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Towards Nearly Zero-Energy Buildings in Cold Rural Mediterranean Zones: The Case of La Rioja (Spain)

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Abstract: The European Union aims for its existing building stock to be highly energy-efficient and decarbonized by 2050 through long-term renovation strategies so that all residential buildings are nearly zero-energy buildings. The objective of this work is to determine the optimal energy renovation solution for rural residential buildings located in cold climate zones of Spain to achieve nearly zero-energy buildings. For this purpose, the energy, environmental and economic impacts of 48 energy renovation proposals in three different climate zones are assessed, taking La Rioja as a case study. Considering these impacts, the optimal solution is a solution that improves the thermal envelope, applying the life cycle cost analysis, and that uses renewable energy sources to meet thermal needs and a portion of the electrical energy needs. Under the optimal solution, overall savings of up to EUR 2.4 can be achieved for each euro invested, resulting in reductions in non-renewable primary energy consumption by up to 97%, total primary energy consumption by up to 81% and CO_2 emissions by up to 97%. The methodology followed and the results obtained can serve as a guide for establishing energy renovation policies in other cold rural Mediterranean zones.

Keywords: sustainable rural development; energy renovation; rural residential buildings; nearly zero-energy buildings; Spain

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1. Introduction

The building sector is responsible for approximately 40% of European Union (EU) energy consumption and 36% of greenhouse gas emissions because approximately 35% of the EU's buildings are over 50 years old, nearly 75% of the building stock is energy-inefficient and only approximately 1% of the building stock is renovated each year [1]. The final energy consumption of the residential sector in the EU was 245.86 Mtoe in 2019, representing 26.28% of the total final energy consumption, and has experienced an average annual decrease of 1.18% since 2010 [2]; greenhouse gas emissions associated with this sector were 753.10 Mt CO_2 equivalent in 2019, representing 24.69% of total greenhouse gas emissions, and have decreased annually by 7.78% on average since 2010 [3]. In addition, approximately 94% of residential buildings were built before 2008 [4]. The characteristics and the energy performance of the residential building stock in numerous European countries were studied at the national, regional and local levels by the Intelligent Energy Europe projects TABULA and EPISCOPE [5]. These projects [5] have made it possible to effectively and transparently develop energy renovation policies and to establish energy performance indicators to measure energy savings [6]. Based on these projects, different research efforts have been carried out in the Mediterranean environment, such as those carried out in Spain [7], France [8,9], Italy [10,11], Bosnia and Herzegovina [12], Serbia [13], Greece [14–17] and Cyprus [18]. A great pending challenge is to take advantage of the energy saving potential of the Mediterranean residential building stock after harmonizing the existing heterogeneous data, as was performed in [19] with data from Eastern European countries.

To promote the energy efficiency of buildings, during the last 20 years, the EU has updated the Energy Performance of Buildings Directive (EPBD) several times [20–22], which is paving the way for achieving nearly zero-energy building (NZEB) stock [23]. The EPBD 2018 [22] urges the establishment of long-term renovation strategies to achieve a highly energy-efficient and decarbonized residential building stock before 2050, amending the EPBD 2010 [21] and the Energy Efficiency Directive 2012 [24]. The EPBD 2010 [21] aimed to make all new residential buildings NZEBs as of 31 December 2020, and was complemented with the comparative methodological framework established by the Commission Delegated Regulation (EU) No. 244/2012 [25]. The achievement of NZEBs in Mediterranean countries through the energy renovation of residential buildings by implementing the EPBD 2010 [21] and the application of the Commission Delegated Regulation (EU) No. 244/2012 [25] are outlined in studies carried out in Portugal [26,27], France [28], Italy [29,30] and Greece [31]. López-Ochoa et al. [32], Monzón-Chavarrías et al. [33] and Cerezo-Narváez et al. [34] studied how to achieve NZEBs through energy renovation and their impact on the Spanish residential sector, implementing the EPBD 2010 [21]. In addition, López-Ochoa et al. [35] illustrated scenarios to assess the energy and environmental impact of implementing the EPBD 2010 [21] in the Spanish residential sector for the period 2020–2050 and showed that this residential sector is well on track to achieve the objectives of the EPBD 2018 [22].

There are few studies on the energy renovation of traditional residential buildings in rural areas in the Mediterranean environment. Rocchi et al. [36] performed a sustainability evaluation of different energy renovation solutions for the roof of an Italian traditional farmhouse, using a hybrid multi-criteria method, which combines energy and thermal comfort optimization with environmental and economic life cycle analysis. Tahsildoost and Zomorodian [37] defined optimal energy renovation strategies for rural buildings in the Iranian Mediterranean-influenced hot-summer humid continental climate. The strategies considered were architectural, constructional and renewable and took into account environmental, economic and comfort performance to perform a carbon emission and cost analysis. In addition, Gouveia et al. [38] developed heating and cooling energy poverty vulnerability indices, which combine the subindices' ability to implement alleviation measures and energy performance gaps. The researchers discovered that the rural areas located across the inland region of mainland Portugal should be prioritized by the country in terms of heating service, given the high rates of unemployment, low income, aging population, low educational levels and more severe winter climate.

Through the Sustainable Rural Development Programme, the Government of Spain and the Spanish Ministry of Agriculture, Fisheries and Food, together with the autonomous communities [39], have prioritized the sustainable development of rural revitalization areas, that is, those rural areas with low population density, important agricultural activity, low income levels and significant geographic isolation or difficulties in land use management. Recently, the Government of Spain and the Spanish Ministry for the Ecological Transition and the Demographic Challenge have promoted building sustainability in demographic challenge municipalities (municipalities or nuclei of up to 5000 inhabitants) through the Energy Renovation Programme for Existing Buildings in demographic challenge municipalities (PREE 5000 Programme) [40]. Therefore, the objective of this work is to assess the energy, environmental and economic impacts of various energy renovation measures for rural residential buildings located in cold Mediterranean climate zones of Spain to achieve NZEBs, taking as a case study the Autonomous Community of La Rioja. For this purpose, it was necessary to study the rural residential building stock of La Rioja and then select representative municipalities and define the characteristic building type of the different rural revitalization areas. Finally, optimal energy renovation solutions were selected that can be extrapolated to other rural areas or demographic challenge areas in both La Rioja and other Spanish autonomous communities.

2. Methodology

The methodology followed in this work is as follows:

1. Analyzing the rural residential building stock of La Rioja, determining the main characteristics of the residential building stock in rural areas to be revitalized and defining their characteristic buildings.
2. Proposing different energy renovation solutions.
3. Verifying compliance with Spanish regulations on energy saving in buildings and the achievement of NZEBs with the proposed solutions.
4. Assessing the energy, environmental and economic impacts of the different proposed solutions.
5. Selecting the optimal solution for energy renovation and estimating its impact for the rural population of La Rioja.

2.1. La Rioja and Its Residential Building Stock

La Rioja is a Spanish autonomous community located in the north of the Iberian Peninsula, with an area of 5045 km^2. It has a population of 319,914 inhabitants and comprises 174 municipalities, with 165 municipalities having fewer than 5001 inhabitants [41]. In addition, La Rioja has 130,000 households [42]. The residential sector of La Rioja consumed 148,616 toe of final energy (2.56 times that of 1991) and 176,888 toe of primary energy (1.86 times the value of 1991) in 2013, with a renewable energy contribution of 23.49% (2.06 times that of 1991) [43]. The energy performance certificates for the residential sector in La Rioja [44] revealed that the average primary energy consumption varied between 229.4 kWh/m^2·year and 309.4 kWh/m^2·year, and the associated CO_2 emissions varied from 51.7 kg CO_2/m^2·year to 72.0 kg CO_2/m^2·year, depending on climate zone.

The different requirements of Spanish regulations regarding energy saving in buildings have always been linked to the climate zone assigned to the municipality where the building is located, with climate zoning having undergone three major changes from 1981 to the present [32]. On the one hand, most existing buildings were built before 2008 [45], so the characteristics of their thermal envelopes were defined as a function of the climate zones according to the Basic Building Norm on Thermal Conditions in Buildings (NBE-CT-79) [46]. The thermal transmittances of the enclosures, as well as the interior partitions, were considered slightly lower than the corresponding NBE-CT-79 maximum allowable thermal transmittances [46], as was considered in [47] and [48]. The climate zones according to the NBE-CT-79 [46] are a combination of the heating climate zones and the January climate zones. La Rioja includes the climate zones DX, DY, EX and EY. The heating degree days with a base temperature of 15 °C are between 1301 and 1800 °C·day/year in heating climate zone D and above 1800 °C·day/year in heating climate zone E, while the average minimum temperature in January is between 1.5 and 3.9 °C in the January climate zone X and lower than 1.5 °C in the January climate zone Y. To determine these climate zones, the temperature data from the meteorological stations of the Government of La Rioja [49,50] were used for municipalities that have them, and the PVGIS database [51] was used for the other municipalities. On the other hand, to proceed with the energy renovation of existing buildings, it is necessary to comply with the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) [52], whose requirements depend on the climate zone according to the CTE-DB-HE [52]. The climate zones according to the CTE-DB-HE [52] are categorized by elevation above sea level of the municipalities of each Spanish province and are a combination of the winter and the summer climate zones, whose characteristics are described in [53]. According to CTE-DB-HE [52], municipalities of La Rioja whose elevation above sea level is less than or equal to 700 m are in climate zone D2, while the remaining municipalities are designated as climate zone E1. Both climate zones correspond to the cold climate zones of Spain [54], with climate zone D2 having a high energy demand for heating and a low energy demand for cooling, and climate zone E1 having a very high energy demand for heating and practically no energy demand for cooling. Finally, combining the climate zones according to the NBE-CT-79 [46] and the CTE-DB-HE [52], 5 possible combined climate zones (CCZs) are obtained for La Rioja: DX-D2, DX-E1, EX-D2, EX-E1 and EY-E1.

Those municipalities with fewer than 5001 inhabitants are considered rural or demographic challenge municipalities [40], representing 94.83% of La Rioja's municipalities. A total of 54.55% of rural municipalities are in the CCZ DX-D2, 26.67% are in the CCZ EY-E1, 12.12% are in the CCZ EX-E1, and the remainder are in the CCZs DX-E1 and EX-D2 (Figure 1a). In addition, within rural municipalities, this study focuses mainly on municipalities in rural revitalization areas according to the Sustainable Rural Development Programme in La Rioja [55], which are Cameros, Najerilla and Rioja Baja (Figure 1b). Based on the INSPIRE services of Cadastral Cartography of the General Directorate for Cadastre [56] and using the QGIS 3.10.10 software program [57], Table 1 was created, which shows that single-family houses represent the majority of residential buildings in the rural residential building stock. Table 1 shows the main characteristics of the single-family houses in the residential building stock in La Rioja, both rural and rural revitalization areas, by CCZ. While single-family houses represent 60.34% of the rural residential building stock and have an average surface area per floor of 91.42 m^2 and 2.74 floors on average, with 92.02% of them built before 2008, they represent 74.90% of the residential building stock in rural revitalization areas with an average surface area per floor of 88.12 m^2 and 2.84 floors on average, with 93.88% of them built before 2008 (Table 1). The average surface area and age of single-family houses in rural revitalization areas are similar to those of rural single-family houses, although their share is greater within their residential building stock (Table 1).

Table 1. Main characteristics of the single-family houses in the residential building stock in La Rioja, both rural and rural revitalization areas, by CCZ.

	CCZ	Number of Municipalities (–)	Number of Single-Family Houses (–)	Average Surface Area Per Floor (m^2)	Number of Floors (–)	Single-Family Houses in the Residential Building Stock (%)	Single-Family Houses Built before 2008 (%)
Rural	DX-D2	90	31,743	93.13	2.72	59.22	91.95
	DX-E1	4	740	75.87	3.11	92.62	95.68
	EX-D2	6	909	90.85	2.78	80.09	91.20
	EX-E1	20	3457	89.21	2.75	78.75	90.31
	EY-E1 *	44	5573	85.20	2.74	53.68	93.07
	Total	164	42,422	91.42	2.74	60.34	92.02
Rural revitalization areas	DX-D2	34	9951	90.27	2.83	70.55	93.74
	DX-E1	3	696	74.59	3.13	92.19	95.98
	EX-D2	6	909	90.85	2.78	80.09	91.20
	EX-E1	15	2158	85.84	2.82	88.01	94.21
	EY-E1	37	4116	85.83	2.83	76.82	94.29
	Total	95	17,830	88.12	2.84	74.90	93.88

* Villarta-Quintana is not included, because no data are available for this municipality in [56].

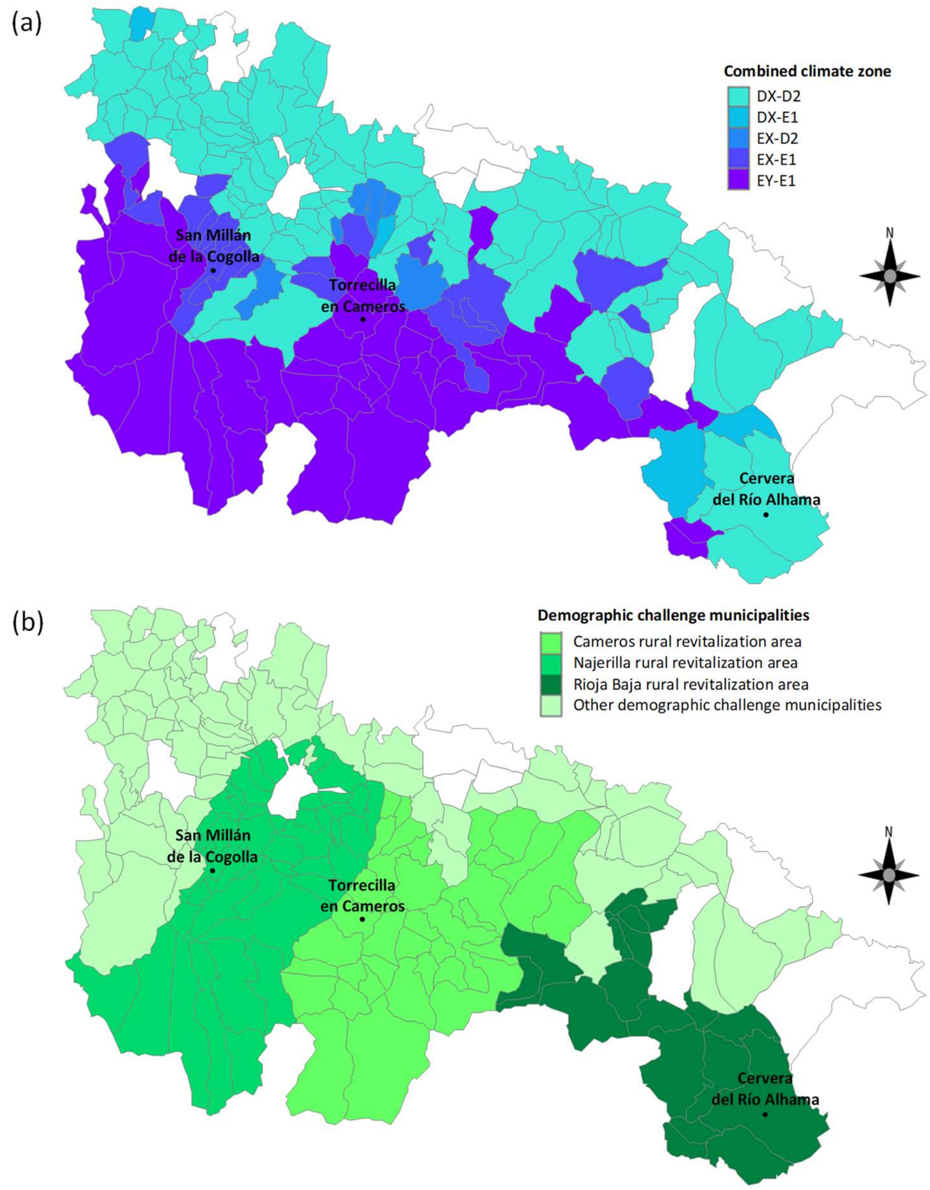

Figure 1. Map of La Rioja: (**a**) the CCZs of the rural municipalities; (**b**) the demographic challenge municipalities.

2.2. Existing Study Buildings Representative of the Rural Revitalization Areas

The selection criteria used to select the representative municipalities of each CCZ were, initially, the selection of the municipality for each rural revitalization area with the greatest number of single-family houses per CCZ. Subsequently, the selection of the representative municipality was prioritized according to the predominance of different CCZs from highest to lowest, that is, following the sequence DX-D2, EY-E1 and EX-E1 (Table 1). Table 2 shows the main characteristics of the single-family houses in the residential building stock of rural revitalization areas, by rural revitalization area and CCZ, highlighting municipalities with the greatest number of single-family houses. With these criteria, Cervera del Río Alhama (Rioja Baja rural revitalization area) was selected as a representative municipality of the CCZ DX-D2, Torrecilla en Cameros (Cameros rural revitalization area) was selected as a representative municipality of the CCZ EY-E1 and San Millán de la Cogolla (Najerilla rural revitalization area) was selected as a representative municipality of the CCZ EX-E1 (Table 2). In Cervera del Río Alhama, 67.66% of the residential building stock comprises single-family houses, with an average floor area of 84.54 m^2 and 2.78 floors on average, with 97.84% of them built before 2008; in San Millan de la Cogolla, 89.41% of the residential building stock comprises single-family houses, with an average floor area of 89.91 m^2 and 3.00 floors on average, with 93.84% of them built before 2008; and in Torrecilla en Cameros, 50.07% of the residential building stock comprises single-family houses, with an average floor area of 84.08 m^2 and 2.52 floors on average, with 95.28% of them built before 2008 (Table 2).

Table 2. Main characteristics of the single-family houses in the residential building stock in rural revitalization areas, by rural revitalization area and CCZ, highlighting those municipalities with the greatest number of single-family houses.

Rural Revitalization Area	CCZ	Municipalities	Number of Municipalities (–)	Number of Single-Family Houses (–)	Average Surface Area per Floor (m^2)	Number of Floors (–)	Single-Family Houses in the Residential Building Stock (%)	Single-Family Houses Built before 2008 (%)
Cameros	DX-D2	Ribafrecha	1	499	84.35	3.15	69.79	86.57
		Total	6	1483	93.41	2.90	60.36	87.73
	DX-E1	Daroca de Rioja	1	71	80.17	2.44	95.95	84.51
		Total	1	71	80.17	2.44	95.95	84.51
	EX-D2	Viguera	1	261	82.64	2.75	63.04	96.55
		Total	2	358	85.29	2.69	69.51	93.30
	EX-E1	Sorzano	1	244	95.87	2.84	82.99	92.21
		Total	4	691	81.98	2.92	83.05	93.78
	EY-E1	Torrecilla en Cameros	1	339	84.08	2.52	50.07	95.28
		Total	22	2372	93.84	2.73	76.52	94.10
	Total		35	4975	91.25	2.80	71.30	91.96
Najerilla	DX-D2	Alesanco	1	649	87.51	2.70	49.06	94.76
		Total	22	5344	94.59	2.78	72.56	93.99
	EX-D2	Matute	1	195	91.45	2.81	97.99	96.41
		Total	4	551	94.46	2.83	88.87	89.84
	EX-E1	San Millán de la Cogolla	1	211	89.91	3.00	89.41	93.84
		Total	9	1150	90.85	2.78	89.56	94.43
	EY-E1	Canales de la Sierra	1	168	84.68	2.55	87.96	92.86
		Total	8	818	78.19	2.84	64.87	93.37
	Total		43	7863	92.33	2.79	74.67	93.70
Rioja Baja	DX-D2	Cervera del Río Alhama	1	1619	84.54	2.78	67.66	97.84
		Total	6	3124	81.38	2.88	72.94	96.16
	DX-E1	Cornago	1	446	67.64	3.15	90.84	98.43
		Total	2	625	73.95	3.21	91.78	97.28
	EX-E1	Préjano	1	255	80.76	2.72	93.75	94.90
		Total	2	317	76.05	2.70	94.35	94.32
	EY-E1	Enciso	1	341	77.60	2.85	89.27	95.01
		Total	7	926	72.09	3.05	92.88	95.57
	Total		17	4992	78.39	2.94	79.28	96.07

Considering the main characteristics of the single-family houses in the rural revitalization areas, a model of the existing characteristic study building for the three CCZs was created. The existing study building is a traditional attached single-family house in representative rural municipalities, consisting of three floors (one ground floor and two upper floors) and having a main façade oriented to the south (Figure 2). The base of the building is rectangular with an area of 85.80 m^2 (7.80 m $\times$ 11 m), and the height of each floor is 3.00 m. The ground floor is uninhabitable, while both the first and second floors are habitable. The roof is gabled and has a height of 2.15 m. The plans of each floor of the building are shown in Figure 3. The window-to-wall ratio is 0.1816, and the building compactness is 2.72 m^3/m^2.

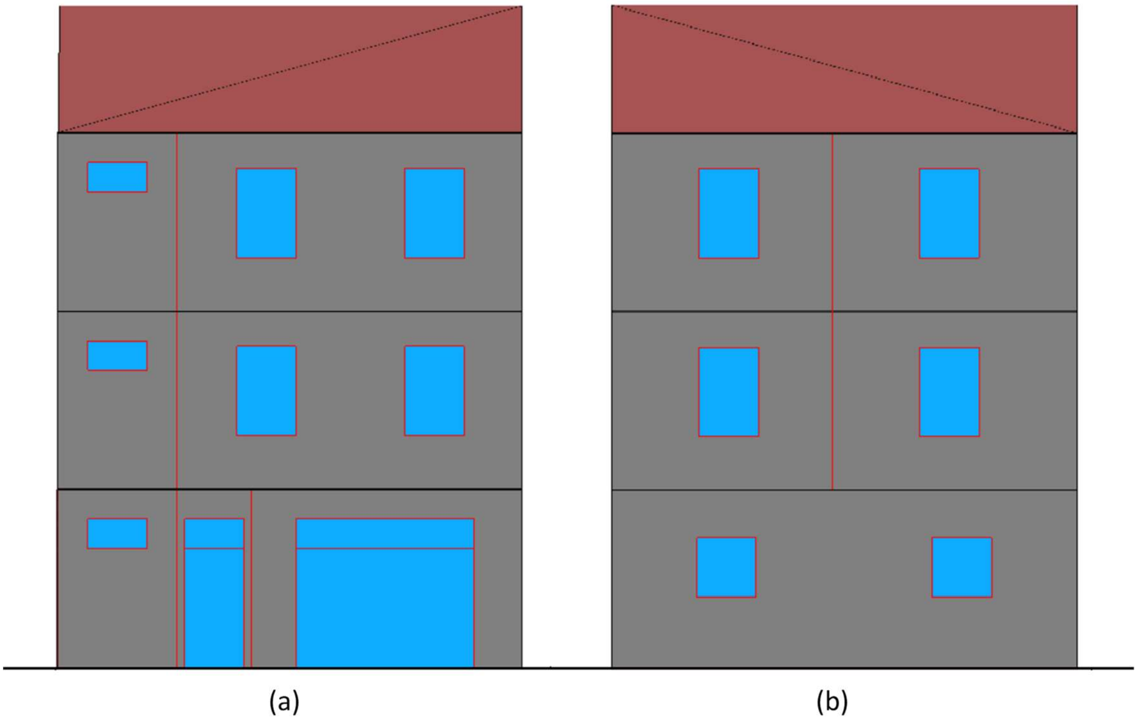

Figure 2. View of the study building: (**a**) south façade and (**b**) north façade.

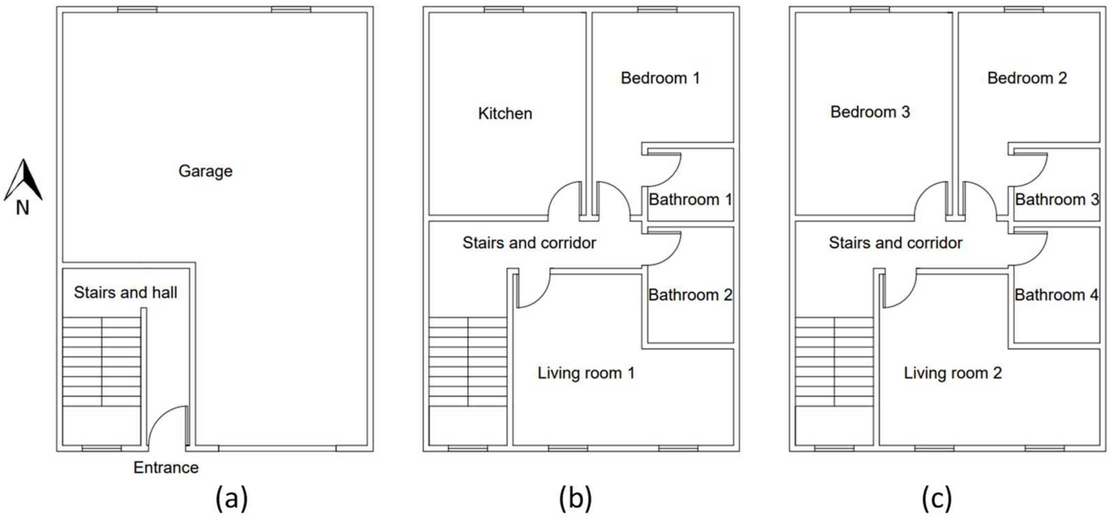

Figure 3. Layout of all the study building floors: (**a**) ground floor, (**b**) first floor and (**c**) second floor.

The main characteristics of the different opaque elements of the thermal envelope and of the interior partitions for the existing study building in the three CCZs are presented in Tables 3–5: the compositions of both the opaque elements and the interior partitions are shown in Table 3, and the thermal transmittance and thicknesses of the original expanded polystyrene (EPS) thermal insulation material with a thermal conductivity of 0.038 W/m·K for each of these elements are shown in Tables 4 and 5. The thermal transmittances, both of the opaque elements of the thermal envelope and of the interior partitions, of the existing study building do not exceed the maximum thermal transmittances set by the NBE-CT-79 [46]. The thermal transmittance of the windows for the existing study building for the three CCZs is 4.65 W/m^2·K. These windows are single-pane glass, with a thermal transmittance of 5.70 W/m^2·K and a g-value of 0.850, within a wooden frame, with a thermal transmittance of 2.20 W/m^2·K and an absorptivity of 0.70. The window frame fraction is 30%, and its air permeability is 27 m^3/h·m^2 with an overpressure of 100 Pa. In addition, the windows have blinds. The doors for the existing study building in the three CCZs are made of medium-density wood with a thermal transmittance of 2.20 W/m^2·K and an absorptivity of 0.70, and the air permeability is 27 m^3/h·m^2 with an overpressure of 100 Pa. Finally, the thermal bridges of the existing study building are those considered by default [58,59].

Table 3. Composition and main characteristics of the opaque elements of the thermal envelope and the interior partitions for the study building. An asterisk (*) indicates that the thickness of thermal insulation material is variable in each case.

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	Original EPS expanded polystyrene (0.038 W/m·K)	*	0.038	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 1/2 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 40mm < E < 60 mm	0.060	0.445	1000	1000
	5	Original EPS expanded polystyrene (0.038 W/m·K)	*	0.038	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	Original EPS expanded polystyrene (0.038 W/m·K)	*	0.038	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	Original EPS expanded polystyrene (0.038 W/m·K)	*	0.038	30	1000
	5	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000

Table 3. *Cont.*

Element	Layer	Material	Thickness (m)	Thermal Conductivity (W/m·K)	Density (kg/m³)	Specific Heat (J/kg·K)
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	Original EPS expanded polystyrene (0.038 W/m·K)	*	0.038	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	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	Original EPS expanded polystyrene (0.038 W/m·K)	*	0.038	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	High-hardness plaster 1200 < d < 1500	0.015	0.560	1350	1000

Table 4. Thermal transmittances (U), in W/m^2·K, and thicknesses of thermal insulation material (t), in m, for ground floor, first-floor framework, roof-floor framework, mezzanine framework, dividing walls and vertical interior partitions of the existing and renovated building by CCZ.

		Existing Building		Renovated Building							
		Original EPS		EPS		MW		PUR		XPS	
CCZ	Element	U	T	U	t *	U	t *	U	t *	U	t *
DX-D2	Ground floor	1.56	0.005	0.46	0.055	0.51	0.045	0.45	0.040	0.47	0.050
	First-floor framework	1.29	0.010	0.46	0.050	0.51	0.040	0.46	0.035	0.48	0.045
	Roof-floor framework	1.29	0.010	0.46	0.050	0.51	0.040	0.46	0.035	0.48	0.045
	Mezzanine framework	1.96	-	1.08	0.015	1.05	0.015	1.10	0.010	1.05	0.015
	Dividing walls	1.58	0.005	0.46	0.055	0.51	0.045	0.45	0.040	0.48	0.050
	Vertical interior partitions	2.79	-	1.09	0.020	1.06	0.020	1.04	0.015	1.06	0.020
EX-E1	Ground floor	1.56	0.005	0.46	0.055	0.51	0.045	0.45	0.040	0.47	0.050
	First-floor framework	1.29	0.010	0.46	0.050	0.51	0.040	0.46	0.035	0.48	0.045
	Roof-floor framework	1.29	0.010	0.46	0.050	0.51	0.040	0.46	0.035	0.48	0.045
	Mezzanine framework	1.96	-	0.94	0.020	0.91	0.020	0.90	0.015	0.91	0.020
	Dividing walls	1.58	0.005	0.46	0.055	0.51	0.045	0.45	0.040	0.48	0.050
	Vertical interior partitions	2.79	-	0.95	0.025	0.91	0.025	0.86	0.020	0.91	0.025

Table 4. *Cont.*

		Existing Building		Renovated Building							
		Original EPS		EPS		MW		PUR		XPS	
CCZ	Element	U	T	U	t *	U	t *	U	t *	U	t *
EY-E1	Ground floor	1.29	0.010	0.46	0.050	0.48	0.045	0.46	0.035	0.48	0.045
	First-floor framework	1.11	0.015	0.46	0.045	0.48	0.040	0.48	0.030	0.48	0.040
	Roof-floor framework	1.10	0.015	0.46	0.045	0.48	0.040	0.47	0.030	0.48	0.040
	Mezzanine framework	1.96	-	0.94	0.020	0.91	0.020	0.90	0.015	0.91	0.020
	Dividing walls	1.31	0.010	0.46	0.050	0.48	0.045	0.46	0.035	0.48	0.045
	Vertical interior partitions	2.79	-	0.95	0.025	0.91	0.025	0.86	0.020	0.91	0.025

* Thickness of thermal insulation material to be added in energy renovation.

Table 5. Thermal transmittance (U), in W/m^2·K, and thicknesses of the thermal insulation material (t), in m, for roof and walls of the existing and renovated building, by CCZ, heating system and thermal insulation material.

				Roof		Walls	
CCZ	Building	Heating System	Thermal Insulation Material	U	t *	U	t *
DX-D2	Existing	Existing heating oil boiler	Original EPS	1.06	0.015	1.59	0.005
	Renovated	New heating oil boiler	EPS	0.28	0.095	0.27	0.110
			MW	0.23	0.115	0.23	0.125
			PUR	0.28	0.065	0.29	0.070
			XPS	0.33	0.070	0.34	0.080
		New natural gas boiler	EPS	0.25	0.110	0.25	0.120
			MW	0.22	0.125	0.22	0.135
			PUR	0.27	0.070	0.26	0.080
			XPS	0.30	0.080	0.31	0.090
		New biomass boiler	EPS	0.33	0.075	0.32	0.090
			MW	0.28	0.090	0.28	0.100
			PUR	0.34	0.050	0.33	0.060
			XPS	0.35	0.065	0.39	0.065
EX-E1	Existing	Existing heating oil boiler	Original EPS	1.06	0.015	1.59	0.005
	Renovated	New heating oil boiler	EPS	0.25	0.110	0.24	0.125
			MW	0.21	0.130	0.21	0.140
			PUR	0.25	0.075	0.26	0.080
			XPS	0.29	0.085	0.29	0.095
		New natural gas boiler	EPS	0.23	0.125	0.23	0.135
			MW	0.19	0.145	0.19	0.155
			PUR	0.24	0.080	0.24	0.090
			XPS	0.27	0.095	0.27	0.105
		New biomass boiler	EPS	0.29	0.090	0.29	0.100
			MW	0.25	0.105	0.25	0.115
			PUR	0.30	0.060	0.31	0.065
			XPS	0.33	0.070	0.35	0.075

Table 5. *Cont.*

				Roof		Walls	
CCZ	**Building**	**Heating System**	**Thermal Insulation Material**	**U**	**t ***	**U**	**t ***
EY-E1	Existing	Existing heating oil boiler	Original EPS	0.82	0.025	1.31	0.010
	Renovated	New heating oil boiler	EPS	0.25	0.100	0.24	0.120
			MW	0.21	0.120	0.21	0.135
			PUR	0.26	0.065	0.25	0.080
			XPS	0.29	0.075	0.29	0.090
		New natural gas boiler	EPS	0.23	0.115	0.23	0.130
			MW	0.19	0.135	0.19	0.150
			PUR	0.24	0.075	0.24	0.085
			XPS	0.27	0.085	0.27	0.100
		New biomass boiler	EPS	0.29	0.080	0.29	0.095
			MW	0.25	0.095	0.25	0.110
			PUR	0.31	0.050	0.30	0.065
			XPS	0.32	0.065	0.35	0.070

* In the existing building, thickness of the thermal insulation material; in the renovated building, thickness of the thermal insulation material to be added.

Heating and domestic hot water (DHW) needs are met using (a) a heating oil boiler with a thermal performance of 0.70 [60] in the existing study building that has not replaced the boiler or (b) a heating oil boiler with a thermal performance of 0.85 [61] in the existing study building with a boiler replaced between 1981 and 2007. The heating system consists of radiators, and there is no solar thermal system for the DHW. In addition, all electrical energy needs are met by connections to the electrical grid.

2.3. Proposals for Energy Renovation and Case Studies

The energy renovation of the existing study building in the three CCZs was conducted, seeking to comply with the CTE-DB-HE [52] (Table A1). The CTE-DB-HE [52] specifies that energy-renovated buildings must meet a series of requirements related to the limitation on energy consumption (CTE-DB-HE0), the conditions for controlling energy demand (CTE-DB-HE1) and the minimum renewable energy contribution to meet DHW demand (CTE-DB-HE4). In addition, the building must meet the requirements of the CTE-DB-HE0 [52] for new buildings if an NZEB is desired.

On the one hand, the following energy renovation measures are proposed for implementation in the thermal envelope and interior partitions:

- Reduction in the thermal transmittance of the ground floor, first-floor framework, mezzanine framework, roof-floor framework, dividing walls and vertical interior partitions by adding the thermal insulation thicknesses necessary to not exceed the corresponding thermal transmittance limit according to CTE-DB-HE1 [52], using the following thermal insulation materials: EPS with a thermal conductivity of 0.036 W/m·K, mineral wool (MW) with a thermal conductivity of 0.034 W/m·K, polyurethane (PUR) with a thermal conductivity of 0.025 W/m·K and extruded polystyrene (XPS) with a thermal conductivity of 0.034 W/m·K.
- Reduction in the thermal transmittance of roof and walls by adding the optimal thermal insulation thicknesses to minimize total heating costs, applying the life cycle cost analysis [47,48,62,63], taking into account both the thermal insulation materials to be used, as mentioned above, and the heating systems to be used, which are a heating oil boiler with a thermal performance of 0.92, a natural gas boiler with a thermal performance of 0.92 and a biomass boiler with a thermal performance of 0.85.

- Replacement of existing windows and doors with new ones. The thermal transmittance of the new windows is 1.38 W/m^2·K. These windows are low-emissive double-pane glass and filled with argon gas, with a thermal transmittance of 1.20 W/m^2·K and a g-value of 0.791, and a three-chamber PVC frame, with a thermal transmittance of 1.80 W/m^2·K and an absorptivity of 0.70. The window frame fraction is 30%, and its air permeability is 9 m^3/h·m^2 with an overpressure of 100 Pa. In addition, new windows have blinds. The new doors are made of medium-low-density wood, with a thermal transmittance of 2.00 W/m^2·K and an absorptivity of 0.70, and the air permeability is 9 m^3/h·m^2 with an overpressure of 100 Pa.

On the other hand, the following energy renovation measures are proposed for implementation, both in the heating and DHW systems and in the incorporation of renewable energies:

- Replacement of the existing heating and DHW system with a new system.
- Incorporation of a solar thermal system.
- Incorporation of a solar photovoltaic system without and with the possibility of selling surplus production to the electrical grid.

Table 4 shows the thermal transmittance of the ground floor, first-floor framework, roof-floor framework, mezzanine framework, dividing walls and vertical interior partitions, and the thicknesses of EPS, MW, PUR and XPS thermal insulation materials to add in the energy renovation of each of these elements to comply with the CTE-DB-HE1 [52] (Table A1) for the existing study building in the three CCZs.

The optimal thickness of the thermal insulation material to be added to the roof or walls, e, of the existing study building to minimize the total heating cost, $x_{opt,e}$, in m, applying the life cycle cost analysis, is obtained by the following equation [47,48]:

$$x_{opt,e} = \left(\frac{0.024 \cdot HDD \cdot C_{fuel} \cdot \lambda_{insu} \cdot PWF}{\eta \cdot C_{insu}}\right)^{0.5} - \lambda_{insu} \cdot R_e^{exis} \quad (1)$$

where HDD represents the heating degree days for a base temperature of 20 °C, in °C·day/year, and is 2857 °C·day/year and 3548 °C·day/year for the climate zones D2 and E1 according to the CTE-DB-HE [52], respectively, according to [64]; C_{fuel} is the price of fuel used, in EUR/kWh, indicated in Table 6; λ_{insu} is the thermal conductivity of the thermal insulation material, in W/m·K; PWF is the present worth factor, dimensionless, with a value of 21.10 because the study is carried out in Spain [47,48]; η is the thermal performance of the heating system used, per unit; C_{insu} is the price of the thermal insulation material used, in EUR/m^3, indicated in Table 6; and R_e^{exis} is the thermal resistance of the element e of the thermal envelope of the existing study building, in m^2·K/W, being 0.94 m^2·K/W for the roof and 0.63 m^2·K/W for the walls in the climate zones DX and EX according to the NBE-CT-79 [46] and 1.22 m^2·K/W for the roof and 0.76 m^2·K/W for the walls in the climate zone EY according to NBE-CT-79 [46] (Tables 3 and 5).

Table 6. Cost of the energy carriers for the starting year, cost of the different energy renovation measures and estimated investment cost of the reference buildings.

		Unit	Value	Reference
Energy carrier	Heating oil	EUR/kWh	0.0743	[65]
	Natural gas	EUR/kWh	0.0879	[66]
	Biomass	EUR/kWh	0.0491	[67]
	Electricity (bought with an annual consumption between 2500 and 5000 kWh)	EUR/kWh	0.2399	[68]
	Electricity (sold)	EUR/kWh	0.0479	[69]

Table 6. *Cont.*

		Unit	Value	Reference
Thermal envelope and interior partitions	EPS with a thermal conductivity of 0.036 W/m·K	EUR/m^3	246.49	[70]
	MW with a thermal conductivity of 0.034 W/m·K	EUR/m^3	189.32	[70]
	PUR with a thermal conductivity of 0.025 W/m·K	EUR/m^3	384.76	[70]
	XPS with a thermal conductivity of 0.034 W/m·K	EUR/m^3	372.86	[70]
	New window	EUR/m^2	402.33	[70]
	New door	EUR/m^2	949.47	[70]
	New garage door	EUR/m^2	1620.90	[71]
Heating and DHW system	Heating oil boiler of 30 kW	EUR	4136.47	[70]
	Natural gas boiler of 30 kW	EUR	3251.21	[70]
	Biomass boiler of 45 kW	EUR	5671.23	[70]
	Radiator of 4 elements of type 1 (331.6 W)	EUR	161.31	[71]
	Radiator of 5 elements of type 1 (414.5 W)	EUR	185.77	[71]
	Radiator of 6 elements of type 1 (497.4 W)	EUR	210.19	[71]
	Radiator of 5 elements of type 2 (777.5 W)	EUR	180.96	[71]
	Radiator of 6 elements of type 2 (933 W)	EUR	204.41	[71]
	Radiator of 7 elements of type 2 (1088.5 W)	EUR	227.90	[71]
	Radiator of 8 elements of type 2 (1244 W)	EUR	251.34	[71]
	Radiator of 9 elements of type 2 (1399.5 W)	EUR	274.84	[71]
	Radiator of 10 elements of type 2 (1555 W)	EUR	298.34	[71]
	All the required additional elements for the heating and DHW system	EUR	3489.64	[70]
Solar thermal system	Solar thermal panel (1.92 m^2, optical efficiency factor of 0.729 and overall loss factor of 4.357 W/m^2·K)	EUR	716.83	[70]
	Structure for 2 solar thermal panels	EUR	160.53	[70]
	DHW storage tank (200 l)	EUR	1263.53	[70]
	All the required additional elements for the solar thermal system	EUR	1096.83	[70]
Solar photovoltaic system	Solar photovoltaic panel (1.80 kW in cases EE2 and 2.40 kW in cases EE3)	EUR/W	1.15	[70]
	Structure for solar photovoltaic panels	EUR/W	0.47	[70]
	Inverter (1.50 kW in cases EE2 and 2.00 kW in cases EE3)	EUR/W	0.50	[70]
	Dynamic power controller (to ensure zero injection to the electrical grid in cases EE2)	EUR	106.95	Estimated
	All the required additional elements for the solar photovoltaic system in cases EE2	EUR	184.06	[70]
	All the required additional elements for the solar photovoltaic system in cases EE3	EUR	245.40	[70]

Table 6. *Cont.*

		Unit	Value	Reference
Estimated investment cost of the reference buildings	Case DX-D2-S1-NoInsu-EE1	EUR	5735.58	Estimated from [70] and [71]
	Case EX-E1-S1-NoInsu-EE1	EUR	5901.78	Estimated from [70] and [71]
	Case EY-E1-S1-NoInsu-EE1	EUR	5700.86	Estimated from [70] and [71]
	Case DX-D2-S2-NoInsu-EE1	EUR	8603.37	Estimated from [70] and [71]
	Case EX-E1-S2-NoInsu-EE1	EUR	8852.66	Estimated from [70] and [71]
	Case EY-E1-S2-NoInsu-EE1	EUR	8551.28	Estimated from [70] and [71]

After applying Equation (1), Table 5 shows the thermal transmittance of the roof and walls and the thicknesses of the EPS, MW, PUR and XPS thermal insulation materials, rounded to the nearest commercial thickness, to add in the energy renovation of each of these elements, according to the heating system used.

In total, 50 cases were studied for each CCZ: 2 cases for the existing study building and 48 cases for the energy-renovated building. Each case study has been named using the nomenclature CCZ-Sx-Insu-EEx, where CCZ corresponds to the CCZ (DX-D2, EX-E1 and EY-E1); Sx corresponds to the system used to meet heating and DHW needs (S1, S2, S3, S4, S5 and S6) consisting of a boiler, and in some cases, supported by a solar thermal system; Insu corresponds to the thermal insulation material to be added (EPS, MW, PUR and XPS), using NoInsu (no thermal insulation material added) for the case of the existing study building; and EEx refers to the alternatives used to meet electrical energy needs (EE1, EE2 and EE3).

To meet the heating and DHW needs of the study building, the following six systems were studied:

- S1: Heating oil boiler with a thermal performance of 0.70 to meet heating and DHW needs.
- S2: Heating oil boiler with a thermal performance of 0.85 to meet heating and DHW needs.
- S3: Heating oil boiler with a thermal performance of 0.92 to meet heating and DHW needs and a solar thermal system to meet a portion of the DHW needs.
- S4: Natural gas boiler with a thermal performance of 0.92 to meet the heating and DHW needs and a solar thermal system to meet a portion of the DHW needs.
- S5: Biomass boiler with a thermal performance of 0.85 to meet the heating and DHW needs.
- S6: Biomass boiler with a thermal performance of 0.85 to meet the heating and DHW needs and a solar thermal system to meet a portion of the DHW needs.

To meet the electrical energy needs of the study building, the following three alternatives were considered:

- EE1: Electrical energy needs are met by connecting to the electrical grid.
- EE2: Electrical energy needs are met by connecting to the electrical grid and using a solar photovoltaic system without selling surpluses to the electrical grid.
- EE3: Electrical energy needs are met by connecting to the electrical grid and using a solar photovoltaic system with the possibility of selling surpluses to the electrical grid.

2.4. Heating System, Solar Thermal System and Solar Photovoltaic System

The heating system for the existing buildings has been estimated, and the heating system has been designed for energy renovation solutions. All the heating systems are monotube systems.

The DHW energy demand has been assessed as required by the CTE-DB-HE [52], and the solar contribution for DHW has been assessed using the f-chart method [72], with the solar thermal system meeting at least 60% of the DHW energy demand (Table A1). The average daily irradiance data were obtained from PVGIS [51], and data on the necessary temperatures were obtained from CTE-DB-HE [52] and PVGIS [51]. The annual solar contribution to DHW achieved by the solar thermal system in cases S3, S4 and S6 is 71.82% for the CCZ DX-D2, 61.40% for the CCZ EX-E1 and 61.27% for the CCZ EY-E1 (Figure A1).

The resulting boiler power for heating and DHW is 50 kW in cases S1 and S2, 30 kW in cases S3 and S4, and 45 kW in cases S5 and S6.

To correctly implement a solar photovoltaic system, it must be designed and dimensioned, taking into account whether there is the possibility of selling surpluses to the electrical grid and making the relevant electrical energy balances:

$$E_{needs,mon} + E_{surplus,mon} = E_{consump,mon} + E_{PV,mon} \tag{2}$$

where $E_{needs,mon}$ are the monthly electrical energy needs, in kWh/month, estimated from the average Spanish electricity consumption per household [73]; $E_{surplus,mon}$ is the monthly surplus electrical energy generated by the solar photovoltaic system, in kWh/month; $E_{consump,mon}$ is the monthly electrical energy consumed by the electrical grid, in kWh/month; and $E_{PV,mon}$ is the monthly electrical energy generated by the solar photovoltaic system, in kWh/month, calculated according to the Technical Specifications for Installations Connected to the Electrical Grid for Solar Photovoltaic Energy Installations of IDAE [74]. The monthly irradiation on the plane of the generator and the monthly ambient temperature were obtained from PVGIS [51].

Equation (2) must be met in case EE3. Applying Equation (2) for the remaining cases shows that Equation (3) should be applied in case EE1 and Equation (4) should be applied in case EE2:

$$E_{needs,mon} = E_{consump,mon} \tag{3}$$

$$E_{needs,mon} = E_{consump,mon} + E_{PV,mon} \tag{4}$$

Using the solar photovoltaic systems, 75.10% of the electrical energy needs are met for the CCZ DX-D2, 67.94% for the CCZ EX-E1 and 68.10% for the CCZ EY-E1 in case EE2; the percentages in case EE3 are 86.13% for the CCZ DX-D2, 80.68% for the CCZ EX-E1 and 80.30% for the CCZ EY-E1 (Figure A2). To assess the electrical energy needs met by solar photovoltaic systems, a calculation period of 30 years [25], a lifetime of 25 years and an annual degradation rate of 0.9% for solar photovoltaic panels were used [75].

2.5. Energy and Environmental Impacts and Requirements of CTE-DB-HE

The energy impact (energy demand, final energy consumption, non-renewable primary energy consumption and energy performance rating in non-renewable primary energy consumption) and the environmental impact (CO_2 emissions and energy performance rating in CO_2 emissions), both broken down by heating, cooling and DHW services as well as the total of the three services, in each case study, were assessed using HULC 2017 [58]. HULC 2017 [58] is the official energy simulation tool in Spain to verify compliance with the previous CTE-DB-HE [76] and to obtain the energy performance certification of buildings. HULC 2017 [58] was used in other research works about energy renovation of residential buildings such as [48]. Table A1 presents the requirements that the energy-renovated building must meet to comply with the current CTE-DB-HE [52] as a renovated building and as a new building. In addition, if only an NZEB is desired, the requirements of the CTE-DB-HE0 [52] must be met for new buildings. Given that HULC 2020 [77] (the new version of HULC) is in the testing phase, HULC 2017 [58] (the previous version of HULC) was used. Therefore, it was necessary to adapt the verification methodology of the previous CTE-DB-HE [76] to verify the current CTE-DB-HE [52]. Although no cooling system was designed or used in this study, HULC 2017 [58] considers, by default, an electric cooling system with a thermal efficiency of 2.00 to meet cooling needs. HULC 2017 [58] also considers operational conditions and use profiles required by the current CTE-DB-HE [52]. In addition, 1.50 air changes per hour were considered for the existing study building [78,79], while 0.63 air changes per hour were considered for the energy-renovated building [58].

To verify compliance with the current CTE-DB-HE [52], it was necessary to verify compliance with its different requirements:

- To verify compliance with the current CTE-DB-HE0 [52], the total primary energy consumption was assessed based on the final energy consumption of the different services and considering the conversion factors from final energy to total primary energy of the different energy carriers [80].
- To verify compliance with the current CTE-DB-HE1 [52], the calculation methods used to assess the global heat transfer coefficient through the thermal envelope of the building, the solar control parameter and the air change ratio with a differential pressure of 50 Pa are indicated by CTE-DB-HE [52] and Supporting Document 1 associated with the CTE-DB-HE [81]. The global heat transfer coefficient through the thermal envelope of the building was assessed by considering the corresponding linear and point thermal transmittance of the different thermal bridges, ensuring the continuity of the thermal insulation in cases of energy renovation according to Supporting Document 3 associated with the CTE-DB-HE [59]. In addition, the absence of surface and interstitial condensation was verified following the indications of Supporting Document 2 associated with the CTE-DB-HE [82].
- To verify compliance with the current CTE-DB-HE4 [52], the renewable energy contribution to meet DHW demand was assessed by considering the conversion factors from final energy to renewable primary energy and to total primary energy of the different energy carriers [80].

The energy impact (final energy consumption, non-renewable primary energy consumption and total primary energy consumption) and the environmental impact (CO_2 emissions) of electrical energy in each case study were assessed by considering the indications in Section 2.4 and the different conversion factors of electricity [80].

Finally, to verify compliance with the CTE-DB-HE [52] in each case study, the heating, cooling and DHW services were considered, discounting the solar thermal energy for DHW and/or the self-consumed electrical energy from solar photovoltaic systems used for these services (heating, cooling and DHW). Additionally, to assess the energy and environmental impact for each case study, the final energy consumption of heating, DHW and electricity was considered, discounting the solar thermal energy for DHW and/or the self-consumed electrical energy from the solar photovoltaic systems.

2.6. Economic Impact

The economic impact of the different energy renovation solutions was assessed by applying the Commission Delegated Regulation (EU) No. 244/2012 [25] and the accompanying guidelines [83]. The Commission Delegated Regulation (EU) No. 244/2012 [25] establishes the comparative methodological framework to be used by the EU Member States to calculate the optimal profitability of the minimum energy efficiency requirements of new and existing buildings and their elements.

The global cost throughout the calculation period, τ, in years, referring to the starting year (τ_0), $C_g(\tau)$, in EUR, was calculated using the following formula:

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{m,i}(j) \cdot R_d(i) + C_{r,i}(j) \cdot R_d(i) + C_{e,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \quad (5)$$

where C_I is the initial investment cost of the set of measures in EUR; $C_{m,i}(j)$ is the maintenance cost during year i for each measure j of the set of measures in EUR; $C_{r,i}(j)$ is the replacement cost during year i for each measure j of the set of measures in EUR; $C_{e,i}(j)$ is the energy cost during year i for each measure j of the set of measures in EUR; $V_{f,\tau}(j)$ is the residual value of each measure j of the set of measures at the end of the calculation period τ in EUR; and $R_d(i)$ is the discount factor for the year i.

$R_d(i)$ is calculated using the following formula:

$$R_d(i) = \left(\frac{1}{1 + (r/100)}\right)^i \tag{6}$$

where r is the real discount rate in %.

The following was considered when assessing the economic impact in all the case studies:

- The calculation period is 30 years [25].
- Real discount rates of 2%, 3% and 4% were used to ensure an accurate sensitivity analysis [25,83].
- The reference buildings are the existing study buildings corresponding to the cases CCZ-S1-NoInsu-EE1 and CCZ-S2-NoInsu-EE1 in each CCZ.
- The initial investment costs for the reference buildings were estimated to assess the maintenance costs, the replacement costs and the respective residual values. These initial investment costs correspond to the heating and DHW systems and were estimated from [70,71] (Table 6).
- The sets of energy renovation measures assessed correspond to the 48 energy renovation solutions proposed in each CCZ.
- The initial investment cost of each different proposed energy renovation measure was assessed using Table 6.
- For the thermal envelope and interior partitions, the lifetime is 50 years [84].
- For systems that meet heating and DHW needs, including solar thermal systems in the corresponding cases, the annual maintenance cost is 2% of the investment cost for cases S1, S2, S3 and S4, and 2.5% of the investment cost for cases S5 and S6, and the lifetime is 20 years [85].
- For solar photovoltaic systems in cases EE2 and EE3, the annual maintenance cost is 1% of the investment cost, and the lifetime is 25 years [75].
- The maintenance costs and the lifetime considered for the different case studies are among the typical values in this type of economic study [86].
- The energy cost was obtained from the price of fuels used and electricity (Table 6). The annual variation rates of energy prices are 3.50% for heating oil according to the evolution of its prices in the period 2009–2019 [65], 4.50% for natural gas according to the evolution of its prices in the period 2009–2019 [66], 2.50% for biomass according to the evolution of its prices in the period 2015–2019 [67] and 4.00% for electricity according to the evolution of its prices in the period 2009–2019 [68].

Finally, in rural revitalization areas, the impacts of the application of the subsidies of the PREE 5000 Programme [40], regulated by Royal Decree 691/2021 [87], and of the aid of the incentive program for implementing self-consumption installations, approved by Royal Decree 477/2021 [88], are assessed, and the number of single-family houses that can benefit is determined.

3. Results and Discussion

3.1. Verification of Compliance with the CTE-DB-HE

After simulating all the case studies in Cervera del Río Alhama (CCZ DX-D2), San Millán de la Cogolla (CCZ EX-E1) and Torrecilla en Cameros (CCZ EY-E1) with HULC 2017 [58], compliance with CTE-DB-HE [52] was verified, as shown in Tables A2–A4. The existing study buildings in the three CCZs do not meet the CTE-DB-HE [52] as renovated buildings, as new buildings or as NZEBs (buildings that meet the CTE-DB-HE0 [52] as new buildings), as was expected (Tables A2–A4). All energy renovation solutions in the three CCZs complied with CTE-DB-HE [52] as renovated buildings (Tables A2–A4). All energy renovation solutions in the CCZ DX-D2 and 93.75% of the energy renovation solutions in the CCZs EX-E1 and EY-E1 are NZEBs (Tables A2–A4). The energy renovation solutions corresponding to cases EX-E1-S3-XPS and EY-E1-S3-XPS cannot be NZEBs (Tables A2–A4). In addition, all the energy renovation solutions in the CCZ DX-D2 and 81.25% of the energy renovation solutions in the CCZs EX-E1 and EY-E1 comply with the CTE-DB-HE [52] as new buildings (Tables A2–A4). The energy renovation solutions for cases EX-E1-S5-XPS, EX-E1-S6-XPS, EY-E1-S5-XPS and EY-E1-S6-XPS, in addition to cases EX-E1-S3-XPS and EY-E1-S3-XPS indicated above, do not comply with the CTE-DB-HE [52] as new buildings (Tables A2–A4).

3.2. Energy and Environmental Impacts

After simulating all the case studies in the three CCZs with HULC 2017 [58] and verifying compliance with CTE-DB-HE [52], the energy and environmental impacts were assessed for all the case studies in the three CCZs (Tables 7–9).

3.2.1. Energy Demand and Final Energy Consumption for Heating and DHW

The heating energy demand of the energy renovation solutions is between 14.67 kWh/m^2·year and 20.42 kWh/m^2·year in the CCZ DX-D2, achieving a reduction in that energy demand of between 85.63% and 89.68% with respect to the existing study building (Table 7); between 23.07 kWh/m^2·year and 30.23 kWh/m^2·year in the CCZ EX-E1, achieving a reduction in that energy demand of between 83.41% and 87.34% with respect to the existing study building (Table 8); and between 22.79 kWh/m^2·year and 30.11 kWh/m^2·year in the CCZ EY-E1, achieving a reduction in that energy demand of between 81.37% and 85.90% with respect to the existing study building (Table 9). The lowest heating energy demand is achieved by the solutions that use natural gas boilers with solar thermal support systems and MW thermal insulation material (cases DX-D2-S4-MW, EX-E1-S4-MW and EY-E1-S4-MW), while the highest heating energy demand occurs in the energy renovation solutions using biomass boilers with or without solar thermal support systems and XPS thermal insulation material (cases DX-D2-S5-XPS, EX-E1-S5-XPS, EY-E1-S5-XPS, DX-D2-S6-XPS, EX-E1-S6-XPS and EY-E1-S6-XPS) (Tables 7–9).

The DHW energy demand of all energy renovation solutions is 16.78 kWh/m^2·year in the CCZ DX-D2, 17.09 kWh/m^2·year in the CCZ EX-E1 and 17.17 kWh/m^2·year in the CCZ EY-E1.

The final energy consumption for heating and DHW of the energy renovation solutions is between 21.00 kWh/m^2·year and 54.00 kWh/m^2·year for CCZ DX-D2, achieving a reduction in that energy consumption of between 76.81% and 90.98% with respect to the existing study building with no boiler replacement and between 72.24% and 89.20% with respect to the existing study building with boiler replacement (Table 7); between 31.90 kWh/m^2·year and 69.30 kWh/m^2·year for CCZ EX-E1, achieving a reduction in that energy consumption of between 76.11% and 89.00% with respect to the existing study building with no boiler replacement and between 71.42% and 86.85% with respect to the existing study building with boiler replacement (Table 8); and between 31.60 kWh/m^2·year and 69.10 kWh/m^2·year for CCZ EY-E1, achieving a reduction in that energy consumption of between 73.44% and 87.86% with respect to the existing study building with no boiler replacement and between 68.23% and 85.47% with respect to the existing study building with boiler replacement (Table 9). The lowest final energy consumption for heating and DHW is achieved in energy renovation solutions that use natural gas boilers with solar thermal support systems and MW thermal insulation material (cases DX-D2-S4-MW, EX-E1-S4-MW and EY-E1-S4-MW), while the highest final energy consumption for heating and DHW is obtained in the solutions that use biomass boilers without solar thermal support systems and XPS thermal insulation material (cases DX-D2-S5-XPS, EX-E1-S5-XPS and EY-E1-S5-XPS) (Tables 7–9).

Table 7. Energy, environmental and economic impacts for each case study in Cervera del Río Alhama (CCZ DX-D2).

	HED ($kWh/m^2 \cdot year$)	CED ($kWh/m^2 \cdot year$)	$FEC_{HEAT+DHW}$ ($kWh/m^2 \cdot year$)	FEC_{ELEC} ($kWh/m^2 \cdot year$)	NRPEC ($kWh/m^2 \cdot year$)	TPEC ($kWh/m^2 \cdot year$)	EM ($kg\ CO_2/m^2 \cdot year$)	NRPEC Rating (Rating; $kWh/m^2 \cdot year$)		EM Rating (Rating; $kg\ CO_2/m^2 \cdot year$)		Global Costs (EUR/m^2)
DX-D2-S1-NoInsu-EE1	142.12	4.55	232.90	19.07	311.96	320.56	77.79	E	279.14	E	72.23	751.75
DX-D2-S2-NoInsu-EE1	142.12	4.55	194.50	19.07	266.82	275.30	65.88	E	234.00	E	60.32	675.24
DX-D2-S3-EPS-EE1	16.38	4.05	22.80	19.07	64.11	72.08	13.32	A	30.81	A	7.68	481.97
DX-D2-S4-EPS-EE1	15.60	4.05	22.00	19.07	63.41	71.42	11.85	A	30.10	A	6.21	493.28
DX-D2-S5-EPS-EE1	18.15	4.04	50.20	19.07	43.06	101.03	7.53	A	9.74	A	1.90	473.40
DX-D2-S6-EPS-EE1	18.15	4.04	36.10	19.07	41.86	85.34	7.28	A	8.54	A	1.64	502.47
DX-D2-S3-MW-EE1	15.21	4.04	21.50	19.07	62.60	70.56	12.93	A	29.29	A	7.29	463.56
DX-D2-S4-MW-EE1	14.67	4.05	21.00	19.07	62.23	70.23	11.60	A	28.91	A	5.96	473.55
DX-D2-S5-MW-EE1	16.95	4.04	48.30	19.07	42.76	98.92	7.47	A	9.44	A	1.83	456.03
DX-D2-S6-MW-EE1	16.95	4.04	34.20	19.07	41.56	83.22	7.22	A	8.24	A	1.58	485.10
DX-D2-S3-PUR-EE1	17.03	4.03	23.50	19.07	64.93	72.90	13.53	A	31.61	A	7.89	488.50
DX-D2-S4-PUR-EE1	16.10	4.04	22.50	19.07	64.01	72.02	11.97	A	30.70	A	6.33	499.77
DX-D2-S5-PUR-EE1	18.62	4.03	50.90	19.07	43.18	101.81	7.56	A	9.86	A	1.92	479.41
DX-D2-S6-PUR-EE1	18.62	4.03	36.80	19.07	41.98	86.12	7.31	A	8.65	A	1.67	508.48
DX-D2-S3-XPS-EE1	18.72	4.03	25.30	19.07	67.03	75.00	14.07	A	33.71	A	8.43	505.35
DX-D2-S4-XPS-EE1	17.62	4.04	24.10	19.07	65.91	73.93	12.38	A	32.59	A	6.73	518.09
DX-D2-S5-XPS-EE1	20.42	4.00	54.00	19.07	43.68	105.26	7.67	A	10.32	A	2.02	497.27
DX-D2-S6-XPS-EE1	20.42	4.00	39.90	19.07	42.48	89.57	7.42	A	9.12	A	1.77	526.34
DX-D2-S3-EPS-EE2	16.38	4.05	22.80	4.75	36.13	38.16	8.58	A	26.85	A	7.01	395.52
DX-D2-S4-EPS-EE2	15.60	4.05	22.00	4.75	35.43	37.50	7.11	A	26.15	A	5.54	406.84
DX-D2-S5-EPS-EE2	18.15	4.04	50.20	4.75	15.08	67.12	2.79	A	5.79	A	1.23	386.95
DX-D2-S6-EPS-EE2	18.15	4.04	36.10	4.75	13.88	51.42	2.54	A	4.59	A	0.97	416.02
DX-D2-S3-MW-EE2	15.21	4.04	21.50	4.75	34.62	36.65	8.19	A	25.34	A	6.62	377.12
DX-D2-S4-MW-EE2	14.67	4.05	21.00	4.75	34.25	36.32	6.86	A	24.96	A	5.29	387.10
DX-D2-S5-MW-EE2	16.95	4.04	48.30	4.75	14.78	65.00	2.73	A	5.50	A	1.16	369.59
DX-D2-S6-MW-EE2	16.95	4.04	34.20	4.75	13.58	49.31	2.48	A	4.30	A	0.91	398.66
DX-D2-S3-PUR-EE2	17.03	4.03	23.50	4.75	36.95	38.98	8.79	A	27.67	A	7.22	402.05

Table 7. *Cont.*

	HED (kWh/m^2·year)	CED (kWh/m^2·year)	$FEC_{HEAT+DHW}$ (kWh/m^2·year)	FEC_{ELEC} (kWh/m^2·year)	NRPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	EM (kg CO_2/m^2·year)	NRPEC Rating (Rating; kWh/m^2·year)		EM Rating (Rating; kg CO_2/m^2·year)		Global Costs (EUR/m^2)
DX-D2-S4-PUR-EE2	16.10	4.04	22.50	4.75	36.03	38.10	7.23	A	26.75	A	5.66	413.32
DX-D2-S5-PUR-EE2	18.62	4.03	50.90	4.75	15.20	67.89	2.82	A	5.92	A	1.25	392.97
DX-D2-S6-PUR-EE2	18.62	4.03	36.80	4.75	14.00	52.20	2.57	A	4.71	A	1.00	422.04
DX-D2-S3-XPS-EE2	18.72	4.03	25.30	4.75	39.05	41.09	9.33	A	29.77	A	7.76	418.90
DX-D2-S4-XPS-EE2	17.62	4.04	24.10	4.75	37.93	40.01	7.64	A	28.65	A	6.06	431.64
DX-D2-S5-XPS-EE2	20.42	4.00	54.00	4.75	15.70	71.34	2.93	A	6.41	A	1.36	410.83
DX-D2-S6-XPS-EE2	20.42	4.00	39.90	4.75	14.50	55.65	2.68	A	5.21	A	1.11	439.90
DX-D2-S3-EPS-EE3	16.38	4.05	22.80	2.65	32.02	33.18	7.89	A	26.85	A	7.01	382.22
DX-D2-S4-EPS-EE3	15.60	4.05	22.00	2.65	31.32	32.52	6.42	A	26.15	A	5.54	393.53
DX-D2-S5-EPS-EE3	18.15	4.04	50.20	2.65	10.97	62.14	2.10	A	5.79	A	1.23	373.65
DX-D2-S6-EPS-EE3	18.15	4.04	36.10	2.65	9.77	46.44	1.85	A	4.59	A	0.97	402.72
DX-D2-S3-MW-EE3	15.21	4.04	21.50	2.65	30.51	31.67	7.50	A	25.34	A	6.62	363.82
DX-D2-S4-MW-EE3	14.67	4.05	21.00	2.65	30.14	31.34	6.17	A	24.96	A	5.29	373.80
DX-D2-S5-MW-EE3	16.95	4.04	48.30	2.65	10.67	60.02	2.04	A	5.50	A	1.16	356.29
DX-D2-S6-MW-EE3	16.95	4.04	34.20	2.65	9.47	44.33	1.79	A	4.30	A	0.91	385.36
DX-D2-S3-PUR-EE3	17.03	4.03	23.50	2.65	32.84	34.00	8.10	A	27.67	A	7.22	388.75
DX-D2-S4-PUR-EE3	16.10	4.04	22.50	2.65	31.92	33.13	6.54	A	26.75	A	5.66	400.02
DX-D2-S5-PUR-EE3	18.62	4.03	50.90	2.65	11.09	62.92	2.13	A	5.92	A	1.25	379.67
DX-D2-S6-PUR-EE3	18.62	4.03	36.80	2.65	9.89	47.22	1.88	A	4.71	A	1.00	408.74
DX-D2-S3-XPS-EE3	18.72	4.03	25.30	2.65	34.94	36.11	8.64	A	29.77	A	7.76	405.60
DX-D2-S4-XPS-EE3	17.62	4.04	24.10	2.65	33.82	35.03	6.95	A	28.65	A	6.06	418.34
DX-D2-S5-XPS-EE3	20.42	4.00	54.00	2.65	11.59	66.37	2.24	A	6.41	A	1.36	397.53
DX-D2-S6-XPS-EE3	20.42	4.00	39.90	2.65	10.39	50.67	1.99	A	5.21	A	1.11	426.60

Note: HED is heating energy demand; CED is cooling energy demand; $FEC_{HEAT+DHW}$ is final energy consumption for heating and domestic hot water (DHW); FEC_{ELECT} is final energy consumption for electricity; NRPEC is non-renewable primary energy consumption for heating, DHW and electricity; TPEC is total primary energy consumption for heating, DHW and electricity; EM is CO_2 emissions for heating, DHW and electricity; NRPEC rating is non-renewable primary energy consumption rating according to CTE-DB-HE [52]; EM rating is CO_2 emissions rating according to CTE-DB-HE [52].

Table 8. Energy, environmental and economic impacts for each case study in San Millán de la Cogolla (CCZ EX-E1).

	HED (kWh/m^2·year)	CED (kWh/m^2·year)	FEC$_{HEAT+DHW}$ (kWh/m^2·year)	FEC$_{ELEC}$ (kWh/m^2·year)	NRPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	EM (kg CO_2/m^2·year)	NRPEC Rating (Rating; kWh/m^2·year)		EM Rating (Rating; kg CO_2/m^2·year)		Global Cost (EUR/m^2)
EX-E1-S1-NoInsu-EE1	182.18	0.38	290.10	19.07	379.47	388.24	95.31	E	342.59	E	89.06	890.22
EX-E1-S2-NoInsu-EE1	182.18	0.38	242.50	19.07	323.41	332.04	80.52	E	286.53	E	74.27	792.05
EX-E1-S3-EPS-EE1	25.20	0.66	34.00	19.07	77.34	85.34	16.75	A	40.72	A	10.55	515.32
EX-E1-S4-EPS-EE1	24.33	0.66	33.10	19.07	76.61	84.67	14.64	A	39.99	A	8.44	536.34
EX-E1-S5-EPS-EE1	27.44	0.64	65.00	19.07	45.43	117.50	8.04	A	8.79	A	1.84	499.73
EX-E1-S6-EPS-EE1	27.44	0.64	53.10	19.07	44.41	104.26	7.83	A	7.78	A	1.62	531.81
EX-E1-S3-MW-EE1	23.95	0.66	32.80	19.07	75.91	83.91	16.38	A	39.29	A	10.18	495.91
EX-E1-S4-MW-EE1	23.07	0.66	31.90	19.07	75.19	83.25	14.34	A	38.57	A	8.14	515.65
EX-E1-S5-MW-EE1	25.83	0.64	62.60	19.07	45.02	114.83	7.95	A	8.39	A	1.75	480.83
EX-E1-S6-MW-EE1	25.83	0.64	50.70	19.07	44.00	101.59	7.74	A	7.37	A	1.53	511.96
EX-E1-S3-PUR-EE1	25.94	0.66	34.80	19.07	78.31	86.31	17.00	A	41.70	A	10.80	523.69
EX-E1-S4-PUR-EE1	24.95	0.67	33.80	19.07	77.44	85.51	14.81	A	40.83	A	8.62	544.83
EX-E1-S5-PUR-EE1	28.23	0.65	66.20	19.07	45.64	118.84	8.08	A	9.01	A	1.88	507.40
EX-E1-S6-PUR-EE1	28.23	0.65	54.30	19.07	44.62	105.59	7.87	A	8.00	A	1.67	539.47
EX-E1-S3-XPS-EE1	27.55	0.64	36.50	19.07	80.27	88.28	17.51	A	43.64	A	11.30	541.70
EX-E1-S4-XPS-EE1	26.44	0.65	35.30	19.07	79.25	87.32	15.20	A	42.62	A	9.00	564.75
EX-E1-S5-XPS-EE1	30.23	0.62	69.30	19.07	46.18	122.29	8.19	A	9.52	A	1.99	525.00
EX-E1-S6-XPS-EE1	30.23	0.62	57.40	19.07	45.16	109.04	7.98	A	8.50	A	1.77	557.08
EX-E1-S3-EPS-EE2	25.20	0.66	34.00	6.11	52.03	54.66	12.46	A	40.08	A	10.44	440.35
EX-E1-S4-EPS-EE2	24.33	0.66	33.10	6.11	51.30	53.99	10.35	A	39.35	A	8.33	461.37
EX-E1-S5-EPS-EE2	27.44	0.64	65.00	6.11	20.12	86.82	3.75	A	8.17	A	1.73	424.76
EX-E1-S6-EPS-EE2	27.44	0.64	53.10	6.11	19.10	73.58	3.54	A	7.16	A	1.51	456.84
EX-E1-S3-MW-EE2	23.95	0.66	32.80	6.11	50.60	53.23	12.09	A	38.65	A	10.07	420.94
EX-E1-S4-MW-EE2	23.07	0.66	31.90	6.11	49.88	52.57	10.05	A	37.92	A	8.03	440.68
EX-E1-S5-MW-EE2	25.83	0.64	62.60	6.11	19.71	84.15	3.66	A	7.76	A	1.64	405.86
EX-E1-S6-MW-EE2	25.83	0.64	50.70	6.11	18.69	70.91	3.45	A	6.74	A	1.42	436.99
EX-E1-S3-PUR-EE2	25.94	0.66	34.80	6.11	53.00	55.63	12.71	A	41.05	A	10.69	448.72
EX-E1-S4-PUR-EE2	24.95	0.67	33.80	6.11	52.13	54.83	10.52	A	40.17	A	8.51	469.86

Table 8. *Cont.*

	HED (kWh/m^2·year)	CED (kWh/m^2·year)	FEC$_{HEAT+DHW}$ (kWh/m^2·year)	FEC$_{ELEC}$ (kWh/m^2·year)	NRPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	EM (kg CO_2/m^2·year)	NRPEC Rating (Rating; kWh/m^2·year)		EM Rating (Rating; kg CO_2/m^2·year)		Global Cost (EUR/m^2)
EX-E1-S5-PUR-EE2	28.23	0.65	66.20	6.11	20.33	88.16	3.79	A	8.38	A	1.77	432.43
EX-E1-S6-PUR-EE2	28.23	0.65	54.30	6.11	19.31	74.91	3.58	A	7.37	A	1.56	464.51
EX-E1-S3-XPS-EE2	27.55	0.64	36.50	6.11	54.96	57.60	13.22	A	43.01	A	11.19	466.74
EX-E1-S4-XPS-EE2	26.44	0.65	35.30	6.11	53.94	56.64	10.91	A	41.99	A	8.89	489.79
EX-E1-S5-XPS-EE2	30.23	0.62	69.30	6.11	20.87	91.61	3.90	A	8.91	A	1.89	450.04
EX-E1-S6-XPS-EE2	30.23	0.62	57.40	6.11	19.85	78.36	3.69	A	7.89	A	1.67	482.11
EX-E1-S3-EPS-EE3	25.20	0.66	34.00	3.68	47.28	48.90	11.66	A	40.08	A	10.44	426.33
EX-E1-S4-EPS-EE3	24.33	0.66	33.10	3.68	46.55	48.24	9.55	A	39.35	A	8.33	447.36
EX-E1-S5-EPS-EE3	27.44	0.64	65.00	3.68	15.37	81.07	2.95	A	8.17	A	1.73	410.75
EX-E1-S6-EPS-EE3	27.44	0.64	53.10	3.68	14.35	67.82	2.74	A	7.16	A	1.51	442.82
EX-E1-S3-MW-EE3	23.95	0.66	32.80	3.68	45.85	47.47	11.29	A	38.65	A	10.07	406.92
EX-E1-S4-MW-EE3	23.07	0.66	31.90	3.68	45.13	46.81	9.25	A	37.92	A	8.03	426.67
EX-E1-S5-MW-EE3	25.83	0.64	62.60	3.68	14.96	78.40	2.86	A	7.76	A	1.64	391.85
EX-E1-S6-MW-EE3	25.83	0.64	50.70	3.68	13.94	65.15	2.65	A	6.74	A	1.42	422.97
EX-E1-S3-PUR-EE3	25.94	0.66	34.80	3.68	48.25	49.88	11.91	A	41.05	A	10.69	434.71
EX-E1-S4-PUR-EE3	24.95	0.67	33.80	3.68	47.38	49.07	9.72	A	40.17	A	8.51	455.84
EX-E1-S5-PUR-EE3	28.23	0.65	66.20	3.68	15.58	82.40	2.99	A	8.38	A	1.77	418.41
EX-E1-S6-PUR-EE3	28.23	0.65	54.30	3.68	14.56	69.16	2.78	A	7.37	A	1.56	450.49
EX-E1-S3-XPS-EE3	27.55	0.64	36.50	3.68	50.21	51.84	12.42	A	43.01	A	11.19	452.72
EX-E1-S4-XPS-EE3	26.44	0.65	35.30	3.68	49.19	50.89	10.11	A	41.99	A	8.89	475.77
EX-E1-S5-XPS-EE3	30.23	0.62	69.30	3.68	16.12	85.85	3.10	A	8.91	A	1.89	436.02
EX-E1-S6-XPS-EE3	30.23	0.62	57.40	3.68	15.10	72.61	2.89	A	7.89	A	1.67	468.10

Note: HED is heating energy demand; CED is cooling energy demand; FEC$_{HEAT+DHW}$ is final energy consumption for heating and domestic hot water (DHW); FEC$_{ELECT}$ is final energy consumption for electricity; NRPEC is non-renewable primary energy consumption for heating, DHW and electricity; TPEC is total primary energy consumption for heating, DHW and electricity; EM is CO_2 emissions for heating, DHW and electricity; NRPEC rating is non-renewable primary energy consumption rating according to CTE-DB-HE [52]; EM rating is CO_2 emissions rating according to CTE-DB-HE [52].

Table 9. Energy, environmental and economic impacts for each case study in Torrecilla en Cameros (CCZ EY-E1).

	HED (kWh/m^2·year)	CED (kWh/m^2·year)	FEC$_{HEAT+DHW}$ (kWh/m^2·year)	FEC$_{ELEC}$ (kWh/m^2·year)	NRPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	EM (kg CO$_2$/m^2·year)	NRPEC Rating (Rating; kWh/m^2·year)		EM Rating (Rating; kg CO$_2$/m^2·year)		Global Cost (EUR/m^2)
EY-E1-S1-NoInsu-EE1	161.65	0.46	260.20	19.07	344.18	352.86	86.14	E	307.38	E	79.90	817.21
EY-E1-S2-NoInsu-EE1	161.65	0.46	217.50	19.07	293.87	302.42	72.87	E	257.07	E	66.63	730.26
EY-E1-S3-EPS-EE1	25.18	0.66	34.00	19.07	77.31	85.31	16.74	A	40.70	A	10.54	510.65
EY-E1-S4-EPS-EE1	24.31	0.66	33.10	19.07	76.57	84.63	14.63	A	39.95	A	8.43	531.67
EY-E1-S5-EPS-EE1	27.42	0.64	65.00	19.07	45.43	117.50	8.04	A	8.79	A	1.83	495.06
EY-E1-S6-EPS-EE1	27.42	0.64	53.10	19.07	44.41	104.26	7.83	A	7.77	A	1.62	527.14
EY-E1-S3-MW-EE1	23.66	0.67	32.50	19.07	75.50	83.49	16.28	A	38.90	A	10.08	493.27
EY-E1-S4-MW-EE1	22.79	0.67	31.60	19.07	74.77	82.82	14.25	A	38.17	A	8.05	513.01
EY-E1-S5-MW-EE1	25.53	0.65	62.10	19.07	44.94	114.27	7.93	A	8.32	A	1.73	478.48
EY-E1-S6-MW-EE1	25.53	0.65	50.20	19.07	43.92	101.03	7.72	A	7.30	A	1.52	510.56
EY-E1-S3-PUR-EE1	25.86	0.67	34.70	19.07	78.19	86.19	16.97	A	41.59	A	10.77	517.24
EY-E1-S4-PUR-EE1	25.09	0.67	33.90	19.07	77.59	85.66	14.85	A	40.98	A	8.65	538.74
EY-E1-S5-PUR-EE1	27.72	0.67	65.40	19.07	45.50	117.95	8.05	A	8.89	A	1.85	500.09
EY-E1-S6-PUR-EE1	27.72	0.67	53.50	19.07	44.48	104.70	7.84	A	7.87	A	1.64	532.17
EY-E1-S3-XPS-EE1	27.62	0.64	36.50	19.07	80.34	88.35	17.52	A	43.71	A	11.32	534.64
EY-E1-S4-XPS-EE1	26.49	0.65	35.40	19.07	79.30	87.37	15.21	A	42.67	A	9.01	558.02
EY-E1-S5-XPS-EE1	30.11	0.62	69.10	19.07	46.15	122.07	8.19	A	9.50	A	1.99	518.50
EY-E1-S6-XPS-EE1	30.11	0.62	57.30	19.07	45.13	108.93	7.98	A	8.48	A	1.77	550.72
EY-E1-S3-EPS-EE2	25.18	0.66	34.00	6.08	51.94	54.56	12.44	A	40.06	A	10.43	435.41
EY-E1-S4-EPS-EE2	24.31	0.66	33.10	6.08	51.20	53.88	10.33	A	39.30	A	8.32	456.44
EY-E1-S5-EPS-EE2	27.42	0.64	65.00	6.08	20.06	86.75	3.74	A	8.16	A	1.72	419.83
EY-E1-S6-EPS-EE2	27.42	0.64	53.10	6.08	19.04	73.50	3.53	A	7.14	A	1.51	451.90
EY-E1-S3-MW-EE2	23.66	0.67	32.50	6.08	50.13	52.74	11.98	A	38.25	A	9.97	418.04
EY-E1-S4-MW-EE2	22.79	0.67	31.60	6.08	49.40	52.07	9.95	A	37.51	A	7.94	437.77
EY-E1-S5-MW-EE2	25.53	0.65	62.10	6.08	19.57	83.52	3.63	A	7.68	A	1.62	403.25
EY-E1-S6-MW-EE2	25.53	0.65	50.20	6.08	18.55	70.28	3.42	A	6.66	A	1.41	435.32
EY-E1-S3-PUR-EE2	25.86	0.67	34.70	6.08	52.82	55.44	12.67	A	40.94	A	10.66	442.00
EY-E1-S4-PUR-EE2	25.09	0.67	33.90	6.08	52.22	54.90	10.55	A	40.33	A	8.54	463.50

Table 9. *Cont.*

	HED (kWh/m^2·year)	CED (kWh/m^2·year)	$FEC_{HEAT+DHW}$ (kWh/m^2·year)	FEC_{ELEC} (kWh/m^2·year)	NRPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	EM (kg CO_2/m^2·year)	NRPEC Rating (Rating; kWh/m^2·year)		EM Rating (Rating; kg CO_2/m^2·year)		Global Cost (EUR/m^2)
EY-E1-S5-PUR-EE2	27.72	0.67	65.40	6.08	20.13	87.19	3.75	A	8.24	A	1.74	424.85
EY-E1-S6-PUR-EE2	27.72	0.67	53.50	6.08	19.11	73.95	3.54	A	7.22	A	1.53	456.93
EY-E1-S3-XPS-EE2	27.62	0.64	36.50	6.08	54.97	57.59	13.22	A	43.08	A	11.21	459.41
EY-E1-S4-XPS-EE2	26.49	0.65	35.40	6.08	53.93	56.62	10.91	A	42.04	A	8.90	482.79
EY-E1-S5-XPS-EE2	30.11	0.62	69.10	6.08	20.78	91.31	3.89	A	8.89	A	1.89	443.27
EY-E1-S6-XPS-EE2	30.11	0.62	57.30	6.08	19.76	78.18	3.68	A	7.87	A	1.67	475.48
EY-E1-S3-EPS-EE3	25.18	0.66	34.00	3.76	47.39	49.05	11.67	A	40.06	A	10.43	421.97
EY-E1-S4-EPS-EE3	24.31	0.66	33.10	3.76	46.65	48.37	9.56	A	39.30	A	8.32	443.00
EY-E1-S5-EPS-EE3	27.42	0.64	65.00	3.76	15.51	81.24	2.97	A	8.16	A	1.72	406.39
EY-E1-S6-EPS-EE3	27.42	0.64	53.10	3.76	14.49	67.99	2.76	A	7.14	A	1.51	438.46
EY-E1-S3-MW-EE3	23.66	0.67	32.50	3.76	45.58	47.23	11.21	A	38.25	A	9.97	404.60
EY-E1-S4-MW-EE3	22.79	0.67	31.60	3.76	44.85	46.56	9.18	A	37.51	A	7.94	424.33
EY-E1-S5-MW-EE3	25.53	0.65	62.10	3.76	15.02	78.01	2.86	A	7.68	A	1.62	389.81
EY-E1-S6-MW-EE3	25.53	0.65	50.20	3.76	14.00	64.77	2.65	A	6.66	A	1.41	421.89
EY-E1-S3-PUR-EE3	25.86	0.67	34.70	3.76	48.27	49.93	11.90	A	40.94	A	10.66	428.56
EY-E1-S4-PUR-EE3	25.09	0.67	33.90	3.76	47.67	49.39	9.78	A	40.33	A	8.54	450.06
EY-E1-S5-PUR-EE3	27.72	0.67	65.40	3.76	15.58	81.68	2.98	A	8.24	A	1.74	411.42
EY-E1-S6-PUR-EE3	27.72	0.67	53.50	3.76	14.56	68.44	2.77	A	7.22	A	1.53	443.49
EY-E1-S3-XPS-EE3	27.62	0.64	36.50	3.76	50.42	52.08	12.45	A	43.08	A	11.21	445.97
EY-E1-S4-XPS-EE3	26.49	0.65	35.40	3.76	49.38	51.11	10.14	A	42.04	A	8.90	469.35
EY-E1-S5-XPS-EE3	30.11	0.62	69.10	3.76	16.23	85.80	3.12	A	8.89	A	1.89	429.83
EY-E1-S6-XPS-EE3	30.11	0.62	57.30	3.76	15.21	72.67	2.91	A	7.87	A	1.67	462.04

Note: HED is heating energy demand; CED is cooling energy demand; $FEC_{HEAT+DHW}$ is final energy consumption for heating and domestic hot water (DHW); FEC_{ELECT} is final energy consumption for electricity; NRPEC is non-renewable primary energy consumption for heating, DHW and electricity; TPEC is total primary energy consumption for heating, DHW and electricity; EM is CO_2 emissions for heating, DHW and electricity; NRPEC rating is non-renewable primary energy consumption rating according to CTE-DB-HE [52]; EM rating is CO_2 emissions rating according to CTE-DB-HE [52].

3.2.2. Final Energy Consumption of Electrical Energy

With solar photovoltaic systems that do not sell surpluses to the electrical grid (cases EE2), 14.32 kWh/m^2·year of self-consumed electrical energy is achieved in the CCZ DX-D2, representing a reduction in final energy consumption of electrical energy of 75.10% with respect to the existing study building; 12.96 kWh/m^2·year of self-consumed electrical energy is achieved in the CCZ EX-E1, representing a reduction of 67.94% with respect to the existing study building; and 12.99 kWh/m^2·year of self-consumed electrical energy is achieved in the CCZ EY-E1, representing a reduction of 68.10% with respect to the existing study building. With solar photovoltaic systems that can sell surpluses to the electrical grid (cases EE3), 16.42 kWh/m^2·year of self-consumed electrical energy is achieved in the CCZ DX-D2, representing a reduction in final energy consumption of electrical energy of 86.13% with respect to the existing study building; 15.39 kWh/m^2·year of self-consumed electrical energy is achieved in the CCZ EX-E1, representing a reduction of 80.68% with respect to the existing study building; and 15.31 kWh/m^2·year of self-consumed electrical energy is achieved in the CCZ EY-E1, representing a reduction of 80.30% with respect to the existing study building (Tables 7–9).

3.2.3. Non-Renewable Primary Energy Consumption, Total Primary Energy Consumption, CO_2 Emissions and Energy Performance Ratings

The lowest non-renewable primary energy consumption and the lowest CO_2 emissions are obtained in the energy renovation solution that uses a biomass boiler with a solar thermal support system, MW thermal insulation material and a solar photovoltaic system that can sell surpluses to the electrical grid (cases DX-D2-S6-MW-EE3, EX-E1-S6-MW-EE3 and EY-E1-S6-MW-EE3). The highest non-renewable primary energy consumption and the highest CO_2 emissions are obtained in the solution using a heating oil boiler with a solar thermal support system, XPS thermal insulation material and no solar photovoltaic system (cases DX-D2-S3-XPS-EE1, EX-E1-S3-XPS-EE1 and EY-E1-S3-XPS-EE1) (Tables 7–9).

The lowest total primary energy consumption is obtained in the energy renovation solution that uses a natural gas boiler with a solar thermal support system, MW thermal insulation material and a solar photovoltaic system that can sell surpluses to the electrical grid (cases DX-D2-S4-MW-EE3, EX-E1-S4-MW-EE3 and EY-E1-S4-MW-EE3). The highest total primary energy consumption is obtained in the solution using a biomass boiler without a solar thermal support system, XPS thermal insulation material and no solar photovoltaic system (cases DX-D2-S5-XPS-EE1, EX-E1-S5-XPS-EE1 and EY-E1-S5-XPS-EE1) (Tables 7–9).

The energy performance ratings for both non-renewable primary energy consumption and CO_2 emissions for all energy renovation solutions in the three CCZs are A, the best possible rating, improving the energy performance ratings of the corresponding existing study buildings by four letters (Tables 7–9).

3.3. Economic Impact

To assess economic impact, the Commission Delegated Regulation (EU) No. 244/2012 [25] and the accompanying guidelines [83] were taken into account. The global cost, with a real discount rate of 3%, for all the case studies is presented for CCZs DX-D2, EX-E1 and EY-E1 in Tables 7–9, respectively, and the breakdown of the initial investment costs of all the energy renovation solutions for these CCZs is presented in Figure 4. In addition to assessing the global cost of the different case studies with a real discount rate of 3%, to ensure an accurate sensitivity analysis, the global cost was also assessed with real discount rates of 2% and 4%. The global cost breakdown of the existing study building with no boiler replacement and with boiler replacement at the three real discount rates for the three CCZs is presented in Figure 5. The global cost breakdown of all the energy renovation solutions at the three real discount rates is presented for CCZs DX-D2, EX-E1 and EY-E1 in Figures 6–8, respectively. The global cost at the three real discount rates and the total primary energy consumption for all energy renovation solutions for these CCZs are presented in Figure 9. As expected, the higher the real discount rate is, the lower the global cost is (Figures 6–9).

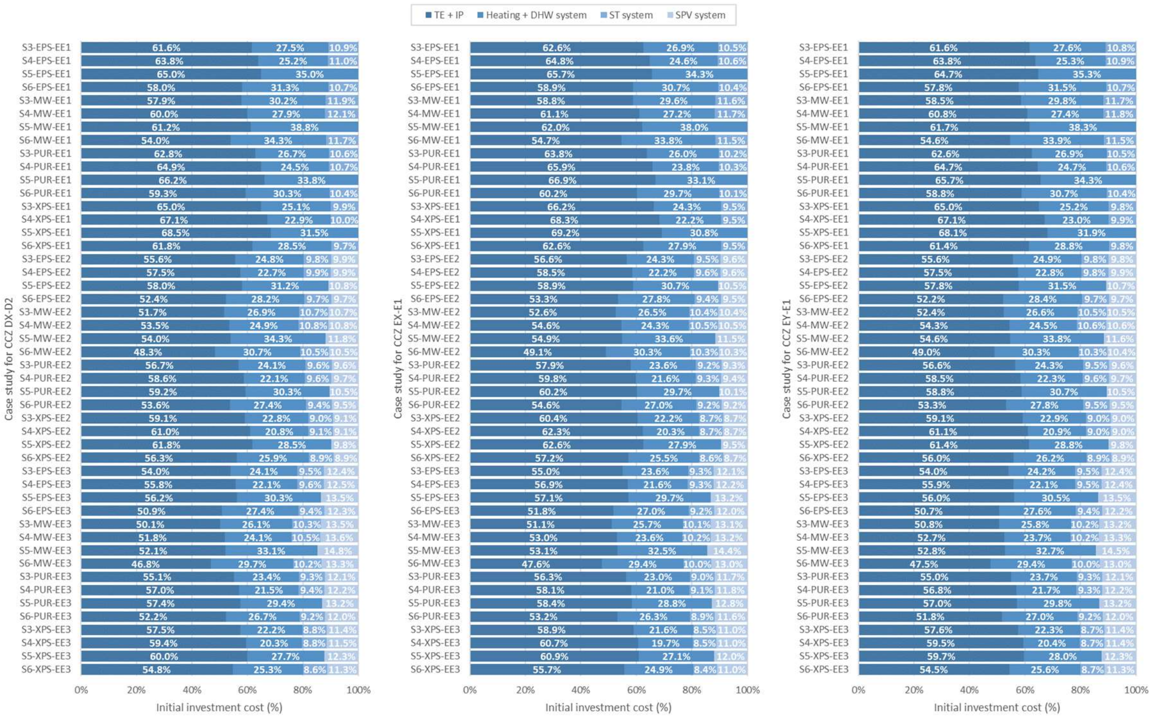

Figure 4. Initial investment cost breakdown by type of energy renovation measure, in %, for each case study in each CCZ. Note: TE + IP is thermal envelope and interior partitions; ST is solar thermal; SPV is solar photovoltaic.

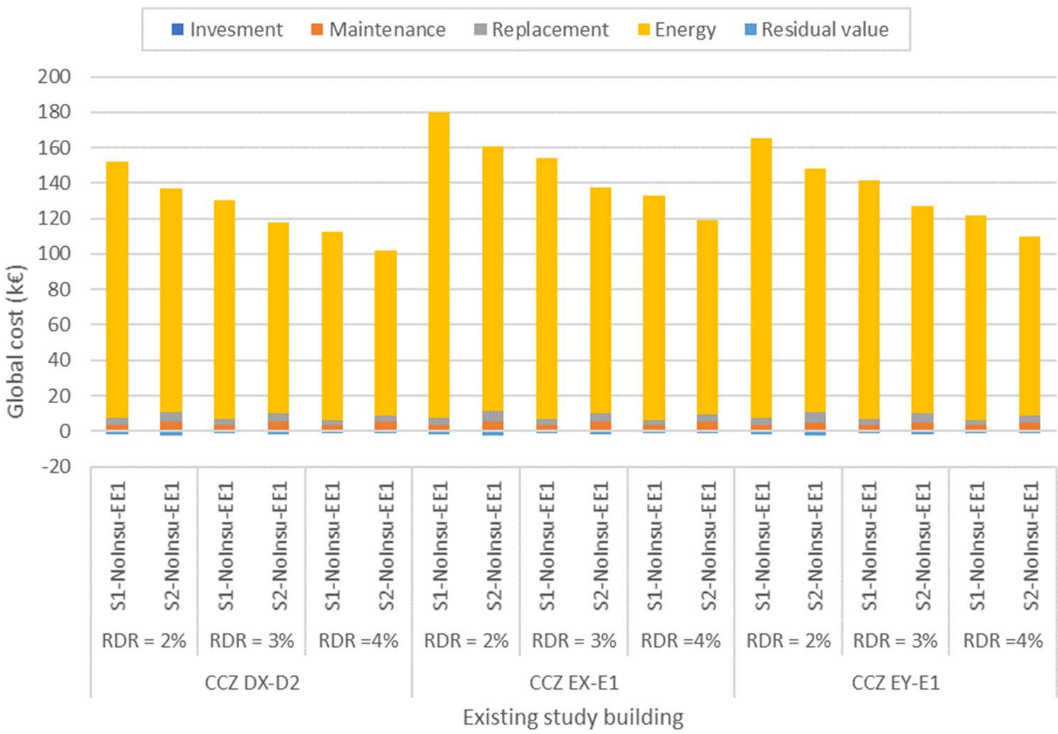

Figure 5. Global cost breakdown by the different costs and residual value, in EUR 1000, for each existing study building by CCZ and real discount rate (RDR).

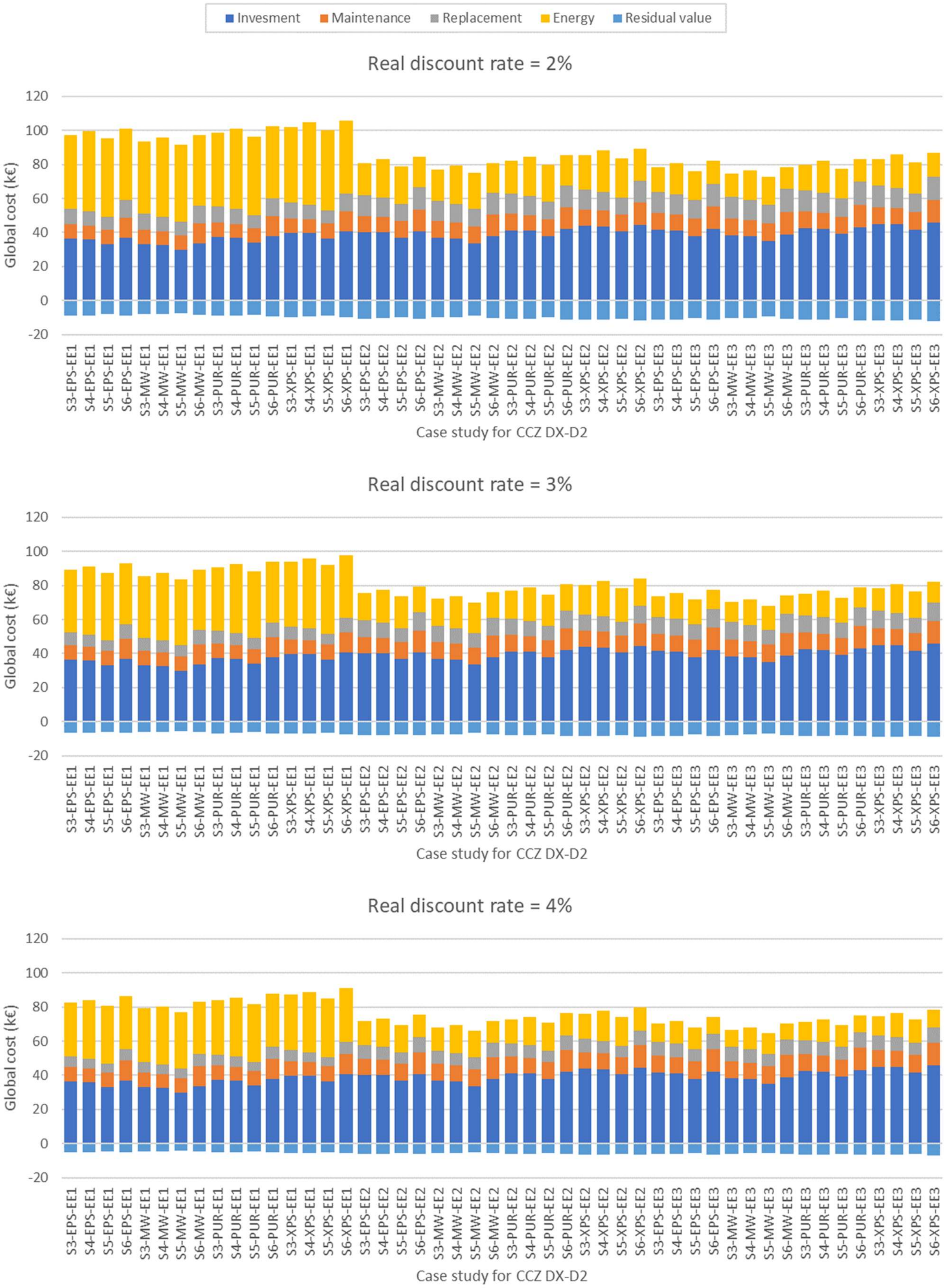

Figure 6. Global cost breakdown by the different costs and residual value, in EUR 1000, for each energy renovation solution in CCZ DX-D2 by real discount rate.

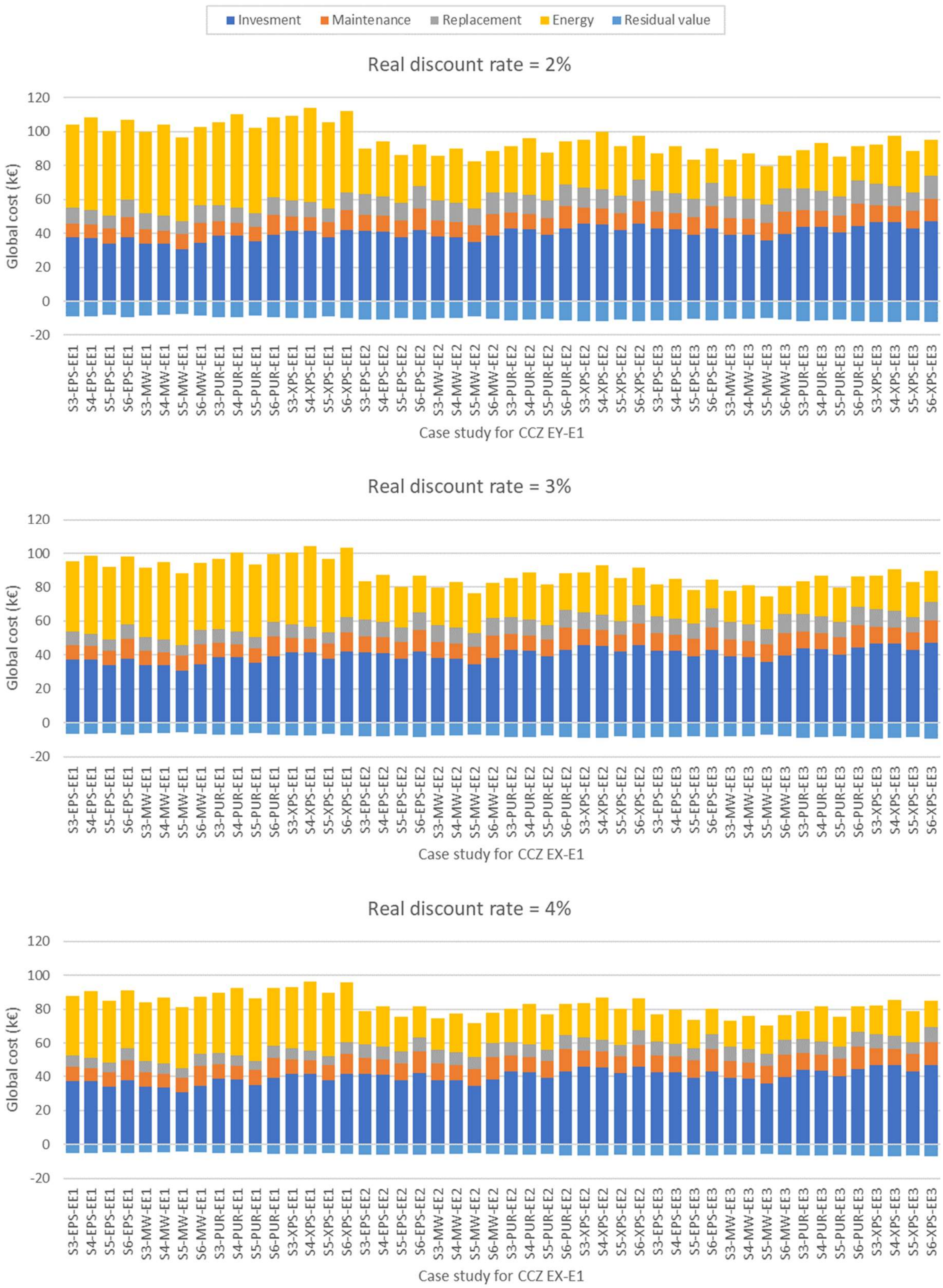

Figure 7. Global cost breakdown by the different costs and residual value, in EUR 1000, for each energy renovation solution in CCZ EX-E1 by real discount rate.

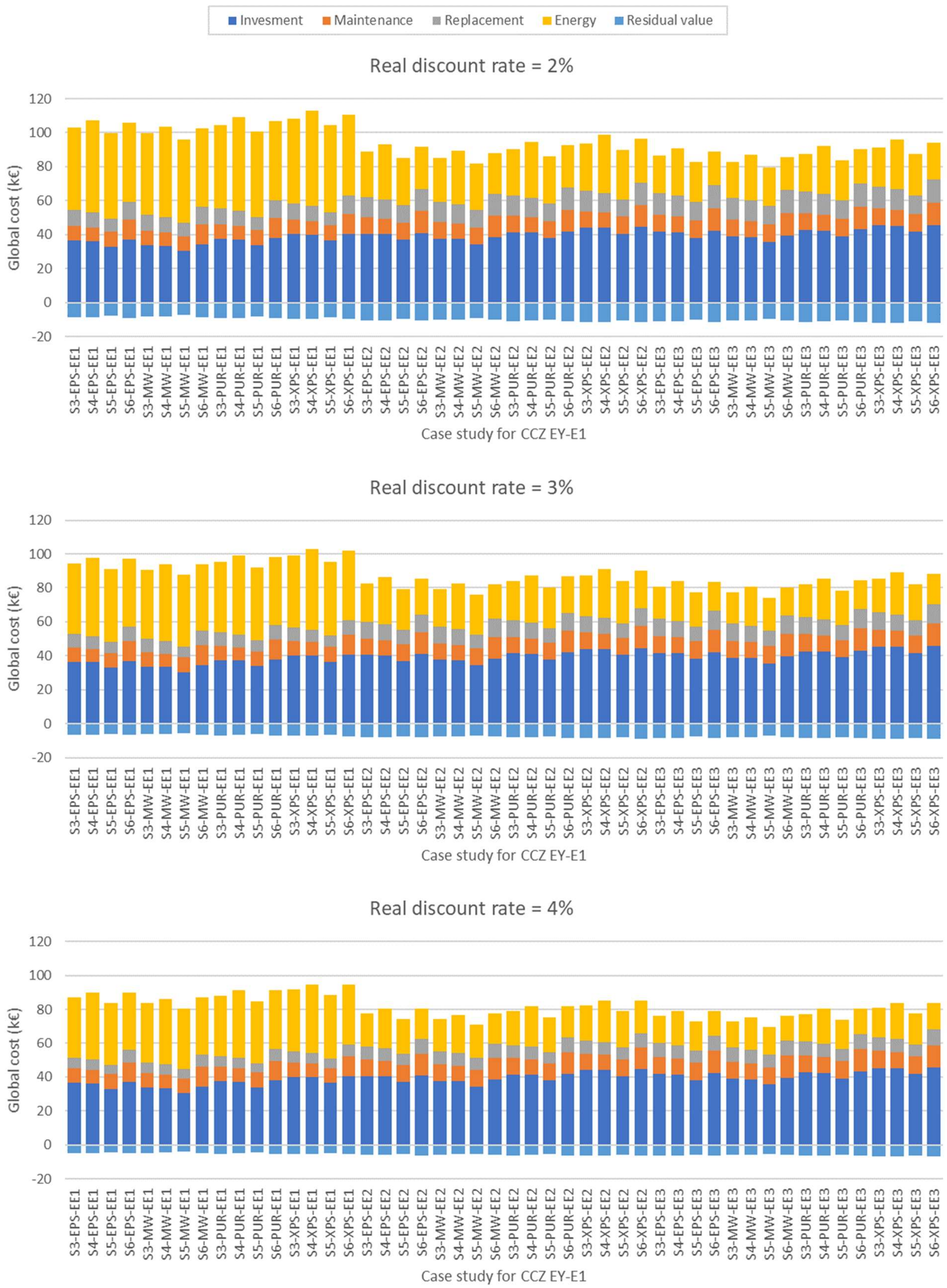

Figure 8. Global cost breakdown by the different costs and residual value, in EUR 1000, for each energy renovation solution in CCZ EY-E1 by real discount rate.

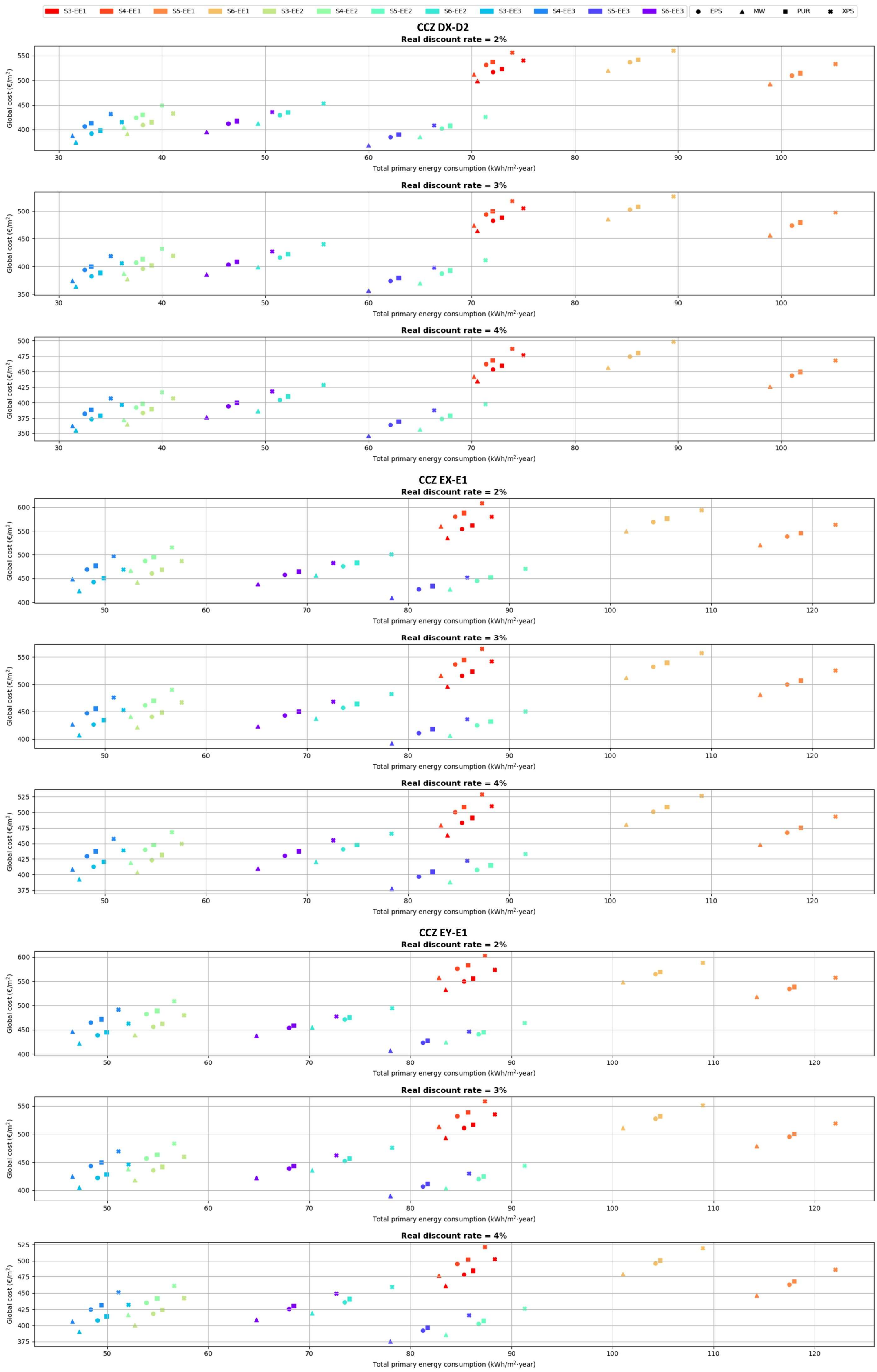

Figure 9. Global cost at the three real discount rates, in EUR/m^2, versus total primary energy consumption, in kWh/m^2·year, for all the energy renovation solutions in each CCZ.

Regarding the global costs in CCZ DX-D2 with a real discount rate of 3%, Figures 6 and 9 reveal that energy renovation solutions without a solar photovoltaic system (cases EE1) have a global cost between 6.32% and 8.03% higher at a real discount rate of 2% and between 5.33% and 6.67% lower at a real discount rate of 4%, solutions with solar photovoltaic systems that do not sell surpluses back to the electrical grid (cases EE2) have a global cost between 2.92% and 4.54% higher at a real discount rate of 2% and between 2.64% and 3.91% lower at a real discount rate of 4%, and solutions with a solar photovoltaic system that can sell surpluses to the electrical grid (cases EE3) have a global cost between 2.07% and 3.64% higher at a real discount rate of 2% and between 1.97% and 3.20% lower at a real discount rate of 4%. The lowest global cost at real discount rates of 2% (368.12 EUR/m^2), 3% (356.29 EUR/m^2) and 4% (345.75 EUR/m^2) is achieved in the energy renovation solution that uses a biomass boiler without a solar thermal support system, MW thermal insulation material and a solar photovoltaic system that can sell surpluses to the electrical grid (case DX-D2-S5-MW-EE3) (Figures 6 and 9). This solution has a total primary energy consumption of 60.02 kWh/m^2·year, a non-renewable primary energy consumption of 10.67 kWh/m^2·year and CO_2 emissions of 2.04 kg CO_2/m^2·year (Table 7), and it achieves the cost-optimal level of minimum energy performance requirements among all solutions (Figure 9).

Regarding the global costs in CCZ EX-E1 with a real discount rate of 3%, Figures 7 and 9 reveal that energy renovation solutions without a solar photovoltaic system (cases EE1) have a global cost between 6.61% and 8.57% higher at a real discount rate of 2% and between 5.56% and 7.10% lower at a real discount rate of 4%, solutions with solar photovoltaic systems that do not sell surpluses back to the electrical grid (cases EE2) have a global cost between 3.83% and 5.86% higher at a real discount rate of 2% and between 3.36% and 4.95% lower at a real discount rate of 4%, and solutions with a solar photovoltaic system that can sell surpluses to the electrical grid (cases EE3) have a global cost between 3.06% and 5.08% higher at a real discount rate of 2% and between 2.75% and 4.34% lower at a real discount rate of 4%. The lowest global cost at real discount rates of 2% (408.52 EUR/m^2), 3% (391.85 EUR/m^2) and 4% (377.35 EUR/m^2) is achieved in the energy renovation solution that uses a biomass boiler without a solar thermal support system, MW thermal insulation material and a solar photovoltaic system that can sell surpluses to the electrical grid (case EX-E1-S5-MW-EE3) (Figures 7 and 9). This solution has a total primary energy consumption of 78.40 kWh/m^2·year, a non-renewable primary energy consumption of 14.96 kWh/m^2·year and CO_2 emissions of 2.86 kg CO_2/m^2·year (Table 8), and it achieves the cost-optimal level of minimum energy performance requirements among all solutions (Figure 9).

Regarding the global costs in CCZ EY-E1 with a real discount rate of 3%, Figures 8 and 9 reveal that energy renovation solutions without a solar photovoltaic system (cases EE1) have a global cost between 6.76% and 8.70% higher at a real discount rate of 2% and between 5.68% and 7.12% lower at a real discount rate of 4%, solutions with solar photovoltaic systems that do not sell surpluses back to the electrical grid (cases EE2) have a global cost between 3.95% and 5.86% higher at a real discount rate of 2% and between 3.46% and 4.96% lower at a real discount rate of 4%, and solutions with a solar photovoltaic system that can sell surpluses to the electrical grid (cases EE3) have a global cost between 3.20% and 5.10% higher at a real discount rate of 2% and between 2.86% and 4.35% lower at a real discount rate of 4%. The lowest global cost at real discount rates of 2% (406.51 EUR/m^2), 3% (389.81 EUR/m^2) and 4% (375.30 EUR/m^2) is achieved in the energy renovation solution that uses a biomass boiler without a solar thermal support system, MW thermal insulation material and a solar photovoltaic system that can sell surpluses to the electrical grid (case EY-E1-S5-MW-EE3) (Figures 8 and 9). This solution has a total primary energy consumption of 78.01 kWh/m^2·year, a non-renewable primary energy consumption of 15.02 kWh/m^2·year and CO_2 emissions of 2.86 kg CO_2/m^2·year (Table 9), and it achieves the cost-optimal level of minimum energy performance requirements among all solutions (Figure 9).

In addition, the energy renovation solution with the lowest global cost in each CCZ obtains an energy performance rating of A both in non-renewable primary energy consumption and in CO_2 emissions (Tables 7–9).

Finally, the global savings of all energy renovation solutions at real discount rates of 2%, 3% and 4% compared to the existing study building with no boiler replacement and the existing study building with boiler replacement are presented for CCZs DX-D2, EX-E1 and EY-E1 in Figure 10.

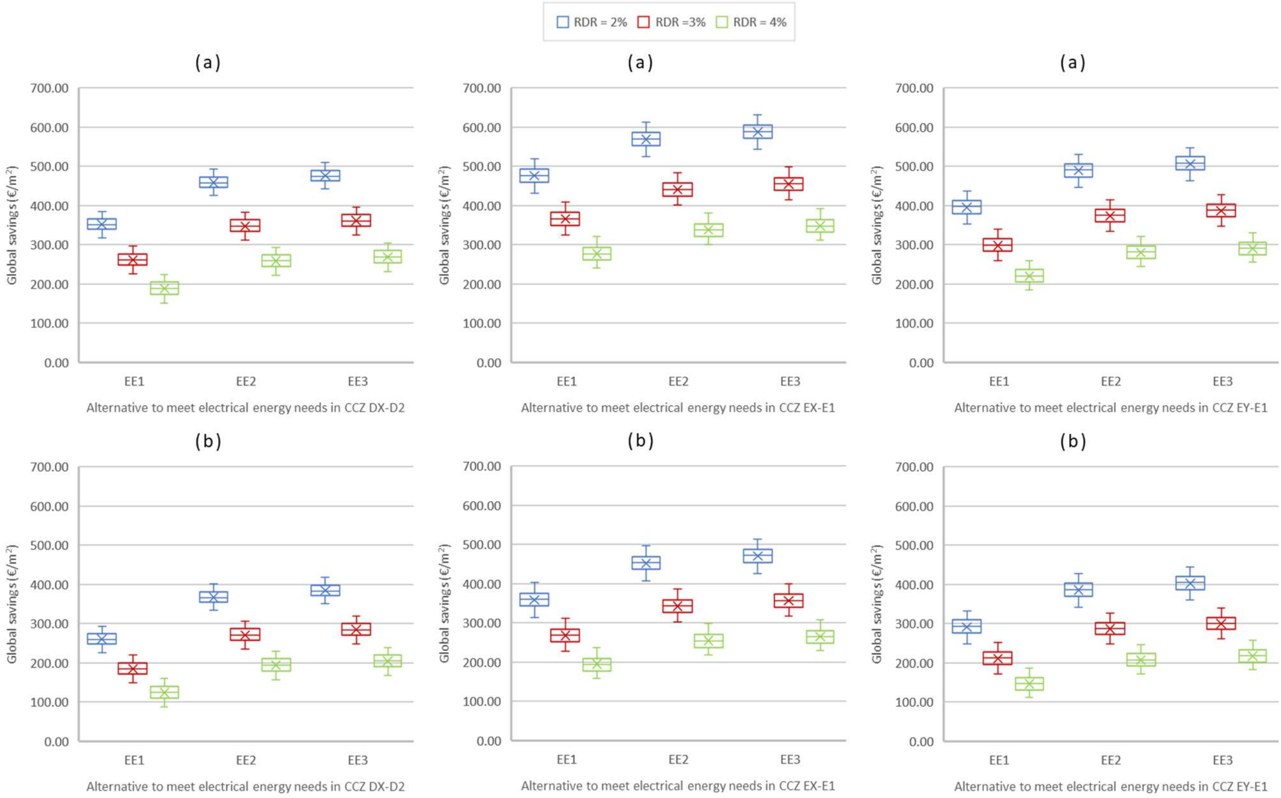

Figure 10. Global savings of all energy renovation solutions, in EUR/m^2, in each CCZ by real discount rate (RDR) and alternative used to meet electrical energy needs, compared to (**a**) the corresponding case CCZ-S1-NoInsu-EE1 and (**b**) the corresponding case CCZ-S2-NoInsu-EE1.

3.4. Optimal Energy Renovation Solution for Rural La Rioja

The best energy renovation solution for each CCZ of study, according to energy, environmental and economic criteria, is the one that uses a biomass boiler without a solar thermal support system, MW thermal insulation material and a solar photovoltaic system with the possibility of selling surpluses to the electrical grid (cases DX-D2-MW-S5-EE3, EX-E1-MW-S5-EE3 and EY-E1-MW-S5-EE3). The replacement of fossil fuel boilers with biomass boilers in residential buildings is a very good strategy for energy renovation, especially in cold winter climate zones [61]. In addition, the use of autochthonous biomass would improve distributed thermal production in rural areas, achieving self-sustaining rural systems, as demonstrated for the municipality of Ezcaray in La Rioja, where boiler replacement occurred alongside the installation of a pellet mill plant [89]. In Spain, the application of CTE-DB-HE [52] in the energy renovation of residential buildings makes biomass boilers and heat pumps the two main alternatives to natural gas boilers to achieve NZEBs [32]. Although decarbonizing the Spanish residential sector is being supported mainly with heat pumps [35,90], this study shows that it is also possible to achieve decarbonization with biomass boilers since they present viable alternatives at all levels and contribute to sustainable rural development. On the other hand, the use of solar photovoltaic systems with the possibility of selling surpluses to the electrical grid is cost-effective in Spain, although its legal framework should be improved and it should be promoted to residential consumers, especially those affected by energy poverty [91].

Applying the PREE 5000 Programme [87] and the incentive program for implementing self-consumption installations without storage of renewable energy sources [88], without considering social criteria, the subsidies and aid that homeowners can receive by carrying out the following energy renovation solutions were assessed:

- The subsidy referring to the action corresponding to an improvement in the energy efficiency of the thermal envelope [87] was estimated at 40% of the associated investment required but not exceeding EUR 12,000, in line with the aid to promote previous building renovation [92] since with the selected energy renovation solutions, notable reductions in the energy demand for heating and cooling are achieved (Tables 7–9) and the requirements of the CTE-DB-HE1 [52] for renovated buildings are met (Tables A2–A4). This subsidy amounts to 42.46 EUR/m^2 in the CCZ DX-D2, 44.42 EUR/m^2 in the CCZ EX-E1 and 43.76 EUR/m^2 in the CCZ EY-E1 (Figure 11).
- The subsidy referring to the action corresponding to an improvement in energy efficiency and renewable energies in thermal installations for heating, air conditioning, ventilation and DHW by replacing conventional energy with biomass in thermal installations [87] is 55% of the associated investment required but not exceeding EUR 24,142 since with the selected energy renovation solutions, reductions in greenhouse gas emissions of at least 80% are achieved (Tables 7–9). For this subsidy, the additional aid for integrated action was taken into account since, in addition to replacing the existing heating and DHW system with a heating oil boiler with a new system with a biomass boiler, the energy demand for heating and cooling was reduced by at least 30% (Tables 7–9). This subsidy amounts to 37.06 EUR/m^2 in the CCZ DX-D2, 37.37 EUR/m^2 in the CCZ EX-E1 and 37.29 EUR/m^2 in the CCZ EY-E1 (Figure 11).
- The aid for self-consumption solar photovoltaic installation is 600 EUR/kW and an additional 55 EUR/kW to be distributed in demographic challenge municipalities [88] since with the energy renovation solutions selected, the installed power of the solar photovoltaic system is less than 2.63 kW and the electrical energy consumed is at least 80% of the electrical energy generated by the solar photovoltaic system (Tables 7–9). This aid amounts to 9.16 EUR/m^2 in all the CCZs of the study (Figure 11).

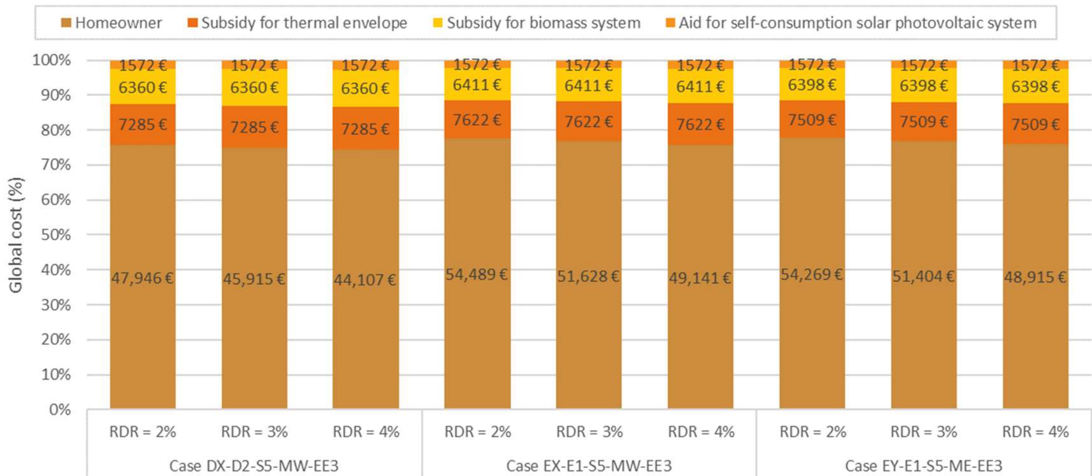

Figure 11. Global cost, in EUR and %, at the different real discount rates for the optimal energy renovation solution in each CCZ, broken down by subsidies and aid to be received by the homeowner and global cost the homeowner is responsible for.

The global cost with the different real discount rates for the energy renovation solution selected in each CCZ, broken down in terms of both the different subsidies and aid to be received by the homeowner and the global cost the homeowner is responsible for, is presented in Figure 11. Figure 11 shows that an overall average reduction of 23.73% is achieved thanks to the different subsidies and aid. Finally, with the budget allocations assigned to La Rioja in [87,88], the comprehensive energy renovation of approximately 62 single-family houses could be carried out, such as the cases studied, assuming the energy renovation of 0.35% of the single-family houses in the existing residential building stock of the rural revitalization areas and 0.15% of the single-family houses in the existing rural residential building stock.

The energy renovation proposals selected can serve as a guide, especially for policymakers of La Rioja and those of other autonomous communities and other Mediterranean states with similar cold climate zones, for achieving the transformation of their existing residential building into NZEBs in rural areas, thus contributing to the achievement of a highly energy-efficient and decarbonized rural building stock and aligning with the objectives of the EPBD 2018 [22]. Finally, the following future research works focused on the energy renovation of buildings in different rural Spanish areas are proposed: (a) the definition of the characteristic residential and non-residential buildings and the selection of the optimal energy renovation solutions; (b) the assessment of the impact of different climate change scenarios; and (c) the study of the implementation of other aspects of the EPBD 2018 [22], such as the electric vehicle charging infrastructure, the building smartification or the building renovation passports.

4. Conclusions

Various measures of energy renovation of rural residential buildings located in La Rioja were assessed to achieve NZEBs, seeking the optimal solution of energy renovation at the energy, environmental and economic levels. The optimal solution for energy renovation was found to use a biomass boiler without a solar thermal support system, MW thermal insulation material and a solar photovoltaic system with the possibility of selling surpluses to the electrical grid. With this solution, compared to the existing study building with boiler replacement, the following was found for the CCZs studied:

- In CCZ DX-D2, with an initial investment cost that represents 57.14% of the global cost, a global savings of 47.24% (EUR 1.57 savings for each euro invested) is achieved, resulting in a reduction of 96.00% in non-renewable primary energy consumption, a reduction of 78.20% in total primary energy consumption and a reduction of 96.91% in CO_2 emissions.
- In CCZ EX-E1, with an initial investment cost that represents 53.35% of the global cost, a global savings of 50.53% (EUR 1.91 savings for each euro invested) is achieved, resulting in a reduction of 95.38% in non-renewable primary energy consumption, a reduction of 76.39% in total primary energy consumption and a reduction of 96.45% in CO_2 emissions.
- In CCZ EY-E1, with an initial investment cost that represents 53.17% of the global cost, a global savings of 46.62% (EUR 1.64 savings for each euro invested) is achieved, resulting in a reduction of 94.89% in non-renewable primary energy consumption, a reduction of 74.20% in total primary energy consumption and a reduction of 96.07% in CO_2 emissions.
- In the three CCZs, an energy performance rating of A is achieved in both non-renewable primary energy consumption and CO_2 emissions.

In addition, with the subsidies and aid that homeowners can receive, without taking into account social criteria, an average global reduction of 23.73% in the global cost of the optimal solution can be achieved.

Finally, the methodology followed and the results obtained in this work can serve as a guide for policymakers to achieve highly energy-efficient and decarbonized rural building stock in other similar cold Mediterranean climate zones by 2050.

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Appendix A

Table A1. Requirements to comply with the CTE-DB-HE [52] as a renovated building and as a new building.

Basic Document	Parameter	Climate Zone D2		Climate Zone E1	
		Renovated Building	New Building	Renovated Building	New Building
CTE-DB-HE0	Non-renewable primary energy consumption limit (kWh/m^2·year)	70.00	38.00	80.00	43.00
	Total primary energy consumption limit (kWh/m^2·year)	105.00	76.00	115.00	86.00
CTE-DB-HE1	Thermal transmittance limit for walls (W/m^2·K)	0.41	0.41	0.37	0.37
	Thermal transmittance limit for roof (W/m^2·K)	0.35	0.35	0.33	0.33
	Thermal transmittance limit for ground floor (W/m^2·K)	0.65	0.65	0.59	0.59
	Thermal transmittance limit for dividing walls (W/m^2·K)	0.65	0.65	0.59	0.59
	Thermal transmittance limit for windows (W/m^2·K)	1.80	1.80	1.80	1.80
	Thermal transmittance limit for doors (W/m^2·K)	5.70	5.70	5.70	5.70
	Global heat transfer coefficient limit through the thermal envelope of the building (W/m^2·K)	0.67	0.59	0.59	0.54
	Solar control parameter limit (kWh/m^2·month)	2.00	2.00	2.00	2.00
	Air permeability limit of the openings of the thermal envelope (m^3/h·m^2)	9.00	9.00	9.00	9.00
	Air change ratio limit with a differential pressure of 50 Pa (h^{-1})	-	4.54	-	4.54
	Thermal transmittance limit for interior partitions that delimit units of the same use (W/m^2·K)	1.20	1.20	1.00	1.00
	Thermal transmittance limit for interior partitions that delimit units of different uses (W/m^2·K)	0.85	0.85	0.70	0.70
	Possibility of surface condensation (Yes/No)	No	No	No	No
	Possibility of interstitial condensation (Yes/No)	No	No	No	No
CTE-DB-HE4	Minimum renewable energy contribution to meet the DHW demand (%)	60.00	60.00	60.00	60.00

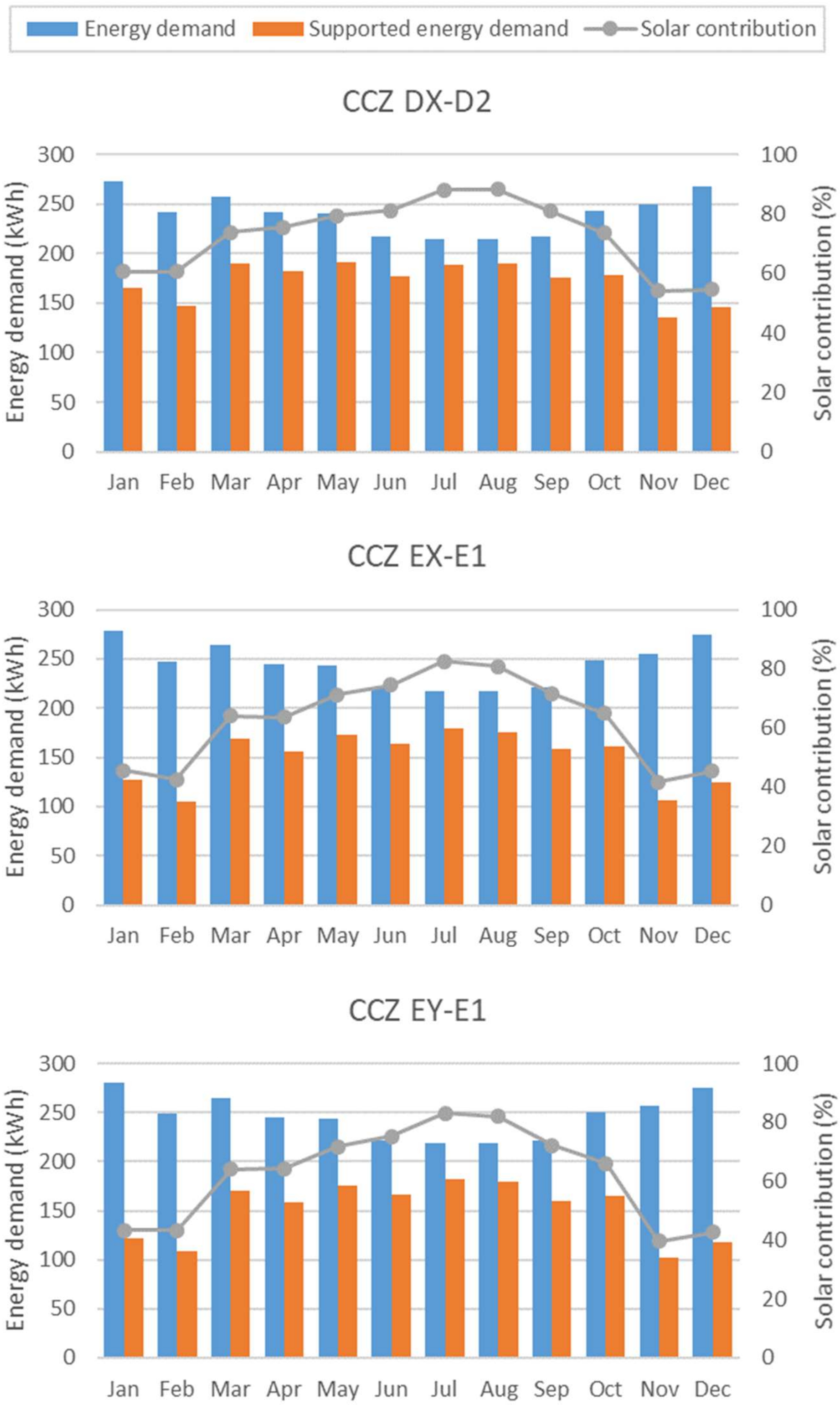

Figure A1. Monthly DHW energy demand, in kWh, monthly DHW energy demand met by the solar thermal system, in kWh, and monthly solar contribution, in %, in each CCZ.

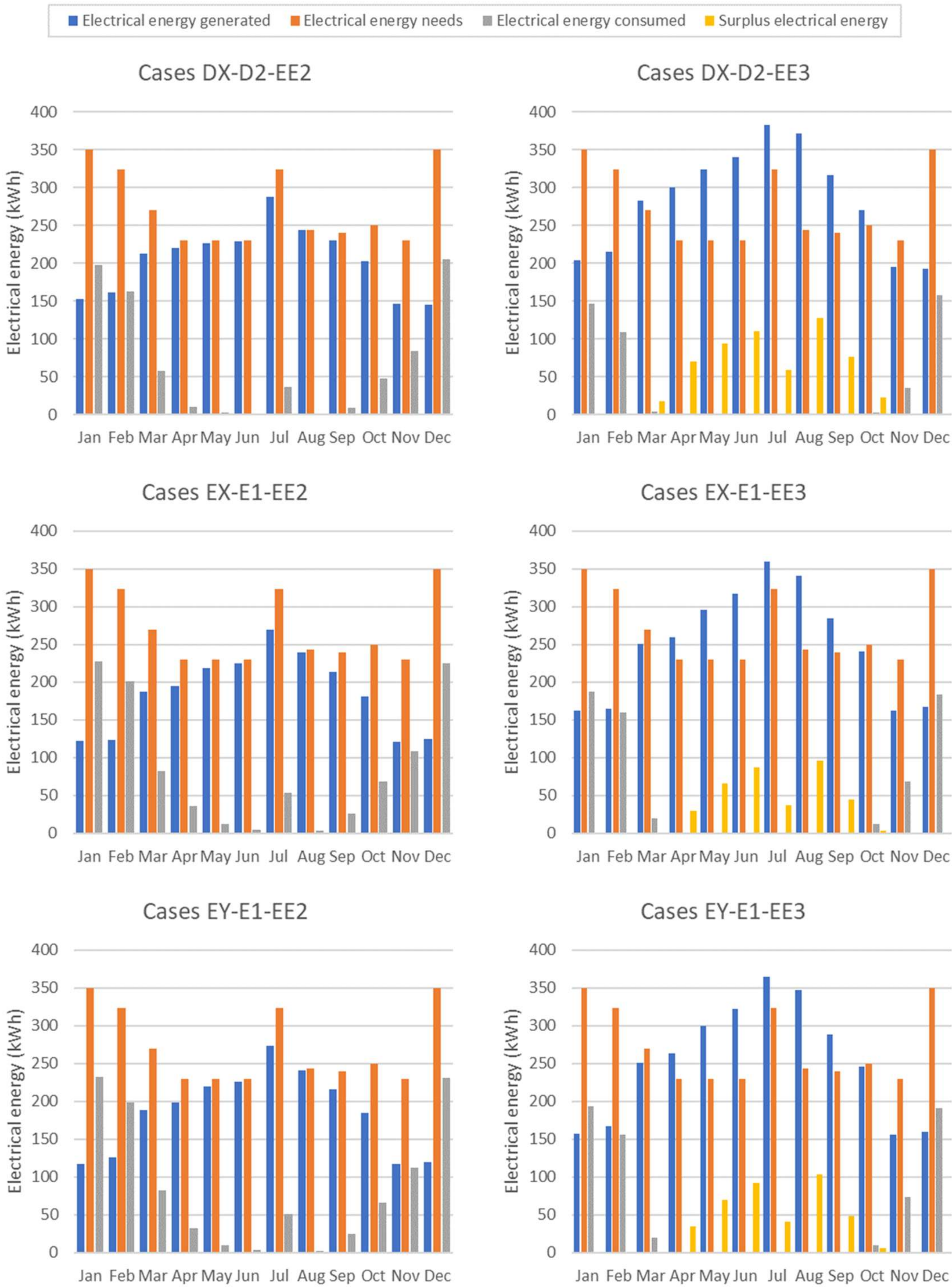

Figure A2. Monthly electrical energy balances for cases EE2 and EE3 in the different CCZs.

Table A2. Verification of compliance with the CTE-DB-HE [52] for each case study in Cervera del Río Alhama (CCZ DX-D2).

	Main Parameters					Compliance with the CTE-DB-HE [52]		
	K ($W/m^2 \cdot K$)	q ($kWh/m^2 \cdot month$)	REC (–)	NRPEC ($kWh/m^2 \cdot year$)	TPEC ($kWh/m^2 \cdot year$)	Renovated Building	New Building	NZEB
DX-D2-S1-NoInsu-EE1	2.025	0.320	0.0025	279.14	280.78	No	No	No
DX-D2-S2-NoInsu-EE1	2.025	0.320	0.0025	234.00	235.52	No	No	No
DX-D2-S3-EPS-EE1	0.500	0.160	0.7189	30.81	31.72	Yes	Yes	Yes
DX-D2-S4-EPS-EE1	0.480	0.160	0.7194	30.10	31.05	Yes	Yes	Yes
DX-D2-S5-EPS-EE1	0.542	0.160	0.9236	9.74	60.61	Yes	Yes	Yes
DX-D2-S6-EPS-EE1	0.542	0.160	0.9785	8.54	44.92	Yes	Yes	Yes
DX-D2-S3-MW-EE1	0.481	0.160	0.7189	29.29	30.19	Yes	Yes	Yes
DX-D2-S4-MW-EE1	0.473	0.160	0.7194	28.91	29.86	Yes	Yes	Yes
DX-D2-S5-MW-EE1	0.518	0.160	0.9236	9.44	58.49	Yes	Yes	Yes
DX-D2-S6-MW-EE1	0.518	0.160	0.9785	8.24	42.80	Yes	Yes	Yes
DX-D2-S3-PUR-EE1	0.505	0.160	0.7189	31.61	32.52	Yes	Yes	Yes
DX-D2-S4-PUR-EE1	0.489	0.160	0.7194	30.70	31.65	Yes	Yes	Yes
DX-D2-S5-PUR-EE1	0.541	0.160	0.9236	9.86	61.39	Yes	Yes	Yes
DX-D2-S6-PUR-EE1	0.541	0.160	0.9785	8.65	45.69	Yes	Yes	Yes
DX-D2-S3-XPS-EE1	0.549	0.160	0.7189	33.71	34.62	Yes	Yes	Yes
DX-D2-S4-XPS-EE1	0.525	0.160	0.7194	32.59	33.55	Yes	Yes	Yes
DX-D2-S5-XPS-EE1	0.577	0.160	0.9236	10.32	64.84	Yes	Yes	Yes
DX-D2-S6-XPS-EE1	0.577	0.160	0.9785	9.12	49.14	Yes	Yes	Yes
DX-D2-S3-EPS-EE2	0.500	0.160	0.7189	26.85	26.92	Yes	Yes	Yes
DX-D2-S4-EPS-EE2	0.480	0.160	0.7194	26.15	26.26	Yes	Yes	Yes
DX-D2-S5-EPS-EE2	0.542	0.160	0.9236	5.79	55.87	Yes	Yes	Yes
DX-D2-S6-EPS-EE2	0.542	0.160	0.9785	4.59	40.18	Yes	Yes	Yes
DX-D2-S3-MW-EE2	0.481	0.160	0.7189	25.34	25.40	Yes	Yes	Yes
DX-D2-S4-MW-EE2	0.473	0.160	0.7194	24.96	25.07	Yes	Yes	Yes
DX-D2-S5-MW-EE2	0.518	0.160	0.9236	5.50	53.76	Yes	Yes	Yes
DX-D2-S6-MW-EE2	0.518	0.160	0.9785	4.30	38.06	Yes	Yes	Yes

Table A2. *Cont.*

	Main Parameters					Compliance with the CTE-DB-HE [52]		
	K ($W/m^2 \cdot K$)	q ($kWh/m^2 \cdot month$)	REC (–)	NRPEC ($kWh/m^2 \cdot year$)	TPEC ($kWh/m^2 \cdot year$)	Renovated Building	New Building	NZEB
DX-D2-S3-PUR-EE2	0.505	0.160	0.7189	27.67	27.74	Yes	Yes	Yes
DX-D2-S4-PUR-EE2	0.489	0.160	0.7194	26.75	26.86	Yes	Yes	Yes
DX-D2-S5-PUR-EE2	0.541	0.160	0.9236	5.92	56.65	Yes	Yes	Yes
DX-D2-S6-PUR-EE2	0.541	0.160	0.9785	4.71	40.96	Yes	Yes	Yes
DX-D2-S3-XPS-EE2	0.549	0.160	0.7189	29.77	29.85	Yes	Yes	Yes
DX-D2-S4-XPS-EE2	0.525	0.160	0.7194	28.65	28.77	Yes	Yes	Yes
DX-D2-S5-XPS-EE2	0.577	0.160	0.9236	6.41	60.10	Yes	Yes	Yes
DX-D2-S6-XPS-EE2	0.577	0.160	0.9785	5.21	44.41	Yes	Yes	Yes
DX-D2-S3-EPS-EE3	0.500	0.160	0.7189	26.85	26.92	Yes	Yes	Yes
DX-D2-S4-EPS-EE3	0.480	0.160	0.7194	26.15	26.26	Yes	Yes	Yes
DX-D2-S5-EPS-EE3	0.542	0.160	0.9236	5.79	55.87	Yes	Yes	Yes
DX-D2-S6-EPS-EE3	0.542	0.160	0.9785	4.59	40.18	Yes	Yes	Yes
DX-D2-S3-MW-EE3	0.481	0.160	0.7189	25.34	25.40	Yes	Yes	Yes
DX-D2-S4-MW-EE3	0.473	0.160	0.7194	24.96	25.07	Yes	Yes	Yes
DX-D2-S5-MW-EE3	0.518	0.160	0.9236	5.50	53.76	Yes	Yes	Yes
DX-D2-S6-MW-EE3	0.518	0.160	0.9785	4.30	38.06	Yes	Yes	Yes
DX-D2-S3-PUR-EE3	0.505	0.160	0.7189	27.67	27.74	Yes	Yes	Yes
DX-D2-S4-PUR-EE3	0.489	0.160	0.7194	26.75	26.86	Yes	Yes	Yes
DX-D2-S5-PUR-EE3	0.541	0.160	0.9236	5.92	56.65	Yes	Yes	Yes
DX-D2-S6-PUR-EE3	0.541	0.160	0.9785	4.71	40.96	Yes	Yes	Yes
DX-D2-S3-XPS-EE3	0.549	0.160	0.7189	29.77	29.85	Yes	Yes	Yes
DX-D2-S4-XPS-EE3	0.525	0.160	0.7194	28.65	28.77	Yes	Yes	Yes
DX-D2-S5-XPS-EE3	0.577	0.160	0.9236	6.41	60.10	Yes	Yes	Yes
DX-D2-S6-XPS-EE3	0.577	0.160	0.9785	5.21	44.41	Yes	Yes	Yes

Note: K is global heat transfer coefficient through the thermal envelope of the building; q is solar control parameter; REC is renewable energy contribution to meet DHW demand; NRPEC is non-renewable primary energy consumption; TPEC is total primary energy consumption.

Table A3. Verification of compliance with the CTE-DB-HE [52] for each case study in San Millán de la Cogolla (CCZ EX-E1).

	Main Parameters					Compliance with the CTE-DB-HE [52]		
	K ($W/m^2 \cdot K$)	q ($kWh/m^2 \cdot month$)	REC (–)	NRPEC ($kWh/m^2 \cdot year$)	TPEC ($kWh/m^2 \cdot year$)	Renovated Building	New Building	NZEB
EX-E1-S1-NoInsu-EE1	2.025	0.302	0.0025	342.59	343.53	No	No	No
EX-E1-S2-NoInsu-EE1	2.025	0.302	0.0025	286.53	287.33	No	No	No
EX-E1-S3-EPS-EE1	0.475	0.151	0.6150	40.72	40.96	Yes	Yes	Yes
EX-E1-S4-EPS-EE1	0.466	0.151	0.6156	39.99	40.29	Yes	Yes	Yes
EX-E1-S5-EPS-EE1	0.512	0.151	0.9236	8.79	73.06	Yes	Yes	Yes
EX-E1-S6-EPS-EE1	0.512	0.151	0.9705	7.78	59.81	Yes	Yes	Yes
EX-E1-S3-MW-EE1	0.465	0.151	0.6150	39.29	39.52	Yes	Yes	Yes
EX-E1-S4-MW-EE1	0.451	0.151	0.6156	38.57	38.88	Yes	Yes	Yes
EX-E1-S5-MW-EE1	0.495	0.151	0.9236	8.39	70.38	Yes	Yes	Yes
EX-E1-S6-MW-EE1	0.495	0.151	0.9705	7.37	57.14	Yes	Yes	Yes
EX-E1-S3-PUR-EE1	0.482	0.151	0.6150	41.70	41.94	Yes	Yes	Yes
EX-E1-S4-PUR-EE1	0.469	0.151	0.6156	40.83	41.15	Yes	Yes	Yes
EX-E1-S5-PUR-EE1	0.520	0.151	0.9236	9.01	74.39	Yes	Yes	Yes
EX-E1-S6-PUR-EE1	0.520	0.151	0.9705	8.00	61.15	Yes	Yes	Yes
EX-E1-S3-XPS-EE1	0.514	0.151	0.6150	43.64	43.88	Yes	No	No
EX-E1-S4-XPS-EE1	0.500	0.151	0.6156	42.62	42.93	Yes	Yes	Yes
EX-E1-S5-XPS-EE1	0.553	0.151	0.9236	9.52	77.84	Yes	No	Yes
EX-E1-S6-XPS-EE1	0.553	0.151	0.9705	8.50	64.60	Yes	No	Yes
EX-E1-S3-EPS-EE2	0.475	0.151	0.6150	40.08	40.18	Yes	Yes	Yes
EX-E1-S4-EPS-EE2	0.466	0.151	0.6156	39.35	39.52	Yes	Yes	Yes
EX-E1-S5-EPS-EE2	0.512	0.151	0.9236	8.17	72.35	Yes	Yes	Yes
EX-E1-S6-EPS-EE2	0.512	0.151	0.9705	7.16	59.10	Yes	Yes	Yes
EX-E1-S3-MW-EE2	0.465	0.151	0.6150	38.65	38.75	Yes	Yes	Yes
EX-E1-S4-MW-EE2	0.451	0.151	0.6156	37.92	38.09	Yes	Yes	Yes
EX-E1-S5-MW-EE2	0.495	0.151	0.9236	7.76	69.67	Yes	Yes	Yes
EX-E1-S6-MW-EE2	0.495	0.151	0.9705	6.74	56.43	Yes	Yes	Yes

Table A3. *Cont.*

	Main Parameters					Compliance with the CTE-DB-HE [52]		
	K ($W/m^2 \cdot K$)	q ($kWh/m^2 \cdot month$)	REC (–)	NRPEC ($kWh/m^2 \cdot year$)	TPEC ($kWh/m^2 \cdot year$)	Renovated Building	New Building	NZEB
EX-E1-S3-PUR-EE2	0.482	0.151	0.6150	41.05	41.15	Yes	Yes	Yes
EX-E1-S4-PUR-EE2	0.469	0.151	0.6156	40.17	40.35	Yes	Yes	Yes
EX-E1-S5-PUR-EE2	0.520	0.151	0.9236	8.38	73.68	Yes	Yes	Yes
EX-E1-S6-PUR-EE2	0.520	0.151	0.9705	7.37	60.44	Yes	Yes	Yes
EX-E1-S3-XPS-EE2	0.514	0.151	0.6150	43.01	43.12	Yes	No	No
EX-E1-S4-XPS-EE2	0.500	0.151	0.6156	41.99	42.17	Yes	Yes	Yes
EX-E1-S5-XPS-EE2	0.553	0.151	0.9236	8.91	77.13	Yes	No	Yes
EX-E1-S6-XPS-EE2	0.553	0.151	0.9705	7.89	63.89	Yes	No	Yes
EX-E1-S3-EPS-EE3	0.475	0.151	0.6150	40.08	40.18	Yes	Yes	Yes
EX-E1-S4-EPS-EE3	0.466	0.151	0.6156	39.35	39.52	Yes	Yes	Yes
EX-E1-S5-EPS-EE3	0.512	0.151	0.9236	8.17	72.35	Yes	Yes	Yes
EX-E1-S6-EPS-EE3	0.512	0.151	0.9705	7.16	59.10	Yes	Yes	Yes
EX-E1-S3-MW-EE3	0.465	0.151	0.6150	38.65	38.75	Yes	Yes	Yes
EX-E1-S4-MW-EE3	0.451	0.151	0.6156	37.92	38.09	Yes	Yes	Yes
EX-E1-S5-MW-EE3	0.495	0.151	0.9236	7.76	69.67	Yes	Yes	Yes
EX-E1-S6-MW-EE3	0.495	0.151	0.9705	6.74	56.43	Yes	Yes	Yes
EX-E1-S3-PUR-EE3	0.482	0.151	0.6150	41.05	41.15	Yes	Yes	Yes
EX-E1-S4-PUR-EE3	0.469	0.151	0.6156	40.17	40.35	Yes	Yes	Yes
EX-E1-S5-PUR-EE3	0.520	0.151	0.9236	8.38	73.68	Yes	Yes	Yes
EX-E1-S6-PUR-EE3	0.520	0.151	0.9705	7.37	60.44	Yes	Yes	Yes
EX-E1-S3-XPS-EE3	0.514	0.151	0.6150	43.01	43.12	Yes	No	No
EX-E1-S4-XPS-EE3	0.500	0.151	0.6156	41.99	42.17	Yes	Yes	Yes
EX-E1-S5-XPS-EE3	0.553	0.151	0.9236	8.91	77.13	Yes	No	Yes
EX-E1-S6-XPS-EE3	0.553	0.151	0.9705	7.89	63.89	Yes	No	Yes

Note: K is global heat transfer coefficient through the thermal envelope of the building; q is solar control parameter; REC is renewable energy contribution to meet DHW demand; NRPEC is non-renewable primary energy consumption; TPEC is total primary energy consumption.

Table A4. Verification of compliance with the CTE-DB-HE [52] for each case study in Torrecilla en Cameros (CCZ EY-E1).

	Main Parameters					Compliance with the CTE-DB-HE [52]		
	K ($W/m^2 \cdot K$)	q ($kWh/m^2 \cdot month$)	REC (–)	NRPEC ($kWh/m^2 \cdot year$)	TPEC ($kWh/m^2 \cdot year$)	Renovated Building	New Building	NZEB
EY-E1-S1-NoInsu-EE1	1.782	0.302	0.0025	307.38	308.25	No	No	No
EY-E1-S2-NoInsu-EE1	1.782	0.302	0.0025	257.07	257.81	No	No	No
EY-E1-S3-EPS-EE1	0.475	0.151	0.6137	40.70	40.93	Yes	Yes	Yes
EY-E1-S4-EPS-EE1	0.466	0.151	0.6143	39.95	40.26	Yes	Yes	Yes
EY-E1-S5-EPS-EE1	0.512	0.151	0.9236	8.79	73.06	Yes	Yes	Yes
EY-E1-S6-EPS-EE1	0.512	0.151	0.9704	7.77	59.81	Yes	Yes	Yes
EY-E1-S3-MW-EE1	0.456	0.151	0.6137	38.90	39.13	Yes	Yes	Yes
EY-E1-S4-MW-EE1	0.442	0.151	0.6143	38.17	38.47	Yes	Yes	Yes
EY-E1-S5-MW-EE1	0.487	0.151	0.9236	8.32	69.83	Yes	Yes	Yes
EY-E1-S6-MW-EE1	0.487	0.151	0.9704	7.30	56.58	Yes	Yes	Yes
EY-E1-S3-PUR-EE1	0.484	0.151	0.6137	41.59	41.82	Yes	Yes	Yes
EY-E1-S4-PUR-EE1	0.472	0.151	0.6143	40.98	41.29	Yes	Yes	Yes
EY-E1-S5-PUR-EE1	0.524	0.151	0.9236	8.89	73.50	Yes	Yes	Yes
EY-E1-S6-PUR-EE1	0.524	0.151	0.9704	7.87	60.26	Yes	Yes	Yes
EY-E1-S3-XPS-EE1	0.518	0.151	0.6137	43.71	43.95	Yes	No	No
EY-E1-S4-XPS-EE1	0.503	0.151	0.6143	42.67	42.98	Yes	Yes	Yes
EY-E1-S5-XPS-EE1	0.553	0.151	0.9236	9.50	77.62	Yes	No	Yes
EY-E1-S6-XPS-EE1	0.553	0.151	0.9704	8.48	64.49	Yes	No	Yes
EY-E1-S3-EPS-EE2	0.475	0.151	0.6137	40.06	40.15	Yes	Yes	Yes
EY-E1-S4-EPS-EE2	0.466	0.151	0.6143	39.30	39.48	Yes	Yes	Yes
EY-E1-S5-EPS-EE2	0.512	0.151	0.9236	8.16	72.35	Yes	Yes	Yes
EY-E1-S6-EPS-EE2	0.512	0.151	0.9704	7.14	59.10	Yes	Yes	Yes
EY-E1-S3-MW-EE2	0.456	0.151	0.6137	38.25	38.34	Yes	Yes	Yes
EY-E1-S4-MW-EE2	0.442	0.151	0.6143	37.51	37.67	Yes	Yes	Yes
EY-E1-S5-MW-EE2	0.487	0.151	0.9236	7.68	69.12	Yes	Yes	Yes
EY-E1-S6-MW-EE2	0.487	0.151	0.9704	6.66	55.87	Yes	Yes	Yes

Table A4. *Cont.*

	Main Parameters					Compliance with the CTE-DB-HE [52]		
	K (W/m^2·K)	q (kWh/m^2·month)	REC (–)	NRPEC (kWh/m^2·year)	TPEC (kWh/m^2·year)	Renovated Building	New Building	NZEB
EY-E1-S3-PUR-EE2	0.484	0.151	0.6137	40.94	41.03	Yes	Yes	Yes
EY-E1-S4-PUR-EE2	0.472	0.151	0.6143	40.33	40.50	Yes	Yes	Yes
EY-E1-S5-PUR-EE2	0.524	0.151	0.9236	8.24	72.79	Yes	Yes	Yes
EY-E1-S6-PUR-EE2	0.524	0.151	0.9704	7.22	59.55	Yes	Yes	Yes
EY-E1-S3-XPS-EE2	0.518	0.151	0.6137	43.08	43.19	Yes	No	No
EY-E1-S4-XPS-EE2	0.503	0.151	0.6143	42.04	42.22	Yes	Yes	Yes
EY-E1-S5-XPS-EE2	0.553	0.151	0.9236	8.89	76.91	Yes	No	Yes
EY-E1-S6-XPS-EE2	0.553	0.151	0.9704	7.87	63.77	Yes	No	Yes
EY-E1-S3-EPS-EE3	0.475	0.151	0.6137	40.06	40.15	Yes	Yes	Yes
EY-E1-S4-EPS-EE3	0.466	0.151	0.6143	39.30	39.48	Yes	Yes	Yes
EY-E1-S5-EPS-EE3	0.512	0.151	0.9236	8.16	72.35	Yes	Yes	Yes
EY-E1-S6-EPS-EE3	0.512	0.151	0.9704	7.14	59.10	Yes	Yes	Yes
EY-E1-S3-MW-EE3	0.456	0.151	0.6137	38.25	38.34	Yes	Yes	Yes
EY-E1-S4-MW-EE3	0.442	0.151	0.6143	37.51	37.67	Yes	Yes	Yes
EY-E1-S5-MW-EE3	0.487	0.151	0.9236	7.68	69.12	Yes	Yes	Yes
EY-E1-S6-MW-EE3	0.487	0.151	0.9704	6.66	55.87	Yes	Yes	Yes
EY-E1-S3-PUR-EE3	0.484	0.151	0.6137	40.94	41.03	Yes	Yes	Yes
EY-E1-S4-PUR-EE3	0.472	0.151	0.6143	40.33	40.50	Yes	Yes	Yes
EY-E1-S5-PUR-EE3	0.524	0.151	0.9236	8.24	72.79	Yes	Yes	Yes
EY-E1-S6-PUR-EE3	0.524	0.151	0.9704	7.22	59.55	Yes	Yes	Yes
EY-E1-S3-XPS-EE3	0.518	0.151	0.6137	43.08	43.19	Yes	No	No
EY-E1-S4-XPS-EE3	0.503	0.151	0.6143	42.04	42.22	Yes	Yes	Yes
EY-E1-S5-XPS-EE3	0.553	0.151	0.9236	8.89	76.91	Yes	No	Yes
EY-E1-S6-XPS-EE3	0.553	0.151	0.9704	7.87	63.77	Yes	No	Yes

Note: K is global heat transfer coefficient through the thermal envelope of the building; q is solar control parameter; REC is renewable energy contribution to meet DHW demand; NRPEC is non-renewable primary energy consumption; TPEC is total primary energy consumption.

In Tables A2–A4, for existing buildings in the three CCZs, the air change ratio with a differential pressure of 50 Pa is 4.87 h^{-1}, and air permeability due to openings in the thermal envelope is 27 $m^3/h \cdot m^2$ with an overpressure of 100 Pa; and, for all energy renovation solutions in the three CCZs, the air change ratio with a differential pressure of 50 Pa is 2.58 h^{-1}, and the air permeability due to openings in the thermal envelope is 9 $m^3/h \cdot m^2$ with an overpressure of 100 Pa.

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