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Adaptation of rural residential buildings in a Mediterranean climate to climate change: A case study of La Rioja (Spain)

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ABSTRACT

Climate change is one of the greatest challenges facing the building sector and rural areas in particular should be prioritised due to their special characteristics. In this work, ways to adapt rural residential buildings in a Mediterranean climate to climate change via energy renovation were studied, taking La Rioja (Spain) as a case study. Different energy renovation solutions were evaluated under different climate change scenarios considering the possible evolution of the climate zones. The energy and economic impacts of these energy-renovated buildings were compared to those of existing buildings. Nearly zero-energy buildings were achieved by changing the thermal envelopes and their corresponding interior partitions. The study discovered that, on the one hand, the heating energy demand was reduced while the cooling energy demand was increased, thus reducing the total energy demand; on the other hand, the best energy renovation solution entails compliance by nearly zero-energy buildings with current building thermal regulation for the current climate zone. This work can serve as a guide to establish and promote energy renovation policies that are effective in addressing climate change and are economically viable. Furthermore, the methodology developed and the results obtained can be extrapolated to other cold Mediterranean climate zones.

1. Introduction

Climate change can be defined as *"a change in the Earth's climate that is directly or indirectly attributed to human activity and that alters the composition of the global atmosphere"* [1]. One of the most important international agreements to address climate change is the Kyoto Protocol [2], which is the subject of many analyses and scientific evaluations [3–5]. However, the Kyoto Protocol is limited in its ability to halt climate change; thus, additional efforts are needed to address this problem [1].

Regarding climate zoning, Beck et al. [6] drew world maps of the Köppen-Geiger climate classification for both the present (1980–2016) and the future (2071–2100), which account for a more pessimistic climate change scenario. In the field of construction,

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the impacts of different climate change scenarios on climate zoning have been studied in various investigations in countries such as the United States [7], Chile [8], Spain [9] and China [10].

In future climate change scenarios for Europe and especially for southern Europe, the increase in the cooling energy demand is greater than the decrease in the heating energy demand, considerably increasing the total energy demand [11–13]. Ciancio et al. [11], after estimating the impact of climate change on multi-family buildings across Europe, emphasised the need to increase energy efficiency in buildings due to the increase in total energy consumption and noted that southern Europe will be more exposed and vulnerable to global warming. Tootkaboni et al. [12] studied the residential building stock in Milan (Italy) and discovered that buildings subject to major energy renovation are less sensitive to climate change, thus indicating the urgency of establishing measures to adapt buildings to climate change. Baglivo et al. [13] analysed the thermal behaviour of a multi-family nearly zero-energy building (NZEB) in Lecce (Italy) and pointed out that building thermal regulations need to be adapted to future climate change scenarios.

Numerous investigations have focused on the adaptation of the residential building stock to different climate change scenarios. Rodrigues and Fernandes [14] determined the ideal values of thermal transmittance (U-values) in the Mediterranean region for 2050, which are similar or even lower than the current U-values, and found that the cooling energy consumption increases both for low and high U-values; the increase in cooling energy consumption will typically be greater than the reduction in heating energy consumption in any choice of U-values; the ideal U-values will not increase the risk of overheating; the impact of climate change tends to increase total energy consumption more in the warmer climates of the Mediterranean; and buildings are less robust to global warming in hotter climates if they have higher U-values. Pajek et al. [15] discovered that, for a multi-family building in Podgorica (Montenegro), in addition to reducing the U-values, the most effective energy renovation actions are providing shading for the activation set-point and implementing intensive natural ventilation cooling. D'Agostino et al. [16] found that the current NZEBs could become positive energy buildings in the Mediterranean climate zone by 2060 with solar photovoltaic systems. Salata et al. [17] evaluated ways to prioritise the energy renovation of residential buildings in Italy and determined that energy renovations should first be carried out in those regions with greater future cooling energy demands and higher population densities.

There is a lack of research regarding energy renovations for traditional residential buildings in rural Mediterranean areas. However, some valuable research has been conducted in Spain [18], Italy [19], Serbia [20], Turkey [21] and Iran [22]. In the Iberian Peninsula, Gouveia et al. [23] suggested that energy renovations for buildings in rural areas of the inland regions of Portugal should be prioritised to avoid energy poverty. López-Ochoa et al. [18] evaluated the energy, environmental and economic impacts of different energy renovation solutions on residential NZEBs in rural or demographic challenge areas [24] in the Autonomous Community of La Rioja (Spain), giving special attention to rural revitalisation areas [25].

The Energy Performance of Buildings Directive (EPBD) 2018 [26] aims to achieve a highly energy efficient and decarbonised building stock in the European Union through energy renovation actions with which to transform existing buildings into NZEBs. The EPBD 2010 [27] defines an NZEB as a building that has a very high energy performance, for which the nearly zero or very low amount of energy required should come predominantly from renewable sources, including energy from renewable sources produced on-site or nearby. Both the EPBD 2010 [27] and the EPBD 2018 [26] have been transposed into the different national regulations of the Member States. The regulations account for the unique characteristics of each Member State when defining the NZEBs. The implementation of the EPBD [26,27] and the design of NZEBs in southern European countries was addressed in Refs. [28,29]. The different EPBDs [26,27] were transposed in Spain through the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) [30–32]. The evolution of the implementation of the EPBD [26,27] in Spain was widely studied in Refs. [33,34].

Currently the European Union has revised the EPBD 2018 [26] through the new EPBD 2024 [35], taking a step forward from the current NZEBs towards zero-emission buildings and aligning the energy performance requirement for new buildings to the longer-term climate neutrality goal and "energy efficiency first principle" [36]. The new EPBD 2024 [35] aims for all new buildings to be zero-emission buildings by 2030 and for the existing building stock to become a zero-emission building stock by 2050. Moreover, the new EPBD 2024 [35] defines a zero-emission building as a building with a very high energy performance, with the very low amount of energy still required fully covered by energy from renewable sources; furthermore, there are no on-site carbon emissions from fossil fuels. How to achieve zero-emission buildings was studied in Ref. [37]. Finally, the new EPBD 2024 [35] both contributes to the reduction of greenhouse gases and can help reduce energy poverty while reinforcing national strategies for the energy renovation of buildings in the long term.

The main objective of this research is to study how Mediterranean rural residential buildings can be adapted to climate change via energy renovation, taking La Rioja as a case study. The energy renovation actions considered are carried out on the thermal envelopes and their corresponding interior partitions to achieve NZEBs. To determine the best energy renovation solutions, the energy and economic impacts of typical existing buildings and their energy renovation in different climate change scenarios are evaluated, considering the possible evolution of their different climate zones. The main novelty of this research is its focus on considering the energy and economic impacts to determine the best energy renovation solutions through which residential buildings, both in demographic challenge municipalities [24] and in rural revitalisation areas [25], can achieve NZEBs in different climate change scenarios.

2. Methodology

The methodology followed in this research is as follows.

a) Determination of the different climate change scenarios and evolution of the climate zones in these scenarios.
b) Definition of the different present and future study buildings.
c) Evaluation of the energy and economic impacts of each case study (each study building in its corresponding possible climate change scenarios).

d) Determination of the best energy renovation solutions to adapt the rural residential buildings in La Rioja to climate change.

2.1. Climate zones

Different Spanish building thermal regulations establish the requirements that new residential buildings built must meet according to the climate zone where they are located [38]. In Spain, between 1981 and 2007, five January climate zones (V, W, X, Y and Z) existed based on the average minimum temperature for January [39]. For mainland Spain, the average minimum temperatures for January are 5 °C in January climate zone W, 3 °C in January climate zone X, 0 °C in January climate zone Y and −2 °C in January climate zone Z [39]. Between 2008 and 2012, five winter climate zones (A, B, C, D and E) along with four summer climate zones (1, 2, 3 and 4) were combined to create a total of 12 climate zones (A3, A4, B3, B4, C1, C2, C3, C4, D1, D2, D3 and E1) [30]. From 2013 to the present, six winter climate zones (α, A, B, C, D and E) and four summer climate zones (1, 2, 3 and 4) have been combined to create 15 climate zones (α3, A2, A3, A4, B2, B3, B4, C1, C2, C3, C4, D1, D2, D3 and E1) [31,32]. At present, winter climate zones are classified according to winter climate severity, with α corresponding to the lowest winter climate severity and a nearly zero energy heating energy demand, and E corresponding to the greatest winter climate severity and the highest heating energy demand [40]. The summer climate zones are classified according to summer climate severity, with 1 corresponding to the lowest summer climate severity and a nearly zero cooling energy demand and 4 corresponding to the greatest summer climate severity and the highest cooling energy demand [40]. The winter climate severity is obtained from the winter degree-days with a base temperature of 20 °C and the quotient of the number of sunlight hours and the maximum number of sunlight hours, using the corresponding values for the months of October to May; and the summer climate severity is obtained from the summer degree-days with a base temperature of 20 °C, using the corresponding values for the months of June to September [40]. In Table 1 the climate zones of mainland Spain are presented according to Ref. [32] based on their climate severities [40]. Furthermore, for mainland Spain, the heating degree-days with a base temperature of 18 °C are 870 °C·day/year for winter climate zone A, 1130 °C·day/year for winter climate zone B, 1650 °C·day/year for winter climate zone C, 2225 °C·day/year for winter climate zone D and 2750 °C·day/year for winter climate zone E; while the cooling degree-days with a base temperature of 25 °C are 30 °C·day/year for summer climate zone 1, 75 °C·day/year for summer climate zone 2, 175 °C·day/year for summer climate zone 3 and 250 °C·day/year for summer climate zone 4 [41].

All the rural municipalities of La Rioja were in January climate zones X and Y between 1981 and 2007 [18]; in climate zones D1, D2 and E1 between 2008 and 2012 [42]; and in climate zones D2 and E1 from 2013 to the present [18]. Fig. 1 presents the climate zones of all the municipalities of La Rioja: Their January climate zone according to Ref. [39] and their current climate zone according to Ref. [32]. While Cervera del Río Alhama is the representative rural municipality of January climate zone X and current climate zone D2, Torrecilla en Cameros is the representative rural municipality of January climate zone Y and current climate zone E1 [18]. Approximately 45 % of mainland Spain is found in January climate zones X and Y [39]. Fig. 2 presents the provinces of mainland Spain whose capitals are in these January climate zones according to Ref. [39] and their corresponding current climate zones according to Ref. [32]. Furthermore, most of the municipalities of each province are in the same January climate zone as their corresponding capital [39].

Table 1
Climate zones of mainland Spain according to Ref. [32] based on their climate severities [40].

	$0 < WCS \leq 0.23$	$0.23 < WCS \leq 0.50$	$0.50 < WCS \leq 0.93$	$0.93 < WCS \leq 1.51$	$WCS > 1.51$
$SCS \leq 0.50$	–	–	C1	D1	E1
$0.50 < SCS \leq 0.83$	A2	B2	C2	D2	–
$0.83 < SCS \leq 1.38$	A3	B3	C3	D3	–
$SCS > 1.38$	A4	B4	C4	–	–

Note: SCS is summer climate severity and WCS is winter climate severity.

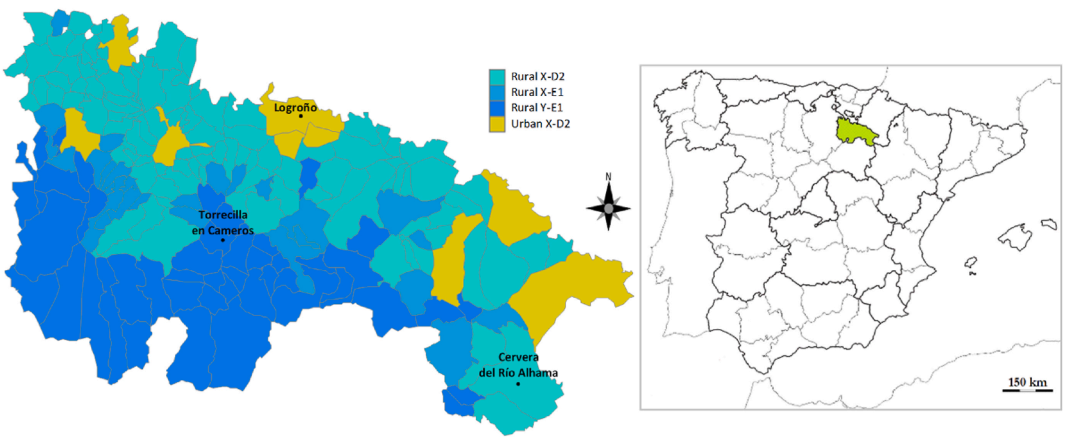

Fig. 1. Climate zones of the municipalities of La Rioja.

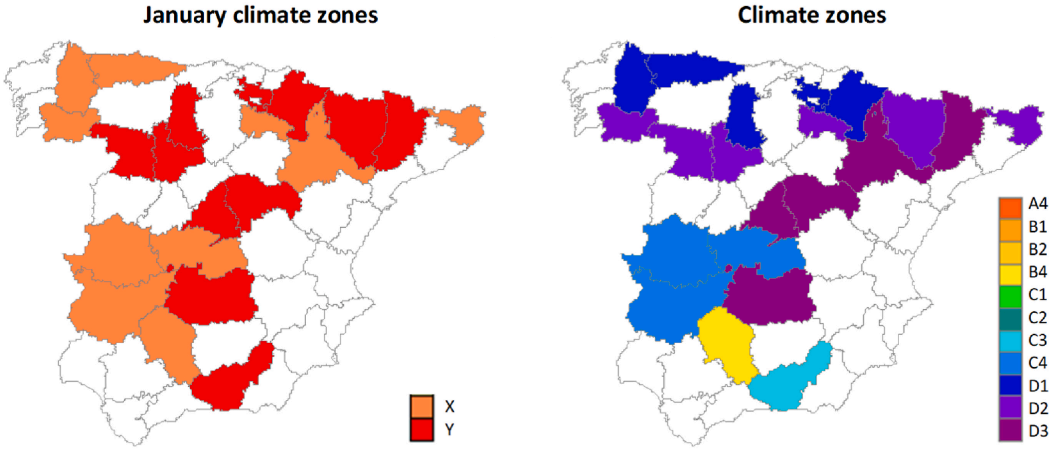

Fig. 2. January climate zones according to Ref. [39] and climate zones according to Ref. [32] of the provincial capitals, which are found in January climate zones X and Y according to Ref. [39].

The future Spanish climate zones associated with the different mainland provincial capitals in 2055 and 2085 for different climate change scenarios were determined by Verichev et al. [9]. The representative concentration pathways (RCPs) for each climate change scenario were created by the Intergovernmental Panel on Climate Change and are used to model greenhouse gas emissions and their effects on the climate throughout the 21st century [1]. These RCP scenarios are characterised by their total radiative forcing (RF) for 2100, which oscillates between 2.6 and 8.5 W/m^2. The RCPs used in this research are defined below.

- RCP 2.6 is the most optimistic scenario, in which emissions decrease rapidly and carbon neutrality is reached before 2100 ($RF = 2.6\ W/m^2$).
- RCP 4.5 is an intermediate scenario in which mitigation policies are established and carbon neutrality is achieved in the second half of the century ($RF = 4.5\ W/m^2$).
- RCP 8.5 is the most pessimistic scenario, in which emissions continue to increase and significant and dangerous climate changes occur for humanity ($RF = 8.5\ W/m^2$).

In Fig. 3 the future climate zones are presented according to Ref. [32] of the different provincial capitals of mainland Spain which are in January climate zones X and Y according to Ref. [39], in 2055 and 2085 for the RCP 4.5 and RCP 8.5 scenarios, determined in Ref. [9]. In this research, the future climate zones of the rural municipalities located in climate zone D2 resemble those corresponding to Logroño city (capital of La Rioja) in Ref. [9], while the future climate zones of the rural municipalities located in climate zone E1 resemble those corresponding to Burgos city and Soria city in Ref. [9]. On this basis, according to the maps developed in Ref. [9], the rural municipalities located in climate zone D2 correspond, for the RCP 4.5 scenario, to climate zone C3 in 2055 and 2085 and, for the RCP 8.5 scenario, to climate zone C3 in 2055 and climate zone B4 in 2085. For the RCP 4.5 scenario, rural municipalities located in climate zone E1 belong to climate zone D2 in 2055 and 2085 and, for the RCP 8.5 scenario, climate zone D2 in 2055 and climate zone C3 in 2085. However, in the RCP 2.6 scenario, the rural municipalities do not change their climate zone. In addition, in this research, since the years corresponding to different climate zone changes in the RCP 4.5 and RCP 8.5 scenarios were not determined in Ref. [9], as many scenarios as necessary are created for all possible climate zone changes. The period of 2021–2091 was divided into 10-year intervals to allow for all possible evolutions of the climate zones to be studied. Therefore, 13 scenarios are developed for all the rural municipalities of La Rioja for each current climate zone: The RCP 2.6 scenario, the RCP 4.5 (a-c) scenarios correspond to the three possible RCP 4.5 scenarios, and the RCP 8.5 scenarios (a-i) correspond to the nine possible RCP 8.5 scenarios. The different scenarios studied are presented in Fig. 4.

2.2. Study buildings

The buildings selected for the study must be representative of existing and future rural residential buildings in La Rioja. Existing residential buildings were studied in Ref. [18]. Energy renovations must permit the existing residential buildings to adapt to possible climate change scenarios and thus involve climate zone designation changes. These climate zone changes, according to the current building thermal regulation, CTE-DB-HE [32], differ in their requirements for NZEBs since they are defined in accordance with the winter climate zone where they are located. Therefore, it is necessary to determine the characteristics of the thermal envelopes and the corresponding interior partitions of future residential buildings based on future climate zones in different climate change scenarios.

The 3D model of the building used in this research is a traditional attached single-family house characteristic of the rural areas selected for energy renovation in La Rioja [18] (Fig. 5). It consists of one non-habitable ground floor and two habitable upper floors; the base is rectangular and is 85.80 m^2; the height of each floor is 3.00 m; the structure has 3 bedrooms; the habitable surface is 171.60 m^2; the roof is gabled and has a height of 2.15 m; the building compactness is 2.72 m^3/m^2; and the window-to-wall ratio is

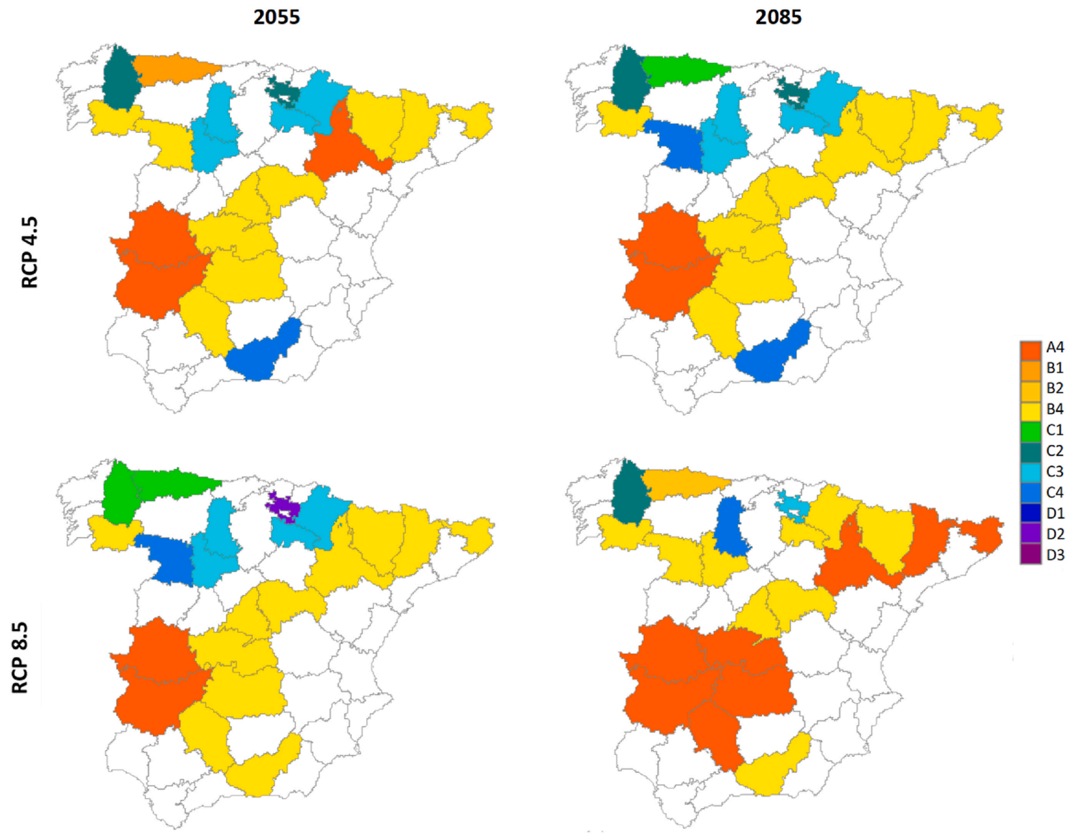

Fig. 3. Future climate zones according to Ref. [32] of the provincial capitals which are in January climate zones X and Y according to Ref. [39], in 2055 and 2085 for the RCP 4.5 and RCP 8.5 scenarios, determined in Ref. [9].

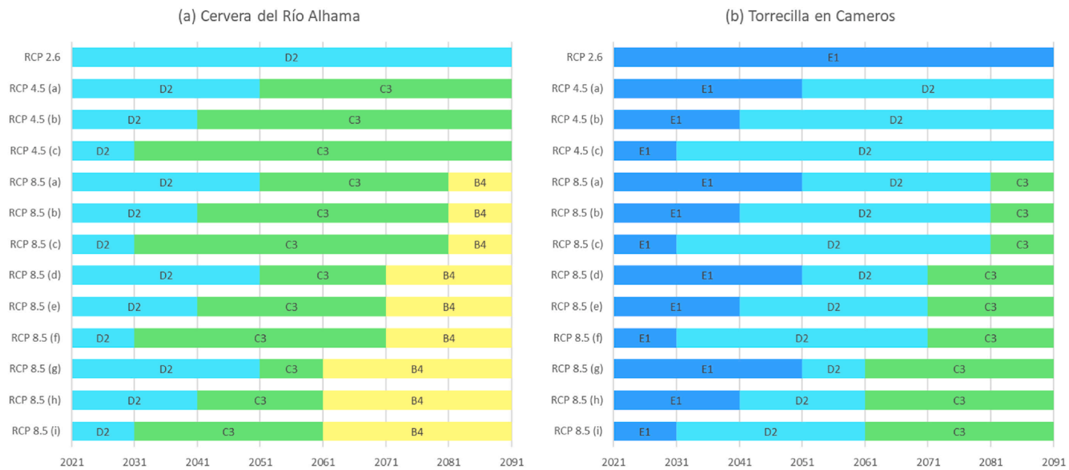

Fig. 4. Climate change scenarios with the evolution of the climate zones.

0.1816. This 3D model (Fig. 5) was used to design eight study buildings to evaluate both present and future rural residential buildings in La Rioja, whose main characteristics considered are detailed in Table 2.

The compositions of both the opaque elements of the thermal envelope and the interior partitions of the existing buildings detailed in Ref. [18] served as the basis for the design of these eight study buildings (Table 3). The thermal insulation material used is expanded polystyrene and has a thermal conductivity of 0.034 W/m·K. In addition, the thicknesses of thermal insulation of all the opaque elements of the thermal envelope and of all the interior partitions were adjusted for the different study buildings. Tables 4 and 5 present the U-values of the elements of both the thermal envelope and the interior partitions of all the study buildings and the thickness of thermal insulation used in each of these elements. The air permeability of the thermal envelope openings with an overpressure of 100 Pa is 27 $m^3/h{\cdot}m^2$ for PreCTE-X, PreCTE-Y and NZEB-XB; and 9 $m^3/h{\cdot}m^2$ for NZEB-XC, NZEB-YC, NZEB-XD, NZEB-YD and

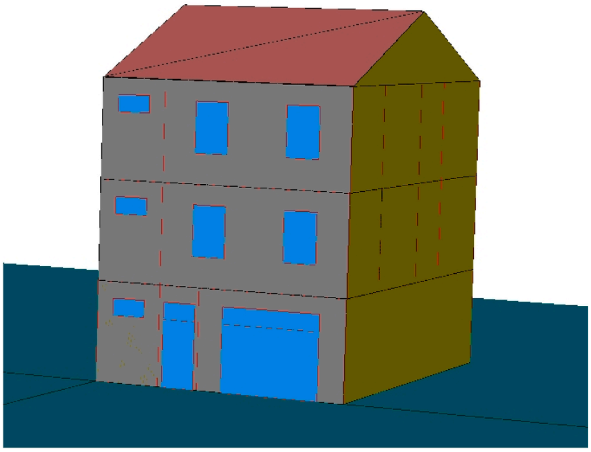

Fig. 5. 3D model of the building.

Table 2
Main characteristics of the buildings in the study.

Municipality	Building model	Building type	Building quality
Cervera del Río Alhama	PreCTE-X	Existing	Typical building in January climate zone X
	NZEB-XB	Energy-renovated	NZEB in winter climate zone B
	NZEB-XC	Energy-renovated	NZEB in winter climate zone C
	NZEB-XD	Energy-renovated	NZEB in winter climate zone D
Torrecilla en Cameros	PreCTE-Y	Existing	Typical building in January climate zone Y
	NZEB-YC	Energy-renovated	NZEB in winter climate zone C
	NZEB-YD	Energy-renovated	NZEB in winter climate zone D
	NZEB-YE	Energy-renovated	NZEB in winter climate zone E

NZEB-YE. Finally, the thermal bridges were those considered by default by CTE-DB-HE [43,44] for PreCTE-X and PreCTE-Y and were evaluated considering that the continuity of the thermal insulation is ensured in and between the different elements of the thermal envelope [43,44] for NZEB-XB, NZEB-XC, NZEB-YC, NZEB-XD, NZEB-YD and NZEB-YE.

On the one hand, for the design of PreCTE-X and PreCTE-Y, the elements of the thermal envelope did not exceed the values set by CE3X [45] for buildings constructed according to Ref. [39], before the entry into effect of the CTE-DB-HE [30]; furthermore, the heating and cooling energy demands in climate zones D2 and E1 are the average energy demands corresponding to rural single-family buildings located in those climate zones. CE3X [45] is an official Spanish software program for the energy performance certification of residential buildings; it contains a database with the default values for the different periods and building thermal regulations and is also the most widely used program [46]. The average heating and cooling energy demands were obtained from a database analysis of energy performance certificates issued by the Department of Sustainability and Ecological Transition of the Government of La Rioja [47], considering the characteristics of its thermal installations listed in Ref. [18].

On the other hand, for the design of the energy-renovated buildings NZEB-XB, NZEB-XC, NZEB-YC, NZEB-XD, NZEB-YD and NZEB-YE, the design criteria used in Ref. [34] to achieve NZEBs that meet the requirements of the current CTE-DB-HE [32] were followed.

2.3. Case studies

In this research, 104 case studies were evaluated: for rural municipalities in La Rioja located in climate zone D2, 4 study buildings were evaluated in 13 climate change scenarios, resulting in 52 case studies; and, for rural municipalities in La Rioja located in climate zone E1, 4 study buildings were evaluated in 13 climate change scenarios, resulting in 52 case studies.

To evaluate the energy impact associated with the different case studies, HULC [44] was selected to evaluate both the heating energy demand and the cooling energy demand. HULC [44] is the official energy simulation software program used in Spain to verify compliance with the previous CTE-DB-HE [31] and obtain building energy performance certifications. HULC [44] considers operational conditions and use profiles required by the CTE-DB-HE [31]. In the present investigation, 1.50 air exchanges per hour [45] were considered for PreCTE-X and PreCTE-Y, and 0.63 air exchanges per hour [44] for NZEB-XB, NZEB-XC, NZEB-YC, NZEB-XD, NZEB-YD and NZEB-YE, similar to other investigations of energy renovations for residential buildings such as Refs. [18,48]. In addition, in the energy simulation carried out with HULC [44], the study buildings were located at the same height above sea level as the representative rural municipalities (549 m for Cervera del Río Alhama and 740 m for Torrecilla en Cameros) in the representative provinces of the different possible climate zones under climate change: Sevilla Province for climate zone B4, Granada Province for climate zone C3, Zamora Province for climate zone D2 and Burgos Province for climate zone E1. These provinces were selected because their provincial capitals are references for the climate zone-specific energy performance indicators used for building energy perfor-

Table 3
Compositions of both the opaque elements of the thermal envelope and the interior partitions of the study buildings based on Ref. [18]. An asterisk * indicates that the thickness of thermal insulation is variable in each study building.

Element	Layer	Material	Thickness (m)	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (J/kg·K)
Roof	1	Ceramic–porcelain roof tile	0.020	1.300	2300	840
	2	Polyvinyl chloride (PVC)	0.002	0.170	1390	900
	3	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.050	1.300	1900	1000
	4	One-way ceramic-reinforced slab	0.250	0.908	1220	1000
	5	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	6	High-hardness plaster 1200 < d < 1500	0.020	0.560	1350	1000
Walls	1	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.025	1.300	1900	1000
	2	Solid metric or Catalan brick of ½ foot 40 mm < G < 50 mm	0.115	0.991	2170	1000
	3	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.025	1.300	1900	1000
	4	Single LH partition 40 mm < E < 60 mm	0.060	0.445	1000	1000
	5	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	6	High-hardness plaster 1200 < d < 1500	0.020	0.560	1350	1000
Ground floor	1	Wafer or ceramic tile	0.015	1.000	2000	800
	2	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.035	1.300	1900	1000
	3	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	4	Mass concrete 2000 < d < 2200	0.200	1.650	2150	1000
	5	Sand and gravel 1700 < d < 2200	0.350	2.000	1450	1050
First-floor framework	1	Wafer or ceramic tile	0.015	1.000	2000	800
	2	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.030	1.300	1900	1000
	3	One-way ceramic-reinforced slab	0.250	0.908	1220	1000
	4	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	5	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000
Roof-floor framework	1	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.050	1.300	1900	1000
	2	One-way ceramic-reinforced slab	0.250	0.908	1220	1000
	3	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	4	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000
Mezzanine framework	1	Wafer or ceramic tile	0.015	1.000	2000	800
	2	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.030	1.300	1900	1000
	3	One-way ceramic-reinforced slab	0.250	0.908	1220	1000
	4	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	5	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000
Dividing walls	1	Triple LH solid block 100 mm < E < 110 mm	0.100	0.427	920	1000
	2	Cement or lime mortar for masonry and for rendering/plastering 1800 < d < 2000	0.020	1.300	1900	1000
	3	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	4	Plasterboard (PYL) 750 < d < 900	0.020	0.250	825	1000
Vertical interior partitions	1	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000
	2	Single LH partition 40 mm < E < 60 mm	0.060	0.445	1000	1000
	3	EPS expanded polystyrene (0.034 W/m·K)	*	0.034	30	1000
	4	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000

mance certificates [49,50]. Thus, via this methodology, the results of the different climate change scenarios can be obtained without modifying the climatic reference data of the different climate zones [40].

To evaluate the economic impact of the different case studies, net present value analysis was used. Initially, the cumulative economic expenditure over the lifetime (2024–2091) of each case study was evaluated. Later, the cumulative economic savings over the lifetime of each case was evaluated relative to nonenergy-renovated buildings (PreCTE-X and PreCTE-Y) in the same climate change scenario. The economic parameters considered were as follows: an investment does not occur; annual interest rates are 2.50 %, 5.00 % and 7.50 %; the electricity price is 0.2918 €/kWh [51]; and the annual increase in the price of electricity is 5.00 %. In addition, to evaluate the economic impact, it was necessary to determine the energy consumption of the study cases. To evaluate the heating energy consumption, an electric heat pump with a seasonal coefficient of performance of 3.50 was used; and to evaluate the cooling energy consumption, an electric heat pump with a seasonal energy efficiency ratio of 3.50 was used.

Finally, after evaluating both the energy and the economic impacts, the best energy renovation solutions to adapt the rural residential buildings in La Rioja to the climate change scenarios, RCP 2.6, RCP 4.5 and RCP 8.5, were identified.

Table 4
U-values, in W/m^2·K, of all elements of the thermal envelope and the interior partitions, and the thickness (t) or thickness increase (Δt) of thermal insulation used, both in m, for the study buildings in Cervera del Río Alhama.

	PreCTE-X		NZEB-XB		NZEB-XC		NZEB-XD	
	U	t	U	Δt	U	Δt	U	Δt
Roof	1.19	0.010	0.33	0.075	0.23	0.120	0.22	0.125
First-floor framework	1.24	0.010	1.05	0.005	0.91	0.010	0.80	0.015
Mezzanine framework	1.96	0.000	1.52	0.005	1.24	0.010	1.05	0.015
Roof-floor framework	1.24	0.010	1.05	0.005	0.91	0.010	0.80	0.015
Dividing walls	1.55	0.005	0.65	0.030	0.47	0.050	0.47	0.050
Walls	1.56	0.005	0.37	0.070	0.29	0.095	0.27	0.105
Vertical interior partitions	2.79	0.000	1.06	0.020	1.06	0.020	1.06	0.020
Ground floor	1.53	0.005	0.65	0.030	0.47	0.050	0.47	0.050
Windows	5.70	–	1.99	–	1.99	–	1.66	–
Doors	5.70	–	2.00	–	2.00	–	2.00	–

Table 5
U-values, in W/m^2·K, of all elements of the thermal envelope and the interior partitions, and the thickness (t) or thickness increase (Δt) of thermal insulation used, both in m, for the study buildings in Torrecilla en Cameros.

	PreCTE-Y		NZEB-YC		NZEB-YD		NZEB-YE	
	U	t	U	Δt	U	Δt	U	Δt
Roof	0.88	0.020	0.23	0.110	0.22	0.115	0.19	0.140
First-floor framework	1.05	0.015	0.91	0.005	0.80	0.010	0.65	0.020
Mezzanine framework	1.96	–	1.24	0.010	1.05	0.015	0.91	0.020
Roof-floor framework	1.05	0.015	0.91	0.005	0.80	0.010	0.65	0.020
Dividing walls	1.26	0.010	0.47	0.045	0.47	0.045	0.47	0.045
Walls	1.27	0.010	0.29	0.090	0.27	0.100	0.23	0.120
Vertical interior partitions	2.79	–	1.06	0.020	1.06	0.020	0.91	0.020
Ground floor	1.53	0.005	0.47	0.050	0.47	0.050	0.47	0.050
Windows	5.70		1.99	–	1.66	–	1.66	–
Doors	5.70		2.00	–	2.00	–	2.00	–

3. Results and discussion

First, the heating and cooling energy demands are evaluated for the different case studies in Cervera del Río Alhama and Torrecilla en Cameros (Figs. 6 and 7). In Section 3.1, the energy impacts of the different study buildings in the different climate change scenarios are analysed. On the one hand, the variations in the energy demands of the different energy-renovated study buildings are evaluated in the different climate change scenarios (a) with respect to the corresponding study building in the RCP 2.6 scenario and (b) with respect to the energy-renovated study building designed to comply with the current CTE-DB-HE [32] in the RCP 2.6 scenario. On the

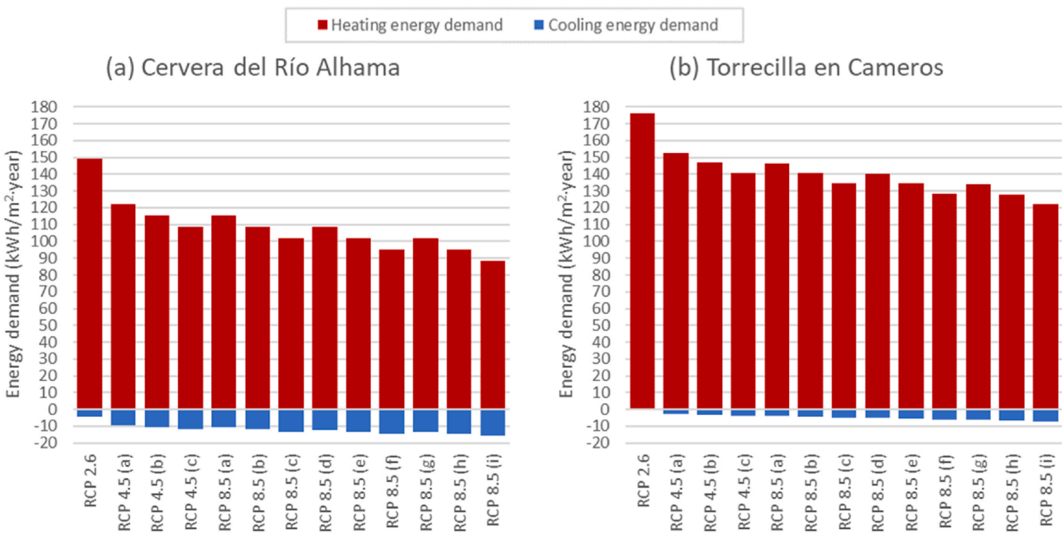

Fig. 6. Heating and cooling energy demands for the existing study buildings in the different climate change scenarios.

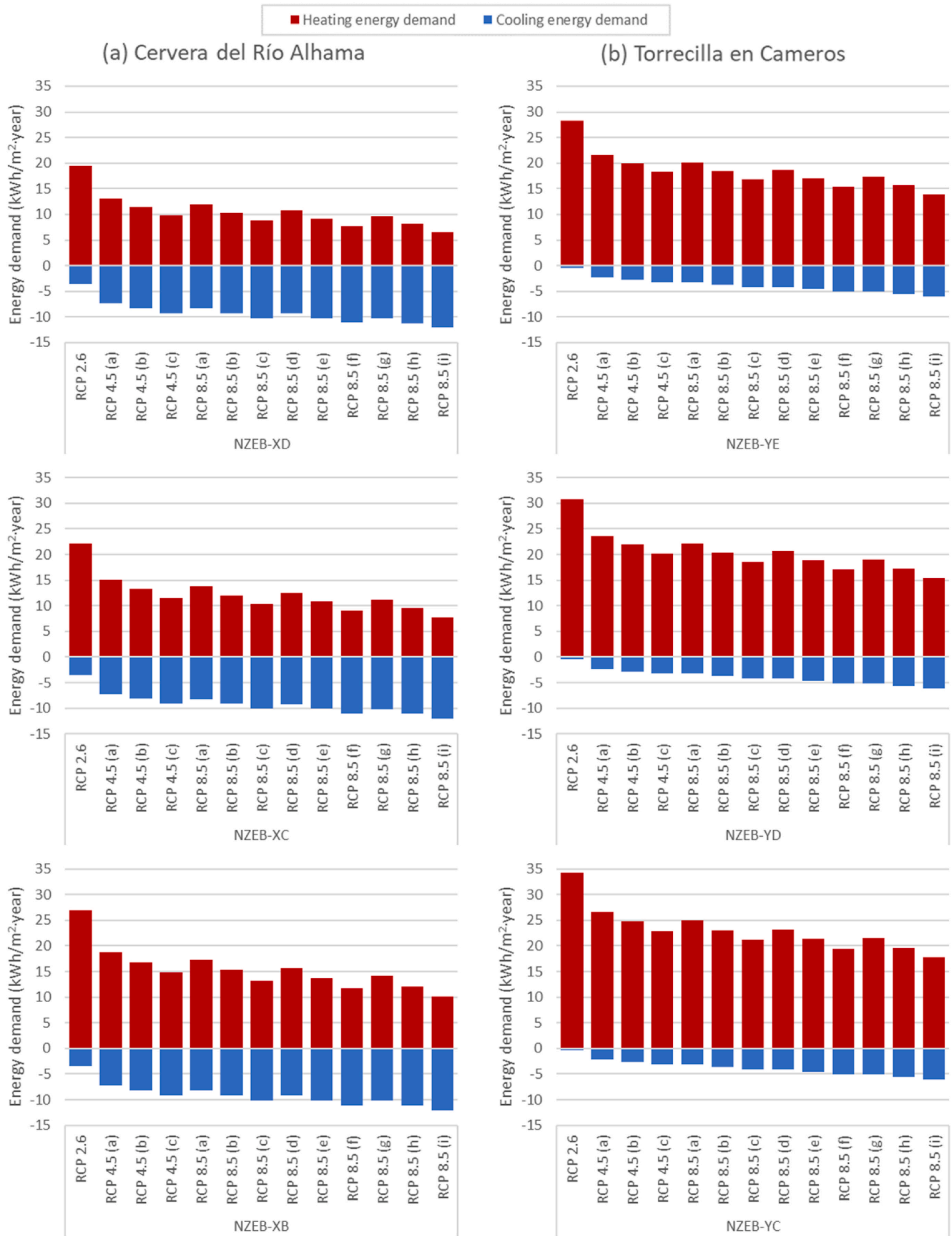

Fig. 7. Heating and cooling energy demands for the energy-renovated study buildings in the different climate change scenarios.

other hand, the energy savings (variations in energy demands) achieved by the energy-renovated study buildings are evaluated with respect to the existing study buildings in the different climate change scenarios.

Subsequently, the cumulative economic expenses over the lifetime are evaluated for the different case studies, with different interest rates, in Cervera del Río Alhama (Fig. 8) and in Torrecilla en Cameros (Fig. 9). In Section 3.2, the economic impacts of the different study buildings in the different climate change scenarios are analysed, noting the cumulative economic savings over the lifetime achieved by the energy-renovated study buildings with respect to the existing study buildings.

The methodology developed enabled the best energy renovation solution to be determined for rural residential buildings in La Rioja. The results obtained can be extrapolated to any rural residential building located in a climate zone whose evolution is similar to

Fig. 8. Cumulative economic expenses over the lifetime, with different interest rates, for the different case studies in Cervera del Río Alhama.

that of La Rioja for different climate change scenarios. To demonstrate the versatility of this methodology, the methodology developed in other rural municipalities similar to those of La Rioja was applied, whose future climate zone presents the greatest summer climatic severity and the lowest winter climatic severity in 2085. Section 3.3 presents the adaptation of the methodology developed for evaluating and analysing the best energy renovation solution based on the energy and economic impacts in those municipalities that will be most affected by climate change. This approach enables the extrapolation of both the methodology and the results obtained in this study to other cold Mediterranean climate zones. Finally, a critical discussion is carried out in Section 3.4.

3.1. Energy impact

In the RCP 4.5 scenarios and the RCP 8.5 scenarios with the different study buildings, in both Cervera del Río Alhama and Torrecilla en Cameros, the total energy demand decreases due to the decreased heating energy demand rather than the increased cooling energy demand (Figs. 6 and 7).

The variations in the heating and cooling energy demands for the different energy-renovated study buildings in the RCP 4.5 scenarios and the RCP 8.5 scenarios with respect to the corresponding RCP 2.6 scenario for Cervera del Río Alhama and Torrecilla en Cameros are presented in Fig. 10. In the RCP 8.5 scenarios, the reductions in the heating energy demand and the increases in the cooling energy demand are greater than those in RCP 4.5 scenarios (Fig. 10). In Cervera del Río Alhama, for NZEB-XD, the greatest reductions in the heating energy demand are achieved (on average, 41.02 % in RCP 4.5 scenarios and 52.45 % in RCP 8.5 scenarios), as are the smallest increases in the cooling energy demand (on average, 133.39 % in RCP 4.5 scenarios and 187.99 % in RCP 8.5 scenarios), while for NZEB-XB, the lowest reductions in the heating energy demand are achieved (on average, 37.28 % in RCP 4.5 scenarios and 48.99 % in RCP 8.5 scenarios), as are the greatest increases in the cooling energy demand (on average, 140.99 % in RCP 4.5 scenarios and 200.16 % in RCP 8.5 scenarios) (Fig. 10). In Torrecilla en Cameros, for NZEB-YE, the greatest reductions in the heating energy demand are achieved (on average, 29.53 % in RCP 4.5 scenarios and 39.65 % in RCP 8.5 scenarios), as well as the smallest increases in the cooling energy demand (on average, 558.47 % in RCP 4.5 scenarios and 1002.45 % in RCP 8.5 scenarios), while for NZEB-YC, the

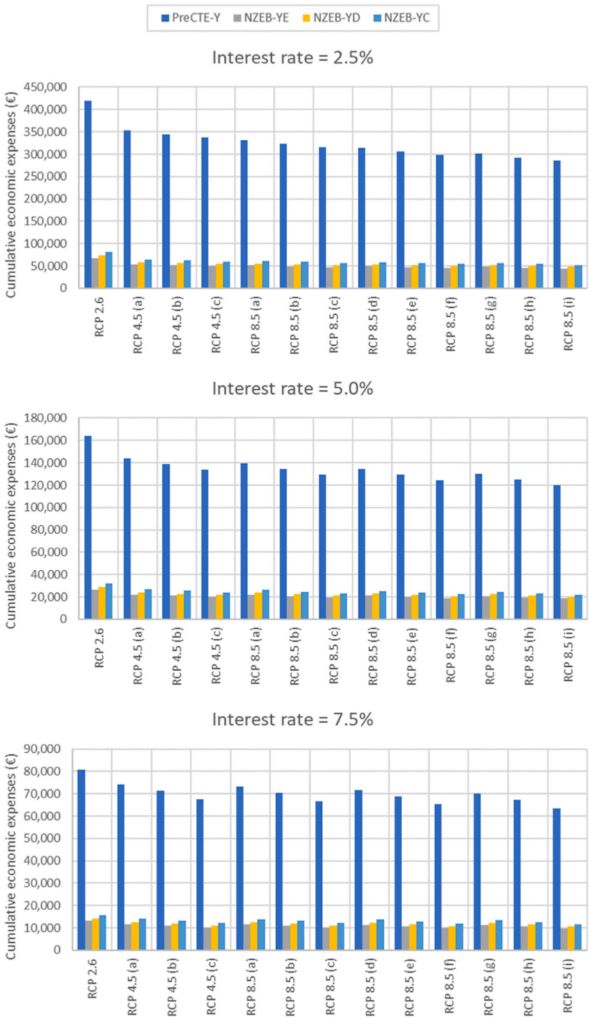

Fig. 9. Cumulative economic expenses over the lifetime, with different interest rates, for the different case studies in Torrecilla en Cameros.

lowest reductions in the heating energy demand are achieved (on average, 27.65 % in RCP 4.5 scenarios and 37.64 % in RCP 8.5 scenarios), as are the greatest increases in the cooling energy demand (on average, 710.78 % in RCP 4.5 scenarios and 1286.54 % in RCP 8.5 scenarios) (Fig. 10).

NZEB-XD in Cervera del Río Alhama and NZEB-YE in Torrecilla en Cameros meet the requirements for NZEBs established by the current CTE-DB-HE [32]. In the RCP 2.6 scenario, in Cervera del Río Alhama, compared to the heating and cooling energy demands for NZEB-XD, the heating energy demand for NZEB-XC increases by 13.68 % and that for NZEB-XB by 38.10 %, while the cooling energy demand decreases by 3.10 % for NZEB-XC and 4.51 % for NZEB-XB (Fig. 7). In Torrecilla en Cameros, compared to the heating and cooling energy demands for NZEB-YE, the heating energy demand for NZEB-YD increases by 8.95 % and for NZEB-YC by 21.20 %, and the cooling energy demand for NZEB-YD decreases by 7.14 % and for NZEB-YC by 21.43 % (Fig. 7). The variations in the heating and cooling energy demands in Cervera del Río Alhama for the different energy-renovated study buildings in the RCP 4.5 scenarios and the RCP 8.5 scenarios compared to those for NZEB-XD in the RCP 2.6 scenario are presented in Fig. 11. The greatest reductions in the heating energy demand and the greatest increases in the cooling energy demand occur for NZEB-XD; the smallest reductions in the heating energy demand occur for NZEB-XB (on average, 13.39 % in RCP 4.5 scenarios and 29.56 % in RCP 8.5 scenarios); and the smallest increases in the cooling energy demand occur for NZEB-XC (on average, 129.67 % in RCP 4.5 scenarios and 184.85 % in RCP 8.5 scenarios) (Fig. 11). In addition, the variations in the heating and cooling energy demands in Torrecilla de Cameros for the different energy-renovated study buildings in the RCP 4.5 scenarios and the RCP 8.5 scenarios compared to NZEB-YE in the RCP 2.6 scenario are presented in Fig. 11. The greatest reductions in the heating energy demand occur for NZEB-YE; the greatest increases in the cooling energy demand occur for NZEB-YD (on average, 561.83 % in the RCP 4.5 scenarios and 1015.62 % in the RCP 8.5 scenarios); the smallest reductions in the heating energy demand occur for NZEB-YC (on average, 12.32 % in the RCP 4.5 scenarios and 24.42 % in the RCP 8.5 scenarios); and the smallest increases in the cooling energy demand occur for NZEB-YC (on average, 537.04 % in the RCP 4.5 scenarios and 989.43 % in the RCP 8.5 scenarios) (Fig. 11).

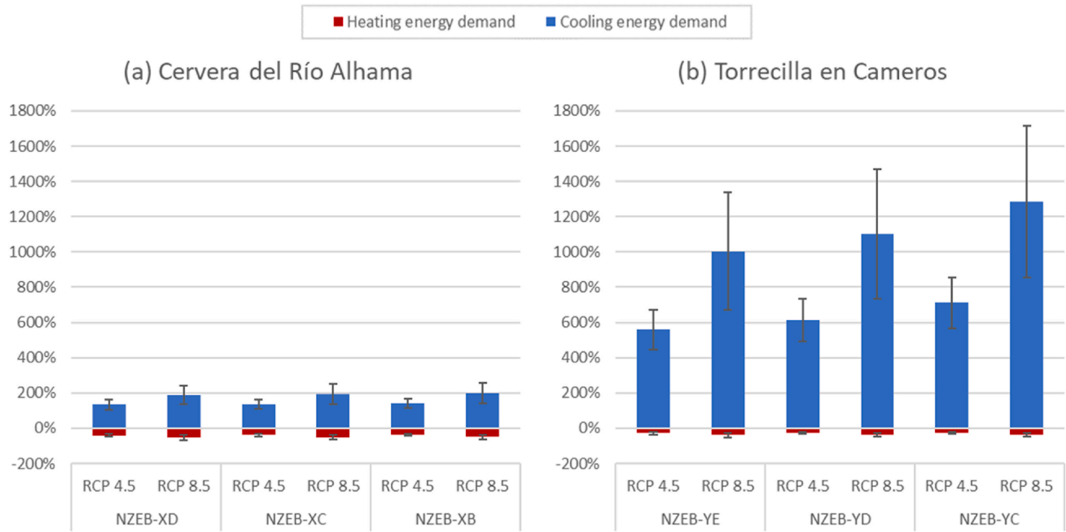

Fig. 10. Variations in the heating and cooling energy demands for the different energy-renovated study buildings in the RCP 4.5 scenarios and the RCP 8.5 scenarios with respect to the corresponding RCP 2.6 scenario.

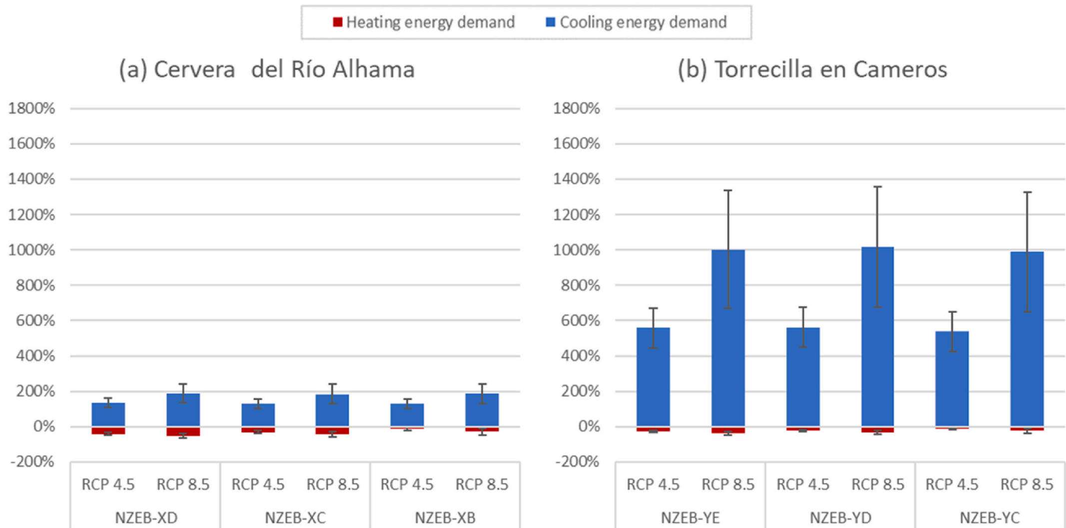

Fig. 11. Variations in the heating and cooling energy demands of the different energy-renovated study buildings under the RCP 4.5 and RCP 8.5 scenarios compared to the energy-renovated building that complies with the current CTE-DB-HE [32] for the corresponding current climate zone under the RCP 2.6 scenario.

On the one hand, in comparisons of all the energy-renovated study buildings with the existing study building, in Cervera del Río Alhama, for NZEB-XD, for all climate change scenarios, the greatest energy savings in heating are achieved (129.71 kWh/m^2·year in the RCP 2.6 scenario, 98.72–109.05 kWh/m^2·year in the RCP 4.5 scenarios and 81.64–103.36 kWh/m^2·year in the RCP 8.5 scenarios), as are the greatest total energy savings (130.37 kWh/m^2·year in the RCP 2.6 scenario, 101.49–111.12 kWh/m^2·year in the RCP 4.5 scenarios and 85.45–105.77 kWh/m^2·year in the RCP 8.5 scenarios), although the lowest energy savings are achieved in cooling (Figs. 6 and 7). However, the greatest energy savings in cooling, with respect to PreCTE-X, are produced with NZEB-XB in the RCP 2.6 scenario (0.82 kWh/m^2·year) and with NZEB-XC in the RCP 4.5 scenarios (2.19–2.91 kWh/m^2·year) and the RCP 8.5 scenarios (2.53–3.92 kWh/m^2·year), while the lowest energy savings in heating and total, for all climate change scenarios, are produced with NZEB-XB (Figs. 6 and 7).

On the other hand, in comparisons of all the energy-renovated study buildings with the existing study building, in Torrecilla en Cameros, NZEB-YE, for all climate change scenarios, achieves the greatest energy savings in heating (148.17 kWh/m^2·year in the RCP 2.6 scenario, 122.63–131.15 kWh/m^2·year in the RCP 4.5 scenarios and 108.16–126.32 kWh/m^2·year in the RCP 8.5 scenarios) and greatest total energy savings (148.07 kWh/m^2·year in the RCP 2.6 scenario, 123.06–131.40 kWh/m^2·year in the RCP 4.5 scenarios and 109.55–126.89 kWh/m^2·year in the RCP 8.5 scenarios); NZEB-YC achieves the lowest energy savings in heating (142.18 kWh/m^2·year in the RCP 2.6 scenario, 117.99–126.06 kWh/m^2·year in the RCP 4.5 scenarios and 104.36–121.51 kWh/m^2·year in the RCP 8.5 scenarios) and the lowest total energy savings (142.17 kWh/m^2·year in the RCP 2.6 scenario, 118.51–126.40 kWh/m²·year in the RCP 4.5 scenarios and 105.79–122.16 kWh/m²·year in RCP 8.5 scenarios) (Figs. 6 and 7). Energy savings in cooling are achieved in the RCP 4.5 scenarios and the RCP 8.5 scenarios, since the cooling energy demand decreases compared to PreCTE-Y; the smallest reductions in the cooling energy demand occur for NZEB-YD (0.25–0.41 kWh/m²·year in the RCP 4.5 scenarios and 0.55–1.31 kWh/m²·year in the RCP 8.5 scenarios) and the greatest reductions in the cooling energy demand occur for NZEB-YC (0.34–0.52 kWh/m²·year in the RCP 4.5 scenarios and 0.65–1.43 kWh/m²·year in the RCP 8.5 scenarios) (Figs. 6 and 7). However, the cooling energy demand increases in the RCP 2.6 scenario (0.10 kWh/m²·year for NZEB-YE, 0.07 kWh/m²·year for NZEB-YD and 0.01 kWh/m²·year for NZEB-YC) (Figs. 6 and 7).

3.2. Economic impact

In Cervera del Río Alhama, with respect to PreCTE-X, the cumulative economic expenditure over the lifetime for an interest rate of 5.0 % is reduced, on average, by 85.00 % for NZEB-XD, 83.34 % for NZEB-XC and 80.28 % for NZEB-XB for the RCP 2.6 scenario; 84.32 % for NZEB-XD, 82.94 % for NZEB-XC and 80.16 % for NZEB-XB for the RCP 4.5 scenarios; and 83.05 % for NZEB-XD, 81.82 % for NZEB-XC and 79.23 % for NZEB-XB for the RCP 8.5 scenarios (Fig. 8). In Torrecilla en Cameros, compared to that for PreCTE-Y, the cumulative economic expenditure over the lifetime for an interest rate of 5.0 % is reduced, on average, by 83.77 % for NZEB-YE, 82.36 % for NZEB-YD and 80.44 % for NZEB-YC for the RCP 2.6 scenario; 84.88 % for NZEB-YE, 83.53 % for NZEB-YD and 81.69 % for NZEB-YC for the RCP 4.5 scenarios; and 84.50 % for NZEB-YE, 83.20 % for NZEB-YD and 81.47 % for NZEB-YC for the RCP 8.5 scenarios (Fig. 9).

As the economic investment required for each energy-renovated study building was not considered, the cumulative economic savings, with respect to the existing study building, is equivalent to the maximum financial investment acceptable for the energy renovation to be economically viable. The cumulative economic savings over the lifetime for the different energy-renovated study buildings, with respect to the corresponding existing study buildings, for the different climate change scenarios in Cervera del Río Alhama and Torrecilla en Cameros are presented in Fig. 12. The economic investment needed, with an interest rate of 5.0 %, to ensure the economic viability of the energy-renovated building that meets the NZEB requirements established by the current CTE-DB-HE [32] (NZEB-XD in Cervera del Rio Alhama and NZEB-YE in Torrecilla en Cameros), with respect to corresponding existing building (PreCTE-X in Cervera del Rio Alhama and the PreCTE-Y in Torrecilla en Cameros), must be less than 703.92 €/m² in the RCP 2.6 scenario, 547.99–599.96 €/m² in the RCP 4.5 scenarios and 461.38–571.09 €/m² in the RCP 8.5 scenarios in Cervera del Río Alhama; and less than 799.48 €/m² in the RCP 2.6 scenario, 664.47–709.47 €/m² in the RCP 4.5 scenarios and 591.48–685.15 €/m² in the RCP 8.5 scenarios in Torrecilla en Cameros (Fig. 12).

NZEB-XC and NZEB-XB, in Cervera del Río Alhama, and NZEB-YD and NZEB-YC, in Torrecilla en Cameros, do not meet the requirements for the NZEBs established by the current CTE-DB-HE [32]. On the one hand, in Cervera del Río Alhama, the economic investment needed, with an interest rate of 5.0 %, to ensure the economic viability of NZEB-XD compared to that of NZEB-XC, must be less than 13.78 €/m² in the RCP 2.6 scenario, 8.54–10.28 €/m² in the RCP 4.5 scenarios and 5.97–9.43 €/m² in the RCP 8.5 scenarios; and, compared to that of NZEB-XB, should be less than 39.15 €/m² in the RCP 2.6 scenario, 26.24–30.55 €/m² in the RCP 4.5 scenarios and 19.34–28.25 €/m² in the RCP 8.5 scenarios (Fig. 12). On the other hand, in Torrecilla en Cameros, the economic investment needed, with an interest rate of 5.0 %, to ensure the economic viability of NZEB-YE, compared to that of NZEB-YD, must be less than 13.51 €/m² in the RCP 2.6 scenario, 10.36–11.41 €/m² in the RCP 4.5 scenarios and 8.79–10.89 €/m² in the RCP 8.5 scenarios; and, compared to that of NZEB-YC, must be less than 31.87 €/m² in the RCP 2.6 scenario, 24.58–27.01 €/m² in the RCP 4.5 scenarios and 20.31–25.59 €/m² in the RCP 8.5 scenarios (Fig. 12).

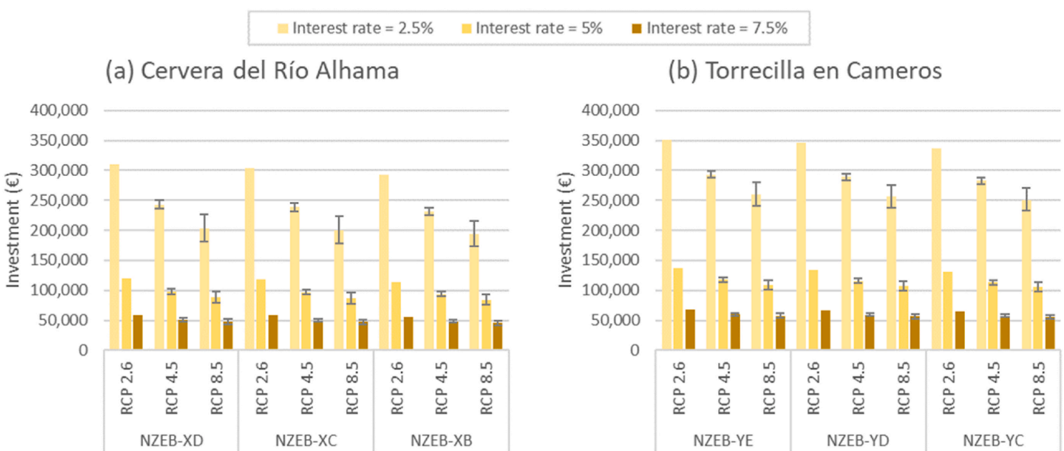

Fig. 12. Economic investment, with different interest rates, for the energy-renovated study buildings, with respect to the corresponding existing study buildings, for the different climate change scenarios.

3.3. Energy and economic impacts in the most pessimistic possible climate change scenario

The rural municipalities of Alcántara, in Cáceres Province, and Olius, in Lérida Province, have been selected to adapt and apply the methodology developed for rural municipalities in La Rioja. Both municipalities are found in the climate zone with the greatest summer climate severity and the lowest winter climate severity (climate zone A4 according to Ref. [32]) in 2085 in the RCP 8.5 scenario according to Ref. [9] (Fig. 3). Moreover, they are demographic challenge municipalities [24] and are located in rural revitalisation areas [25], similar to the municipalities selected and studied in La Rioja. Alcántara is 291 m above sea level, was in January climate zone X according to Ref. [39] and is currently in the climate zone C4 according to Ref. [32]; and Olius is 565 m above sea level, was in January climate zone Y according to Ref. [39] and is currently in the climate zone D3 according to Ref. [32]. The methodology followed in this work for the rural municipalities of La Rioja was used to develop the climate change scenarios for these rural municipalities in accordance with the evolution of their climate zones. These climate change scenarios are presented in Fig. 13. Moreover, the RCP 4.5 scenarios and the RCP 8.5 scenarios are the same for Alcántara.

Existing building PreCTE-X and energy-renovated building NZEB-XC were used in Alcántara; existing building PreCTE-Y and energy-renovated building NZEB-YD were used in Olius. It was necessary to design energy-renovated buildings NZEB-XA (NZEB that meets the requirements of the current CTE-DB-HE [32] in winter climate zone A) for Alcántara and energy-renovated buildings NZEB-YA (NZEB that meets the requirements of the current CTE-DB-HE [32] in winter climate zone A) and NZEB-YB (NZEB that meets the requirements of the current CTE-DB-HE [32] in winter climate zone B) for Olius. Table 6 presents the U-values of the elements of both the thermal envelope and the interior partitions of all these new study buildings and the thickness of thermal insulation used in each of these elements. The air permeability of the thermal envelope openings with an overpressure of 100 Pa is 27 $m^3/h{\cdot}m^2$ para NZEB-XA, NZEB-YA y NZEB-YB. To design these new energy-renovated buildings, the design criteria used in Ref. [34] were followed.

In the energy simulation with HULC [44], 0.63 air exchanges [44] were considered for NZEB-XA, NZEB-YA and NZEB-YB. Moreover, in order to carry out the energy simulation with HULC [44], the representative provinces of the possible new climate zones under climate change are Almería Province for climate zone A4, Toledo Province for climate zone C4 and Madrid Province for climate zone D3 [49,50].

A total of 73 additional case studies were evaluated: for Alcántara, 3 study buildings were evaluated in 7 climate change scenarios, resulting in 21 case studies; and, for Olius, 4 study buildings were evaluated in 13 climate change scenarios, resulting in 52 case studies.

Initially, the heating and cooling energy demands are evaluated for the different case studies in Alcántara and Olius (Figs. 14–16). Subsequently, the cumulative economic expenses over the lifetime are evaluated for the different case studies, with different interest rates, in Alcántara (Fig. 17) and in Olius (Fig. 18). On the one hand, in comparisons of all the energy-renovated study buildings with the existing study building, in Alcantara, NZEB-XC, for all climate change scenarios, achieves the greatest total energy savings, between 49.57 $kWh/m^2{\cdot}year$ in the RCP 4.5 (c) and the RCP 8.5 (c) scenarios and 100.57 $kWh/m^2{\cdot}year$ in the RCP 2.6 scenario (Figs. 14

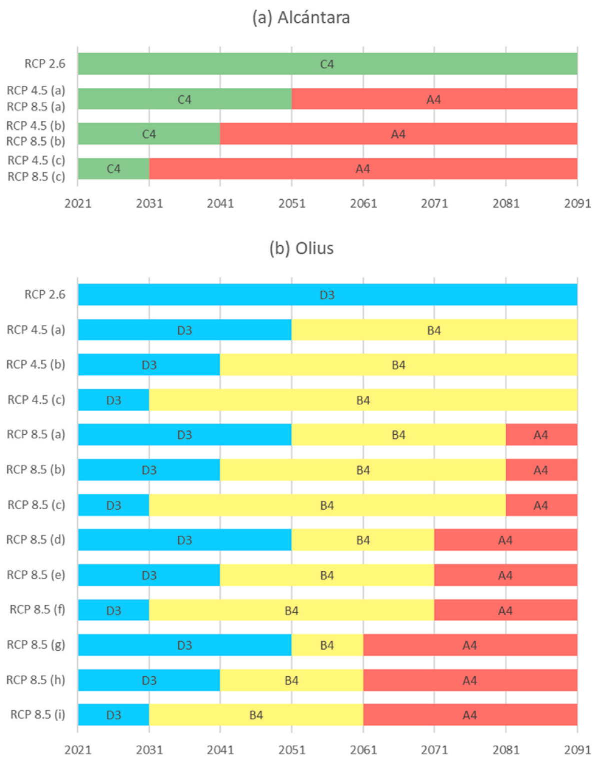

Fig. 13. Climate change scenarios with the evolution of the climate zones for (a) Alcántara and (b) Olius.

Table 6
U-values, in W/m^2·K, of all elements of the thermal envelope and the interior partitions, and the thickness increase (Δt) of thermal insulation used, in m, for the new study buildings in Alcántara and Olius.

	NZEB-XA		NZEB-YA		NZEB-YB	
	U	Δt	U	Δt	U	Δt
Roof	0.43	0.050	0.43	0.040	0.33	0.065
First-floor framework	1.24	0.000	1.05	0.000	1.05	0.000
Mezzanine framework	1.52	0.005	1.52	0.005	1.52	0.005
Roof-floor framework	1.24	0.000	1.05	0.000	1.05	0.000
Dividing walls	0.72	0.025	0.72	0.020	0.65	0.025
Walls	0.47	0.050	0.47	0.045	0.37	0.065
Vertical interior partitions	1.25	0.015	1.25	0.015	1.06	0.020
Ground floor	0.80	0.020	0.80	0.020	0.65	0.030
Windows	2.62	–	2.62	–	1.99	–
Doors	2.20	–	2.20	–	2.00	–

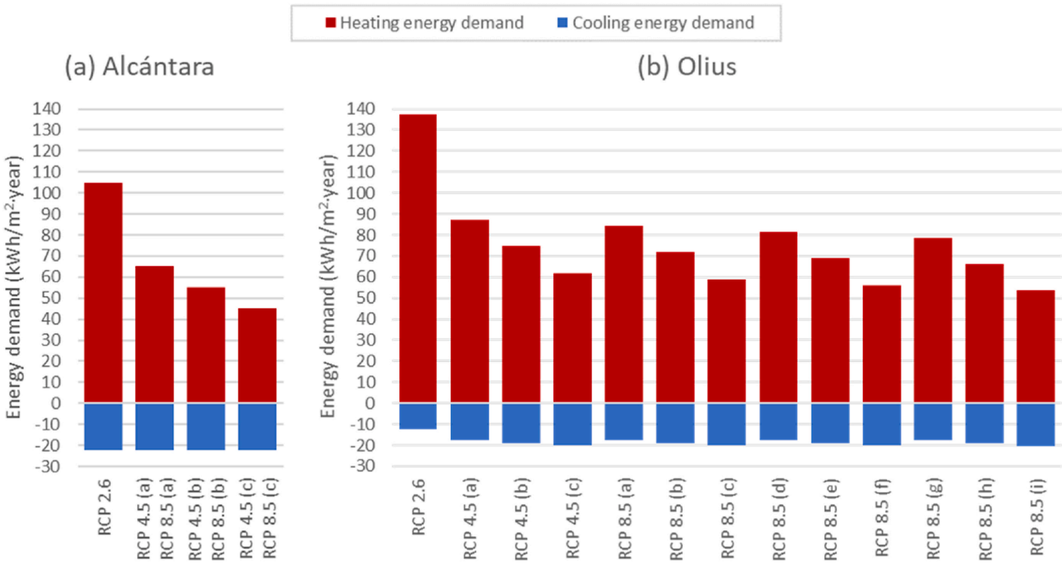

Fig. 14. Heating and cooling energy demands for the existing study buildings in the different climate change scenarios for (a) Alcántara and (b) Olius.

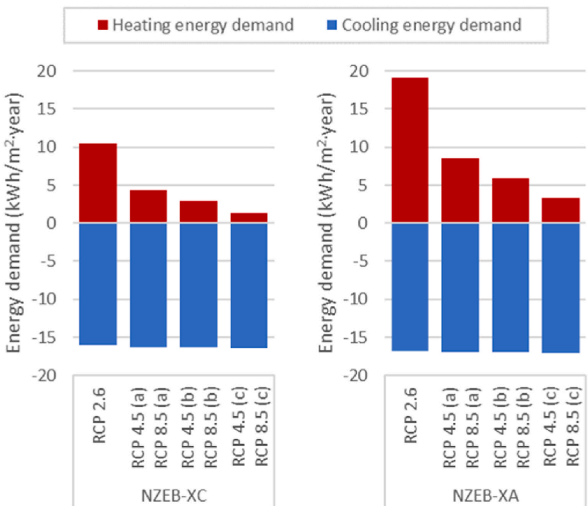

Fig. 15. Heating and cooling energy demands for the energy-renovated study buildings in the different climate change scenarios for Alcántara.

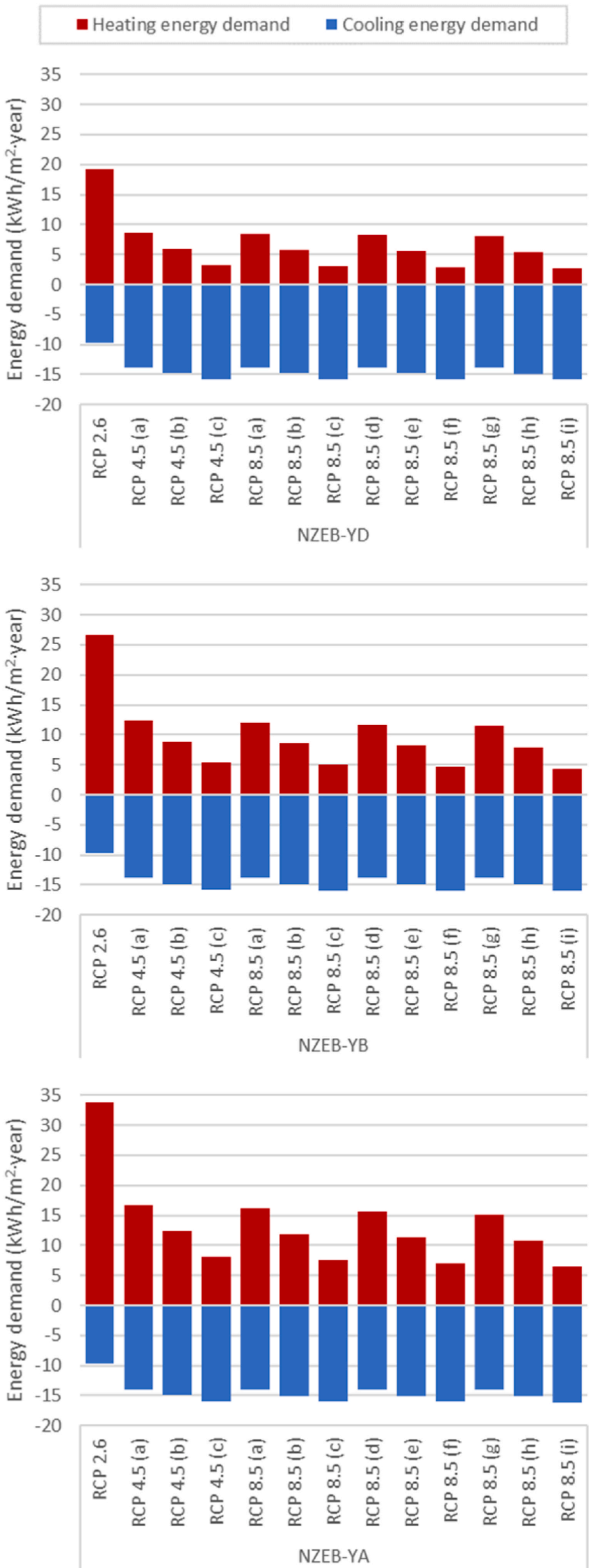

Fig. 16. Heating and cooling energy demands for the energy-renovated study buildings in the different climate change scenarios for Olius.

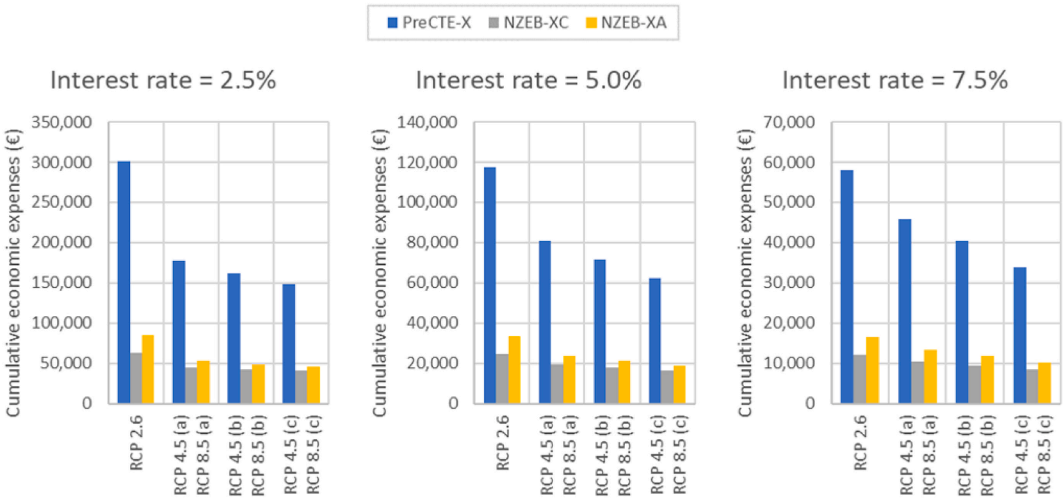

Fig. 17. Cumulative economic expenses over the lifetime, with different interest rates, for the different case studies in Alcántara.

Fig. 18. Cumulative economic expenses over the lifetime, with different interest rates, for the different case studies in Olius.

and 15). Moreover, the economic investment needed, with an interest rate of 5.0 %, to ensure its economic viability must be less than 543.02 €/m^2 in the RCP 2.6 scenario and 267.65–359.44 €/m^2 in the RCP 4.5 and the RCP 8.5 scenarios (Fig. 17). On the other hand, in comparisons of all the energy-renovated study buildings with the existing study building, in Olius, NZEB-YD, for all climate change scenarios, achieves the greatest total energy savings, between 55.12 kWh/m^2·year in the RCP 8.5 (i) scenario and 120.86 kWh/m^2·year in the RCP 2.6 scenario (Figs. 14 and 16). Moreover, the economic investment needed, with an interest rate of 5.0 %, to ensure its economic viability must be less than 652.57 €/m^2 in the RCP 2.6 scenario, 341.19–444.98 €/m^2 in the RCP 4.5 scenarios and 297.60–430.45 €/m^2 in the RCP 8.5 scenarios (Fig. 18).

3.4. Critical discussion

This research proposes a prospective vision for the Spanish rural residential sector. The results obtained for the different study buildings in the climate change scenarios reveal that the total energy demand decreases due to the decreased heating energy demand rather than the increased cooling energy demand. These results are similarly to those obtained for the cold Italian climate zones by Baglivo et al. [52]. In the different climate change scenarios, the winter climate severity of the future climate zones decreases and, therefore, the best energy renovation solutions will always be those NZEBs that meet the requirements of the current CTE-DB-HE [32] in their current winter climate zone. It was found, for the different climate change scenarios, that the best energy renovation solutions were NZEB-XD for Cervera del Río Alhama and NZEB-YE for Torrecilla en Cameros in rural municipalities of La Rioja; and NZEB-XC for Alcántara and NZEB-YD for Olius in other rural municipalities of Spain whose future climate zone presents the greatest summer climate severity and the lowest winter climate severity in 2085. Lower U-values reduce the total energy demand, although the cooling energy demand increases and, therefore, there is a greater risk of overheating in summer, as pointed out by Rodrigues and Fernandes [14]. Buildings that undergo greater energy renovation are better prepared for climate change, as indicated by Tootkaboni et al. [12]. The NZEBs that are better isolated and adequately optimised for their current climate zone are more resilient to climate change, as D'Agostino et al. [16] discovered. Moreover, in this research, the economic investments required to ensure the economic viability of the different energy-renovated study buildings in different climate change scenarios were evaluated. On the one hand, this economic parameter is key and of great interest, as it allows policy-makers can establish and promote adequate energy renovation policies; on the other hand, it allows stakeholders to determine the most appropriate and economically viable energy renovation measures.

In future works, the effectiveness of the Spanish building thermal regulation to mitigate climate change needs to be evaluated in greater depth, as was done by Fereidani et al. [53] with the Iranian building code; the ideal or optimal U-values should be determined for the different elements of the thermal envelopes of Spanish residential buildings and can be used to minimise the effects of climate change, following the steps carried out by Rodrigues and Fernades [14] in the Mediterranean environment, Verichev et al. [54] in Chile and Rodrigues et al. [55] in Iran; and how to adapt the Spanish residential sector to climate change through both passive and active energy renovation actions can be aligned with how to achieve a zero-emission residential sector according to the new EPBD 2024 [35]. Furthemore, based on the advances and discoveries made with this research for the different RCPs of the Intergovernmental Panel on Climate Change [1], it would be interesting to evaluate the energy, economic and environmental impacts of the NZEBs for the different shared socioeconomic pathways of the Intergovernmental Panel on Climate Change [56]. Finally, the proposed methodology can be adapted to other cold Mediterranean climatic zones, taking into account specific climatic and socioeconomic variables, to develop robust rural residential buildings that are resistant to climate change.

4. Conclusions

This research studied how the rural residential buildings in La Rioja can be adapted to face climate change through energy renovation; it evaluates the energy and economic impacts in different climate change scenarios and considers the possible evolution of their climate zones. Furthermore, the methodology developed can be extrapolated to other cold Mediterranean climate zones, and due to its versatility, can be applied in other climate zones, as was demonstrated for Alcántara and Olius.

The greatest reductions in both the total energy demand and the cumulative economic expenditure over the lifetime are achieved with NZEBs that meet the current building thermal regulation for the current climate zone. For rural municipalities in La Rioja, compared to the corresponding existing study building, reductions in the total energy demand and economic savings, with an interest rate of 5.0 %, are achieved in Cervera del Río Alhama at rates of 130.37 kWh/m^2·year and 10.35 €/m^2 year in the RCP 2.6 scenario, of 101.49–111.12 kWh/m^2·year and 8.06–8.82 €/m^2·year in the RCP 4.5 scenarios, and of 85.44–105.77 kWh/m^2·year and 6.78–8.40 €/m^2·year in the RCP 8.5 scenarios. In Torrecilla en Cameros, reductions in the total energy demand and economic savings are achieved at rates of 148.07 kWh/m^2·year and 11.76 €/m^2·year in the RCP 2.6 scenario, of 123.06–131.40 kWh/m^2·year and 9.77–10.43 €/m^2·year in the RCP 4.5 scenarios, and of 109.55–126.89 kWh/m^2·year and 8.70–10.08 €/m^2·year in the RCP 8.5 scenarios.

In terms of energy, in the different climate change scenarios, the heating energy demand is reduced, and the cooling energy demand is increased, thus reducing the total energy demand. Economically, the maximum economic investments required to ensure the economic viability of the different energy renovations were determined from the cumulative expenditures over the lifetime by evaluating the economic savings accumulated over the lifetime.

Finally, based on the results obtained, this work can serve as a guide to establish and promote energy renovation policies that are effective against climate change and economically viable.

CRediT authorship contribution statement

Luis M. López-Ochoa: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jesús Las-Heras-Casas:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Manuel Carpio:** Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Enrique Sagredo-Blanco:** Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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