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

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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

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 Derradj 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 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 | - | 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 | The 81 provincial capitals, Turkey |
| [18]      | LCCA   | Environmental 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 | Heating + Cooling | Antalya, Samsun, Ankara and Erzurum, Turkey |
| [20]      | P₁-P₂  | Energy impact and eco-efficiency of the envelope insulation in residential buildings | XPS, EPS, Rock wool, PUR | Natural gas, Electricity | Heating + Cooling | Mersin, Çanakkale, Elazığ 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 | 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 | Ardabil, Tehran and Khuzestan, Iran |
| [23]      | P₁-P₂  | Economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate | EPS | - | Electricity | Cooling | Douala, Cameroon |
| [24]      | P₁-P₂  | 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 | - | Heating + 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 CO₂ emissions | EPS                           | Natural gas                  | Electricity                 | Heating + Cooling     | All the regions, except Macao and Hong Kong, and Paracel Islands, China |
| [26]      | P₁₋P₂ | Optimum insulation thicknesses and energy conservation of building thermal insulation materials in humid subtropical climate zone | XPS and PUR foam              | Coal                        | Electricity                 | Heating + Cooling     | Shanghai, China |
| [27]      | LCCA   | Optimal combination of thermal resistance of insulation materials and primary fuel sources for all the different climate zones | EPS and XPS                   | (Electricity) Coal           | (Electricity) Natural gas   | 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 m², 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 m². Figure 2 shows the floor plan and a 3D view of the study building. The exchange surfaces of the thermal envelope are 1107.16 m² of walls, 491.93 m² of roof, 484.00 m² of FFF, and 212.84 m² 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 | 0 < WCS ≤ 0.23 | 0.23 < WCS ≤ 0.50 | 0.50 < WCS ≤ 0.93 |
|-------------------------|----------------|-------------------|-------------------|
| SCS ≤ 0.50              |                |                   | C1                |
| 0.50 < SCS ≤ 0.83      |                |                   | C2                |
| 0.83 < SCS ≤ 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   | Sevilla        | Alicante/Alacant and Sevilla Córdoba |
| C1 | 2384 | 95  | W   | Bilbao/Bilbo   | Bilbao/Bilbo, La Coruña/A Coruña, Pontevedra and Santander |
| C2 | 2237 | 226 | Y   | Barcelona      | Barcelona               |
| C3 | 2123 | 429 | Y   | Granada        | Granada                 |
| C4 | 2088 | 596 | W   | Jaén           | Jaén                   |
|    |     |     |     | Toledo         | Toledo, 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/m²·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      | 20.00      | 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.

| Thermal envelope | Unit | Value | References |
|------------------|------|-------|------------|
| EPS insulation (0.034 W/m·K) | €/m³ | 263.78 | [43] |
| MW insulation (0.034 W/m·K) | €/m³ | 181.50 | [43] |
| PUR insulation (0.025 W/m·K) | €/m³ | 302.50 | [43] |
| XPS insulation (0.034 W/m·K) | €/m³ | 267.00 | [43] |
| New openings (1.92 W/m²·K) | €/m² | 282.63 | [43] |

| Energy carrier | Unit | Value | References |
|----------------|------|-------|------------|
| 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/m²·K, is calculated using the following equation:

\[
U_e = \frac{1}{R_e}
\]

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 m²·K/W, and it is calculated using the following equations:

\[
R_e = R_e^{exist} + R_e^{insu}
\]

\[
R_e^{exist} = R_{si,e} + \sum n R_{n,e} + R_{se,e}
\]

\[
R_{n,e} = \frac{x_{n,e}}{\lambda_{n,e}}
\]

\[
R_{e}^{insu} = \frac{x_{e}}{\lambda}
\]

where \( R_e^{exist} \) is the thermal resistance of element \( e \) of the existing building, in m²·K/W; \( R_e^{insu} \) is the thermal resistance of the insulation added to element \( e \) of the building, in m²·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 m²·K/W; \( R_{n,e} \) is the thermal resistance of layer \( n \) of element \( e \) of the thermal envelope of the existing building, in m²·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 $W/m\cdot K$; $x_e$ is the insulation thickness added to element $e$ of the building, in m; and $\lambda$ is the thermal conductivity of the insulation material used, in $W/m\cdot K$.

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 $kWh/m^2\cdot year$, 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 $20^\circ C$ (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 €/$m^2\cdot year$, 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; $\eta$ is the thermal performance or seasonal coefficient of performance of the heating system, per unit, as reported in Table 6; and $\varepsilon$ 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:

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

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:

$$TC_{heat,e} = EC_{heat,e} \cdot PWF + C_{insu,e} \tag{13}$$
$$TC_{cool,e} = EC_{cool,e} \cdot PWF + C_{insu,e} \tag{14}$$
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, \(x_{\text{heat\_opt},e}\), \(x_{\text{cool\_opt},e}\), and \(x_{\text{heat\_+cool\_opt},e}\), 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:

\[
x_{\text{heat\_opt},e} = \left( \frac{0.024 \cdot \text{HDD} \cdot C_{\text{fuel}} \cdot \text{PWF} \cdot \lambda}{\eta \cdot C_{\text{insu}}} \right)^{0.5} - \lambda \cdot R_{\text{exis}}
\]

\[
x_{\text{cool\_opt},e} = \left( \frac{0.024 \cdot \text{CDD} \cdot C_{\text{elec}} \cdot \text{PWF} \cdot \lambda}{\epsilon \cdot C_{\text{insu}}} \right)^{0.5} - \lambda \cdot R_{\text{exis}}
\]

\[
x_{\text{heat\_+cool\_opt},e} = \left( \frac{0.024 \cdot \text{HDD} \cdot C_{\text{fuel}} \cdot \text{PWF} \cdot \lambda}{\eta \cdot C_{\text{insu}}} + \frac{0.024 \cdot \text{CDD} \cdot C_{\text{elec}} \cdot \text{PWF} \cdot \lambda}{\epsilon \cdot C_{\text{insu}}} \right)^{0.5} - \lambda \cdot R_{\text{exis}}
\]
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, \(FEC_{\text{total}}\), in kWh/m\(^2\)·year, is

\[
FEC_{\text{total}} = FEC_{\text{heat}} + FEC_{\text{cool}} + FEC_{DHW}
\]

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

\[
NRPEC_{\text{total}} = FEC_{\text{heat}} \cdot f_{\text{fuel}}^{NRPE} + FEC_{\text{cool}} \cdot f_{\text{elec}}^{NRPE} + FEC_{DHW} \cdot f_{\text{fuel}}^{NRPE}
\]

where \(f_{\text{fuel}}^{NRPE}\) is the conversion factor from the final energy to the non-renewable primary energy for the fuel used, in kWh\(_{\text{NRPE}}$/kWh\(_{\text{FE}}\); and \(f_{\text{elec}}^{NRPE}\) is the conversion factor from the final energy to the non-renewable primary energy for electricity, in kWh\(_{\text{NRPE}}$/kWh\(_{\text{FE}}\). 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 \([35]\).

| NRPE Conversion Factor \((\text{kWh}_{\text{NRPE}}/\text{kWh}_{\text{FE}})\) | TPE Conversion Factor \((\text{kWh}_{\text{TPE}}/\text{kWh}_{\text{FE}})\) | \(\text{CO}_2\) Emissions Conversion Factor \((\text{kg CO}_2/\text{kWh}_{\text{FE}})\) |
|---|---|---|
| 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, \(EC_{\text{heat},y}\) and \(EC_{\text{cool},y}\), respectively, in €/m\(^2\)·year, are calculated using the following equations:

\[
EC_{\text{heat},y} = \frac{0.024 \cdot \text{HDD} \cdot C_{\text{fuel}}^{\text{heat}} \cdot U_y}{\eta}
\]

\[
EC_{\text{cool},y} = \frac{0.024 \cdot \text{CDD} \cdot C_{\text{elec}} \cdot U_y}{\varepsilon}
\]

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, $C_{\text{reno/opr}}$, in €/m², is calculated using the following equation:

$$C_{\text{reno/opr}} = \sum y C_{\text{reno/opr}, y} \frac{A_{\text{exch,y}}}{A_{\text{liv}}}$$  \hfill (30)

where the subscript $\text{opr}$ corresponds to the optimization criterion used to minimize either the total heating costs ($\text{heat}$), the total cooling costs ($\text{cool}$), or the total heating and cooling costs ($\text{heat} + \text{cool}$); and $C_{\text{reno/opr}, y}$ denotes the energy renovation cost for element $y$ of the renovated building per unit of exchange surface, in €/m². $C_{\text{reno/opr}, y}$ is obtained for new openings from Table 7 and calculated for the walls, roof, and FFF with the following equation:

$$C_{\text{reno/opr}, y} = C_{\text{insu}} x_{\text{opr}, y}$$  \hfill (31)

Using the insulation thickness optimized under the chosen optimization criterion, the total net savings per unit of living area for the renovated building, $\text{ECS}_{\text{reno/opr}}$, in €/m²·year, is calculated using the following equation:

$$\text{ECS}_{\text{reno/opr}} = \sum y [(C_{\text{exis/heat}, y} + C_{\text{exis/cool}, y}) - (C_{\text{reno/heat}, y} + C_{\text{reno/cool}, y})] \frac{A_{\text{exch,y}}}{A_{\text{liv}}}$$  \hfill (32)

where $C_{\text{exis/heat}, y}$ and $C_{\text{exis/cool}, y}$ are the annual heating energy costs per unit of exchange surface of element $y$ of the existing and renovated buildings, respectively, in €/m²·year, and are calculated using Equation (28); $C_{\text{cool}, y}$ and $C_{\text{cool}, y}$ are the annual cooling energy costs per unit of exchange surface of element $y$ of the existing and renovated buildings, respectively, in €/m²·year, and are calculated using Equation (29). $C_{\text{exis/heat}, y}$ and $C_{\text{exis/cool}, y}$ 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, $P_{\text{reno/opr}}$, in years, is calculated using the following equation:

$$P_{\text{reno/opr}} = \frac{C_{\text{reno/opr}}}{\text{ECS}_{\text{reno/opr}}}$$  \hfill (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/m²·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/m²·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/m²·year, using Equation (27).

4. Evaluation of the total primary energy consumption of the building per unit of living area per year, $TPE_{total}$, in kWh/m²·year, which is calculated using the following equation:

$$TPE_{total} = FEC_{heat} \cdot f_{fuel}^{TPE} + FEC_{cool} \cdot f_{elec}^{TPE} + FEC_{DHW} \cdot f_{fuel}^{TPE}$$  \hspace{1cm} (34)

where $f_{fuel}^{TPE}$ is the conversion factor from the final energy to the total primary energy for the fuel used, in kWh$_{TPE}$/kWh$_{FE}$; and $f_{elec}^{TPE}$ 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$_2$/m²·year, which are calculated using the following equation:

$$EM_{total} = FEC_{heat} \cdot f_{fuel}^{EM} + FEC_{cool} \cdot f_{elec}^{EM} + FEC_{DHW} \cdot f_{fuel}^{EM}$$  \hspace{1cm} (35)

where $f_{fuel}^{EM}$ is the conversion factor from the final energy to the CO$_2$ emissions for the fuel used, in kg CO$_2$/kWh$_{FE}$; and $f_{elec}^{EM}$ 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:

$$PP = \frac{ERC}{TNS}$$  \hspace{1cm} (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:

$$TNS = \left[ \left( FEC_{heat}^{exis} \cdot C_{fuel} + FEC_{cool}^{exis} \cdot C_{elec} \right) - \left( FEC_{heat}^{reno} \cdot C_{fuel} + FEC_{cool}^{reno} \cdot C_{elec} \right) \right] \cdot A_{liv}$$  \hspace{1cm} (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 and cooling costs; and those that use system 3, optimizing the insulation thickness to minimize the total heat 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 | 0.087 |
| 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-S4-XPS-HC             | 0.084  | 0.079 | 0.087 |
| A3-W-S5-MW-HC              | 0.106  | 0.100 | 0.109 |
| A3-W-S5-PUR-HC             | 0.069  | 0.065 | 0.071 |
| A3-W-S5-XPS-HC             | 0.084  | 0.078 | 0.087 |
| A3-W-S6-MW-HC              | 0.091  | 0.086 | 0.094 |
| A3-W-S6-PUR-HC             | 0.094  | 0.089 | 0.097 |
| A3-W-S6-XPS-HC             | 0.094  | 0.089 | 0.097 |
| A3-W-S7-MW-HC              | 0.061  | 0.057 | 0.064 |
| A3-W-S7-PUR-HC             | 0.090  | 0.084 | 0.093 |
| A4-W-S1-EPS-HC             | 0.079  | 0.073 | 0.082 |
| A4-W-S1-MW-H               | 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-PUR-HC             | 0.073  | 0.069 | 0.075 |
| A4-W-S2-XPS-HC             | 0.089  | 0.084 | 0.092 |
| A4-W-S3-PUR-HC             | 0.079  | 0.073 | 0.082 |
| A4-W-S3-XPS-HC             | 0.099  | 0.093 | 0.102 |
| A4-W-S4-EP-HC              | 0.079  | 0.073 | 0.082 |
| A4-W-S4-XPS-HC             | 0.064  | 0.060 | 0.067 |
| A4-W-S5-XPS-HC             | 0.078  | 0.073 | 0.081 |
| A4-W-S6-EP-HC              | 0.078  | 0.072 | 0.081 |
| A4-W-S6-XPS-HC             | 0.078  | 0.072 | 0.081 |
| A4-W-S7-EP-HC              | 0.078  | 0.072 | 0.081 |
| A4-W-S7-XPS-HC             | 0.098  | 0.092 | 0.101 |
| A4-W-S8-EP-HC              | 0.063  | 0.060 | 0.066 |
| A4-W-S8-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  | 0.119 | 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/m²·K, heating energy demand (HED), in kWh/m²·year, cooling energy demand (CED), in kWh/m²·year, total primary energy consumption (TPEC), in kWh/m²·year, non-renewable primary energy consumption (NRPEC), in kWh/m²·year, CO₂ emissions (EM), kg CO₂/m²·year, non-renewable primary energy consumption rating (RNPRPEC), and CO₂ emissions rating (REM) 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   | RNPRPEC | REM  |
|-----------|--------|-------|------|------|------|------|-------|------|---------|------|
| 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| 79.04 | 3.43 | B       | B    |
| A3-W-S4   | 1.60   | 1.40  | 1.97 | 36.18| 14.53| 57.39| 47.36 | 8.02 | C       | 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| 71.05 | 20.15| E       | E    |
| A3-W*-S4  | 1.60   | 1.40  | 1.97 | 36.17| 14.53| 72.84| 62.86 | 8.95 | D       | C    |
| 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| 82.66 | 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| 102.72| 21.65| E       | E    |
| B3-W-S4   | 1.60   | 1.40  | 1.97 | 55.77| 14.66| 76.21| 62.86 | 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| 111.44| 28.35| 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 | 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| 88.58 | 15.01| 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      |
| C3-Y-S3    | 1.39  | 0.89 | 1.15| 80.40| 15.08| 148.47| 11.99 | 2.51 | A          | A      |
| 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  | 1.40 | 1.97| 94.40| 23.62| 173.31| 168.07| 42.17| E          | E      |
| C4-X-S2    | 1.60  | 1.40 | 1.97| 94.40| 23.62| 110.37| 91.07 | 15.43| D          | D      |

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/m²·K, heating energy demand (HED), in kWh/m²·year, cooling energy demand (CED), in kWh/m²·year, total primary energy consumption (TPEC), in kWh/m²·year, non-renewable primary energy consumption (NRPEC), in kWh/m²·year, CO₂ emissions (EM), kg CO₂/m²·year, energy renovation costs per unit of living area (C), in €/m², total net savings per unit of living area per year (ECS), in €/m²·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 |
|---------------------------|-----------------------|-----------------------|-----|-----|------|-------|----|-----------|--------|----|-----|----|
| A3-W-S1-EPS-HC            | 0.090                 | 0.080                 | 0.33| 0.31| 0.32 | 2.13  | 12.47| 27.88     | 25.26  | 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  | 5.40| 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  | 5.46| 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  | 5.51| C   | 49.13| 3.11| 15.82|
| A3-W-S2-EPS-HC            | 0.110                 | 0.100                 | 0.110| 0.27| 0.26 | 0.27 | 1.83 | 12.45     | 27.01  | 4.65| C   | 48.86| 3.10| 15.76|
| A3-W-S2-MW-HC             | 0.070                 | 0.070                 | 0.080| 0.28| 0.29 | 0.27 | 1.98 | 12.45     | 26.60  | 4.56| C   | 45.50| 3.13| 14.55|
| A3-W-S2-PUR-HC            | 0.090                 | 0.090                 | 0.090| 0.33| 0.31 | 0.32 | 2.13 | 12.47     | 27.01  | 4.65| C   | 49.13| 3.10| 15.85|
| A3-W-S2-XPS-HC            | 0.100                 | 0.090                 | 0.100| 0.30| 0.28 | 0.29 | 1.97 | 12.46     | 26.89  | 15.36| 2.60| B   | 43.79| 2.11| 20.75|
| A3-W-S3-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   | 43.79| 2.94| 14.92|
| A3-W-S3-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   | 46.37| 2.93| 15.84|
| A3-W-S3-XPS-HC            | 0.110                 | 0.090                 | 0.090| 0.33| 0.31 | 0.32 | 2.13 | 12.47     | 29.31  | 28.82| 7.97| C   | 48.86| 3.11| 15.73|
| A3-W-S4-PUR-HC            | 0.090                 | 0.080                 | 0.090| 0.33| 0.31 | 0.32 | 2.13 | 12.47     | 28.61  | 28.11| 7.27| C   | 48.86| 3.10| 15.77|
Table 13. Cont.

| Energy Renovation Solution | Thickness to Be Added | Thermal Transmittance | HED | CED | TPEC | NRPEC | EM | RNRPEC | REm | C | ECS | PP |
|---------------------------|-----------------------|------------------------|-----|-----|------|-------|----|--------|------|---|-----|----|
|                          | Walls | Roof | FFF | Walls | Roof | FFF |     |       |      |   |     |    |
| A3-W                     | 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-MW-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-PUR-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-S2-XPS-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-S3-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-MW-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 |

... (continued)
Table 13. Cont.

| Energy Renovation Solution | Thickness to Be Added | Thermal Transmittance | HED | CED | TPEC | NRPEC | EM | RNRPEC | REM | 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/m²·K, heating energy demand (HED), in kWh/m²·year, cooling energy demand (CED), in kWh/m²·year, total primary energy consumption (TPEC), in kWh/m²·year, non-renewable primary energy consumption (NRPEC), in kWh/m²·year, CO₂ emissions (EM), kg CO₂/m²·year, non-renewable primary energy consumption rating (RNRPEC), CO₂ emissions rating (REM), energy renovation costs per unit of living area (C), in €/m², total net savings per unit of living area per year (ECS), in €/m²·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 | RNRPEC | REM | 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 | 0.110 | 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 | 0.130 | 0.120 | 0.130 | 0.24 | 0.22 | 0.23 | 17.53 | 0.97 | 43.60 | 4.16 | 0.84 | A | A | 44.20 | 4.37 | 10.12 |
| C1-W-S4-MW-HC | 0.130 | 0.120 | 0.130 | 0.24 | 0.22 | 0.23 | 17.53 | 0.97 | 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/m²·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/m²·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/m²·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](image-url)

**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 (HDD₂₀) and cooling degree-days with a base temperature of 20 °C (CDD₂₀) 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\textsubscript{15} and CDD\textsubscript{24}, degree-days with the base temperatures used for Eurostat statistics [60]; HDD\textsubscript{18} and CDD\textsubscript{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\textsubscript{20} and CDD\textsubscript{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\(^2\)-K, heating energy demand (HED), in kWh/m\(^2\)-K, and cooling energy demand (CED), in kWh/m\(^2\)-K, for different combinations of degree-days.

|            | HDD\textsubscript{15} and CDD\textsubscript{24} | HDD\textsubscript{18} and CDD\textsubscript{22} | HDD\textsubscript{20} and CDD\textsubscript{25} |
|------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| HDD        | 528                                         | 1067                                        | 1508                                        |
| CDD        | 234                                         | 405                                         | 168                                         |
| \(t_{\text{walls}}\) (U_{\text{walls}}) | 70 (0.37)                                  | 100 (0.28)                                 | 100 (0.28)                                 |
| \(t_{\text{roof}}\) (U_{\text{roof}})  | 60 (0.40)                                   | 90 (0.30)                                  | 90 (0.30)                                  |
| \(t_{\text{FF}}\) (U_{\text{FF}})      | 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 €/m²·year, versus CO₂ emissions reduction, in kg CO₂/m²·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 €/m²·year, versus non-primary energy consumption, in kWh/m²·year, and CO₂ emissions reductions, in kg CO₂/m²·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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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/m²·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/m²·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/m²·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.

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