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Characterization of housing stock for energy retrofitting purposes in Spain

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Research Article

Abstract

Energy saving in existing buildings is of vital importance. In this work, the characterization of housing stock in Spain for energy retrofitting purposes has been performed. The regulations in force when the existing stock was constructed (1980–2007) were considered to model the envelope and thermal systems of single-family and block housing. Building energy consumption and CO_2 emissions were estimated for each type of dwelling and location, ranging from 44.2 to 130.6 kWh/(m²·year) (13.6–32 kg CO_2/(m²·year)) for multi-family homes, and 85.5 to 213.5 kWh/(m²·year) (17.1–45.2 kg CO_2/(m²·year)) for single-family homes. A global picture of the energy performance and emissions for 13 different climate zones was obtained with a total of 504 simulations. Retrofitting of the envelope allowed the reduction of consumption and emissions from 37.7% to 58%, depending on the climate zone. Energy consumption per square meter in block housing was lower than in single-family housing; nevertheless, single-family houses responded more effectively to energy improvement actions. Finally, non-renewable primary energy savings seem a better indicator of the improvement by retrofitting than the energy label. The building models designed in this work may serve as a reference for subsequent research concerning energy retrofitting and energy savings of housing stock.

Keywords

housing stock characterization;
building retrofitting;
representative building;
climate zone;
simulation model

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1 Introduction

1.1 Spanish building stock

In 2020, the building sector accounted for 36% of global final energy consumption and 37% of energy related CO_2 emissions in the world (IEA 2021). According to the latest report by the United Nations Environment Program (UNEP), that figure must be reduced by more than 50% to achieve carbon neutrality by 2050. Sustainable development – fighting climate change, universal access to energy and improvement in air quality – requires reducing the emissions produced by the housing stock by a third (United Nations Environment Programme 2019). The International Energy Agency (IEA) has developed actions to achieve decarbonization based on the rehabilitation of existing buildings and energy efficiency of thermal systems while promoting the use of materials with low carbon emissions (IEA 2020).

In the European Union (EU), less than 3% of new buildings achieve the maximum energy rating and 97% of existing ones must be rehabilitated, to meet environmental objectives (BPIE 2017). Efficiency in construction sector has become a priority for the EU to address the challenges of saving energy and reducing CO_2 emissions. In addition, potential energy savings in buildings and thermal modernization of building stock implies economic, social and environmental benefits (Głęboka Termomodernizacja 2012). Directive 2018/844 (European Union 2018) on energy efficiency in buildings estimated that heating and cooling consumption account for 50% of the final energy in the EU, of which 80% is consumed in the residential sector (European Union 2018). According to that Directive, actions on the thermal envelope and thermal systems in buildings are vital in order to reduce energy consumption.

Concerning Spain, in 2020, the Spanish building stock consisted of 25,712,744 homes; 67.9% are block dwellings and the rest are single-family dwellings (Ministry of Transport of Spain 2020a). A total of 23,493,772, almost 91.4% of the

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Advances in Modeling and Simulation Tools

Abbreviations

AENOR	Normalization Spanish Association (Asociación Española de Normalización y Certificación)
CERMA	Abridged Method for Certification of New Residential Buildings in Spain (Calificación Energética Residencial Método Abreviado)
CTE	Building Technical Code
CTE-DB-HE	Basic Document on Energy Saving of the Technical Building Code (Documento Básico de Ahorro de energía del Código Técnico de la Edificación)
CZ	climate zone
DHW	domestic hot water
EPC	Energy Performance Certificate
ETICS	External Thermal Insulation Composite System
EU	European Union
$g^{\perp}$	solar factor
IDAE	Institute for Energy Diversification and Saving (Instituto para la Diversificación y Ahorro de la Energía)
K_G	global thermal transmission coefficient
MITECO	Ministry for Ecological Transition and Demographic Challenge (Ministerio para la Transición Ecológica y el Reto Demográfico)
NBE-CT-79	Basic Document Norm on Thermal Conditions in Buildings (Norma Básica de Edificación sobre Condiciones Térmicas en los Edificios)
NRPE	non-renewable primary energy
RICAS	Regulation of Heating, Air Conditioning and Domestic Hot Water Installations (Reglamentos de Instalaciones de Calefacción Climatización y Agua Caliente Sanitaria)
RITE	Regulations for Thermal Installations in Buildings (Reglamento de Instalaciones Térmicas en los Edificios)
SCS	summer climate severity
SCZ	summer climate zone
U	thermal transmittance
UNE	Spanish Association for Standardization (Una Norma Española)
WCS	winter climate severity
WCZ	winter climate zone

housing stock, has been built before the entry into force in 2007 of the Building Technical Code (CTE) (Ministry of Housing of Spain 2006; Ministry of Development of Spain 2019). Therefore, less than 9% are projected and executed under the energy-saving and efficiency premises arising from European directives. This opens the possibility of potential energy savings if the retrofitting of existing buildings is considered. Figure 1 shows the distribution of Spanish homes built up to 2014, based on the specified year intervals (European Commission 2020), reflecting their age and the potential market available for renovation.

Hence, to perform the characterization of existing building stock, the regulations that were in force during their construction must be considered. The first regulation that established the characteristics of building enclosures was the Basic Document Norm on Thermal Conditions in Buildings (NBE-CT-79) (Ministry of the Presidency of Spain 1979) which was mandatory from 1980 to 2007 (Figure 1). On the other hand, thermal systems in buildings and their technical requirements were regulated by standards and codes that have undergone considerable evolution. The Regulation of Heating, Air Conditioning and Domestic Hot Water Installations (RICAS) (Ministry of the Presidency of Spain 1980) entered into force in 1980, being replaced by the Regulation of Thermal Installations in Buildings (RITE) in 1998 (Ministry of the Presidency of Spain 1998) and its final replacement in 2007 (Ministry of the Presidency of Spain 2007). The Spanish Ministry of Transport (Ministry of Transport of Spain 2020b) estimated that 21% of residential buildings in Spain are over 50 years old, and 58% were built before the first regulation introducing energy efficiency criteria.

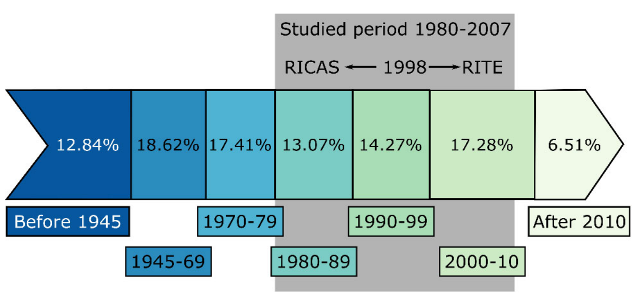


Fig. 1 Breakdown of Spanish residential building stock by construction year and period studied in this work

Due to the high energy saving potential from the retrofitting of the existing building stock, the National Integrated Energy and Climate Plan 2021–2030 (PNIEC) (Ministry for Ecological Transition and the Demographic Challenge of Spain 2021b) was developed to plan the retrofitting process, which is depicted in Figure 2 and it is expected to reduce final energy consumption in 4,755 ktoe.

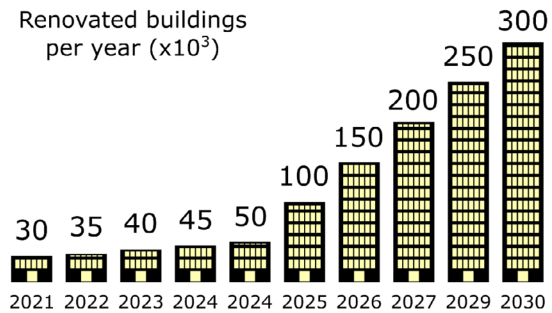


Fig. 2 Annual forecast of energy-efficient rehabilitated dwellings in Spain (own elaboration from data in Ministry of the Presidency of Spain (1980))

It must be noted that the most recent energy consumption restrictions apply to the new constructed buildings and thus are not applicable to the retrofitting of the already existing housing stock (Ministry of Housing of Spain 2006).

The developed plan led to the entry in force of the RD 737/2020 (Ministry for Ecological Transition and the Demographic Challenge of Spain 2020b), which regulates the eligibility for subsidies regarding the renovation of existing residential buildings constructed before 2007. The Energy Performance Certificate (EPC) label, based on the reduction of CO_2 emissions/(m^2·year), is used to assess the behavior of the building. This label goes from "A" being the most efficient building to "G" being the least efficient. In order to be eligible for subsidies, this label must be improved at least in one letter and, the resulting building does not need to comply with the requirements of the CTE (Ministry of Housing 2006 of Spain; Ministry of Development of Spain 2019), the calculations must follow the new procedure established in the RD 390/2021 for the EPC calculation (Ministry of the Presidency of Spain 2021).

1.2 Related works

Regarding precedent scientific works in the context of energy retrofitting, He et al. (2021) presented an international review of 1090 works in energy and environmental issues, finding that research with the highest impact is focused on building energy retrofitting. Simulation of energy behavior of buildings with computer tools has been performed by Khalil et al. (2018), who analyzed residential building energy retrofitting in Sidi-Gaber district, Alexandria, with EnergyPlus. By introducing a water wall system, a double skin façade and an integral control, they found that initial investment was similar to traditional building methods, but inner comfort was substantially increased. The same geographical location was studied by William et al. (2020) with the same software, calculating the energy demand from the thermal equipment of a hospital in Alexandria. Their results revealed that savings up to 67% may be achieved through retrofitting of the building envelope and thermal systems. In the European context, other strategies used to assess building energy behavior is the Energy Performance Certificate (EPC). Hjortling et al. (2017) studied residential buildings in Sweden, finding that building typology had a great influence on its behavior and that regulations help to encourage energy saving. Droutsa et al. (2016) also used the EPC metric to analyze the four existing climate zones in Greece, concluding that more than half of the existing building stock has a low "F" or "G" EPC label, due to scarce insulation and low-efficiency thermal systems. The Life Cycle Analysis approach is also employed in energy retrofitting, with Luo and Oyedele (2021) using it to highlight the energy saving obtained when insulating walls and roofs when retrofitting the envelope and thermal systems of a UK building. Tensorial Analysis of Networks (TANS) was employed by Ravelo et al. (2020), who evaluated the thermal response of a building in northern France by means of a mathematic model when changing the layers in the building envelope composition and calculated the potential energy savings. Finally, the case study in Toronto (Canada) studied by Wills et al. (2021) with the Canadian Hybrid Residential End-use Energy and GHG Emissions models, showed that deep envelope retrofits and fuel switching from natural gas to electric heat pump systems reduce community energy demand by 69%.

In Spain, researchers have chosen different strategies to assess energy savings caused by retrofitting. Monitoring of actual buildings has been performed by Giancola et al. (2014) in two multi-family social buildings located in Madrid, as well as by Casquero-Modrego and Goñi-Modrego (2019) in a multi-family building in Barcelona. The decisive influence of the occupants and their customs – e.g. ventilation patterns and set-point temperatures – was highlighted in both works. The energy simulation software EnergyPlus has been used by Ávila-Delgado et al. (2021) to study cases in three cities: Barcelona, Seville and Malaga. Using the same software, Ghoreishi et al. (2021), analyzed how the improvement in glazing, ventilation and boiler efficiency helps to reach better comfort levels in a southern Spain house. Employing another simulation software, HULC, Monzón and López-Mesa (2018) proposed a series of physical indicators to detect the worst performing dwellings in terms of energy efficiency in Zaragoza, grading the retrofitting of the most affected ones. The software Abridged Method for Certification of New Residential Buildings in Spain (CERMA), was used by Serrano-Lanzarote et al. (2016) to analyze energy savings and costs incurred during retrofitting of existing buildings in the Community of Valencia. CERMA was also used by Carpio et al. (2013), to examine the impact of using biomass boilers on the energy rating and CO_2 emissions, in six cities located in the Iberian Peninsula with different climatic conditions, as well as in Carpio et al. (2015) to propose a new classification scale for climate zones. CERMA has been used as well by Castellano et al. (2014) to evaluate both the energy rating scale for buildings and the CO_2 emission levels for the construction of sustainable buildings. Afterwards, they developed an alternative methodology for the calculation of CO_2 emissions per square meter and per year during the useful life of buildings (Castellano et al. 2015). Finally, EPCs have been used to characterize existing buildings in different climate zones. Gangolells et al. (2016), applied them in Catalonia, analyzing energy consumption depending on the construction year and finding that heating demand (70%–75%) clearly outweighs the rest of energy demand sources. Las-Heras-Casas et al. (2018) and López-González et al. (2016), analyzed EPCs in four climate zones in the Communities of Aragon and La Rioja. In both studies, characterization was done by energy rating, based on the climate zone and construction year.

From the literature review, it is apparent that most of the works are limited to a particular location, a particular region or just a few climate zones. Besides, the building typology is rarely considered nor the particular characteristics from its construction date. The authors of this work have not found a complete comparative analysis of block and single-family homes, which has a great relevance due to their relative weight in residential buildings stock and their different characteristics. Regarding the choice of thermal systems, the type of generator and the performance required in each regulatory period are typically not considered, which is a crucial aspect to assess energy consumption. Additionally, some environmental aspects, such as the predominant energy sources in the country, which is a vital parameter for the calculation of CO_2 emissions, are usually disregarded. Finally, with a current trend towards near-zero building emissions, which is relatively affordable in new construction, the potential energy saving in existing buildings, which represent most of the total energy consumption, is left behind.

Therefore, the objective of this work is the characterization of housing stock for energy retrofitting purposes due to its high energy saving potential, providing insight into the performance of the building in a wide range of climate zones. Single-family and block housing constructed in the period 1980–2007, which represent almost 45% of the housing stock, have been characterized according to the requirements of the regulations that were in force at the construction date. After performing this characterization, improvements in the building envelope are proposed, evaluating the overall energy saving that might be achieved for every situation and climate zone.

2 Methodology

The energetic behavior of the representative morphology of Spanish real estate stock regarding single-family and blockhouses has been analyzed in the period 1980–2007. The enclosures have been designed according to the maximum transmittance enforced by the NBE-CT-79 (Ministry of the Presidency of Spain 1979) and eight constructive solutions have been considered to improve the building envelope. The equipment meets the requirements of the two legislative periods, 1980-97 (RICAS) (Ministry of the Presidency of Spain 1980) and 1997–2007 (RITE) (Ministry of the Presidency of Spain 1998), allowing the simulation of the energy performance of buildings depending on their construction year. The methodology, shown in Figure 3, parts from the climate zone location of the building and the corresponding regulations to determine the minimum requirements for the thermal enclosure, depending on the building typology. Then, the simulations for every building type and climate zone are performed, obtaining the energy demand for heating, DHW and cooling. These values, coupled with the thermal power generating systems required by the specific regulations in force for each period, allow to determine the energy consumption of the building. Knowing the type of primary energy, it is possible to determine the share of Non-Renewable Primary Energy (NRPE) and CO_2 emissions.

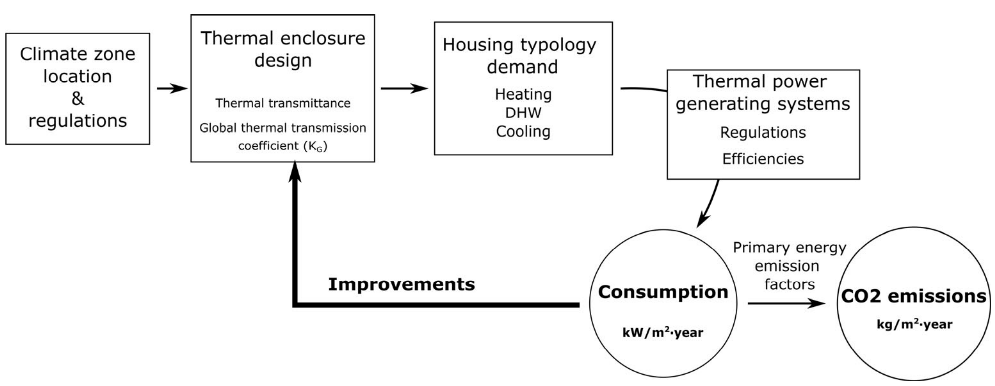


Fig. 3 Methodology followed in this study

2.1 Selection of the emplacement

In 1979, the Spanish territory was divided into Climate Zones (CZs) based on the estimated heating demand. The corresponding regulation, NBE-CT-79 (Ministry of the Presidency of Spain 1979), established a first classification in five zones depending on the degree-days based on 15 °C, as established in the Spanish Association for Standardization (UNE) 100002 (AENOR 1988), from zone A having the lowest values and E the highest ones. This first letter is followed by another letter from V to Y representing the average minimum temperatures in January, with V being the lowest and Y the highest.

Currently, the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) (Ministry of Development of Spain 2019) defines six zones depending on Winter Climate Severity (WCS), from α (the lowest) to E (the highest) and four zones depending on Summer Climate Severity (SCS), from 1 (the lowest) to 4 (the highest), resulting in a total of 13 CZs. More details may be found in Ministry of Industry of Spain (2016).

A province capital has been selected and analyzed for every CZ as defined by the NBE-CT-79 (Ministry of the Presidency of Spain 1979) and the current CTE-DB-HE (Ministry of Development of Spain 2019). Figure 4 shows the situation of these representative capitals, according to the corresponding classifications (left – NBE-CT-79; right – current CTE). It must be noted that buildings constructed according to the older regulations may be retrofitted to improve their energy behavior, but they do not need to comply with the minimum requirements of the current CTE if the modifications are outside the cases considered in Ministry of Housing of Spain (2006).

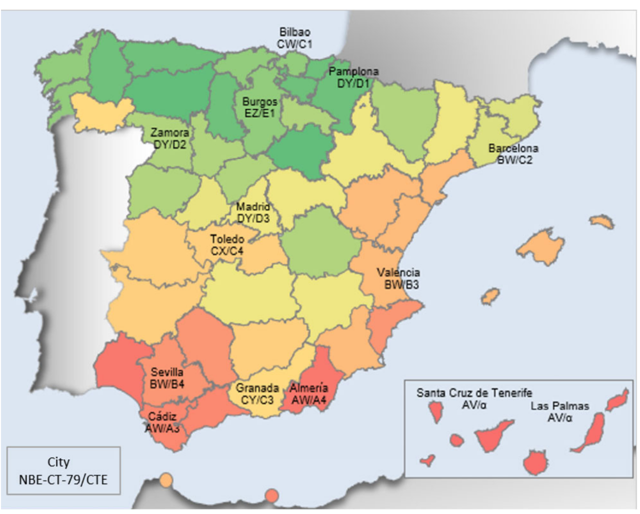


Fig. 4 Representative capitals for the climate zones defined in the regulations (left – NBE-CT-79; right – CTE)

2.2 Definition of the representative housing types

The MITECO website (Ministry for Ecological Transition and the Demographic Challenge of Spain 2021a) provides floor plans of representative single-family and block housing stock with geometrical data, floor height and building orientation. The single-family house is a two-story building with a useful area of 102.76 m², as shown in Table 1. It consists of a living room, a hall, a toilet and a kitchen on the ground floor, and three bedrooms, two bathrooms and a living room on the first floor, as displayed in Figures 5 and 6.

Table 1 Single-family house characteristics

	ID	Zone	Surface (m²)
Ground floor	S1	Living room	25.15
	S2	Hall	5.44
	S3	Toilet	6.38
	S4	Kitchen	10.82
First floor	S5	Bedroom 1	11.39
	S6	Bedroom 2	12.39
	S7	Bathroom	5.79
	S8	Living room	9.67
	S9	Bedroom 3	9.83
	S10	Bathroom	5.88
Single-family house surface			102.76
Single-family volume			277.45 m³

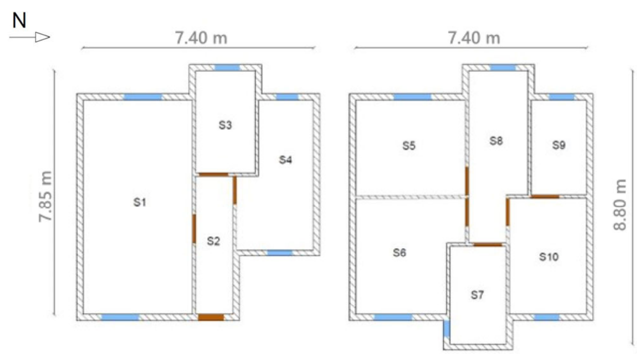


Fig. 5 Floor plan of the single-family house

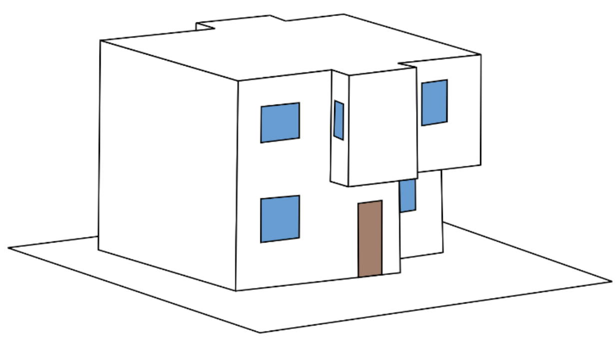


Fig. 6 3D visualization of the single-family house

The blockhouse is a five-story building, as shown in Figures 7 and 8, with four housing units on each floor. It occupies a floor area of 301.30 m^2, which is divided into 63.16 m^2 useful per dwelling and 48.66 m^2 for common areas, as shown in Table 2.

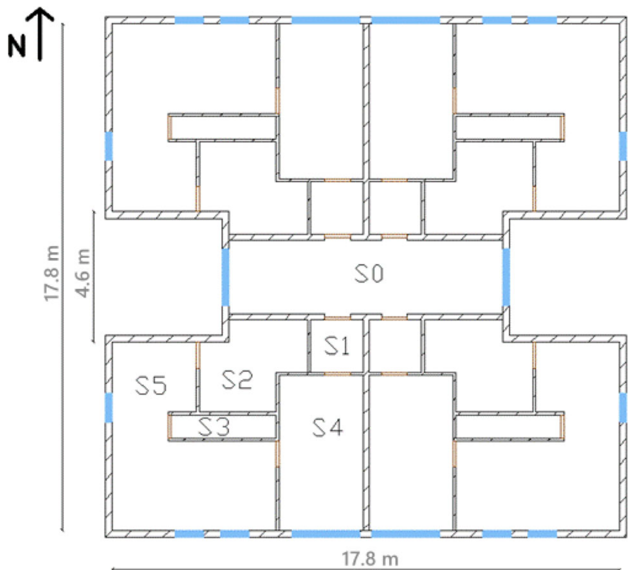


Fig. 7 Floor plan of the blockhouse

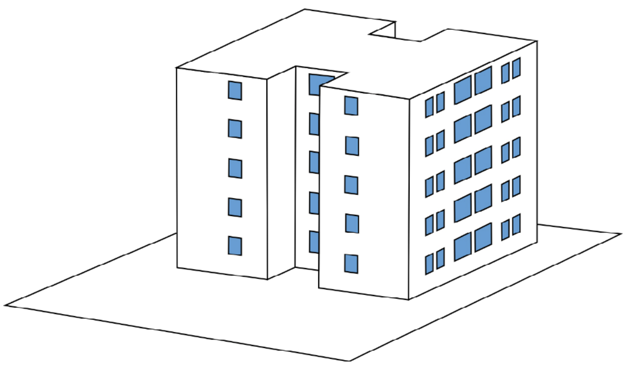


Fig. 8 3D visualization of the blockhouse

Table 2 Blockhouse characteristics

ID	Zone	Surface (m^2)
S0	Corridor	26.88
S1	Hall	4
S2	Bedroom 1	10.73
S3	Bathroom	3.42
S4	Bedroom 2	17.04
S5	Salon-kitchen	27.97
	Blockhouse surface	63.16
	Multi-family housing volume	170.53 m^3

2.3 Requirements of the NBE-CT-79 regarding enclosures

From the geometrical data provided in the floor plans in (Ministry for Ecological Transition and the Demographic Challenge of Spain 2021a), the building envelope has been designed, takings as a reference the minimum requirements of the NBE-CT-79 (Ministry of the Presidency of Spain 1979). This regulation defines the maximum transmittance values for each enclosure, as well as the maximum value for the global heat transmission coefficient of the building, K_G, and the air permeability of the openings.

Following these criteria, screeds without perimeter thermal insulation have been selected for the floors. The value indicated for linear conductivity is k = 1.75 W/(m·K). For single-family homes, L = 32.16 m and S = 54.11 m^2, so that the thermal conductivity is U = 1.04 W/(m^2·K). For block dwellings, L = 87.60 m, S = 301.3 m^2 and U = 0.51 W/(m^2·K). A maximum value for the permeability of the gaps of 20 m^3/(h·m^2) was chosen, considering a differential pressure of 100 Pa (Sánchez 2003). Doors have been modelled with the values taken from Section 2.8.4 (Ministry of the Presidency of Spain 1980) of the standard, considering opaque wood with U = 3.5 W/(m^2·K), whereas openings are modelled with values from Section 2.8.3 (Ministry of the Presidency of Spain 1980), considering monolithic glass with a wooden frame and U = 5 W/(m^2·K), occupying 80% of the hole.

With all the considered assumptions, the maximum limit transmittance values for the buildings were obtained. These values are summarized in Table 3.

The second criterion, regarding the maximum value of K_G, was also considered. In the single-family house studied in this work, the form factor is f = 0.93, whereas in the blockhouse f = 0.540, values between $0.25 < f < 1$. Hence, the maximum values of K_G for each CZ, considering that natural gas is used as a primary energy, were calculated and are summarized in Table 4. Final maximum transmittance values of the envelope for the single-family and block housing are reported in Table 5 and 6, respectively, defining the characteristics of each particular enclosure for all the CZs in Spain and representing the base case study of this work.

Table 3 Maximum limit thermal transmittance values for the single family and block building

Enclosure	V and W	X	Y	Z
	U (W/(m^2·K))			
Exterior wall	1.20	1.20	1.20	1.20
Cavities	5	5	5	5
Door	3.49	3.49	3.49	3.49
Party wall	2	1.80	1.60	1.60
Roof	1.40	1.20	0.90	0.70
Floor-single family	1.04	1.04	1.04	1.04
Floor-block building	0.51	0.51	0.51	0.51

Table 4 Maximum values of K_G (W/(m²·K)) for each climate zone

Climate zone	A	B	C	D	E
Single family house	1.22	0.94	0.81	0.73	0.69
Multi-family housing block	1.45	1.11	0.97	0.87	0.82

Table 5 Maximum thermal transmittance values for the envelopes of single-family housing

	A-V, W	BW	CW	CX	CY	DY	EZ
Enclosure	*U* (W/(m²·K))						
Exterior wall	1.2	1.12	0.95	1.01	1.08	0.98	0.95
Cavities	5	4.64	4	4.21	4.51	4.06	3.97
Door	3.49	3.24	2.79	2.94	3.14	2.84	2.77
External slab	1	0.93	0.8	0.76	0.72	0.65	0.56
Party wall	2	1.86	1.6	1.51	1.44	1.3	1.27
Roof	1.4	1.29	1.12	1.01	0.8	0.73	0.56
Floor	1.12	0.97	0.83	0.87	0.93	0.84	0.83

Table 6 Maximum thermal transmittance values for the envelopes of block housing

	A-V, W	BW	CW	CX	CY	DY	EZ
Enclosure	*U* (W/(m²·K))						
Exterior wall	1.2	1.2	1.05	1.08	1.1	1.1	0.97
Cavities	5	5	4.38	4.5	4.51	4.06	3.97
Door	3.49	3.49	3.49	3.49	4.63	4.63	4.02
Party wall	2	2	1.76	1.62	1.49	1.49	1.29
Roof	1.4	1.4	1.22	1.08	0.9	0.9	0.56
Floor	0.51	0.51	0.45	0.47	0.51	0.51	0.41

From these data, the building envelopes were designed, according to the materials specified in the Catalogue of Constructive Elements (Ministry of Public Works of Spain 2011), which collects the material hygrothermal characteristics with the aim of helping constructors to meet the legislation design requirements. The opaque enclosures manual (Rozas et al. 2006) has been also considered, as it contains the most used materials in construction.

2.4 Thermal generation systems

Natural gas, the fuel with the highest degree of penetration in the building sector in Spain (IDAE 2016), has been considered for the simulation of the energy consumption of single-family and block dwellings as the energy vector for heating services and domestic hot water (DHW). On the other hand, electricity has been considered to run the building heat pump, according to the MITECO Secretary of State report of the Government of Spain (Ministry for Ecological Transition and the Demographic Challenge of Spain 2020a). Regarding the equipment, an individual conventional boiler and refrigerator were selected, according to the Institute for Energy Diversification and Saving (IDAE) reports of heating generation systems in Spain (IDAE 2011).

The minimum thermal power to satisfy heating and DHW needs is determined from the flow required for a shower apparatus. A water consumption of 28 L/(day·person) at 60 °C has been considered, according to the CTE-DB-HE4 (Ministry of Development of Spain 2019), resulting in a thermal power of 24 kW installed in both single-family homes and every home in the block-housing. Regarding refrigeration requirements, they have been adapted to the thermal demand of each CZ (Baxi-Roca 2005).

The legislation of thermal generation systems in the study period, 1980–2007, has evolved significantly. Two main regulatory periods can be distinguished, the first one between 1980 and 1998 and the second one from 1999 to 2007. In the first period, the minimum performance required from heating appliances (75%) and the EER to the cooling ones (1.8) was regulated by the RICAS (IT 04.2.3) (Ministry of the Presidency of Spain 1980). In the second period, the RITE (Ministry of the Presidency of Spain 1998) required a minimum boiler performance based on their nominal power, so that $\eta \geq 90 + 2\log Pn$, where Pn was the boiler nominal power. In this case study, therefore, this value must be $\eta \geq 92.76$. The required EER for refrigeration appliances, 2.6, is described in Regulation (EU) No. 206/2012 (Annex I, section 2).

2.5 Calculation

The energetic behavior of the buildings has been simulated using CERMA software (TATECYR 2021), developed by ATECYR (Spanish Technical Association for Air Conditioning and Refrigeration), the IVE (Valencian Building Institute), and the technical collaboration of the FREDSOL group of the Department of Applied Thermodynamics of the Polytechnic University of Valencia. It is an officially accepted computer application for the energy dynamic simulation of new and existing residential buildings, with single-family and block typology. CERMA (ATECYR 2021) qualifies and certifies them according to the Spanish Royal Decree 390/2021 (Ministry of the Presidency of Spain 2021), which is the main reference document recognized by the Government of Spain (Ministry for Ecological Transition and the Demographic Challenge of Spain 2021c). In this context, it has become a solid tool for evaluating the energy performance of buildings, providing data on demand and consumption in heating, cooling and DHW, as well as the CO_2 emissions corresponding to each service (Carpio et al. 2013; Serrano-Lanzarote et al. 2016).

CERMA is a single thermal zone simulation engine which determines the energy demand for heating, refrigeration and DHW from the definition of the building envelope, the operating conditions (see Tables A1, A2 and A3 from the Appendix, which is in the Electronic Supplementary Material (ESM) in the online version of this paper) and the climate zone data (.met CLIMAS files (Ministry of Transport of Spain 2022b)). Additionally, the fulfilment of maximum transmittance and carpentry permeability values (see section HE1 from the Spanish Building Technical Code (Ministry of Public Works of Spain 2019a)). The thermal behavior of the building is calculated hour by hour, in transient regime, considering external and internal loads and the effects of thermal mass. The method used by CERMA also considers external loads of solar irradiation, as well as shadows, filtrations, etc.

Concerning the thermal generation systems hourly performance, their hourly consumption is calculated considering partial-load behavior, operating conditions and sensible and latent loads. More details may be found in (IDAE 2009; Ministry of Public Works of Spain 2020), where the validation and calibration tests passed by CERMA are collected, as well as the complete calculation methodology.

The simulation process requires the entry of the building location, number of airchanges per hour, the building constructive elements and their materials and characteristics, as well as the thermal power and nominal performance of the thermal generators for heating, DHW and cooling. Thermal generation systems have been chosen individually, according to the documents published by the IDAE (2011, 2016). Outdoor conditions are collected in Spanish climate databases (Ministry of Transport of Spain 2022a): dry and sky temperature, direct and diffuse irradiance, specific and relative humidity, wind speed and direction, azimuth and zenith. The occupational and functional conditions are integrated into the software and include sensitive and latent occupation, lighting, domestic equipment power, ventilation and set temperatures (Lastra et al. 2008). With these data, the simulation is carried out with a time step of one hour for a whole year (Ministry for Ecological Transition and the Demographic Challenge of Spain 2021c). The calculation method is dynamic and based on heat transfer functions.

For the calculation of non-renewable primary energy (NRPE) and CO_2 emissions, the step factors shown in Table 7 are used, established by the Ministry of Industry, Energy and Tourism (Ministry of Industry of Spain 2016), depending on the energy used by the heat generator.

2.6 Improvements of the building thermal envelope

From the designed base case, several improvements have been proposed in the building envelope. Renovation of windows, improvement of the external enclosures of the buildings – walls and roofs – and their combinations have led to different building rehabilitation scenarios

Table 7 Step factors for the calculation of non-renewable primary energy

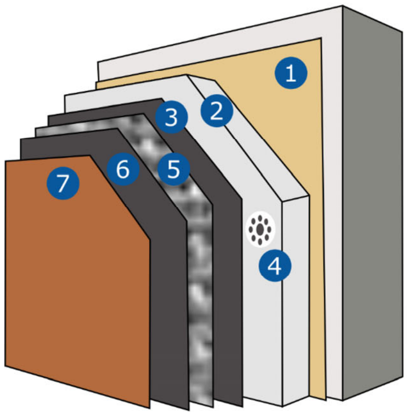
Energy	Primary energy	CO_2 emissions
Natural gas	1.190 kWh/kWht	252 g CO_2/kWht
Mainland electricity	1.954 kWh/kWhe	331 g CO_2/kWhe
Canary Islands electricity	2.924 kWh/kWhe	776 g CO_2/kWhe
Balearic Islands electricity	2.968 kWh/kWhe	932 g CO_2/kWhe

Regarding the building envelope, an External Thermal Insulation Composite System (ETICS) has been added to the exterior walls and/or roof. This is one of the most commonly employed insulation systems to prevent thermal bridges and condensation (Varela Luján et al. 2019). This system is composed of an adhesive mortar, an insulating panel, a profile, an anchor, a regulating mortar, a reinforcing mesh and a finishing mortar. Figure 9 shows the different layers of this system, which reduces the thermal transmittance of the enclosure. The main insulating component is the extruded polystyrene panel, with a typical thickness value of 8 cm or 10 cm. Technical specifications and requirements are specified by Normalization Spanish Association (AENOR) in the UNE standards 13495 (AENOR 2020) 13498 (AENOR 2003a) and 13499 (AENOR 2003b).

Roof insulation consists of the same constructive solution with 5 cm thick insulation. In order to improve the behavior of the openings, monolithic glass has been replaced by double 4-6-4 glasses (U = 3.30 W/(m²·K)) with a Polyvinyl Chloride (PVC) frame with two chambers (U = 2.20 W/(m²·K)) and a solar factor ($g_\perp$) equal to 0.85.

The ETICS (External Thermal Insulation Composite System) used in the walls and roof has a high-resistance barrier for waterproofing. The most exterior layer of the envelope has a surface treatment, and not an added layer, that guarantees tightness and prevents water from entering into the inner layers of the insulation. It also complies with the Spanish Building Technical Code, more specifically, with the basic document DB-HS1, section 2.3.2 (Ministry of Public Works of Spain 2019b), which deals with the constructive requirements of walls and façades, having the maximum degree of resistance against filtrations. Due to its low thickness and conductivity, it will not be considered in the thermal energy calculations.

Considering the base study case (Case B) with the two building typologies, complying with the minimum requirements of the NBE-CT-79 (Ministry of the Presidency of Spain 1979), the following construction improvements have been studied:



Components	Thickness (m)	Conductivity (W/(m·K))
1. Adhesive mortar	0.01	0.40
2.EPS insulating panels	0.08–0.10	0.037
3.Start-up profile	—	—
4.Anchors	—	—
5.Reforcement		
6. Finishing layer	0.0015	0.20
7. Topcoat	0.0015	0.20

Fig. 9 Construction detail and characteristics of the chosen layers

- Case C: Improved cavities, with PVC frame and double glass (4-6-4).
- Case R: Roof improvement using ETICS with 5 cm of EPS insulation.
- Case E8: Improvement of the façade using ETICS with 8 cm of EPS insulation.
- Case E10: Improvement of the façade using ETICS with 10 cm of EPS insulation.

Additionally, in cases E8 and E10 cavities have been improved (cases E8+C and E10+C), and roof has been also improved (cases E8+C+R and E10+C+R). The different scenarios have been combined with the heating and cooling generation systems, with the technical specifications as a function of the construction year, as detailed in Section 2.4. Four general cases were simulated, arising from the combination of single-family and blockhouses with the equipment installed in according with the two different legislation periods. Each of these four cases was simulated in the 13 different climate zones, providing 9 different constructive solutions, resulting in a total of 504 simulations (Table 8).

3 Results and discussions

Tables A4 and A5 (in Appendix A) show the numerical results obtained in the simulation process for single-family and multi-family dwellings. NRPE consumption and CO_2 emissions have been obtained for all CZs in Spain. From the base case, which characterizes the envelope and the thermal systems for each study time interval, the effects on the energy performance and emissions of the 8 types of improvements defined in the methodology are showed. The different modifications studied produce significant improvements regarding the energy rating, CO_2 emissions

Table 8 Simulations performed in this study

Housing typology	Single-family / blockhouse	
Climate zones	13	
Constructive solutions	Case name	Case description
	B	Base study case
	C	Improved cavities
	R	Improved roof
	E8	Improved façade (8 cm insulation)
	E10	Improved façade (10 cm insulation)
	E8+C	Combination of E8 and C
	E10+C	Combination of E10 and C
	E8+C+R	Combination of E8, C and R
	E10+C+R	Combination of E10, C and R
Thermal equipment legislation	RICAS (Ministry of the Presidency of Spain1980)	1980–1998
	RITE (Ministry of the Presidency of Spain 1998)	1999–2007
Thermal envelope legislation	NBE-CT-79 (Ministry of the Presidency of Spain 1979)	1980–2007
Total number of simulations	504	

and NRPE consumptions. The main cause is the lower thermal transmittance of the construction materials and the higher efficiency of the thermal systems employed.

Figures 10 and 11 show the most significant results obtained on the NRPE consumption for single-family house and block housing, respectively. For each CZ the WCS establishes the trend in consumption, rising with increasing SCS. CZ E1 has the highest consumption in the single-family house and CZ D3 in the multi-family house. The improvement of the systems allows saving more energy in single-family housing than in multi-family housing. Figures 10 and 11 also show that the effect of the improvement in the thermal systems efficiency with RITE allows having lower consumption than with RICAS legislation (Ministry of the Presidency of Spain 1980). Although, in general, WCS sets the main trend in NRPE consumption values, which increase with the increase in severity, a waving behavior is observed in the curves. This effect may be ascribed to the shifts to lower SCS values for the same WCS, which result in a decrease in refrigeration demand and thus a slight decrease in the general NRPE values. It may be appreciated in the transitions from A4 to B3, B4 to C1 and C4 to D1. However, from D3 to E1, this effect is not observed, because the WCS of the E1 zone is the one with the highest heating demand in Spain.

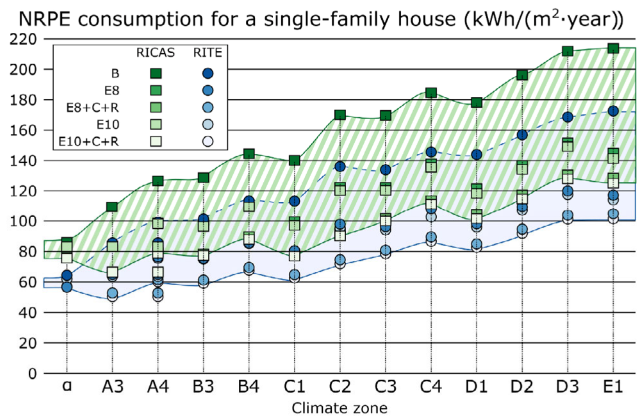


Fig. 10 NRPE consumption for a single-family house depending on the thermal equipment (RICAS/RITE)

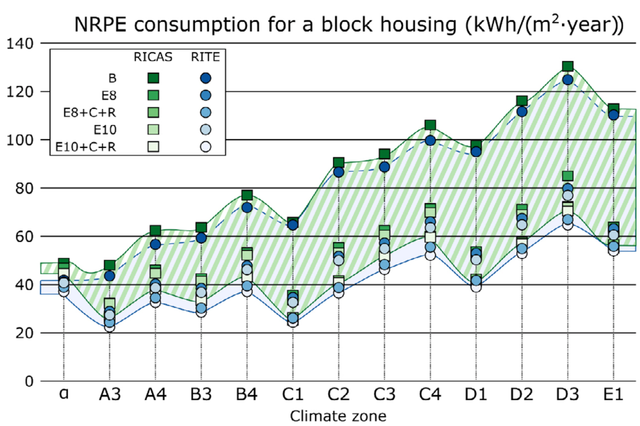


Fig. 11 NRPE consumption for a block housing depending on the thermal equipment (RICAS/RITE)

3.1 Particularities of the α climate zone

The α climate zone, due to tropical weather, is the only zone in which the heating demand is null and is the CZ with the lowest energy consumption in the case B. Considering the single-family home (Figure 12), the consumption of NRPE is even lower than in other climate zones with E10+C renovation. On the other hand, the block building consumes more NRPE in α zone than in the rest of the CZs. Improvements in the thermal envelope or equipment have almost no effect in the energy consumption in this zone. The influence of the gaps in energy consumption is clearly observed, being the most effective renovation, in this case, the replacement of glass with a lower solar factor value ($g^{\perp}$). Low thermal transmittances reduce heating energy demand, whereas low $g^{\perp}$ values are key for the reduction of the cooling demand. Because of these factors, the α zone reaches the highest energy saving values among all zones when upgrading the RICAS to RITE equipment, with a reduction in NRPE consumption of 15% and 25% for the block and single-family typologies, respectively.

Regarding the emissions rating label, the CZ α starts from an "E" rating in the base case for a single-family home with both RICAS and RITE equipment. After renovations, it only improves its energy rating to D in the case of RITE equipment. Regarding the block housing, case B with RICAS has an initial "G" rating that improves to F with the E8+C+R renovation. With RITE equipment, case B has an initial F rating that improves to E. In the NRPE rating, initial labels "F" or "G" are not modified in any of the studied scenarios.

After discussing the results for this particular case, a comparative analysis is performed for the rest of CZs.

3.2 Evolution of NRPE in single-family housing

For the single-family home, the CZs with the lowest and highest NRPE consumption, both for RICAS and RITE

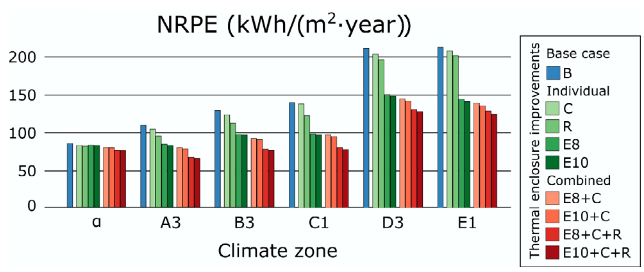


Fig. 12 Comparison of results for single-family housing in α and other CZs with RITE equipment

facilities, are A3 and E1 respectively. Regarding RICAS and RITE equipment for the B case, the consumption of E1 zone is almost twice the consumption of A3. This difference between climate zones becomes lower as deeper renovations are performed in the respective buildings.

Regarding B as the reference case with RICAS equipment, climate zones with higher WCS reach higher energy savings in most of renovations. Hence, E8 renovation allows a saving of 32.18% and 31.85% in E1 and D1 zones respectively, whereas in A4 and B4 only reaches 21.82% and 23.06%. Considering the renovation of roof and cavities, higher savings are achieved in the zones with lower WCS: for zones A and B, energy consumption is reduced in a value ranging from 11.22% and 12.17%; whereas for D and E zones, these values are only between 3.81% and 4.35%. Regarding RITE equipment, the results are similar, with the better performances achieved by the areas with lower WCS and higher SCS (average savings between 22% and 25%).

Figure 13 shows the evolution in E1 zone of the different improvements in the thermal envelope with RICAS and RITE equipment for the single-family home. If improvements are made to the envelope, NRPE reductions over the reference case B up to 41.36% and 41.44% may be achieved with RICAS and RITE equipment, respectively. If the reference case B with RICAS is upgraded with RITE equipment and the rest of renovations are performed, a maximum saving of 50.71%. Regarding emissions, the B energy rating may be obtained either by combining RICAS equipment and the E10+C+R upgrade, or by RITE equipment and E8+C+R upgrades.

3.3 Evolution of CO_2 emissions in single-family housings

CO_2 emissions are represented by a "D" energy label in the reference case B for all climate zones for the RICAS single-family home, except for C2 zone, with an "E" label. When an E8 renovation is performed, D and E zones improve their energy rating up to C, except for the D3 zone, which requires an additional S10 improvement. The same situation occurs in C3 zone with an E8+C and the C1 zone with E10+HC renovations. For the rest of CZs, the improvement happens when an E8+C+R renovation is performed. With RITE equipment, the same improvement towards "C" rating occurs with the E8 renovation for all climate zones. Additionally, D1 and E1 zones obtain a "B" rating with the E8+C+R renovation. Maximum emissions are produced with the reference case B and RICAS equipment, in E1 zone (45.2 kg $CO_2/(m^2 \cdot year)$), while minimum ones are produced in A3 (21.70 kg $CO_2/(m^2 \cdot year)$). These limit values are improved when the low thermal transmittance renovation E10+C+R is performed, reaching 26.50 kg $CO_2/(m^2 \cdot year)$ and 12.90 kg $CO_2/(m^2 \cdot year)$ respectively. With RITE equipment, emissions are reduced by 22.48% and 13.93% over case B.

Figure 14 shows CO_2 emissions of the single-family house in the D2 zone. The maximum reduction of emissions RICAS and RITE equipment is 41.42% and 41.77% respectively. The change from RICAS to RITE equipment alongside the building envelope renovation reduces emissions by 53.19%.

3.4 Evolution of NRPE in block housing

For block housing, CZs D3 and A3 are the zones with highest and lowest NRPE consumption values, respectively. For the reference case B and considering RICAS equipment, consumption of D3 is around 2.70 times the consumption of A3. With the S10+H renovation, D3 consumption becomes only 2.55 times the consumption of A3. Regarding RITE equipment, differences vary between 2.72 and 2.95 times depending on the different renovations. Minimum deviation happens with S10+H renovation and maximum with C renovation.

Average consumption savings with RICAS equipment is maximum in zone D, followed by zones C and E, considering the reference case B. C1 zone reaches 61% and D1 zone 58% with the solution E10+C+R. With RITE equipment, average saving is greater than in the previous case and optimal energy performance happens in CZs C, D and E. The upgrade of thermal equipment from RICAS to RITE has a smaller influence on the blockhouse NRPE consumption, being more significant in areas with higher SCS (1.4%–14%).

Figure 15 shows a small influence of the thermal equipment upgrade for the C1 zone, as NRPE consumptions

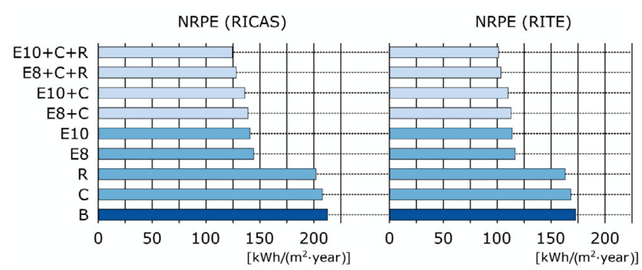


Fig. 13 NRPE single family home CZ E1

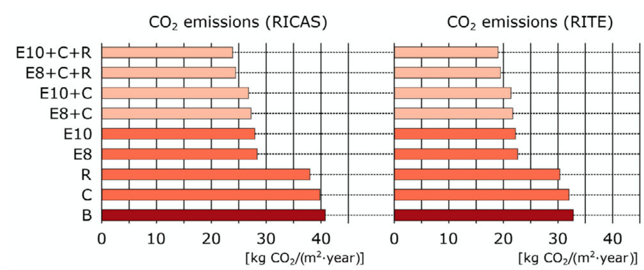


Fig. 14 CO_2 emissions single family house CZ D2

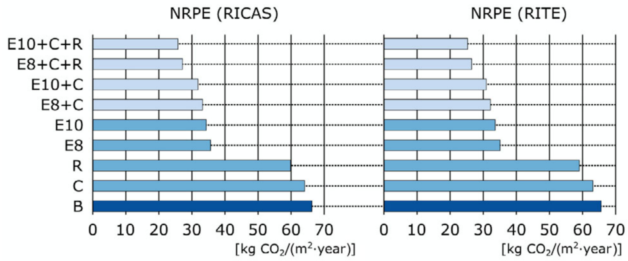


Fig. 15 NRPE block housing CZ C1

are very similar. On the other hand, improvements of enclosures become relevant, with an E8 improvement reaching an energy saving of 46% with RICAS equipment and an E10+C+R improvement with RITE equipment, a 61.88%.

3.5 Evolution of CO_2 emissions in block housing

With RICAS equipment in the reference case B, a "D" energy rating is reached by all climate zones except A4, B4 and C2, where an E is obtained. Any renovation performed in A4 and B4 improves this rating up to "C"; while C2 improves to "D" with gap renovation and to "C" with the E10+C solution. Concerning the rest of CZs, A3 and B3 keep their rating regardless of the renovation; C1, D1 and E1 reach a "C" rating with a S8 renovation, D2 with a S10 one, D3 with the E8+C, C3 with an E8+C+R and C4 with E10+C+R. With RITE equipment all CZs have an initial "D" rating. Climate zones A zone does not improve with renovations, and the following zones improve with the following renovations: B zones through E8+C+R; C1, D1, D2 and E1, with S8; D3, with S10; C2 and C3, with E8+C and C4 with E10+C.

CO_2 emissions in the block with RICAS equipment for the reference case B vary depending on the zone: 14.3–16.8 kg CO_2/(m^2·year) for zone A; 17.7–19.9 CO_2/(m^2·year) for zone B; 19.6–26.1 CO_2/(m^2·year) for zone C, 26.4–32 CO_2/(m^2·year) for zone D; and 29.8 CO_2/(m^2·year) in zone E. The maximum reduction in emissions is 33.33% in A-type zones, 38.98% in B-type zones , 46.06% in C-type zones, 46.21% in D-type zones and 41.28% in E-type zones.

Particularly, for B4 zone, Figure 16 shows a similarity between E8 and E10 upgrades regarding emissions (a difference less than 1% for both solutions). It is in this zone that the building of new gaps becomes important, reducing emissions by 9.05% when combined with RITE equipment, the highest percentage from all CZs.

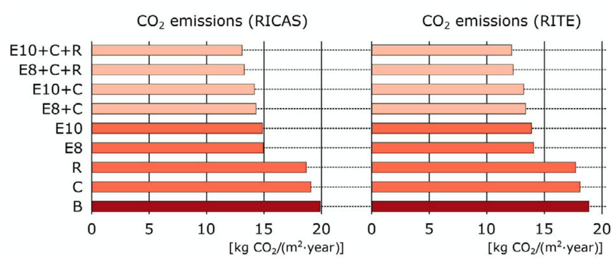


Fig. 16 CO_2 emissions for multiblock housing CZ B4

3.6 Comparison between RICAS and RITE

After analysing the climate zones for the reference case B in the single-family house, the maximum and minimum RICAS and RITE consumption ratio values are 2.26 in A3 zone and 1.62 in D3 zone. For a block housing, values are 1.93 and 1.35 in the same CZs. Generally, greater differences are appreciated with smaller SCS.

In the single-family home, replacement of RICAS by RITE thermal systems reduces NRPE consumption from 19% to 24%, depending on the renovation applied. In block housing, on the other hand, these savings are only from 1.36% to 14%. Figure 17 shows the different energy saving values in both house typologies when replacing RICAS with RITE equipment.

For both housing types, regardless of the installed thermal equipment, similar improvements in emissions are obtained for the E8, E8+C, E10, E10+C renovations, especially in the CZs with lower WCS. Proportionally, CO_2 emissions in the blockhouse are higher than in the single-family house, for a given NRPE consumption. For a 130.60 kWh/(m^2·year) consumption, block housing in D3 zone with RICAS equipment, emits around 32 kg CO_2/(m^2·year), whilst a single-family home produces around 26.50 kg CO_2/(m^2·year).

In general, CZs with the best improvement in energy ratings are those with high WSC and low SCS. C1, D1 and E1 zones, starting from a "D" label, reach a "C" with simpler construction solutions than the rest.

Following this analysis, it may be observed that for a particular building improvement, the energy label of the building improves or not as a function of the climate zone and the relative position of the building label to the label limits. For instance, for the single-family house with RITE equipment (Table A4) with an E8+C+R improvement, only E1 and D1 climate zones improve to a "B" energy label, whereas the rest of climate zones do not change their initial rating.

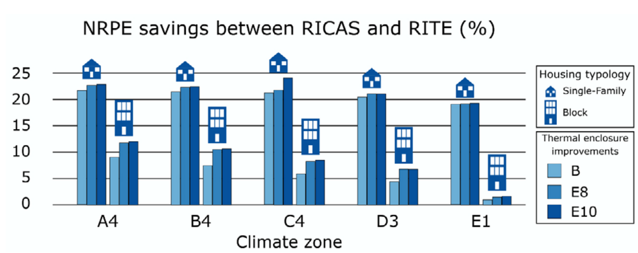


Fig. 17 Energy savings RICAS-RITE

4 Conclusions

In this work, the characterization of housing stock for energy retrofitting purposes in Spain has been performed. The requirements of the regulations in force when the existing stock was constructed (1980–2007) were considered to model the envelope and thermal systems of both single-family and block housing typologies. CERMA software (ATECYR 2021) has allowed to obtain the NRPE consumption and CO_2 emissions for each type of dwelling and location, obtaining a global picture of the energy performance and emissions for 13 different climate zones. These simulations have served as the basis for proposing and evaluating different improvements in the thermal envelope, estimating the overall energy saving that might be achieved for every situation and climate zone.

The main conclusions extracted from this study are the following ones:

- Consumption values for single-family and block housing range from 44.2 to 213.5 kWh/(m²·year) (13.6–45.2 kg CO_2/(m²·year)), depending on the construction year. The retrofitting of existing building walls with 10 cm and roofs with 5 cm of insulation respectively and the substitution of single-glazing by double-glazing resulted in a reduction in consumption values from 37.7% to 58% and savings up to 88.3 kWh/(m²·year) (18.7 kg CO_2/(m²·year)) depending on the climate zone and housing typology. In order to achieve significant reductions in energy consumptions, both the envelope and thermal systems must be considered.
- The influence of the climate zone was found to be crucial. The same modifications in the envelope and thermal equipment of a building resulted in significant changes in estimated energy savings depending on the location. This result support two conclusions: firstly, retrofitting procedures must be studied considering the specific conditions of each climate zone; secondly, the wide range of climate conditions in Spain justify its selection as a reference for this and future studies. Specifically, in areas with high SCS (particularly, zone α), glasses with low solar factor values and high-performance refrigeration equipment seem the best solution for energy improvement. Mild climate zones, such as C1, achieve the highest energy saving values for any possible renovation scenario, housing typology or equipment when compared to other climate zones.
- Regarding housing typology, block housing uses less NRPE per square meter than the single-family home. In general, retrofitting achieves higher energy improvements in block housing for any thermal equipment, up to a point in which a single-family home with the most efficient retrofitting requires more NRPE than the reference case of the block housing. However, single-family homes respond more effectively to the improvement of thermal generation systems than block housings; hence, the percentage of single-family and block housing in a particular region must be assessed when considering retrofitting. The relatively high energy consumption in single-family houses in comparison with block buildings raises the question of whether a different scale for measuring energy performance would be appropriate.
- Existing housing stock presents difficulties to reach the highest EPC label. Hence, for energy retrofitting purposes, the label that reflects CO_2 emissions, represented by a letter, does not quantify the energy consumption or the improvement caused by renovations, the current complementary indicator, kWh/(m²·year), should become more relevant. Consequently, the authors of this work consider that criteria for subsidies should be based in the actual NRPE savings and not in the improvement of the EPC label, as intervals between different energy labels are too wide, especially in zones with high WCS.
- Block housing typology is the most common in Spanish buildings. In these buildings, heating and cooling systems are individual for each home, so retrofitting of the building envelope is easier than renovation of thermal systems. Improvements on the envelope allow to achieve considerable energy savings; nevertheless, modifications on thermal systems will help to increase energy efficiency in residential buildings even more.

Finally, the building models designed in this work may serve as reference models of real estate stock for subsequent research regarding energy efficiency policies, implementation of renewable energies in housing stock, technical-economic feasibility studies, as well as life-cycle analyses about the materials concerned and their environmental impact. The results of this work may be extrapolated to countries that share any of their climate zones with one of the 13 Spanish ones, contributing to higher energy savings and the decarbonization of the building stock.

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