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Research paper

Towards nearly zero-energy educational buildings with the implementation of the Energy Performance of Buildings Directive via energy rehabilitation in cold Mediterranean zones: The case of Spain

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ABSTRACT

The European Union, through the Energy Performance of Buildings Directive and the Energy Efficiency Directive, has been establishing requirements and expectations regarding energy savings and efficiency in buildings. The objective of this study is to explore energy rehabilitation solutions for educational buildings of the 1980s in cold climate zones of Spain by applying the corresponding adaptation of the European legislation, which is the Basic Document for Energy Saving of the Technical Building Code. The evolution of regulation is studied using three cases, and 12 proposals for achieving nearly zero-energy educational buildings are studied. The analysis of the results obtained shows how changes in energy and environmental policies affect those buildings. Regarding the baseline building, average reductions of more than 66% in non-renewable primary energy consumption and of more than 71% in CO_2 emissions were observed. Additional reductions of at least 10% in non-renewable primary energy consumption and 8% in CO_2 emissions are achieved with the alternatives proposed to achieve nearly zero-energy educational buildings. The knowledge of the sector is deepened with this study, which allows the design of future energy rehabilitation policies and promotes policy changes.

1. Introduction

In the European Union, the non-residential sector consumed 146.9 Mtoe, which makes this sector responsible for 13.6% of the total energy consumption (European Union, 2017). Non-residential buildings account for 25% of the total stock and comprise a more complex and heterogeneous sector compared to the residential sector. Educational buildings are the third largest category, with a floor space corresponding to 17% of the total non-residential floor space, and the category's final energy consumption (FEC) is 12% of the total FEC for non-residential buildings (Buildings Performance Institute Europe, 2011). The objective of European policies focused on buildings is to achieve a sustainable and competitive low-carbon economy by 2020. Therefore, for non-residential buildings, the aim is to reduce energy consumption and achieve nearly zero-energy buildings (NZEBs) via rehabilitation measures and the use of renewable energy sources (D'Agostino et al., 2017b). The general standards and requirements that Member States must meet to ensure energy efficiency and savings for buildings are established in Directive 2010/31/EU (European Union, 2010), which is a consolidated version of Directive 2002/91/EC (European Union, 2002) and is strengthened by Directive 2012/27/EU (European Union, 2012).

The energy saving and efficiency policies, as well as the energy performance certification methods, for buildings from the different European Mediterranean countries are different even if their climates are similar (Abela et al., 2016; Asdrubali et al., 2008) and are based on the same policy framework. To create a future common regulation for all these countries, it is necessary to further the knowledge of each national regulation and standardize the NZEB. There are several studies on the energy and environmental impacts of European Performance of Buildings Directive (EPBD) implementation in the residential sector of Mediterranean countries such as Portugal (Magalhães and Leal, 2014), Spain (López-Ochoa et al., 2019), Italy (Salvalai et al., 2015), Greece (Gaglia et al., 2017), and Cyprus (Fokaides et al., 2017). In the residential sector, several studies have been conducted, and there are entire databases; however, in the non-residential sector, this is not the case because the impacts of EPBD implementation are much more diverse. This creates the need to study each of the different existing typologies, with the goal of creating

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Abbreviations

CTE-DB-HE:	Basic Document for Energy Saving of the Technical Building Code (Documento Básico de Ahorro de Energía del Código Técnico de la Edificación)
DHW:	Domestic Hot Water
ED:	Energy Demand
EDI:	Energy Demand Index
EM:	CO_2 Emissions
EMI:	CO_2 Emissions Index
EPBD:	Energy Performance of Buildings Directive
FEC:	Final Energy Consumption
NBE-CT-79:	Basic Document Norm on Thermal Conditions in Buildings (Norma Básica de Edificación sobre Condiciones Térmicas en los Edificios)
NRPEC:	Non-Renewable Primary Energy Consumption
NRPECI:	Non-Renewable Primary Energy Consumption Index
NZEB:	Nearly Zero-Energy Building

distinctive models to understand the existing stock. The Green-Building Programme promoted and improved energy efficiency in new and existing European non-residential buildings. The overall results of the data collected were focused on building characteristics, energy performance, efficiency measures and energy savings (D'Agostino et al., 2017a; Valentová and Bertoldi, 2011). The development of models will enable administrations to define nearly zero-energy standards by the end of 2018 (European Union, 2010) and outline energy rehabilitation scenarios that will consider at least a 3% annual renewal of the existing stock (European Commission, 2011; European Union, 2012).

Most Southern European countries are not adequately prepared for the implementation of the NZEB standard, especially given the challenge and opportunity provided by the rehabilitation of existing buildings. Therefore, a common approach to further develop NZEB targets, concepts and definitions is essential (Attia et al., 2017). Moreover, the cost-optimal measures to design NZEBs vary with climate (D'Agostino and Parker, 2018). However, with the aim of extrapolating the results, it is interesting to compare the energy performance and NZEB requirements between climatically different European zones (Ahmed et al., 2018). Finally, to design cost-optimal nearly zero-energy non-residential buildings in temperate European climates, it is important to consider the thermal envelope and the heating and cooling systems, requiring both an improvement in energy efficiency and the integration of renewable energy (Congedo et al., 2015).

Within the non-residential building sector, this study focuses on energy rehabilitation of educational buildings. Dascalaki and Sermpetzoglou (2011) analyzed 135 educational buildings in Greece and found that, between insulated and non-insulated school buildings, the heating energy consumption was reduced by 14% in the warmer climate zone and 25% in the colder climate zone. In addition, with different energy conservation measures, the primary energy savings could be ranged from 2 to 70%, and the corresponding CO_2 emissions (EM) reduction could be ranged from 7 to 83%. Meanwhile, Katafygiotou and Serghides (2014) used surveys to study the energy consumption of existing educational buildings in Cyprus and analyzed them as a whole and by climate zone. The results obtained coincided with those obtained in Greece (Dascalaki and Sermpetzoglou, 2011) due to the similar climatic conditions. They found that the maximum possible savings in primary energy was as high as 31.9% by adding insulation to the walls and roof, as high as 3.6% by replacing windows, as high as 23.5% by improving the heating system, and as high as 10.6% by installing photovoltaic panels. In addition, they recommended to install thermal solar systems.

In Italy, Capozzoli et al. (2015) developed two models that estimate the heating energy consumption of school buildings for local planning policies in the province of Turin. They analyzed the consumption of eighty school buildings for this purpose and discovered that the most influencing parameters were the gross heated volume, heat transfer surface, boiler size, and thermal transmittance of windows. Meanwhile, Rospi et al. (2017) studied the rehabilitation of 15 educational buildings in the city of Matera. Meeting the requirements of the Italian adaptation of the 2002 EPBD (European Union, 2002), the maximum savings achieved by buildings was between 78% and 86%. Additionally, Salvalai et al. (2017) analyzed different energy conservation strategies for existing school buildings in Lecco, a Pre-Alpine region in the Lombardy region. The results implied that the new building envelope meets the U-value limits of the Italian legislation due to the adaptation of the 2010 EPBD (European Union, 2010). It was found that primary energy demand for heating can be reduced by 22.17% with external insulation of the building envelope, by 9.67% with window replacement and by 36.44% with new plant installation. The improvement of external insulation was the best cost-benefit strategy because window replacement were subjected to a requalification in time and the high cost of intervention was due to new plant installation. In addition, it was proposed to install photovoltaic panels.

Dall'O' and Sarto (2013) studied the potential and limitations of improving energy efficiency of space heating in 49 school building complexes in the Lombardy region. This study demonstrated that achieving NZEB and reaching high levels of energy performance to comply with the 2010 EPBD (European Union, 2010) could be very difficult or not cost-effective in many cases. Sometimes this cost of energy rehabilitation was comparable with the cost of a new building. Furthermore, to achieve a nearly zero-energy educational building, Ascione et al. (2017) applied cost-optimal retrofit solutions to a Department of the University of Sannio in Benevento. The most profitable configurations of energy retrofit included installation of an air-source heat pump for space heating and of a full-roof photovoltaic system. The improvement that could be achieved by refurbishing the building envelope was not feasible. Moreover, the primary energy demand of the building could be drastically lowered to a value of approximately 12 kWh/m^2 year. Finally, Zinzi et al. (2016) presented the deep energy retrofit of an existing school in the framework of the "School of the Future" European Union Project (Erhorn-Kluttig and Erhorn, 2014). They focused their efforts on improving the thermal envelope and efficiency of the heating system and found space heating savings of 84%; electricity savings, including renewable energy, of 100%; total final energy savings of 84%; and total primary energy savings of 86%.

In Spain, the 2002 EPBD (European Union, 2002) was adapted through the Basic Document for Energy Saving of the Technical Building Code (CTE-DB-HE 2009) (Spanish Ministry of Housing, 2006, 2007, 2009). Subsequently, the adaptation of the 2010 EPBD (European Union, 2010) caused a major update that resulted in CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). The CTE-DB-HE 2009 standards (Spanish Ministry of Housing, 2006, 2007, 2009) were then raised, the limitation of non-renewable primary energy consumption (NRPEC) was increased, and the definition of NZEB appeared. In addition, the application of the 2012 Energy Efficiency Directive (European

Fig. 1. The educational building used as a model.

Union, 2012) modified the basic procedure for energy performance certification (Spanish Ministry of the Presidency, 2013; Spanish Ministry of the Presidency and for Territorial Administrations, 2017), including the future obligation that all new public buildings have to be NZEBs as of December 31, 2018 and all other new buildings as of December 31, 2020, always according to the CTE-DB-HE in effect at any given time. The objective of this study is to analyze how the evolution of the CTE-DB-HE impacts, at the energy and environmental levels, the rehabilitation of educational buildings located in 11 cities representing cold climate zones of Spain. To do this, an actual educational building typical of the 1980s, a construction period prior to the CTE-DB-HE, is used as a baseline. The Spanish adaptation of the EPBD is studied in the pursuit of achieving an educational building that meets the required standards for rehabilitated buildings, CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009), and new buildings, CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). In addition, an evaluation of 12 proposals to achieve NZEBs is included, based on buildings that comply with the CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and the CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). This paper is structured into the following sections. Section 2 describes the studied building and explains the methodology used for the evaluation of the energy and environmental parameters, taking into account the evolution of the regulation applied. The various case studies are listed, and finally, solutions to achieve NZEBs are proposed. Section 3 provides the results and discussion. Finally, Section 4 presents the most relevant conclusions.

2. Methodology

2.1. Description of the educational building

The educational building to be studied, which was used for modeling, is based on an educational building located in the city of Logroño, in the Autonomous Community of La Rioja (Fig. 1). It was built according to the Basic Document Norm on Thermal Conditions in Buildings (NBE-CT-79) (Presidency of the Government of Spain, 1979), which is the first legislation that considers the use of thermal insulation and made it mandatory between 1981 and 2007. In addition, its distribution and building type is typical of the cold central-northern region of Spain. The educational building has a ground floor and two stories, with a total surface area of 4595.60 m^2; Fig. 2 show the distribution per floor of the classrooms and all the rooms into which it is divided. All rooms, except the storage room, elevator and facilities room, are heated by a conventional heating-oil boiler that also covers all domestic hot water (DHW) requirements. In addition, according to the lighting system specifications of indoor areas (Institute for Energy Diversification and Saving, 2001), the educational building has seven zones: classrooms (Z1), laboratories (Z2), a design room (Z3), a library (Z4), offices (Z5), a management and administration area (Z6), a cafeteria (Z7) and common areas, restrooms and a storage room (Z8).

2.2. Climate zones and selection of cities

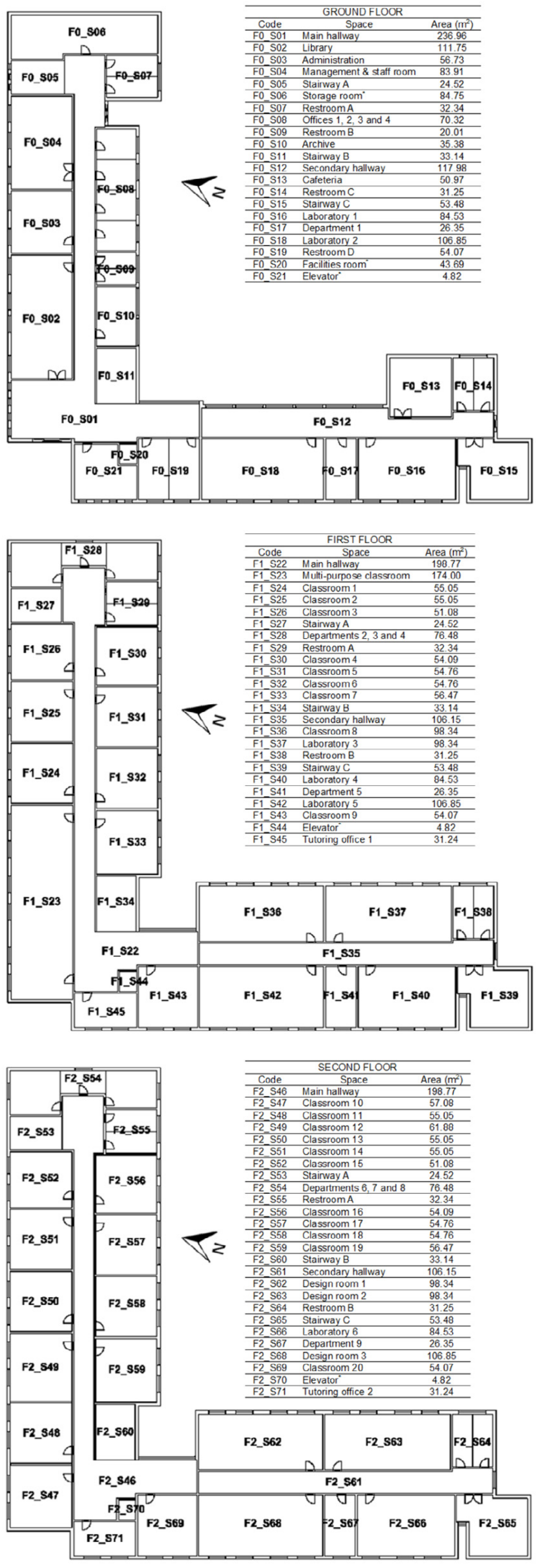
The model of the studied educational building will be simulated in 11 cold provincial capitals that are currently located in climate zones D1, D2 and D3. All these capitals have been selected because their climate zone did not change from CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) to CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b), and according to the NBE-CT-79 (Presidency of the Government of Spain, 1979), their climate zones were D–X and D–Y. Fig. 3 shows the map of the studied provincial capitals and the evolution of their climate zone.

2.3. Thermal simulation software and the educational building model

In this study, the thermal simulation tool used was the LIDER-CALENER Unified Tool (HULC, 2017). It is the official tool used in Spain both for verifying compliance with CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) and for energy certification of buildings, and it was developed by Spanish Ministry of Industry, Energy, and Tourism and the Spanish Ministry of Development. It consists of three modules: LIDER, CALENER and PostCALENER (Institute for Energy Diversification and Saving, 2014b). LIDER (2009) and CALENER-VYP (2012), LIDER (2009) and CALENER-GT (2013), or HULC (2017) were used in López-Ochoa et al. (2017, 2018), Rodríguez Serrano and Porras Álvarez (2016), Herrando et al. (2016), Las-Heras-Casas et al. (2018), Aparicio Ruiz et al. (2016) and Braulio-Gonzalo and Bovea (2017).

LIDER is used to verify the limitation of energy demand of buildings. Its calculation engine is S3PAS, developed by the University of Seville and validated by the International Energy Agency Building Energy Simulation Test (Institute for Energy Diversification and Saving, 2009a). To start, a 3D model of the building is created based on drawings and characteristics of the thermal envelope and usage conditions. Subsequently, the heating and cooling energy demands are obtained to verify compliance with CTE-DB-HE1 2013 (Spanish Ministry of Development, 2013a,b, 2017b).

CALENER is an applications and electronic documents environment intended for rating the energy efficiency of buildings. To do this, CALENER starts by using the model generated with LIDER to simulate the thermal behavior of the building with its facilities. CALENER is divided into CALENER-VYP, which is intended for



GROUND FLOOR		
Code	Space	Area (m^2)
F0_S01	Main hallway	236.96
F0_S02	Library	111.75
F0_S03	Administration	56.73
F0_S04	Management & staff room	83.91
F0_S05	Stairway A	24.52
F0_S06	Storage room*	84.75
F0_S07	Restroom A	32.34
F0_S08	Offices 1, 2, 3 and 4	70.32
F0_S09	Restroom B	20.01
F0_S10	Archive	35.38
F0_S11	Stairway B	33.14
F0_S12	Secondary hallway	117.98
F0_S13	Cafeteria	50.97
F0_S14	Restroom C	31.25
F0_S15	Stairway C	53.48
F0_S16	Laboratory 1	84.53
F0_S17	Department 1	26.35
F0_S18	Laboratory 2	106.85
F0_S19	Restroom D	54.07
F0_S20	Facilities room*	43.69
F0_S21	Elevator*	4.82

FIRST FLOOR		
Code	Space	Area (m^2)
F1_S22	Main hallway	198.77
F1_S23	Multi-purpose classroom	174.00
F1_S24	Classroom 1	55.05
F1_S25	Classroom 2	55.05
F1_S26	Classroom 3	51.08
F1_S27	Stairway A	24.52
F1_S28	Departments 2, 3 and 4	76.48
F1_S29	Restroom A	32.34
F1_S30	Classroom 4	54.09
F1_S31	Classroom 5	54.76
F1_S32	Classroom 6	54.76
F1_S33	Classroom 7	56.47
F1_S34	Stairway B	33.14
F1_S35	Secondary hallway	106.15
F1_S36	Classroom 8	98.34
F1_S37	Laboratory 3	98.34
F1_S38	Restroom B	31.25
F1_S39	Stairway C	53.48
F1_S40	Laboratory 4	84.53
F1_S41	Department 5	26.35
F1_S42	Laboratory 5	106.85
F1_S43	Classroom 9	54.07
F1_S44	Elevator*	4.82
F1_S45	Tutoring office 1	31.24

SECOND FLOOR		
Code	Space	Area (m^2)
F2_S46	Main hallway	198.77
F2_S47	Classroom 10	57.08
F2_S48	Classroom 11	55.05
F2_S49	Classroom 12	61.88
F2_S50	Classroom 13	55.05
F2_S51	Classroom 14	55.05
F2_S52	Classroom 15	51.08
F2_S53	Stairway A	24.52
F2_S54	Departments 6, 7 and 8	76.48
F2_S55	Restroom A	32.34
F2_S56	Classroom 16	54.09
F2_S57	Classroom 17	54.76
F2_S58	Classroom 18	54.76
F2_S59	Classroom 19	56.47
F2_S60	Stairway B	33.14
F2_S61	Secondary hallway	106.15
F2_S62	Design room 1	98.34
F2_S63	Design room 2	98.34
F2_S64	Restroom B	31.25
F2_S65	Stairway C	53.48
F2_S66	Laboratory 6	84.53
F2_S67	Department 9	26.35
F2_S68	Design room 3	106.85
F2_S69	Classroom 20	54.07
F2_S70	Elevator*	4.82
F2_S71	Tutoring office 2	31.24

Fig. 2. Layout of all the educational building floors.

determining the energy rating of residential buildings and small and medium-sized buildings of the non-residential or services sectors, whose systems are not complex or are comparable to dwellings, and CALENER-GT, which handles the energy rating of large commercial buildings. To determine the energy rating of the building based on NRPEC and EM, CALENER calculates the FEC, primary energy consumption, NRPEC and EM per year (Institute for Energy Diversification and Saving, 2008).

ESTO2 is the calculation engine of CALENER-VYP and simulates the behavior of heating, cooling, and DHW systems (Institute for Energy Diversification and Saving, 2009c). DOE-2.2 is the calculation engine of CALENER-GT to simulate the behavior of heating, cooling, DHW, ventilation, lighting and auxiliary systems. DOE-2.2 was developed by Lawrence Berkeley National Laboratory for the United States Department of Energy and is one of the most prestigious energy analysis software packages worldwide. It is widely validated and reliable and has gone through an in-depth debugging process. DOE-2 offers the ability to update and incorporate the improvements that are developed, just as it has been doing since its first version. In addition, it allows adjusting its calculation power and includes performance curves of the equipment in its databases. These curves are essential for the simulation of the different systems and can replace those from specific manufacturers (Institute for Energy Diversification and Saving, 2009b).

PostCALENER allows scenarios to be developed from the results obtained with CALENER to obtain the corresponding modified results (Association of Heating and Cooling Network Companies, 2012; PostCALENER, 2013).

Finally, HULC, in addition to serving as a link between the different modules, generates the verification reports of compliance with CTE-DB-HE1 2013 (Spanish Ministry of Development, 2013a,b, 2017b) and CTE-DB-HE0 2013 (Spanish Ministry of Development, 2013a,b, 2017b) and of energy performance certification of the building (HULC, 2017).

Specifically, for the studied educational building (Fig. 4), LIDER was used to create the 3D model and assess energy demands, CALENER-GT was used to obtain the results of the evolution of the EPBD, and PostCALENER was used to obtain the results of the path to follow to achieve nearly zero-energy educational buildings.

2.4. Energy demands for heating and cooling

The NBE-CT-79 (Presidency of the Government of Spain, 1979) aimed to establish the required thermal conditions of buildings using energy-saving criteria, and it was the first legislation to address the energy efficiency of buildings and to introduce thermal insulation. It mandated that the thermal transmittance of the different opaque enclosures that make up the thermal envelope of the building could not exceed certain maximum values according to their January climate zone. In addition, the overall thermal transmittance of the building could not exceed a certain value depending on its heating climate zone, the shape factor of the building (ratio between external surface area of the building envelope, and the inner volume of the building) and the type of energy used for heating. It also limited the air permeability of windows and doors and both surface and interstitial condensation. However, this legislation does not comprehensively address the issue of transparent enclosures or openings, and focuses only on the air permeability of these and not on limiting their thermal transmittance as it does with opaque enclosures. Table A.1 shows the global thermal transmittance values of buildings in heating climate zone D, and Table A.2 shows the maximum thermal transmittance values of the different opaque enclosures that make up their thermal envelope for different January climate zones. The maximum values in Table A.2 are similar to the default values used for buildings constructed between 1981 and 2007 using CE3X (Institute for Energy Diversification and Saving, 2012). CE3X is the most widely used tool in Spain for certifying the energy efficiency of existing buildings (López-González et al., 2016a; Patiño Cambeiro et al., 2017).

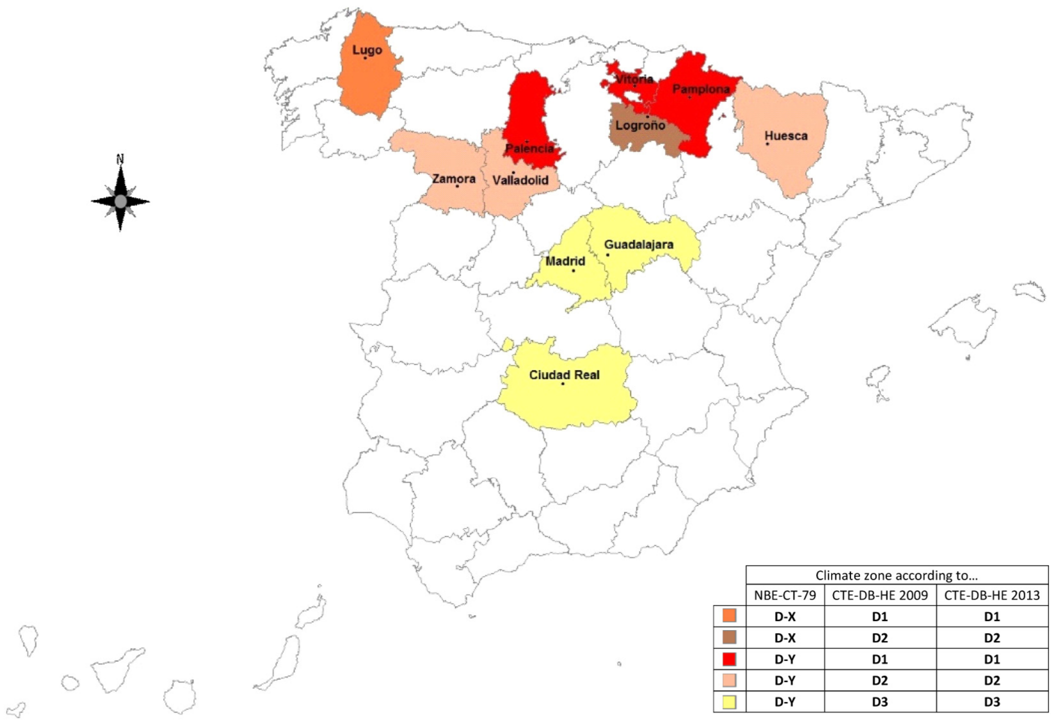


Fig. 3. Map of the studied provincial capitals by evolution of their climate zone.

CTE-DB-HE1 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) includes the requirements of energy demand limitation that any new or existing building must meet if the existing building undergoes modifications, alterations or renovations of a certain size (an existing building with a total useful floor area over 1000 m^2 and a renovation of more than 25% of its envelope). These requirements are as follows: (i) The energy demand of the building is limited according to the climate zone where the building is located and the internal loads; it also must be less than that of its corresponding reference building. The reference building is a building derived from the target building, with the same shape, size, orientation, internal floor plan, use of each space, and same surrounding obstacles and with standard structural solutions, whose characteristic parameters of the thermal envelope components are the limit values stated for its climate zone. In addition, to avoid imbalances between the thermal qualities of the different spaces, each component of the thermal envelope should have a thermal transmittance lower than the maximum values established, based on the winter climate zone of the building. (ii) There cannot be any superficial or interstitial condensation in the building enclosures, interior walls or thermal bridges in contact with air. (iii) The air permeability of windows and doors of openings must be less than the established values. These verifications could be carried out filling out compliance reports or using LIDER (2009).

CTE-DB-HE1 2013 (Spanish Ministry of Development, 2013a,b, 2017b) applies to new buildings and modifications to existing buildings, whether these are expansions, remodeling or change of use. The energy demand of buildings is limited depending on the climate zone of the locality where they are located and their intended use. Buildings for uses other than private residential use must meet a minimum percentage of savings of the combined energy demand for heating and cooling, with respect to their reference buildings. The combined energy demand, ED_{comb}, is understood as the demand for energy obtained from the weighted sum of the heating energy demand, ED_{heat}, and cooling energy demand, ED_{cool}. For buildings located in peninsular territory, $ED_{comb} = ED_{heat} + 0.70 \cdot ED_{cool}$. Those buildings located in summer climate zones 1 and 2 whose loads from internal sources are low (<6 W/m^2), medium (6–9 W/m^2) and high (9–12 W/m^2) must achieve at least 25% savings in combined energy demand with respect to the reference building. For those with very high loads from internal sources (>12 W/m^2), a minimum of 10% savings is required. In contrast, those buildings located in summer climate zones 3 and 4 with low loads from internal sources must achieve at least 25% savings in combined energy demand with respect to the reference building; those with medium loads from internal sources, 20% minimum savings; those with high loads from internal sources, 15% minimum savings; and those with very high loads from internal sources, 0% minimum savings, without exceeding the demand limit of the reference building. All these savings should be calculated assuming a ventilation rate of 0.8 air changes/hour during the occupancy period for the target building and for the reference building from HULC (2017). In the case of remodeling where more than 25% of the total surface area of the final thermal envelope of the building is renovated, it is only necessary to limit the combined energy demand of the building in such a manner that it is lower than that of the reference building, which is similar to the CTE-DB-HE1 2009 requirements (Spanish Ministry of Housing, 2006, 2007, 2009).

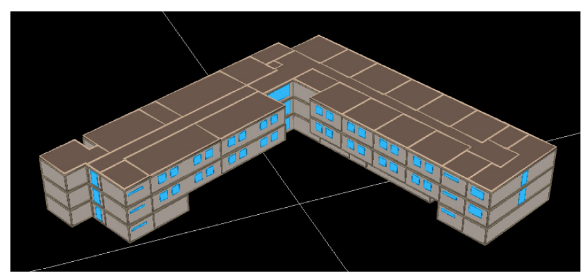


Fig. 4. 3D model of the educational building created in HULC (2017).

The limit values of the average characteristic parameters of the reference building are the same for both CTE-DB-HE1 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and for CTE-DB-HE1 2013 (Spanish Ministry of Development, 2013a,b, 2017b), while the maximum values for each characteristic parameter of the envelope of the target building have been reduced substantially with the current CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) (Table A.3). In addition to all this, in both CTE-DB-HE1 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE1 2013 (Spanish Ministry of Development, 2013a,b, 2017b), openings must not exceed a limit value (as a function of the case study, between 0.30 and 0.61, or without limits) for their solar factor adjusted on the basis of the internal load, orientation and percentage of openings in the façade; no surface or interstitial condensation may occur in the enclosures, interior walls or thermal bridges in contact with air; and the air permeability of windows and doors of the openings cannot be greater than established values (27 $m^3/h\ m^2$ with an overpressure of 100 Pa for winter climate zone D).

2.5. Energy demand for DHW and solar contribution to DHW

The main new feature included in both CTE-DB-HE4 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b) is the requirement that a part of the DHW requirements needs to be met through a solar support system. For this reason, a minimum annual solar contribution is established to cover those requirements depending on the solar climate zone and the total DHW demand of the building (at a reference temperature of 60 °C). First, the demand for the reference DHW at 60 °C for schools without showers has changed from 3 l/student day in CTE-DB-HE4 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) to 4 l/person day in CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b). It is noted that the current CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b), besides requiring a greater DHW demand per user, counts all users of the educational building. Second, the minimum annual solar contribution is the ratio between the annual values of the contribution of solar energy and the annual energy demand for DHW, obtained from monthly values. The minimum required solar contributions for the total DHW demand of between 50 and 5000 l/day for solar climate zones I, II, III, IV and V were 30%, 30%, 50%, 60% and 70%, respectively, in CTE-DB-HE4 2009 (Spanish Ministry of Housing, 2006, 2007, 2009); these are currently 30%, 30%, 40%, 50% and 60%, respectively, in CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b). It is noted that for solar climate zones III, IV and V, the required minimum solar contribution has decreased by 10% with the current CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b). For this study, the highest DHW demand required will be used, which is indicated by CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b) for the full occupancy rate. In addition, for each solar climate zone, the highest minimum solar contribution required is always considered, namely, that of CTE-DB-HE4 2009 (Spanish Ministry of Housing, 2006, 2007, 2009).

The energy demand for DHW will be assessed for each educational building located in each provincial capital studied using the calculation method of the Technical Specifications of Low Temperature Facilities for Solar Thermal Energy (Institute for Diversification and Saving of Energy, 2009d), already used in López-Ochoa et al. (2017, 2018), and similar to that used by CALENER-GT (2013), according to Institute for Energy Diversification and Saving (2009b), the equation for which is the following:

$$ED_{DHW} = \frac{\sum_{i=1}^{12} D_{DHW} \cdot c \cdot N_i \cdot \left(T_{DHW} - T_{tap,i}\right)}{A} \quad (1)$$

where ED_{DHW} is the DHW energy demand in kWh/m^2 year; D_{DHW} is the daily DHW demand obtained for the target building after applying the daily demand required by CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b) in kg/day (1 l/day = 1 kg/day); c is the specific heat of water, whose value is 0.00116 kWh/kg °C; N_i is the number of days in month i; T_{DHW} is the DHW temperature, whose value is 60 °C; $T_{tap,i}$ is the average daily temperature of the cold water supply for the different provincial capitals for month i, obtained from Appendix B of CTE-DB-HE4 2013 (Spanish Ministry of Development, 2013a,b, 2017b) in °C; and A is the useful floor area of the habitable spaces in m^2.

2.6. Energy efficiency of the lighting installations

CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b) apply to indoor lighting installations in new construction or in modifications or rehabilitation of existing buildings of the services sector with a final total useful surface area greater than 1000 m^2, where more than 25% of the lit surface area is renovated.

In addition to the applicable requirements in CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) or in CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b), the recommendations of the Technical Guide for Energy Efficiency of Lighting Installations for Educational Buildings (Institute for Energy Diversification and Saving, 2001) were considered in the design of the lighting installations of the studied educational building. This Technical Guide (Institute for Energy Diversification and Saving, 2001) establishes the following criteria for the selection of luminaires: (i) average horizontal illuminance (lux), quality regarding direct glare and color performance according to the use of each space; (ii) minimum luminous efficacy (lumens/W); (iii) depreciation factor; and (iv) the coefficient of utilization.

The distribution of luminaires was established by determining enough light spots based on the length, width and distance from the working plane to the luminaires of the different rooms. All rooms have manual on and off systems and are connected to the corresponding electrical panel that controls the luminaires. Transit areas such as hallways and stairs have motion sensing systems with timers. In addition, rooms with natural lighting have light sensors installed to take proper advantage the natural lighting.

Both CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b) establish that the value of energy efficiency of the installation (VEEI) of every interior area cannot exceed a certain limit. VEEI is the parameter used to determine the energy efficiency of the lighting installation of each space and is expressed in power per square meter per 100 lux (W/m^2 for each 100 lux) through the following expression:

$$VEEI = (P \cdot 100)/(S \cdot E_{\mathrm{m}}) \quad (2)$$

where P is the installed lighting power used by the luminaires, including auxiliary equipment, in W; S the lighted floor surface in m^2; and E_m is the average maintained horizontal illuminance in lux.

Table A.4 shows the VEEI limits for each interior area of the studied educational building according to CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and according to CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b). In addition, the recommendations of the Technical Guide (Institute for Energy Diversification and Saving, 2001) were taken into account, which implies that the overall average VEEI has to be 3.5, and it may vary from 2.0 (optimal VEEI) to 4.5 (maximum VEEI) for each area.

CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b), in addition to requiring a lower VEEI than that of CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009), requires limiting the maximum average installed lighting power density per surface area as a function of building use, which must be equal to or less than 15 W/m^2 for an educational building.

To summarize, Table A.5 shows the recommendations and requirements for the overall characteristics of the lighting installation of the studied educational building, and Table A.4 shows the same but for each type of area.

2.7. Final energy and non-renewable primary energy consumptions, CO_2 emissions and labeling

To assess the FEC for heating, the performance of the boilers used to cover that energy demand has to be considered. In addition, the NRPEC and EM were assessed using the conversion factors from final energy to non-renewable primary energy and from final energy to EM (Spanish Ministry of Industry, Energy, and Tourism and Spanish Ministry of Public Works, 2016). The FEC, NRPEC, and EM for both heating and lighting were calculated with HULC (2017), taking into account the procedure required by the Spanish Ministry of Industry, Energy, and Tourism and the Spanish Ministry of Development (Institute for Diversification and Saving of Energy, 2016). Moreover, the energy consumption for DHW was calculated in accordance with Section 2.5, using the performance of the boilers used to cover the DHW energy demand, the most restrictive minimum solar contribution and the corresponding conversion factors (Spanish Ministry of Industry, Energy, and Tourism and Spanish Ministry of Public Works, 2016).

CTE-DB-HE0 2013 (Spanish Ministry of Development, 2013a,b, 2017b) limits the NRPEC of buildings depending on the climate zone where they are located and their intended use. For new buildings for all uses other than private residential, such as the educational building, it requires that the energy rating for the NRPEC indicator of the building or the expansion, if applicable, must meet or exceed a class B efficiency, in accordance with the basic procedure for energy performance certification of buildings (Spanish Ministry of the Presidency, 2013; Spanish Ministry of the Presidency and for Territorial Administrations, 2017). Because the energy efficiency ratings of the buildings from the different locations were obtained, compliance with this requirement can be verified, even though it is not mandatory for rehabilitated buildings, as is the case of the educational building under study.

Finally, HULC (2017) was used to assign the labels of NRPEC and EM. Buildings intended for uses other than private residential (housing) will be classified for each efficiency indicator on a scale of seven letters ranging from A (most efficient building) to G (least efficient building). The rating index (I) of this type of building is the ratio between the indicator value for the building being certified and the indicator value of the reference building (Institute for Energy Diversification and Saving, 2015) (Table A.6).

2.8. Cases to study

The evolution of the EPBD for the educational building under study, located in each city selected, was analyzed through the following cases:

- Case 1 (C1): A baseline building, whose model is the combination of the constructive parameters of the original project with those collected in NBE-CT-79 (Presidency of the Government of Spain, 1979) and in CE3X (Institute for Energy Diversification and Saving, 2012), and the constructive solutions of the Energy Performance Rating for Existing Buildings (Institute for Energy Diversification and Saving, 2011), for buildings constructed between 1981 and 2007. The boiler used is conventional and runs on heating oil with a performance of 85%, without a solar support system for DHW.
- Case 2 (C2): A rehabilitated building that meets the requirements of CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) for rehabilitated buildings. The boiler used is conventional and runs on natural gas with a performance of 90%.
- Case 3 (C3): A rehabilitated building that meets the requirements of CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) for new buildings. A natural gas condensation boiler with a performance of 95% is used.

Table 1 shows the different thermal transmittances of the different opaque enclosures that make up the thermal envelope of the educational building, whose components are detailed in Table B.1 for C1, Table B.2 for C2 and Table B.3 for C3. For the rehabilitation of the roof of C1, it is necessary to add a new 4-cm layer of type 1 EPS insulation ($\lambda = 0.046$ W/m K) between layers 2 and 3 for C2 and a 10-cm layer of type 2 EPS ($\lambda = 0.029$ W/m K) for C3. For the mezzanine frameworks in contact with the exterior of C1, it is necessary to add 3 cm of type 1 EPS to the exterior for C2 and 8 cm of type 2 EPS for C3, and in both cases, the exterior needs to be covered with manufactured stone. For the two types of exterior wall of C1, it is necessary to replace the outer layer (sandstone) with 3 cm of type 1 EPS for C2 and 8 cm of type 2 EPS for C3, and in both cases, the exterior needs to be covered with manufactured stone. Finally, for the ground floor of C1, it is necessary to add a new 5-cm layer of type 1 EPS insulation between layers 2 and 3 for C2 and a new 10-cm layer of type 2 EPS for C3. However, the rest of the mezzanine frameworks, as well as the interior partitions, do not change between the different cases. In C2 and C3, it was necessary to replace the glazed enclosure of C1 with one with characteristics similar to those of their respective exterior façade walls. By using the external thermal insulation composite systems in this rehabilitation, with respect to C1, the thermal transmittance of the roof has been reduced by 40.51% in C2 and 73.42% in C3; for the mezzanine frameworks in contact with the exterior, by 33.33% in C2 and 68.00% in C3; for the exterior façade walls, by 47.48% in C2 and 79.14% in C3; for the glazed enclosure, by 79.08% in C2 and 91.69% in C3; and for the ground floor, by 65.52% in C2 and 85.63% in C3.

Table 2 shows the key features of each type of opening that make up the thermal envelope of the educational building. The openings of C1 use vertically positioned single-pane glass with U = 5.70 W/m^2 K and g = 0.85 and vertically positioned metallic frames without thermal bridge breaks with U = 5.70 W/m^2 K and α = 0.7. The openings of C2 have vertically positioned double-glazed glass (4-12-4) with U = 2.80 W/m^2 K and g = 0.7 and vertically positioned metallic frames with thermal bridge breaks greater than 12 mm with U = 3.20 W/m^2 K and α = 0.7. Finally, the openings of C3 have low-emissivity vertically positioned double-glazed panes (4-20-4) with U = 1.40 W/m^2 K and g = 0.7 and three-chambered PVC frames vertically positioned with U = 1.80 W/m^2 K and α = 0.7. With the substitution of openings, the average thermal transmittance of openings was reduced by 47.91% in C2 (2.97 W/m^2 K) and by 72.47% in C3 (1.57 W/m^2 K), with respect to C1 (5.70 W/m^2 K).

Table 3 shows the characteristics of the lighting installation for each zone type of the educational building. First, most zones of

Table 1
Thermal transmittance of each type of enclosure used in each case studied and maximum values and limits allowed by each regulation, in W/m^2 K.

Enclosure	C1	Maximum value according to NBE-CT-79	C2	Maximum value according to CTE-DB-HE 2009	C3	Maximum value according to CTE-DB-HE 2013	Limit value according to CTE-DB-HE 2009 and CTE-DB-HE 2013
Roof	0.79	0.90	0.47	0.49	0.21	0.40	0.38
Mezzanine framework	1.77	–	1.77	–	1.77	–	–
Mezzanine framework in contact with the exterior	0.75	0.80	0.50	0.64	0.24	0.40	0.49
Exterior façade wall floor 0	1.39	1.40	0.73	0.86	0.29	0.60	0.66
Exterior façade wall floors 1 and 2	1.39	1.40	0.73	0.86	0.29	0.60	0.66
Glazed enclosure	3.49	1.40	0.73	0.86	0.29	0.60	0.66
Ground floor	1.74	1.20	0.60	0.86	0.25	0.60	0.66
Interior partition	1.98	–	1.98	–	1.98	–	–

Table 2
Main characteristics of each type of opening: Framework percentage (FP), in %, and total area (A), in m^2; and thermal transmittance (U), in W/m^2 K, and adjusted solar factor (F), in parts per unit, for each case studied.

Type of opening	FP (%)	A (m^2)	C1		C2		C3	
			U	F	U	F	U	F
Normal windows	43.75	470.23	5.70	0.55	2.97	0.43	1.57	0.42
Long window	55.17	33.47	5.70	0.47	3.02	0.36	1.62	0.34
High department windows	23.17	6.20	5.70	0.69	2.89	0.56	1.49	0.55
Entrance door	44.16	46.30	5.70	0.55	2.98	0.43	1.58	0.41
Window of the stairway C	38.50	9.00	5.70	0.58	2.95	0.46	1.55	0.45
Wide department windows	37.05	6.00	5.70	0.59	2.95	0.47	1.55	0.46
Facilities room door	78.67	3.00	5.70	0.31	3.11	0.22	1.71	0.19
Small window	34.52	4.32	5.70	0.61	2.94	0.49	1.54	0.48
Large window floors 1 and 2	29.20	36.43	5.70	0.65	2.92	0.52	1.52	0.51
Archive window	27.88	6.50	5.70	0.66	2.91	0.53	1.51	0.52

Table 3
Characteristics of the lighting installation for each zone type of the educational building in each case studied, recommended values according to Technical Guide (Institute for Energy Diversification and Saving, 2001) and limit allowed values according to CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b).

Zone	Average horizontal illuminance (lux)				VEEI (W/m^2 100 lux)					Average installed lighting power density per surface area (W/m^2)		
	C1	C2	C3	Recommended value according to Technical Guide	C1	C2	Limit value according to CTE-DB-HE3 2009	C3	Limit value according to CTE-DB-HE3 2013	C1	C2	C3
Z1	200	300	300	300	6.8	2.3	4.0	2.0	3.5	13.6	7.0	6.0
Z2	300	500	500	500	6.8	2.3	4.0	2.0	3.5	20.4	11.6	10.0
Z3	350	750	750	750	6.8	2.3	4.0	2.0	3.5	23.7	17.5	15.0
Z4	200	500	500	500	6.8	2.3	6.0	2.0	5.0	13.6	11.6	10.0
Z5	200	300	300	300	6.8	2.3	4.0	2.0	3.5	13.6	7.0	6.0
Z6	300	500	500	500	6.8	2.3	3.5	2.0	3.0	20.4	11.6	10.0
Z7	200	200	200	200	6.8	2.3	4.5	2.0	4.0	13.6	4.7	4.0
Z8	100	150	150	150	6.8	2.3	4.5	2.0	4.0	6.8	3.5	3.0

C1 do not meet the average horizontal illuminance recommended by the Technical Guide (Institute for Energy Diversification and Saving, 2001), and none of them meet the VEEI limits required by both CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b). Second, all zones of C2 and C3 comply with the average horizontal illuminance recommended by the Technical Guide (Institute for Energy Diversification and Saving, 2001) and with the VEEI limits required by their respective CTE-DB-HE3: CTE-DB-HE3 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) for C2 and CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b) for C3. The average installed lighting power of each zone of C1 is 1.7 times that of C2 and 1.9 times that of C3.

Table 4 shows the overall characteristics of the lighting installation. C2 and C3 comply with all the recommendations of the Technical Guide (Institute for Energy Diversification and Saving, 2001), and C1 only complies with the coefficient of utilization recommended by Institute for Energy Diversification and Saving (2001); additionally, the depreciation factors of C2 and C3 are very close to the optimum values recommended by Institute for Energy Diversification and Saving (2001). Although the efficiency of C3 is 1.2 times that of C2 and 2.5 times that of C1, the average horizontal illuminance is reduced by approximately 40% in C2 and C3 in comparison to C1, and the average installed lighting power of C1, C2 and C3 meets the requirement of CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b) by not exceeding 15 W/m^2. Regarding the VEEIs, those of C1 are very far from the values recommended by Institute for Energy Diversification and Saving (2001), those of C2 are close to the optimal value, and those of C3 meet the optimum value.

The DHW demand in cases C1, C2 and C3 is 4152 l/day. While there is no solar contribution for DHW in C1, in C2 and C3 the solar contribution for DHW is 30% in Lugo, Palencia, Pamplona, Valladolid and Vitoria; in Huesca, Logroño and Zamora, it is 50%; and in Ciudad Real, Guadalajara and Madrid, it is 60%.

For the simulation of the building, it was assumed that the intensity of use of its habitable spaces is medium with 16 h of use. Table 5 shows the ventilation of these spaces and the occupancy, lighting and equipment internal loads for each case. The ventilation was reduced by 3.28% in C2 and C3 with respect to C1 to adapt the building to the indoor air quality requirements

Table 4
Overall characteristics of the lighting installation of the educational building in each case studied, recommended values according to Technical Guide (Institute for Energy Diversification and Saving, 2001) and required values according to CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b).

	C1	C2	C3	Recommended and required values	References
Luminous efficacy (lúmenes/W)	40	86	100	≥60	Institute for Energy Diversification and Saving (2001)
Depreciation factor	0.65	0.88	0.88	0.8–1.0 (≥0.9)	Institute for Energy Diversification and Saving (2001)
Coefficient of utilization	0.567	0.567	0.567	≥0.5	Institute for Energy Diversification and Saving (2001)
Average horizontal illuminance (lux)	189.71	313.04	310.00	–	
Average installed lighting power density per surface area (W/m^2)	12.90	7.20	6.20	≤15	Spanish Ministry of Development (2013a,b, 2017b)
VEEI (W/m^2 100 lux)	6.8	2.3	2.0	3.5 (2.0 ≤ VEEI ≤ 4.5)	Institute for Energy Diversification and Saving (2001)

Table 5
Ventilation, in air changes/hour, and occupancy, lighting and equipment internal loads, in W/m^2, for each case.

	C1	C2	C3
Ventilation (air changes/h)	1.83	1.77	1.77
Occupancy internal load (W/m^2)	13.81	13.81	13.81
Lighting internal load (W/m^2)	12.90	7.20	6.20
Equipment internal load (W/m^2)	4.50	5.50	6.60

of the Basic Document for Health of the Technical Building Code (Spanish Ministry of Development, 2017a), and the total internal loads were decreased by 15.06% in C2 and by 14.74% in C3 in comparison to C1. The occupancy internal loads remained constant in all cases, but in comparison to C1, the lighting internal loads decreased by 44.18% in C2 and by 51.94% in C3 due to the improvement of luminaries driven by CTE-DB-HE3 2013 (Spanish Ministry of Development, 2013a,b, 2017b), and the internal loads from equipment increased by 22.22% in C2 and by 46.67% in C3 due to the addition of computers, projectors and other equipment.

The following parameters were calculated for the studied educational building in each city selected: energy demand for heating, cooling, combined and DHW; FEC for heating, lighting, DHW and total; NRPEC for heating, lighting, DHW and total; EM for heating, lighting, DHW and total; the different totals for the indices energy demand, NRPEC and EM; and the disaggregated indices NRPEC and EM for heating, lighting and DHW.

2.9. Proposals to achieve NZEBs

The last update of CTE-DB-HE 2013 (Spanish Ministry of Development, 2017b) states that NZEBs are those buildings that meet the requirements of CTE-DB-HE for new buildings. In this study, it is proposed that in the upcoming CTE-DB-HE, the NZEBs will be those that achieve an A rating for both NRPEC and EM, as proposed by López-Ochoa et al. (2017). From the results obtained for C2 and C3 and ensuring the minimum solar contribution required for DHW, the following proposals to achieve the nearly zero-energy educational building are studied:

- Proposal 1 (P1): Reduction of the overall thermal transmittance of the building through external thermal insulation composite systems and substitution of openings in order to reduce the FEC of heating by half.
- Proposal 2 (P2): Replacement of the existing boiler with a biomass boiler with a performance of 90% to meet the heating and DHW needs.
- Proposal 3 (P3): Addition of a heat pump with a 4.44 seasonal coefficient of performance (SCOP) for 40 °C to meet the heating needs (the coefficient of performance (COP) of the selected heat pump is 6.80 for 35 °C).
- Proposal 4 (P4): Replacement of the existing boiler with a heat pump with a 4.44 SCOP for 40 °C to meet the heating needs and a 2.81 SCOP for 60 °C to meet the DHW needs (the COP of the selected heat pump is 6.80 for 35 °C).
- Proposal 5 (P5): Addition of a solar photovoltaic system that covers 45% of the lighting needs.
- Proposal 6 (P6): P1 + P3.
- Proposal 7 (P7): P1 + P4.
- Proposal 8 (P8): P1 + P5.
- Proposal 9 (P9): P3 + P5.
- Proposal 10 (P10): P4 + P5.
- Proposal 11 (P11): P1 + P3 + P5.
- Proposal 12 (P12): P1 + P4 + P5.

For each proposal, the NRPEC for heating, lighting and DHW will be estimated, as well as their respective NRPEC indices; the EM for heating, lighting and DHW will also be estimated, as well as their respective EM indices. The SCOP was determined using Institute for Energy Diversification and Saving (2014a), which is based on EN 14825 (European Committee for Standardization, 2016).

3. Results and discussion

3.1. Evolution of the EPBD

Table 6 shows the energy demand, FEC, NRPEC and EM values obtained in each case for the studied building by city and climate zone. Figs. 5–7 show the energy demand, NRPEC and EM indices, as well as the breakdown of the latter two, for each city of climate zones D1, D2 and D3, respectively. In addition, Figs. 8–10 show the average NRPEC and EM, as well as their associated overall index, for each case of climate zones D1, D2 and D3, respectively.

The 2002 EPBD (European Union, 2002), through CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009), and the 2010 EPBD (European Union, 2010), through CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b), have been gradually requiring a substantial reduction of the thermal transmittance of the envelope of educational buildings in Spain, which has ensured a reduction in the energy demand, FEC, NRPEC and EM of buildings with respect to the previous construction legislation in Spain. CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) requires that the thermal transmittance of building envelopes produces a combined energy demand for heating and cooling that is equal to or less than that of the reference building. CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) requires that the thermal transmittance produces energy demands (with the internal loads of the studied building) that are at least 25% lower for summer climate zones 1 and 2 and at least 15% lower than those of the reference building for summer climate zones 3 and 4.

Table 6
Results for the studied educational buildings in the 11 selected provincial capitals, grouped by climate zone, for each case.

		D1				D2				D3		
		Lugo	Palencia	Pamplona	Vitoria	Huesca	Logroño	Valladolid	Zamora	Ciudad Real	Guadalajara	Madrid
C1	ED for heating (kWh/m^2 year)	87.79	85.14	87.41	86.92	86.42	86.87	84.16	84.87	83.96	83.34	84.30
	ED for cooling (kWh/m^2 year)	10.57	10.73	10.59	10.62	22.21	22.18	22.36	22.31	37.97	37.99	37.97
	ED for DHW (kWh/m^2 year)	19.42	19.32	19.12	19.42	18.82	18.86	19.12	19.06	18.66	18.82	18.59
	FEC for heating (kWh/m^2 year)	110.00	110.00	110.00	101.08	104.72	104.72	104.72	104.72	101.08	101.08	101.08
	FEC for lighting (kWh/m^2 year)	55.80	55.80	55.80	55.80	55.80	55.80	55.80	55.80	55.80	55.80	55.80
	FEC for DHW (kWh/m^2 year)	22.85	22.73	22.49	22.85	22.14	22.19	22.49	22.42	21.95	22.14	21.87
	NRPEC for heating (kWh/m^2 year)	149.53	150.18	149.62	137.58	141.97	141.87	142.52	142.34	137.44	137.62	137.36
	NRPEC for lighting (kWh/m^2 year)	109.04	109.04	109.04	109.04	109.04	109.04	109.04	109.04	109.04	109.04	109.04
	NRPEC for DHW (kWh/m^2 year)	26.94	26.80	26.52	26.94	26.10	26.16	26.52	26.44	25.88	26.10	25.79
	EM for heating (kg CO_2/m^2 year)	39.30	39.47	39.33	36.17	37.32	37.29	37.46	37.42	36.13	36.18	36.11
	EM for lighting (kg CO_2/m^2 year)	18.47	18.47	18.47	18.47	18.47	18.47	18.47	18.47	18.47	18.47	18.47
	EM for DHW (kg CO_2/m^2 year)	7.11	7.07	7.00	7.11	6.89	6.90	7.00	6.97	6.83	6.89	6.80
C2	ED for heating (kWh/m^2 year)	66.68	64.07	66.30	65.82	68.68	66.12	63.44	64.14	63.51	62.89	63.84
	ED for cooling (kWh/m^2 year)	12.29	12.53	12.33	12.37	23.15	23.11	23.35	23.29	36.97	36.99	36.96
	ED for DHW (kWh/m^2 year)	19.42	19.32	19.12	19.42	18.82	18.86	19.12	19.06	18.66	18.82	18.59
	FEC for heating (kWh/m^2 year)	52.28	52.28	52.28	50.66	51.26	51.26	51.26	51.26	50.66	50.66	50.66
	FEC for lighting (kWh/m^2 year)	31.24	31.24	31.24	31.24	31.24	31.24	31.24	31.24	31.24	31.24	31.24
	FEC for DHW (kWh/m^2 year)	15.10	15.03	14.87	15.10	10.46	10.48	14.87	10.59	8.29	8.36	8.26
	NRPEC for heating (kWh/m^2 year)	77.65	78.34	77.74	75.46	75.97	75.86	76.58	76.38	75.62	75.80	75.53
	NRPEC for lighting (kWh/m^2 year)	61.04	61.04	61.04	61.04	61.04	61.04	61.04	61.04	61.04	61.04	61.04
	NRPEC for DHW (kWh/m^2 year)	17.97	17.88	17.70	17.97	12.44	12.47	17.70	12.60	9.87	9.95	9.83
	EM for heating (kg CO_2/m^2 year)	16.40	16.55	16.42	15.94	16.05	16.03	16.18	16.14	15.98	16.01	15.96
	EM for lighting (kg CO_2/m^2 year)	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34
	EM for DHW (kg CO_2/m^2 year)	4.53	4.51	4.46	4.53	3.14	3.14	4.46	3.18	2.49	2.51	2.48
C3	ED for heating (kWh/m^2 year)	41.70	39.31	41.35	40.92	41.16	41.58	39.08	39.74	39.64	39.05	39.94
	ED for cooling (kWh/m^2 year)	18.12	18.61	18.19	18.28	29.38	29.31	29.75	29.63	42.49	42.55	42.46
	ED for DHW (kWh/m^2 year)	19.42	19.32	19.12	19.42	18.82	18.86	19.12	19.06	18.66	18.82	18.59
	FEC for heating (kWh/m^2 year)	16.11	16.11	16.11	15.73	15.80	15.80	15.80	15.80	15.73	15.73	15.73
	FEC for lighting (kWh/m^2 year)	26.93	26.93	26.93	26.93	26.93	26.93	26.93	26.93	26.93	26.93	26.93
	FEC for DHW (kWh/m^2 year)	14.31	14.24	14.09	14.31	9.91	9.93	14.09	10.03	7.86	7.92	7.83
	NRPEC for heating (kWh/m^2 year)	27.90	28.51	27.98	27.43	27.39	27.29	27.92	27.74	27.72	27.87	27.63
	NRPEC for lighting (kWh/m^2 year)	52.62	52.62	52.62	52.62	52.62	52.62	52.62	52.62	52.62	52.62	52.62
	NRPEC for DHW (kWh/m^2 year)	17.03	16.94	16.77	17.03	11.79	11.81	16.77	11.94	9.35	9.43	9.31
	EM for heating (kg CO_2/m^2 year)	5.89	6.02	5.91	5.79	5.78	5.76	5.89	5.85	5.85	5.88	5.83
	EM for lighting (kg CO_2/m^2 year)	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91
	EM for DHW (kg CO_2/m^2 year)	4.29	4.27	4.22	4.29	2.97	2.98	4.22	3.01	2.36	2.38	2.35

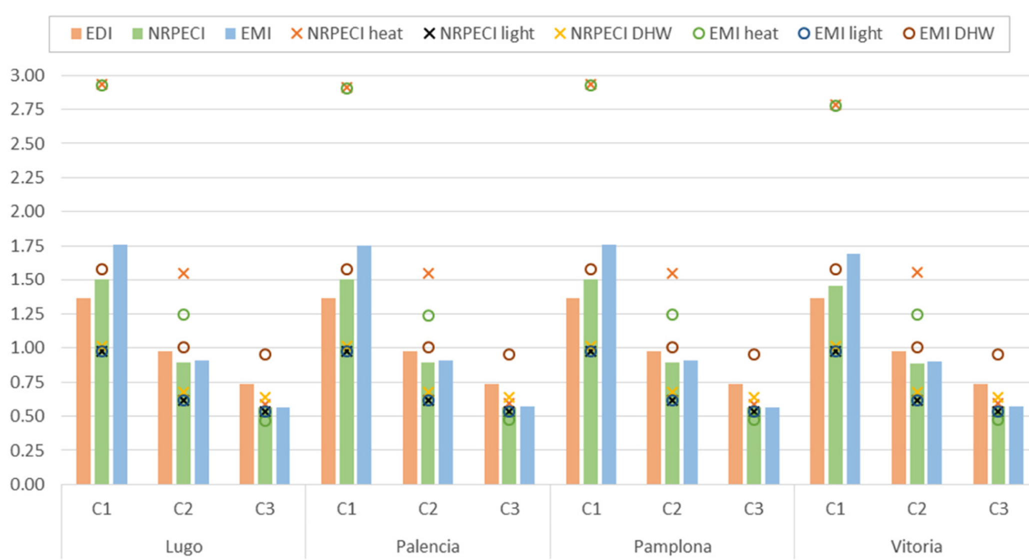


Fig. 5. Energy demand, NRPEC and EM indices (EDI, NRPECI and EMI) and disaggregated NRPECI and EMI (for heating, lighting and DHW) for climate zone D1.

The study reveals that as the thermal transmittance of the envelope of the educational building is reduced, the heating energy demand decreases and the cooling energy demand increases. This reduces the relevance that heating has within all demands. Additionally, it is observed that while educational buildings constructed in the same winter climate zone have similar heating energy demands, the cooling energy demand is higher as the summer climate severity increases. On average, with respect to the baseline educational building, the heating energy demand is reduced by 23.98% while the cooling energy demand increases by 3.19% in the building constructed according to CTE-DB-HE

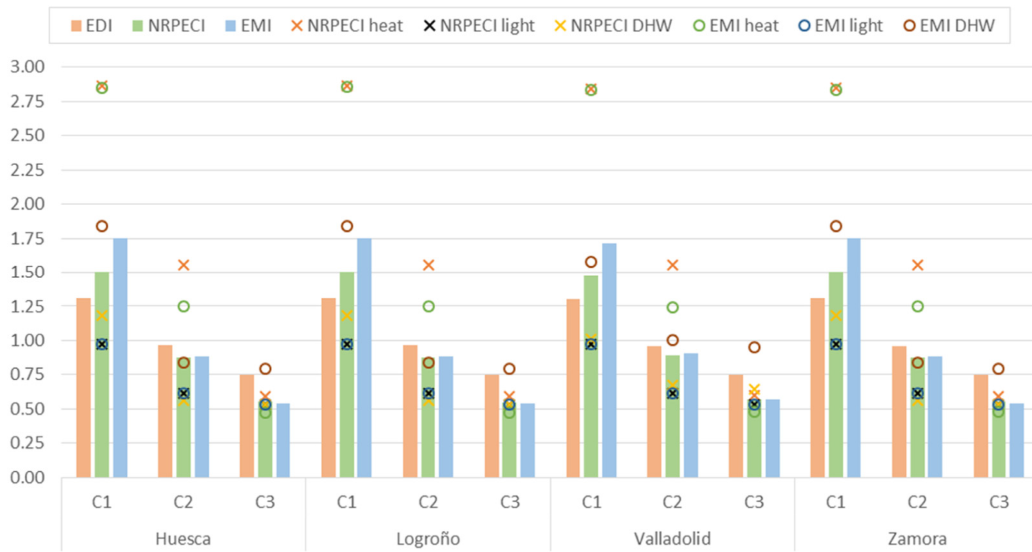


Fig. 6. Energy demand, NRPEC and EM indices (EDI, NRPECI and EMI) and disaggregated NRPECI and EMI (for heating, lighting and DHW) for climate zone D2.

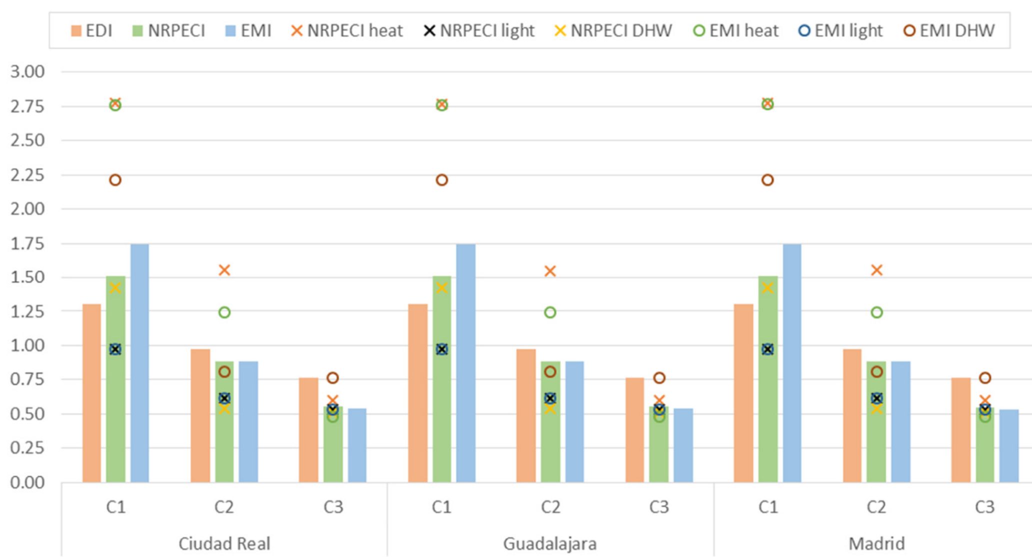


Fig. 7. Energy demand, NRPEC and EM indices (EDI, NRPECI and EMI) and disaggregated NRPECI and EMI (for heating, lighting and DHW) for climate zone D3.

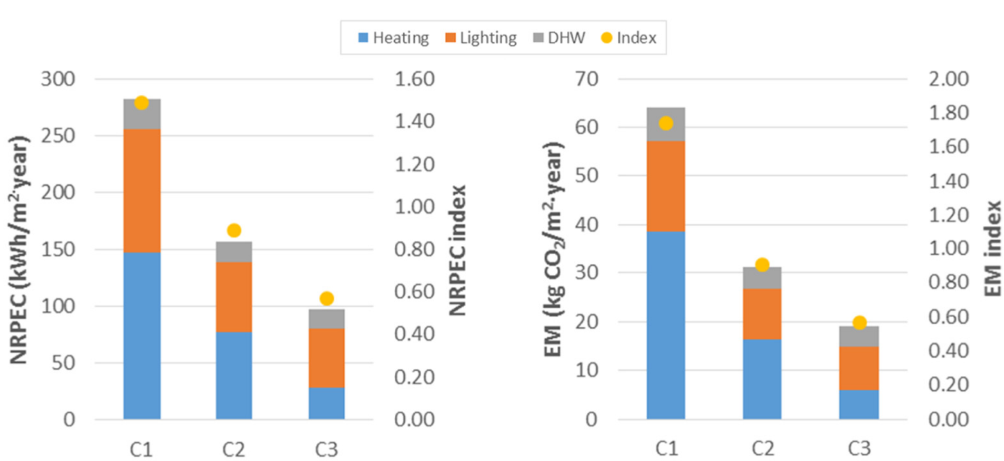


Fig. 8. Average NRPEC and average EM as well as their associated overall index for climate zone D1.

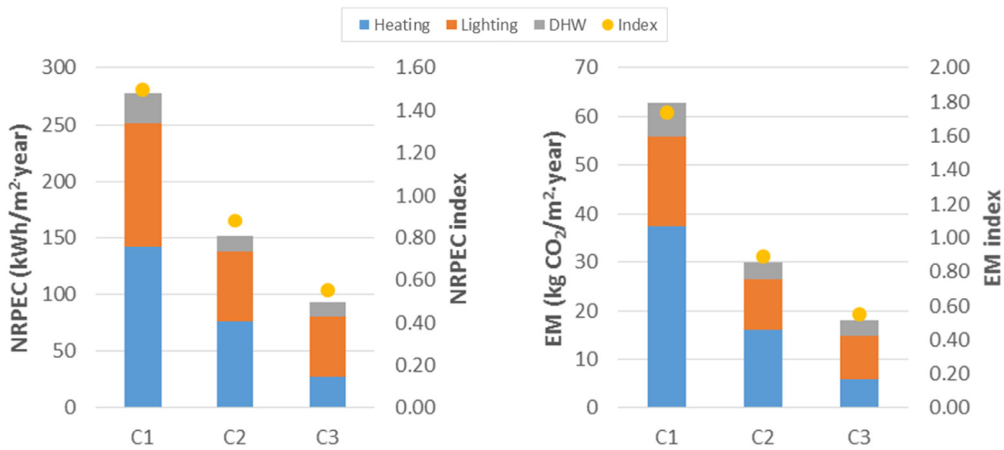


Fig. 9. Average NRPEC and average EM as well as their associated overall index for climate zone D2.

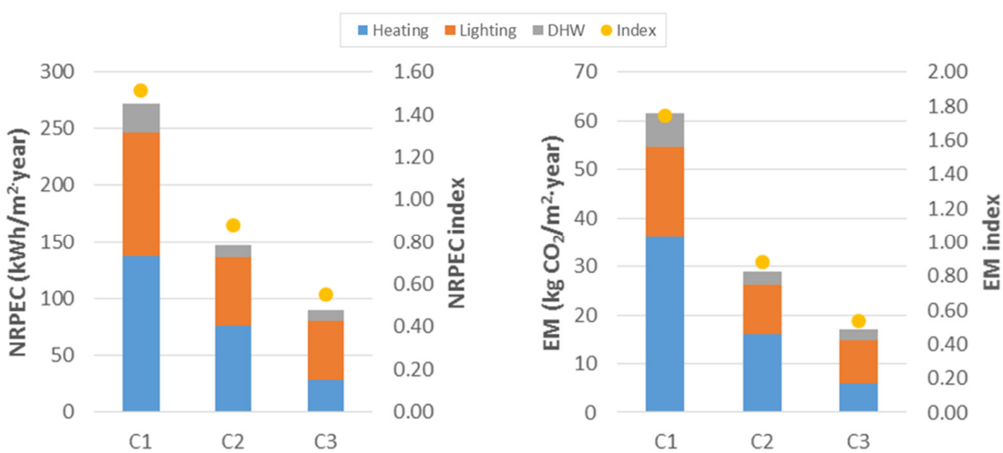


Fig. 10. Average NRPEC and average EM as well as their associated overall index for climate zone D3.

2009 (Spanish Ministry of Housing, 2006, 2007, 2009). In contrast, the heating energy demand is reduced by 52.88% while the cooling energy demand increases by 29.85% in the building constructed according to CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). Regarding the reference building, the combined energy demand of the baseline building needs to be reduced by 18.36% in the educational building to comply with CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and by 35.77% to comply with CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). The average combined energy demand of the baseline building is 1.33 times that of the reference building, for the building constructed according to CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009), it is 0.97 times, and for the building constructed according to CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b), it is 0.75 times. In addition, regarding the improvement of the thermal envelope, the legislation has indirectly made it mandatory to replace heating oil boilers with natural gas boilers and to improve their performance. As result, the heating system of the educational building, after applying CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009), has reduced its FEC by 51.05%, its NRPEC by 46.37% and its EM by 56.90%; after applying CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b), its FEC dropped by 84.87%, its NRPEC by 80.52% and its EM by 84.36%.

The adaptation of the EPBD ensures improvements in the lighting installations of buildings, by requiring lower VEEIs and gradually decreasing the maximum average installed lighting power required. Consequently, the lighting FEC, NRPEC and EM can be reduced by 44.02% if CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) is implemented and by 51.74% if CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) is implemented.

Another new requirement is that a portion of the DHW must be supplied through a solar support system depending on the daily DHW consumption and the solar climate zone of the building. This contribution varies from 30 to 70%. Regarding the DHW of the baseline educational building, the implementation of CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) reduces FEC by 48.46%, NRPEC by 47.98% and EM by 50.31%, while the implementation of CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) reduces FEC by 49.42%, NRPEC by 48.94% and EM by 51.22%. In addition to the improvement in the boiler, there is wide fluctuation in the results among the different climate zones studied. This is mainly due to their solar climate zones. The solar contribution demanded by educational buildings located in climate zone D1 is 30% on average, for those located in climate zone D2, it is 45% on average, and those located in climate zone D3 require 60% on average.

The average FEC of the baseline educational building drops from 183.01 kWh/m^2 year to 94.51 kWh/m^2 year with the implementation of CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and to 54.11 kWh/m^2 year with the implementation of CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). Additionally, its ratings change from E in NRPEC

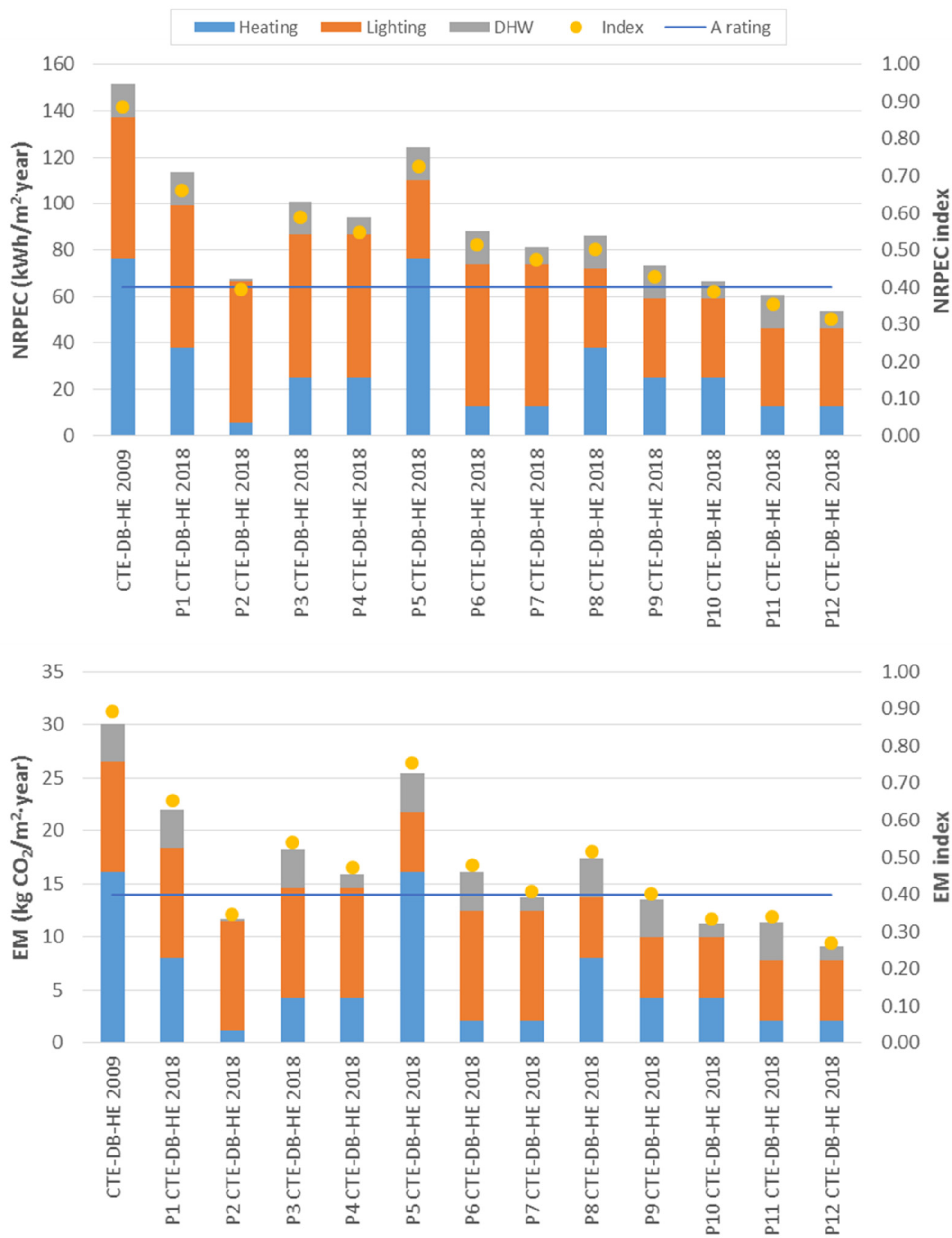


Fig. 11. Disaggregated average NRPEC and disaggregated average EM, as well as their respective overall indices, achieved with the different proposals with respect to the educational building that meets CTE-DB-HE 2009 (C2)

(151.71 kWh/m^2 year) and F in EM (62.90 kg CO_2/m^2 year) to C in both (151.71 kWh/m^2 year and 30.07 kg CO_2/m^2 year) with the implementation of CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and to B in both (93.85 kWh/m^2 year and 18.16 kg CO_2/m^2 year) with the implementation of CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b). The total FEC is reduced by 48.36%, the total NRPEC by 45.42% (a 2-letter improvement), and the total EM by 52.19% (a 3-letter improvement) with the implementation of CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) with respect to the baseline building. However, if CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) is implemented, the total FEC is reduced by 70.43%, the total NRPEC by 66.24% (a 3-letter improvement), and the total EM by 71.12% (a 4-letter improvement), with respect to the baseline building.

3.2. Proposals to achieve NZEBs

Fig. 11 shows the disaggregated average NRPECs and disaggregated average EM as well as their respective global indices achieved with the different proposals in relation to the educational building that meets CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) (C2). To achieve a double A rating, it is necessary to reduce the NRPEC by at least 54.81% and the EM by 55.20%. It was found that this objective is achievable:

(i) Replacing the existing combi boiler with a biomass combi boiler reduces NRPEC by 55.50% and EM by 61.07% (P2).

(ii) Replacing the existing boiler by a heat pump that meets the heating and DHW needs and has a solar photovoltaic system achieves reductions of NRPEC by 56.15% and of EM by 62.53% (P10). If this change is also accompanied by rehabilitation of the

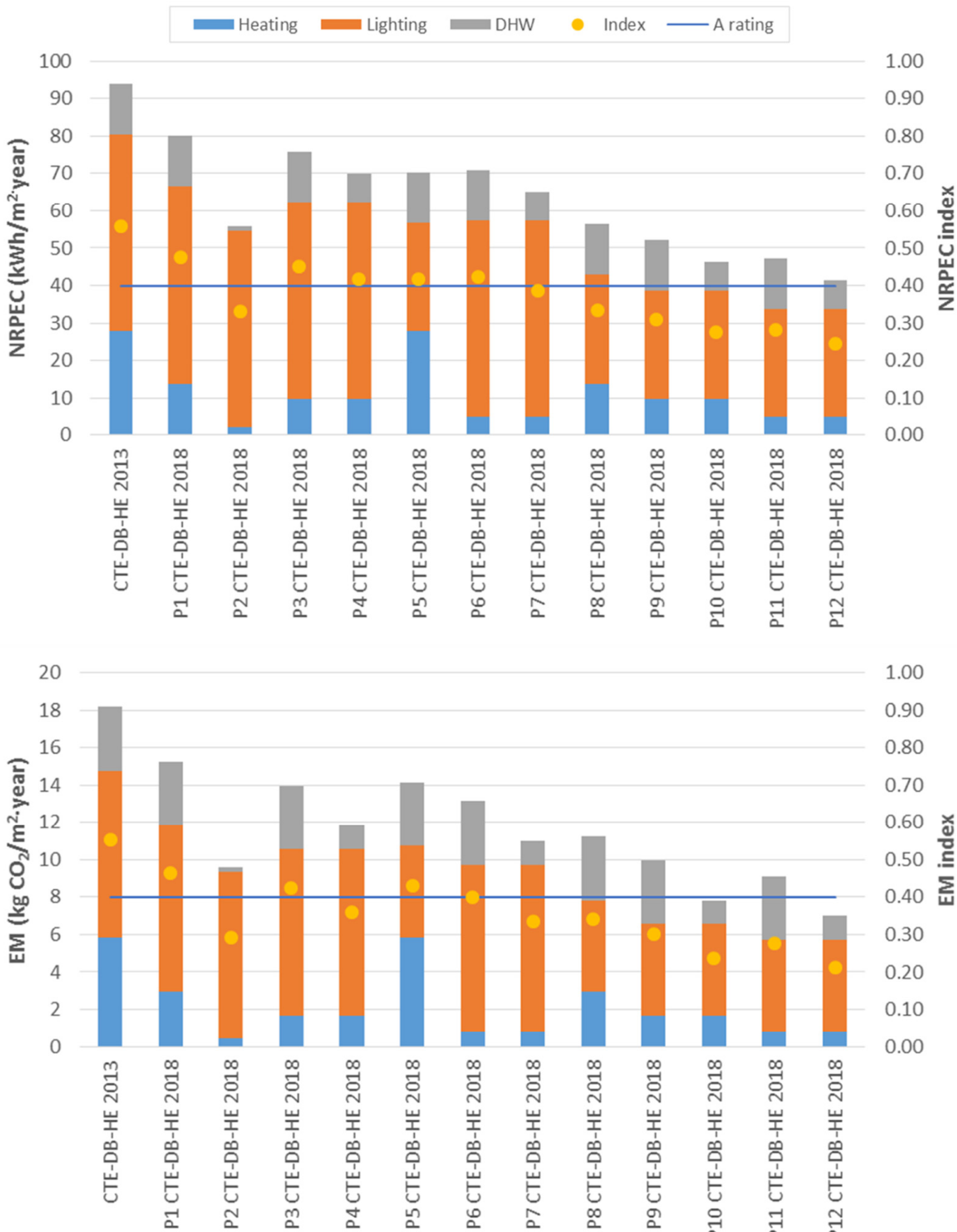


Fig. 12. Disaggregated average NRPEC and disaggregated average EM, as well as their respective overall indices, achieved with the different proposals with respect to the educational building that meets CTE-DB-HE 2013 (C3)

thermal envelope, further reductions of 8.40% in NRPEC and 7.16% in EM are achieved (P12).

(iii) Keeping the existing boiler to meet DHW needs and adding a heat pump for heating along with rehabilitating the thermal envelope and including a solar photovoltaic system lead to reductions of 60.11% in NRPEC and 62.02% in EM (P11).

Fig. 12 shows the disaggregated average NRPECs and disaggregated average EM, as well as their respective global indices, achieved with the different proposals in relation to the educational building that meets CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) (C3). To achieve a double A rating, the NRPEC needs to be reduced by at least 28.35% and the EM by 27.55%. It was found that this objective is achievable:

(i) Replacing the existing combi boiler by a biomass combi boiler reduces NRPEC by 40.62% and EM by 47.33% (P2).

(ii) By keeping the existing boiler, rehabilitating the thermal envelope and adding a solar photovoltaic system, reductions of 40.01% in NRPEC and 38.20% in EM can be achieved (P8).

Table A.1
Maximum global thermal transmittance limit ($K_{G,lim}$), in W/m^2 K, by type of heating and shape factor (f) for heating climate zone D (Presidency of the Government of Spain, 1979).

	Case	$K_{G,lim}$
Heating using solid, liquid or gaseous fuels	$f \leq 0.25$	1.47
	$0.25 < f < 1.00$	$0.21 \cdot (3 + 1/f)$
	$f \geq 1.00$	0.84
Without heating or electric heating	$f \leq 0.25$	1.05
	$0.25 < f < 1.00$	$0.15 \cdot (3 + 1/f)$
	$f \geq 1.00$	0.60

Table A.2
Maximum thermal transmittance ($U_{máx}$), in W/m^2 K, of opaque enclosures by January climate zone for heating climate zone D (Presidency of the Government of Spain, 1979).

Opaque enclosure	January climate zone		
	X	Y	Z
Roof	1.20	0.90	0.70
Exterior façade wall	1.60	1.40	1.40
Floor in contact with air	0.90	0.80	0.70
Ground floor	1.40	1.20	1.20

Table A.3
Maximum values and limits of the average characteristic parameters of the building envelope, in W/m^2 K, according to CTE-DB-HE1 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) and CTE-DB-HE1 2013 (Spanish Ministry of Development, 2013a,b, 2017b).

	Limit value according to CTE-DB-HE1 2009 and CTE-DB-HE1 2013	Maximum value according to CTE-DB-HE1 2009	Maximum value according to CTE-DB-HE1 2013
Transmittance of façade walls	0.66	0.86	0.60
Transmittance of elements in contact with the ground	0.66	0.86	0.60
Transmittance of floors in contact with air	0.49	0.64	0.40
Transmittance of roofs	0.38	0.49	0.40
Transmittance of openings in the façade[a]	1.90–3.50	3.50	2.70

[a]Depending on orientation and percentage of openings in the façade.

Table A.4
Characteristics of the lighting installation for each zone type of the educational building.

Zona	Average horizontal illuminance (lux)	VEEI (W/m^2 100 lux)	
	Recommended value according to Institute for Energy Diversification and Saving (2001)	Limit value according to CTE-DB-HE3 2009	Limit value according to CTE-DB-HE3 2013
Z1	300	4.0	3.5
Z2	500	4.0	3.5
Z3	750	4.0	3.5
Z4	500	6.0	5.0
Z5	300	4.0	3.5
Z6	500	3.5	3.0
Z7	200	4.5	4.0
Z8	150	4.5	4.0

(iii) Keeping the existing boiler to meet DHW needs and adding a heat pump for heating and a solar photovoltaic system lead to reductions of 44.42% in NRPEC and 45.26% in EM (P9). If this is accompanied by a rehabilitation of the thermal envelope, further reductions of 5.19% in NRPEC and 4.53% in EM are achieved (P11). (iv) By replacing the existing boiler by a heat pump that meets the needs of heating and DHW along with rehabilitating the thermal envelope, reductions of 30.75% in NRPEC and 39.41% in EM are achieved (P7). However, if a solar photovoltaic system is added instead of the proposed rehabilitation, reductions of 50.78% in NRPEC and 56.93% in EM are achieved (P10). The implementation of these three improvements achieves a reduction of 55.97% in NRPEC and 61.47% in EM (P12).

Table A.5
Overall characteristics of the lighting installation of the educational building.

Characteristic	Value	Recommendation/Requirement
Luminous efficacy (lúmenes/W)	$\geq$ 60	Institute for Energy Diversification and Saving (2001)
Depreciation factor	0.8–1.0 ($\geq$ 0.9)	Institute for Energy Diversification and Saving (2001)
Coefficient of utilization	$\geq$ 0.5	Institute for Energy Diversification and Saving (2001)
Maximum average installed lighting power density per surface area (W/m^2)	15	Spanish Ministry of Development (2013a,b, 2017b)
VEEI (W/m^2 100 lux)	3.5 (2.0 $\leq$ VEEI $\leq$ 4.5)	Institute for Energy Diversification and Saving (2001)

Table A.6
NRPEC and EM ratings and rating indices (I) for energy performance certification for buildings for uses other than private residence (Institute for Energy Diversification and Saving, 2001).

Rating	Index
A	$I < 0.40$
B	$0.40 \leq I < 0.65$
C	$0.65 \leq I < 1.00$
D	$1.00 \leq I < 1.30$
E	$1.30 \leq I < 1.60$
F	$1.60 \leq I < 2.00$
G	$2.00 \leq I$

This study demonstrates that the double A rating can be achieved by the incorporation of biomass combi boilers in educational buildings that meet CTE-DB-HE 2009 (Spanish Ministry of Housing, 2006, 2007, 2009) or CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b), as was obtained in López-Ochoa et al. (2017) and Las-Heras-Casas et al. (2018) by incorporating them in multi-family buildings under different regulations in cold climate zones of Spain. In addition to all these savings, further savings of up to 33.33% in final thermal energy (heating and cooling), up to 27.93% in final energy for DHW, and up to 19.63% in final electric power (lighting and auxiliary systems) can be achieved by incorporating building automation control systems and technical building management systems and applying EN 15232 (European Committee for Standardization, 2014). In Ippolito et al. (2014) and López-González et al. (2016b), it was demonstrated that the implementation of these systems and the application of EN 15232 (European Committee for Standardization, 2014) can achieve savings of up to 26.36% of the final thermal energy and of up to 14.81% of the final electric power in residential buildings.

In future studies, a detailed analysis will be carried out on the FEC, NRPEC and EM of the different proposals made for educational buildings located in all climate zones of Spain and on the possible savings from the implementation of cogeneration systems, hybrid systems and building automation control and technical building management systems. In addition, the different proposals will be assessed through cost-effectiveness and cost-optimal analyses because the rehabilitation that presents the greatest NRPEC and EM savings is not always economically viable. All of this is with the goal of establishing the framework of requirements for the upcoming CTE-DB-HE and proposing national rehabilitation plans that pursue the objectives of Europe 2020 (European Commission, 2010) and 2030 (European Commission, 2014a,b).

Table B.1
Compositions and main characteristics of enclosure walls and interior partitions of the studied educational buildings for C1.

Enclosure	Layer	Material	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Thermal resistance (m^2 K/W)
Roof	1	Sand and gravel 1700 < d < 2200	0.150	2.000	1450	1050	
	2	Sublayer felt	0.010	0.050	120	1300	
	3	Low density polyethylene (LDPE)	0.010	0.330	920	2200	
	4	Cement or lime mortar for masonry and for rendering/plastering d > 2000	0.020	1.800	2100	1000	
	5	EPS Expanded Polystyrene (0.037 W/mK)	0.020	0.038	30	1000	
	6	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	7	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Exterior façade wall floor 0	1	Sandstone 2200 < d < 2600	0.040	3.000	2400	1000	
	2	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	3	Solid metric or Catalan brick of 1/2 foot 40 mm < G < 50 mm	0.115	0.991	2170	1000	
	4	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	5	Horizontal air chamber without ventilation 5 cm					0.160
	6	Single hollow brick wall 40 mm < E < 60 mm	0.060	0.445	1000	1000	
	7	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
	8	Wafer or ceramic tile	0.020	1.000	2000	800	
Exterior façade wall floors 1 and 2	1	Solid metric or Catalan brick of 1/2 foot 40 mm < G < 50 mm	0.115	0.991	2170	1000	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.020	0.400	875	1000	
	3	Horizontal air chamber without ventilation 5 cm					0.160
	4	Single hollow brick wall 40 mm < E < 60 mm	0.060	0.445	1000	1000	
	5	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	6	Wafer or ceramic tile	0.020	1.000	2000	800	
Glazed enclosure	1	Pressed glass	0.140	1.200	2000	750	
Ground floor	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	4	Sand and gravel 1700 < d < 2200	0.200	2.000	1450	1050	
	5	Cement or lime mortar for masonry and for rendering/plastering 1000 < d < 1250	0.020	0.550	1125	1000	
	6	Rammed earth, adobes, blocks of compressed earth blocks	0.035	1.100	1885	1000	
Mezzanine framework in contact with the exterior	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.015	0.400	875	1000	
	3	EPS Expanded Polystyrene (0.046 W/mK)	0.035	0.046	30	1000	
	4	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	5	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.040	0.400	875	1000	
	6	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Mezzanine framework	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.015	0.400	875	1000	
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	4	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.040	0.400	875	1000	
	5	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Interior partition	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	3	Double hollow brick wall 60 mm < E < 90 mm	0.070	0.432	930	1000	
	4	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	5	Wafer or ceramic tile	0.020	1.000	2000	800	

4. Conclusions

This study presents a comprehensive analysis of the regulatory changes in the fields of energy saving and efficiency that apply to educational buildings, the third most widespread typology within the diverse non-residential building sector. Remarkable progress is made on the knowledge of these buildings at the energy and environmental levels for cold climate zones in Mediterranean countries. In addition, an in-depth analysis is first carried out of different energy rehabilitation options available that involve the improvement of the thermal envelope and efficiency of the building facilities; second, alternatives to achieve the NZEB standard are analyzed.

The main conclusions from the energy rehabilitation of the educational building under study can be summarized as follows:

- Compared to the baseline situation, the reduction in average total NRPEC is 126.35 kWh/m^2 year and 185.05 kWh/m^2 year for rehabilitated and new buildings, respectively, if CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) is implemented in climate zone D1; these values are

Table B.2
Compositions and main characteristics of enclosure walls and interior partitions of the studied educational buildings for C2.

Enclosure	Layer	Material	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Thermal resistance (m^2 K/W)
Roof	1	Sand and gravel 1700 < d < 2200	0.150	2.000	1450	1050	
	2	Sublayer felt	0.010	0.050	120	1300	
	3	EPS Expanded Polystyrene (0.046 W/mK)	0.040	0.046	30	1000	
	4	Low density polyethylene (LDPE)	0.010	0.330	920	2200	
	5	Cement or lime mortar for masonry and for rendering/plastering d > 2000	0.020	1.800	2100	1000	
	6	EPS Expanded Polystyrene (0.037 W/mK)	0.020	0.038	30	1000	
	7	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	8	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Exterior façade wall floor 0	1	Manufactured stone	0.008	1.300	1700	1000	
	2	EPS Expanded Polystyrene (0.046 W/mK)	0.030	0.046	30	1000	
	3	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	4	Solid metric or Catalan brick of ½ foot 40 mm < G < 50 mm	0.115	0.991	2170	1000	
	5	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	6	Horizontal air chamber without ventilation 5 cm					0.160
	7	Single hollow brick wall 40 mm < E < 60 mm	0.060	0.445	1000	1000	
	8	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
	9	Wafer or ceramic tile	0.020	1.000	2000	800	
Exterior façade wall floors 1 and 2	1	Manufactured stone	0.008	1.300	1700	1000	
	2	EPS Expanded Polystyrene (0.046 W/mK)	0.030	0.046	30	1000	
	3	Solid metric or Catalan brick of ½ foot 40 mm < G < 50 mm	0.115	0.991	2170	1000	
	4	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.020	0.400	875	1000	
	5	Horizontal air chamber without ventilation 5 cm					0.160
	6	Single hollow brick wall 40 mm < E < 60 mm	0.060	0.445	1000	1000	
	7	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	8	Wafer or ceramic tile	0.020	1.000	2000	800	
Ground floor	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	3	EPS Expanded Polystyrene (0.046 W/mK)	0.050	0.046	30	1000	
	4	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	5	Sand and gravel 1700 < d < 2200	0.200	2.000	1450	1050	
	6	Cement or lime mortar for masonry and for rendering/plastering 1000 < d < 1250	0.020	0.550	1125	1000	
	7	Rammed earth, adobes, blocks of compressed earth blocks	0.035	1.100	1885	1000	
Mezzanine framework in contact with the exterior	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.015	0.400	875	1000	
	3	EPS Expanded Polystyrene (0.046 W/mK)	0.035	0.046	30	1000	
	4	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	5	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.040	0.400	875	1000	
	6	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
	7	EPS Expanded Polystyrene (0.046 W/mK)	0.030	0.046	30	1000	
	8	Manufactured stone	0.008	1.300	1700	1000	
Mezzanine framework	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.015	0.400	875	1000	
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	4	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.040	0.400	875	1000	
	5	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Interior partition	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	3	Double hollow brick wall 60 mm < E < 90 mm	0.070	0.432	930	1000	
	4	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	5	Wafer or ceramic tile	0.020	1.000	2000	800	

126.48 kWh/m^2 year and 184.24 kWh/m^2 year in climate zone D2 and 125.86 kWh/m^2 year and 182.71 kWh/m^2 year in climate zone D3. The main reductions are achieved in heating, which obtains an 80.52% reduction on average by adapting the educational building to the requirements of CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) for new buildings, while in lighting

Table B.3
Compositions and main characteristics of enclosure walls and interior partitions of the studied educational buildings for C3.

Enclosure	Layer	Material	Thickness (m)	Conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)	Thermal resistance (m^2 K/W)
Roof	1	Sand and gravel 1700 < d < 2200	0.150	2.000	1450	1050	
	2	Sublayer felt	0.010	0.050	120	1300	
	3	EPS Expanded Polystyrene (0.029 W/mK)	0.100	0.029	30	1000	
	4	Low density polyethylene (LDPE)	0.010	0.330	920	2200	
	5	Cement or lime mortar for masonry and for rendering/plastering d > 2000	0.020	1.800	2100	1000	
	6	EPS Expanded Polystyrene (0.037 W/mK)	0.020	0.038	30	1000	
	7	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	8	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Exterior façade wall floor 0	1	Manufactured stone	0.008	1.300	1700	1000	
	2	EPS Expanded Polystyrene (0.029 W/mK)	0.080	0.029	30	1000	
	3	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	4	Solid metric or Catalan brick of 1/2 foot 40 mm < G < 50 mm	0.115	0.991	2170	1000	
	5	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	6	Horizontal air chamber without ventilation 5 cm					0.160
	7	Single hollow brick wall 40 mm < E < 60 mm	0.060	0.445	1000	1000	
	8	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
	9	Wafer or ceramic tile	0.020	1.000	2000	800	
Exterior façade wall floors 1 and 2	1	Manufactured stone	0.008	1.300	1700	1000	
	2	EPS Expanded Polystyrene (0.029 W/mK)	0.080	0.029	30	1000	
	3	Solid metric or Catalan brick of 1/2 foot 40 mm < G < 50 mm	0.115	0.991	2170	1000	
	4	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.020	0.400	875	1000	
	5	Horizontal air chamber without ventilation 5 cm					0.160
	6	Single hollow brick wall 40 mm < E < 60 mm	0.060	0.445	1000	1000	
	7	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	8	Wafer or ceramic tile	0.020	1.000	2000	800	
Ground floor	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 1250 < d < 1450	0.020	0.700	1350	1000	
	3	EPS Expanded Polystyrene (0.029 W/mK)	0.100	0.029	30	1000	
	4	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	5	Sand and gravel 1700 < d < 2200	0.200	2.000	1450	1050	
	6	Cement or lime mortar for masonry and for rendering/plastering 1000 < d < 1250	0.020	0.550	1125	1000	
	7	Rammed earth, adobes, blocks of compressed earth blocks	0.035	1.100	1885	1000	
Mezzanine framework in contact with the exterior	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.015	0.400	875	1000	
	3	EPS Expanded Polystyrene (0.046 W/mK)	0.035	0.046	30	1000	
	4	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	5	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.040	0.400	875	1000	
	6	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
	7	EPS Expanded Polystyrene (0.029 W/mK)	0.080	0.029	30	1000	
	8	Manufactured stone	0.008	1.300	1700	1000	
Mezzanine framework	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.015	0.400	875	1000	
	3	Unidirectional forged concrete infill, 250 mm span	0.250	1.323	1330	1000	
	4	Cement or lime mortar for masonry and for rendering/plastering 750 < d < 1000	0.040	0.400	875	1000	
	5	Medium hardness plaster 600 < d < 900	0.015	0.300	750	1000	
Interior partition	1	Wafer or ceramic tile	0.020	1.000	2000	800	
	2	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	3	Double hollow brick wall 60 mm < E < 90 mm	0.070	0.432	930	1000	
	4	Medium hardness plaster 600 < d < 900	0.020	0.300	750	1000	
	5	Wafer or ceramic tile	0.020	1.000	2000	800	

and DHW, the reductions are 51.74% and 48.94%, respectively. The energy efficiency rating for NRPEC achieved a 3-letter improvement and reached a B rating.

- Compared to the baseline situation, the average total CO_2 emission reduction is 32.93 kg CO_2/m^2 year and 45.02 kg CO_2/m^2 year for rehabilitated and new buildings, respectively, if CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) is implemented in climate zone D1; these values are 32.86 kg CO_2/m^2 year and 44.76 kg CO_2/m^2 year in climate zone D2 and 32.63 kg CO_2/m^2 year and

44.33 kg CO_2/m^2 year in climate zone D3. The main reductions are achieved in heating, which achieves an 84.36% reduction on average by adapting the educational building to the requirements of CTE-DB-HE 2013 (Spanish Ministry of Development, 2013a,b, 2017b) for new buildings, while in lighting and DHW, the reductions are 51.76% and 51.22%, respectively. The energy efficiency rating for emissions had a 4-letter improvement and reached a B rating.

- With regard to the building that meets the current CTE-DB-HE (Spanish Ministry of Development, 2013a,b, 2017b), obtaining the double A rating as a precondition for achieving NZEBs is possible using a biomass boiler for heating and DHW (P2); using a heat pump for heating and DHW and a solar photovoltaic system to cover part of the lighting system (P10); decreasing the overall thermal transmittance of the building and using a heat pump for heating, the existing boiler for DHW and a solar photovoltaic system to cover part of the lighting system (P11); or decreasing the overall thermal transmittance of the building and using a heat pump for heating and DHW and a solar photovoltaic system to cover part of the lighting system (P12). In all these proposals, the solar thermal system is kept for covering part of the DHW.

This work can serve as a guide to change the manner in which NZEBs are designed today. The definition of this type of building is key to our cities becoming more energy efficient and respectful of the environment. The great challenge of the rehabilitation of existing buildings has been addressed realistically, taking advantage of the opportunities offered for these types of buildings. The proposed solutions can serve as an example for other climate zones within Spain and be extrapolated to other Mediterranean countries with the appropriate methods. In this manner, states and decision makers will be able to design future energy rehabilitation policies and promote policy changes regarding educational buildings. In future studies, these and other proposals should be analyzed in greater detail, and a comprehensive cost analysis must be done to select not only those solutions that will achieve a double A rating but also those that are economically viable.

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

See Tables A.1–A.6.

Appendix B

See Tables B.1–B.3.

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