2 \cdot$year)	FEC_{vent} (kWh/ $m^2 \cdot$year)	PV_{self} (kWh/ $m^2 \cdot$year)	f_{RE}(−)	NRPEC (kWh/ $m^2 \cdot$year)	R_{NRPEC} (−)	RPEC (kWh/ $m^2 \cdot$year)	TPEC (kWh/ $m^2 \cdot$year)	EM (kg CO_2/ $m^2 \cdot$year)	R_{EM} (−)
Las Palmas	1	0.89	0.51	2.97	0.00	13.46	21.35	0.00	1.86	9.13	0.23	6.31	0.6067	17.00	C	19.45	36.45	3.93	B
	2	0.89	0.51	2.97	0.00	13.46	21.35	0.00	1.86	25.12	0.23	6.31	0.9236	8.27	B	32.27	40.54	2.08	A
	3	0.89	0.51	2.97	0.00	13.46	21.35	0.00	2.91	2.99	1.02	10.02	0.8598	20.26	C	23.31	43.57	5.38	C
	4	1.09	0.51	2.97	0.00	13.11	21.35	0.00	1.83	9.13	0.23	6.21	0.6067	16.88	C	19.35	36.23	3.90	B
	5	1.09	0.51	2.97	0.00	13.11	21.35	0.00	1.83	25.12	0.23	6.21	0.9236	8.15	B	32.17	40.33	2.05	A
	6	1.09	0.51	2.97	0.00	13.11	21.35	0.00	2.82	2.96	1.01	10.02	0.8613	19.86	C	23.30	43.16	5.27	C
Málaga	1	0.83	0.57	2.97	0.39	12.15	22.06	0.43	1.21	9.28	0.15	6.53	0.6128	14.22	B	20.66	34.87	2.90	B
	2	0.83	0.57	2.97	0.39	12.15	22.06	0.46	1.21	25.95	0.15	6.53	0.9236	4.91	A	34.25	39.15	0.93	A
	3	0.83	0.57	2.97	0.39	12.15	22.06	0.05	2.38	3.72	1.29	9.39	0.8315	14.52	B	25.99	40.51	2.46	A
	4	0.99	0.57	2.97	0.95	12.11	22.06	1.03	1.23	9.28	0.15	6.49	0.6128	14.97	B	20.63	35.60	3.06	B
	5	0.99	0.57	2.97	0.95	12.11	22.06	1.11	1.23	25.95	0.15	6.49	0.9236	5.00	A	34.89	39.89	0.94	A
	6	0.99	0.57	2.97	0.95	12.11	22.06	0.12	2.38	3.77	1.31	9.39	0.8289	14.80	B	26.44	41.24	2.51	A
Sevilla	1	0.63	0.37	2.98	0.99	17.89	22.06	1.08	3.02	9.12	0.30	6.84	0.6197	18.62	A	21.94	40.56	3.67	A
	2	0.63	0.37	2.98	0.99	17.89	22.06	1.17	3.02	25.95	0.30	6.84	0.9236	8.79	A	36.09	44.89	1.59	A
	3	0.63	0.37	2.98	0.99	17.89	22.06	0.15	4.06	3.58	1.20	10.28	0.8376	17.56	A	27.95	45.51	2.97	A
	4	0.80	0.37	2.98	2.15	18.04	22.06	2.34	3.08	9.12	0.30	6.84	0.6197	20.23	B	21.97	42.20	4.00	A
	5	0.80	0.37	2.98	2.15	18.04	22.06	2.53	3.08	25.95	0.30	6.84	0.9236	9.03	A	37.52	46.54	1.63	A
	6	0.80	0.37	2.98	2.15	18.04	22.06	0.33	4.12	3.69	1.24	10.28	0.8328	18.32	A	28.93	47.25	3.10	A
Barcelona	1	0.54	0.35	2.63	4.91	5.49	22.85	5.33	0.00	9.74	0.00	5.25	0.6076	17.94	A	19.20	37.14	3.80	A
	2	0.54	0.35	2.63	4.91	5.49	22.85	5.77	0.00	26.88	0.00	5.25	0.9236	2.78	A	38.81	41.59	0.59	A
	3	0.54	0.35	2.63	4.91	5.49	22.85	0.98	0.70	4.06	1.39	8.65	0.8221	13.93	A	28.82	42.75	2.36	A
	4	0.73	0.35	2.62	8.69	5.30	22.85	9.44	0.00	9.74	0.00	5.17	0.6076	22.83	A	19.15	41.98	4.83	A
	5	0.73	0.35	2.62	8.69	5.30	22.85	10.22	0.00	26.88	0.00	5.17	0.9236	3.15	A	43.30	46.46	0.67	A
	6	0.73	0.35	2.62	8.69	5.30	22.85	1.81	0.66	4.21	1.44	8.65	0.8157	15.88	A	31.94	47.82	2.69	A
Madrid	1	0.48	0.56	2.69	8.99	13.69	23.18	9.78	1.76	10.03	0.22	6.52	0.6021	27.43	A	21.40	48.83	5.64	A
	2	0.48	0.56	2.69	8.99	13.69	23.18	10.58	1.76	27.27	0.22	6.52	0.9236	7.08	A	46.26	53.34	1.34	A
	3	0.48	0.56	2.69	8.99	13.69	23.18	1.92	2.90	4.93	1.61	8.96	0.7872	22.21	A	34.02	56.22	3.76	A
	4	0.62	0.56	2.67	13.25	13.70	23.18	14.40	1.76	10.03	0.22	6.52	0.6021	32.93	A	21.42	54.36	6.81	A
	5	0.62	0.56	2.67	13.25	13.70	23.18	15.58	1.76	27.27	0.22	6.52	0.9236	7.51	A	51.40	58.91	1.43	A
	6	0.62	0.56	2.67	13.25	13.70	23.18	2.88	2.91	5.11	1.68	8.96	0.7794	24.57	A	37.56	62.14	4.16	A
León	1	0.44	0.52	2.70	13.61	2.54	24.27	14.79	0.00	10.52	0.00	4.07	0.6012	30.12	A	18.79	48.91	6.38	A
	2	0.44	0.52	2.70	13.61	2.54	24.27	16.01	0.00	28.55	0.00	4.07	0.9236	3.79	A	49.89	53.67	0.80	A
	3	0.44	0.52	2.70	13.61	2.54	24.27	2.91	0.26	4.82	1.56	8.09	0.8014	18.67	A	36.35	55.03	3.16	A
	4	0.58	0.52	2.68	19.09	2.37	24.27	20.75	0.00	10.52	0.00	4.01	0.6012	37.21	A	18.75	55.96	7.88	A
	5	0.58	0.52	2.68	19.09	2.37	24.27	22.46	0.00	28.55	0.00	4.01	0.9236	4.34	A	56.44	60.78	0.92	A
	6	0.58	0.52	2.68	19.09	2.37	24.27	4.16	0.24	5.01	1.63	8.09	0.7935	21.58	A	40.89	62.47	3.66	A

Note: K is coefficient of global heat transfer through the thermal envelope of the building; $q_{sol;jul}$ is solar control parameter; n_{50} is air change ratio with a differential pressure of 50 Pa; ED is energy demand; heat is for heating service; cool is for cooling service; and DHW is for DHW service; FEC is final energy consumption; vent is for ventilation service; PV_{self} is photovoltaic solar self-consumption; f_{RE} is renewable energy contribution to meet DHW demand; NRPEC is non-renewable primary energy consumption; R is rating; RPEC is renewable primary energy consumption; TPEC is total primary energy consumption; and EM is CO_2 emissions.

Table 7
Evolution of the indicators of the main energy-saving requirements related to the different regulations for energy saving in buildings.

		NBE-CT-79 [64]	CTE-DB-HE 2009 [39–41] (EPBD 2002 [4])	CTE-DB-HE 2013 [42–44] (EPBD 2010 [1])	CTE-DB-HE 2019 [45] (EPBD 2010 [1])	CTE-DB-HE 2022 [45,46] (EPBD 2018 [2])
Limitation on energy consumption	Non-renewable primary energy consumption	No	No	Yes	Yes	Yes
	Total primary energy consumption	No	No	No	Yes	Yes
	Number of hours outside the setpoint	No	No	No	Yes	Yes
Conditions for controlling energy demand	Thermal transmittances for different elements of the thermal envelope	Yes	Yes	Yes	Yes	Yes
	Coefficient of global heat transfer through the thermal envelope of the building	Yes	No	No	Yes	Yes
	Energy demand for heating	No	Yes	Yes	No	Yes
	Energy demand for cooling	No	Yes	Yes	No	Yes
	Solar control parameter	No	No	No	Yes	Yes
	Air permeability of openings	Yes	Yes	Yes	Yes	Yes
	Air change ratio with a differential pressure of 50 Pa	No	No	No	Yes	Yes
	Thermal transmittances for interior partitions	No	No	Yes	Yes	Yes
	Superficial and interstitial condensation	Yes	Yes	Yes	Yes	Yes
Minimum renewable energy contribution to meet DHW demand		No	Yes	Yes	Yes	Yes
Minimum generation of electrical energy from renewable energy sources		No	No	No	No	Yes
Minimum provisions for electric vehicle charging infrastructure		No	No	No	No	Yes
NZEB definition		No	No	Yes	Yes	Yes

non-renewable primary energy consumption and defines first-generation NZEBs. Both the CTE-DB-HE 2019 [45] and the CTE-DB-HE 2022 [45,46] additionally limit the total primary energy consumption and the number of hours outside the setpoint, and define second-generation NZEBs.

- Limitations on the coefficient of global heat transfer through the thermal envelope of the building, which were previously only considered in the NBE-CT-79 [64], are a requirement in both the CTE-DB-HE 2019 [45] and the CTE-DB-HE 2022 [45,46].
- Limitations on the energy demands for heating and cooling are present in the CTE-DB-HE 2009 [39–41], the CTE-DB-HE 2013 [42–44] and the CTE-DB-HE 2022 [45,46]. The CTE-DB-HE 2009 [39–41] required that the combined energy demands (energy demand for heating and cooling) of the target building not exceed the combined energy demand of the corresponding reference building. The CTE-DB-HE 2022 [45,46] allows for fulfilment of the limitation on the coefficient of global heat transfer through the thermal envelope if the energy demands for heating and cooling equal to those demanded by the Passive House standard are not exceeded [65]. In addition, Borrallo-Jiménez et al. [66] discovered that the requirements of the CTE-DB-HE 2019 [45] and the CTE-DB-HS3 2019 [39–41,44,45] are equally or more restrictive than those of the Passive House standard [65] and that the Passive House standard [65] does not guarantee a competitive advantage in warm Spanish zones.
- The minimum renewable energy contribution to meet DHW demand is a requirement that has been maintained from the CTE-DB-HE 2009 [39–41] through to the CTE-DB-HE 2022 [45,46]. Although these documents presented different alternatives to meet this requirement, both the CTE-DB-HE 2009 [39–41] and the CTE-DB-HE 2013 [42–44] focused mainly on solar thermal energy.
- The requirements related to the minimum generation of electrical energy from renewable energy sources and the minimum provisions for the infrastructure for electric vehicle charging are exclusive to the CTE-DB-HE 2022 [45,46].

To evaluate the impact of the CTE-DB-HE 2022 [45,46] on new buildings with respect to the previous regulations for energy saving in buildings, Refs. [51,52] were used. The impact of both the CTE-DB-HE 2009 [39–41] and the CTE-DB-HE 2013 [42–44] in WCZs A, B and C was studied in Ref. [52], while in WCZs D and E, it was studied in Ref. [51]. From the results obtained by applying the CTE-DB-HE 2022 [45,46], those corresponding to case 1 were used to allow homogeneous comparison, since in each regulation, the reference systems are defined by the regulation itself. No previous study in the literature has evaluated the impact of previous regulations for energy saving in buildings in WCZ α. In this study, the energy and environmental impacts are estimated in WCZ α by applying the methodology used in Ref. [52]: For the NBE-CT-79 [64], the energy demand for cooling and the DHW energy demand were obtained from Ref. [67]; for the CTE-DB-HE 2009 [39–41], its study was discarded because WCZ α was not present; and, for the CTE-DB-HE 2013 [42–44], the energy demand for cooling was set to the limit required by the CTE-DB-HE1 2013 [42–44], the energy demand for DHW was calculated according to the CTE-DB-HE4 2013 [42–44], and the solar contribution was 0.70, the most restrictive minimum required by the CTE-DB-HE4 2009 [39–41] and the CTE-DB-HE4 2013 [42–44]. In addition, the results corresponding to existing multi-family buildings built before 2008 from Refs. [51,52] were assimilated to those buildings that meet the NBE-CT-79 [64], and it was necessary to calculate the primary renewable energy consumption and the total primary energy consumption for the building that meet the previous regulations to the CTE-DB-HE 2022 [45,46]. Table 8 presents the energy and environmental impacts of all regulations for energy saving on new buildings.

On the one hand, in peninsular cities, the application of the CTE-DB-HE 2022 [45,46] reduces the energy demand for heating by between 92% (WCZ E) and 99% (WCZ A) with respect to the NBE-CT-79 [64], between 76% (WCZ E) and 96% (WCZ A) with respect to the CTE-DB-HE 2009 [39–41], and between 61% (WCZ E) and 86% (WCZ A) with respect to the CTE-DB-HE 2013 [42–44] (Table 8). Moreover, the energy demand for cooling is reduced by between 28% (WCZ D) and 57% (WCZs A and B) with respect to the NBE-CT-79 [64], between less than 1% (WCZ A) and 10% (WCZ B) with respect to the CTE-DB-HE 2009 [39–41], and between 4% (WCZ D) and 13% (WCZ C) with respect to the CTE-DB-HE 2013 [42–44]. In WCZ E, energy demand for cooling is increased by 54% with respect to the CTE-DB-HE 2009 [39–41] and 8% with respect to the CTE-DB-HE 2013 [42–44] (Table 8). The non-renewable primary energy consumption is reduced by between 85% (WCZs A and B) and 88% (WCZs C and E) with respect to the NBE-CT-79 [64], between 57% (WCZs A and B) and 67% (WCZ C) with respect to

Table 8
Energy and environmental impacts of all regulations for energy saving on new buildings.

City	Regulations for energy saving in buildings	ED_{heat} (kWh/ m^2·year)	ED_{cool} (kWh/ m^2·year)	ED_{DHW} (kWh/ m^2·year)	NRPEC (kWh/ m^2·year)	RPEC (kWh/ m^2·year)	TPEC (kWh/ m^2·year)	EM (kg CO_2/ m^2·year)
Las Palmas	NBE-CT-79 [64]	0.00	19.60	11.80	43.92	0.75	44.67	13.45
	CTE-DB-HE 2013 [42–44]	0.00	15.00	17.60	28.76	12.87	41.63	10.10
	CTE-DB-HE 2022 [45,46]	0.00	13.46	21.35	17.00	19.45	36.45	3.93
Málaga	NBE-CT-79 [64]	41.40	28.40	12.30	97.21	6.17	103.38	19.41
	CTE-DB-HE 2009 [39–41]	9.05	12.20	18.25	33.07	13.56	46.63	6.50
	CTE-DB-HE 2013 [42–44]	2.78	13.55	18.25	26.28	13.81	40.09	5.00
	CTE-DB-HE 2022 [45,46]	0.39	12.15	22.06	14.22	20.66	34.87	2.91
Sevilla	NBE-CT-79 [64]	52.90	41.20	12.30	124.59	8.88	133.47	24.68
	CTE-DB-HE 2009 [39–41]	12.85	19.80	18.24	43.04	16.97	60.01	8.30
	CTE-DB-HE 2013 [42–44]	6.54	19.49	18.24	34.58	16.87	51.45	6.52
	CTE-DB-HE 2022 [45,46]	0.99	17.89	22.06	18.62	21.94	40.56	3.69
Barcelona	NBE-CT-79 [64]	87.40	14.60	12.80	143.87	3.57	147.44	29.86
	CTE-DB-HE 2009 [39–41]	24.93	5.69	18.96	54.97	7.07	62.05	11.41
	CTE-DB-HE 2013 [42–44]	14.22	6.31	18.96	41.73	7.14	48.87	8.58
	CTE-DB-HE 2022 [45,46]	4.91	5.49	22.85	17.94	19.20	37.14	3.86
Madrid	NBE-CT-79 [64]	121.20	19.10	13.00	192.25	4.68	196.93	39.92
	CTE-DB-HE 2009 [39–41]	42.74	14.09	19.27	79.02	14.75	93.77	16.15
	CTE-DB-HE 2013 [42–44]	25.06	14.28	19.27	56.34	14.70	71.03	11.34
	CTE-DB-HE 2022 [45,46]	8.99	13.69	23.18	27.43	21.40	48.83	5.72
León	NBE-CT-79 [64]	179.10	0.00	13.60	249.25	1.05	250.30	52.78
	CTE-DB-HE 2009 [39–41]	56.69	1.65	20.26	88.04	10.83	98.88	18.58
	CTE-DB-HE 2013 [42–44]	34.46	2.35	20.26	59.97	10.86	70.83	12.60
	CTE-DB-HE 2022 [45,46]	13.61	2.54	24.27	30.12	18.79	48.91	6.45

the CTE-DB-HE 2009 [39–41], and between 46% (WCZs A and B) and 57% (WCZ C) with respect to the CTE-DB-HE 2013 [42–44] (Table 8). The total primary energy consumption is reduced by between 66% (WCZ A) and 80% (WCZ E) with respect to the NBE-CT-79 [64], between 25% (WCZ A) and 51% (WCZ E) with respect to the CTE-DB-HE 2009 [39–41], and between 13% (WCZ A) and 31% (WCZs D and E) with respect to the CTE-DB-HE 2013 [42–44] (Table 8). Finally, the CO_2 emissions are reduced by between 85% (WCZs A and B) and 88% (WCZ E) with respect to the NBE-CT-79 [64], between 55% (WCZ A) and 67% (WCZ C) with respect to the CTE-DB-HE 2009 [39–41], and between 42% (WCZ A) and 56% (WCZ C) with respect to the CTE-DB-HE 2013 [42–44] (Table 8).

On the other hand, in WCZ α, which is characteristic of the cities of the Canary Islands, the implementation of the CTE-DB-HE 2022 [45,46] reduces the energy demand for cooling by 31% with respect to the NBE-CT-79 [64] and the CTE-DB-HE 2013 [42–44]; the non-renewable primary energy consumption is reduced by 70% with respect to the NBE-CT-79 [64] and 58% with respect to the CTE-DB-HE 2013 [42–44]; the total primary energy consumption is reduced by 18% with respect to the NBE-CT-79 [64] and 12% with respect to the CTE-DB-HE 2013 [42–44]; and the CO_2 emissions are reduced by 71% with respect to the NBE-CT-79 [64] and 61% with respect to the CTE-DB-HE 2013 [42–44] (Table 8).

Pagliaro et al. [68] analysed the energy performance certificate data of residential buildings in Italy and found that both the non-renewable primary energy consumption and CO_2 emissions were reduced by more than 25% with the implementation of the EPBD 2002 [4] with respect to existing buildings built before 2005 and by approximately 40% with the implementation of the EPBD 2010 [1] with respect to existing buildings built before 2015.

3.3. Comparison between the CTE-DB-HE 2019 and the CTE-DB-HE 2022

Applying the CTE-DB-HE 2019 [45], Cerezo-Narváez et al. [26] found energy savings of between 69% and 127%, a reduction in CO_2 emissions of between 65% and 118%, and a decrease in energy bills of between 71% and 125%, with respect to the NBE-CT-79 [64]; and Monzón-Chavarrías et al. [10] found reductions in CO_2 emissions of between 71% and 94%, renovating buildings built in 1961–1980 period.

The requirement introduced by the CTE-DB-HE 2022 [45,46] to incorporate photovoltaic solar systems is a significant advantage over the CTE-DB-HE 2019 [45] for the achievement of NZEBs. Considering the cases studied in Madrid and the thermal envelope recommendations in Annex E of the CTE-DB-HE 2019 [45] and the CTE-DB-HE 2022 [45,46], the cases described in Table 9 are evaluated to compare the achievement of NZEB status by applying the CTE-DB-HE 2019 [45] and the CTE-DB-HE 2022 [45,46].

The final energy consumption, non-renewable primary energy consumption, renewable primary energy consumption, total primary energy consumption and CO_2 emissions for all the proposed cases were evaluated through energy simulation. The final monthly energy consumption, broken down by service, for each proposed case is presented in Fig. 3, and the different energy consumptions and CO_2 emissions are presented in Table 10.

As shown in Table 10, when applying the CTE-DB-HE 2019 [45], the use of heat recovery systems together with natural gas boilers or electric heat pumps is essential to achieve NZEBs, while with biomass boilers, it

Table 9
Case studies for comparing the CTE-DB-HE 2019 [45] and the CTE-DB-HE 2022 [45,46].

Case	Case on which it is based	Heating and DHW system	Thermal solar system for DHW	Photovoltaic solar system	Heat recovery system
A	3	Electric heat pump	No	Yes	No
B	1	Natural gas boiler	Yes	No	No
C	1	Natural gas boiler	Yes	No	Yes
D	2	Biomass boiler	No	No	No
E	2	Biomass boiler	No	No	Yes
F	3	Electric heat pump	No	No	No
G	3	Electric heat pump	No	No	Yes
H	3	Electric heat pump	No	Yes	Yes

[a]With an efficiency of 82.16%.

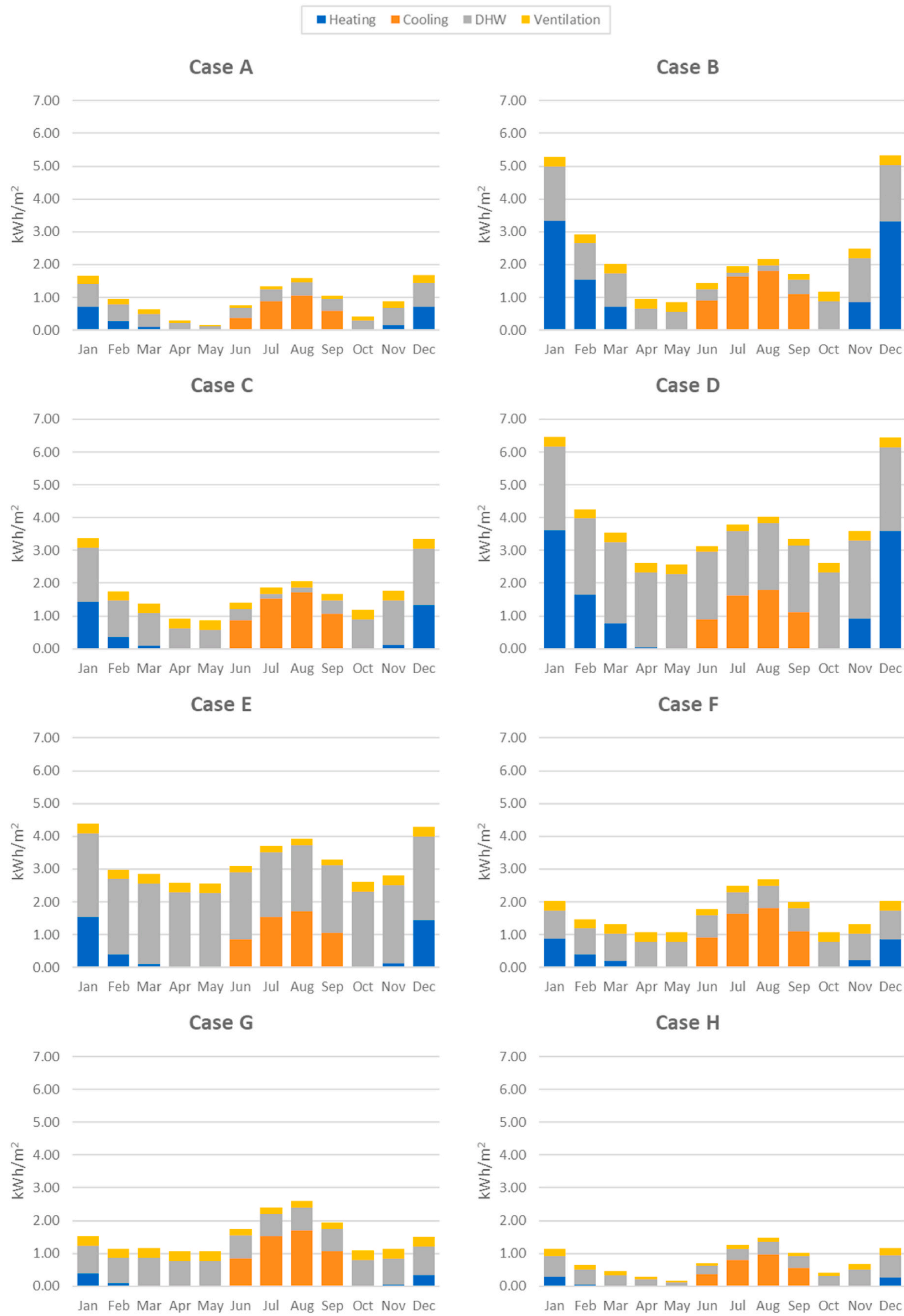

Fig. 3. Final monthly energy consumption, in kWh/m^2, broken down by service, for each proposed case in Madrid.

Table 10
Energy consumptions and CO_2 emissions for each proposed case in Madrid.

Case	FEC (kWh/m^2·year)	NRPEC (kWh/m^2·year)	RPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	EM (kg CO_2/m^2·year)
A	11.37	22.21	34.02	56.22	3.76
B	28.30	40.18	17.57	57.75	7.80
C	21.55	31.92	17.42	49.34	6.08
D	46.35	19.83	42.43	62.26	3.50
E	39.06	18.68	35.11	53.79	3.28
F	20.33	39.72	28.76	68.48	6.73
G	18.35	35.86	23.68	59.54	6.07
H	9.39	18.35	28.93	47.28	3.11

is optional. NZEBs are also achieved without a photovoltaic solar system; with natural gas boilers, thermal solar support systems for DHW and heat recovery systems (case C); with biomass boilers (case D); with biomass boilers and heat recovery systems (case E); and with electric heat pumps and heat recovery systems (case G). Regarding case A, the non-renewable primary energy consumption increases by 44%, while the total primary energy consumption decreases by 12% in case C; the non-renewable primary energy consumption decreases by 11%, while the total primary energy consumption increases by 11% in case D; the non-renewable primary energy consumption decreases by 16% and the total primary energy consumption decreases by 4% in case E; the non-renewable primary energy consumption increases by 61% and the total primary energy consumption increases by 6% in case G (Table 10). Additionally, as expected, with the incorporation of the heat recovery system into the reference case (case H), NZEB status is achieved, and primary energy consumption decreases with respect to case A, thereby reducing the non-renewable primary energy consumption by 17% and the total primary energy consumption by 16% (Table 10).

3.4. Projection for residential building stock in 2030 and 2050

Comparison of the impact on the residential building stock of the CTE-DB-HE 2019 [45] with that of the CTE-DB-HE 2022 [45,46] starts from the scenario in which new homes meet the CTE-DB-HE 2019 [45] for new buildings, while renovated homes meet the CTE-DB-HE 2019 [45] for buildings renovated during the period 2020–2050, obtained in Ref. [25]. The projection model developed in this work to determine the impact of the CTE-DB-HE 2022 [45,46] in 2030 and 2050 is based on an update of the model developed in Ref. [25]. The main parameters of this new model are summarized in Table 11. The new future scenario considered is one in which new homes meet the CTE-DB-HE 2022 [45, 46] for new buildings, while renovated homes meet the CTE-DB-HE 2022 [45,46] for buildings renovated during the period 2023–2050, taking as a starting point the results obtained during the period 2020–2022 in Ref. [25]. On the one hand, the 3D model of the building used has been validated as a typical reference building for new and existing Spanish building stock in Ref. [25]. On the other hand, cases 3 and 6 were selected as reference cases for the projection model developed according to the Long-Term Strategy for Energy Renovation in the Building Sector in Spain of 2020 [71] and Integrated National Energy and Climate Plan of 2021–2030 [73]. These cases use an electric heat pump as a heating and DHW system, as well as a photovoltaic solar system, and correspond to new and renovated buildings, respectively. In addition, the design criteria established in this study for the different residential buildings under study ensure compliance with the different requirements of the CTE-DB-HE 2022 [45,46] in each WCZ.

The main energy and environmental indicators of the residential sector in 2020, 2030 and 2050, considering the impact of the CTE-DB-HE 2019 [45] and of the CTE-DB-HE 2022 [45,46], are presented in Fig. 4. Compared to 2020, final energy consumption will decrease by 9% in 2030 and 47% in 2050; the non-renewable primary energy consumption will decrease by 31% in 2030 and 93% in 2050; total primary

Table 11
Main parameters of the projection model developed.

Parameter	Source	Reference
Evolution of the number of homes by WCZ (2020–2050)	López-Ochoa et al.	[25]
	Winter climate zoning	[45,46]
	Continuous Household Survey (2019)	[69]
	Household Projection (2020–2035)	[70]
	Long-Term Strategy for Energy Renovation in the Building Sector in Spain 2020	[71]
Average surface area of homes	Continuous Household Survey (2019)	[69]
Final energy consumption of existing homes for heating and DHW by WCZ (2020–2050)	Energy performance rating for existing buildings	[67]
	Residential final energy consumption (2010–2018)	[72]
Final energy consumption of renovated and new homes for heating and DHW by WCZ (2020–2022)	López-Ochoa et al.	[53]
Final energy consumption of renovated and new homes for heating and DHW by WCZ (2023–2050)	Cases 3 and 6 (case studies in this research)	N/A
Conversion factors from final energy to non-renewable primary energy, total primary energy and CO_2 emissions for electricity, heating and DHW (2020, 2030 and 2050)	López-Ochoa et al.	[25]
	Conversion factors for the different energy carriers	[58]
	Long-Term Strategy for Energy Renovation in the Building Sector in Spain 2020	[71]
	Residential final energy consumption (2010–2018)	[72]
	Integrated National Energy and Climate Plan 2021–2030	[73]

Note: N/A is not applicable.

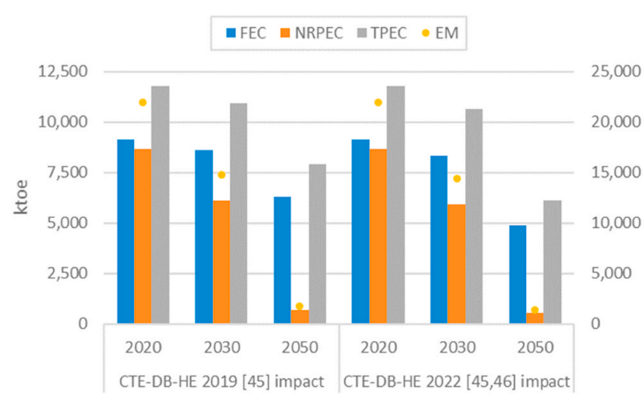

Fig. 4. Main energy and environmental indicators of the residential sector in 2020, 2030 and 2050, considering the impact of the CTE-DB-HE 2019 [45] and of the CTE-DB-HE 2022 [45,46].

energy consumption will decrease by 10% in 2030 and 48% in 2050; and CO_2 emissions will decrease by 35% in 2030 and 94% in 2050 (Fig. 4). With respect to the previous scenario of Ref. [25], the final energy consumption, non-renewable primary energy consumption, total primary energy consumption, and CO_2 emissions will be reduced by 3% in 2030; final energy consumption will be reduced by 23% in 2050; non-renewable primary energy consumption and CO_2 emissions will be reduced by 19% in 2050; and total primary energy consumption will be reduced by 22% in 2050 (Fig. 4).

This research, focused on the achievement of a highly energy-efficient and decarbonized residential building stock in Spain by 2050, satisfactorily meets both the scope and objectives set out in this work. In addition, research on regulations for energy saving in buildings, such as that presented in this study for Spain, can serve as a reference for other Mediterranean and Latin American countries with the corresponding adaptations [74]. Finally, it should be noted that according to the CTE-DB-HE0 2022 [45,46], every residential building designated to become an NZEB should not exceed certain limit values of energy consumption, per square metre and per year, depending on the WCZ where it is located, regardless of its compactness, whether it is a single-family or multi-family building, or whether it is a new or renovated building. Therefore, future research proposes (a) the development of models that consider different additional buildings for the different construction periods that represent the existing building stock in the most precise way possible to define strategies at a regional level for energy renovation of the existing building stock, as in Refs. [75,76]; (b) the study of the implications of different climate change scenarios with regard to both climatie zones and the associated energy impact, as in Refs. [77,78], respectively; and (c) the evaluation of the impact of the implementation of other aspects included in the EPBD 2018 [2], such as smart readiness indicators or building renovation passports.

4. Conclusions

This research analysed in detail the implications of the implementation of the EPBD 2018 [2] in the Spanish residential sector, studying the main novelties introduced by the CTE-DB-HE 2022 [45,46] and evaluating its energy and environmental impacts with respect both to the previous regulations for energy saving in buildings and for the future residential sector in 2030 and 2050.

The NZEBs in compliance with the CTE-DB-HE 2022 [45,46] reduce, at least, the non-renewable primary energy consumption in WCZs A, B, C, D and E by 85% with respect to the NBE-CT-79 [64], 57% with respect to the CTE-DB-HE 2009 [39–41] and 46% with respect to the CTE-DB-HE 2013 [42–44]. Furthermore, these NZEBs reduce, at least, the total primary energy consumption by 66% with respect to the NBE-CT-79 [64], 25% with respect to the CTE-DB-HE 2009 [39–41] and 13% with respect to the CTE-DB-HE 2013 [42–44]. In WCZ α, the new NZEBs reduce non-renewable primary energy consumption by 70% with respect to the NBE-CT-79 [64] and 58% with respect to the CTE-DB-HE 2013 [42–44]. Moreover, these NZEBs reduce total primary energy consumption by 18% with respect to the NBE-CT-79 [64] and 12% with respect to the CTE-DB-HE 2013 [42–44]. In addition, buildings constructed using the CTE-DB-HE 2019 [45] need to use biomass boilers or incorporate photovoltaic solar systems or heat recovery systems to become NZEBs.

The main energy and environmental indicators of the residential building stock in 2050 considering the CTE-DB-HE 2022 [45,46] are reduced by at least 19% with respect to those indicators considering the CTE-DB-HE 2019 [45], achieving reductions of 47% in final energy consumption, 93% in non-renewable primary energy consumption, 48% in total primary energy consumption and 94% in CO_2 emissions compared to 2020 figures.

Therefore, although it is necessary to continue undertaking actions to improve the existing Spanish building stock to achieve the ambitious objectives of the EU, Spain is on the right path towards achieving a highly energy-efficient and decarbonized residential building stock by 2050. In addition, this study can serve as a basis for the achievement of NZEBs in Mediterranean and Latin American countries with climates similar to those of Spain.

Credit author statement

Luis M. López-Ochoa: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition. **Jesús Las-Heras-Casas:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing, Visualization. **Juan M. González-Caballín:** Methodology, Software, Validation, Formal Analysis. Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Manuel Carpio:** Methodology, Software, Validation, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization, Funding Acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This research was supported in part by the Agencia Nacional de Investigación y Desarrollo (ANID) of Chile, through the project ANID BASAL FB210015 CENAMAD.

Appendix A

Table A1
Composition and main characteristics of the opaque enclosures of the study building for Las Palmas, Málaga and Sevilla [52].

Envelope	Layer	Material	Thickness (m)	Conductivity (W/m·K)	Density (kg/m^3)	Specific heat (J/kg·K)
Roof	1	Ceramic-porcelain roof tile	0.020	1.300	2300	840
	2	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.050	1.300	1900	1000
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.020	1180	1000
	4	EPS Expanded polystyrene (0.029 W/m·K)	*	0.029	30	1000
	5	High hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000
Walls	1	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.025	1.300	1900	1000
	2	Perforated brick metric or Catalan ½ foot 40 mm < G < 50 mm	0.115	0.991	2170	1000
	3	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.025	1.300	1900	1000
	4	Mineral wood (0.031 W/m·K)	*	0.031	40	1000
	5	Single LH partition 40 mm < E < 60 mm	0.040	0.445	1000	1000
	6	High hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000

(*continued on next page*)

Table A1 (*continued*)

Envelope	Layer	Material	Thickness (m)	Conductivity (W/m·K)	Density (kg/m^3)	Specific heat (J/kg·K)
First floor framework	1	Wafer or ceramic tile	0.015	1.000	2000	800
	2	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.035	0.700	1350	1000
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.020	1180	1000
	4	EPS Expanded polystyrene (0.029 W/m·K)	*	0.029	30	1000
	5	High hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000

Note: * indicates that the thickness of insulation is variable in each case.

Table A2
Composition and main characteristics of the opaque enclosures of the study building for Barcelona [52].

Envelope	Layer	Material	Thickness (m)	Conductivity (W/m·K)	Density (kg/m^3)	Specific heat (J/kg·K)
Roof	1	Ceramic-porcelain roof tile	0.020	1.300	2300	840
	2	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.040	0.700	1350	1000
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.020	1180	1000
	4	EPS Expanded polystyrene (0.029 W/m·K)	*	0.029	30	1000
	5	High hardness plaster 1200 < d < 1500	0.020	0.560	1350	1000
Walls	1	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.025	1.300	1900	1000
	2	Perforated brick metric or Catalan ½ foot 40 mm < G < 50 mm	0.115	0.991	2170	1000
	3	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.025	1.300	1900	1000
	4	MW Mineral wood (0.031 W/m·K)	*	0.031	40	1000
	5	Single LH partition 40 mm < E < 60 mm	0.050	0.445	1000	1000
	6	High hardness plaster 1200 < d < 1500	0.020	0.560	1350	1000
First floor framework	1	Wafer or ceramic tile	0.015	1.000	2000	800
	2	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.040	1.300	1900	1000
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.020	1180	1000
	4	EPS Expanded polystyrene (0.029 W/m·K)	*	0.029	30	1000
	5	High hardness plaster 1200 < d < 1500	0.020	0.560	1350	1000

Note: * indicates that the thickness of insulation is variable in each case.

Table A3
Composition and main characteristics of the opaque enclosures of the study building for Madrid and León [51].

Enclosure	Layer	Material	Thickness (m)	Conductivity (W/m·K)	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal resistence (m^2·K/W)
Roof	1	Wafer or ceramic tile	0.015	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 500 < d < 750	0.040	0.300	625	1000	
	3	Sublayer felt	0.001	0.050	120	1300	
	4	XPS Expanded with CO_2 (0.034 W/m·K)	*	0.034	38	1000	
	5	Sublayer felt	0.001	0.050	120	1300	
	6	Bitumen felt or sheet	0.003	0.230	1100	1000	
	7	Sublayer felt	0.001	0.050	120	1300	
	8	Cement or lime mortar for masonry and for rendering/plastering 500 < d < 750	0.020	0.300	625	1000	
	9	Expanded clay (loose aggregate)	0.100	0.148	538	1000	
	10	Unidirectional forged concrete infill, 300 mm span	0.300	1.422	1240	1000	
	11	Unventilated 10 cm horizontal air chamber	–	–	–	–	0.18
	12	Plasterboard (PYL) 750 < d < 900	0.015	0.250	825	1000	
Exterior façade wall	1	Cement or lime mortar for masonry and for rendering/plastering 500 < d < 750	0.015	0.300	625	1000	
	2	Perforated metric or Catalan brick of ½ foot 40 mm < G < 60 mm	0.115	0.667	1140	1000	
	3	Cement mortar with high resistance to filtration	0.015	1.800	625	800	
	4	MW Mineral wool (0.031 W/m·K)	*	0.031	40	1000	
	5	Slightly ventilated 2 cm vertical air chamber	–	–	–	–	0.085
	6	MW Mineral wool (0.031 W/m·K)	*	0.031	40	1000	
	7	Low density polyethylene (LDPE)	0.001	0.330	920	2200	
	8	Plasterboard (PYL) 750 < d < 900	0.015	0.250	825	1000	
First floor framework	1	Wafer or ceramic tile	0.015	1.000	2000	800	
	2	MW Mineral wool (0.031 W/m·K)	*	0.031	40	1000	
	3	Unidirectional forged concrete infill, 300 mm span	0.300	1.422	1240	1000	
	4	MW Mineral wool (0.031 W/m·K)	*	0.031	40	1000	
	5	Plasterboard (PYL) 750 < d < 900	0.015	0.250	825	1000	

Note: * indicates that the thickness of insulation is variable in each case.

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