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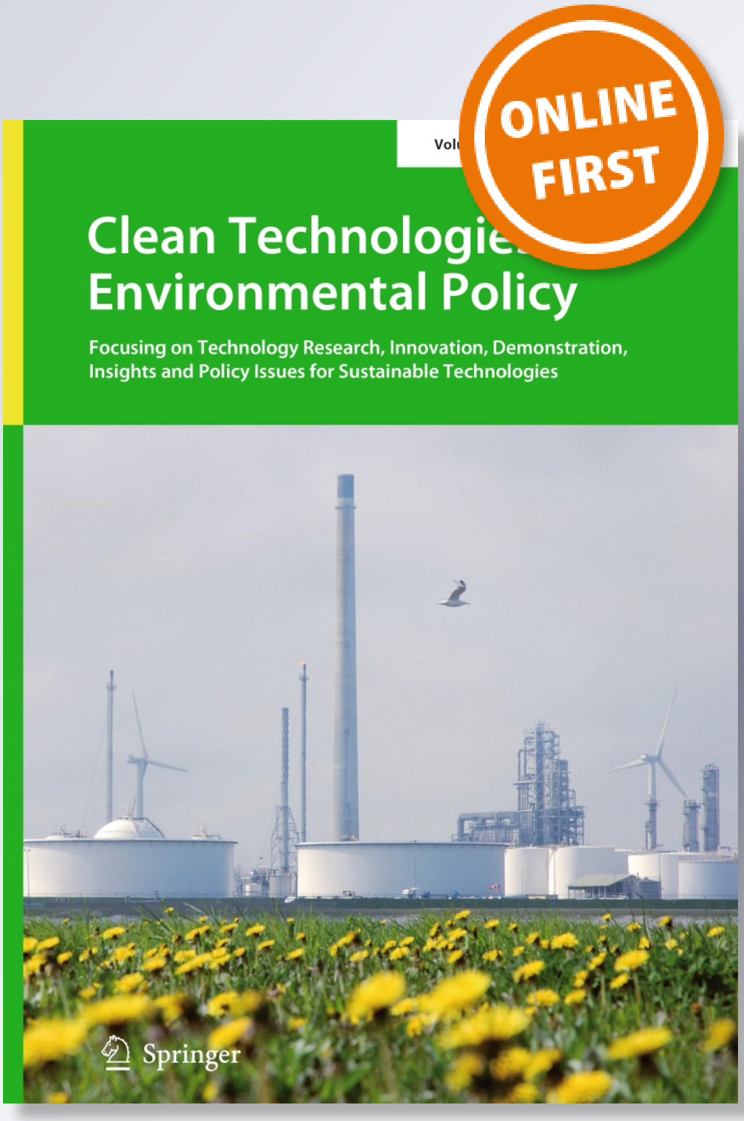

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ORIGINAL PAPER

Effect of the climatic conditions in energy efficiency of Spanish existing dwellings

Juan Carlos Ríos Fernández[1] · **Juan M. González-Caballín**[1] · **Antonio José Gutiérrez-Trashorras**[1]

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Abstract

The member states of the European Union must increase the energy efficiency in residential buildings within the plan to reduce the external energy dependence and energy shortage. In the present work, a standard building representative of the existing buildings in Spain built before 1980 was used. An evaluation of the energy rating of that building in each climatic zone of Spain was carried out to assess the influence of these climatic conditions on energy consumption and greenhouse gas emissions. This analysis was carried out with Cerma software according to the calculation procedure demanded by the Spanish Building Technical Code. Results show that E or F energy score was obtained for the different climatic zones and with significant differences in CO_2 emissions, even for climatic zones with the same energy rating. A sensitivity study of the necessary enhancements in each climatic zone was carried out to analyze the influence of most common energy demand and thermal system improvements, and combinations of them. Also, the minimum requirements to obtain D qualification in each Spanish climatic zone were obtained. As a result, it is possible to reduce emissions in Spain by over 3.5 Mt CO_2 per year. In climatic zones with initial qualification E, it is possible to reach a D label, avoiding 40% of the initial CO_2 emissions and reducing primary energy consumption to about 50 kWh/m^2 year (over 60% reduction). For the climatic zones with initial qualification F, over 53% of the initial CO_2 emissions are avoided by reaching D label. Zones with the highest heating demand (over 230 kWh/m^2 year) and very low cooling demand need to improve thermal systems by means of a heat pump. Finally, some policy measures to create lines of financial aids or subsidies for the implementation of actions to reduce energy demand in Spanish homes are proposed.

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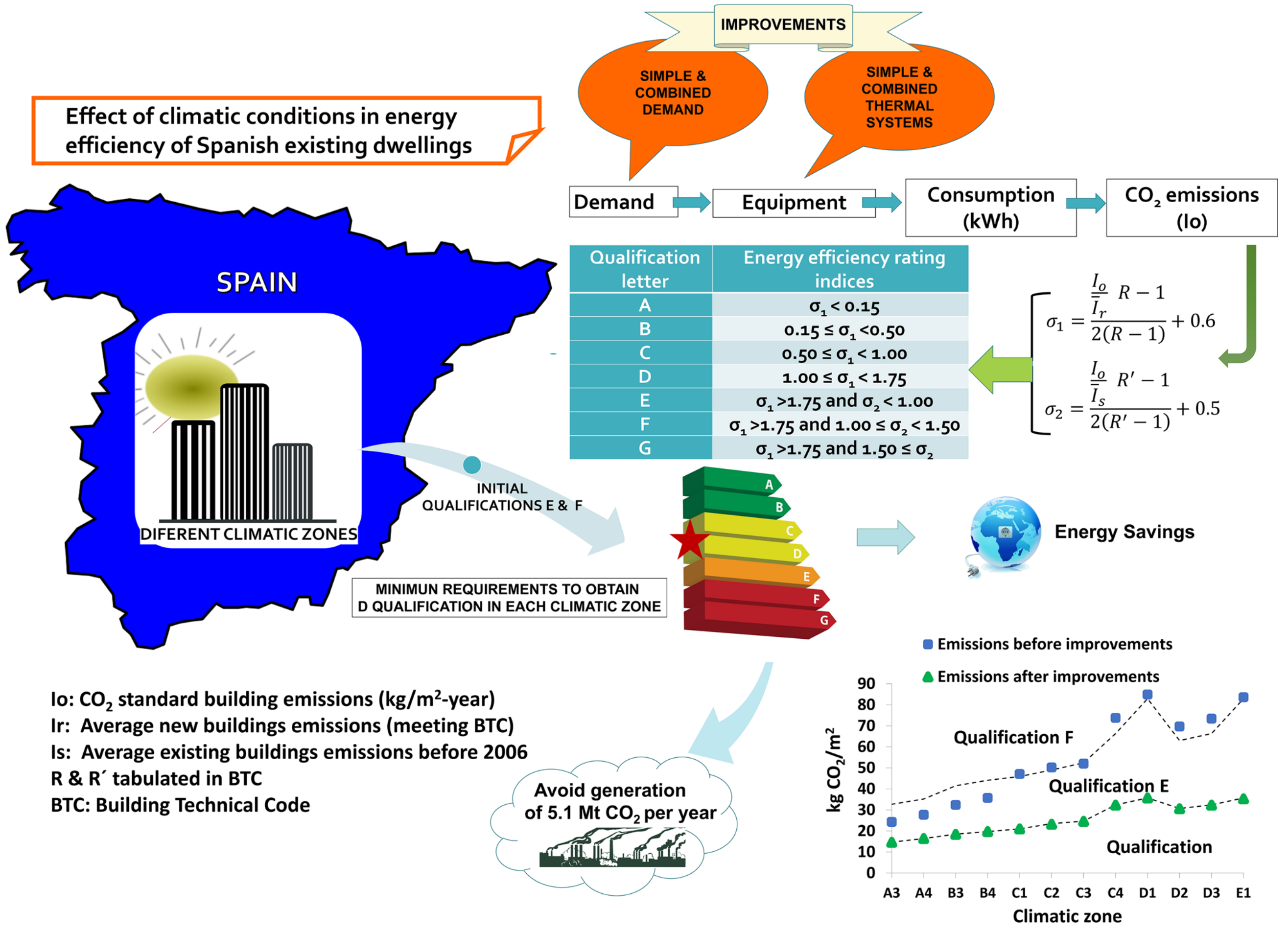
Graphic abstract



Keywords Spanish climatic zones · Residential building · Existing dwellings · Energy efficiency · Energy performance certificate · Greenhouse gas emission reduction

List of symbols

I_0	CO$_2$ emissions generated by the building (kg CO$_2$/m^2 year)
I_r	Average CO$_2$ emissions from residential buildings strictly meeting CTE requirements (kg CO$_2$/m^2 year)
I_S	Average CO$_2$ emissions from existing residential buildings in 2006 (kg CO$_2$/m^2 year)
nr	Air renewals
R	Ratio between CO$_2$ emissions of 50th and 10th percentiles in residential buildings strictly meeting BTC requirements
R'	Ratio between CO$_2$ emissions of 50th and 10th percentiles in existing residential building stock
U	Thermal transmittance (W/m^2 K)
λ	Thermal conductivity (W/m^2 K)
σ_1	First energy efficiency rating index
σ_2	Second energy efficiency rating index

Abbreviations

Bio	Biomass
BREEAM	Building Research Establishment Environmental Assessment Method
BTC	Building Technical Code
COP	Coefficient of performance
DHW	Domestic hot water
EEOnt	Energy efficiency ontology
EER	Energy efficiency ratio
EESs	Energy efficiency services
EU	European Union
GHG	Greenhouse gases
HP	Heat pump

IDAE	Institute for Energy Diversification and Saving
IEA	International Energy Agency
INE	National Statistics Institute
LEED	Leadership in Energy and Environmental Design
LPG	Liquefied petroleum gas
MINETUR	Ministry of Industry, Energy and Tourism
MSF	Modified solar factor
NBC	National Building Code
NEEAP	National Energy Efficiency Action Plan
NG	Natural gas
RBHI	Regulations on Building Heating Installations
RD	Royal decree
SB	Standard building
SF	Solar factor
TI	Thermal insulation

Chemical symbol

CO_2	Carbon dioxide

Introduction

Energy efficiency is one of the most effective ways for reducing greenhouse gas (GHG) emissions and other pollutants (European Commission 2011). Particularly, energy efficiency in buildings is essential for economic, social and environmental reasons. Achieving sustainable development based on the use of renewable energies and the development of energy efficiency is a necessity within the economic model of the European Union (EU) by 2020 (Ríos 2019). Green building refers to both a structure and the use of processes that are environmentally responsible and resource-efficient throughout a building's life cycle. Leadership in Energy and Environmental Design (LEED) is a set of rating systems for the design, construction, operation and maintenance of green buildings which was developed by the US Green Building Council (US Green Building Council 2013; Heidarinejad et al. 2014). Scofield studied the efficacy of LEED certification in reducing energy consumption and GHG emissions for large New York City office buildings (2013). The results suggest that LEED building certification is not moving NYC toward its goal of climate neutrality. Other certificate system that confirms the sustainability of buildings is the British Building Research Establishment Environmental Assessment Method (BREEAM) for buildings and large-scale developments (Harris 1999).

The building sector has a huge impact on the environment (Hossaini et al. 2015). Buildings are accountable for over 40% of final energy consumption in the European Union (EU). Approximately 27% correspond to residential ones (Eurostat 2019). About 35% of the EU's buildings are existing buildings over 50 years old (European Commission 2019). Improving energy performance on these buildings could be an important opportunity to save energy. Sustainability of buildings is a necessary condition safeguarding the environment and insuring the well-being of the global population (Milutiene et al. 2012). EU has adopted a number of measures to improve energy efficiency. In particular, in the European Community the energy efficiency in buildings has been the aim of diverse European Directives. The 2010/31/EU Energy Performance of Buildings Directive (EPBD) and the 2012/27/EU Energy Efficiency Directive (EU 2012) are the EU's main legislation when it comes to reducing the energy consumption of buildings (EU 2010; Gaglia et al. 2019).

Under current European legislation, buildings have to be certified with an energy efficiency index. A fair comparison of the energy performance in buildings requires a global and unified representation. For example, Vinagre et al. (2013) proposed the energy efficiency ontology (EEOnt) to provide a foundation upon which this requirement can be built. Salleh et al. (2016) discussed methods to benchmark energy efficiency in school buildings use energy efficiency. Gamalath et al. (2018) propose a condition assessment framework for the energy system of existing multi-unit residential buildings, which combines the concepts of asset rating and operational rating. In Bagheri et al. (2013), the authors presented a technical procedure for developing energy performance label for office buildings in Iran. It consists of a building energy simulator software tool applied to simulate office buildings. Energy consumption indexes from modeling reference buildings were applied to conclude the boundaries for grades A–G of the label. A comparison of building energy codes and policies in the USA, Germany and China was done by Hu and Qiu (2019). Finally, the label appearance was designed and authorized to be applied for both the existent and new buildings. Martínez-Molina et al. (2016) offered a review about energy efficiency and thermal comfort in historic buildings. Labanca et al. (2015) studied energy efficiency services (EESs) for residential buildings in the European Union. They claimed that a stronger collaboration of governments or local administrations with banks to finance EESs is still very necessary in many EU countries.

Borgstein et al. (2016) evaluated energy performance in non-domestic buildings. A review of the available methods for analyzing, classifying, benchmarking, rating and evaluating energy performance in non-domestic buildings was performed. According to the review, there is a need to further develop interactions between the main modeling techniques to produce simple, robust and validated models. Also, evaluation techniques must be developed to consider comfort or service provision in the buildings as a factor in energy performance. De Boeck et al. (2015) reviewed the methods to improve the energy performance of residential buildings. In the analysis conducted, they considered the following topics: area of application and design variables, objectives and performance measures, type of analysis, solution methodology, software tools, case study location and type of building. The development of new solution techniques should consider the possibility of examining the residential building as a whole instead of approaching individual components and should be more flexible and user-friendly. An example of energy efficiency initiatives and regulations for residential buildings including non-European Countries was developed by Chandel et al. (2016).

The study analyzed roofing regulation type, code structure, regulatory assessment and energy efficiency measures along with the role of regulations in changing energy consumption trend in 17 countries including India. As a result, building envelope, building materials, climate and site conditions are the most important parameters for energy efficiency needed to be developed in order to integrate them into the National Building Code (NBC) and building regulations. Also, Silvero et al. (2019) proposed the path toward buildings energy efficiency in South American countries. Andaloro et al. (2010) presented a comparative analysis of progress in energy certification of buildings toward implementation in European countries. The analysis conducted reveals how varied the situation regarding energy certification in each country is in terms of implementation and scope of application and it also reveals that most countries are still at a halfway stage toward achieving excellence. Spain, as an EU member state, has established its own regulations and software tools to accomplish the EU targets. The main documents related to the energy efficiency in dwellings are: the revision of the Regulations on Building Heating Installations (RBHI) (RD 2007), the approval and revisions of the Building Technical Code (BTC) (RD 2006) and the approval of the Building Energy Performance Certificate for newly constructed and existing buildings (RD 2013). Spain has also developed the National Energy Efficiency Action Plan (NEEAP) 2014–2020 (Ministerio de Industria, Energía y Turismo 2014) under the Energy Efficiency Directive. The NEEAP includes the current situation and the long-term national building renovation strategies. Energy certification of buildings is a key policy instrument for reducing the energy consumption and improving the energy performance of new and existing buildings (IEA 2010).

The "energy performance of a building" is defined as the amount of energy actually consumed or estimated to meet the different needs associated with a standardized use of the building. The energy performance certificate includes an energy performance rating (from A, the most efficient, to G, the least efficient), also called energy qualification, and recommendations for cost-effective improvements, and it is calculated according to a methodology based on the general framework set out by the EPBD (Poel et al. 2007). Carpio et al. (2015) conducted a comparative study by an expert panel of documents recognized for energy efficiency certification of buildings in Spain. The analysis indicates that although all the documents recognized by the Spanish Government are equally valid for energy certification, when certain types of residence are involved, there may be as much as a 26% difference in the determination of CO_2 emissions. According to the analysis on the certification of energy efficiency in new buildings in Spain (Trashorras et al. 2015), the most significant results are the similarity in the energy certification values obtained in all scenarios and the lack of concordance between the energy rating scale, energy consumption and CO_2 emissions.

Existing buildings stock in European countries accounts for over 40% of final energy consumption in the EU, and residential use represents 63% of total energy consumption in the buildings sector (Trashorras et al. 2015). According to the Institute for Energy Diversification and Saving (IDAE 2011), a high percentage of households in Spain, 70%, live in blocks of housing, 49% of these were built before 1980, and therefore, they have no requirement for efficiency and energy savings. It is known that the energy efficiency measures of buildings can produce significant savings for consumers. Building energy certification systems emerged in the 1990s as an essential method for improving energy efficiency, minimizing energy consumption and allowing greater transparency regarding the use of energy in buildings (Pérez-Lombard et al. 2009). The number of buildings built before 1980 refurbished between 2009 and 2013 represents only 0.62% of the total of the buildings in Spain (Cuchí 2016).

The objective of this paper is to study the influence of the different Spanish climatic conditions in the result of the energy performance certificate of existing buildings built before 1980 and the necessary improvements to guarantee the accomplishment of the actual regulations. For this purpose, a typical and representative Spanish existing building is placed in the different Spanish climatic zones. The energy certificate is obtained in each zone in order to analyze the sensitivity of the energy qualification process with respect to the climatic conditions.

Methodology

In this study, a predefined "standard building" (SB) is used to assess the energy efficiency of the existing dwellings stock in Spain, built before 1980. Placing this building in the different climatic zones of Spain with different climatic conditions, the energy performance is evaluated. The European Directive on the Energy Efficiency of Buildings (EU 2010) determines that in each EU member state it will have a national methodology for calculating the energy performance of buildings but on a general frame of reference. The said methodology must include at least the following aspects:

(a) Thermal characteristics of the building.
(b) Installation of heating and domestic hot water (DHW).
(c) Installation of air-conditioning.
(d) Ventilation.
(e) Position and orientation of the buildings considering the external climatic conditions.
(f) Passive solar systems and solar protection.
(g) Natural ventilation.
(h) Indoor environmental conditions.

Cerma software (Cerma 2017) has been used to obtain the energy performance certificate of the SB including energy performance rating, primary energy consumption and CO_2 emissions. This program allows obtaining the energy efficiency certificate of an existing building. The software is accepted by the Spanish Ministry of Industry, Energy and Tourism (MINETUR), as well as by the Ministry of Public Works. Furthermore, measurements have been implemented in order to improve the energy performance of the building and to meet the minimum Building Technical Code (BTC) (Ministerio de Fomento 2019) requirements for each climatic zone. After improvements, new energy performance rating, primary energy consumption and CO_2 emissions of the building were calculated and compared with results obtained before improvements.

The simulation of the building behavior is done hour by hour throughout the annual calendar, established by default in Cerma software. Internal loads are defined in the simulation software in terms of both sensitive and latent loads by occupancy, ventilation and setpoint temperatures. It also allows the simulation of an improved building in which components of demand or systems have been changed and compared it with the base building. Through this tool, it is possible to make comparisons between different actions that seek energy improvement. The program provides the savings as a result of each change proposed. Cerma breaks down the results in detail, so they can be better analyzed. Also, it enables the comparisons and makes it easier to detail the measures for improvements. For example, it allows the study of savings obtained by changing the windows in only one room and keeping the rest.

Standard building definition

The SB has been chosen as a representative building of the existing residential building stock in Spain. It was selected using data available from the Energy Diversification and Savings Institute (IDAE) and MINETUR and statistics from National Statistics Institute (INE) related to geometry, materials used in construction of the enclosure and thermal installations. For the selection of the geometric characteristics of the building, it has been taken into account that, according to the IDAE (Trashorras et al. 2015), the Spanish average of the surface in block dwellings is approximately of 102 m^2.

As regards constructive solutions, according to the Ministry of Development (Ministerio de Fomento 2014), in the blocks of houses built before 1980, the double-leaf brick wall with intermediate air chamber as enclosure wall predominates, as well as flat roofs without isolation. The carpentry is made of wood or metal profiles, which does not improve its thermal conductivity nor its air tightness; and the sill is a floor laid on a compacted soil or with a gravel subbase. The SB is a cuboid-shaped block without attic or basement. It is a four-story building (including the ground floor) with 2 dwellings per floor. Figure 1 shows a layout of each floor of the building. Total floor area is 220 m^2. The orientation of the main facade is south and main facade length is 14 m. The percentage of openings for the different facades is 26.18% of main facade, 22.03% of rear facade and 16.82% of lateral facade. Total area of stairwells is 16 m^2, with staircase depth of 3 m. Bottom floor is not isolated underneath. Technical characteristics of the SB are summarized in Table 1.

Climatic conditions

The Spanish climate is classified according to the severity of summer and winter, which depend on temperature and solar radiation. The severity of winter is expressed in letters ranging from A (milder winter) to E (colder winter). This scale has no relationship with the energy rating even if they use the same letters. The summer severity scale is expressed with numbers 1 through 4, where higher numbers correspond to warmer climates. In this way, each Spanish region obtains a letter and a number to determine its climatic classification. Of the 20 possible combinations, only 12 are actually needed to define all the climatic zones of Spain. According to the BTC, in Spain there are 12 climatic zones. For this study, a representative city of each climatic zone has been selected and is included in Table 2. Figure 2 shows the Spanish climatic zones.

The standard building is placed in these different locations applying the specific climatic conditions of each one.

CO_2 emissions and energy performance assessment

Since the appearance of the Spanish Royal decree RD 235/2013, the law requires classification of existing buildings related to CO_2 emissions. For existing residential buildings, the energy performance is expressed as an

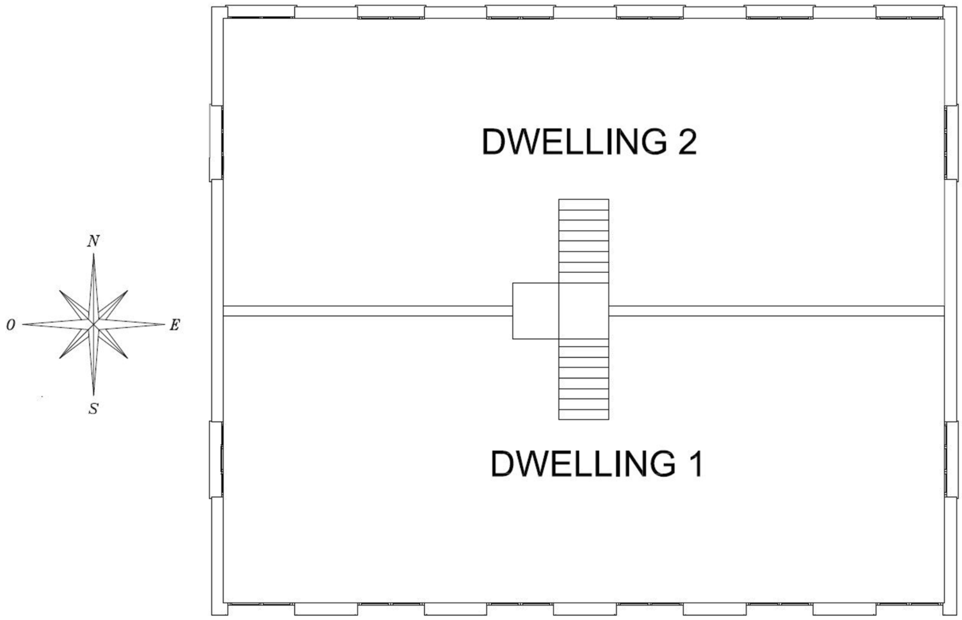


Fig. 1 Story layout of the standard building

Table 1 "Standard building" characteristics

Multi-family building (8 dwellings)	
Geometry	
Living area	896 m^2
Conditioned volume	3136 m^3
Floors	4 (2 dwelling per floor)
Distribution	Master bedroom, single bedroom, kitchen, living room and bathroom
Constructive solutions	
Thermal transmittance U (W/m^2 K)	
Facade	1.58 (4 facades with same characteristics)
Roof	1.60
Floor	2.65
Windows	5.70
Solar factor (SF)	0.85
Modified SF (Summer)	0.85
Permeability (m^3/hm^2 100 Pa)	457
Thermal installations	
Heating	8 conventional boilers 24 kW
	Performance: 75% (natural gas)
DHW	8 conventional boiler 24 kW
	Performance: 81% (natural gas)
Cooling	8 individual equipment with energy efficiency ratio (EER): 1.7 (electricity)

energy label. The label is based on the CO_2 emissions per square meter generated by the building in 1 year. It is expressed as a letter ranging from A to G (Ministerio de Industria 2011; Gangolells et al. 2016).

For the determination of the qualification letter, energy efficiency rating indices (σ_1 and σ_2) of single-family or block houses are calculated (Ministerio de Industria 2011) according to the following equations:

$$\sigma_1 = \frac{\left(\frac{I_0}{I_r} \cdot R\right) - 1}{2 \cdot (R - 1)} + 0.6; \quad \sigma_2 = \frac{\left(\frac{I_0}{I_r} \cdot R'\right)}{2 \cdot (R' - 1)} + 0.5$$

Table 2 Spanish climatic zones and representative cities

Climatic zone	Representative city
A3	Cadiz
A4	Almeria
B3	Valencia
B4	Seville
C1	Bilbao
C2	Barcelona
C3	Granada
C4	Toledo
D1	Lugo
D2	Zamora
D3	Madrid
E1	Burgos

I_0 is denoted as the CO_2 emissions generated by the building. I_r is the energy performance regulation benchmark and corresponds to the average CO_2 emissions in residential buildings that strictly meet the requirements stated in the BTC. R is the ratio between CO_2 emissions corresponding to the 50th and 10th percentiles of residential buildings that strictly meet the requirements stated in the BTC. I_S is the building stock benchmark and represents the average CO_2 emissions in existing residential buildings in 2006. R' is the ratio between CO_2 emissions corresponding to the 50th and 10th percentiles of the existing residential building stock. The values of the parameters R and R' are tabulated in the Spanish Building Technical Code for the different climatic zones.

Cerma software was used to obtain the energy performance, the energy demand and CO_2 emissions of the building. The energy rating is assigned based on the energy efficiency rating

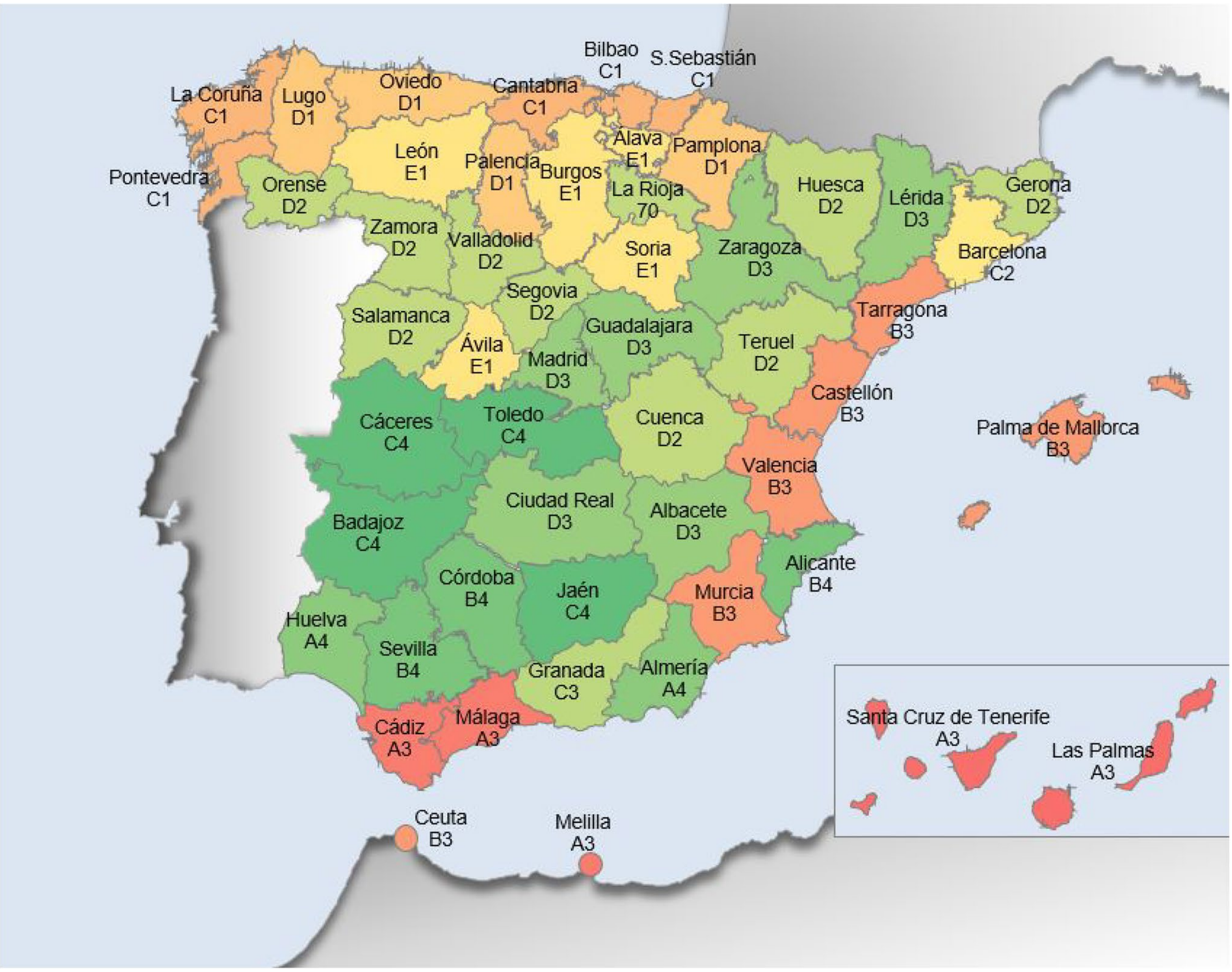


Fig. 2 Map of the Spanish climatic zones

Table 3 Energy rating for residential buildings

Qualification letter	Energy efficiency rating indices
A	$\sigma_1 < 0.15$
B	$0.15 \leq \sigma_1 < 0.50$
C	$0.50 \leq \sigma_1 < 1.00$
D	$1.00 \leq \sigma_1 < 1.75$
E	$\sigma_1 > 1.75$ and $\sigma_2 < 1.00$
F	$\sigma_1 > 1.75$ and $1.00 \leq \sigma_2 < 1.50$
G	$\sigma_1 > 1.75$ and $1.50 \leq \sigma_2$

indices obtained, within a seven-letter scale ranging from A (most efficient building) to G (least efficient building). Table 3 shows the correspondence between the energy performance letter and values of σ_1 and σ_2.

"Standard building" improvements in the Spanish climatic zones

The improvements applied to the reduction in energy consumption in buildings can be:

- Improvement in the thermal performance of the building envelope (reducing energy demand)
- Upgrading thermal installations (reducing energy use).
- Supplying part or the total energy demand by renewable sources (reducing primary energy use) (Terés-Zubiaga et al. 2015).

To achieve the D rating, different measures were applied depending on the climatic zone in which the building was located and to meet the BTC requirements. The chosen measures were selected considering the criteria of energy consumption in dwellings and efficiency analysis for the building sector by IDAE and MINETUR in the NEEAP 2014–2020 (Ministerio de Industria, Energía y Turismo 2014). There are mainly two types of improvements:

- Improvements in demand (insulation, windows, reduction of surfaces, reduction in the number of air renewals).
- Improvements in thermal systems (DHW installations, heating and cooling).

Tables 4 and 5 show the standardized improvements in each mentioned type. In addition to simple demand and system improvements, combinations of demand improvements, combinations of system improvements and combinations of demands and systems are studied in this work.

Results and discussion

In this section, the results and the analysis of the different energy ratings obtained as well as the values of CO_2 emissions and energy demand are presented. To this end, the methodology described above was applied to the SB in each climate zone. Energy performance rate, CO_2 emissions and energy demand were calculated using Cerma for the different climatic zones and for the building before and after improvements.

Energy performance rate and CO_2 emission results

Results for the energy qualification (letter) and CO_2 emissions of the SB before improvements are shown in Fig. 3. The qualification is very similar in the different climatic zones:

- Qualification E in zones A3, A4, B3 and B4.
- Qualification F in zones C1, C2, C3, C4, D1, D2, D3 and E1.

However, CO_2 emissions have important differences for the same qualification letter. For example, zones C1 and E1, both have F qualification, but the CO_2 emissions are 47.1 and 83.6 $kgCO_2/m^2$ year, respectively, being in zone E1 almost twice emissions than in C1.

Energy consumption before improvements

Energy qualification and primary energy consumption of the SB before improvements are shown in Fig. 4. It includes primary energy consumption, heating demand and cooling demand in each zone. Results show that identical qualification does not correspond with the same primary energy consumption in the different climatic zones. Cooling demand is similar to heating demand for those zones with qualification E. For the other zones, the demand is mainly for heating.

Improvements analysis

Once the results of the energy rating of the SB in each of the Spanish climatic zone were obtained, a study of different improvements and combinations of them and how they affect in each representative city has been carried out. Common improvements used in this type of construction are proposed in order to analyze the impact of on the production of CO_2 emissions and therefore on the energy qualification of the building (Tables 4, 5).

Figures 5, 6 and 7 show the changes experienced in the energy rating and in the CO_2 emissions due to each of the

Table 4 Simple demand improvements

<table>
<tr><th colspan="13">DEMAND IMPROVEMENTS</th></tr>
<tr><th colspan="13">Thermal insulation</th></tr>
<tr><td rowspan="2"></td><td colspan="12">Thermal conductivity (insulation)
λ= 0.004 W/m^2-K</td></tr>
<tr><td colspan="12">Insulation thickness (mm)</td></tr>
<tr><td>Roofs</td><td colspan="2">+10</td><td colspan="2">+20</td><td colspan="2">+30</td><td colspan="2">+40</td><td colspan="2">+60</td><td colspan="2">+80</td></tr>
<tr><td>Walls</td><td colspan="2">+10</td><td colspan="2">+20</td><td colspan="2">+30</td><td colspan="2">+40</td><td colspan="2">+60</td><td colspan="2">+80</td></tr>
<tr><td>Floors</td><td colspan="2">+10</td><td colspan="2">+20</td><td colspan="2">+30</td><td colspan="2">+40</td><td colspan="2">+60</td><td colspan="2">+80</td></tr>
<tr><td>Roofs + walls + floors</td><td colspan="2">+10</td><td colspan="2">+20</td><td colspan="2">+30</td><td colspan="2">+40</td><td colspan="2">+60</td><td colspan="2">+80</td></tr>
<tr><td rowspan="2">Thermal Bridges</td><td colspan="12">Thermal insulation (TI)</td></tr>
<tr><td colspan="3">Continuous TI</td><td colspan="3">Isolated pillars</td><td colspan="3">TI up to the frame</td><td colspan="3">Isolated pillars +TI frame</td></tr>
<tr><th colspan="13">Windows</th></tr>
<tr><td rowspan="2"></td><td colspan="12">Thermal transmittance U (W/m^2-K)</td></tr>
<tr><td colspan="4">Type 1
Composition 4-6-4</td><td colspan="4">Type 2
Composition 4-6-4</td><td colspan="4">Type 3
Composition 4-10-4</td></tr>
<tr><td>Glass</td><td colspan="4">3.3 (double)</td><td colspan="4">2.5 (double and low-emissivity glass)</td><td colspan="4">1.8 (double and low-emissivity glass)</td></tr>
<tr><td>Frame</td><td colspan="4">4.0 metallic & thermal bridge breakage</td><td colspan="4">2.2 (wood)</td><td colspan="4">1.8 (PVC 3 layers)</td></tr>
<tr><td>Glass + frame</td><td colspan="4">3.3 + 4</td><td colspan="4">2.5 + 2.2</td><td colspan="4">1.8 + 1.8</td></tr>
<tr><td>Glass SF</td><td colspan="4">0.75</td><td colspan="4">0.5</td><td colspan="4">0.25</td></tr>
<tr><td>Modified SF (Summer)</td><td colspan="4">0.75</td><td colspan="4">0.5</td><td colspan="4">0.25</td></tr>
<tr><td>Permeability (m^3/hm^2 100 Pa)</td><td colspan="4">27</td><td colspan="4">9</td><td colspan="4">3</td></tr>
<tr><th colspan="13">Reductions (%)</th></tr>
<tr><td>Windows</td><td colspan="3">-5</td><td colspan="3">-10</td><td colspan="3">-15</td><td colspan="3">-20</td></tr>
<tr><td>Walls</td><td colspan="3">-5</td><td colspan="3">-10</td><td colspan="3">-15</td><td colspan="3">-20</td></tr>
<tr><td>Number of air renewalls</td><td colspan="3">-5</td><td colspan="3">-10</td><td colspan="3">-15</td><td colspan="3">-20</td></tr>
</table>

improvements in the city of Madrid (climate zone D3), which has been selected as a representative example (initial energy rating F).

Simple demand improvements

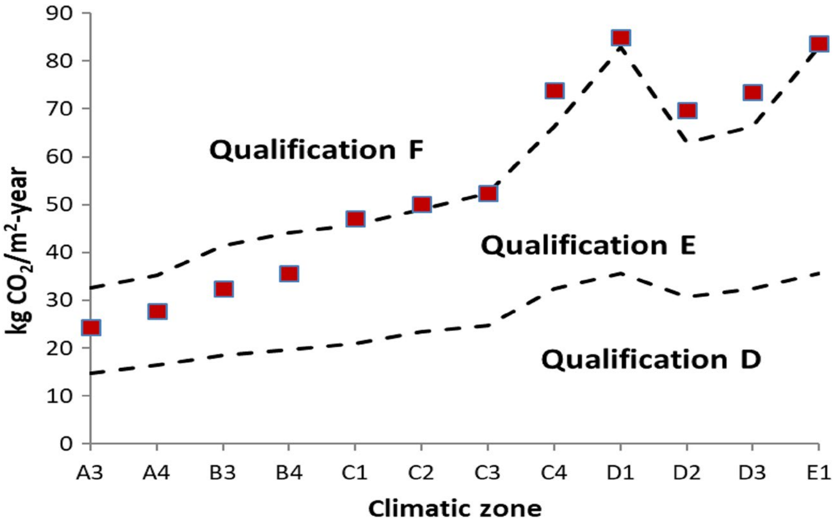
- Insulation thickness

In climatic zones with initial rating F (Fig. 5), neither the energy rating nor the emissions are modified by improving the insulation in the roofs and hardly changes in the soils. However, an E rating is achieved by improving the insulation on walls and the combination of roof, walls and floors, but practically equal to that obtained by improving only the walls. In climatic zones with initial rating E, the energy rating is not modified in any case, as in the previous case, there is a slight improvement when modifying walls and the combination of walls, floors and roofs. Summarizing, by increasing the insulation thickness, emissions are slightly diminished and even for those who have an initial F rating, an E rating can be reached.

Table 5 Simple thermal system improvements

Thermal system improvements:				
Boiler	**Seasonal performance (%)**			
Natural gas	80	85	90	95
Gasoil C	80	85	90	95
LPG	80	85	90	95
Biomass	80	85	90	95
Air-water Heat pump	**COP (seasonal)**			
Electricity	2	2.33	2.66	3
Cooling				
Cooling equipment	**EER (seasonal)**			
Electricity	1.7	2	2.33	2.66
DHW				
Boiler	**Seasonal performance (%)**			
Natural gas	80	85	90	95
LPG	80	85	90	95
Biomass	80	85	90	95
Joule's effect	**Seasonal performance (%)**			
Electricity	80	85	90	95
Air-water Heat pump	**COP (seasonal)**			
Electricity	2	2.33	2.66	3

Fig. 3 CO_2 emissions of the SB in the Spanish climatic zones



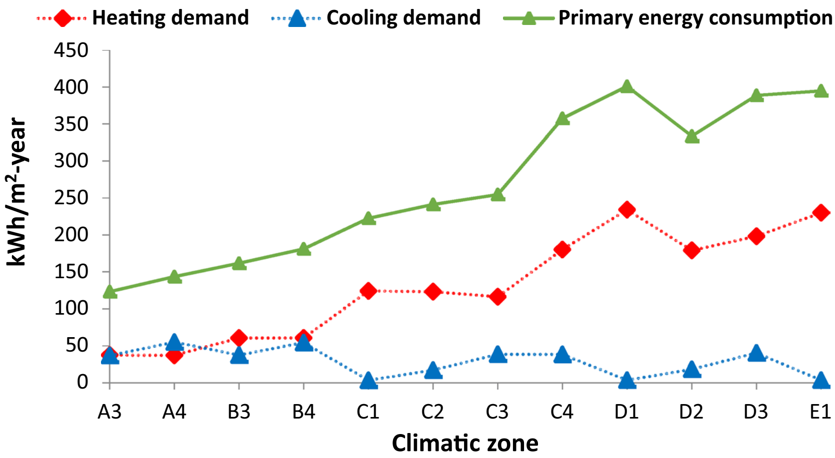


Fig. 4 Energy consumption and demands in the different Spanish climatic zones

- Insulation of thermal bridges

In all climatic zones, the best solution is the continuous insulation of thermal bridges and the worst solution is insulation up to the frame. For climatic zones with initial rating E, the rating is maintained, improving CO_2 emissions. There are different results in the climatic zones with initial rating F. In Madrid, Zamora and Toledo, the qualification is not improved. In Vitoria, Burgos, Bilbao and Barcelona, it improves up to E in any option, except when applying the insulation up to the frame.

- Window improvements

The same trend in the example shown in Fig. 5 is followed for all the climatic zones when windows are improved. The best option is to modify the glass and the frame together, followed by the glass improvement and finally the frame. Climatic zones with initial rating E maintain E qualification with all improvements. However, emissions do improve, following the trend mentioned above. As for the climatic zones with initial rating F, in most cases the E rating is reached by modifying both glass and frame, or the glass individually. F rating is maintained when only frame is improved. It is noticed that Burgos with an initial F rating and being one of the areas with the most unfavorable climatic conditions, E grade is reached in most of the improvements.

- Glass SF

SF is the quotient between the total heat gain through the glass and the incident solar radiation, that is, the quotient between the solar radiation at normal incidence that is introduced into the building through the glazing and the one that would be introduced if the glazing was replaced by a perfectly transparent gap. The modified solar factor is defined as the product of the solar factor by the shadow factor. In all climatic zones, as the SF of the glass decreases, CO_2 emissions increase and the same rating is maintained. Even for some zones with initial F rating, such as Madrid (Fig. 5), Zamora, Barcelona and Toledo G qualification is reached. Regarding the modified solar factor (MSF), it decreases emissions in almost all climatic zones (except for Vitoria and Burgos where it is not modified) as MFS decreases. The qualification is maintained, except in Barcelona, where it reaches an E rating for a MFS of 0.25.

- Permeability

It is the air flow rate in m^3/h m^2 that infiltrates through the window when it is subjected to a pressure difference of 100 Pa. All zones maintain the initial rating when improving the permeability despite improving the CO_2 emissions.

- Surface reductions

As the percentage of windows and walls is reduced, increases in emissions are improved but not the rating, in climatic zones with initial rating E. Somewhat different results are seen in the climatic zones with initial rating F. For example, areas such as Madrid (Fig. 5) and Zamora only improve the qualification by reducing the walls by 20%. In Burgos, the E grade is reached for all the improvement options, but in Toledo, the F rating is maintained. Figure 5 shows the CO_2 emissions per year due to simple demand improvements in Madrid.

Simple thermal system improvements

- Heating system

According to the obtained results, as the boiler performance increases emissions, in some zones the qualifications improve. The best option to obtain better rating and lower emissions is the biomass boiler, even reaching an A and B rating in Burgos and Zamora, respectively. In climatic

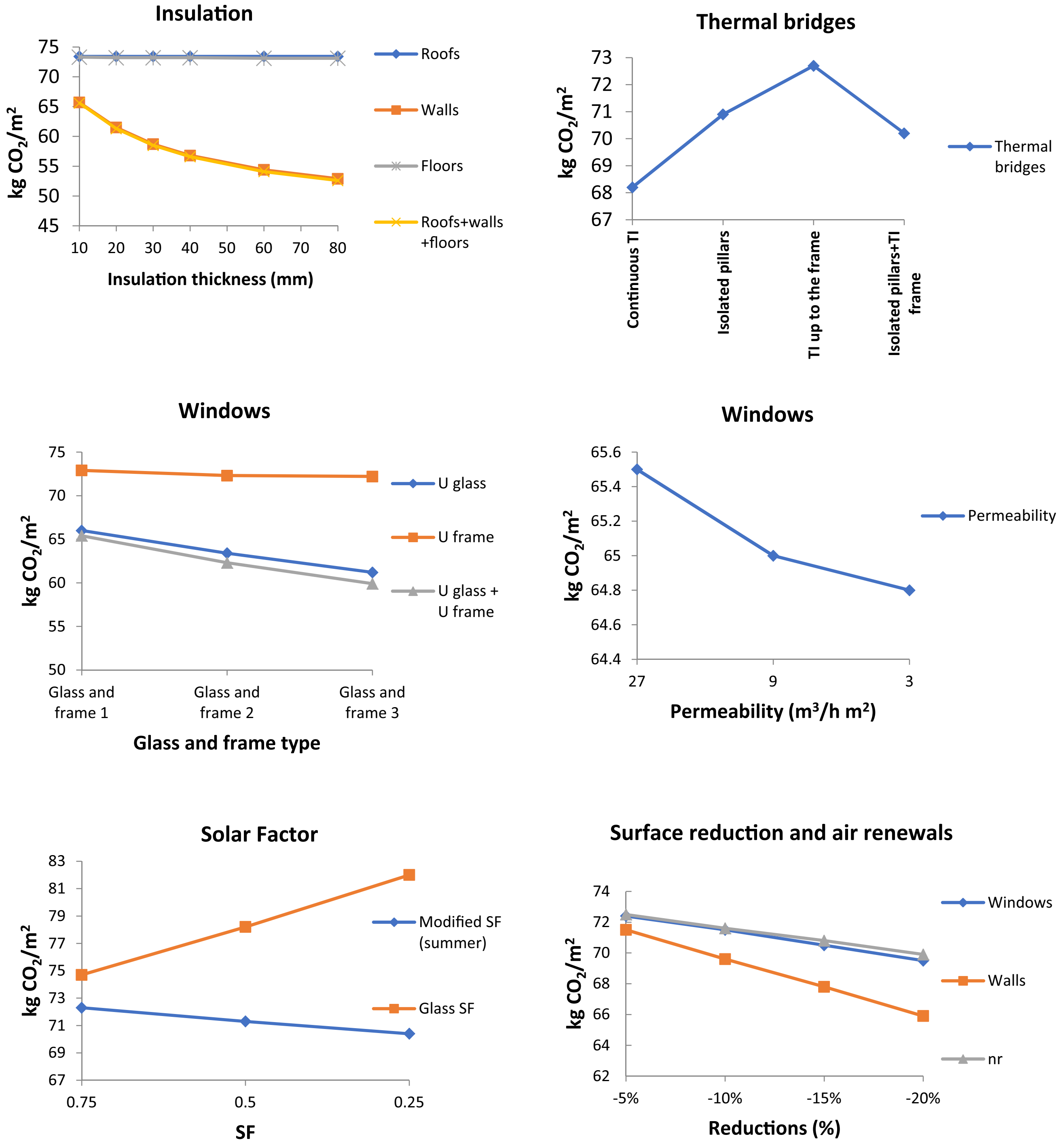


Fig. 5 CO$_2$ emissions per year due to simple demand improvements in Madrid. *TI* thermal insulation, *U* thermal transmittance, *nr* air renewals, *SF* Solar factor

zones with initial rating E, it is maintained regardless of fuel, except for the biomass with which very good results are obtained. On the contrary, in the climatic zones with initial rating F, it improves up to the E with most of the used fuels (Table 5), observing very good results with the biomass and not so good with the diesel C. On the other hand, by using a heat pump (HP) for heating, emissions and even qualification are improved as the COP increases. In climatic zones E, the rating is maintained, and in the case of Valencia, a D is reached with a COP = 3. In the climatic zones with initial

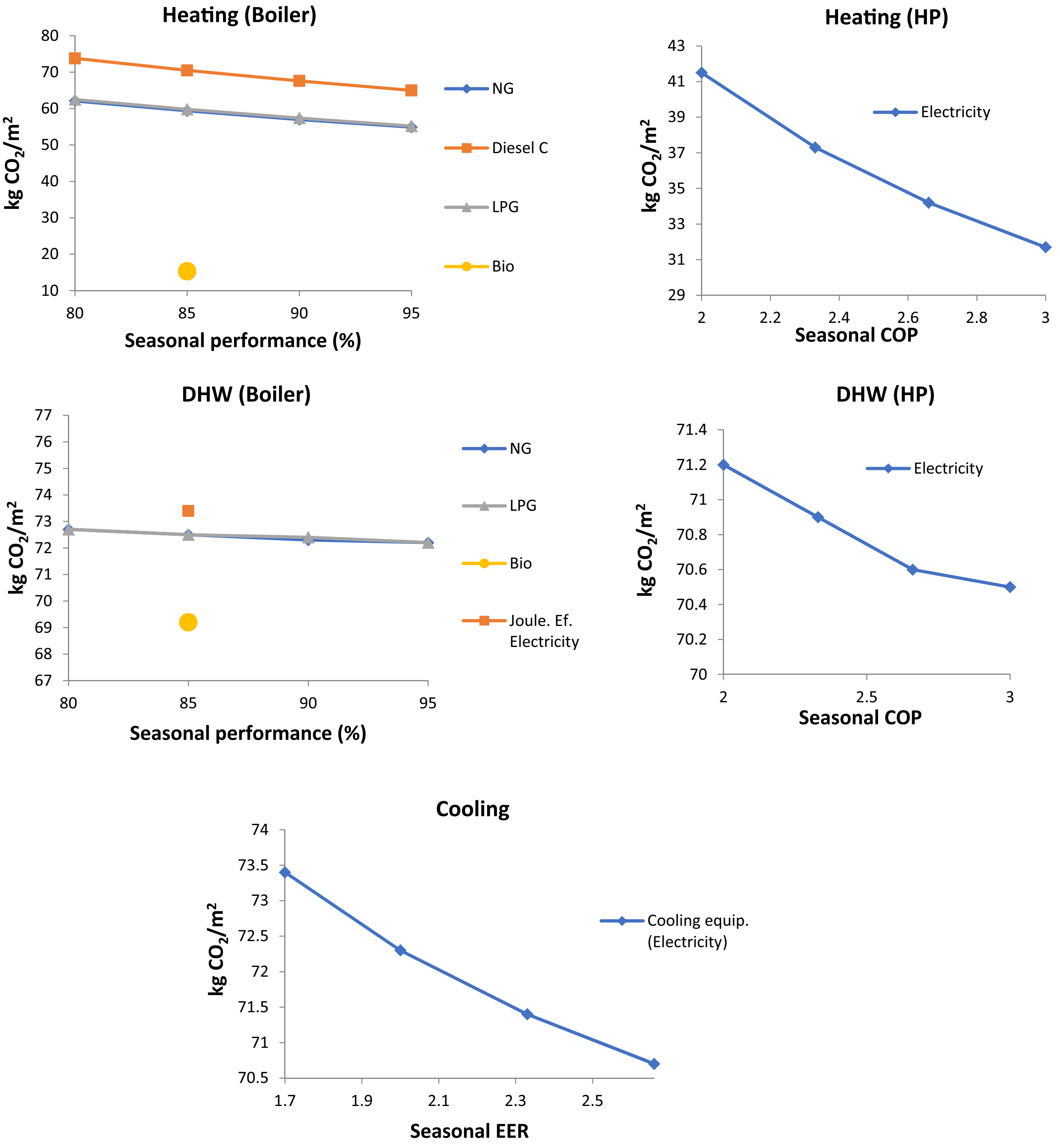


Fig. 6 CO$_2$ emissions per year due to simple thermal system improvements in Madrid. *NG* natural gas, *LPG* liquefied petroleum gas, *Bio* biomass, *HP* heat pump, *COP* coefficient of performance, *DHW* domestic hot water, *EER* energy efficiency ratio

qualification F, it is easily reached up to an E qualification, and through HP with COP = 2.66, a D can be obtained in Zamora, Vitoria, Burgos, Barcelona and Bilbao, and with a COP = 3 in Madrid and Toledo.

- Cooling system

All climatic zones follow the same trend by simple improvements in refrigeration. They maintain the same initial rating and slightly improve emissions by increasing the seasonal EER from 1.7 to 2.66. In areas where summer climate conditions are milder, and therefore do not need

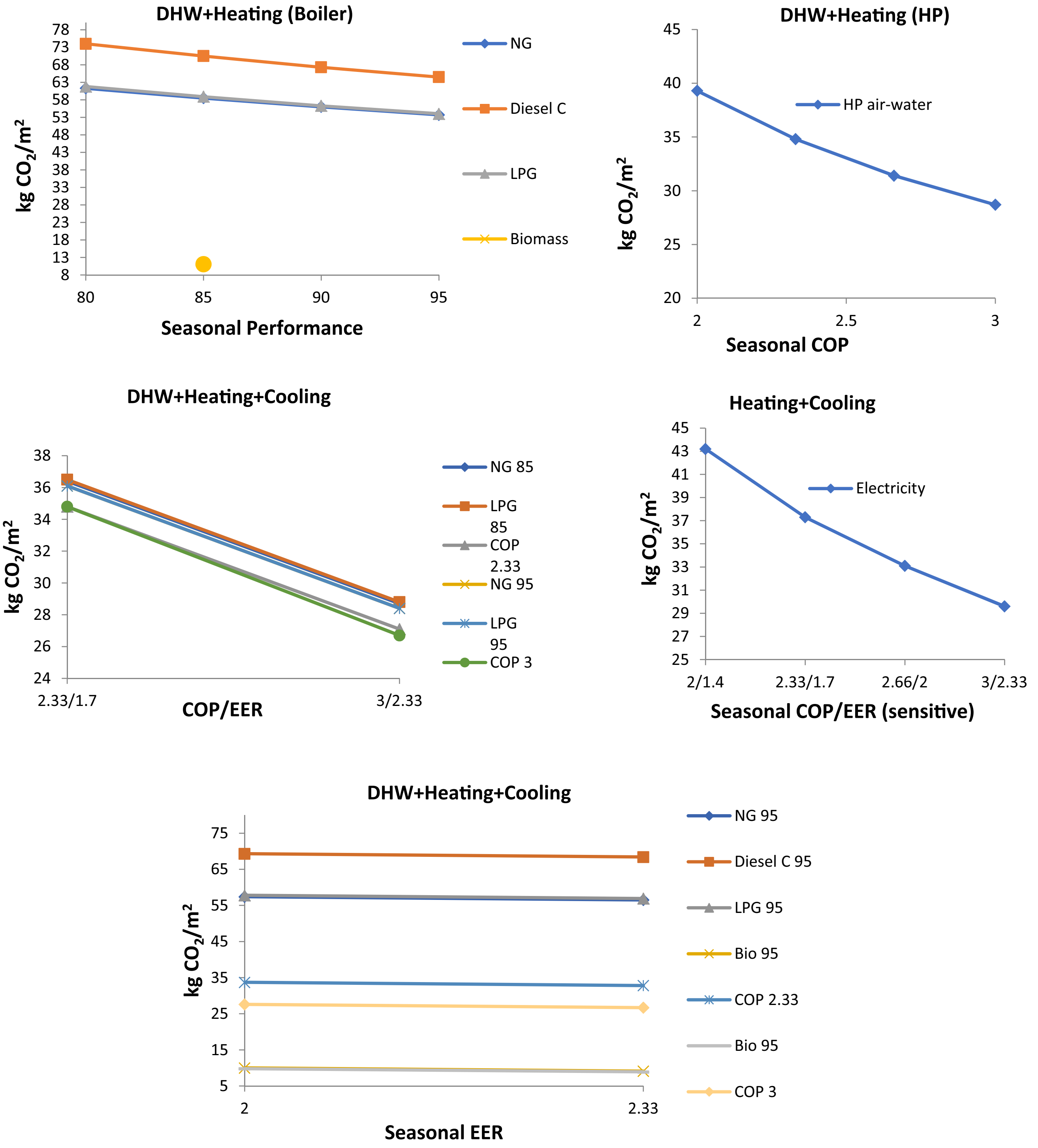


Fig. 7 CO_2 emissions per year due to combined thermal system improvements in Madrid. *NG* natural gas, *LPG* liquefied petroleum gas, *Bio* biomass, *HP* heat pump, *COP* coefficient of performance, *DHW* domestic hot water, *EER* energy efficiency ratio

refrigeration, CO_2 emissions are worsened (Vitoria, Burgos and Bilbao).

- Heating and domestic hot water (DHW) system

In this analysis of the simple improvements in DHW, the Joule's effect boiler is also included, which works with electricity. The emissions are slightly improved by increasing the seasonal performance of the boiler, and the best result of the reduction in emissions is obtained by using biomass as a fuel. However, the rating is not modified in any of the climatic zones except for Vitoria, Bilbao and Barcelona, in which an E rating is obtained with a biomass boiler, and in Burgos, where an E is reached with a natural gas (NG) boiler, liquefied petroleum gas (LPG) and biomass, and it is maintained in F with a boiler of Joule's effect.

By using air–water HP for DHW, the emissions are improved as the seasonal COP of the equipment increases, but in the great majority of cases it is not enough to improve the rating, except in the case of Vitoria, Burgos, Bilbao and Barcelona, in which an E is achieved. Figure 6 shows the CO_2 emissions due to simple thermal system improvements in Madrid.

Combined demand improvements

The simple improvements in demand mentioned above are combined, so that three types of windows defined in Table 4 are joined with different thicknesses of insulation walls, roofs and thermal bridges. Results using type 1 window show that for all zones the best results are obtained by acting on the insulation of roofs, walls and thermal bridges together, especially the continuous insulation of thermal bridges. In addition, the emissions are reduced as the thickness of the insulation increases. However, CO_2 emissions when acting in the insulation of walls and in the roof + walls are identical. Figure 7 shows the results for Madrid. In all zones, the rating E is reached, even D in the more favorable cases discussed above. With type 2 window, similar trends are obtained to those obtained with the type 1. D rating is more easily achieved since the window has better characteristics. In the climatic zones with initial qualification F, it is improved until E, even reaching qualification D. For all climatic zones with initial qualification E, it is possible to reach D by increasing the insulation thickness. The improvements made with type 3 window follow the same trend as in types 1 and 2. Better results are obtained in all cases, making it even easier to reach the D rating.

Combined thermal system improvements

Combining improvements in DHW and boiler heating systems, a clear improvement is obtained as seasonal performance increases in all climatic zones. Specifically, in the climatic zones with qualification with initial rating E, this qualification is maintained. Similar results are obtained with both natural gas boiler and LPG. The worse results are obtained with diesel fuel and the best with biomass boiler, even achieving grade C. Climatic zones with initial rating F maintain the same trend but with better results. It improves up to the E rating with natural gas and LPG, and although the results with a Gasoil boiler are not good, an E can be reached with a boiler with a 95% efficiency. Also, with the biomass boiler, better results are obtained, even reaching the A grade in areas such as Zamora, Vitoria, Burgos, Bilbao and Barcelona.

In the case of combined improvements in DHW and heating with HP, there is an improvement in both the emissions and the rating, increasing the seasonal COP. In the climatic zones with E qualification, they maintain the rating with low COP and improve the rating to D from COP = 2.33 in Granada, COP = 2.66 in Cadiz and Valencia and with COP = 3 in Almeria and Seville. In the climatic zones with initial qualification F, the qualification to E is reached, even with low COP, and a D is reached, in some cases from COP = 2.66 as in Madrid, Zamora and Toledo and in the rest of cases from COP = 2.33. Figure 7 shows the CO_2 emissions due to combined thermal system improvements in Madrid.

Minimum requirements to obtain D qualification in each climatic zone

The effects on the energy performance due to the improvement in the thermal envelope and/or thermal installations of the "standard building" have been studied. In order to achieve "D" qualification and to meet the BTC requirements, the minimum improve measurements have been applied for each climatic zone.

Table 6 shows the minimum improvements in each city to obtain D rating. In addition, percentages of CO_2 emissions are avoided and PEC savings obtained with the improvements are presented in Table 6. Figure 8a shows the building qualification and the CO_2 emissions before and after improvements. According to those results, CO_2 emissions were considerably reduced and differences among climatic zones decreased. Figure 8b presents primary energy consumption (PEC) before and after improvements in the different Spanish climatic zones.

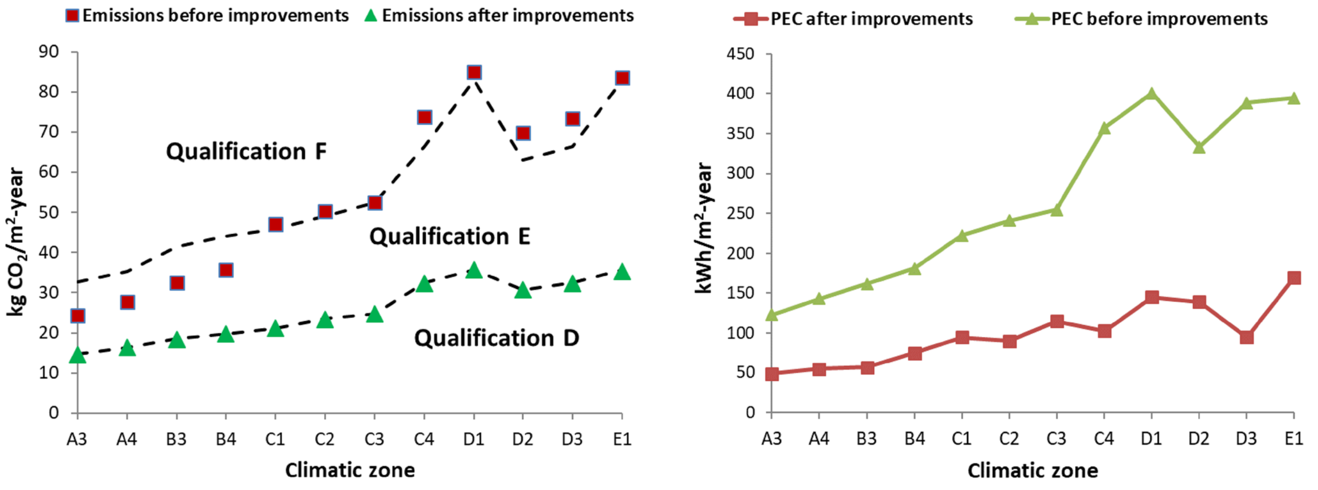
In climatic zones with mild winters and warm summers, initial qualification was E label. In those zones, initial heating demand was quite similar to cooling demand. According to the previous sensitivity analysis, it is possible to reach a D label with only demand improvements, except for Almeria (A4) in which heating system is also to be improved. In those zones, about 40% of the initial CO_2 emissions are avoided with the improvements, and primary energy consumption (PEC) is reduced to about 50 kWh/m^2 year (over 60% reduction).

As a general rule, for the rest of climatic zones (with initial qualification F label), in which initial heating demand is much higher than cooling demand, both demand and thermal systems have to be improved for obtaining a qualification D. It avoids over 53% of the initial CO_2 emissions, and PEC is significantly reduced. There are two zones, Barcelona (C2) and Madrid (D3), in which an increase in the isolation of roof and walls up to 60 mm in thickness the aim is

Table 6 Minimum improvements in each city (Climatic zone) to obtain D rating

City (zone)	Minimum improvement		CO_2 emissions avoided (%)	PEC savings (%)
	Demand improvements	Thermal system improvements		
Cadiz (A3)	Window type 2 and 20 mm insulation in walls		39.92	60.16
Almeria (A4)	Window type 1 and 20 mm insulation in roof and walls	DHW and heating with a LPG boiler (85% seasonal performance)	40.79	61.62
Valencia (B3)	Window type 1 and 20 mm insulation roof and walls		43.21	64.73
Seville (B4)	Window type 1 and 60 mm insulation in walls		44.82	58.54
Bilbao (C1)	Window type 1 and 20 mm insulation in roof and walls	DHW and heating with a LPG boiler (90% seasonal performance) and cooling system with EER = 2.33	55.41	57.28
Barcelona (C2)	Window type 2 and 60 mm insulation in roof and walls		53.78	62.69
Granada (C3)	Window type 2 and 40 mm insulation in roof	DHW and heating with diesel C boiler (95% seasonal performance) and cooling system with EER = 1.7	53.05	54.83
Toledo (C4)	Window type 2 and 20 mm insulation in roof and walls	DHW and heating with LPG boiler (95% seasonal performance) and cooling system with EER = 1.7	56.23	71.17
Vitoria (D1)		DHW, heating and cooling with a heat pump (COP/EER = 2.33/1.7)	57.95	63.82
Zamora (D2)	Window type 1 and 40 mm insulation in roof and walls	DHW and heating, with a LPG boiler (85% seasonal performance)	56.10	58.31
Madrid (D3)	Window type 3 and 60 mm insulation roof and walls		55.99	75.55
Burgos (E1)		DHW, heating and cooling with a heat pump (COP/EER = 2.33/1.7)	57.78	56.92

obtained. In those cases, thermal systems do not need to be improved and PEC is reduced to about 95 kWh/m^2 year. On the other hand, Vitoria (D1) and Burgos (E1), zones with very cold winters (highest initial heating demand over 230 kWh/m^2 year) and very low cooling demand, can reach qualification D with a heat pump and demand improvements are not needed.



(a) (b)

Fig. 8 Results before and after improvements in the different Spanish climatic zones: **a** CO_2 emissions per year and energy ratings, **b** primary energy consumption (PEC)

According to Fig. 8, percentages of CO_2 emission reduction per square meter and year range from 40% (A3) to 58% (D1). In 2014 residential sector, emissions were 16.4 Mt CO_2 (Ministerio de Transición Ecológica 2014) and over 54% of Spanish housing stock were built before 1980 (Cuchí 2016). Thus, between 3.5 Mt CO_2 and 5.1 Mt CO_2 per year could be avoided applying the improvements defined in Table 6.

Policy measures to upgrade efficiency

According to the Directive 2012/27/EU (EU 2012), the IDAE (2016) carried out a "Program of aid for the energy rehabilitation of existing buildings" in Spain. For property owners to access this program, they must make improvements to the thermal envelope and/or thermal installations and obtain an improvement in the energy rating, at least, of a letter measured in the scale of emissions of carbon dioxide carbon with respect to the initial energy rating of the building. The amounts of aid range from 20 to 70% of the amount invested in the action. It also offers a financing line with an interest rate of Euribor + 0%, with a maximum repayment term of 12 years.

Results obtained in the present study suggest that more measures should be carried out in Spain to reduce the significant CO_2 emissions resulting from the stock of buildings built before 1980 and improve energy efficiency.

The measures proposed by the authors are divided into two blocks: financial aids and tax reductions.

1. Types of sources and methods of financing to improve energy efficiency in buildings:
    - Access to state financing at low interest rates and even access to agreements to enhance electricity and gas rates applied to users who have implemented measures to improve energy efficiency in their homes.
    - Access to financing at low interest rates in financial institutions that have reached collaboration agreements with the state.
    - Direct capital grants from different state or local administrations.
    - The costs of implementing energy efficiency improvement measures can be financed by the savings generated by the reduction in energy consumption through an agreement with the agent that is contracted for the reform. These energy agents can receive tax improvements to their business activity from governments.
2. Tax relief and tax reductions:
    - Application of reduced rates of value-added tax (VAT) on works to improve energy efficiency.
    - Tax relief for homeowners for the expenses generated in the application of improvements in energy efficiency.
    - Reduction in the council tax, decreasing as the energy efficiency of the home increases.

It is necessary to promote public and private financing measures and associate them with tax relief for individuals who apply measures to improve energy efficiency in their dwellings, as well as for companies to have available different private financial mechanisms for the development of building energy efficiency projects. According to the Spanish administrative structure, those lines of economic support should be managed by the state and autonomous communities of Spain.

Conclusions

The "standard building" energy qualification (letter) was similar in the different climatic zones. However, the values of CO_2 emissions and primary energy consumption were really different among the zones.

Similar energy ratings (E and F) were obtained in the different climatic zones and with CO_2 emissions close to the minimum values of the E rating. However, the values of CO_2 emissions were very different between the different zones.

The minimum necessary improvements for the different zones that allow to meet the BTC requirements and to achieve "D" energy label were considered. After improvements, both CO_2 emissions and primary energy consumption were considerably reduced and the differences in the obtained values decreased among the different climatic zones.

With regard to improvements, it was observed that the better the initial energy rating, the more the modifications were necessary to improve the energetic rating and its emissions.

The vast majority of the minimum improvements needed to achieve a D rating were accomplished with the combination of demand improvements or the combination of demand and equipment improvements, except in Burgos (zone E1) and Lugo (zone D1) where it was better to act in the combination of equipment.

With the application of simple measures that improve the energy efficiency of buildings built in Spain before 1980 up to a D rating, it would be possible to reduce emissions by over 3.5 Mt CO_2 per year.

In consequence, energy savings must be made in buildings, acting on the enclosure of existing buildings and/or replacing the thermal installations by others with better efficiencies. As future work, it is interesting to analyze in detail the improvements studied in this paper from an economic and social point of view. In that sense, some lines of financial aid or subsidies for the implementation of measures aimed at reducing energy demand in Spanish homes are proposed in this paper. The lines of economic aids should be managed by the state and autonomous communities of Spain, and they would aim at obtaining at least a D energy rating in dwellings built before 1980.

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