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Evaluating European directives impacts on residential buildings' energy performance: a case study of Spanish detached houses

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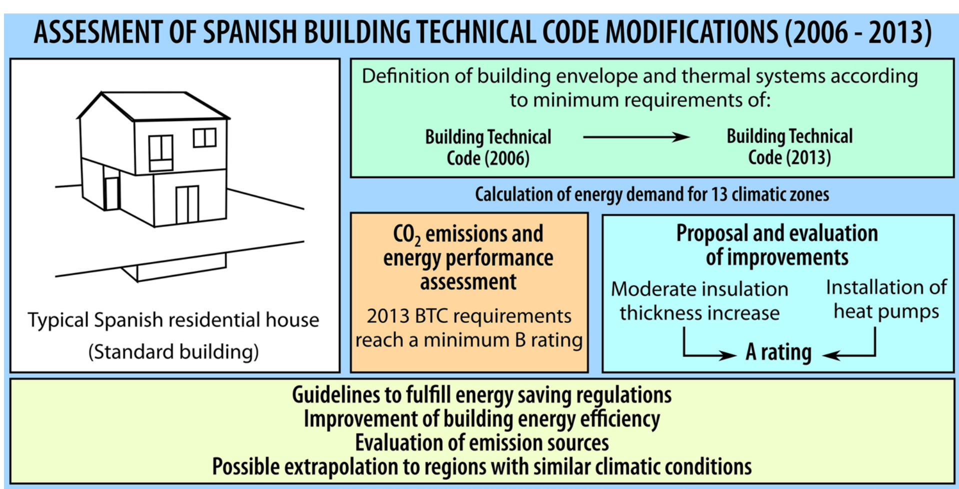
Abstract

Spain has a high level of energy consumption and CO_2 emissions in detached houses, being the lack of an adequate insulation level and efficient energy systems the main causes. The Spanish Government has been performing modifications on its Building Technical Code (BTC) to address this issue, following European Directives. An assessment of the development of the Spanish BTC from its first 2006 version has been conducted in this work. A standard Spanish detached house was placed in the different Spanish climatic zones, designed with the minimum requirements of the 2006 and 2013 BTCs, and was then analyzed using the software Cerma. The results show that energy demand is reduced and the energy rating is improved with the stricter requirements introduced in the 2013 BTC. Although energy demand and CO_2 emissions vary significantly among the 13 different climatic zones studied, the BTC modifications allow to reach a minimum energy rating independently of the climatic zone where the house is located. Opaque enclosures and internal loads were found to be the main contributors to building-related emissions. Additionally, possible actions to improve energy rating in detached houses are evaluated, finding that a moderate insulation thickness increase and the installation of heat pumps allow to reach the highest energy rating, being the improvement more apparent in northern and central regions. The results of this work may be extrapolated to other countries with similar climatic conditions to the studied zones, providing guidelines to fulfill energy saving regulations, evaluate emission sources and improve building energy efficiency.

Graphic abstract



Keywords Spanish climatic zones · Cerma software · Spanish building technical code · Greenhouse gas emissions reduction · Zero consumption buildings · Building energy regulations

Extended author information available on the last page of the article

Introduction

Architecture has been extensively affected by the development of design techniques, with human comfort becoming increasingly important with time (Erdem et al. 2019). However, the building sector generates a harmful impact on the environment (Hossaini et al. 2015), being responsible for more than 40% of global energy use and 30% of global greenhouse gas emissions (Yang et al. 2016). The increase in building energy consumption is highly affected by building design, change of comfort standards, building operation and maintenance, as well as heating, ventilation, and air conditioning (HVAC) systems (Satrio et al. 2019). In the European Union (EU), 40% of energy consumption can be ascribed to the building sector. The 2019 Eurostat report (Eurostat 2019) makes the residential sector accountable for 27% of this total consumption, so the improvement of the energy performance of residential buildings becomes an important opportunity to save energy. Building sustainability could help to safeguard the environment as well as ensure wellbeing of population (Labanca et al. 2015). Building retrofitting strategies, including improvement of building envelope performance; application of renewable technologies; improvement of the efficiency of energy systems; and intelligent operation and energy management are actions that may be considered by authorities to achieve carbon reduction aims while maintaining comfortability and sustainability in built environments (Li et al. 2018). Likewise, inherent problems of climate change caused by greenhouse gases (GHG) have led to a change in the sensitivity towards energy issues and a growing global concern, resulting in international and regulatory agreements to avoid GHG emissions (Ríos 2019).

In an increasingly energy-conscious world, a detailed understanding of the significant energy consumption of residential sector becomes relevant to prepare for future scenarios (Wang et al. 2020). The EU, through the Energy Performance of Buildings Directive (European Union 2018) and the Energy Efficiency Directive (European Union 2012), has been setting requirements and expectations regarding energy savings and efficiency in buildings (López-Ochoa et al. 2019). The additional commitments signed by the EU member states at COP 25 represent a greater involvement of countries in the current climatic emergency (United Nations 2019). Among these commitments stands out the prioritization of energy efficiency in residential facilities and constructions, with the European Commission considering it one of the most effective ways to reduce GHG and other pollution emissions. The European Green Deal signed in 2019 (European Commission 2019) reaffirms the commitment of the EU to adopt environmental protection actions and fighting climate change. Part of these measures include the support for investments in cleaner technologies, sustainable solutions, use of renewable energy sources and energy efficiency actions. This sets the achievement of a high-efficiency building model as a challenge for both the EU (Ríos et al. 2020) and the rest of the world.

In the 90 s, energy certification systems emerged as a mechanism to identify the level of energy consumption of buildings. Nowadays, they have consolidated as an essential method for the improvement of energy efficiency, minimization of energy consumption and greater transparency regarding the energy use in buildings (Pérez-Lombard et al. 2009). Technical regulations aimed at energy consumption reduction tend to classify buildings attending to the level of energy consumption and associated emissions. Some examples are the British Building Research Establishment Environmental Assessment Method BREEAM (Harris 1999) or the USA Leadership in Energy and Environmental Design (LEED) (US Green Building Council 2013; Heidarinejad et al. 2014). Nevertheless, the results of the Scofield studies from 2013 concluded that the application of LEED certification in New York City office buildings did not achieve the desired objectives regarding building GHG emissions and energy consumption. These results posed the necessity of the analysis and improvement of certification procedures to assess their effectiveness in increasing building energy efficiency.

On 12/16/2002, the Directive 2002/91/EC of the European Parliament and Council (European Union 2002) established a common framework with the aim of promoting energy efficiency in community buildings. This Directive considered climatic conditions, local particularities of each area and the internal environmental requirements of the building, as well as the cost-effectiveness of the solutions proposed. On 05/19/2010, the Directive 2010/31/EU of the European Parliament and Council (European Union 2010) amended it by incorporating the basic procedure for energy efficiency certification of existing buildings. In Spain, the requirements established by the Directive 2002/91/EC were transposed into the Spanish Royal Decree RD/47/2007 (Ministerio de la Presidencia de España 2007a), of January 19th, setting a basic procedure for the energy certification of newly constructed buildings. Likewise, the Directive 2010/31/EU was partially transposed. Later, on 10/25/2012, the Directive 2012/27/EU of the European Parliament and Council (European Union 2012) on energy efficiency was approved, amending previous Directives and making Spanish regulations adapt to the new requirements. The Spanish Ministry of Housing and Ministry of Energy, Tourism and Digital Agenda, working with the Institute for Energy Diversification and Saving (IDAE), determined the requirements for the calculation procedure in order to obtain the building energy certification and specified them in the Spanish RD 235/2013 (Ministerio de la Presidencia de España. 2013) of April 5th, which approves the basic procedure for the energy efficiency certification of buildings.

The European legislation establishes the requirement for all buildings to possess an energy certification, which must be provided by unified and global approach. A comparison of energy certification processes in different European countries was presented by Andaloro et al. (2010). In 2013, the Energy Efficiency Ontology (Vinagre et al. 2013) and the energy labeling method of office buildings in Iran (Bagheri et al. 2013) were presented. Labanca et al. (2015) studied the energy efficiency services (EESs) for residential buildings in the European Union. They concluded that energy efficiency policies supporting EES markets in the residential segment are extremely needed. EU policies can increase trust into EESs and a stronger cooperation with banks and governments to finance EESs is necessary in most EU countries. Later, Salleh et al. (2016) developed methods for the analysis of energy efficiency in school buildings. According to their results, the main factors to achieved energy efficiency improvements are building design, services design, and occupant behavior. Martínez-Molina et al. (2016) presented a review of the different methods and techniques used to achieve refurbishments implementation. Their work aimed to prove the viability of preserving historic buildings with improvements in energy efficiency and thermal comfort. The projects and strategies presented provide useful examples for worldwide governments and cities. Borgstein et al. (2016) reviewed the energy rating methods for non-domestic buildings. Methodologies were grouped in five groups: statistical methods, engineering calculations, simulations, machine learning and others. Additionally, they mapped the use of performance evaluation in energy efficiency standards. Chandel et al. (2016) developed regulations and energy efficiency initiatives for residential buildings, concluding that the building envelope and materials, weather and site conditions are the most important variables regarding energy efficiency, so they should be integrated into construction regulations. Simona et al. (2017) presented the increasing energy efficiency in collective residential buildings and an analysis of the freezing point influence in the thermal insulation of the external walls. Their study determines the influence of the insulation in the energy demand of buildings. A review of methods for climatic zoning for building energy efficiency programs was conducted by Walsh et al. (2017). They concluded that the combination of cluster analysis and building performance simulation offers an effective tool to deal with the complex relationships between climate and building energy efficiency. Later, the same authors (Walsh et al. 2018) introduced a quality index and a procedure based on building simulation regarding the building stock targeted by policies in each climatic zone. Both the proposed index and procedure are effective for emphasizing virtues and weaknesses of existing climatic zoning methods. Gramalath et al. (2018) reviewed energy rating systems in residential buildings and remarked the lack of consideration of the building life cycle in the literature. Their work proposes an assessment framework for the energy systems of existing multi-unit residential buildings (MURB), combining asset and operational ratings. A fuzzy logic-based method was applied to face data uncertainty. Regarding regulations, an analysis of regulatory instruments promoting building energy efficiency was presented by Blumberga et al. (2018). It was noticed that grant schemes are helpful for the energy efficiency measures but not enough for the fast completion of large-scale energy efficiency enhancements. According to the results obtained by Fan et al. (2018), gradual pattern mining is an encouraging technique for detecting valuable patterns from building operational data. Based on that, valuable insights on building performance characteristics and prospects for building energy efficiency improvements can be obtained. Silvero et al. (2019) reviewed the main standards implemented in South American countries for improving building energy efficiency. Energy policy implications were analyzed to conclude that energy efficiency is related to the use of the most environmentally friendly energy source. Economidou (2020) conducted a comprehensive review of EU energy efficiency policies for buildings. The work studied the effect of political priorities in reshaping how energy efficiency is directed by EU policymakers, providing proposals and insight into the development of the EU capability to save energy in buildings. Mazzaferro et al. (2020) showed the importance of relying on building performance data to improve the quality of climatic zone distributions in regulations for building energy efficiency. Pylsy et al. (2020) developed a model including district cooling and heating, heat pumps and combined heat and power (CHP) systems. This model is an effective computation tool to assess the effect of buildings' energy efficiency measures on the reduction in CO_2 emissions. The results highlighted the importance of the interconnection between energy systems and building efficiency. Recently, Al-Homoud and Krarti (2021) have presented a review of the status and roadmap on energy efficiency of residential buildings in Saudi Arabia. The most representative measures are: development and enforcement of comprehensive energy efficiency codes and standards for buildings; promotion of the use of building performance simulation for design and conditioning of buildings; and encouragement of on-site clean energy generation.

In European countries, existing buildings account for over 40% of final energy consumption, with residential use representing 63% of total energy consumption in the building sector (Trashorras et al. 2015). According to the Institute for Energy Diversification and Saving (IDAE 2011), energy consumption associated with detached houses in Spain accounts for 46% of the residential sector. As a member country of the EU, Spain has established a series of legislation and software tools to meet the EU requirements. The essential regulations regarding energy certification in Spain are the following: Building Technical Code (BTC) (Ministerio de la Presidencia de España 2006) and its subsequent revisions (Ministerio de la Presidencia de España 2007a), the Regulations on Building Heating Installations (RBHI) (Ministerio de la Presidencia de España 2007b) and the Building Energy Performance Certificate for buildings (Ministerio de la Presidencia de España 2013). Additionally, Spain has implemented National Plans such as the National Energy Efficiency Action Plan (NEEAP) 2014–2020 (Ministerio de Industria, Energía y Turismo 2014) and the NEEAP 2017–2020 (Ministerio para la Transición Ecológica 2017). Under the EU Energy Efficiency Directives, the NEEAPs have become the central tool of Spanish energy policy.

In 1999, the Law on Building Management (LOE) (Ministerio de la Presidencia de España 1999) was published. It established a series of requirements for the rational use of energy and defined the Building Technical Code (BTC) as the regulatory framework that determines the quality requirements for buildings and their installations. The European Directive 2002/91/EC (European Union2002), which established the requirements for building energy performance, was transposed into the Spanish Royal Decree 314/2006 (Ministerio de Vivienda, 2015). Subsequently, the Directive 2010/31/EU (EBDP) (European Union 2010) on building energy performance was approved, amending Directive 2002/91/EC. That Directive was transposed in Spain by the Royal Decree 235/2013 on the energy certification of buildings (Ministerio de la Presidencia de España 2013). This decree led to the update of the Spanish BTC by the Order FOM/1635/2013 (Ministerio de Fomento 2013). After that, the BTC was amended following the energy consumption limits for new buildings imposed by the Royal Decree 732/2019 (Ministerio de la Presidencia de España 2019). It should be noted that Directive 2010/31/EU includes nearly zero energy buildings consumption (NZEB) for the first time, with the Energy Performance Certificate (EPC) as an instrument to assess building energy savings and energy efficiency. NZEB are also defined in the Royal Decree 732/2019. The latest European Directive 2018/844 (European Union 2018) on energy efficiency, which amends the aforementioned directive, has not yet been transposed in Spain.

Several studies have used the EPC as a reference for the assessment of building energy efficiency. Li et al. (2019) consider that, at European level, input data for energy certification programs may be highly subjective and therefore of low quality, e.g., frequently, the equipment performance and the enclosures are not thoroughly assessed. To avoid this, they proposed Building Information Modeling (BIM) as a calculation tool that combines information, fast calculation, and reliability. They also consider indoor air quality as a variable to be controlled. Finally, they highlight that there is lack of adequate information for the homeowners about the assessment results. (Patiño-Cambeiro et al. 2019) evaluated the energy renovation of 11 tertiary buildings constructed before the mandatory enforcement of the BTC, located in three Climatic Zones (CZs) (D1, D2 and C1) in the Spanish Atlantic region. They performed active measures (thermal equipment and lighting, depending on their needs) and passive measures in four of them (improvement of facades, roofs and insulation), concluding that active measures are feasible and more effective than passive measures. In their work, 3 CZs out of a total of 13 are analyzed, but only with a very specific type of building, so it is difficult to generalize the results obtained to the whole country.

Other studies aim at the development of actions that reduce energy consumption. To this end, different scenarios have been considered in "Greater Bangkok," at medium-term (2030) and long-term (2050) (Chaichaloempreecha et al. 2019). The scenarios were based on the implementation of saving policies and the deployment of energy efficient technologies in commercial, industrial and residential fields. In the latter sector, they promoted specific action plans: energy labeling, an energy efficiency resource standard (EERS), use of LED lamps and solar water heater. Regarding energy systems, advanced technologies in cooling (refrigeration and air conditioning) and cooking systems are being sought. They also propose to replace LPG in rural areas by Biogas. Their work reveals that LED and EERS measures are slightly successful, being the implementation of advanced technologies the most successful one, saving a total of 19.6 Mt-CO_2 (GHG). Lee et al. (2018) consider that Energy Performance Certificates (EPC) should be public and provide essential information to future home buyers. They also claim that high efficiency buildings should not have a higher price, aiming at government intervention to avoid malpractice. Lopez-Gonzalez et al. (2016) conducted a study of buildings constructed in La Rioja (Spain), covering three CZs (D1, D2 and E1), by means of the EPC. This methodology allows the calculation and verification of the average primary energy consumption and the corresponding yearly CO_2 emissions in the region studied. The data from this work may be used as the basis to develop different energy rehabilitation scenarios.

The inclusion of energy saving techniques in buildings will allow the transition to a more sustainable energy model that is also less polluting and less dependent on foreign supplies. Moreover, the objectives of the energy policy should be to guarantee responsible energy consumption, minimize energy losses associated with buildings, reduce adverse environmental impacts, improve standards of living and improve the competitiveness of the building sector. A review of current and emerging financing instruments on energy renovation of residential buildings in the EU was conducted by Bertoldi et al. (2020). In addition to "traditional" financial policies it assesses innovative financing methods such as energy efficiency feed-in tariffs and energy efficiency mortgages. The Spanish Government has been promoting state housing plans since 1981. The current State Housing Plan 2018–2021 (Ministerio de Transportes, Movilidad y Agenda Urbana 2018) aims to aid people evicted from their residences, to encourage housing rental and to renovate urban and rural housing stock. Regarding this last aspect, the "Programme to promote the improvement of energy efficiency and sustainability in housing" provides financial support to improve building energy efficiency and sustainability, with special attention to thermal envelopes of existing buildings. In order to be eligible for such subsidies, reductions in primary energy consumption ranging from 20 to 35% depending on the CZ are required (Ministerio de la Presidencia de España 2018). In parallel, IDAE manages the European Regional Development Funds (ERDF), financing and developing programs for building renovation. The Building Energy Renovation Program (PREE) from 2020 regulates actions regarding subsidies for the energy renovation of existing buildings (Ministerio de la Presidencia de España 2020).

The works found in the literature regarding energy efficiency of buildings in Spain focus on one or several specific Spanish regions with particular climatic conditions, but do not consider the climatic disparity of the Spanish territory reflected in its thirteen CZs. In addition, most of the buildings studied are very singular and therefore, they are not representative of the building typology in Spain. Consequently, in order to analyze thoroughly the energy efficiency of buildings in Spain, a building that meets the general characteristics of the Spanish building stock should be studied and the specific conditions of the different Spanish climatic zones should be assessed. Considering the variety of CZs in Spain, an extrapolation of the results to other countries with similar constructive patterns in buildings could be performed. Additionally, since Spanish regulations provide detailed information and procedures to evaluate building energy efficiency, the analysis of the evolution and improvements in the Building Technical Code may be very useful for other countries to establish their own procedures.

The objective of this work is the analysis of the development of the Spanish BTC from its first 2006 version to assess how energy efficiency in detached houses has been implemented, according to the subsequent European Directives on that matter. A reference building has been defined as representative of the Spanish building stock in terms of typology and morphology. According to the previous literature review, detached houses consume almost half the final energy of the residential sector in Spain. Therefore, a case study of Spanish detached houses has been performed. In order to analyze the impact of changes in the BTC requirements regarding building energy efficiency, the case study is developed so that the house meets the minimum requirements of the different BTC versions. Then, the house energy performance is studied for every Spanish CZs. Finally, the assessment of possible modifications in the house envelope and thermal systems to improve its energy efficiency is conducted.

Methodology

In order to assess the differences regarding building energy certifications between the 2006 and 2013 Spanish BTCs, a typical residential house representing the Spanish building archetype was defined [in the following referred to as "Standard Building (SB)"]. This representative house is placed at the capital cities of Spanish provinces representing 13 different CZs with different weather conditions. The first 12 zones were designated according to summer (SV) and winter (SI) climate severity with numbers from 1 to 4 and letters from A to E, respectively. The 13th climatic zone α, corresponding to the Canary Islands, was added with the 2013 update of the BTC after readjustment of the CZs (Ministerio de Fomento 2015). The building envelope and thermal systems were selected according to the minimum requirements of the 2006 and 2013 BTCs for each climatic zone. Then, the energy demand and CO_2 emissions were calculated and the energy performance was assessed. This allowed the proposal and evaluation of possible improvements in the building to achieve the highest energy qualification. This process is depicted in Fig. 1.

Standard building definition

The selected SB is representative of the typical Spanish detached house. A frontal and lateral view of the building are shown in Fig. 2. To define building data, databases from the Spanish Ministry of Industry, Commerce and Tourism (MINETUR) (Ministerio de Industria, Energía y Turismo 2021), the National Statistics Institute (INE) (INE 2021) and the Institute for Diversification and Saving of Energy (IDAE) (IDAE 2021) have been considered. The average usable space of detached houses in Spain, according to the criteria of IDAE, approximately 108.8 m^2.

Construction solutions for the SB were selected according to the criteria of the Spanish Ministry of Development on housing construction. The building envelope was adapted to comply with the maximum transmittances allowed by the 2006 and 2013 BTCs, as well as the limitation of the demand described therein for the 13 Spanish CZs. Overall, the double-leaf break with intermediate air chamber and the sloping insulated roof are the main solutions. Carpentry is mainly built of polyvinyl chloride (PVC) profiles with double glazed

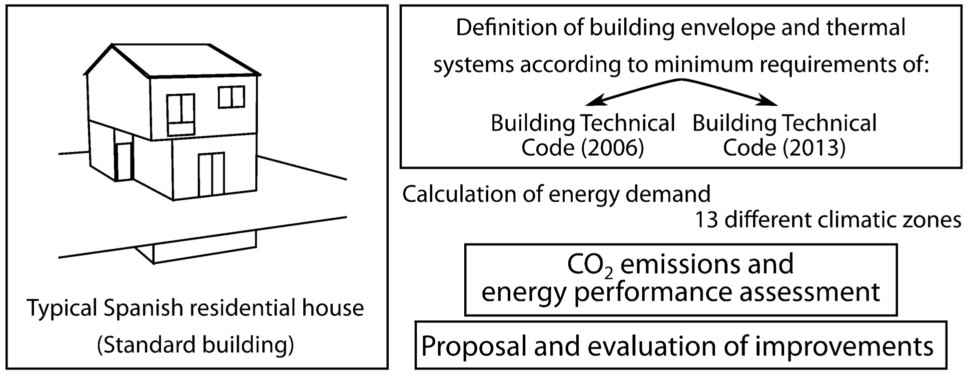


Fig. 1 Scheme of the methodology followed in this study

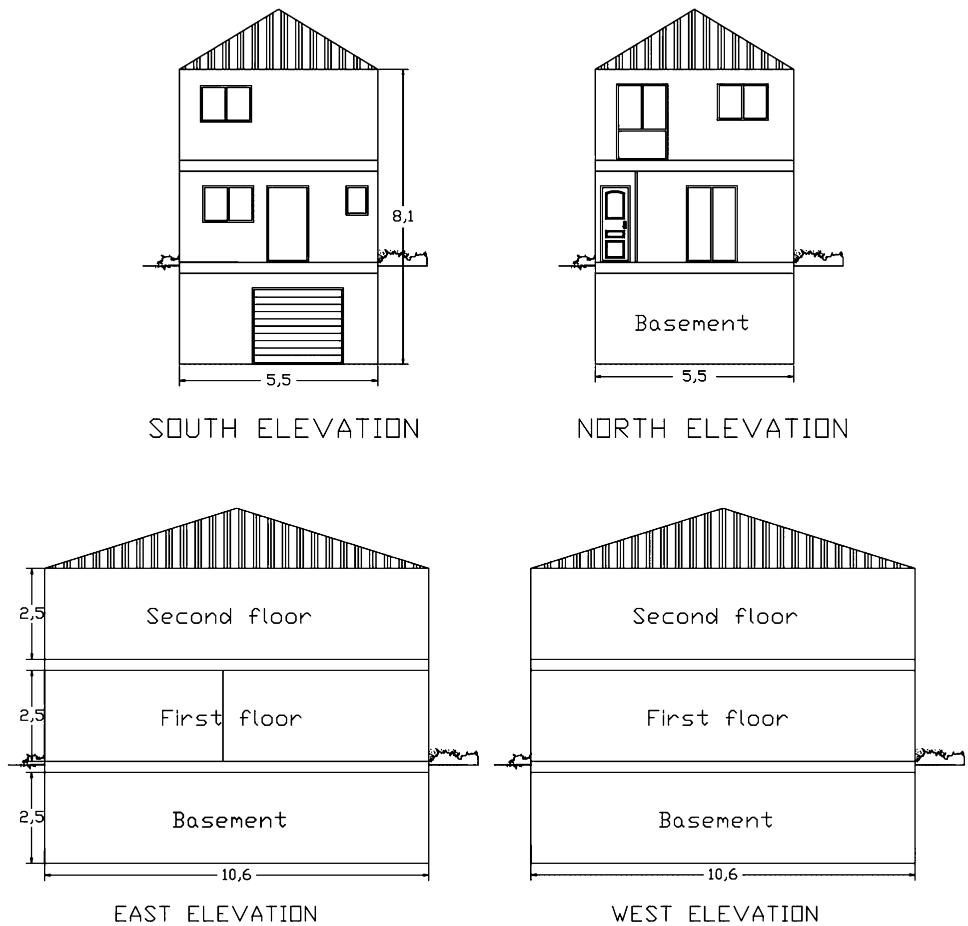


Fig. 2 Frontal and lateral views of the Standard Building (SB)

air chambers, enhancing both thermal conductivity and air tightness. The 3-story SB consists of three bedrooms (one master and two single), a living room, a kitchen and two bathrooms, with a total area of 108.8 m^2 and a conditioned volume of 319.4 m^3. The dimensions of the different building zones and openings are collected in Table 1, whereas its technical characteristics may be found in Table 2.

The SB has PVC windows (10% fraction) with north and south orientation and solar factor (SF) of 0.75. The windows to the north are double glazed with 4/12/4 air chamber with thermal transmittance $U = 2.43$ W/ m^2 K and the windows to the south are double glazed with 4/6/4 air chamber with thermal transmittance $U = 1.62$ W/m^2 K.

Climatic conditions

The different CZs in Spain are defined according to the temperature and solar radiation values in summer and winter. The severity degree in winter is assessed using letters from A to E, with A being the warmest winter and

Table 1 Technical characteristics of the Standard Building (SB)

Zone	Area (m^2)	Openings	wxh (mxm)
Basement	57.49	North	
Ground Floor	51.28	2 uds	1.4×2.1
First Floor	57.49	1 ud	1.4×1
Facades		South	
North	20.25	2 uds	1.4×1
South	21.57	1 ud	1.15×2.1
East	61.82	1 ud	0.8×0.6
West	61.82		
Roof	59.01		
Ground	59.01		

E the coldest winter. It is important to note the difference between this scale and the final energy rating, although the same letters are used. The severity degree in summer is assessed with numbers from 1 to 4, being 4 the warmest summer. Hence, every region may be classified using a number and a letter, resulting in 12 different combinations required to define all Spanish CZs (and an additional α zone for the Canary Islands). The conditions of 13 representative cities selected for each climatic zone, collected in Table 3, were applied to the SB to generate the study cases. The CZs defined in the 2006 and 2013 BTCs are depicted in Fig. 3.

Calculation of energy demand

Building energy demand was estimated regarding the following aspects:

1. Two seasonal periods are considered: summer, including the months from June to September; and winter, including the months from January to May and from October to December
2. Heating, cooling and domestic hot water (DHW) equipment are considered as follows:

Table 2 Technical characteristics of the Standard Building (SB)

Constructive solutions	2006 BTC	2013 BTC	Constructive solutions	2006 BTC	2013 BTC
Floor Slab-Exposed to the Outside			*Sloping Roof*		
1.Medium weight fronda	1.8 cm	1.8 cm	1. Clay roofing tile	2 cm	2 cm
2. Ceramic tile	2 cm	2 cm	2. Medium weight conifer	2 cm	2 cm
3. Cement mortar for masonry or plaster	1.5 cm	1.5 cm	3. Extruded polystyrene (XPS) expanded with CO_2	7 cm	17 cm
4. Expanded polystyrene (EPS)	5 cm	14 cm	4. One-way spanning slab. Ceramic Framework	30 cm	30 cm
5. OWSJ lighted concrete joisting	30 cm	30 cm	5. Black plaster	1.5 cm	1.5 cm
6. White plaster	1.5 cm	1.5 cm	6. White plaster	1.5 cm	1.5 cm
he ($W/m^2{\cdot}K$)	10	10	he ($W/m^2{\cdot}K$)	10	10
hi ($W/m^2{\cdot}K$)	10	10	hi ($W/m^2{\cdot}K$)	25	25
U ($W/m^2{\cdot}K$)	0.53	0.23	U ($W/m^2{\cdot}K$)	0.36	0.18
North Outer Wall			South-East–West Outer Wall		
1. Masonry mortar/black plaster	2 cm	2 cm	1. Masonry mortar/black plaster	2 cm	2 cm
2. Ceramic joist filler block with conventional mortar	24 cm	24 cm	2. Ceramic joist filler block with conventional mortar	24 cm	24 cm
3. XPS Expanded with CO_2	5 cm	15 cm	3. XPS Expanded with CO_2	3 cm	13 cm
4. Double hollow brick partition	7 cm	7 cm	4. Double hollow brick partition	7 cm	7 cm
5. White plaster	1.5 cm	1.5 cm	5. White plaster	1.5 cm	1.5 cm
he ($W/m^2{\cdot}K$)	7.69	7.69	he ($W/m^2{\cdot}K$)	7.69	7.69
hi ($W/m^2{\cdot}K$)	25	25	hi ($W/m^2{\cdot}K$)	25	25
U ($W/m^2{\cdot}K$)	0.58	0.20	U ($W/m^2{\cdot}K$)	0.58	0.20
Basement Wall			Ground		
1. Armed concrete	25 cm	25 cm	1. Ceramic tile	2.5 cm	2.5 cm
2. EPS	3 cm	15 cm	2. Particle board	2 cm	2 cm
3. Laminated plasterboard	2 cm	2 cm	3. Cement mortar for masonry or plaster	2 cm	2 cm
U ($W/m^2{\cdot}K$)	0.47	0.23	4. XPS expanded with CO_2	4 cm	14 cm
			5. OWSJ concrete joisting	30 cm	30 cm
			U ($W/m^2{\cdot}K$)	0.54	0.23

Table 3 Representative cities of each Spanish climate zone

Zone	City	Zone	City	Zone	City	Zone	City
A3	Cadiz	C1	Bilbao	D1	Lugo	E1	Burgos
A4	Almeria	C2	Barcelona	D2	Zamora	α	Las Palmas
B3	Valencia	C3	Granada	D3	Madrid		
B4	Sevilla	C4	Toledo				

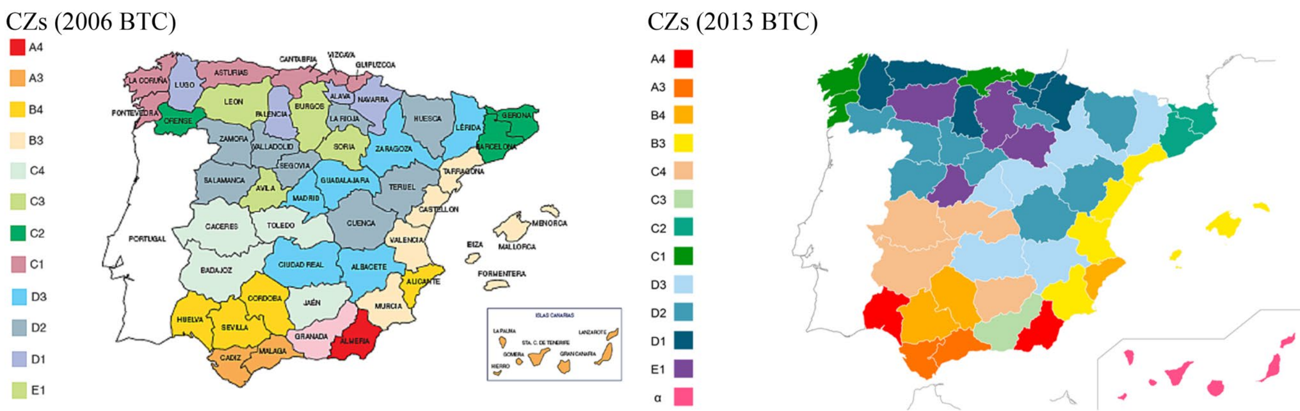


Fig. 3 Spanish CZs according to the different building technical codes

- Heating demand is provided by a diesel boiler with a seasonal efficiency of 92% and a nominal power of 24 kW.
- Cooling demand is supplied by a default system with a seasonal yield of 1.75.
- DHW demand is covered by a system with a nominal yield of 92%, adjusting the solar energy production according to the requirements of the BTC.

3. Regarding occupational and operational indices, a low load intensity was considered as the SB is a residential building. A latent occupation of 2.00 W/m^2, a sensitive occupation of 1.26 W/m^2 and a load intensity due to different equipment of 1.50 W/m^2 values were selected.
4. Permeability was chosen depending on the climatic zone to be evaluated: for climate zones A and B, 50 m^3/h m^2; and for zones C, D and E, 27 m^3/h m^2.

Assessment of energy performance and CO_2 emissions

The European Directive on Energy Efficiency of Buildings (European Parliament and Council, 2018) requires that EU member states calculate the energy performance of buildings using a methodology that considers at least the following aspects: thermal characteristics of the building, heat and domestic heat water (DHW), air conditioning, ventilation, position and orientation of buildings depending on external climatic conditions, passive solar systems and sun protection, natural ventilation and indoor environmental conditions.

The energy rating is expressed using indicators for the energy behavior of a building. These indicators are obtained from the energy required by the building to meet the energy demand depending on the climatic conditions. The software Cerma v.4.2.5 (Cerma 2020) was used to perform the study cases. This software is recognized for energy efficiency certification by Article 3 of Spanish RD 47/2007 (Ministerio de la Presidencia de España 2007a), from January 19th, for both new and existing residential buildings, according to the resolution of June 27th 2013 from the Permanent Advisory Commission for Energy Certification of the Spanish Ministry of Industry, Commerce and Tourism and the Spanish Ministry of Public Works. In addition to the energy certification, Cerma software provides significant data such as heating and cooling demand, primary and final energy, as well as generated CO_2 emissions (Instituto Valenciano de la Edificación 2017). The software allows to perform hour-by-hour yearly simulations of the building behavior. Internal loads may be defined as sensitive or latent loads depending on occupation, set point temperature values and ventilation. Therefore, it is possible to compare different improvements that may be performed to the building to increase its energy performance.

After the Spanish RD 235/2013 (Ministerio de la Presidencia de España 2013) was approved, every building must be classified by its level of CO_2 emissions. A so-called ecological label with a letter ranging from A to G, based on the yearly CO_2 emissions per square meter generated by the building, is used to certify its energy efficiency (Ministerio de Industria, Energía y Turismo 2011; Gangolells et al. 2016). Two energy efficiency rating indices, $\boldsymbol{\sigma_1}$ and $\boldsymbol{\sigma_2}$, allow to obtain the building energy rating (Ministerio de Industria, Energía y Turismo 2011):

$$\boldsymbol{\sigma_1} = \frac{\left(\frac{I_0}{I_r} \cdot R\right) - 1}{2 \cdot (R - 1)} + \mathbf{0.6} \tag{1}$$

$$\boldsymbol{\sigma_2} = \frac{\left(\frac{I_0}{I_S} \cdot R'\right)}{2 \cdot (R' - 1)} + \mathbf{0.5} \tag{2}$$

where $\boldsymbol{I_0}$ represents the building CO_2 emissions; $\boldsymbol{I_r}$, the average CO_2 emissions in residential buildings that strictly meet the BTC requirements; $\boldsymbol{R}$, the ratio between CO_2 emissions of the 50th and 10th percentile of residential buildings that strictly meet the BTC requirements; $\boldsymbol{I_s}$, the average CO_2 emissions in existing residential buildings in 2006; and $\boldsymbol{R'}$, the ratio between CO_2 emissions corresponding to the 50th and 10th percentile of the existing residential building stock. The values $\boldsymbol{R}$ and $\boldsymbol{R'}$ are tabulated in the Spanish BTC for the different CZs. The methodology employed for the calculation of the building energy rating considers CO_2 emissions in kg/m^2 as the main energy indicator, with kWh/m^2 as a complementary indicator. The method for obtaining CO_2 emissions is based on a regression between final energy use and fuel consumption at the energy generation plants, as a function of the generation system employed. Generation and transport energy losses, energy efficiency values and CO_2 fuel emissions are considered and collected into a so-called step factor that allows translating final energy use at each building into CO_2 emissions (Ministerio de Industria, Energía y Turismo 2014). If renewable energy sources, such as solar thermal of PV are employed, CO_2 emissions become lower, the building becomes more environmentally friendly and the methodology provides a discount in energy consumption. Therefore, CO_2 emissions seem a better metric regarding the actual carbon footprint of the building, serving as well as a boost for renewable energy sources. Data from the general Spanish energy mix and from the specific Spanish regions is published every year by the Spanish Ministry for Ecologic Transition (Ministerio para la Transición Ecológica 2020) so that the method remains useful over time.

Cerma software allows to obtain the energy demand, the level of CO_2 emissions and the building energy efficiency. Letters from A to G are used to assess the energy rating, with A representing the highest energy efficiency value and G the lowest one. Figure 4 shows the correspondence between σ_1 and σ_2 values and the qualification letters.

The 2013 BTC sets a limit in building energy consumption with the aim of bringing Spain closer to the target of zero consumption. This fact means that new buildings must obtain at least a B indicator in primary energy consumption. Additionally, a maximum of non-renewable primary energy and maximum demand is set by the BTC. Hence, an improvement in the energy rating is not only obtained by changing thermal systems, i.e., heating, DHW or refrigeration, since this energy demand limit must be met. The BTC also poses a restriction in the transmittance limits of the building enclosures, with a maximum value that depends on the winter climatic zone.

Results and discussion

Energy performance and CO_2 emissions

The energy rating of a building is stated as the letter from the ecological label followed by a number that expresses the CO_2 kg per square meter emitted by the building (Ministerio de Fomento 2015). The results obtained with the Cerma software for the 12 CZs (excluding Canary Islands) are shown in Table 4 for the 2006 and 2013 BTCs.

The difference between the different ratings obtained for the two BTCs highlights the significant tightening of the requirements from the 2006 to the 2013 BTC. It may be appreciated how the minimum requirements of the 2013 BTC allow to obtain at least a B energy rating, whereas the minimum requirements from the 2006 BTC only achieve D and E ratings (with Burgos even out of the scale). In this sense, the improvement from the 2006 to the 2013 BTC is clear, as its minimum requirements allow to achieve the same energy rating (B) independently of the climatic zone

Fig. 4 Correspondence between energy efficiency rating indices for residential buildings and ecological labels

Table 4 Energy ratings according to the climate zone depending on the BTC version

Climate zone		City	2013 BTC	2006 BTC
A	A4	Almería	B7.5	D19.3
	A3	Cádiz	B6.4	D15.9
B	B4	Sevilla	B9.1	D26.1
	B3	Valencia	B8.1	D24.5
C	C4	Toledo	B16.2	D40.4
	C3	Granada	B12.7	D35.7
	C2	Barcelona	B12.3	E31.4
	C1	Bilbao	B12.0	E35.8
D	D3	Madrid	B17.8	E40.4
	D2	Zamora	B17.0	E47.5
	D1	Vitoria	B21.4	E52
E	E1	Burgos	B21.1	NR

in which the building is placed. Nonetheless, emissions of CO_2 kg per square meter ranges from 6.4 (A3) to 21.4 (D1). Figure 5 shows the upper and lower limits that define B rating regarding CO_2 emissions, and the results obtained for the SB in the 13 CZs with Cerma software, confirming this argumentation. It may be noted that, since climatic conditions in the Canary Islands are milder regarding winter conditions from the other zones, the emission limits are stricter than for the rest of regions (see upper limit for B rating in Fig. 5) and thus the SB is only able to reach a C rating with the minimum requirements of the 2013 BTC.

A building like the one from this work was studied to validate the suitability of the Cerma software itself (Cerma 2020). Additionally, the energy ratings obtained in this study are similar to the values obtained by López-González et al. (2016) in zones D1, D2 and E1 in La Rioja province both for the 2006 and 2013 regulations.

Energy demand analysis

The main variables affecting energy rating were analyzed as well, in order to obtain more insight into the different components of the building energy demand. Figure 6 shows the variables with the highest impact on CO_2 emissions for the SB placed in Madrid (D3 climatic zone) depending on the minimum requirements of the 2006 and 2013 BTCs.

Firstly, it may be observed that CO_2 emissions related to heating services are much higher than the ones related to cooling services for both BTCs. In general, the most influencing variable is opaque enclosures, followed by ventilation in the case of heating and internal load in the case of cooling. Nevertheless, the most significant result is probably the reduction in total CO_2 emissions in more than 50% with the modifications introduced in the BTC from 2006 to 2013, passing from 40.4 to 17.8 kg CO^2/m^2. A significant reduction in the contribution of thermal bridging to CO_2 emissions related to heating services has been achieved. Concurrently, internal load has become the main contributor to CO_2 emissions in the case of cooling. Finally, the increase in the relative contribution of domestic hot water (DHW) to total emissions from 2006 to 2013 BTC compared to other sources is a clear indicator of the improvement of the overall energy efficiency of the building.

Collecting and comparing the results obtained for the 12 CZs, the general behavior of the SB may be explained. The trends in the contribution of the different building variables to CO_2 emissions from 2006 to 2013 follow similar patterns for all the CZs studied. Regarding heating services, opaque enclosures have the greatest weight in total CO_2 emissions, ranging from a minimum of 45.76% in A3 zone to a maximum of 50.13% in E1 zone with the 2013 BTC. Considering the 2006 BTC, this percentage ranged between 48.01% in D1 zone and 49.26% in B3 zone (González-Caballín 2013). Concerning cooling services, whereas with the 2006 BTC the components with the highest impact were opaque enclosures with percentage values

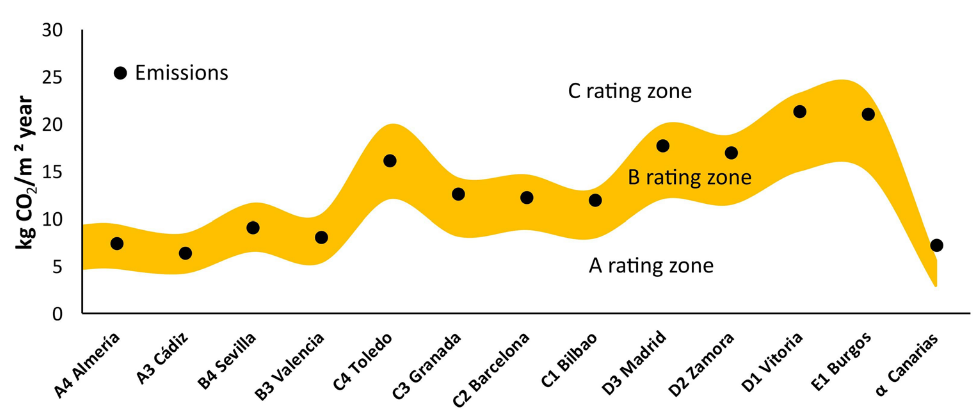


Fig. 5 CO_2 emissions of the SB for the Spanish CZs with the 2013 BTC minimum requirements

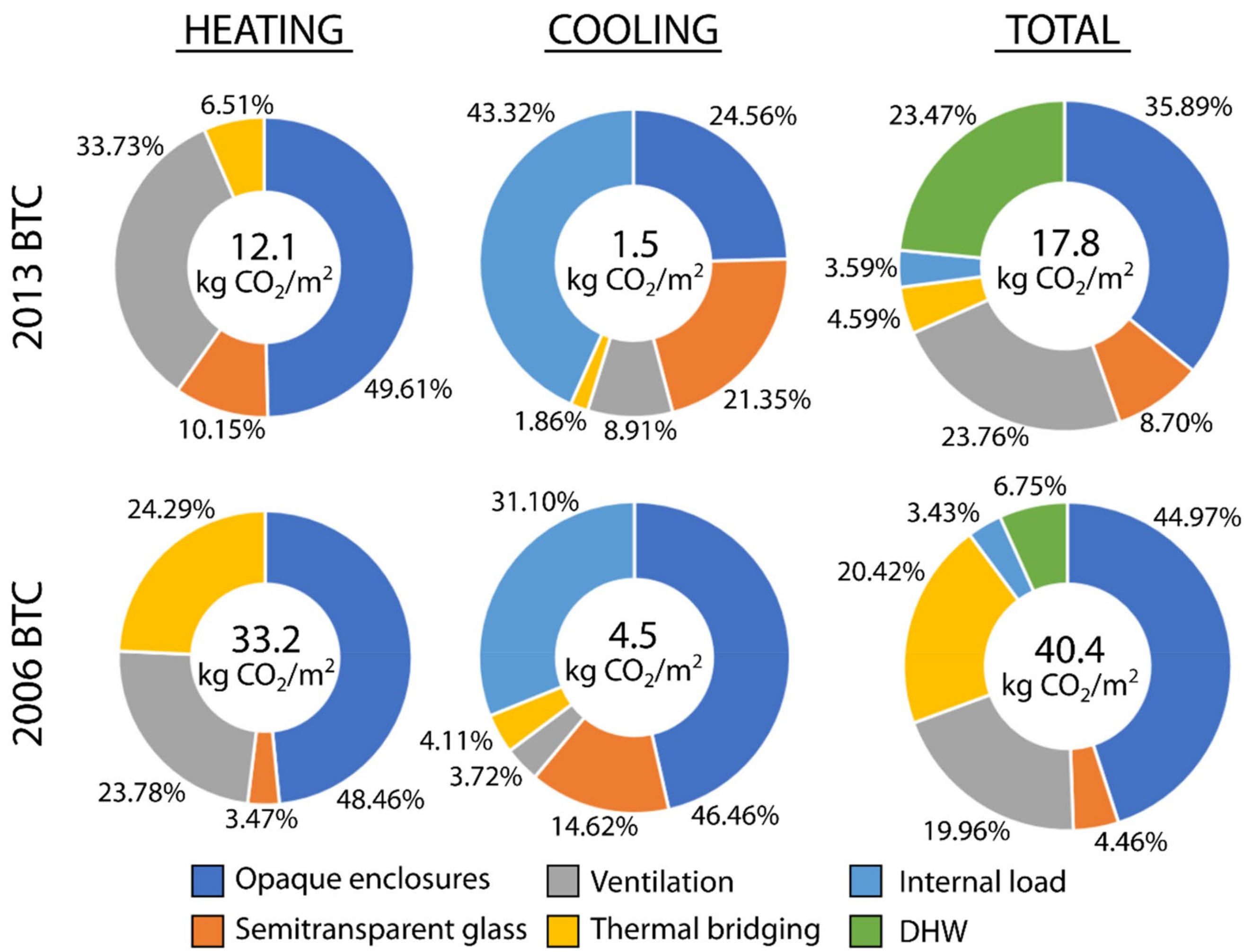


Fig. 6 Variables with highest impact on CO_2 depending on the BTC minimum requirements (D3 climatic zone)

around 45%, with the 2013 BTC the main contributor to CO_2 emissions becomes the internal load. It must be noted that for the CZs C1, D1 and E1 a cooling system is not required due to their low summer climatic severity.

Proposal and evaluation of improvements

The final stage of this work was the proposal and evaluation of improvements for the building designed according to the minimum requirements of the 2013 BTC. The criteria of IDAE and MINETUR in the NEEAP 2014–2020 (Ministerio de Industria, Energía y Turismo 2014) propose two types of actions: actions regarding energy demand reduction, considering passive systems such as insulation, windows, reduction in surfaces or reduction in air renewals; and actions regarding the improvement of the efficiency of thermal systems, considering mainly heating, cooling and DHW active systems.

Cerma software allowed the implementation of these modifications to evaluate the possible improvement in the energy rating of the building. According to the energy demand analysis performed, the elements that have the greatest influence on CO_2 emissions are opaque enclosures. Figure 7 shows the effect of increasing insulation thickness up to 40 mm. It may be observed that improvements in passive systems (constructive improvements) were insufficient to obtain an A rating (or required a too great expense of materials) for all 13 CZs. However, noticeable improvements in the reduction in CO_2 emissions were achieved in CZs with the coldest winter severities (D and E). For the particular case of Madrid, an improvement from a B17.8 to a B16.7 rating was obtained. A further increase in insulation thickness resulted in almost negligible rating improvements. In the case of Canary Islands, increasing insulation thickness showed no effect in CO_2 emissions, maintaining the same energy rating.

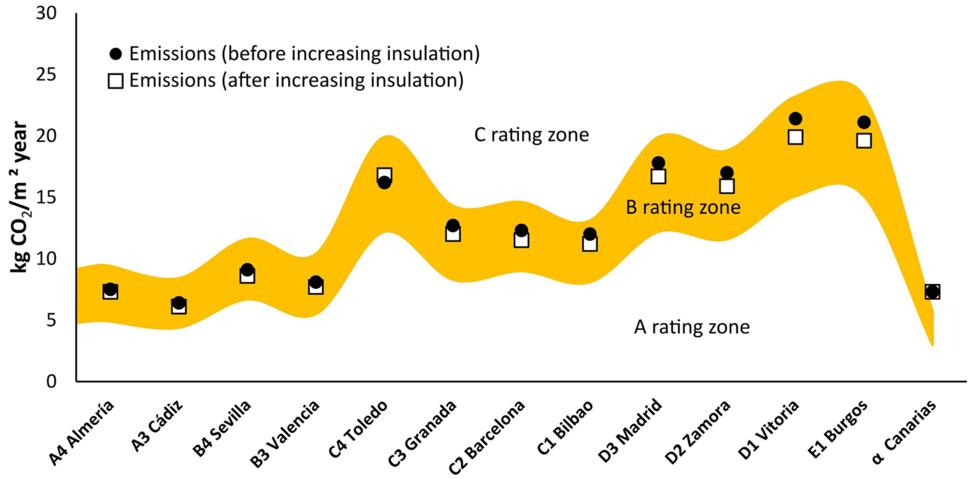


Fig. 7 Effect of increasing insulation thickness to 40 mm in CO_2 emissions

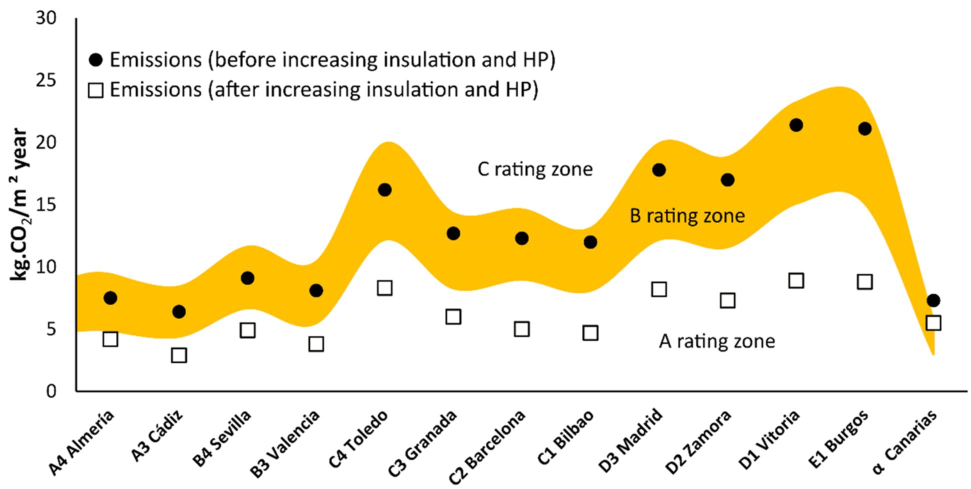


Fig. 8 Effect of increasing insulation thickness to 20 mm and using a heat pump with COP = 3 in CO_2 emissions

The only actions that allowed reaching an A energy rating for the other 12 CZs were actions regarding thermal systems, such as changing heating, cooling and DHW for biomass systems or heat pumps (HP). It was decided to combine an insulation thickness of 20 mm and a HP with a seasonal COP equal to 3. The results are shown in Fig. 8, with Canary Islands being the only exception that does not reach an A rating, reaching in this case the B rating.

Currently, Spanish house owners may demand state subsidies through the State Housing Plan 2018–2021 (Ministerio de Transportes, Movilidad y Agenda Urbana 2018). This Plan collects, among others, subsidies for the "Improvement of the energy efficiency of thermal envelopes." In order to be eligible for the subsidy, the building energy demand must be reduced as a function of the climatic zone in a percentage ranging from 20% for α, A and B zones; 25% for the C zone and 35% for D and E zones. The maximum amount that is granted for each detached or semi-detached house must be lower than 12,000€ for a single-family house, and 8,000€ for residential blocks. In this sense, this work reveals a way to reach the required energy saving values, providing guidelines to obtain the previously mentioned subsidies.

With the data obtained in this work, it can be concluded that in Spain it is necessary to perform more actions aimed at reducing energy consumption and associated polluting emissions. The inclusion of energy saving techniques in buildings will allow the transition to a more sustainable energy model that is also less polluting and less dependent on foreign supplies. The objectives of the energy policy should be to guarantee responsible energy consumption, minimize the energy losses associated with buildings, reduce adverse environmental impacts, improve standards of living and improve the competitiveness of the building sector.

Conclusions

Spain has a high level of energy consumption in detached houses, which implies high levels of CO_2 emissions. More than half of these consumption is a consequence of the lack of an adequate level of insulation in building enclosures. In addition, the high energy dependence levels and the unstoppable increase in worldwide energy prices set the focus on building energy saving policies as one of the priority objectives. In this sense, the Government of Spain has been modifying its Building Technical Code, setting stricter requirements for both new and existing buildings in terms of energy efficiency to reduce final energy use and CO_2 emissions. Moreover, the geographic location of the building affects the building energy performance, so the BTC divides the country in different climatic zones to set the limit values for energy use and emissions. In the 2013 Spanish BTC, a new CZ was created for the Canary Islands (previously included in zone A3).

An assessment of the development of the Spanish BTC from its first 2006 version has been performed in this work, in order to discuss how energy efficiency in detached houses has been implemented following the European Directives on that matter. The results of this study show that emissions emitted by the same house in different climatic zones are quite different. Therefore, the readjustment of the BTC climatic zones in 2013 represents a great success.

The difference between the energy ratings obtained for houses with the minimum requirements of the 2006 and 2013 BTCs is rather significant. With the 2006 BTC minimum requirements, D and E energy ratings were obtained, whereas with the 2013 BTC ones, a B rating was obtained. The requirements of the 2013 BTC are much more demanding; consequently, energy consumption and CO_2 emissions are much lower. The 2013 BTC endured a significant and vital adjustment with respect to the 2006 BTC to achieve an actual change in the amount of CO_2 emissions in Spanish detached housing, reaching the objectives of almost zero consumption buildings.

The impact of the different building demand factors to CO_2 emissions follows similar patterns for all the CZs and BTC versions. Opaque enclosures have the greatest influence in heating services, with percentages about 50%. They also present the highest impact in cooling services with the 2006 BTC requirements (around 45%). Nevertheless, the requirements of the 2013 BTC reduce their energy losses due to opaque enclosures, so that internal loads become the main contributor to CO_2 emissions.

Additionally, possible actions to improve the energy rating of detached houses by applying the criteria of the 2013 BTC were evaluated. The main solutions to improve the energy rating of the building are an increase in the thickness of the insulation, a modification to the glass and frames of the openings, or a mixture of both. The improvement obtained when increasing the insulation thickness was very small, regardless the CZ. Therefore, this kind of measure is not enough to achieve the highest energy rating. It is necessary to combine improvements in energy demand with actions enhancing thermal systems to obtain a significant improvement. Specifically, a moderate insulation thickness increase and the installation of a heat pump showed promising results, reaching the highest energy rating. The improvement is more significant in the northern or central areas of Spain, presenting a higher reduction in CO_2 emissions.

The results of this work provide guidelines to reach the energy saving values required by the regulations, helping Spanish building owners to obtain the subsidies available in the State Housing Plan 2018–2021. These findings may be extrapolated to other UE countries or regions with similar climatic conditions to the 13 studied zones. Additionally, similar procedures to increase building energy efficiency according to UE Directives may be developed. Analogous coefficients to Spanish ones could be defined for those countries according to their own data to evaluate the sources of CO_2 emissions in the energy demand, as well as to learn how to improve the energy efficiency of buildings.

As a future analysis, it would be interesting to enrich this study with a social and economic viewpoint. With the aim of achieving buildings with low or zero CO_2 emissions, the measures reflected in the BTC modifications could be supported with financial assistance to enhance energy efficiency in buildings. In this context, the role of public administration becomes vital to reach this objective. Possible actions could involve direct financial support or tax reductions to the most efficient housing solutions.

Compliance with ethical standards

Conflict of interest The authors declare that there are not known conflicts of interests associated with this publication and there has not been financial support for this work that could have influenced its outcome.

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