applied sciences

MDPI

Article

Energy Renovation of Residential Buildings in Hot and Temperate Mediterranean Zones Using Optimized Thermal Envelope Insulation Thicknesses: The Case of Spain

Jesús Las-Heras-Casas *, Luis M. López-Ochoa, Luis M. López-González and Pablo Olasolo-Alonso

TENECO Research Group, Department of Mechanical Engineering, University of La Rioja, Calle San José de Calasanz, 31, 26004 Logroño, La Rioja, Spain; luis-maria.lopezo@unirioja.es (L.M.L.-O.); luis-maria.lopez@unirioja.es (L.M.L.-G.); pablo.olasolo@unirioja.es (P.O.-A.)

* Correspondence: jesus.las-herasc@unirioja.es

Abstract: One of the greatest challenges facing the European Union is the conversion of the existing residential building stock into nearly zero-energy buildings (NZEBs) by 2050 through energy renovation, given that the residential sector is one of the largest consumers of final energy and that approximately two-thirds of existing dwellings were built before 1980. The objective of this study is to assess the energy, environmental, and economic impacts of the energy renovation of thermal envelopes of existing multi-family buildings in the hot and temperate climate zones of Spain by using life cycle cost analysis (LCCA) to determine the optimal thicknesses of insulation to be added to the walls, roof, and first floor framework of the buildings and replacing existing building openings to achieve NZEBs. Four thermal insulation materials are considered with four different heating and cooling systems and ten different models. With the methodology developed, the best energy renovation solutions are estimated and then thermally simulated. In total, 67 of the 576 proposed energy renovation solutions achieve NZEBs. This study fills in the gap between LCCA estimates and reality.

Keywords: optimum insulation thickness; life cycle cost analysis; energy renovation; residential buildings; nearly zero-energy buildings; Spain

check for updates

Citation: Las-Heras-Casas, J.; López-Ochoa, L.M.; López-González, L.M.; Olasolo-Alonso, P. Energy Renovation of Residential Buildings in Hot and Temperate Mediterranean Zones Using Optimized Thermal Envelope Insulation Thicknesses: The Case of Spain. *Appl. Sci.* **2021**, *11*, 370. https://doi.org/10.3390/app11010370

Received: 3 November 2020
Accepted: 28 December 2020
Published: 1 January 2021

1. Introduction

In 2018, the final energy consumption in the European Union reached 283.2 Mtoe in the residential sector and 151.6 Mtoe in the service sector, with 41.0% of the final energy consumption coming from the building sector [1]. In the residential sector, 67.0% of energy consumption results from space heating, 13.0% results from water heating, and 0.4% results from space cooling [2]. Although space cooling barely consumes any energy, 70.8% of the cooling energy demand of the European Union residential sector is concentrated in Italy, Spain, Greece, and Portugal [3]. In addition to the elevated energy consumption of the residential sector, the residential building stock is old, and 67.6% of existing dwellings were built before 1980 [4]. Therefore, with the Energy Performance of Buildings Directive 2018 [5], the European Union seeks to establish a long-term strategy to support the renovation of its building stock, transforming it into a building stock with a high energy efficiency and decarbonizing it before 2050 to facilitate the economically profitable transformation of existing buildings into nearly zero-energy buildings (NZEBs).

In the renovation of the residential building stock, one of the most effective methods to reduce both the heating and cooling energy demands is to increase the thermal insulation of the opaque elements of the thermal envelope [6–8]. The greater the insulation thickness, the lower the heat losses for heating and the heat gains for cooling through the thermal envelope but the greater the required investment, assuming that the required investment not associated with the insulation material would be similar for different energy renovation solutions of the thermal envelope of the building. Therefore, it is necessary to find a balance between the cost of the insulation used and the potential heating and cooling savings in buildings [9]. Life cycle cost analysis (LCCA) [10] and the P_1-P_2 method [11] are used to determine the optimum insulation thickness. A summary of the main studies [12–27] that have determined the optimum insulation thickness using these methods for residential buildings is presented in Table 1. The vast majority of these studies were focused on external walls, but Sisman et al. [15] determined the optimum insulation thickness for both walls and roofs, and López-Ochoa et al. [12] and Evin and Ucar [20] addressed the problem globally for all the opaque components of the thermal envelope of a building. Bektas Ekici et al. [16], Alsayed and Tayeh [21], Nematchoua et al. [23], Cyrille Vincelas et al. [24], and Huang et al. [26] evaluated the optimum insulation thickness for different types of external walls in the cities studied, while López-Ochoa et al. [12] and Yuan et al. [25] considered construction differences according to the climatic zone. In addition, only López-Ochoa et al. [12] and Annibaldi et al. [13] focused on solving this problem for existing buildings, while the rest considered new buildings, although some authors such as Annibaldi et al. [14] considered the possibility of energy renovation. At the national level, Rosas-Flores and Rosas-Flores [28] mapped the optimum insulation thicknesses required for all residential buildings in Mexican municipalities by applying LCCA. In their study, they differentiated the climates into extremely hot, tropical, and temperate and evaluated the potential economic savings, the heating and cooling energy savings, and the potential reduction in CO_2 emissions. In addition to these studies, Ozel [29] and Derradji et al. [30] studied the influence of glazing on the optimum insulation thickness in residential buildings in Elazığ, Turkey, and the Algiers region of Algeria, respectively; and, based on weight coefficients, Jie et al. [31] developed an optimization model to determine the optimum insulation thicknesses of the walls and roofs of existing buildings based on primary energy consumption, global cost, and pollutant emissions, and Amiri and Fallahi [32] developed a novel energy, environmental, and economic method to determine the optimum insulation thickness of walls.

Table 1. Main studies that have determined the optimum insulation thickness using life cycle cost analysis (LCCA) and P_1-P_2 method for residential buildings.

Reference	Method	Main Aims and/or Parameters Assessed	Thermal Insulation Materials	Sources for Heating System	Sources for Cooling System	Optimization Criteria	Locations
[12]	LCCA	Energy renovation of residential buildings in cold Mediterranean zones using optimized thermal envelope insulation thicknesses	EPS MW PUR XPS	Heating oil Natural gas Biomass Electicity	Electricity	Heating Heating + Cooling	The 26 provincial capitals in the cold climate zones, Spain
[13]	LCCA	Environmental and economic benefits of optimal insulation thickness	Wood fiber Hemp fiber Linen fiber Cork Rock wool Fiber glass EPS XPS PUR Sheep wool	Natural gas	-	Heating	Aielli, Province of L'Aquila, Italy
[14]	LCCA	A sustainable solution for energy efficiency	Hemp fiber	Natural gas	Electricity	Heating + Cooling	Abruzzo, Campania and Piedmont regions, Italy
[15]	LCCA	Optimum insulation thicknesses of the external walls and roof	Rock wool	Coal	-	Heating	Izmir, Bursa, Eskişehir and Erzurum, Turkey

Table 1. *Cont.*

Reference	Method	Main Aims and/or Parameters Assessed	Thermal Insulation Materials	Sources for Heating System	Sources for Cooling System	Optimization Criteria	Locations
[16]	LCCA	Optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones	Fiberglass XPS EPS Foamed PUR	Coal Liquified petroleum gas Electricity Fuel-oil Natural gas	-	Heating	Antalya, Istanbul, Elazig and Kayseri, Turkey
[17]	LCCA	Optimum insulation thickness for building walls by using heating and cooling degree-day values	XPS EPS Glass wool Rock wool PUR	Natural gas Coal Fuel-oil Liquified petroleum gas	Electricity	Heating Cooling Heating + Cooling	The 81 provincial capitals, Turkey
[18]	LCCA	Ecological impact and financial feasibility of Energy Recovery Model for natural insulation material optimization	Wood fiber plate Wood wool slab Expanded perlite Expanded cork	Coal Natural gas Fuel-oil	-	Heating	The 14 provincial capitals in Eastern Anatolia region, Turkey
[19]	LCCA	Environmental impact of insulation thickness of poultry building walls	XPS EPS	Natural gas Coal Fuel-oil Liquified petroleum gas Electricity	Electricity	Heating Cooling Heating + Cooling	Antalya, Samsun, Ankara and Erzurum, Turkey
[20]	P_1-P_2	Energy impact and eco-efficiency of the envelope insulation in residential buildings	XPS EPS Rock wool PUR	Natural gas	Electricity	Heating Cooling Heating + Cooling	Mersin, Çanakkale, Elaziğ and Van, Turkey
[21]	LCCA	Life cycle cost analysis for determining optimal insulation thickness in external walls	Polystyrene PUR rigid foam Rock wool	Liquified petroleum gas	Electricity	Heating Cooling Heating + Cooling	Jerusalem, Israel Hebron, Israel and Palestine Jericho, Tulkarem, Gaza, Bethlehem, Jenin and Nablus, Palestine
[22]	LCCA	Thermoeconomic analysis for determining optimal insulation thickness for new composite prefabricated wall block as an external wall member in buildings	XPS PUR foam sheet	Natural gas	Electricity	Heating Cooling Heating + Cooling	Ardabil, Tehran and Khuzestan, Iran
[23]	P_1-P_2	Economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate	EPS	-	Electricity	Cooling	Douala, Cameroon
[24]	P_1-P_2	Influence of the types of fuel and building material on energy savings into building in tropical region	EPS XPS Foamed PVC Foamed PUR Rock wool Glass wool	-	Hydroelectricity Photovoltaic Fuel oil Natural gas Liquified petroleum gas	Cooling	Douala, Cameroon

Table 1. *Cont.*

Reference	Method	Main Aims and/or Parameters Assessed	Thermal Insulation Materials	Sources for Heating System	Sources for Cooling System	Optimization Criteria	Locations
[25]	LCCA	Optimum insulation thickness for building exterior walls to save energy and reduce CO_2 emissions	EPS	Natural gas Coal Electricity	Electricity	Heating + Cooling	All the regions, except Macao and Hong Kong, and Paracel Islands, China
[26]	P_1-P_2	Optimum insulation thicknesses and energy conservation of building thermal insulation materials in humid subtropical climate zone	XPS EPS PUR foam Glass fiber Aerogel blankets	Coal Natural gas Liquified petroleum gas Electricity	Electricity	Heating + Cooling	Shangai, China
[27]	LCCA	Optimal combination of thermal resistance of insulation materials and primary fuel sources for all the different climate zones	EPS Foam board Rock wool XPS	(Electricity) Coal Natural gas Liquified natural gas Fuel-oil	(Electricity) Coal Natural gas Liquified natural gas Fuel oil	Heating + Cooling	Sapporo, Akita, Fukushima, Osaka, Kagoshima and Naha, Japan

Note: expanded polystyrene (EPS); mineral wool (MW); polyurethane (PUR); extruded polystyrene (XPS); polyvinyl chloride (PVC).

The objective of this study is to assess the energy, environmental, and economic impacts of the energy renovation of the thermal envelope of existing residential buildings in hot and temperate climate zones in Spain, complementing the results in [12] conducted for cold climate zones in Spain. LCCA is used to assess the optimum insulation thickness to be added to the walls, roof, and first floor framework (FFF), and existing building openings are replaced. The insulation thickness is optimized to minimize the total heating costs, total cooling costs, and total heating and cooling costs. Four thermal insulation materials, expanded polystyrene (EPS), mineral wool (MW), polyurethane (PUR), and extruded polystyrene (XPS), and different heating and cooling systems, including heating oil boilers, natural gas boilers, biomass boilers, and electric heat pumps, are considered. The residential building studied is a multi-family housing block, and its existing thermal envelope has the main features of the thermal envelopes of the existing residential stock in the studied climate zones. This study improves and adapts the methodology developed in [12] to determine the energy renovation solutions that will achieve NZEBs. These solutions are thermally simulated to fill in the gap between LCCA estimates and reality.

2. Methodology

The methodology developed in this study is as follows: (i) Selection of Spanish cities with hot and temperate Mediterranean climate and identification of their combined climate zones, taking into account the current climate zones and the climate zones considered in the construction period of existing buildings (1981–2007); (ii) Definition of the studied building with a thermal envelope that represents the main characteristics of the existing residential building stock; (iii) For the case studies, determination of the thermal insulation materials, heating and cooling systems, and costs; (iv) Evaluation of the optimum insulation thicknesses to be added to the walls, roof, and FFF to minimize the total heating costs, total cooling costs, and total heating and cooling costs using LCCA; (v) For each combined climate zone, selection of the energy renovation solutions that are expected to reach NZEBs, and if this is not possible, selection of the best solution from the economic point of view for each system; (vi) Evaluation of the heating and cooling energy demands of the selected energy renovation solutions by thermal simulation, with previously rounding up the optimum insulation thicknesses to commercial thicknesses; and (vii) Evaluation of the energy, environmental, and economic impacts and verification of the achievement of NZEBs. The methodology developed in [12] is improved in (iv) and (v).

2.1. Climate Zones

The Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) [33] establishes 15 climate zones in Spain according to winter climate severity and summer climate severity [34]. The winter climate severity defines the winter climate zone, which is represented by a letter, and determines the heating energy demand. The winter climate severity is obtained from the winter degree-days with a base temperature of 20 °C and the ratio between the number of sunlight hours and the maximum number of sunlight hours in winter, using the corresponding values for the months from October to May. The summer climate severity defines the summer climate zone, which is represented by a number, and determines the cooling energy demand. The summer climate severity is obtained from the summer degree-days with a base temperature of 20 °C in summer, using the corresponding values for the months from June to September. As this study focuses on hot and temperate Mediterranean climate zones, the studied buildings are located in the most representative Spanish cities in climate zones A3, A4, B3, B4, C1, C2, C3, and C4 [33,35]. The cities selected for the study include 22 provincial capitals and two autonomous cities. All the provincial capitals are located in the Iberian Peninsula, except for Palma de Mallorca in the Balearic Islands, and the two autonomous cities, Ceuta and Melilla, are located in North Africa. In addition, because this study addresses the energy renovation of existing buildings and the thermal envelopes of buildings have always been designed according to climate zones, it is essential to know the January climate zones that the Basic Document Norm on Thermal Conditions in Buildings [36] used in the period 1981–2007. The selected cities correspond to the January climate zones W, X, and Y, which were established based on the minimum mean temperatures during January (5 °C for W, 3 °C for X, and 0 °C for Y). Figure 1 shows both the climate zones and the January climate zones of the selected cities of Spain. Table 2 shows the winter climate severity and the summer climate severity for the climate zones of the selected cities. Table 3 shows the climate zones, the corresponding heating and cooling degree-days, the January climate zones, and the reference cities of the cities studied. The heating degree-days and cooling degree-days, both with a base temperature of 20 °C, were obtained from the Ministry of Industry, Energy and Tourism and the Institute for Energy Diversification and Saving (IDAE) [37]. Each combined climate zone is defined as CZ-JCZ, where CZ is the current climate zone, and JCZ is the January climate zone.

2.2. Main Characteristics of the Study Building

The study building [12,35,38] has a ground floor and five levels. The square base has an area of 484.00 m^2, the height of each floor is 3.00 m, and the hip roof has a height of 2.00 m. The main façade has a northern orientation. Each of the five floors has four types of dwellings (A, B, C, and D), for a total living area of 2216.57 m^2. Figure 2 shows the floor plan and a 3D view of the study building. The exchange surfaces of the thermal envelope are 1107.16 m^2 of walls, 491.93 m^2 of roof, 484.00 m^2 of FFF, and 212.84 m^2 of openings. The window-to-wall ratio is 0.1612. The main entrance and a car parking space are located on the ground floor.

The values of the thermal transmittance of the components of the thermal envelope of existing buildings are equal to the maximum values of thermal transmittance allowed for each January climatic zone by the Basic Document Norm on Thermal Conditions in Buildings [36], which are used by default for the energy performance certification of existing buildings built prior to 2008 [39]. These values are used to determine the optimum insulation thicknesses by LCCA. However, the composition and main characteristics of the different elements that make up the building enclosures and the composition of the building openings adapted from [40] (Cádiz and Valencia for January climate zone W, Cáceres for January climate zone X, and Madrid for January climate zone Y) are used for thermal simulation. The values of the thermal transmittance of the components of the thermal envelope of existing buildings for LCCA and thermal simulation are presented in Table 4.

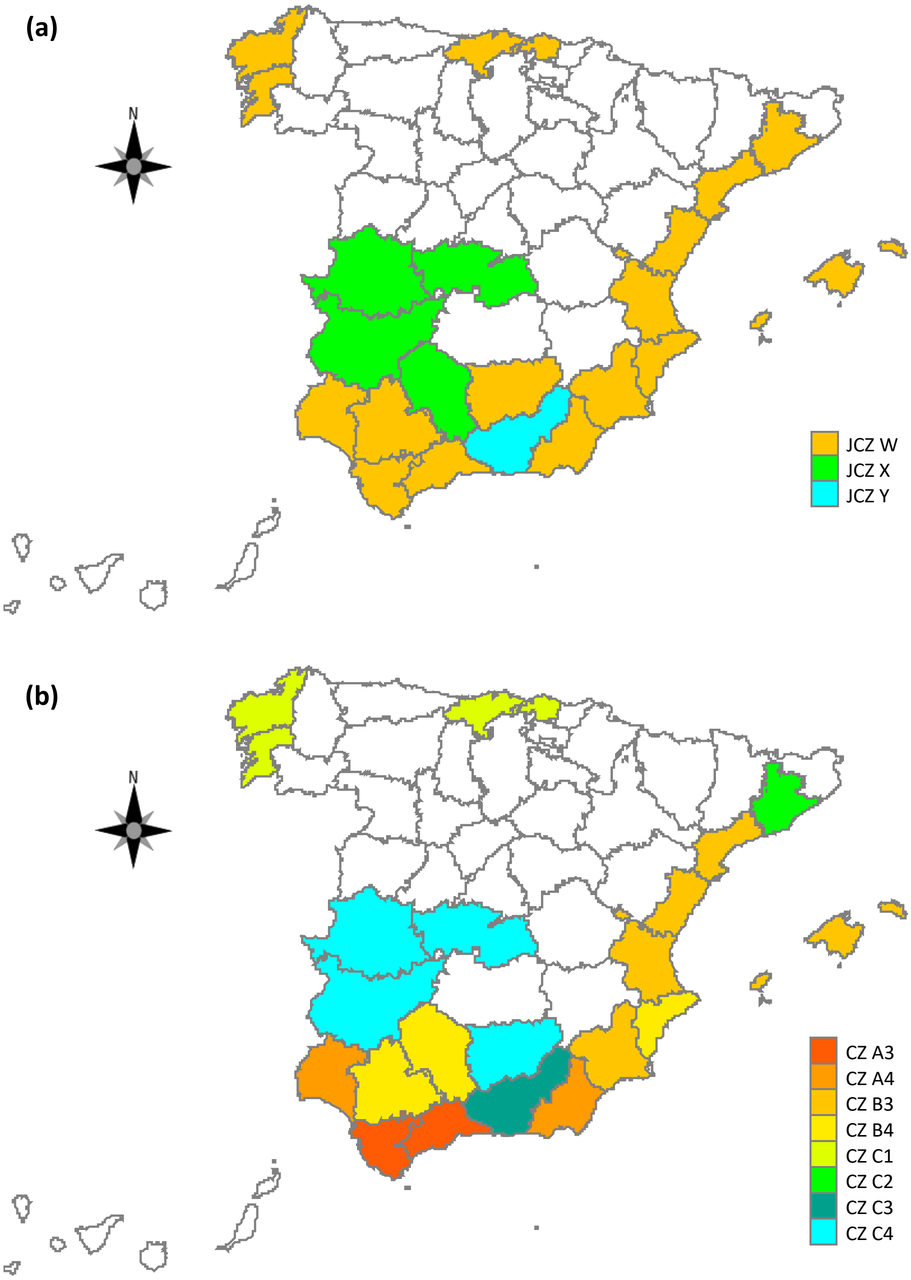

Figure 1. Climate zoning of the selected Spanish provincial capitals and autonomous cities: (**a**) January climate zones (JCZs) [36] and (**b**) climate zones (CZs) [33].

Table 2. Winter climate severity (WCS) and summer climate severity (SCS) for the climate zones of the selected cities [34].

Summer Climate Severity	Winter Climate Severity		
	$0 < WCS \leq 0.23$	$0.23 < WCS \leq 0.50$	$0.50 < WCS \leq 0.93$
$SCS \leq 0.50$			C1
$0.50 < SCS \leq 0.83$			C2
$0.83 < SCS \leq 1.38$	A3	B3	C3
$SCS > 1.38$	A4	B4	C4

Table 3. Climate zones (CZs), the corresponding heating degree-days (HDD) and cooling degree-days (CDD), the January climate zones (JCZs) and the reference cities of the cities studied.

CZ	HDD	CDD	JCZ	Reference City	Cities
A3	1235	494	W	Cádiz	Cádiz, Málaga and Melilla
A4	1199	663	W	Almería	Almería and Huelva
B3	1543	470	W	Valencia/València	Castellón/Castelló, Ceuta, Murcia, Palma de Mallorca, Tarragona and Valencia/València
B4	1508	636	W X	Sevilla Córdoba	Alicante/Alacant and Sevilla Córdoba
C1	2384	95	W	Bilbao/Bilbo	Bilbao/Bilbo, La Coruña/A Coruña, Pontevedra and Santander
C2	2237	226	W	Barcelona	Barcelona
C3	2123	429	Y	Granada	Granada
C4	2088	596	W X	Jaén Toledo	Jaén Badajoz, Cáceres and Toledo

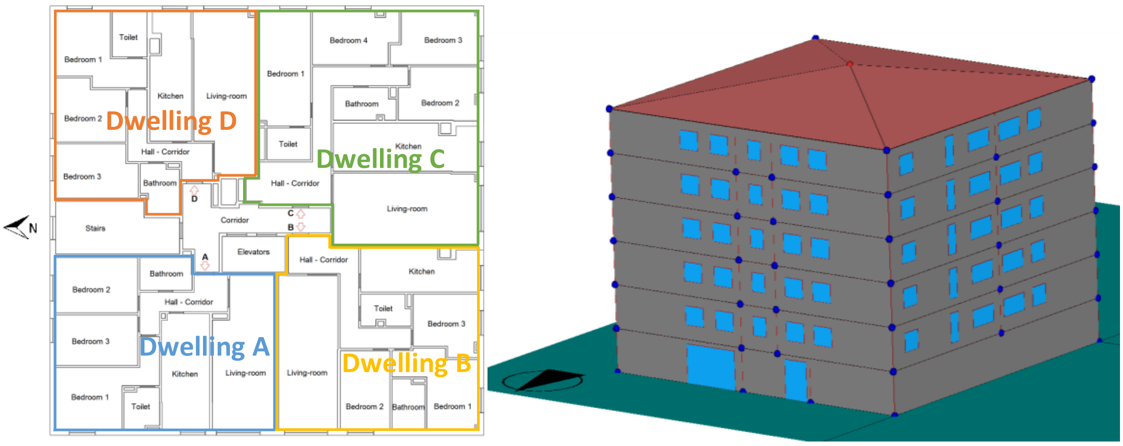

Figure 2. Floor plan of the four types of dwellings and a 3D view of the study building.

Table 4. Thermal transmittance, in $W/m^2{\cdot}K$, for each element of the thermal envelope of the existing building by JCZ for LCCA [36,39] and thermal simulation [40].

JCZ	Thermal Transmittance [36,39]				Thermal Transmittance [40]			
	Walls	Roof	FFF	Openings	Walls	Roof	FFF	Openings
W	1.80	1.40	2.17	5.70	1.75	1.40	1.97	5.70
X	1.60	1.20	1.40	5.70	1.60	1.18	1.40	5.70
Y	1.40	0.90	1.20	3.50	1.39	0.89	1.15	3.51

2.3. Requirements to Achieve NZEBs

The definition of an NZEB was established in the CTE-DB-HE [33], the national transposition of the Energy Performance of Buildings Directive 2010 [41]. NZEBs are buildings that meet the CTE-DB-HE [33] requirements for new buildings, including a limitation of the heating energy demand, a limitation of the cooling energy demand, and a minimum solar contribution to cover the domestic hot water (DHW) energy demand. In addition, the buildings must be thermally simulated with HULC [42] to determine if they achieve NZEB status. HULC [42] is the official software tool used to verify compliance with the energy consumption and energy demand restrictions of CTE-DB-HE [33] and to certify the energy performance of buildings. The limit values of the energy parameters, which should not be exceeded, as well as the solar contribution for DHW considered, were determined in [35] and are presented in Table 5 for the combined climate zones considered in this work.

Table 5. Limit value of the heating energy demand (HED_{lim}), cooling energy demand (CED_{lim}), and non-renewable primary energy consumption ($NRPEC_{lim}$), in kWh/m^2·year, as well as the solar contribution for domestic hot water (DHW) considered (SC), per unit, for the combined climate zones [35]. (*) Non-mainland combined climate zone.

Combined Climate Zone	HED_{lim}	CED_{lim}	SC	$NRPEC_{lim}$
A3-W	15.00	15.00	0.60	40.45
A3-W *	15.00	15.00	0.70	48.45
A4-W	15.00	20.00	0.70	40.45
B3-W	15.00	15.00	0.58	45.45
B3-W *	15.00	15.00	0.65	54.45
B4-W	15.00	20.00	0.70	45.45
B4-X	15.00	20.00	0.60	45.45
C1-W	20.45	15.00	0.30	50.68
C2-W	20.45	15.00	0.30	50.68
C3-Y	20.45	15.00	0.60	50.68
C4-W	20.45	20.00	0.60	50.68
C4-X	20.45	20.00	0.67	50.68

2.4. Case Studies

This study evaluates the optimum insulation thicknesses to be added to the walls, roof, and FFF of the thermal envelope of the study building that minimize the total heating costs, total cooling costs, and total heating and cooling costs of the energy renovation in each combined climate zone considering four different insulation materials (EPS, MW, PUR, and XPS) and four different systems. Moreover, the existing building openings are replaced by new openings.

The thermal conductivity of EPS, MW, and XPS is 0.034 W/m·K, and the thermal conductivity of PUR is 0.025 W/m·K. The main characteristics of the systems used to meet the heating, cooling, and DHW needs are presented in Table 6. The thermal transmittance of the new openings is 1.92 W/m^2·K. The new openings are composed of a double-chamber PVC frame and low-emissivity double-pane glass, with 30% of the space occupied by the framework. All the 2018 prices used for the insulation materials [43], the new openings [43], and the different energy carriers (fuels [44–47] and electricity [48]) are reported in Table 7. Electricity price 1 is used for systems 1, 2, and 3, and Electricity price 2 is used for system 4. The characteristics of the systems used, the insulation materials used, and the new openings, as well as the different prices applied, are the same as in [12], allowing the results of the two works to be compared and to provide an overall reference for Spain.

Table 6. Main characteristics of the different systems.

System	Main Characteristics	Unit	Value
1	Thermal performance of the heating oil boiler	-	0.85
	Thermal efficiency of the electric cooling system	-	2.00
2	Thermal performance of the natural gas boiler	-	0.92
	Thermal efficiency of the electric cooling system	-	2.00
3	Thermal performance of the biomass boiler	-	0.85
	Thermal efficiency of the electric cooling system	-	2.00
4	Seasonal coefficient of performance of the electric heat pump	-	2.50
	Seasonal energy efficiency ratio of the electric heat pump	-	3.00

Table 7. The 2018 prices for insulation materials, new openings, and energy carriers.

		Unit	Value	References
Thermal envelope	EPS insulation (0.034 W/m·K)	€/m^3	263.78	[43]
	MW insulation (0.034 W/m·K)	€/m^3	181.50	[43]
	PUR insulation (0.025 W/m·K)	€/m^3	302.50	[43]
	XPS insulation (0.034 W/m·K)	€/m^3	267.00	[43]
	New openings (1.92 W/m^2·K)	€/m^2	282.63	[43]
Energy carrier	Heating oil	€/kWh	0.0713	[44,45]
	Natural gas (20–200 GJ/year)	€/kWh	0.0770	[46]
	Biomass (A1 certified pellet in bulk)	€/kWh	0.0462	[47]
	Electricity 1 (2500–5000 kWh/year)	€/kWh	0.2430	[48]
	Electricity 2 (5000–15,000 kWh/year)	€/kWh	0.2042	[48]

In addition, the energy, environmental, and economic impacts are assessed for the energy renovation, and the energy renovation is evaluated to determine if it generates an NZEB.

2.5. Optimum Insulation Thickness for Walls, Roof, and FFF

LCCA is used to determine the optimum insulation thickness of the thermal envelope of the building (walls, roof, and FFF) that achieves the maximum net savings in terms of the heating and cooling costs. The analysis considers the heating and cooling degree-days, the costs and properties of both the insulation materials and the fuels used, the main characteristics of the heating and cooling systems, the electricity costs, and the economic parameters, such as the interest rate, inflation rate, and lifetime [17]. To evaluate the total cost in the entire life cycle, one must take into account the manufacture stage cost, the transportation stage cost, the installation stage cost, the heating and cooling energy costs, the demolition stage cost, and the disposal stage cost [26]. However, in the present study, only the thermal insulation cost and the heating and cooling energy costs are considered.

The thermal transmittance of an element e of the thermal envelope of a building, U_e, in W/m^2·K, is calculated using the following equation:

$$U_e = \frac{1}{R_e} \tag{1}$$

where e corresponds to the walls, roof, and FFF; and R_e corresponds to the thermal resistance of element e of the building envelope, in m^2·K/W, and it is calculated using the following equations:

$$R_e = R_e^{exist} + R_e^{insu} \tag{2}$$

$$R_e^{exist} = R_{si,e} + \sum\nolimits_n R_{n,e} + R_{se,e} \tag{3}$$

$$R_{n,e} = \frac{x_{n,e}}{\lambda_{n,e}} \tag{4}$$

$$R_e^{insu} = \frac{x_e}{\lambda} \tag{5}$$

where R_e^{exist} is the thermal resistance of element e of the existing building, in m^2·K/W; R_e^{insu} is the thermal resistance of the insulation added to element e of the building, in m^2·K/W; $R_{si,e}$ and $R_{se,e}$ are the surface thermal resistance of element e of the thermal envelope of the building for indoor air and outdoor air, respectively, in m^2·K/W; $R_{n,e}$ is the thermal resistance of layer n of element e of the thermal envelope of the existing building, in m^2·K/W; $x_{n,e}$ is the thickness of layer n of element e of the thermal envelope of the existing building, in m; $\lambda_{n,e}$ is the thermal conductivity of the material that makes up layer n of element e of the thermal envelope of the existing building, in W/m·K; x_e is the insulation thickness added to element e of the building, in m; and λ is the thermal conductivity of the insulation material used, in W/m·K.

Equations (1)–(5) were adapted from [49]; $R_{si,e}$ and $R_{se,e}$ were obtained from [49]; and $x_{n,e}$ and $\lambda_{n,e}$ were obtained from [40].

The terms $ED_{heat,e}$ and $ED_{cool,e}$ denote the heating and cooling energy demands for element e of the building per unit of exchange surface per year, respectively, in kWh/m^2·year, and they are calculated using the following equations:

$$ED_{heat,e} = 0.024 \cdot HDD \cdot U_e \tag{6}$$

$$ED_{cool,e} = 0.024 \cdot CDD \cdot U_e \tag{7}$$

where HDD and CDD are the heating and cooling degree-days, respectively, with a base temperature of 20 °C (Table 3).

The terms $EC_{heat,e}$ and $EC_{cool,e}$ denote the annual heating and cooling energy costs per unit of exchange surface of element e of the building, respectively, in €/m^2·year, and they are calculated using the following equations:

$$EC_{heat,e} = \frac{0.024 \cdot HDD \cdot C_{fuel} \cdot U_e}{\eta} \tag{8}$$

$$EC_{cool,e} = \frac{0.024 \cdot CDD \cdot C_{elec} \cdot U_e}{\varepsilon} \tag{9}$$

where C_{fuel} is the price of the fuel used, in €/kWh, as reported in Table 7; C_{elec} is the price of electricity, in €/kWh, as reported in Table 7; η is the thermal performance or seasonal coefficient of performance of the heating system, per unit, as reported in Table 6; and ε is the thermal efficiency or seasonal energy efficiency ratio of the cooling system, per unit, as reported in Table 6. For heat pumps, $C_{fuel} = C_{elec}$.

The present worth factor, PWF, is calculated from the interest rate, i, per unit, and the inflation rate, g, per unit, using the following equation:

$$PWF = \begin{cases} \frac{N}{1+i} & \text{if } i = g \\ \frac{(1+r)^N - 1}{r \cdot (1+r)^N} & \text{if } i \neq g \end{cases} \tag{10}$$

where N is the lifetime, in years; and r is the actual interest rate, per unit, which is calculated using the following equation:

$$r = \begin{cases} \frac{i-g}{1+g} & \text{if } i > g \\ \frac{g-i}{1+i} & \text{if } i < g \end{cases} \tag{11}$$

At an interest rate of 5.00%, an inflation rate of 2.50%, and a lifetime of 30 years [50,51], a PWF of 21.10 is obtained by applying Equations (10) and (11).

The insulation cost of element e of the building, $C_{insu,e}$, in €/m^2, is calculated using the following equation:

$$C_{insu,e} = C_{insu} \cdot x_e \tag{12}$$

where C_{insu} is the insulation cost, in €/m^3, as reported in Table 7.

The total heating cost, the total cooling cost, and the total heating and cooling cost per unit of exchange surface of element e of the building, $TC_{heat,e}$, $TC_{cool,e}$, and $TC_{heat+cool,e}$, respectively, in €/m^2, are calculated using the following equations:

$$TC_{heat,e} = EC_{heat,e} \cdot PWF + C_{insu,e} \tag{13}$$

$$TC_{cool,e} = EC_{cool,e} \cdot PWF + C_{insu,e} \tag{14}$$

$$TC_{heat+cool,e} = (EC_{heat,e} + EC_{cool,e}) \cdot PWF + C_{insu,e} \quad (15)$$

The optimum insulation thickness that minimizes the total heating cost of element e of the building, the optimum insulation thickness that minimizes the total cooling cost of element e of the building, and the optimum insulation thickness that minimizes the total heating and cooling cost of element e of the building, $x_{opt,e}^{heat}$, $x_{opt,e}^{cool}$, and $x_{opt,e}^{heat+cool}$, respectively, in m, are determined by setting the derivatives of Equations (13)–(15) with respect to the insulation thickness to zero [9] and are calculated, in m, using the following equations:

$$x_{opt,e}^{heat} = \left(\frac{0.024 \cdot HDD \cdot C_{fuel} \cdot PWF \cdot \lambda}{\eta \cdot C_{insu}} \right)^{0.5} - \lambda \cdot R_e^{exis} \quad (16)$$

$$x_{opt,e}^{cool} = \left(\frac{0.024 \cdot CDD \cdot C_{elec} \cdot PWF \cdot \lambda}{\varepsilon \cdot C_{insu}} \right)^{0.5} - \lambda \cdot R_e^{exis} \quad (17)$$

$$x_{opt,e}^{heat+cool} = \left(\frac{0.024 \cdot HDD \cdot C_{fuel} \cdot PWF \cdot \lambda}{\eta \cdot C_{insu}} + \frac{0.024 \cdot CDD \cdot C_{elec} \cdot PWF \cdot \lambda}{\varepsilon \cdot C_{insu}} \right)^{0.5} - \lambda \cdot R_e^{exis} \quad (18)$$

Equations (6)–(18) were adapted from [17], and Equations (16) and (18) were used in [12].

2.6. Estimation of the Best Energy Renovation Solutions

To select the best energy renovation solutions, it is necessary to estimate the energy parameters required to achieve NZEBs and the economic impact of the different case studies.

2.6.1. Estimation of the Energy Parameters to Achieve NZEB

The heating and cooling energy demands for element y of the building per unit of exchange surface per year, $ED_{heat,y}$ and $ED_{cool,y}$, respectively, in kWh/m^2·year, are calculated using the following equations:

$$ED_{heat,y} = 0.024 \cdot HDD \cdot U_y \quad (19)$$

$$ED_{cool,y} = 0.024 \cdot CDD \cdot U_y \quad (20)$$

where y denotes the walls, roof, FFF, and openings that make up the thermal envelope of the building; and U_y is the thermal transmittance of element y of the thermal envelope of the building, in W/m^2·K.

Equations (19) and (20) were adapted from [17].

The heating and cooling energy demands of the building per unit of living area per year, ED_{heat} and ED_{cool}, respectively, in kWh/m^2·year, are calculated using the following equations:

$$ED_{heat} = \sum\nolimits_y ED_{heat,y} \cdot \frac{A_{exch,y}}{A_{liv}} \quad (21)$$

$$ED_{cool} = \sum\nolimits_y ED_{cool,y} \cdot \frac{A_{exch,y}}{A_{liv}} \quad (22)$$

where $A_{exch,y}$ is the exchange surface of element y of the thermal envelope of the building, in m^2, and A_{liv}, which is the living area of the building.

Equations (21) and (22) were adapted from [12].

The final energy consumptions for heating, cooling, and DHW of the building per unit of living area per year, FEC_{heat}, FEC_{cool} and FEC_{DHW}, respectively, in kWh/m^2·year, are calculated using the following equations:

$$FEC_{heat} = \frac{ED_{heat}}{\eta} \quad (23)$$

$$FEC_{cool} = \frac{ED_{cool}}{\varepsilon} \quad (24)$$

$$FEC_{DHW} = \frac{ED_{DHW} \cdot (1 - f)}{\eta} \quad (25)$$

where ED_{DHW} is the DHW energy demand of the building per unit of living area per year, in kWh/m^2·year, and f is the annual solar contribution to meet the DHW requirement, per unit. For the existing building, ED_{DHW} is the average DHW energy demand per year for existing multi-family buildings built before 2008 (in the selected cities with the same climate zone and January climate zone) obtained from IDAE [52], and f is zero. For the corresponding renovated building, ED_{DHW} is the average energy demand of DHW per unit of living area per year according to the CTE-DB-HE [33], as calculated in [35], and f is the solar contribution for DHW considered for the studied building to meet the CTE-DB-HE [33], as reported in Table 5.

The resulting final energy consumption of the building per unit of living area per year, FEC_{total}, in kWh/m^2·year, is

$$FEC_{total} = FEC_{heat} + FEC_{cool} + FEC_{DHW} \quad (26)$$

The non-renewable primary energy consumption of the building per unit of living area per year, $NRPEC_{total}$, in kWh/m^2·year, is calculated using the following equation:

$$NRPEC_{total} = FEC_{heat} \cdot f_{NRPE}^{fuel} + FEC_{cool} \cdot f_{NRPE}^{elec} + FEC_{DHW} \cdot f_{NRPE}^{fuel} \quad (27)$$

where f_{NRPE}^{fuel} is the conversion factor from the final energy to the non-renewable primary energy for the fuel used, in kWh_{NRPE}/kWh_{FE}; and f_{NRPE}^{elec} is the conversion factor from the final energy to the non-renewable primary energy for electricity, in kWh_{NRPE}/kWh_{FE}. The aforementioned conversion factors were obtained from IDAE [53] (Table 8) and are the same as those used by HULC [42].

Equations (23)–(27) were used in [35].

Table 8. Factors of conversion from final energy (FE) to non-renewable primary energy (NRPE), total primary energy (TPE), and CO_2 emissions [53].

	NRPE Conversion Factor (kWh_{NRPE}/kWh_{FE})	TPE Conversion Factor (kWh_{TPE}/kWh_{FE})	CO_2 Emissions Conversion Factor (kg CO_2/kWh_{FE})
Mainland electricity	1.954	2.368	0.331
Non-mainland electricity	2.937	3.011	0.833
Heating oil	1.179	1.182	0.311
Natural gas	1.190	1.195	0.252
Densified biomass (pellets)	0.085	1.113	0.018

2.6.2. Estimation of the Economic Impact

The annual heating and cooling energy cost per unit of exchange surface of element y of the building, $EC_{heat,y}$ and $EC_{cool,y}$, respectively, in €/m^2·year, are calculated using the following equations:

$$EC_{heat,y} = \frac{0.024 \cdot HDD \cdot C_{fuel} \cdot U_y}{\eta} \quad (28)$$

$$EC_{cool,y} = \frac{0.024 \cdot CDD \cdot C_{elec} \cdot U_y}{\varepsilon} \quad (29)$$

Equations (28) and (29) were adapted from [17].

Using the insulation thickness optimized under the chosen criterion, the energy renovation cost per unit of living area of the building, C_{opcr}^{reno}, in €/m^2, is calculated using the following equation:

$$C_{opcr}^{reno} = \sum_y C_{opcr,y}^{reno} \cdot \frac{A_{exch,y}}{A_{liv}} \tag{30}$$

where the subscript $opcr$ corresponds to the optimization criterion used to minimize either the total heating costs (*heat*), the total cooling costs (*cool*), or the total heating and cooling costs ($heat + cool$); and $C_{opcr,y}^{reno}$ denotes the energy renovation cost for element y of the renovated building per unit of exchange surface, in €/m^2. $C_{opcr,y}^{reno}$ is obtained for new openings from Table 7 and calculated for the walls, roof, and FFF with the following equation:

$$C_{opcr,y}^{reno} = C_{insu} \cdot x_{opt,y}^{opcr} \tag{31}$$

Using the insulation thickness optimized under the chosen optimization criterion, the total net savings per unit of living area for the renovated building, ECS_{opcr}^{reno}, in €/m^2·year, is calculated using the following equation:

$$ECS_{opcr}^{reno} = \sum_y \left[\left(EC_{heat,y}^{exis} + EC_{cool,y}^{exis} \right) - \left(EC_{heat,y}^{reno} + EC_{cool,y}^{reno} \right) \right] \cdot \frac{A_{exch,y}}{A_{liv}} \tag{32}$$

where $EC_{heat,y}^{exis}$ and $EC_{heat,y}^{reno}$ are the annual heating energy costs per unit of exchange surface of element y of the existing and renovated buildings, respectively, in €/m^2·year, and are calculated using Equation (28); $EC_{cool,y}^{exis}$ and $EC_{cool,y}^{reno}$ are the annual cooling energy costs per unit of exchange surface of element y of the existing and renovated buildings, respectively, in €/m^2·year, and are calculated using Equation (29). $EC_{cool,y}^{exis}$ and $EC_{cool,y}^{reno}$ in Equation (32) are zero when the optimum insulation thickness that minimizes the total heating cost is used.

Using the insulation thickness optimized under the chosen optimization criterion, the payback period for the renovated building, PP_{opcr}^{reno}, in years, is calculated using the following equation:

$$PP_{opcr}^{reno} = \frac{C_{opcr}^{reno}}{ECS_{opcr}^{reno}} \tag{33}$$

Equations (30)–(33) were adapted from [12].

2.6.3. Selection of the Best Energy Renovation Solutions

For each combined climate zone, those energy renovation solutions that reach NZEB status, i.e., those solutions for which the heating energy demand, cooling energy demand, and non-renewable primary energy consumption do not exceed the corresponding limit values shown in Table 5, are selected. In the event that no solution is obtained in a combined climate zone, the best solution from an economic point of view, i.e., the solution with the lowest payback period, is selected for each system used as the best renovation solution for that combined climate zone.

2.7. Thermal Simulation

The existing buildings and the selected energy renovation solutions are thermally simulated with HULC [42] to evaluate the energy, environmental, and economic impacts and to determine whether the energy renovation achieves an NZEB. Braulio-Gonzalo and Bovea [54] employed HULC [42] to evaluate the impacts of the thermal insulation thicknesses required for different scenarios of reducing the heating energy demand in a single-family house located in Castellón de la Plana, Spain. The model of the base building corresponds to the building used in [40]. The insulation thicknesses to be added to the walls, roof, and FFF are the optimum insulation thicknesses obtained in the LCCA rounded up to the nearest cm (to commercial thicknesses). While the LCCA only takes into account the heat transfer losses and gains, the thermal simulation with HULC [42] also considers factors such as the air exchange per hour, the thermal bridges, the internal thermal loads, the use profiles, and the climate data of reference climates.

The process followed is as follows:

1. Thermal simulation of the building with HULC [42] in the corresponding reference city (Table 3) to obtain the heating and cooling energy demands of the building per unit of living area per year, in kWh/m^2·year, taking into account 1.50 air exchange/h for existing buildings [39,55] and 0.63 air exchange/h for renovated buildings [42].
2. Evaluation of the final energy consumption for heating, cooling, and DHW and the total of the building per unit of living area per year, in kWh/m^2·year, using Equations (23)–(26), taking into account the DHW energy demands of [52] for existing buildings and those of [35] for renovated buildings, a null solar contribution for existing buildings, the solar contributions in Table 5 for renovated buildings, the respective thermal performance or seasonal coefficient of performance of the heating system and the thermal efficiency or seasonal energy efficiency ratio of the cooling system (Table 6).
3. Evaluation of the non-renewable primary energy consumption of the building per unit of living area per year, in kWh/m^2·year, using Equation (27).
4. Evaluation of the total primary energy consumption of the building per unit of living area per year, $TPEC_{total}$, in kWh/m^2·year, which is calculated using the following equation:

$$TPEC_{total} = FEC_{heat} \cdot f_{TPE}^{fuel} + FEC_{cool} \cdot f_{TPE}^{elec} + FEC_{DHW} \cdot f_{TPE}^{fuel} \quad (34)$$

where f_{TPE}^{fuel} is the conversion factor from the final energy to the total primary energy for the fuel used, in kWh_{TPE}/kWh_{FE}; and f_{TPE}^{elec} is the conversion factor from the final energy to the total primary energy for electricity, in kWh_{TPE}/kWh_{FE}. The aforementioned conversion factors were obtained from IDAE [53] (Table 8) and are the same as those used by HULC [42].
5. Evaluation of the CO_2 emissions of the building per unit of living area per year, EM_{total}, in kg CO_2/m^2·year, which are calculated using the following equation:

$$EM_{total} = FEC_{heat} \cdot f_{EM}^{fuel} + FEC_{cool} \cdot f_{EM}^{elec} + FEC_{DHW} \cdot f_{EM}^{fuel} \quad (35)$$

where f_{EM}^{fuel} is the conversion factor from the final energy to the CO_2 emissions for the fuel used, in kg CO_2/kWh_{FE}; and f_{EM}^{elec} is the conversion factor from the final energy to the CO_2 emissions for the electricity in kg CO_2/kWh_{FE}. The aforementioned conversion factors were obtained from IDAE [53] (Table 8) and are the same as those used by HULC [42].
6. Assignment of labels for the non-renewable primary energy consumption and CO_2 emissions using the class boundaries of HULC [42,56] (Table 9).
7. Verification of compliance with the requirements for NZEBs (Table 5). Evaluation of economic impacts. The payback period for the renovated building, PP, in years, is calculated using the following equation:

$$PP = \frac{ERC}{TNS} \quad (36)$$

where ERC is the energy renovation cost of the building, in €, including insulation costs and the cost of new openings; and TNS is the total net savings of the renovated building compared to the existing building, in €/year, which is calculated using the following equation:

$$TNS = \left[\left(FEC_{heat}^{exis} \cdot C_{fuel} + FEC_{cool}^{exis} \cdot C_{elec} \right) - \left(FEC_{heat}^{reno} \cdot C_{fuel} + FEC_{cool}^{reno} \cdot C_{elec} \right) \right] \cdot A_{liv} \quad (37)$$

where FEC_{heat}^{exis} and FEC_{heat}^{reno} are the final energy consumptions for heating of the existing building and the renovated building per unit of living area per year, respectively, in kWh/m^2·year; and FEC_{cool}^{exis} and FEC_{cool}^{reno} are the final energy consumptions for cooling of the existing building and the renovated building per unit of living area per year, respectively, in kWh/m^2·year.
Equation (34) was used in [38] and Equation (35) was used in [35].

Table 9. Upper limit values for the non-renewable primary energy consumption, in kWh/m^2·year, and CO_2 emissions, in kg CO_2/m^2·year, labels for multi-family buildings in each climate zone [56]. (*) Non-mainland climate zone.

Climate Zone	Labels for Non-Renewable Primary Energy Consumption						Labels for CO_2 Emissions					
	A	B	C	D	E	F	A	B	C	D	E	F
A3	12.3	23.3	39.4	63.1	134.2	146.2	2.9	5.4	9.2	14.7	32.7	36.9
A3 *	13.6	25.7	43.5	69.7	146.8	160.0	3.6	6.9	11.6	18.6	40.5	45.8
A4	13.7	25.9	43.8	70.2	144.6	157.6	3.2	6.1	10.3	16.4	35.2	38.4
B3	15.6	29.6	50.0	80.1	173.7	189.4	3.6	6.8	11.5	18.5	41.5	46.9
B3 *	17.2	32.5	55.0	88.2	183.2	199.7	4.5	8.6	14.5	23.2	50.4	56.9
B4	19.2	33.1	54.0	84.8	184.3	200.9	4.4	7.7	12.5	19.7	44.1	48.1
C1	24.2	39.2	60.7	93.4	200.0	226.0	5.4	8.8	13.7	21.0	45.9	55.0
C2	26.8	43.4	67.3	103.5	212.9	240.5	6.1	9.9	15.3	23.5	49.0	57.3
C3	24.5	42.3	69.1	108.5	226.7	247.1	5.6	9.7	15.8	24.7	52.4	59.2
C4	26.2	45.2	73.7	115.8	237.0	267.8	6.0	10.4	16.9	26.5	54.9	62.1

3. Results and Discussion

A total of 576 energy renovation solutions were proposed, given that there are 12 combined climate zones, four systems, four types of insulation, and three optimization criteria. To name each of these solutions, the nomenclature CZ-JCZ-Sx-Insu-OC is used, where CZ refers to the climate zone, JCZ refers to the January climate zone, Sx refers to the system used (S1, S2, S3 or S4), Insu refers to the thermal insulation material (EPS, MW, PUR, or XPS) and OC refers to the optimization criteria (H for heating, C for cooling, or HC for heating and cooling).

Applying the methodology developed in Sections 2.5 and 2.6, for each proposed energy renovation solution, the optimum insulation thicknesses were determined, and the energy parameters required to achieve NZEBs and the economic impacts were estimated. Within each combined climate zone, those solutions that comply with the NZEB requirements were selected, and in the absence of any solution, the best solution from the economic point of view was selected for each system used.

Table 10 shows the 51 energy renovation solutions that would comply with the NZEB requirements. The renovated buildings that could become NZEBs include the following:

- Those located in climate zone A3, both mainland and non-mainland, that use system 1 or 2, optimizing the insulation thickness to minimize the total heating and cooling costs; those that use system 3 and MW insulation, optimizing the insulation thickness to minimize the total heating and cooling costs; and those that use system 4 and MW or PUR insulation, optimizing the insulation thickness to minimize the total heating and cooling costs.
- Those located in climate zone A4 that use system 1 or 2, optimizing the insulation thickness to minimize the total heating and cooling costs, or those that use MW insulation, optimizing the insulation thickness to minimize the total heating costs; those that use system 3, optimizing the insulation thickness to minimize the total heating and cooling costs; and those that use system 4, optimizing the insulation thickness to minimize the total heating and cooling costs, or those that use MW insulation, optimizing the insulation thickness to minimize the total heating costs.
- Those located in climate zones B4, C3, and C4 that use system 1 or 2 and MW insulation, optimizing the insulation thickness to minimize the total heating and cooling costs.

Table 10. Optimum insulation thicknesses to be added to the walls, roof, and FFF, in m, for the energy renovation solutions that would comply with the NZEB requirements. (*) Non-mainland combined climate zone.

Energy Renovation Solution	Walls	Roof	FFF
A3-W-S1-EPS-HC	0.084	0.079	0.088
A3-W-S1-MW-HC	0.106	0.100	0.109
A3-W-S1-PUR-HC	0.069	0.065	0.071
A3-W-S1-XPS-HC	0.084	0.078	0.087
A3-W-S2-EPS-HC	0.084	0.079	0.088
A3-W-S2-MW-HC	0.106	0.100	0.109
A3-W-S2-PUR-HC	0.069	0.065	0.071
A3-W-S2-XPS-HC	0.084	0.078	0.087
A3-W-S3-MW-HC	0.091	0.086	0.094
A3-W-S4-MW-HC	0.094	0.089	0.097
A3-W-S4-PUR-HC	0.061	0.057	0.064
A3-W *-S1-EPS-HC	0.084	0.079	0.088
A3-W *-S1-MW-HC	0.106	0.100	0.109
A3-W *-S1-PUR-HC	0.069	0.065	0.071
A3-W *-S1-XPS-HC	0.084	0.078	0.087
A3-W *-S2-EPS-HC	0.084	0.079	0.088
A3-W *-S2-MW-HC	0.106	0.100	0.109
A3-W *-S2-PUR-HC	0.069	0.065	0.071
A3-W *-S2-XPS-HC	0.084	0.078	0.087
A3-W *-S3-MW-HC	0.091	0.086	0.094
A3-W *-S4-MW-HC	0.094	0.089	0.097
A3-W *-S4-PUR-HC	0.061	0.057	0.064
A4-W-S1-EPS-HC	0.090	0.084	0.093
A4-W-S1-MW-H	0.079	0.073	0.082
A4-W-S1-MW-HC	0.112	0.107	0.115
A4-W-S1-PUR-HC	0.073	0.069	0.076
A4-W-S1-XPS-HC	0.089	0.084	0.092
A4-W-S2-EPS-HC	0.090	0.084	0.093
A4-W-S2-MW-H	0.079	0.073	0.082
A4-W-S2-MW-HC	0.112	0.107	0.115
A4-W-S2-PUR-HC	0.073	0.069	0.075
A4-W-S2-XPS-HC	0.089	0.084	0.092
A4-W-S3-EPS-HC	0.079	0.073	0.082
A4-W-S3-MW-HC	0.099	0.093	0.102
A4-W-S3-PUR-HC	0.064	0.060	0.067
A4-W-S3-XPS-HC	0.078	0.073	0.081
A4-W-S4-EPS-HC	0.078	0.072	0.081
A4-W-S4-MW-H	0.078	0.072	0.081
A4-W-S4-MW-HC	0.098	0.092	0.101
A4-W-S4-PUR-HC	0.063	0.060	0.066
A4-W-S4-XPS-HC	0.077	0.072	0.080
B4-W-S1-MW-HC	0.120	0.115	0.123
B4-W-S2-MW-HC	0.120	0.115	0.123
B4-X-S1-MW-HC	0.118	0.111	0.115
B4-X-S2-MW-HC	0.118	0.111	0.115
C3-Y-S1-MW-HC	0.123	0.110	0.119
C3-Y-S2-MW-HC	0.123	0.110	0.119
C4-W-S1-MW-HC	0.134	0.129	0.138
C4-W-S2-MW-HC	0.134	0.129	0.137
C4-X-S1-MW-HC	0.132	0.125	0.129
C4-X-S2-MW-HC	0.132	0.125	0.129

The results summarized in Table 10 for the hot and temperate climate zones together with the optimum insulation thicknesses obtained in [12] to achieve NZEBs in cold climate zones provide an overview of the average thicknesses to be added to the walls, roof, and FFF of the study building for all the winter climate zones and January climate zones in

Spain (Figure 3). To renovate existing buildings within the same winter climate zone, it is necessary to use thicker insulation as the minimum mean temperatures of January increase. This is because the Basic Document Norm on Thermal Conditions in Buildings [36] established the more restrictive thermal transmittances for thermal envelopes, the lower the January temperature, based on which the January climate zone was defined.

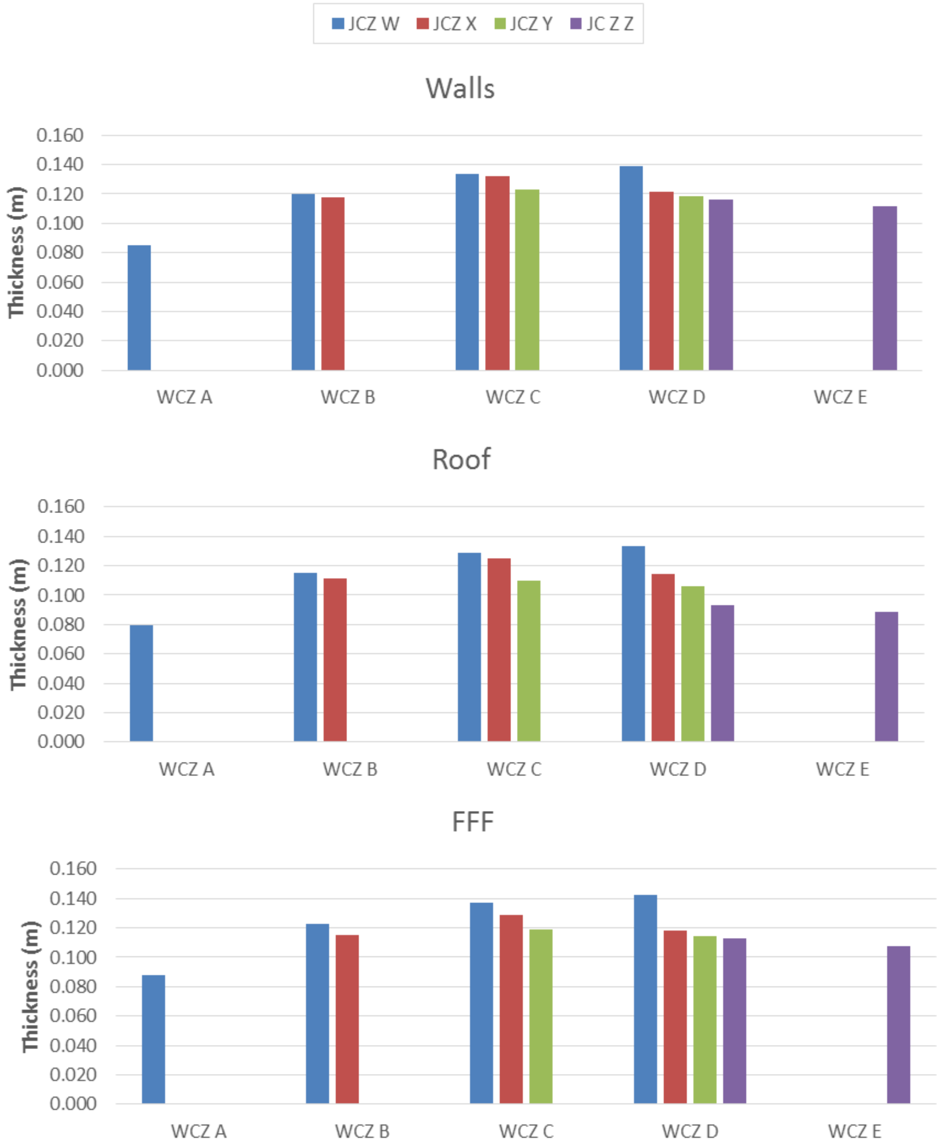

Figure 3. Average thicknesses to be added to the walls, roof, and FFF of the study building, in m, for all the winter climate zones (WCZs) and January climate zones (JCZs).

Table 11 shows the 16 energy renovation solutions that present the best solution from an economic point of view, i.e., the solution with the lowest payback period, in the combined climate zones where an NZEB was not achieved. For climate zones B3, C1, and C2, Table 11 reveals that the best renovated building solutions from an economic point of view are those that use MW as insulation, optimizing the insulation thickness to minimize the total heating and cooling costs, regardless of the system used.

Table 11. Optimum insulation thicknesses to be added to the walls, roof, and FFF, in m, for the energy renovation solutions that present the best solution from an economic point of view in the combined climate zones where an NZEB was not been achieved. (*) Non-mainland combined climate zone.

Energy Renovation Solution	Walls	Roof	FFF
B3-W-S1-MW-HC	0.114	0.109	0.117
B3-W-S2-MW-HC	0.114	0.109	0.117
B3-W-S3-MW-HC	0.097	0.091	0.100
B3-W-S4-MW-HC	0.104	0.098	0.107
B3-W *-S1-MW-HC	0.114	0.109	0.117
B3-W *-S2-MW-HC	0.114	0.109	0.117
B3-W *-S3-MW-HC	0.097	0.091	0.100
B3-W *-S4-MW-HC	0.104	0.098	0.107
C1-W-S1-MW-HC	0.123	0.117	0.126
C1-W-S2-MW-HC	0.123	0.117	0.126
C1-W-S3-MW-HC	0.097	0.091	0.100
C1-W-S4-MW-HC	0.119	0.114	0.122
C2-W-S1-MW-HC	0.124	0.119	0.127
C2-W-S2-MW-HC	0.124	0.118	0.127
C2-W-S3-MW-HC	0.100	0.095	0.103
C2-W-S4-MW-HC	0.118	0.113	0.121

Table 12 presents the thermal transmittance of the walls, roof, and FFF and the energy and environmental impacts obtained for existing buildings in the different combined climate zones using HULC [42]. Tables 13 and 14 show the optimized and rounded-up insulation thicknesses to be added to the walls, roof, and FFF, the thermal transmittance of the walls, roof, and FFF, and the energy and environmental impacts obtained for the energy renovation solutions shown in Tables 10 and 11, respectively, in the different combined climate zones using HULC [42]. Tables 13 and 14 reveal that all the selected energy renovation solutions achieve compliance with the NZEB requirements.

Table 12. Thermal transmittances of walls, roof, and FFF, in W/m^2·K, heating energy demand (HED), in kWh/m^2·year, cooling energy demand (CED), in kWh/m^2·year, total primary energy consumption (TPEC), in kWh/m^2·year, non-renewable primary energy consumption (NRPEC), in kWh/m^2·year, CO_2 emissions (EM), kg CO_2/m^2·year, non-renewable primary energy consumption rating (R_{NRPEC}), and CO_2 emissions rating (R_{EM}) for the thermal simulation of each existing building by combined climate zone and system used. (*) Non-mainland combined climate zone.

Case	Walls	Roof	FFF	HED	CED	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
A3-W-S1	1.60	1.40	1.97	36.18	14.53	84.62	81.44	20.14	E	E
A3-W-S2	1.60	1.40	1.97	36.18	14.53	80.17	76.90	15.68	E	E
A3-W-S3	1.60	1.40	1.97	36.18	14.53	80.68	19.04	3.43	B	B
A3-W-S4	1.60	1.40	1.97	36.18	14.53	57.39	47.36	8.02	D	C
A3-W *-S1	1.60	1.40	1.97	36.17	14.53	89.14	88.43	23.75	E	E
A3-W *-S2	1.60	1.40	1.97	36.17	14.53	84.70	83.90	19.30	E	E
A3-W *-S3	1.60	1.40	1.97	36.17	14.53	85.21	26.17	7.08	C	C
A3-W *-S4	1.60	1.40	1.97	36.17	14.53	72.84	71.05	20.15	E	E
A4-W-S1	1.60	1.40	1.97	35.95	23.38	94.64	89.63	21.49	E	E
A4-W-S2	1.60	1.40	1.97	35.95	23.38	90.22	85.12	17.06	E	E
A4-W-S3	1.60	1.40	1.97	35.95	23.38	90.73	27.66	4.89	C	B
A4-W-S4	1.60	1.40	1.97	35.95	23.38	64.06	52.86	8.95	D	C
B3-W-S1	1.60	1.40	1.97	55.77	14.66	112.26	108.98	27.40	E	E
B3-W-S2	1.60	1.40	1.97	55.77	14.66	106.00	102.60	21.12	E	E
B3-W-S3	1.60	1.40	1.97	55.77	14.66	106.72	21.15	3.87	B	B
B3-W-S4	1.60	1.40	1.97	55.77	14.66	76.21	62.89	10.65	D	C
B3-W *-S1	1.60	1.40	1.97	55.75	14.66	116.98	116.19	31.08	E	E
B3-W *-S2	1.60	1.40	1.97	55.75	14.66	110.72	109.81	24.80	E	E
B3-W *-S3	1.60	1.40	1.97	55.75	14.66	111.44	28.35	7.55	B	B
B3-W *-S4	1.60	1.40	1.97	55.75	14.66	96.91	94.53	26.81	E	E
B4-W-S1	1.60	1.40	1.97	55.85	23.24	122.28	117.23	28.78	E	E

Table 12. *Cont.*

Case	Walls	Roof	FFF	HED	CED	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
B4-W-S2	1.60	1.40	1.97	55.85	23.24	116.04	110.86	22.51	E	E
B4-X-S1	1.60	1.18	1.40	54.16	23.14	119.96	114.93	28.18	E	E
B4-X-S2	1.60	1.18	1.40	54.16	23.14	113.85	108.70	22.06	E	E
C1-W-S1	1.60	1.40	1.97	99.75	0.73	157.62	157.07	41.36	E	E
C1-W-S2	1.60	1.40	1.97	99.75	0.73	147.28	146.52	31.00	E	E
C1-W-S3	1.60	1.40	1.97	99.75	0.73	148.47	11.99	2.51	A	A
C1-W-S4	1.60	1.40	1.97	99.75	0.73	107.35	88.58	15.01	D	D
C2-W-S1	1.60	1.40	1.97	99.17	5.46	162.17	160.64	41.87	E	E
C2-W-S2	1.60	1.40	1.97	99.17	5.46	151.90	150.17	31.57	E	E
C2-W-S3	1.60	1.40	1.97	99.17	5.46	153.08	16.53	3.27	A	A
C2-W-S4	1.60	1.40	1.97	99.17	5.46	110.37	91.07	15.43	D	D
C3-Y-S1	1.39	0.89	1.15	80.40	15.08	147.60	144.15	36.63	E	E
C3-Y-S2	1.39	0.89	1.15	80.40	15.08	139.04	135.41	28.05	E	E
C4-W-S1	1.60	1.40	1.97	94.40	23.62	176.34	171.08	42.95	E	E
C4-W-S2	1.60	1.40	1.97	94.40	23.62	166.56	161.09	33.14	E	E
C4-X-S1	1.60	1.18	1.40	91.92	23.50	173.31	168.07	42.17	E	E
C4-X-S2	1.60	1.18	1.40	91.92	23.50	163.72	158.28	32.55	E	E

Table 13. Optimized and rounded-up insulation thicknesses to be added to the walls, roof, and FFF, in m, and their corresponding thermal transmittances obtained, in $W/m^2{\cdot}K$, heating energy demand (HED), in $kWh/m^2{\cdot}$year, cooling energy demand (CED), in $kWh/m^2{\cdot}$year, total primary energy consumption (TPEC), in $kWh/m^2{\cdot}$year, non-renewable primary energy consumption (NRPEC), in $kWh/m^2{\cdot}$year, CO_2 emissions (EM), kg $CO_2/m^2{\cdot}$year, non-renewable primary energy consumption rating (R_{NRPEC}), CO_2 emissions rating (R_{EM}), energy renovation costs per unit of living area (C), in €/m^2, total net savings per unit of living area per year (ECS), in €/$m^2{\cdot}$year, and payback period (PP), in years, for the thermal simulation of each energy renovation solution that would comply with the NZEB requirements. (*) Non-mainland combined climate zone.

Energy Renovation Solution	Thickness to Be Added			Thermal Transmittance			HED	CED	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	C	ECS	PP
	Walls	Roof	FFF	Walls	Roof	FFF										
A3-W-S1-EPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	27.88	25.26	5.51	C	C	48.86	3.11	15.73
A3-W-S1-MW-HC	0.110	0.100	0.110	0.27	0.26	0.27	1.83	12.45	27.44	24.83	5.40	C	C	45.50	3.13	14.52
A3-W-S1-PUR-HC	0.070	0.070	0.080	0.28	0.29	0.27	1.98	12.45	27.65	25.04	5.46	C	C	47.70	3.12	15.28
A3-W-S1-XPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	27.88	25.26	5.51	C	C	49.13	3.11	15.82
A3-W-S2-EPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	27.01	24.38	4.65	C	B	48.86	3.10	15.76
A3-W-S2-MW-HC	0.110	0.100	0.110	0.27	0.26	0.27	1.83	12.45	26.60	23.97	4.56	C	B	45.50	3.13	14.55
A3-W-S2-PUR-HC	0.070	0.070	0.080	0.28	0.29	0.27	1.98	12.45	26.79	24.17	4.60	C	B	47.70	3.12	15.31
A3-W-S2-XPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	27.01	24.38	4.65	C	B	49.13	3.10	15.85
A3-W-S3-MW-HC	0.100	0.090	0.100	0.30	0.28	0.29	1.97	12.46	26.89	13.10	2.26	B	A	43.79	2.11	20.75
A3-W-S4-MW-HC	0.100	0.090	0.100	0.30	0.28	0.29	1.97	12.46	18.62	15.36	2.60	B	A	43.79	2.94	14.92
A3-W-S4-PUR-HC	0.070	0.060	0.070	0.32	0.29	0.30	2.05	12.47	18.70	15.43	2.61	B	A	46.37	2.93	15.84
A3-W *-S1-EPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	29.31	28.82	7.97	C	C	48.86	3.11	15.73
A3-W *-S1-MW-HC	0.110	0.100	0.110	0.27	0.26	0.27	1.83	12.45	28.86	28.37	7.85	C	C	45.50	3.13	14.52
A3-W *-S1-PUR-HC	0.070	0.070	0.080	0.28	0.29	0.27	1.98	12.45	29.07	28.58	7.90	C	C	47.70	3.12	15.28
A3-W *-S1-XPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	29.31	28.82	7.97	C	C	49.13	3.11	15.82
A3-W *-S2-EPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	28.61	28.11	7.27	C	C	48.86	3.10	15.77

Table 13. *Cont.*

Energy Renovation Solution	Thickness to Be Added			Thermal Transmittance			HED	CED	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	C	ECS	PP
	Walls	Roof	FFF	Walls	Roof	FFF										
A3-W *-S2-MW-HC	0.110	0.100	0.110	0.27	0.26	0.27	1.83	12.45	28.19	27.69	7.18	C	C	45.50	3.13	14.55
A3-W *-S2-PUR-HC	0.070	0.070	0.080	0.28	0.29	0.27	1.98	12.45	28.39	27.89	7.22	C	C	47.70	3.11	15.32
A3-W *-S2-XPS-HC	0.090	0.080	0.090	0.33	0.31	0.32	2.13	12.47	28.61	28.11	7.27	C	C	49.13	3.10	15.85
A3-W *-S3-MW-HC	0.100	0.090	0.100	0.30	0.28	0.29	1.97	12.46	28.47	19.04	5.35	B	B	43.79	2.11	20.75
A3-W *-S4-MW-HC	0.100	0.090	0.100	0.30	0.28	0.29	1.97	12.46	21.44	20.91	5.93	B	B	43.79	2.93	14.92
A3-W *-S4-PUR-HC	0.070	0.060	0.070	0.32	0.29	0.30	2.05	12.47	21.54	21.01	5.96	B	B	46.37	2.93	15.84
A4-W-S1-EPS-HC	0.090	0.090	0.100	0.30	0.31	0.29	2.07	18.96	32.92	28.97	5.89	C	B	50.03	3.38	14.80
A4-W-S1-MW-H	0.080	0.080	0.090	0.33	0.34	0.32	2.25	19.01	33.23	29.26	5.97	C	B	41.18	3.36	12.26
A4-W-S1-MW-HC	0.120	0.110	0.120	0.25	0.24	0.25	1.71	18.88	32.32	28.39	5.75	C	B	47.20	3.42	13.81
A4-W-S1-PUR-HC	0.080	0.070	0.080	0.28	0.26	0.27	1.85	18.93	32.58	28.63	5.81	C	B	49.21	3.40	14.47
A4-W-S1-XPS-HC	0.090	0.090	0.100	0.30	0.31	0.29	2.07	18.96	32.92	28.97	5.89	C	B	50.30	3.38	14.89
A4-W-S2-EPS-HC	0.090	0.090	0.100	0.30	0.31	0.29	2.07	18.96	32.23	28.26	5.20	C	B	50.03	3.37	14.83
A4-W-S2-MW-H	0.080	0.080	0.090	0.33	0.34	0.32	2.25	19.01	32.52	28.54	5.26	C	B	41.18	3.35	12.29
A4-W-S2-MW-HC	0.120	0.110	0.120	0.25	0.24	0.25	1.71	18.88	31.67	27.72	5.09	C	B	47.20	3.41	13.83
A4-W-S2-PUR-HC	0.080	0.070	0.080	0.28	0.26	0.27	1.85	18.93	31.91	27.95	5.13	C	B	49.21	3.39	14.50
A4-W-S2-XPS-HC	0.090	0.090	0.100	0.30	0.31	0.29	2.07	18.96	32.23	28.26	5.20	C	B	50.30	3.37	14.92
A4-W-S3-EPS-HC	0.080	0.080	0.090	0.33	0.34	0.32	2.25	19.01	32.60	19.34	3.31	B	B	47.55	2.36	20.12
A4-W-S3-MW-HC	0.100	0.100	0.110	0.27	0.28	0.27	1.91	18.92	32.05	19.22	3.29	B	B	44.59	2.39	18.64
A4-W-S3-PUR-HC	0.070	0.060	0.070	0.32	0.29	0.30	2.05	18.98	32.30	19.29	3.30	B	B	46.37	2.38	19.51
A4-W-S3-XPS-HC	0.080	0.080	0.090	0.33	0.34	0.32	2.25	19.01	32.60	19.34	3.31	B	B	47.80	2.36	20.23
A4-W-S4-EPS-HC	0.080	0.080	0.090	0.33	0.34	0.32	2.25	19.01	22.31	18.41	3.12	B	A	47.55	3.05	15.59
A4-W-S4-MW-H	0.080	0.080	0.090	0.33	0.34	0.32	2.25	19.01	22.31	18.41	3.12	B	A	41.18	3.05	13.50
A4-W-S4-MW-HC	0.100	0.100	0.110	0.27	0.28	0.27	1.91	18.92	21.91	18.08	3.06	B	A	44.59	3.08	14.46
A4-W-S4-PUR-HC	0.070	0.060	0.070	0.32	0.29	0.30	2.05	18.98	22.09	18.23	3.09	B	A	46.37	3.07	15.11
A4-W-S4-XPS-HC	0.080	0.080	0.080	0.33	0.34	0.35	2.28	19.02	22.34	18.44	3.12	B	A	47.21	3.05	15.50
B4-W-S1-MW-HC	0.120	0.120	0.130	0.24	0.24	0.23	5.63	18.77	37.68	33.75	7.17	C	B	48.00	4.76	10.09
B4-W-S2-MW-HC	0.120	0.120	0.130	0.24	0.24	0.23	5.63	18.77	36.66	32.71	6.15	B	B	48.00	4.75	10.11
B4-X-S1-MW-HC	0.120	0.120	0.120	0.23	0.24	0.24	5.43	18.96	40.25	36.28	7.82	C	C	47.61	4.60	10.36
B4-X-S2-MW-HC	0.120	0.120	0.120	0.23	0.24	0.24	5.43	18.96	39.07	35.08	6.64	C	B	47.61	4.59	10.38
C3-Y-S1-MW-HC	0.130	0.110	0.120	0.23	0.22	0.23	15.11	12.93	46.98	44.23	10.47	C	C	48.11	5.74	8.38
C3-Y-S2-MW-HC	0.130	0.110	0.120	0.23	0.22	0.23	15.11	12.93	44.90	42.10	8.38	B	B	48.11	5.73	8.40
C4-W-S1-MW-HC	0.140	0.130	0.140	0.22	0.21	0.22	15.53	19.10	54.57	50.53	11.57	C	C	50.62	7.16	7.06

Table 13. *Cont.*

Energy Renovation Solution	Thickness to Be Added			Thermal Transmittance			HED	CED	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	C	ECS	PP
	Walls	Roof	FFF	Walls	Roof	FFF										
C4-W-S2-MW-HC	0.140	0.130	0.140	0.22	0.21	0.22	15.53	19.10	52.46	48.38	9.46	C	B	50.62	7.15	7.08
C4-X-S1-MW-HC	0.140	0.130	0.130	0.21	0.21	0.22	14.99	19.25	52.37	48.31	10.97	C	C	50.22	6.97	7.21
C4-X-S2-MW-HC	0.140	0.130	0.130	0.21	0.21	0.22	14.99	19.25	50.42	46.32	9.01	C	B	50.22	6.96	7.22

Table 14. Optimized and rounded-up insulation thicknesses to be added to the walls, roof, and FFF, in m, and their corresponding thermal transmittances obtained, in W/m^2·K, heating energy demand (HED), in kWh/m^2·year, cooling energy demand (CED), in kWh/m^2·year, total primary energy consumption (TPEC), in kWh/m^2·year, non-renewable primary energy consumption (NRPEC), in kWh/m^2·year, CO_2 emissions (EM), kg CO_2/m^2·year, non-renewable primary energy consumption rating (R_{NRPEC}), CO_2 emissions rating (R_{EM}), energy renovation costs per unit of living area (C), in €/m^2, total net savings per unit of living area per year (ECS), in €/m^2·year, and payback period (PP), in years, for the thermal simulation of each energy renovation solution that presents the best solution from an economic point of view in the combined climate zones where an NZEB was not been achieved. (*) Non-mainland combined climate zone.

Energy Renovation Solution	Thickness to Be Added			Thermal Transmittance			HED	CED	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	C	ECS	PP
	Walls	Roof	FFF	Walls	Roof	FFF										
B3-W-S1-MW-HC	0.120	0.110	0.120	0.25	0.24	0.25	5.60	12.48	33.54	30.91	7.00	C	C	47.20	4.47	10.55
B3-W-S2-MW-HC	0.120	0.110	0.120	0.25	0.24	0.25	5.60	12.48	32.31	29.65	5.76	C	B	47.20	4.46	10.57
B3-W-S3-MW-HC	0.100	0.100	0.100.	0.27	0.28	0.29	6.06	12.48	33.05	13.59	2.36	A	A	44.20	2.97	14.90
B3-W-S4-MW-HC	0.110	0.100	0.110	0.27	0.26	0.27	5.84	12.49	22.87	18.87	3.20	B	A	45.50	4.23	10.77
B3-W *-S1-MW-HC	0.120	0.110	0.120	0.25	0.24	0.25	5.60	12.48	35.62	35.12	9.63	C	C	47.20	4.47	10.56
B3-W *-S2-MW-HC	0.120	0.110	0.120	0.25	0.24	0.25	5.60	12.48	34.51	33.98	8.51	C	B	47.20	4.46	10.58
B3-W *-S3-MW-HC	0.100	0.100	0.100	0.27	0.28	0.29	6.06	12.48	35.24	19.58	5.46	B	B	44.20	2.97	14.90
B3-W *-S4-MW-HC	0.110	0.100	0.110	0.27	0.26	0.27	5.84	12.49	27.40	26.73	7.58	B	B	45.50	4.22	10.77
C1-W-S1-MW-HC	0.130	0.120	0.130	0.24	0.22	0.23	17.53	0.97	44.31	43.99	11.52	C	C	48.91	6.87	7.12
C1-W-S2-MW-HC	0.130	0.120	0.130	0.24	0.22	0.23	17.53	0.97	41.46	41.09	8.66	C	B	48.91	6.85	7.14
C1-W-S3-MW-HC	0.100	0.100	0.100	0.27	0.28	0.29	18.94	0.94	43.60	4.16	0.84	A	A	44.20	4.37	10.12
C1-W-S4-MW-HC	0.120	0.120	0.130	0.24	0.24	0.23	18.81	0.96	31.37	25.88	4.38	B	A	48.00	6.60	7.28
C2-W-S1-MW-HC	0.130	0.120	0.130	0.24	0.22	0.23	17.43	5.23	48.89	47.70	12.10	C	C	48.91	6.88	7.10
C2-W-S2-MW-HC	0.130	0.120	0.130	0.24	0.22	0.23	17.43	5.23	46.07	44.82	9.28	C	B	48.91	6.87	7.12
C2-W-S3-MW-HC	0.100	0.100	0.110	0.27	0.28	0.27	18.72	5.21	48.06	8.29	1.54	A	A	44.59	4.40	10.13
C2-W-S4-MW-HC	0.120	0.120	0.130	0.24	0.24	0.23	17.70	5.23	33.46	27.61	4.68	B	A	48.00	6.67	7.20

For each winter climate zone, the CTE-DB-HE [33] establishes maximum thermal transmittances for each element of the thermal envelope of the building and the interior partitions. In addition, it recommends thermal transmittance values for the different elements of the thermal envelope of the building for each winter climate zone. In winter climate zone A, the average thermal transmittance for walls, roofs, and FFF is 0.30, 0.30, and 0.29 W/m^2·K, respectively (Tables 13 and 14). This represents a reduction of 35.5%, 40.8%, and 44.4% (76.4% if horizontal interior partitions are considered), respectively, with respect to the thermal transmittance recommended for each element by the CTE-DB-HE [33]. In winter climate zone B, the average thermal transmittance for walls, roofs, and FFF is 0.25, 0.25, and 0.26 W/m^2·K, respectively (Tables 13 and 14). This represents a reduction of 23.7%, 34.2%, and 44.6% (76.8% if horizontal interior partitions are considered), respectively, with respect to the thermal transmittance recommended for each element by the CTE-DB-HE [33]. Finally, in winter climate zone C, the average thermal transmittance for walls, roofs, and FFF is 0.24, 0.23, and 0.23 W/m^2·K, respectively (Tables 13 and 14). This represents an increase of 2.5% with respect to the thermal transmittance recommended for walls by the CTE-DB-HE [33], but it is 52.9% lower than the maximum thermal transmittance established for walls by the CTE-DB-HE [33], and it represents a reduction of 21.2% and 34.9% (75.3% if horizontal interior partitions are considered), respectively, with respect to the recommended thermal transmittance for roofs and floors in contact with air by the CTE-DB-HE [33]. Figure 4 shows the variations between the minimum thermal transmittance obtained in Tables 13 and 14 and the maximum thermal transmittance and that recommended by the CTE-DB-HE [33], as well as the variations between the maximum thermal transmittance obtained in Tables 13 and 14 and the maximum thermal transmittance and that recommended by the CTE-DB-HE [33], by winter climate zone for walls, roof, and FFF (FFF is compared with the maximum thermal transmittance and that recommended for floor in contact with air, and it is also compared with the maximum thermal transmittance for horizontal interior partitions that delimit units of different use).

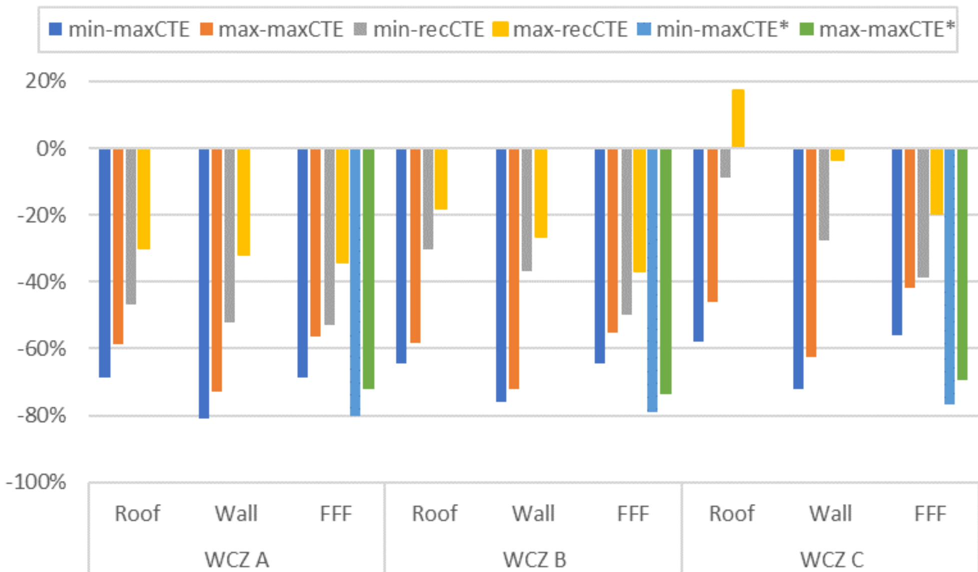

Figure 4. Variations between the minimum thermal transmittance obtained and the maximum thermal transmittance (min-maxCTE) and that recommended (min-recCTE) by CTE-DB-HE [33], as well as the variations between the maximum thermal transmittance obtained (max-maxCTE) and the maximum thermal transmittance and that recommended (max-recCTE) by CTE-DB-HE [33], by winter climate zone (WCZ) for roof, wall, and FFF. (*) FFF is compared with the maximum thermal transmittance for interior partitions that delimit units of different use.

This study has taken into account the heating degree-days with a base temperature of 20 °C (HDD_{20}) and cooling degree-days with a base temperature of 20 °C (CDD_{20}) because these degree-days are used by the CTE-DB-HE [33] to define thermal envelopes by climate zone in Spain [34]. Degree-days with different base temperatures are used in the building sector to establish the energy-saving requirements to be met (thermal envelopes, energy demands, and energy consumptions depending on the climate zones) [57] and to estimate heating and cooling energy demands [58,59]. To evaluate the influence that the chosen base temperature of the degree-day has on the energy renovation of the study building, the insulation thicknesses of the opaque elements of the thermal envelope and the heating and cooling energy demands for the following combinations of degree-days in an example city are calculated: HDD_{15} and CDD_{24}, degree-days with the base temperatures used for Eurostat statistics [60]; HDD_{18} and CDD_{22}, degree-days with the base temperatures used to evaluate the influence of climate change on electricity consumption in 31 European countries [61]; and HDD_{20} and CDD_{25}, degree-days with the highest base temperatures available in Spain [37] and used to suggest NZEBs in southern European countries [57].

For each combination of degree-days, the optimal insulation thicknesses to be added to the opaque elements of the thermal envelope of the building in Sevilla (B4-X) were determined by LCCA, considering system 2, MW insulation, and optimization to minimize the heating and cooling costs. After rounding up these thicknesses to commercial thicknesses in cm, the resulting renovated buildings were simulated with HULC [42], obtaining the corresponding heating and cooling energy demands (Table 15).

Table 15. HDD, CDD, thickness (t), in mm, thermal transmittance (U), in $W/m^2 \cdot K$, heating energy demand (HED), in $kWh/m^2 \cdot K$, and cooling energy demand (HED), in $kWh/m^2 \cdot K$, for different combinations of degree-days.

	HDD_{15} and CDD_{24}	**HDD_{18} and CDD_{22}**	**HDD_{20} and CDD_{25}**
HDD	528	1067	1508
CDD	234	405	168
t_{walls} (U_{walls})	70 (0.37)	100 (0.28)	100 (0.28)
t_{roof} (U_{roof})	60 (0.40)	90 (0.30)	90 (0.30)
t_{FFF} (U_{FFF})	60 (0.44)	90 (0.32)	100 (0.29)
HED	7.46	6.26	6.21
CED	19.04	18.87	18.87

Regarding the energy renovation solution B4-X-S2-MW-HC (Table 13), the different insulation thicknesses decrease between 16.67% and 50.00%, the heating energy demands increase between 14.36% and 37.38%, and the cooling energy demands vary by less than 1.00%. Reducing the base temperature of the HDD and increasing that of the CDD cause the thermal transmittance of the opaque elements of the thermal envelope to increase, the heating energy demand to increase, and the cooling energy demand to be maintained.

The lowest non-renewable primary energy consumption and the lowest CO_2 emissions are achieved by using MW insulation and optimizing the insulation thickness to minimize the total heating and cooling costs in the solutions that use system 2 in climate zones B4, C3, and C4, in those that use system 3 in climate zones A3, B3, C1, and C2 and in those that use system 4 in climate zone A4. Of these solutions, only label A achieves the best possible energy performance rating, in terms of both non-renewable primary energy consumption and CO_2 emissions, in mainland climate zones B3, C1, and C2, while the best rating obtained in the two non-mainland climate zones is label B in terms of both non-renewable primary energy consumption and CO_2 emissions (Tables 13 and 14).

For the selected thermally simulated renovation solutions (Tables 13 and 14), Figure 5 shows the total net savings from the reduction in the non-renewable primary energy consumption for each system according to the combined climate zone and insulation type, and Figure 6 shows the total net savings from the reduction in CO_2 emissions for each system according to the combined climate zone and insulation type. On the one hand, in mainland Spain, for system 1 and system 2, the greatest economic savings are accompanied by the largest reductions in the non-renewable primary energy consumption and CO_2

emissions and are achieved in the combined climate zone C4-W by using MW insulation and optimizing the insulation thickness to minimize the total heating and cooling costs; for system 3, the greatest economic savings are accompanied by the greatest reductions in CO_2 emissions and are achieved in the combine climate zone C2-W by using MW insulation and optimizing the insulation thickness to minimize the total heating and cooling costs, while the greatest reductions in the non-renewable primary energy consumption are achieved in the combined climate zone A4-W by using MW insulation and optimizing the insulation thickness to minimize the total heating and cooling costs; and for system 4, the greatest economic savings accompany the greatest reductions in the non-renewable primary energy consumption and CO_2 emissions and are achieved in the combined climate zone C2-W by using MW insulation and optimizing the insulation thickness to minimize the total heating and cooling costs. On the other hand, in non-mainland Spain, the greatest economic savings accompany the greatest reductions in the non-renewable primary energy consumption and CO_2 emissions and are achieved in the combined climate zone B3-W by using MW insulation and optimizing the thickness of insulation to minimize the total heating and cooling costs, regardless of the system used.

Figures 5 and 6 present the reductions and savings for the same system between the energy renovation solutions (Tables 13 and 14) and the existing building (Table 12), thus showing only the effect of the different thermal insulation materials used. To evaluate the effect of the system change, Figure 7 illustrates the reductions and savings in the energy renovation solutions obtained with systems 2, 3, and 4 and the existing building that uses system 1 in Almería (climate zone A4) and Bilbao (climate zone C1). In this study, climate zone A4 has the highest summer climate severity and the lowest winter climate severity, while climate zone C1 has the highest winter climate severity and the lowest summer climate severity.

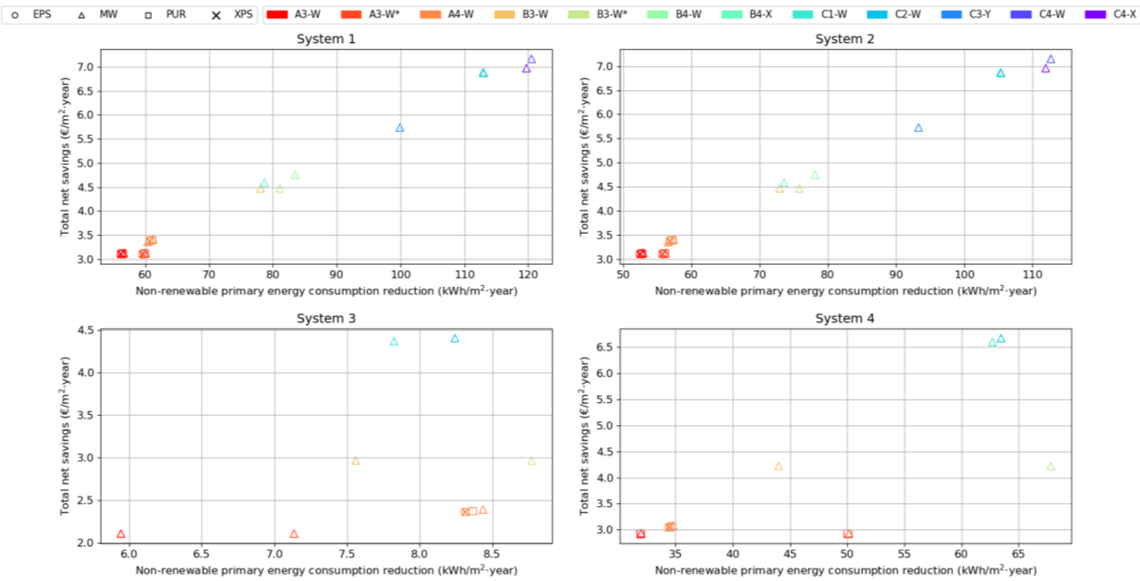

Figure 5. Total net savings, in €/m^2·year, versus non-renewable primary energy consumption reduction, in kWh/m^2·year, for all the selected energy renovation solutions that achieve compliance with the NZEB requirements by system used. (*) Non-mainland combined climate zone.

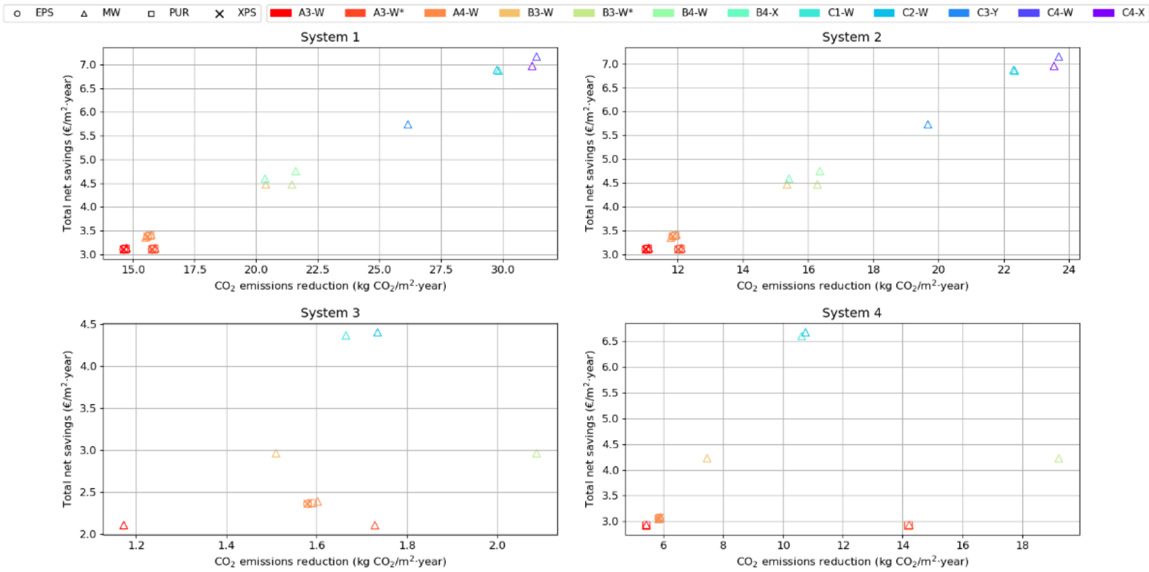

Figure 6. Total net savings, in €/m^2·year, versus CO_2 emissions reduction, in kg CO_2/m^2·year, for all the selected energy renovation solutions that achieve compliance with the NZEB requirements by system used. (*) Non-mainland combined climate zone.

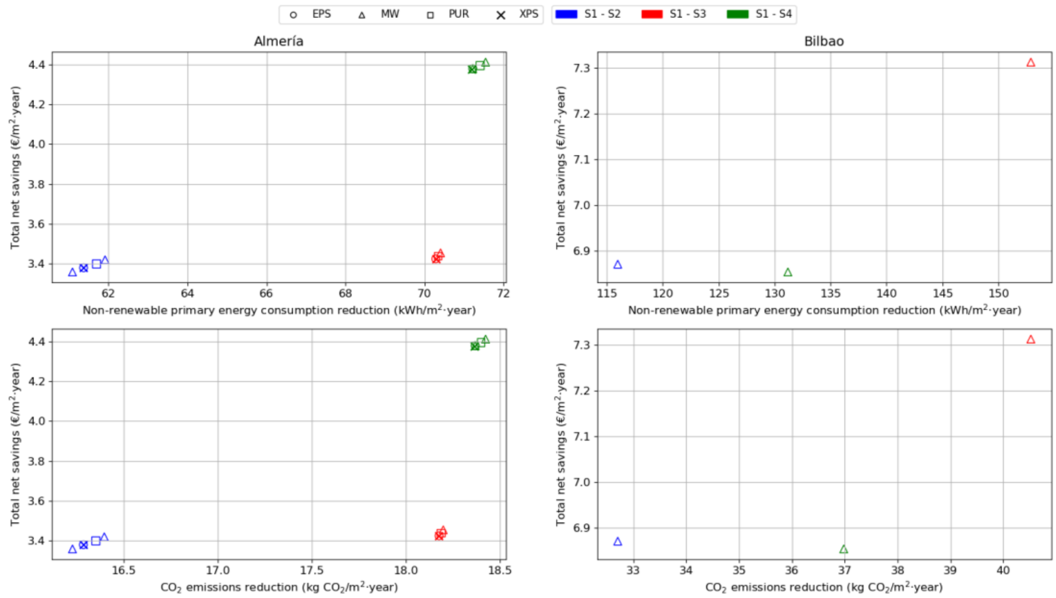

Figure 7. Total net savings, in €/m^2·year, versus non-primary energy consumption, in kWh/m^2·year, and CO_2 emissions reductions, in kg CO_2/m^2·year, in the energy renovation solutions obtained with systems 2, 3, and 4 and the existing building that uses system 1 in Almería and Bilbao.

Regarding the corresponding existing building with system 1, both the greatest total net savings and the greatest reductions in both non-renewable primary energy consumption and CO_2 emissions are achieved by using system 4 in Almería (total net savings of 74.93% and 79.57% reductions in non-renewable primary energy consumption and 85.56% in CO_2 emissions) and system 3 in Bilbao (total net savings of 86.48% and 97.35% reductions in non-renewable primary energy consumption and 97.96% in CO_2 emissions). In both cities, solutions employing system 2 achieve the lowest total net savings and the lowest reductions in both non-renewable primary energy consumption and CO_2 emissions. The results show that heat pump solutions are better in climate zones with high summer climate severity and low winter climate severity, whereas biomass boiler solutions are better in climate zones with high winter climate severity and low summer climate severity; both solutions are better than those that use natural gas and heating oil.

4. Conclusions

In this study, the energy, environmental, and economic impacts were assessed for the best energy renovation solutions of the thermal envelope of existing residential buildings in 24 cities representative of the hot and temperate climate zones of Spain. The insulation thicknesses to be added to the walls, roof, and FFF were optimized by LCCA, and the building openings were replaced. The optimization of the insulation thickness was carried out to minimize the total heating costs, total cooling costs, and total heating and cooling costs, and four types of insulation materials and four different heating and cooling systems were considered. Of the 576 proposed energy renovation solutions, 67 solutions meet all the requirements established by the CTE-DB-HE [33] for newly built residential buildings and therefore yield NZEBs. In addition, NZEBs are not achieved with insulation thicknesses that only minimize total cooling energy costs.

Energy renovation solutions in winter climate zone A require U-values between 0.24 and 0.35 $W/m^2 \cdot K$ for the opaque elements of the thermal envelope, with a payback period between 12.26 and 20.75 years; the solutions in winter climate zone B require U-values between 0.23 and 0.29 $W/m^2 \cdot K$ for the opaque elements of the thermal envelope, and the payback period is between 10.09 and 14.90 years; and the solutions in winter climate zone C require U-values between 0.21 and 0.29 $W/m^2 \cdot K$ for the opaque elements of the thermal envelope, and the payback period is from 7.06 to 10.13 years. Within the same winter climate zone, higher insulation thicknesses are required for the energy renovation of the existing buildings in January climate zones with a higher minimum mean temperature of January. Although the solutions carried out in the zones with the most severe winter climate require thicker thermal insulation, they have the lowest payback periods.

The methodology is versatile and can be easily adapted to other European Mediterranean countries, as it is necessary to adopt the thermal regulations established by different countries to achieve NZEBs and to adapt the tools used for thermal simulation. In addition, this approach can be used by stakeholders and policy-makers to decide what energy renovation strategies should be followed to contribute to achieving a decarbonized energy-efficient residential building stock.

Author Contributions: Conceptualization, J.L.-H.-C. and L.M.L.-O.; Data curation, L.M.L.-O.; Formal analysis, J.L.-H.-C., L.M.L.-O. and P.O.-A.; Investigation, J.L.-H.-C. and L.M.L.-O.; Methodology, J.L.-H.-C.; Project administration, L.M.L.-G.; Resources, L.M.L.-G.; Software, J.L.-H.-C. and L.M.L.-O.; Supervision, L.M.L.-G.; Validation, J.L.-H.-C. and L.M.L.-O.; Visualization, P.O.-A.; Writing—original draft, L.M.L.-O.; Writing—review and editing, J.L.-H.-C., L.M.L.-O., L.M.L.-G. and P.O.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Commission. Energy Statistics, Energy Datasheets: EU Countries. 2020. Available online: https://ec.europa.eu/energy/sites/ener/files/energy_statistical_countrydatasheets.xlsx (accessed on 31 July 2020).
2. European Commission. EU Buildings Database. Available online: https://ec.europa.eu/energy/en/eu-buildings-database (accessed on 24 October 2019).
3. Jakubcionis, M.; Carlsson, J. Estimation of European Union residential sector space cooling potential. *Energy Policy* **2017**, *101*, 225–235. [CrossRef]
4. ENTRANZE. Available online: http://www.entranze.enerdata.eu/ (accessed on 24 October 2019).

5. European Union. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency. 2018. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN (accessed on 24 October 2019).
6. Ballarini, I.; Corrado, V.; Madonna, F.; Paduos, S.; Ravasio, F. Energy refurbishment of the Italian residential building stock: Energy and cost analysis through the application of the building typology. *Energy Policy* **2017**, *105*, 148–160. [CrossRef]
7. Aguacil, S.; Lufkin, S.; Rey, E.; Cuchi, A. Application of the cost-optimal methodology to urban renewal projects at the territorial scale based on statistical data—A case study in Spain. *Energy Build.* **2017**, *144*, 42–60. [CrossRef]
8. Varela Luján, S.; Viñas Arrebola, C.; Rodríguez Sánchez, A.; Aguilera Benito, P.; González Cortina, M. Experimental comparative study of the thermal performance of the façade of a building refurbished using ETICS, and quantification of improvements. *Sustain. Cities Soc.* **2019**, *51*, 101713. [CrossRef]
9. Çengel, Y.A. *Heat and Mass Transfer: A Practical Approach*, 3rd ed.; McGraw Hill: New York, NY, USA, 2007.
10. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
11. Duffie, J.A.; Beckman, W.A. *Solar Engineering of Thermal Processes*, 4th ed.; Wiley: Hoboken, NJ, USA, 2013.
12. López-Ochoa, L.M.; Las-Heras-Casas, J.; López-González, L.M.; García-Lozano, C. Energy Renovation of Residential Buildings in Cold Mediterranean Zones Using Optimized Thermal Envelope Insulation Thicknesses: The Case of Spain. *Sustainability* **2020**, *12*, 2287. [CrossRef]
13. Annibaldi, V.; Cucchiella, F.; De Berardinis, P.; Rotilio, M.; Stornelli, V. Environmental and economic benefits of optimal insulation thickness: A life-cycle cost analysis. *Renew. Sustain. Energy Rev.* **2019**, *116*, 109441. [CrossRef]
14. Annibaldi, V.; Cucchiella, F.; Rotilio, M. A Sustainable Solution for Energy Efficiency in Italian Climatic Contexts. *Energies* **2020**, *13*, 2817. [CrossRef]
15. Sisman, N.; Kahya, E.; Aras, N.; Aras, H. Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions. *Energy Policy* **2007**, *35*, 5151–5155. [CrossRef]
16. Bektas Ekici, B.; Aytac Gulten, A.; Aksoy, U.T. A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey. *Appl. Energy* **2012**, *92*, 211–217. [CrossRef]
17. Kurekci, N.A. Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers. *Energy Build.* **2016**, *118*, 197–213. [CrossRef]
18. Sagbansua, L.; Balo, F. Ecological impact & financial feasibility of Energy Recovery (EIFFER) Model for natural insulation material optimization. *Energy Build.* **2017**, *148*, 1–14. [CrossRef]
19. Küçüktopcu, E.; Cemek, B. A study on environmental impact of insulation thickness of poultry building walls. *Energy* **2018**, *150*, 583–590. [CrossRef]
20. Evin, D.; Ucar, A. Energy impact and eco-efficiency of the envelope insulation in residential buildings in Turkey. *Appl. Therm. Eng.* **2019**, *154*, 573–584. [CrossRef]
21. Alsayed, M.F.; Tayeh, R.A. Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings. *J. Build. Eng.* **2019**, *22*, 101–112. [CrossRef]
22. Ziapour, B.M.; Rahimi, M.; Yousefi Gendeshmin, M. Thermoeconomic analysis for determining optimal insulation thickness for new composite prefabricated wall block as an external wall member in buildings. *J. Build. Eng.* **2020**, *31*, 101354. [CrossRef]
23. Nematchoua, M.K.; Raminosoa, C.R.R.; Mamiharijaona, R.; René, T.; Orosa, J.A.; Elvis, W.; Meukam, P. Study of the economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate: Case of Cameroon. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1192–1202. [CrossRef]
24. Cyrille Vincelas, F.F.; Ghislain, T.; Robert, T. Influence of the types of fuel and building material on energy savings into building in tropical region of Cameroon. *Appl. Therm. Eng.* **2017**, *122*, 806–819. [CrossRef]
25. Yuan, J.; Farnham, C.; Emura, K. Optimum Insulation Thickness for Building Exterior Walls in 32 Regions of China to Save Energy and Reduce CO_2 Emissions. *Sustainability* **2017**, *9*, 1711. [CrossRef]
26. Huang, H.; Zhou, Y.; Huang, R.; Wu, H.; Sun, Y.; Huang, G.; Xu, T. Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. *Sustain. Cities Soc.* **2020**, *52*, 101840. [CrossRef]
27. Yuan, J.; Farnham, C.; Emura, K. Optimal combination of thermal resistance of insulation materials and primary fuel sources for six climate zones of Japan. *Energy Build.* **2017**, *153*, 403–411. [CrossRef]
28. Rosas-Flores, J.A.; Rosas-Flores, D. Potential energy savings and mitigation of emissions by insulation for residential buildings in Mexico. *Energy Build.* **2020**, *209*, 109698. [CrossRef]
29. Ozel, M. Influence of glazing area on optimum thickness of insulation for different wall orientations. *Appl. Therm. Eng.* **2019**, *147*, 770–780. [CrossRef]
30. Derradji, L.; Imessad, K.; Amara, M.; Boudali Errebai, F. A study on residential energy requirement and the effect of the glazing on the optimum insulation thickness. *Appl. Therm. Eng.* **2017**, *112*, 975–985. [CrossRef]
31. Jie, P.; Zhang, F.; Fang, Z.; Wang, H.; Zhao, Y. Optimizing the insulation thickness of walls and roofs of existing buildings based on primary energy consumption, global cost and pollutant emissions. *Energy* **2018**, *159*, 1132–1147. [CrossRef]
32. Amiri Rad, E.; Fallahi, E. Optimizing the insulation thickness of external wall by a novel 3E (energy, environmental, economic) method. *Constr. Build. Mater.* **2019**, *205*, 196–212. [CrossRef]

33. Spanish Ministry of Development. Basic Document on Energy Saving of the Technical Building Code (Documento Básico de Ahorro de Energía del Código Técnico de la Edificación, CTE-DB-HE). 2017. Available online: https://www.codigotecnico.org/images/stories/pdf/ahorroEnergia/DBHE.pdf (accessed on 24 October 2019).
34. Spanish Ministry of Development. Descriptibe Document on Reference Climates (Documento Descriptivo Climas de Referencia). 2017. Available online: https://www.codigotecnico.org/images/stories/pdf/ahorroEnergia/20170202-DOC-DB-HE-0-Climas%20de%20referencia.pdf (accessed on 31 July 2020).
35. López-Ochoa, L.M.; Las-Heras-Casas, J.; López-González, L.M.; Olasolo-Alonso, P. Environmental and energy impact of the EPBD in residential buildings in hot and temperate Mediterranean zones: The case of Spain. *Energy* **2018**, *161*, 618–634. [CrossRef]
36. Presidency of the Government of Spain. Royal Decree 2429/1979 Approving the Basic Building Norm on Thermal Conditions in Buildings (Real Decreto 2429/1979, de 6 de Julio, por el que se Aprueba la Norma Básica de Edificación NBE-CT-79, Sobre Condiciones Térmicas en los Edificios). 1979. Available online: http://www.boe.es/boe/dias/1979/10/22/pdfs/A24524-24550.pdf (accessed on 24 October 2019).
37. Institute for Energy Diversification and Saving. Frequencies Software, Version 1.2 (Programa Frecuencias, Versión 1.2). 2014. Available online: https://www.idae.es/sites/default/files/documentos/publicaciones_idae/documentos_FRECUENCIAS_71e4fba3.exe (accessed on 24 October 2019).
38. López-Ochoa, L.M.; Las-Heras-Casas, J.; López-González, L.M.; Olasolo-Alonso, P. Towards nearly zero-energy buildings in Mediterranean countries: Energy Performance of Buildings Directive evolution and the energy rehabilitation challenge in the Spanish residential sector. *Energy* **2019**, *176*, 335–352. [CrossRef]
39. Institute for Energy Diversification and Saving. Technical Fundamentals manual of Energy Certification for Existing Buildings CE3X (Manual de Fundamentos Técnicos de Calificación Energética de Edificios Existentes CE3X). 2012. Available online: https://www.idae.es (accessed on 1 December 2020).
40. Las-Heras-Casas, J.; López-Ochoa, L.M.; Paredes-Sánchez, J.P.; López-González, L.M. Implementation of biomass boilers for heating and domestic hot water in multi-family buildings in Spain: Energy, environmental, and economic assessment. *J. Clean. Prod.* **2018**, *176*, 590–603. [CrossRef]
41. European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast). 2010. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN (accessed on 24 October 2019).
42. HULC. LIDER-CALENER Unified Tool, Version 1.0.1564.1124 (Herramienta Unificada LIDER-CALENER, Versión 1.0.1564.1124). 2017. Available online: https://www.codigotecnico.org/images/stories/pdf/aplicaciones/lider-calener/iCTEHE2013_last (accessed on 24 October 2019).
43. Valencia Institute of Building. Construction Database of the Valencia Institute of Building 2018. Available online: https://www.five.es/productos/herramientas-on-line/visualizador-2018/ (accessed on 24 October 2019).
44. Corporation of Strategic Reserves of Petroleum Products. Annual Statistical Report CORES 2018 (Informe Estadístico Anual CORES 2018). 2019. Available online: https://www.cores.es/sites/default/files/archivos/publicaciones/informe-estadistico-anual-2018.pdf (accessed on 24 October 2019).
45. European Commission. Weekly Oil Bulletin, Prices over Time, 2005 Onwards. Available online: http://ec.europa.eu/energy/observatory/reports/Oil_Bulletin_Prices_History.xlsx (accessed on 24 October 2019).
46. EUROSTAT. Gas Prices for Household Consumers—Bi-Annual Data (From 2007 Onwards) (nrg_pc_202). Available online: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_202&lang=en (accessed on 24 October 2019).
47. Institute for Energy Diversification and Saving. Biomass Price Report for Thermal Uses. 4th Quarter of 2018 (Informe de Precios de la Biomasa Para Usos Térmicos. 4º Trimestre de 2018). 2019. Available online: https://www.idae.es/sites/default/files/estudios_informes_y_estadisticas/informe_precios_biomasa_usos_termicos_4t_2018.v2.pdf (accessed on 24 October 2019).
48. EUROSTAT. Electricity Prices for Household Consumers—Bi-Annual Data (From 2007 Onwards) (nrg_pc_204). Available online: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en (accessed on 24 October 2019).
49. Spanish Ministry of Development. Supporting Document 1 Associated with the CTE-DB-HE: Calculation of Characteristic Envelope Parameters (Documento de Apoyo 1 al CTE-DB-HE: Cálculo de Parámetros Característicos de la Envolvente). 2015. Available online: https://www.codigotecnico.org/images/stories/pdf/ahorroEnergia/DA-DB-HE-1-Calculo_de_parametros_caracteristicos.pdf (accessed on 24 October 2019).
50. European Commission. Guidelines Accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 Supplementing Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings by Establishing a Comparative Methodology Framework for Calculating Cost-Optimal Levels of Minimum Energy Performance Requirements for Buildings and Building Elements. 2012. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2012:115:0001:0028:EN:PDF (accessed on 31 July 2020).
51. Spanish National Statistics Institute. Standard of Living and Living Conditions. 2020. Available online: https://www.ine.es/dyngs/INEbase/en/categoria.htm?c=Estadistica_P&cid=1254735976604 (accessed on 31 July 2020).
52. Institute for Energy Diversification and Saving. Energy Performance Rating for Existing Buildings (Escala de Calificación Energética Para Edificios Existentes). 2011. Available online: http://www.minetad.gob.es/energia/desarrollo/EficienciaEnergetica/CertificacionEnergetica/DocumentosReconocidos/OtrosDocumentos/Calificaci%C3%B3n%20energ%C3%A9tica.%20Viviendas/Escala_Calif%20_Edif%20_Existentes_accesible.pdf (accessed on 24 October 2019).

53. Spanish Ministry of Industry, Energy and Tourism; Spanish Ministry of Public Works. Recognized Document from the Regulations for Thermal Installations in Buildings (RITE): CO_2 Emission Factors and Primary Energy Conversion Coefficients of Different Final Energy Sources Consumed in the Building Sector in Spain (Joint Resolution of the Ministry of Industry, Energy, and Tourism and the Ministry of Public Works) (Documento Reconocido del Reglamento de Instalaciones Térmicas en los Edificios (RITE): Factores de Emisión de CO_2 y Coeficientes de Paso a Energía Primaria de Diferentes Fuentes de Energía Final Consumidas en el Sector de Edificios en España (Resolución Conjunta de los Ministerios de Industria, Energía y Turismo, y Ministerio de Fomento)). 2016. Available online: http://www.minetad.gob.es/energia/desarrollo/EficienciaEnergetica/RITE/Reconocidos/Reconocidos/Otros%20documentos/Factores_emision_CO2.pdf (accessed on 24 October 2019).
54. Braulio-Gonzalo, M.; Bovea, M.D. Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation. *Energy Build.* **2017**, *150*, 527–545. [CrossRef]
55. Institute for Energy Diversification and Saving. Technical Fundamentals Manual of Energy Certification for Existing Buildings CE3 (Manual de Fundamentos Técnicos de Calificación Energética de Edificios Existentes CE3). 2012. Available online: https://www.idae.es (accessed on 1 December 2020).
56. Institute for Energy Diversification and Saving. Energy Performance Rating for Buildings (Calificación de la Eficiencia Energética de los Edificios). 2015. Available online: https://energia.gob.es/desarrollo/EficienciaEnergetica/CertificacionEnergetica/DocumentosReconocidos/normativamodelosutilizacion/20151123-Calificacion-eficiencia-energetica-edificios.pdf (accessed on 24 October 2019).
57. Attia, S.; Eleftheriou, P.; Xeni, F.; Morlot, R.; Ménézo, C.; Kostopoulos, V.; Betsi, M.; Kalaitzoglou, I.; Pagliano, L.; Cellura, M.; et al. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. *Energy Build.* **2017**, *155*, 439–458. [CrossRef]
58. Lee, K.; Baek, H.-J.; Cho, C. The Estimation of Base Temperature for Heating and Cooling Degree-Days for South Korea. *J. Appl. Meteorol. Climatol.* **2014**, *53*, 300–309. [CrossRef]
59. Park, S.; Shim, J.; Song, D. Issues in calculation of balance-point temperatures for heating degree-days for the development of building-energy policy. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110211. [CrossRef]
60. EUROSTAT. Energy Statistics—Cooling and Heating Degree Days (nrg_chdd). Available online: https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm (accessed on 1 December 2020).
61. Eskeland, G.S.; Mideksa, T.K. Electricity demand in a changing climate. *Mitig. Adapt. Strateg. Glob. Chang.* **2010**, *15*, 877–897. [CrossRef]