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

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Abstract: The residential sector of the European Union consumes 27% of the final energy of the European Union, and approximately two-thirds of the existing dwellings in the European Union were built before 1980. For this reason, the European Union aims to transform the existing residential building stock into nearly zero-energy buildings by 2050 through energy renovation. The most effective method to achieve this goal is to increase the thermal insulation of opaque elements of the thermal envelope. This study aims to assess the energy, environmental and economic impacts of the energy renovation of the thermal envelopes that are typical of the existing multi-family buildings of the 26 provincial capitals in the cold climate zones of Spain. To achieve this goal, the insulation thickness to be added to the walls, roof and first floor framework is optimized by a life cycle cost analysis, and the existing building openings are replaced, thus minimizing both the total heating costs and the total heating and cooling costs. The study uses four thermal insulation materials for four different heating and cooling systems in 10 different models. The results obtained will be used to propose energy renovation solutions to achieve nearly zero-energy buildings both in Spain and in similar Mediterranean climate zones.

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

1. Introduction

The final energy consumption in the European Union reached 288 Mtoe in the residential sector and 154 Mtoe in the service sector in 2017, with 42% of the final energy consumption coming from the building sector [1]. Energy consumption from space heating accounted for 67% of the residential energy consumption [2]. In addition to the elevated energy consumption of the residential sector (27% of the total), the residential building stock is aged, with 68% of existing dwellings built before 1980 [3]. In light of this problem, the European Union, through the Energy Performance of Buildings Directive (EPBD) 2018 [4], intends to achieve a decarbonized and highly energy-efficient housing stock by 2050 and to ensure a long-term renovation that transforms the existing buildings into nearly zero-energy buildings. For that purpose, Member States are required to establish a strategy of renovating residential, non-residential, public, and private buildings with short-term (2030), medium-term (2040), and long-term (2050) goals. EPBD 2018 [4] amends both EPBD 2010 [5] and the Energy Efficiency Directive 2012 [6].

EPBD 2010 [5] was added to the building regulations on the energy savings of the different Member States. The energy and environmental impact of the implementation of EPBD 2010 [5] on the residential sector of European countries with Mediterranean climates was analyzed in Spain [7], Italy [8], Greece [9], Cyprus [10], and Portugal [11]. These regulations have restricted both heating and cooling energy demands and have established maximum thermal transmittances for the elements that make up the thermal envelope of a building, depending on the climate zone in which the building is located. The most effective method for the energy refurbishment of the residential building stock is to increase the thermal insulation of the opaque elements of the thermal envelope; this increased insulation achieved average energy savings of 45% in Italy [12] and 40% in Spain [13]. In addition, Varela Luján et al. [14] found that, in Spain, renovating façades using external thermal insulation composites reduced energy losses by 57% and energy gains by 39% compared to those with the façade in its original state. However, it is neither practical nor economical to increase the insulation thickness until both the heat losses for heating and heat gains for cooling are eliminated through the thermal envelope. It is, therefore, necessary to find a balance between the cost of the insulation used and the potential heating and cooling savings in the building [15]. The optimum insulation thickness of the thermal envelope of a building can be determined by a life cycle cost analysis to achieve maximum net savings in terms of heating and cooling costs, taking into account the heating and cooling degree-days; the costs and properties of both the insulation materials and 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 [16].

The optimum insulation thickness for different elements of the thermal envelope of buildings has been evaluated in several studies conducted in Turkey. Sisman et al. [17] determined the optimum insulation thickness for external walls and roof for different degree-day regions. Bektas Ekici et al. [18] studied the optimum insulation thickness for various types of external walls with respect to different materials, fuels and climate zones. Kurekci [16] determined the optimum insulation thickness for building walls by using the heating and cooling degree-day values of all provincial centers. Ozel studied the effect of the exterior surface solar absorptivity on the thermal characteristics and optimum insulation thickness [19]; conducted a cost analysis for the optimum thicknesses and assessed the environmental impact of different insulation materials [20]; carried out a thermal, economic and environmental analysis of insulated building walls in cold climates [21]; and studied the effect of the glazing area on the optimum insulation thickness for different wall orientations [22]. Sagbansua and Balo [23] studied the potential use of eco-efficient materials in buildings instead of conventional materials using the optimum insulation thickness method, considering both the ecological impact and the financial feasibility. In addition, in the Mediterranean environment, Annibaldi et al. [24] studied the environmental and economic benefits of the optimum insulation thickness using a life cycle cost analysis of historic buildings in Italy, and Derradji et al. [25] determined the energy savings due to glazing effects on the optimum insulation thickness in a classic home in Algeria. Outside the Mediterranean environment, Yuan et al. [26] calculated the optimum insulation thickness for different insulation materials and fuels for six different climate zones in Japan, and Nematchoua et al. [27] studied the most economical and optimum thermal insulation thickness for buildings in wet and hot tropical climates in Cameroon.

This study aims to assess the energy, environmental and economic impacts of the energy renovation of the thermal envelope of existing residential buildings in the cold climate zones of Spain and to assess the optimum insulation thickness to be added to the walls, roof and first floor framework by a life cycle cost analysis and the replacement of the existing building openings. The optimization of the insulation thickness is performed to minimize both the total heating costs and the total heating and cooling costs using thermal insulation materials including expanded polystyrene (EPS), mineral wool (MW), polyurethane (PUR), and extruded polystyrene (XPS) for different heating and cooling systems with heating oil boilers, natural gas boilers, biomass boilers and electric heat pumps. The residential building studied is the multi-family housing block that was used in [7,28,29] to assess the energy and environmental impacts of the EPBD in Spain. The existing thermal envelope of the building has the main features of the thermal envelopes of the existing residential stock in the studied areas [30]. The methodology developed includes the evaluation of the main energy and environmental parameters of the renovated buildings to be able to compare the obtained solutions with other different energy renovation solutions. In addition, it is expected that the results of this study will help propose energy renovation solutions for existing residential buildings in order to achieve nearly zero-energy buildings according to the current regulation, namely, the Basic Document on Energy Saving of the Technical Building Code (CTE-DB-HE) [31].

2. Methodology

The methodology developed in this study is as follows: (i) identification of the main cities located in cold climate zones and the main characteristics of these climate zones; (ii) definition of the studied building with a thermal envelope that represents the main characteristics of the existing residential building stock; (iii) evaluation of the optimal thickness of the thermal insulation for the walls, roof and first floor framework to minimize the total heating costs and the total heating and cooling costs with different thermal insulation materials and heating and cooling systems; and (iv) evaluation of the main energy and environmental parameters of the renovated building and verifying whether it is a nearly zero-energy building in accordance with the current CTE-DB-HE [31].

2.1. Climate Zones

The studied buildings will be located in all the Spanish provincial capitals in climate zones D1, D2, D3 and E1, which are the Spanish cold climate zones [28,31]. This study uses heating degree-days with a base temperature of 20 °C and cooling degree-days with a base temperature of 20 °C, which correspond to the reference weather for these climate zones as provided by the Ministry of Industry, Energy and Tourism and the Institute for Diversification and Saving of Energy (IDAE) [32]. The heating degree-days and cooling degree-days are used in the energy simulations of buildings using HULC [33], which is the official software tool used to verify compliance with the energy consumption and energy demand restrictions of CTE-DB-HE [31] and to certify the energy performance of buildings. To proceed with the energy renovation of the buildings, it is important to understand the climate zones in which the design of the thermal envelopes of the buildings was based. According to the Basic Document Norm on Thermal Conditions in Buildings [34], the selected Spanish provincial capitals are in January climate zones W, X, Y and Z, with minimum mean temperatures during January of 5 °C, 3 °C, 0 °C and −2 °C, respectively.

Figure 1 shows both the climate zones and January climate zones of the selected provincial capitals of Spain. Table 1 shows the climate zones and their corresponding heating degree-days and cooling degree-days, as well as the January climate zones, of the provincial capitals studied.

Table 1. Climate zones (CZs) and their corresponding heating degree-days (HDD) and cooling degree-days (CDD), and January climate zones (JCZs) of the cities studied.

CZ	HDD	CDD	JCZ	Cities
D1	3004	87	W	San Sebastián/Donostia
			Y	Palencia, Pamplona/Iruña, Vitoria/Gasteiz
			X	Lugo, Oviedo
D2	2857	217	X	Gerona/Girona, Logroño, Orense/Ourense
			Y	Huesca, Valladolid, Zamora
			Z	Cuenca, Salamanca, Segovia, Teruel
D3	2743	420	X	Zaragoza
			Y	Ciudad Real, Guadalajara, Lérida/Lleida, Madrid
			Z	Albacete
E1	3548	81	Z	Ávila, Burgos, León, Soria

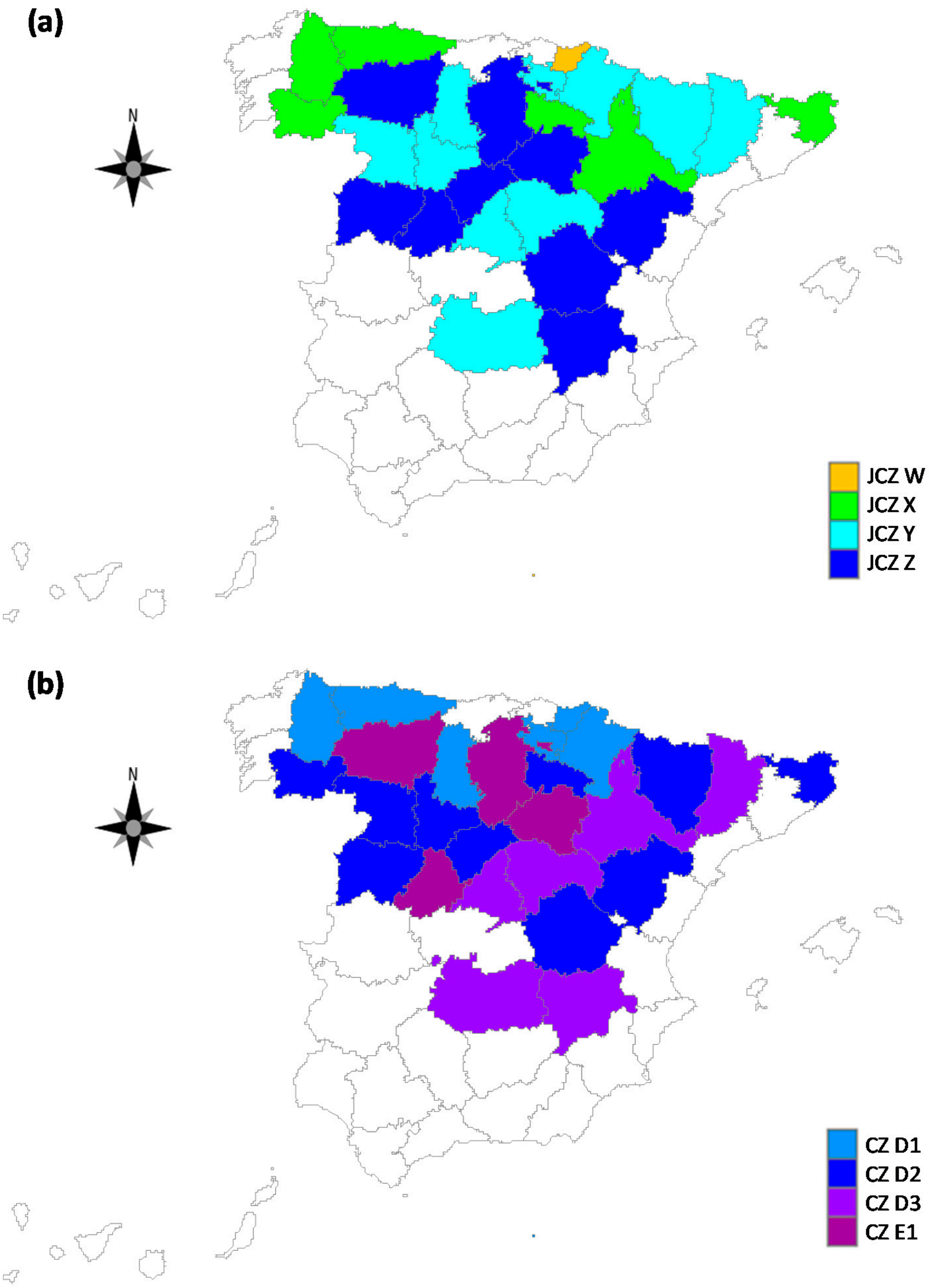

Figure 1. Climate zoning of the selected Spanish provincial capitals: (**a**) January climate zones (JCZs) [34] and (**b**) climate zones (CZs) [31].

2.2. Main Characteristics of the Studied Building

The studied building [7,28,29] has a ground floor and 5 levels. The base is square with an area of 484.00 m^2, and the height of each floor is 3.00 m. The main façade has a northerly orientation. Figure 2 shows the floor plan and a 3D view of the studied building. On the ground floor are the main entrance and a car parking space. Each of the 5 floors has 4 types of dwellings, with a total living area of 2216.57 m^2. The window-to-wall ratio is 0.1612. Table 2 shows the spaces that compose each type of dwelling. The roof is hipped and has a height of 2.00 m.

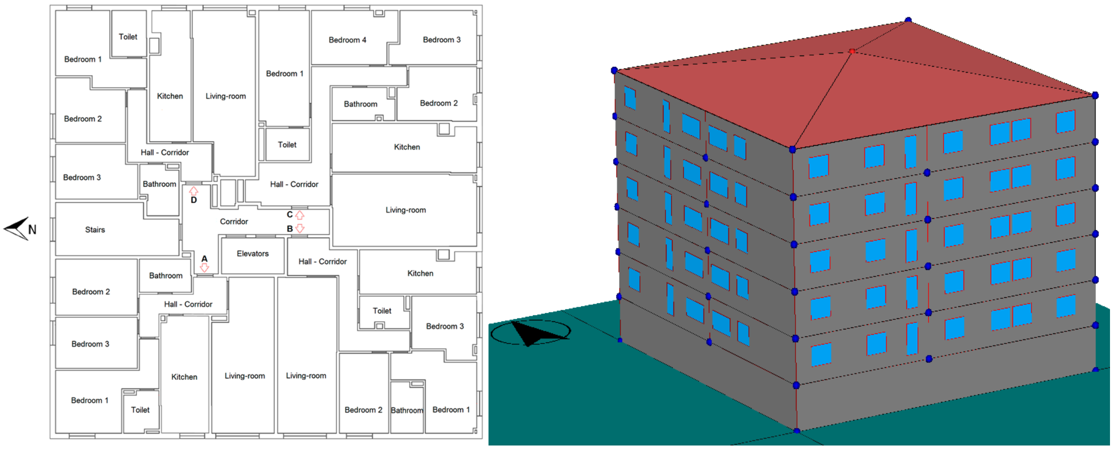

Figure 2. Floor plan of the four types of dwellings and a 3D view of the studied building.

Table 2. Distributions of the spaces, in m^2, in the studied building by type of dwelling.

Type of Dwelling	Space	Area (m^2)
A	Living room	27.24
	Kitchen	14.55
	Hall/corridor	7.98
	Toilet	3.99
	Bathroom	4.98
	Bedroom 1	15.78
	Bedroom 2	12.31
	Bedroom 3	13.23
B	Living room	27.19
	Kitchen	13.87
	Hall/corridor	14.15
	Toilet	4.33
	Bathroom	4.81
	Bedroom 1	14.46
	Bedroom 2	11.71
	Bedroom 3	11.42
C	Living room	31.08
	Kitchen	18.76
	Hall/corridor	20.69
	Toilet	4.40
	Bathroom	5.80
	Bedroom 1	17.83
	Bedroom 2	12.40
	Bedroom 3	13.31
	Bedroom 4	13.36

Table 2. *Cont.*

Type of Dwelling	Space	Area (m^2)
D	Living room	28.30
	Kitchen	14.37
	Hall/corridor	9.78
	Toilet	4.78
	Bathroom	5.42
	Bedroom 1	14.44
	Bedroom 2	12.20
	Bedroom 3	12.65

The thermal envelope for the existing building of each January climate zone is equal to the maximum thermal transmittances allowed by the Basic Document Norm on Thermal Conditions in Buildings [34] (in effect from 1981 to 2007). Moreover, these maximum thermal transmittances are used by default for residential buildings built before 2008 by CE3X [35], which is the most frequently used official tool for the energy performance certification of existing buildings [36]. Table 3 shows the thermal transmittance according to the January climate zone for each element of the thermal envelope of the building and the corresponding exchange surfaces. The compositions of the different elements that make up the building enclosures and their main characteristics, as well as the compositions of the building openings, were reported in [30], where Cádiz and Valencia correspond to January climate zone W, Cáceres corresponds to January climate zone X, Madrid corresponds to January climate zone Y and León corresponds to January climate zone Z.

Table 3. Thermal transmittance (U) according to the January climate zone for each element of the thermal envelope of the building, in $W/m^2{\cdot}K$, and the corresponding exchange surface, in m^2.

	January Climate Zone	Walls	Roof	First Floor Framework	Openings
U ($W/m^2{\cdot}K$)	W	1.80	1.40	2.17	5.70
	X	1.60	1.20	1.40	5.70
	Y	1.40	0.90	1.20	3.50
	Z	1.40	0.70	1.20	3.50
Exchange surface (m^2)		1107.16	491.93	484.00	212.84

2.3. Case Studies

This study calculates the optimum insulation thickness to be added to the walls, roof and first floor framework of the thermal envelope of the studied building in order to minimize the total heating costs and total heating and cooling costs of the energy renovation. In addition, this study assesses the energy, environmental and economic impacts of this energy renovation using the thermal insulation materials EPS, MW, PUR and XPS with the following systems to meet the thermal requirements of the buildings:

- System 1: Heating oil boilers with thermal performances of 0.85 to meet the heating and domestic hot water (DHW) requirements and electric cooling systems with thermal efficiencies of 2.00.
- System 2: Natural gas boilers with thermal performances of 0.92 to meet the heating and DHW requirements and electric cooling systems with thermal efficiencies of 2.00.
- System 3: Biomass boilers with thermal performances of 0.85 to meet the heating and DHW requirements and electric cooling systems with thermal efficiencies of 2.00.

- System 4: Electric heat pumps with seasonal coefficients of performance of 2.50 and seasonal energy efficiency ratios of 3.00 to meet the heating, cooling and DHW requirements.

The existing building openings are replaced by openings with a thermal transmittance of 1.92 W/m^2·K (double-chamber PVC frame and low-emissivity double-pane glass, with 30% of the space occupied by the framework) and a price of 282.63 €/m^2 in 2018; these data are from the construction database of the Valencia Institute of Building [37]. The thermal conductivity and price of the insulation materials used, corresponding to 2018, were also extracted from the database [37] (Table 4). Moreover, Table 5 shows the prices of the different energy carriers (fuels and electricity) used in 2018. The price of electricity depends on its annual consumption: the price of electricity 2 is used with system 4, and the price of electricity 1 is used with the remaining systems.

Table 4. Thermal conductivity, in W/m·K, and price, in €/m^3, of the insulation materials used [37].

Insulation Material	Thermal Conductivity (W/m·K)	Price (€/m^3)
EPS	0.034	263.78
MW	0.034	181.50
PUR	0.025	302.50
XPS	0.034	267.00

Table 5. Prices of different energy carriers, in €/kWh.

Energy Carrier	Price (€/kWh)	Source
Heating oil	0.0713	[38,39]
Natural gas (annual consumption between 20 and 200 GJ)	0.0770	[40]
Biomass (A1 certified pellets in bulk)	0.0462	[41]
Electricity 1 (annual consumption between 2500 and 5000 kWh)	0.2430	[42]
Electricity 2 (annual consumption between 5000 and 15,000 kWh)	0.2042	[42]

2.4. Thermal Transmittance and Overall Thermal Transmittance

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

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

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

$$R_e = R_{si,e} + \sum_n R_{n,e} + R_{se,e}, \tag{2}$$

where $R_{si,e}$ 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, and $R_{n,e}$ is the thermal resistance, in m^2·K/W, of layer n of element e of the thermal envelope of the building, calculated with the following equation:

$$R_{n,e} = \frac{x_{n,e}}{\lambda_{n,e}}, \tag{3}$$

where $x_{n,e}$ is the thickness of layer n of element e of the thermal envelope of the building, in m, and $\lambda_{n,e}$ is the thermal conductivity of the material that makes up layer n of element e of the thermal envelope of the building, in W/m·K.

Equations (1)–(3) and the values used for $R_{si,e}$ and $R_{se,e}$ were obtained from [43].

Thus, the result of the overall thermal transmittance of the thermal envelope of the building, $\overline{U}$, in W/m^2·K, is:

$$\overline{U} = \frac{\sum_e U_e \cdot A_{exch,e}}{\sum_e A_{exch,e}}, \quad (4)$$

where e is the walls, roof, first floor framework and openings that make up the thermal envelope of the building and $A_{exch,e}$ is the exchange surface of element e of the thermal envelope of the building, in m^2, reported in Table 3.

2.5. Energy and Environmental Impacts of the Existing Building

The heating and cooling energy demands for element e of the existing building per unit of the exchange surface and year, $ED^{exis}_{heat,e}$ and $ED^{exis}_{cool,e}$, respectively, in kWh/m^2·year, are calculated with the following equations:

$$ED^{exis}_{heat,e} = 0.024 \cdot HDD \cdot U^{exis}_e, \quad (5)$$

$$ED^{exis}_{cool,e} = 0.024 \cdot CDD \cdot U^{exis}_e, \quad (6)$$

where HDD is the heating degree-days with a base temperature of 20 °C (Table 1); CDD is the cooling degree-days with a base temperature of 20 °C (Table 1); and U^{exis}_e is the thermal transmittance of element e of the existing building, in W/m^2·K (Table 3).

The annual heating and cooling energy costs per unit of exchange surface of element e of the existing building, $EC^{exis}_{heat,e}$ and $EC^{exis}_{cool,e}$, respectively, in €/m^2·year, are calculated with the following equations:

$$EC^{exis}_{heat,e} = \frac{0.024 \cdot HDD \cdot C_{fuel} \cdot U^{exis}_e}{\eta}, \quad (7)$$

$$EC^{exis}_{cool,e} = \frac{0.024 \cdot CDD \cdot C_{elec} \cdot U^{exis}_e}{\varepsilon}, \quad (8)$$

where C_{fuel} is the price of the fuel used, in €/kWh, reported in Table 5; C_{elec} is the price of electricity, in €/kWh, reported in Table 5; η is the thermal performance or seasonal coefficient of performance of the heating system, expressed per-unit; and ε is the thermal efficiency or seasonal energy efficiency ratio of the cooling system, expressed per-unit. For heat pumps, $C_{fuel} = C_{elec}$.

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

$$ED^{exis}_{heat} = \sum_e ED^{exis}_{heat,e} \cdot \frac{A_{exch,e}}{A_{liv}}, \quad (9)$$

$$ED^{exis}_{cool} = \sum_e ED^{exis}_{cool,e} \cdot \frac{A_{exch,e}}{A_{liv}}, \quad (10)$$

where A_{liv} is the living area of the building, which is 2216.57 m^2.

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

$$FEC^{exis}_{heat} = \frac{ED^{exis}_{heat}}{\eta}, \quad (11)$$

$$FEC^{exis}_{cool} = \frac{ED^{exis}_{cool}}{\varepsilon}, \quad (12)$$

$$FEC^{exis}_{DHW} = \frac{ED^{exis}_{DHW}}{\eta}, \quad (13)$$

where ED_{DHW}^{exis} is the average DHW energy demand per unit of living area and year for existing multi-family buildings built before 2008 (in the selected cities with the same climate zone and January climate zone), in kWh/m^2·year, obtained from the corresponding energy demands in [44].

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

$$FEC_{total}^{exis} = FEC_{heat}^{exis} + FEC_{cool}^{exis} + FEC_{DHW}^{exis}. \tag{14}$$

The total primary energy consumption and non-renewable primary energy consumption of the existing building per unit of living area and year, $TPEC_{total}^{exis}$ and $NRPEC_{total}^{exis}$, respectively, in kWh/m^2·year, are calculated using the following equations:

$$TPEC_{total}^{exis} = FEC_{heat}^{exis} \cdot f_{TPE}^{fuel} + FEC_{cool}^{exis} \cdot f_{TPE}^{elec} + FEC_{DHW}^{exis} \cdot f_{TPE}^{fuel}, \tag{15}$$

$$NRPEC_{total}^{exis} = FEC_{heat}^{exis} \cdot f_{NRPE}^{fuel} + FEC_{cool}^{exis} \cdot f_{NRPE}^{elec} + FEC_{DHW}^{exis} \cdot f_{NRPE}^{fuel}, \tag{16}$$

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}; f_{TPE}^{elec} is the conversion factor from the final energy to the total primary energy for electricity, in kWh_{TPE}/kWh_{FE}; 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 factors of conversion from the final energy to the total primary energy and the factors of conversion from the final energy to the non-renewable primary energy were obtained from IDAE [45] (Table 6).

Table 6. Factors of conversion from final energy (FE) to non-renewable primary energy (NRPE), total primary energy (TPE) and CO_2 emissions [45].

	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
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

The CO_2 emissions of the existing building per unit of living area and year, EM_{total}^{exis}, in kg CO_2/m^2·year, are calculated with the following equation:

$$EM_{total}^{exis} = FEC_{heat}^{exis} \cdot f_{EM}^{fuel} + FEC_{cool}^{exis} \cdot f_{EM}^{elec} + FEC_{DHW}^{exis} \cdot f_{EM}^{fuel}, \tag{17}$$

where f_{EM}^{fuel} is the conversion factor from the final energy to 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 CO_2 emissions for electricity in kg CO_2/kWh_{FE}. The conversion factors from the final energy to CO_2 emissions were obtained from IDAE [45] (Table 6).

Equations (5)–(8) were obtained and adapted from [16,17], and Equations (11)–(17) were used in [28,29].

The IDAE conversion factors [45] (Table 6) are the same as those used by CE3X [35] and HULC [33]. Finally, the assignment of labels for the non-renewable primary energy consumption and CO_2 emissions was made using the boundaries between classes used by CE3X [35] and HULC [33] (Table 7).

Table 7. Limit values among classes for the non-renewable primary energy consumption and CO_2 emissions labels for multi-family buildings in each climate zone [46].

	Non-Renewable Primary Energy Consumption (kWh/m²·year)				CO_2 Emissions (kg CO_2/m²·year)			
	D1	D2	D3	E1	D1	D2	D3	E1
A	P < 37.5	P < 35.3	P < 37.1	P < 46.9	E < 8.4	E < 7.9	E < 8.4	E < 10.4
B	37.5 ≤ P < 57.7	35.3 ≤ P < 57.2	37.1 ≤ P < 60.1	46.9 ≤ P < 72.1	8.4 ≤ E < 12.9	7.9 ≤ E < 12.9	8.4 ≤ E < 13.6	10.4 ≤ E < 16.1
C	57.7 ≤ P < 86.1	57.2 ≤ P < 88.7	60.1 ≤ P < 93.2	72.1 ≤ P < 107.5	12.9 ≤ E < 19.3	12.9 ≤ E < 20.0	13.6 ≤ E < 21.1	16.1 ≤ E < 24.0
D	86.1 ≤ P < 128.2	88.7 ≤ P < 136.3	93.2 ≤ P < 143.3	107.5 ≤ P < 160.1	19.3 ≤ E < 28.7	20.0 ≤ E < 30.7	21.1 ≤ E < 32.4	24.0 ≤ E < 35.7
E	128.2 ≤ P < 271.9	136.3 ≤ P < 284.7	143.3 ≤ P < 298.1	160.1 ≤ P < 358.8	28.7 ≤ E < 59.9	30.7 ≤ E < 63.0	32.4 ≤ E < 66.3	35.7 ≤ E < 82.9
F	271.9 ≤ P < 318.1	284.7 ≤ P < 333.1	298.1 ≤ P < 336.8	358.8 ≤ P < 419.8	59.9 ≤ E < 71.8	63.0 ≤ E < 73.7	66.3 ≤ E < 79.6	82.9 ≤ E < 97.0
G	318.1 ≤ P	333.1 ≤ P	336.8 ≤ P	419.8 ≤ P	71.8 ≤ E	73.7 ≤ E	79.6 ≤ E	97.0 ≤ E

2.6. *Energy, Environmental and Economic Impacts of the Renovated Building*

The heating and cooling energy demands of element *e* of the renovated building per unit of exchange surface and year, $ED^{reno}_{heat,e}$ and $ED^{reno}_{cool,e}$, respectively, in kWh/m^2·year, are calculated using the following equations:

$$ED^{reno}_{heat,e} = 0.024 \cdot HDD \cdot U^{reno}_{e}, \tag{18}$$

$$ED^{reno}_{cool,e} = 0.024 \cdot CDD \cdot U^{reno}_{e}, \tag{19}$$

where U^{reno}_{e} is the thermal transmittance of element *e* of the renovated building, in W/m^2·K, and U^{reno}_{e} for openings is 1.92 W/m^2·K. Equation (1) and Equation (2) are used to calculate U^{reno}_{e} for the walls, roof and first floor framework, and thus, the thermal resistance of element *e* of the renovated building, R^{reno}_{e}, in m^2·K/W, is:

$$R^{reno}_{e} = R^{exis}_{e} + R^{insu}_{e}, \tag{20}$$

where R^{exis}_{e} is the thermal resistance of element *e* of the existing building, in m^2·K/W, obtained using Equation (1) with U^{exis}_{e}, and R^{insu}_{e} is the thermal resistance of the insulation added to element *e* of the building, in m^2·K/W, obtained from Equation (3) using both the optimum insulation thickness required, in m, and the thermal conductivity of the selected insulation, in W/m·K (Table 4).

The annual heating and cooling energy cost per unit of exchange surface of element *e* of the renovated building, $EC^{reno}_{heat,e}$ and $EC^{reno}_{cool,e}$, respectively, in €/m^2·year, are calculated with the following equations:

$$EC^{reno}_{heat,e} = \frac{0.024 \cdot HDD \cdot C_{fuel} \cdot U^{reno}_{e}}{\eta}, \tag{21}$$

$$EC^{reno}_{cool,e} = \frac{0.024 \cdot CDD \cdot C_{elec} \cdot U^{reno}_{e}}{\varepsilon}. \tag{22}$$

A life cycle cost analysis is used to determine the optimum insulation thickness [47], considering a 5.00 % interest rate, *i*, and 2.50 % inflation rate, *g*. Since *i* is higher than *g*, the present worth factor, *PWF*, is calculated with the following equation:

$$PWF = \frac{(1+r)^{N} - 1}{r \cdot (1+r)^{N}}, \tag{23}$$

where *N* is the lifetime, in years, and *r* is the actual interest rate, calculated with the following equation:

$$r = \frac{i-g}{1+g}. \tag{24}$$

The value of *r* obtained using Equation (24) is 2.44%. In addition, considering an *N* of 30 years and applying Equation (23), the *PWF* obtained is 21.10.

The optimum insulation thickness is calculated to minimize both the total heating cost and the total heating and cooling costs, since in cold climate zones, the calculation to minimize the total cooling cost is meaningless, as suggested in [48].

Accordingly, the optimum insulation thickness that minimizes the total heating cost of element e of the building, $x_{opt,e}^{heat}$, in m, is calculated with the following equation:

$$x_{opt,e}^{heat} = \left(\frac{0.024 \cdot HDD \cdot C_{fuel} \cdot PWF \cdot \lambda}{C_{insu} \cdot \eta}\right)^{0.5} - \lambda \cdot R_e^{exis}, \tag{25}$$

where λ is the thermal conductivity of the insulation used, in W/m·K, reported in Table 4.

The cost of the insulation that minimizes the total heating cost for element e of the building per unit of exchange surface, $C_{insu,e}^{heat}$, in €/m^2, is calculated using the following equation:

$$C_{insu,e}^{heat} = C_{insu} \cdot x_{opt,e}^{heat}, \tag{26}$$

where C_{insu} is the insulation cost, in €/m^3, reported in Table 4.

The cost of the energy renovation of element e of the building with an optimized insulation thickness that minimizes the total heating cost per unit of exchange surface, $C_{heat,e}^{reno}$, in €/m^2, is obtained from Equation (26) for the walls, roof and first floor framework, and its value is 282.63 €/m^2 for the openings, since the current openings are replaced with new openings.

The total heating cost per unit of exchange surface of element e of the building, $TC_{heat,e}^{reno}$, in €/m^2, is calculated using the following equation:

$$TC_{heat,e}^{reno} = EC_{heat,e}^{reno} \cdot PWF + C_{heat,e}^{reno}. \tag{27}$$

The total net savings for element e of the renovated building with an optimized insulation thickness that minimizes the total heating cost per unit of exchange surface, $ECS_{heat,e}^{reno}$, in €/m^2·year, is calculated using the following equation:

$$ECS_{heat,e}^{reno} = EC_{heat,e}^{exis} - EC_{heat,e}^{reno}. \tag{28}$$

The payback period for element e of the renovated building with an optimized insulation thickness that minimizes the total heating cost, $PP_{heat,e}^{reno}$, in years, is calculated using the following equation:

$$PP_{heat,e}^{reno} = \frac{C_{heat,e}^{reno}}{ECS_{heat,e}^{reno}}. \tag{29}$$

The cost of the energy renovation of the building with an optimized insulation thickness that minimizes the total heating cost per unit of living area, C_{heat}^{reno}, in €/m^2, is calculated with the following equation:

$$C_{heat}^{reno} = \sum_e C_{heat,e}^{reno} \cdot \frac{A_{exch,e}}{A_{liv}}. \tag{30}$$

The total net savings for the renovated building with an optimized insulation thickness that minimizes the total heating cost per unit of living area, ECS_{heat}^{reno}, in €/m^2·year, is calculated using the following equation:

$$ECS_{heat}^{reno} = \sum_e ECS_{heat,e}^{reno} \cdot \frac{A_{exch,e}}{A_{liv}}. \tag{31}$$

The payback period for the renovated building with an optimized insulation thickness that minimizes the total heating cost, PP_{heat}^{reno}, in years, is calculated using the following equation:

$$PP_{heat}^{reno} = \frac{C_{heat}^{reno}}{ECS_{heat}^{reno}}. \quad (32)$$

Furthermore, the optimum insulation thickness that minimizes the total heating and cooling costs for element *e* of the building, $x_{opt,e}^{heat+cool}$, in m, is calculated with the following equation:

$$x_{opt,e}^{heat+cool} = \left(\frac{0.024 \cdot HDD \cdot C_{fuel} \cdot PWF \cdot \lambda}{C_{insu} \cdot \eta} + \frac{0.024 \cdot CDD \cdot C_{elec} \cdot PWF \cdot \lambda}{C_{insu} \cdot \varepsilon}\right)^{0.5} - \lambda \cdot R_e^{exis}. \quad (33)$$

The cost of the insulation that minimizes the total heating and cooling costs per unit of exchange surface for element *e* of the building, $C_{insu,e}^{heat+cool}$, in €/m^2, is calculated using the following equation:

$$C_{insu,e}^{heat+cool} = C_{insu} \cdot x_{opt,e}^{heat+cool}. \quad (34)$$

The cost of the energy renovation of element *e* of the building with an optimized insulation thickness that minimizes the total heating and cooling costs per unit of exchange surface, $C_{heat+cool,e}^{reno}$, in €/m^2, is obtained from Equation (34) for the walls, roof and first floor framework, and its value is 282.63 €/m^2 for the openings, since the current openings are replaced with new openings.

The total heating and cooling costs per unit of exchange surface for element *e* of the building, $TC_{heat+cool,e}^{reno}$, in €/m^2, is calculated using the following equation:

$$TC_{heat+cool,e}^{reno} = \left(EC_{heat,e}^{reno} + EC_{cool,e}^{reno}\right) \cdot PWF + C_{heat+cool,e}^{reno}. \quad (35)$$

The total net savings for element *e* of the renovated building with an optimized insulation thickness that minimizes the total heating and cooling costs per unit of exchange surface, $ECS_{heat+cool,e}^{reno}$, in €/m^2·year, is calculated using the following equation:

$$ECS_{heat+cool,e}^{reno} = \left(EC_{heat,e}^{exis} + EC_{cool,e}^{exis}\right) - \left(EC_{heat,e}^{reno} + EC_{cool,e}^{reno}\right). \quad (36)$$

The payback period for element *e* of the renovated building with an optimized insulation thickness that minimizes the total heating and cooling costs, $PP_{heat+cool,e}^{reno}$, in years, is calculated using the following equation:

$$PP_{heat+cool,e}^{reno} = \frac{C_{heat+cool,e}^{reno}}{ECS_{heat+cool,e}^{reno}}. \quad (37)$$

The cost of the energy renovation of the building with an optimized insulation thickness that minimizes the total heating and cooling costs per unit of living area, $C_{heat+cool}^{reno}$, in €/m^2, is calculated with the following equation:

$$C_{heat+cool}^{reno} = \sum_e C_{heat+cool,e}^{reno} \cdot \frac{A_{exch,e}}{A_{liv}}. \quad (38)$$

The total net savings for the renovated building with an optimized insulation thickness that minimizes the total heating and cooling costs per unit of living area, $ECS_{heat+cool}^{reno}$, in €/m^2·year, is calculated using the following equation:

$$ECS_{heat+cool}^{reno} = \sum_e ECS_{heat+cool,e}^{reno} \cdot \frac{A_{exch,e}}{A_{liv}}. \quad (39)$$

The payback period for the renovated building with an optimized insulation thickness that minimizes the total heating and cooling costs, $PP_{heat+cool}^{reno}$, in years, is calculated using the following equation:

$$PP_{heat+cool}^{reno} = \frac{C_{heat+cool}^{reno}}{ECS_{heat+cool}^{reno}}. \tag{40}$$

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

$$ED_{heat}^{reno} = \sum_{e} ED_{heat,e}^{reno} \cdot \frac{A_{exch,e}}{A_{liv}}, \tag{41}$$

$$ED_{cool}^{reno} = \sum_{e} ED_{cool,e}^{reno} \cdot \frac{A_{exch,e}}{A_{liv}}. \tag{42}$$

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

$$FEC_{heat}^{reno} = \frac{ED_{heat}^{reno}}{\eta}, \tag{43}$$

$$FEC_{cool}^{reno} = \frac{ED_{cool}^{reno}}{\varepsilon}, \tag{44}$$

$$FEC_{DHW}^{reno} = \frac{ED_{DHW}^{reno} \cdot (1 - f)}{\eta}, \tag{45}$$

where ED_{DHW}^{reno} is the average energy demand of DHW per unit of living area and year for the studied building in the cities selected with the same climate zone and January climate zone, according to the current CTE-DB-HE [31], in kWh/m^2·year, calculated in [28], and f is the average of the minimum solar contributions required for the studied building in cities selected with the same climate zone and January climate zone according to the current CTE-DB-HE [7,31], expressed per unit.

Thus, the final energy consumption of the renovated building per unit of living area and year, FEC_{total}^{reno}, in kWh/m^2·year, is:

$$FEC_{total}^{reno} = FEC_{heat}^{reno} + FEC_{cool}^{reno} + FEC_{DHW}^{reno}. \tag{46}$$

The total primary energy consumption and non-renewable primary energy consumption of the renovated building per unit of living area and year, $TPEC_{total}^{reno}$ and $NRPEC_{total}^{reno}$, respectively, in kWh/m^2·year, are calculated using the following equations:

$$TPEC_{total}^{reno} = FEC_{heat}^{reno} \cdot f_{TPE}^{fuel} + FEC_{cool}^{reno} \cdot f_{TPE}^{elec} + FEC_{DHW}^{reno} \cdot f_{TPE}^{fuel}. \tag{47}$$

$$NRPEC_{total}^{reno} = FEC_{heat}^{reno} \cdot f_{NRPE}^{fuel} + FEC_{cool}^{reno} \cdot f_{NRPE}^{elec} + FEC_{DHW}^{reno} \cdot f_{NRPE}^{fuel}. \tag{48}$$

The CO_2 emissions of the renovated building per unit of living area and year, EM_{total}^{reno}, in kg CO_2/m^2·year, are calculated with the following equation:

$$EM_{total}^{reno} = FEC_{heat}^{reno} \cdot f_{EM}^{fuel} + FEC_{cool}^{reno} \cdot f_{EM}^{elec} + FEC_{DHW}^{reno} \cdot f_{EM}^{fuel}. \tag{49}$$

Equations (18)–(29) and Equations (33)–(37) were obtained and adapted from [16,17], and Equations (43)–(49) were used in [28,29].

The IDAE conversion factors [45] (Table 6) are the same as those used by CE3X [35] and HULC [33]. Finally, the labels for the non-renewable primary energy consumption and CO_2 emissions are assigned using the boundaries between classes used by CE3X [35] and HULC [33] (Table 7).

In addition, whether the renovated building is a nearly zero-energy building according to the current CTE-DB-HE [31] is verified. To accomplish this task, it must be demonstrated that in climate zones D1, D2 and D3, the energy demand for heating is less than or equal to 27.90 kWh/m^2·year, the energy demand for cooling is less than or equal to 15.00 kWh/m^2·year, and the non-renewable primary energy consumption is less than or equal to 61.35 kWh/m^2·year and that in climate zone E1, the energy demand for heating is less than or equal to 41.35 kWh/m^2·year, the energy demand for cooling is less than or equal to 15.00 kWh/m^2·year, and the non-renewable primary energy consumption is less than or equal to 71.80 kWh/m^2·year [28].

3. Results and Discussion

Tables 8–11 show the optimized insulation thicknesses to be added to the walls, roof and first floor framework in order to minimize the total heating costs and total heating and cooling costs, as well as the corresponding energy renovation costs, total net savings and payback period, for each of the climate zones by the January climate zone, the system used and the insulation material. The overall thermal transmittance, the heating and cooling energy demands, the final energy consumption, the total primary energy consumption, the non-renewable primary energy consumption, the CO_2 emissions, the non-renewable primary energy consumption rating and the CO_2 emissions rating for each climate zone by the January climate zone, the system used and the insulation material are shown in Table 12 for the existing buildings (no additional insulation material required) and in Tables 13–16 for the renovated buildings. In addition, the total net savings from the reduction in non-renewable primary energy consumption are presented for each of the systems used by the climate zone, January climate zone and insulation material and with an optimization of the insulation thickness to minimize the total heating costs (Figure 3) and the total heating and cooling costs (Figure 4). The total net savings due to the CO_2 emissions reduction for each system used by the climate zone, January climate zone and insulation material with the optimization of the insulation thickness to minimize the total heating costs (Figure 5) and the total heating and cooling costs (Figure 6) are also presented.

Table 8. Optimized insulation thicknesses to be added to the walls, roof and first floor framework (FFF), in m; energy renovation cost per unit of living area (C), in €/m^2; total net savings per unit of living area (ECS), in €/m^2·year; and payback period (PP), in years, for climate zone D1 by January climate zone, system used, insulation material and optimization criterion.

			January Climate Zone W						January Climate Zone X						January Climate Zone Y					
System	**Insulation Material**	**Optimization Criterion**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**
1	EPS	Heat	0.109	0.104	0.113	54.12	10.87	4.98	0.107	0.100	0.104	53.07	8.98	5.91	0.104	0.090	0.100	51.89	6.43	8.07
		Heat + Cool	0.112	0.107	0.115	54.78	11.36	4.82	0.110	0.103	0.107	53.73	9.39	5.72	0.107	0.093	0.103	52.55	6.73	7.80
	MW	Heat	0.136	0.130	0.139	50.20	11.13	4.51	0.133	0.126	0.130	49.48	9.24	5.36	0.130	0.117	0.126	48.66	6.69	7.28
		Heat + Cool	0.139	0.134	0.142	50.75	11.62	4.37	0.137	0.129	0.134	50.03	9.65	5.18	0.134	0.120	0.129	49.21	7.00	7.03
	PUR	Heat	0.089	0.085	0.091	52.28	10.99	4.76	0.087	0.082	0.085	51.39	9.10	5.65	0.085	0.075	0.082	50.39	6.56	7.69
		Heat + Cool	0.091	0.087	0.093	52.88	11.48	4.60	0.089	0.084	0.087	52.00	9.52	5.47	0.087	0.077	0.084	51.00	6.86	7.43
	XPS	Heat	0.109	0.103	0.112	54.25	10.86	5.00	0.106	0.099	0.103	53.20	8.97	5.93	0.103	0.090	0.099	52.00	6.42	8.10
		Heat + Cool	0.111	0.106	0.114	54.92	11.35	4.84	0.109	0.102	0.106	53.86	9.38	5.74	0.106	0.092	0.102	52.66	6.72	7.83
2	EPS	Heat	0.109	0.104	0.112	54.08	10.84	4.99	0.107	0.100	0.104	53.04	8.96	5.92	0.104	0.090	0.100	51.85	6.42	8.08
		Heat + Cool	0.112	0.106	0.115	54.74	11.33	4.83	0.110	0.102	0.106	53.70	9.37	5.73	0.106	0.093	0.102	52.51	6.72	7.82
	MW	Heat	0.136	0.130	0.139	50.17	11.10	4.52	0.133	0.126	0.130	49.45	9.22	5.37	0.130	0.117	0.126	48.64	6.67	7.29
		Heat + Cool	0.139	0.133	0.142	50.72	11.59	4.37	0.136	0.129	0.133	50.00	9.63	5.19	0.133	0.120	0.129	49.18	6.98	7.05
	PUR	Heat	0.089	0.085	0.091	52.24	10.97	4.76	0.087	0.082	0.085	51.36	9.08	5.66	0.085	0.075	0.082	50.36	6.54	7.70
		Heat + Cool	0.091	0.087	0.093	52.85	11.46	4.61	0.089	0.084	0.087	51.97	9.49	5.47	0.087	0.077	0.084	50.97	6.84	7.45
	XPS	Heat	0.108	0.103	0.112	54.22	10.84	5.00	0.106	0.099	0.103	53.16	8.95	5.94	0.103	0.090	0.099	51.96	6.41	8.11
		Heat + Cool	0.111	0.106	0.114	54.88	11.32	4.85	0.109	0.102	0.106	53.83	9.36	5.75	0.106	0.092	0.102	52.63	6.71	7.84
3	EPS	Heat	0.084	0.079	0.088	47.92	6.81	7.04	0.082	0.075	0.079	46.87	5.58	8.40	0.079	0.065	0.075	45.69	3.93	11.62
		Heat + Cool	0.088	0.082	0.091	48.73	7.29	6.69	0.085	0.078	0.082	47.69	5.98	7.97	0.082	0.069	0.078	46.50	4.23	11.00
	MW	Heat	0.106	0.100	0.109	45.06	7.01	6.42	0.103	0.096	0.100	44.34	5.79	7.66	0.100	0.087	0.096	43.52	4.14	10.52
		Heat + Cool	0.110	0.104	0.113	45.73	7.50	6.10	0.107	0.100	0.104	45.01	6.20	7.26	0.104	0.091	0.100	44.20	4.44	9.96
	PUR	Heat	0.069	0.065	0.071	46.58	6.91	6.74	0.067	0.062	0.065	45.70	5.68	8.04	0.065	0.055	0.062	44.70	4.03	11.09
		Heat + Cool	0.071	0.067	0.074	47.33	7.39	6.40	0.070	0.064	0.067	46.45	6.09	7.63	0.067	0.058	0.064	45.45	4.33	10.50
	XPS	Heat	0.084	0.078	0.087	48.02	6.80	7.06	0.081	0.074	0.078	46.96	5.58	8.42	0.078	0.065	0.074	45.76	3.92	11.66
		Heat + Cool	0.087	0.082	0.090	48.84	7.28	6.71	0.085	0.078	0.082	47.78	5.98	7.99	0.082	0.068	0.078	46.58	4.22	11.04

Table 8. *Cont.*

System	Insulation Material	Optimization Criterion	January Climate Zone W						January Climate Zone X						January Climate Zone Y					
			Walls	Roof	FFF	C	ECS	PP	Walls	Roof	FFF	C	ECS	PP	Walls	Roof	FFF	C	ECS	PP
4	EPS	Heat	0.108	0.102	0.111	53.70	10.57	5.08	0.105	0.098	0.102	52.65	8.73	6.03	0.102	0.089	0.098	51.47	6.24	8.24
		Heat + Cool	0.109	0.104	0.112	54.08	10.84	4.99	0.107	0.100	0.104	53.03	8.95	5.92	0.104	0.090	0.100	51.84	6.41	8.08
	MW	Heat	0.134	0.128	0.137	49.85	10.82	4.61	0.131	0.124	0.128	49.13	8.98	5.47	0.128	0.115	0.124	48.32	6.50	7.44
		Heat + Cool	0.136	0.130	0.139	50.16	11.09	4.52	0.133	0.126	0.130	49.44	9.21	5.37	0.130	0.117	0.126	48.63	6.67	7.29
	PUR	Heat	0.087	0.083	0.090	51.89	10.69	4.86	0.086	0.081	0.083	51.01	8.85	5.77	0.083	0.074	0.081	50.01	6.37	7.86
		Heat + Cool	0.089	0.085	0.091	52.24	10.96	4.77	0.087	0.082	0.085	51.35	9.08	5.66	0.085	0.075	0.082	50.35	6.54	7.70
	XPS	Heat	0.107	0.102	0.110	53.83	10.56	5.10	0.105	0.097	0.102	52.77	8.72	6.05	0.102	0.088	0.097	51.57	6.23	8.27
		Heat + Cool	0.108	0.103	0.112	54.21	10.83	5.01	0.106	0.099	0.103	53.15	8.94	5.94	0.103	0.090	0.099	51.95	6.40	8.11

Table 9. Optimized insulation thicknesses to be added to the walls, roof and first floor framework (FFF), in m; energy renovation cost per unit of living area (C), in €/m^2; total net savings per unit of living area (ECS), in €/m^2·year; and payback period (PP), in years, for climate zone D2 by January climate zone, system used, insulation material and optimization criterion.

System	Insulation Material	Optimization Criterion	January Climate Zone X						January Climate Zone Y						January Climate Zone Z					
			Walls	Roof	FFF	C	ECS	PP	Walls	Roof	FFF	C	ECS	PP	Walls	Roof	FFF	C	ECS	PP
1	EPS	Heat	0.104	0.097	0.101	52.29	8.50	6.15	0.101	0.087	0.097	51.10	6.08	8.40	0.101	0.077	0.097	50.47	5.83	8.66
		Heat + Cool	0.111	0.103	0.107	53.95	9.52	5.66	0.107	0.094	0.103	52.76	6.83	7.72	0.107	0.083	0.103	52.13	6.55	7.96
	MW	Heat	0.130	0.122	0.126	48.83	8.76	5.58	0.126	0.113	0.122	48.01	6.33	7.58	0.126	0.102	0.122	47.58	6.08	7.83
		Heat + Cool	0.138	0.131	0.135	50.21	9.79	5.13	0.135	0.121	0.131	49.39	7.10	6.96	0.135	0.110	0.131	48.95	6.81	7.18
	PUR	Heat	0.085	0.079	0.082	50.67	8.63	5.87	0.082	0.072	0.079	49.67	6.20	8.01	0.082	0.064	0.079	49.14	5.95	8.26
		Heat + Cool	0.090	0.085	0.088	52.20	9.65	5.41	0.088	0.078	0.085	51.20	6.96	7.36	0.088	0.070	0.085	50.66	6.68	7.59
	XPS	Heat	0.103	0.096	0.100	52.40	8.50	6.17	0.100	0.087	0.096	51.20	6.07	8.43	0.100	0.076	0.096	50.56	5.82	8.69
		Heat + Cool	0.110	0.103	0.107	54.08	9.51	5.68	0.107	0.093	0.103	52.87	6.82	7.75	0.107	0.082	0.103	52.24	6.54	7.99

Table 9. *Cont.*

			January Climate Zone X						January Climate Zone Y						January Climate Zone Z					
System	**Insulation Material**	**Optimization Criterion**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**
2	EPS	Heat	0.104	0.097	0.101	52.25	8.48	6.16	0.101	0.087	0.097	51.07	6.07	8.42	0.101	0.076	0.097	50.43	5.81	8.68
		Heat + Cool	0.110	0.103	0.107	53.92	9.50	5.67	0.107	0.094	0.103	52.73	6.82	7.73	0.107	0.083	0.103	52.10	6.54	7.97
	MW	Heat	0.129	0.122	0.126	48.80	8.73	5.59	0.126	0.113	0.122	47.98	6.32	7.60	0.126	0.102	0.122	47.55	6.06	7.84
		Heat + Cool	0.137	0.130	0.134	50.18	9.77	5.14	0.134	0.121	0.130	49.36	7.08	6.97	0.134	0.110	0.130	48.93	6.80	7.20
	PUR	Heat	0.084	0.079	0.082	50.64	8.60	5.89	0.082	0.072	0.079	49.64	6.19	8.02	0.082	0.064	0.079	49.11	5.93	8.28
		Heat + Cool	0.090	0.085	0.088	52.17	9.63	5.42	0.088	0.078	0.085	51.17	6.94	7.37	0.088	0.070	0.085	50.63	6.66	7.60
	XPS	Heat	0.103	0.096	0.100	52.37	8.48	6.18	0.100	0.086	0.096	51.17	6.06	8.45	0.100	0.076	0.096	50.53	5.80	8.71
		Heat + Cool	0.110	0.103	0.107	54.04	9.49	5.69	0.107	0.093	0.103	52.84	6.81	7.76	0.107	0.082	0.103	52.20	6.53	8.00
3	EPS	Heat	0.079	0.072	0.076	46.24	5.28	8.76	0.076	0.063	0.072	45.05	3.71	12.14	0.076	0.052	0.072	44.42	3.54	12.53
		Heat + Cool	0.088	0.081	0.085	48.28	6.28	7.69	0.085	0.071	0.081	47.09	4.44	10.60	0.085	0.060	0.081	46.46	4.25	10.93
	MW	Heat	0.100	0.093	0.097	43.81	5.48	7.99	0.097	0.084	0.093	43.00	3.91	10.99	0.097	0.073	0.093	42.56	3.75	11.36
		Heat + Cool	0.110	0.103	0.107	45.50	6.50	7.00	0.107	0.093	0.103	44.68	4.66	9.58	0.107	0.083	0.103	44.25	4.47	9.90
	PUR	Heat	0.065	0.060	0.063	45.12	5.38	8.39	0.063	0.053	0.060	44.12	3.81	11.59	0.063	0.045	0.060	43.59	3.64	11.97
		Heat + Cool	0.072	0.066	0.069	46.99	6.39	7.36	0.069	0.059	0.066	45.99	4.55	10.11	0.069	0.051	0.066	45.45	4.35	10.44
	XPS	Heat	0.079	0.072	0.076	46.32	5.27	8.78	0.076	0.062	0.072	45.12	3.70	12.19	0.076	0.052	0.072	44.48	3.54	12.58
		Heat + Cool	0.087	0.080	0.084	48.37	6.27	7.71	0.084	0.070	0.080	47.17	4.44	10.63	0.084	0.060	0.080	46.53	4.24	10.97
4	EPS	Heat	0.102	0.095	0.099	51.88	8.26	6.28	0.099	0.086	0.095	50.69	5.90	8.59	0.099	0.075	0.095	50.06	5.65	8.85
		Heat + Cool	0.106	0.099	0.103	52.83	8.83	5.98	0.103	0.089	0.099	51.64	6.32	8.17	0.103	0.079	0.099	51.01	6.06	8.42
	MW	Heat	0.128	0.120	0.125	48.49	8.51	5.70	0.125	0.111	0.120	47.67	6.15	7.75	0.125	0.100	0.120	47.24	5.90	8.00
		Heat + Cool	0.132	0.125	0.129	49.28	9.09	5.42	0.129	0.116	0.125	48.46	6.58	7.37	0.129	0.105	0.125	48.03	6.31	7.61
	PUR	Heat	0.083	0.078	0.081	50.30	8.38	6.00	0.081	0.071	0.078	49.30	6.02	8.19	0.081	0.063	0.078	48.76	5.77	8.45
		Heat + Cool	0.086	0.081	0.084	51.17	8.95	5.71	0.084	0.074	0.081	50.17	6.44	7.78	0.084	0.066	0.081	49.64	6.18	8.03
	XPS	Heat	0.101	0.094	0.098	51.99	8.25	6.30	0.098	0.085	0.094	50.79	5.89	8.62	0.098	0.074	0.094	50.15	5.64	8.88
		Heat + Cool	0.105	0.098	0.102	52.95	8.82	6.00	0.102	0.089	0.098	51.75	6.31	8.20	0.102	0.078	0.098	51.11	6.05	8.45

Table 10. Optimized insulation thicknesses to be added to the walls, roof and first floor framework (FFF), in m; energy renovation cost per unit of living area (C), in €/m^2; total net savings per unit of living area (ECS), in €/m^2·year; and payback period (PP), in years, for climate zone D3 by January climate zone, system used, insulation material and optimization criterion.

			January Climate Zone X						January Climate Zone Y						January Climate Zone Z					
System	**Insulation Material**	**Optimization Criterion**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**	**Walls**	**Roof**	**FFF**	**C**	**ECS**	**PP**
1	EPS	Heat	0.101	0.094	0.098	51.66	8.14	6.35	0.098	0.085	0.094	50.48	5.81	8.69	0.098	0.074	0.094	49.84	5.56	8.96
		Heat + Cool	0.114	0.107	0.111	54.86	10.11	5.43	0.111	0.098	0.107	53.68	7.27	7.39	0.111	0.087	0.107	53.04	6.97	7.61
	MW	Heat	0.126	0.119	0.123	48.31	8.38	5.76	0.123	0.110	0.119	47.49	6.06	7.84	0.123	0.099	0.119	47.06	5.81	8.10
		Heat + Cool	0.142	0.135	0.139	50.96	10.38	4.91	0.139	0.126	0.135	50.15	7.54	6.65	0.139	0.115	0.135	49.71	7.24	6.87
	PUR	Heat	0.083	0.077	0.080	50.10	8.25	6.07	0.080	0.070	0.077	49.10	5.93	8.28	0.080	0.062	0.077	48.56	5.68	8.55
		Heat + Cool	0.093	0.088	0.091	53.04	10.24	5.18	0.091	0.081	0.088	52.04	7.40	7.04	0.091	0.073	0.088	51.50	7.10	7.26
	XPS	Heat	0.101	0.093	0.098	51.78	8.13	6.37	0.098	0.084	0.093	50.58	5.80	8.72	0.098	0.073	0.093	49.94	5.56	8.99
		Heat + Cool	0.113	0.106	0.110	55.00	10.10	5.45	0.110	0.097	0.106	53.79	7.26	7.41	0.110	0.086	0.106	53.16	6.96	7.64
2	EPS	Heat	0.101	0.094	0.098	51.63	8.12	6.36	0.098	0.085	0.094	50.44	5.80	8.70	0.098	0.074	0.094	49.81	5.55	8.97
		Heat + Cool	0.114	0.107	0.111	54.83	10.09	5.43	0.111	0.098	0.107	53.65	7.25	7.40	0.111	0.087	0.107	53.01	6.95	7.63
	MW	Heat	0.126	0.119	0.123	48.28	8.36	5.77	0.123	0.110	0.119	47.47	6.04	7.86	0.123	0.099	0.119	47.03	5.80	8.11
		Heat + Cool	0.142	0.135	0.139	50.94	10.36	4.92	0.139	0.125	0.135	50.12	7.52	6.66	0.139	0.115	0.135	49.69	7.22	6.88
	PUR	Heat	0.082	0.077	0.080	50.07	8.23	6.08	0.080	0.070	0.077	49.07	5.91	8.30	0.080	0.062	0.077	48.53	5.67	8.56
		Heat + Cool	0.093	0.088	0.091	53.01	10.22	5.19	0.091	0.081	0.088	52.01	7.38	7.05	0.091	0.073	0.088	51.48	7.08	7.27
	XPS	Heat	0.100	0.093	0.097	51.74	8.11	6.38	0.097	0.084	0.093	50.54	5.79	8.73	0.097	0.073	0.093	49.90	5.54	9.00
		Heat + Cool	0.113	0.106	0.110	54.96	10.08	5.45	0.110	0.097	0.106	53.76	7.24	7.42	0.110	0.086	0.106	53.12	6.94	7.65
3	EPS	Heat	0.077	0.070	0.074	45.74	5.05	9.06	0.074	0.061	0.070	44.55	3.54	12.59	0.074	0.050	0.070	43.92	3.38	13.00
		Heat + Cool	0.093	0.086	0.090	49.61	6.99	7.10	0.090	0.077	0.086	48.43	4.96	9.76	0.090	0.066	0.086	47.80	4.75	10.06
	MW	Heat	0.098	0.091	0.095	43.39	5.24	8.28	0.095	0.081	0.091	42.58	3.74	11.40	0.095	0.070	0.091	42.14	3.58	11.78
		Heat + Cool	0.117	0.109	0.114	46.61	7.22	6.46	0.114	0.100	0.109	45.79	5.19	8.82	0.114	0.089	0.109	45.36	4.98	9.11
	PUR	Heat	0.063	0.058	0.061	44.66	5.14	8.69	0.061	0.051	0.058	43.66	3.63	12.02	0.061	0.043	0.058	43.12	3.47	12.41
		Heat + Cool	0.076	0.071	0.074	48.22	7.10	6.79	0.074	0.064	0.071	47.22	5.07	9.31	0.074	0.056	0.071	46.68	4.86	9.61
	XPS	Heat	0.077	0.070	0.074	45.81	5.04	9.09	0.074	0.060	0.070	44.61	3.53	12.63	0.074	0.049	0.070	43.97	3.37	13.04
		Heat + Cool	0.092	0.085	0.089	49.72	6.98	7.12	0.089	0.076	0.085	48.52	4.95	9.79	0.089	0.065	0.085	47.88	4.74	10.10

Table 10. *Cont.*

System	Insulation Material	Optimization Criterion	January Climate Zone X						January Climate Zone Y						January Climate Zone Z					
			Walls	Roof	FFF	C	ECS	PP	Walls	Roof	FFF	C	ECS	PP	Walls	Roof	FFF	C	ECS	PP
4	EPS	Heat	0.100	0.093	0.097	51.26	7.90	6.49	0.097	0.083	0.093	50.07	5.64	8.88	0.097	0.072	0.093	49.44	5.40	9.16
		Heat + Cool	0.107	0.100	0.104	53.12	9.01	5.90	0.104	0.091	0.100	51.93	6.45	8.05	0.104	0.080	0.100	51.30	6.18	8.30
	MW	Heat	0.125	0.117	0.122	47.98	8.15	5.89	0.122	0.108	0.117	47.16	5.88	8.02	0.122	0.097	0.117	46.73	5.64	8.28
		Heat + Cool	0.134	0.126	0.131	49.52	9.26	5.35	0.131	0.117	0.126	48.70	6.71	7.26	0.131	0.106	0.126	48.26	6.44	7.50
	PUR	Heat	0.081	0.076	0.079	49.73	8.02	6.20	0.079	0.069	0.076	48.73	5.75	8.47	0.079	0.061	0.076	48.20	5.52	8.74
		Heat + Cool	0.087	0.082	0.085	51.43	9.13	5.63	0.085	0.075	0.082	50.43	6.57	7.67	0.085	0.067	0.082	49.90	6.31	7.91
	XPS	Heat	0.099	0.092	0.096	51.37	7.90	6.51	0.096	0.082	0.092	50.17	5.63	8.91	0.096	0.072	0.092	49.53	5.39	9.19
		Heat + Cool	0.106	0.099	0.103	53.24	9.00	5.92	0.103	0.090	0.099	52.04	6.44	8.08	0.103	0.079	0.099	51.40	6.17	8.33

Table 11. Optimized insulation thicknesses to be added to the walls, roof and first floor framework (FFF), in m; energy renovation cost per unit of living area (C), in €/m^2; total net savings per unit of living area (ECS), in €/m^2·year; and payback period (PP), in years, for climate zone E1 and January climate zone Z by system used, insulation material and optimization criterion.

System	Insulation Material	Optimization Criterion	Walls	Roof	FFF	C	ECS	PP
1	EPS	Heat	0.115	0.091	0.111	54.02	7.42	7.28
		Heat + Cool	0.117	0.093	0.113	54.58	7.70	7.09
	MW	Heat	0.144	0.119	0.140	50.52	7.70	6.56
		Heat + Cool	0.147	0.122	0.142	50.99	7.98	6.39
	PUR	Heat	0.094	0.076	0.091	52.40	7.56	6.93
		Heat + Cool	0.096	0.078	0.093	52.92	7.83	6.76
	XPS	Heat	0.114	0.090	0.110	54.13	7.41	7.30
		Heat + Cool	0.117	0.092	0.112	54.70	7.68	7.12
2	EPS	Heat	0.115	0.091	0.111	53.98	7.40	7.29
		Heat + Cool	0.117	0.093	0.113	54.54	7.68	7.11
	MW	Heat	0.144	0.119	0.140	50.49	7.68	6.57
		Heat + Cool	0.146	0.122	0.142	50.96	7.96	6.40
	PUR	Heat	0.094	0.076	0.091	52.36	7.54	6.95
		Heat + Cool	0.095	0.078	0.092	52.88	7.81	6.77
	XPS	Heat	0.114	0.090	0.110	54.09	7.39	7.32
		Heat + Cool	0.116	0.092	0.112	54.66	7.67	7.13
3	EPS	Heat	0.088	0.064	0.084	47.28	4.55	10.39
		Heat + Cool	0.091	0.066	0.087	47.98	4.82	9.96
	MW	Heat	0.111	0.087	0.107	44.93	4.78	9.41
		Heat + Cool	0.114	0.090	0.110	45.51	5.05	9.01
	PUR	Heat	0.072	0.054	0.069	46.21	4.66	9.92
		Heat + Cool	0.074	0.056	0.071	46.85	4.93	9.50
	XPS	Heat	0.087	0.063	0.083	47.35	4.54	10.42
		Heat + Cool	0.090	0.066	0.086	48.06	4.81	9.99
4	EPS	Heat	0.113	0.089	0.109	53.56	7.21	7.43
		Heat + Cool	0.115	0.090	0.111	53.88	7.36	7.32
	MW	Heat	0.142	0.117	0.137	50.14	7.48	6.70
		Heat + Cool	0.143	0.119	0.139	50.41	7.64	6.60
	PUR	Heat	0.092	0.074	0.089	51.98	7.34	7.08
		Heat + Cool	0.093	0.075	0.090	52.27	7.49	6.98
	XPS	Heat	0.112	0.088	0.108	53.67	7.20	7.46
		Heat + Cool	0.114	0.089	0.110	54.00	7.35	7.35

Table 12. Overall thermal transmittance ($\overline{U}$), in W/m^2·K; heating energy demand (HED), in kWh/m^2·year; cooling energy demand (CED), in kWh/m^2·year; final energy consumption (FEC), 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), in kg CO_2/m^2·year; non-renewable primary energy consumption rating (R_{NRPEC}); and CO_2 emissions rating (R_{EM}) for each climate zone (CZ) by January climate zone (JCZ) and system used for existing buildings.

CZ	JCZ	System	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
D1	W	1	2.15	160.84	4.66	207.09	247.54	245.96	64.45	E	F
		2	2.15	160.84	4.66	191.51	231.58	229.67	48.44	E	E
		3	2.15	160.84	4.66	207.09	233.41	21.96	4.46	A	A
		4*	2.15	160.84	4.66	71.95	170.37	140.58	23.81	E	D
		4	2.15	160.84	4.66	71.17	168.53	139.07	23.56	E	D
	X	1	1.85	138.32	4.01	180.50	215.72	214.36	56.17	E	E
		2	1.85	138.32	4.01	166.91	201.81	200.16	42.22	E	E
		3	1.85	138.32	4.01	180.50	203.40	19.09	3.88	A	A
		4*	1.85	138.32	4.01	62.69	148.45	122.50	20.75	D	D
		4	1.85	138.32	4.01	62.02	146.87	121.19	20.53	D	D
	Y	1	1.45	107.94	3.13	144.35	172.47	171.40	44.92	E	E
		2	1.45	107.94	3.13	133.48	161.35	160.04	33.76	E	E
		3	1.45	107.94	3.13	144.35	162.62	15.19	3.09	A	A
		4*	1.45	107.94	3.13	50.11	118.66	97.91	16.59	D	C
		4	1.45	107.94	3.13	49.59	117.43	96.90	16.41	D	C
D2	X	1	1.85	131.55	9.99	175.14	212.94	210.36	54.57	E	E
		2	1.85	131.55	9.99	162.19	199.68	196.82	41.27	E	E
		3	1.85	131.55	9.99	175.14	201.20	24.22	4.72	A	A
		4*	1.85	131.55	9.99	62.84	148.81	122.80	20.80	D	D
		4	1.85	131.55	9.99	61.18	144.87	119.54	20.25	D	D
	Y	1	1.45	102.66	7.80	140.23	170.38	168.36	43.69	E	E
		2	1.45	102.66	7.80	129.86	159.76	157.51	33.03	E	E
		3	1.45	102.66	7.80	140.23	160.97	19.21	3.74	A	A
		4*	1.45	102.66	7.80	50.25	119.00	98.19	16.63	D	C
		4	1.45	102.66	7.80	48.95	115.92	95.65	16.20	D	C
	Z	1	1.40	99.61	7.57	136.80	166.18	164.22	42.62	E	E
		2	1.40	99.61	7.57	126.68	155.82	153.64	32.22	E	E
		3	1.40	99.61	7.57	136.80	157.00	18.70	3.65	A	A
		4*	1.40	99.61	7.57	49.01	116.05	95.76	16.22	D	C
		4	1.40	99.61	7.57	47.75	113.06	93.30	15.80	D	C

Table 12. *Cont.*

CZ	JCZ	System	$\bar{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
D3	X	1	1.85	126.30	19.34	173.44	216.47	211.97	54.13	E	E
		2	1.85	126.30	19.34	160.97	203.71	198.95	41.33	E	E
		3	1.85	126.30	19.34	173.44	205.17	32.81	6.15	A	A
		4*	1.85	126.30	19.34	65.35	154.75	127.69	21.63	D	D
		4	1.85	126.30	19.34	62.13	147.12	121.40	20.56	D	C
	Y	1	1.45	98.56	15.09	138.83	173.04	169.52	43.33	E	E
		2	1.45	98.56	15.09	128.84	162.81	159.08	33.06	E	E
		3	1.45	98.56	15.09	138.83	163.98	25.90	4.86	A	A
		4*	1.45	98.56	15.09	52.18	123.57	101.96	17.27	D	C
		4	1.45	98.56	15.09	49.67	117.61	97.05	16.44	D	C
	Z	1	1.40	95.64	14.64	135.25	168.55	165.13	42.21	E	E
		2	1.40	95.64	14.64	125.51	158.58	154.96	32.21	E	D
		3	1.40	95.64	14.64	135.25	159.72	25.18	4.73	A	A
		4*	1.40	95.64	14.64	50.82	120.33	99.30	16.82	D	C
		4	1.40	95.64	14.64	48.38	114.55	94.53	16.01	D	C
E1	Z	1	1.40	123.70	2.82	163.06	194.42	193.35	50.74	E	E
		2	1.40	123.70	2.82	150.76	181.82	180.49	38.10	E	E
		3	1.40	123.70	2.82	163.06	183.26	16.50	3.38	A	A
		4*	1.40	123.70	2.82	56.37	133.49	110.15	18.66	D	C
		4	1.40	123.70	2.82	55.90	132.38	109.23	18.50	D	C

* Heating only mode using the corresponding seasonal coefficient of performance and a default seasonal energy efficiency ratio of 2.00 for the energy simulations of the buildings [33].

Table 13. Overall thermal transmittance ($\overline{U}$), in $W/m^2 \cdot K$; heating energy demand (HED), in $kWh/m^2 \cdot year$; cooling energy demand (CED), in $kWh/m^2 \cdot year$; final energy consumption (FEC), 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), in kg $CO_2/m^2 \cdot year$; non-renewable primary energy consumption rating (R_{NRPEC}); and CO_2 emissions rating (R_{EM}) for climate zone D1 by January climate zone, system used, insulation type and optimization criterion for renovated buildings.

			January Climate Zone W									January Climate Zone X									January Climate Zone Y								
System	Insulation Material	Optimization Criterion	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
1	EPS	Heat	0.42	31.25	0.91	53.37	63.62	63.28	16.61	C	C	0.42	31.25	0.91	53.64	63.94	63.60	16.69	C	C	0.42	31.25	0.91	53.68	63.99	63.64	16.70	C	C
		Heat + Cool	0.41	30.89	0.89	52.94	63.10	62.76	16.47	C	C	0.41	30.89	0.89	53.21	63.42	63.08	16.56	C	C	0.41	30.89	0.89	53.25	63.47	63.13	16.57	C	C
	MW	Heat	0.38	28.19	0.82	49.72	59.26	58.94	15.47	C	C	0.38	28.19	0.82	50.00	59.58	59.26	15.56	C	C	0.38	28.19	0.82	50.04	59.63	59.31	15.57	C	C
		Heat + Cool	0.37	27.89	0.81	49.36	58.83	58.51	15.36	C	C	0.37	27.89	0.81	49.63	59.15	58.83	15.44	C	C	0.37	27.89	0.81	49.68	59.20	58.88	15.46	C	C
	PUR	Heat	0.40	29.79	0.86	51.62	61.53	61.20	16.06	C	C	0.40	29.79	0.86	51.89	61.85	61.52	16.15	C	C	0.40	29.79	0.86	51.94	61.90	61.57	16.16	C	C
		Heat + Cool	0.39	29.45	0.85	51.22	61.05	60.72	15.94	C	C	0.39	29.45	0.85	51.50	61.37	61.04	16.02	C	C	0.39	29.45	0.85	51.54	61.42	61.09	16.04	C	C
	XPS	Heat	0.42	31.36	0.91	53.50	63.78	63.43	16.65	C	C	0.42	31.36	0.91	53.77	64.10	63.75	16.73	C	C	0.42	31.36	0.91	53.81	64.15	63.80	16.75	C	C
		Heat + Cool	0.42	31.00	0.90	53.06	63.25	62.91	16.51	C	C	0.42	31.00	0.90	53.34	63.57	63.23	16.60	C	C	0.42	31.00	0.90	53.38	63.62	63.28	16.61	C	C
2	EPS	Heat	0.42	31.27	0.91	49.37	59.52	59.09	12.48	C	B	0.42	31.27	0.91	49.62	59.82	59.39	12.54	C	B	0.42	31.27	0.91	49.66	59.87	59.44	12.55	C	B
		Heat + Cool	0.41	30.91	0.90	48.96	59.04	58.61	12.37	C	B	0.41	30.91	0.90	49.21	59.34	58.91	12.44	C	B	0.41	30.91	0.90	49.25	59.38	58.95	12.45	C	B
	MW	Heat	0.38	28.21	0.82	45.99	55.44	55.04	11.62	B	B	0.38	28.21	0.82	46.24	55.74	55.34	11.68	B	B	0.38	28.21	0.82	46.28	55.78	55.38	11.69	B	B
		Heat + Cool	0.37	27.90	0.81	45.65	55.03	54.64	11.54	B	B	0.37	27.90	0.81	45.91	55.33	54.94	11.60	B	B	0.37	27.90	0.81	45.94	55.38	54.98	11.61	B	B
	PUR	Heat	0.40	29.80	0.86	47.75	57.57	57.15	12.07	B	B	0.40	29.80	0.86	48.00	57.87	57.45	12.13	B	B	0.40	29.80	0.86	48.04	57.91	57.49	12.14	B	B
		Heat + Cool	0.39	29.47	0.85	47.38	57.12	56.71	11.97	B	B	0.39	29.47	0.85	47.63	57.42	57.00	12.04	B	B	0.39	29.47	0.85	47.67	57.46	57.05	12.05	B	B
	XPS	Heat	0.42	31.38	0.91	49.49	59.67	59.24	12.51	C	B	0.42	31.38	0.91	49.74	59.97	59.54	12.57	C	B	0.42	31.38	0.91	49.78	60.02	59.58	12.58	C	B
		Heat + Cool	0.42	31.01	0.90	49.08	59.18	58.75	12.40	C	B	0.42	31.01	0.90	49.33	59.48	59.05	12.47	C	B	0.42	31.01	0.90	49.37	59.52	59.09	12.48	C	B
3	EPS	Heat	0.48	35.61	1.03	58.55	65.82	5.94	1.22	A	A	0.48	35.61	1.03	58.83	66.12	5.96	1.22	A	A	0.48	35.61	1.03	58.87	66.17	5.97	1.22	A	A
		Heat + Cool	0.47	34.92	1.01	57.73	64.89	5.85	1.20	A	A	0.47	34.92	1.01	58.01	65.19	5.88	1.20	A	A	0.47	34.92	1.01	58.05	65.24	5.88	1.20	A	A
	MW	Heat	0.43	31.80	0.92	54.02	60.71	5.45	1.12	A	A	0.43	31.80	0.92	54.29	61.01	5.48	1.12	A	A	0.43	31.80	0.92	54.34	61.05	5.48	1.12	A	A
		Heat + Cool	0.42	31.23	0.90	53.34	59.94	5.38	1.10	A	A	0.42	31.23	0.90	53.61	60.24	5.40	1.11	A	A	0.42	31.23	0.90	53.66	60.29	5.41	1.11	A	A
	PUR	Heat	0.45	33.78	0.98	56.38	63.37	5.71	1.17	A	A	0.45	33.78	0.98	56.65	63.67	5.73	1.17	A	A	0.45	33.78	0.98	56.70	63.72	5.73	1.17	A	A
		Heat + Cool	0.44	33.15	0.96	55.63	62.52	5.63	1.15	A	A	0.44	33.15	0.96	55.90	62.82	5.65	1.16	A	A	0.44	33.15	0.96	55.94	62.87	5.65	1.16	A	A
	XPS	Heat	0.48	35.74	1.04	58.72	66.00	5.96	1.22	A	A	0.48	35.74	1.04	58.99	66.30	5.98	1.22	A	A	0.48	35.74	1.04	59.03	66.35	5.98	1.22	A	A
		Heat + Cool	0.47	35.05	1.02	57.89	65.07	5.87	1.20	A	A	0.47	35.05	1.02	58.16	65.37	5.89	1.21	A	A	0.47	35.05	1.02	58.20	65.42	5.90	1.21	A	A
4	EPS	Heat	0.42	31.49	0.91	18.54	43.91	36.24	6.14	A	A	0.42	31.49	0.91	18.64	44.13	36.42	6.17	A	A	0.42	31.49	0.91	18.65	44.17	36.44	6.17	A	A
		Heat + Cool	0.42	31.28	0.91	18.30	43.34	35.77	6.06	A	A	0.42	31.28	0.91	18.40	43.56	35.95	6.09	A	A	0.42	31.28	0.91	18.41	43.60	35.97	6.09	A	A
	MW	Heat	0.38	28.39	0.82	17.26	40.87	33.72	5.71	A	A	0.38	28.39	0.82	17.35	41.09	33.90	5.74	A	A	0.38	28.39	0.82	17.36	41.12	33.93	5.75	A	A
		Heat + Cool	0.38	28.21	0.82	17.05	40.37	33.31	5.64	A	A	0.38	28.21	0.82	17.14	40.59	33.49	5.67	A	A	0.38	28.21	0.82	17.15	40.62	33.52	5.68	A	A
	PUR	Heat	0.40	30.01	0.87	17.93	42.45	35.03	5.93	A	A	0.40	30.01	0.87	18.02	42.67	35.21	5.96	A	A	0.40	30.01	0.87	18.03	42.71	35.24	5.97	A	A
		Heat + Cool	0.40	29.81	0.86	17.70	41.92	34.59	5.86	A	A	0.40	29.81	0.86	17.79	42.14	34.77	5.89	A	A	0.40	29.81	0.86	17.81	42.17	34.80	5.89	A	A
	XPS	Heat	0.42	31.60	0.92	18.59	44.02	36.33	6.15	A	A	0.42	31.60	0.92	18.68	44.24	36.51	6.18	A	A	0.42	31.60	0.92	18.70	44.27	36.53	6.19	A	A
		Heat + Cool	0.42	31.39	0.91	18.35	43.45	35.85	6.07	A	A	0.42	31.39	0.91	18.44	43.67	36.03	6.10	A	A	0.42	31.39	0.91	18.46	43.70	36.06	6.11	A	A

Table 14. Overall thermal transmittance ($\overline{U}$), in $W/m^2{\cdot}K$; heating energy demand (HED), in $kWh/m^2{\cdot}year$; cooling energy demand (CED), in $kWh/m^2{\cdot}year$; final energy consumption (FEC), 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), in kg $CO_2/m^2{\cdot}year$; non-renewable primary energy consumption rating (R_{NRPEC}); and CO_2 emissions rating (R_{EM}) for climate zone D2 by January climate zone, system used, insulation type and optimization criterion for renovated buildings.

			January Climate Zone X									January Climate Zone Y									January Climate Zone Z								
System	Insulation Material	Optimization Criterion	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
1	EPS	Heat	0.42	30.16	2.29	51.05	61.70	61.08	15.90	C	C	0.42	30.16	2.29	51.30	61.99	61.37	15.98	C	C	0.42	30.16	2.29	50.72	61.31	60.69	15.80	C	C
		Heat + Cool	0.41	29.27	2.22	49.97	60.38	59.77	15.56	C	C	0.41	29.27	2.22	50.21	60.67	60.06	15.64	C	C	0.41	29.27	2.22	49.64	59.99	59.39	15.46	C	C
	MW	Heat	0.38	27.17	2.06	47.42	57.28	56.71	14.77	B	C	0.38	27.17	2.06	47.67	57.57	57.00	14.85	B	C	0.38	27.17	2.06	47.10	56.89	56.32	14.67	B	C
		Heat + Cool	0.37	26.43	2.01	46.53	56.18	55.63	14.49	B	C	0.37	26.43	2.01	46.77	56.47	55.92	14.57	B	C	0.37	26.43	2.01	46.20	55.80	55.25	14.39	B	C
	PUR	Heat	0.40	28.73	2.18	49.31	59.58	58.98	15.36	C	C	0.40	28.73	2.18	49.56	59.87	59.27	15.43	C	C	0.40	28.73	2.18	48.98	59.19	58.60	15.26	C	C
		Heat + Cool	0.39	27.91	2.12	48.32	58.37	57.79	15.05	C	C	0.39	27.91	2.12	48.56	58.66	58.08	15.12	C	C	0.39	27.91	2.12	47.99	57.98	57.40	14.95	C	C
	XPS	Heat	0.43	30.26	2.30	51.18	61.86	61.23	15.94	C	C	0.43	30.26	2.30	51.43	62.15	61.52	16.02	C	C	0.43	30.26	2.30	50.85	61.47	60.84	15.84	C	C
		Heat + Cool	0.41	29.37	2.23	50.09	60.53	59.92	15.60	C	C	0.41	29.37	2.23	50.34	60.82	60.21	15.68	C	C	0.41	29.37	2.23	49.76	60.14	59.54	15.50	C	C
2	EPS	Heat	0.42	30.18	2.29	47.27	57.84	57.13	12.00	B	B	0.42	30.18	2.29	47.50	58.11	57.40	12.06	C	B	0.42	30.18	2.29	46.97	57.48	56.77	11.93	B	B
		Heat + Cool	0.41	29.28	2.22	46.27	56.60	55.91	11.75	B	B	0.41	29.28	2.22	46.50	56.87	56.18	11.81	B	B	0.41	29.28	2.22	45.97	56.23	55.55	11.67	B	B
	MW	Heat	0.38	27.19	2.07	43.91	53.69	53.04	11.15	B	B	0.38	27.19	2.07	44.14	53.96	53.31	11.20	B	B	0.38	27.19	2.07	43.61	53.32	52.68	11.07	B	B
		Heat + Cool	0.37	26.45	2.01	43.08	52.66	52.03	10.93	B	B	0.37	26.45	2.01	43.30	52.93	52.30	10.99	B	B	0.37	26.45	2.01	42.77	52.29	51.67	10.86	B	B
	PUR	Heat	0.40	28.74	2.18	45.66	55.85	55.17	11.59	B	B	0.40	28.74	2.18	45.89	56.12	55.44	11.65	B	B	0.40	28.74	2.18	45.36	55.49	54.81	11.52	B	B
		Heat + Cool	0.39	27.92	2.12	44.74	54.71	54.05	11.36	B	B	0.39	27.92	2.12	44.97	54.98	54.32	11.42	B	B	0.39	27.92	2.12	44.44	54.35	53.69	11.28	B	B
	XPS	Heat	0.43	30.28	2.30	47.39	57.99	57.28	12.03	C	B	0.43	30.28	2.30	47.62	58.26	57.55	12.09	C	B	0.43	30.28	2.30	47.09	57.62	56.92	11.96	B	B
		Heat + Cool	0.41	29.39	2.23	46.38	56.74	56.05	11.78	C	B	0.41	29.39	2.23	46.61	57.01	56.32	11.83	B	B	0.41	29.39	2.23	46.08	56.38	55.69	11.70	B	B
3	EPS	Heat	0.48	34.40	2.61	56.20	64.20	7.22	1.42	A	A	0.48	34.40	2.61	56.45	64.47	7.24	1.43	A	A	0.48	34.40	2.61	55.88	63.83	7.19	1.41	A	A
		Heat + Cool	0.46	32.76	2.49	54.21	61.90	6.93	1.37	A	A	0.46	32.76	2.49	54.46	62.17	6.95	1.37	A	A	0.46	32.76	2.49	53.88	61.53	6.91	1.36	A	A
	MW	Heat	0.43	30.69	2.33	51.70	59.00	6.57	1.30	A	A	0.43	30.69	2.33	51.94	59.28	6.59	1.30	A	A	0.43	30.69	2.33	51.37	58.64	6.54	1.29	A	A
		Heat + Cool	0.41	29.33	2.23	50.05	57.10	6.34	1.25	A	A	0.41	29.33	2.23	50.29	57.37	6.36	1.25	A	A	0.41	29.33	2.23	49.72	56.73	6.31	1.24	A	A
	PUR	Heat	0.46	32.62	2.48	54.04	61.71	6.91	1.36	A	A	0.46	32.62	2.48	54.29	61.98	6.93	1.37	A	A	0.46	32.62	2.48	53.72	61.34	6.88	1.35	A	A
		Heat + Cool	0.44	31.12	2.36	52.21	59.60	6.65	1.31	A	A	0.44	31.12	2.36	52.46	59.87	6.67	1.31	A	A	0.44	31.12	2.36	51.89	59.23	6.62	1.30	A	A
	XPS	Heat	0.49	34.53	2.62	56.37	64.38	7.24	1.43	A	A	0.49	34.53	2.62	56.61	64.65	7.26	1.43	A	A	0.49	34.53	2.62	56.04	64.02	7.21	1.42	A	A
		Heat + Cool	0.46	32.88	2.50	54.36	62.07	6.95	1.37	A	A	0.46	32.88	2.50	54.61	62.34	6.98	1.37	A	A	0.46	32.88	2.50	54.03	61.70	6.93	1.36	A	A
4	EPS	Heat	0.43	30.39	2.31	18.22	43.13	35.59	6.03	B	A	0.43	30.39	2.31	18.30	43.33	35.76	6.06	B	A	0.43	30.39	2.31	18.10	42.87	35.38	5.99	B	A
		Heat + Cool	0.42	29.86	2.27	17.60	41.68	34.40	5.83	A	A	0.42	29.86	2.27	17.69	41.88	34.56	5.85	A	A	0.42	29.86	2.27	17.49	41.42	34.18	5.79	A	A
	MW	Heat	0.39	27.37	2.08	16.89	40.00	33.00	5.59	A	A	0.39	27.37	2.08	16.97	40.19	33.17	5.62	A	A	0.39	27.37	2.08	16.78	39.73	32.79	5.55	A	A
		Heat + Cool	0.38	26.92	2.04	16.35	38.73	31.96	5.41	A	A	0.38	26.92	2.04	16.44	38.93	32.12	5.44	A	A	0.38	26.92	2.04	16.24	38.46	31.74	5.38	A	A
	PUR	Heat	0.41	28.94	2.20	17.58	41.63	34.35	5.82	A	A	0.41	28.94	2.20	17.66	41.83	34.52	5.85	A	A	0.41	28.94	2.20	17.47	41.37	34.13	5.78	A	A
		Heat + Cool	0.40	28.45	2.16	17.00	40.27	33.23	5.63	A	A	0.40	28.45	2.16	17.09	40.46	33.39	5.66	A	A	0.40	28.45	2.16	16.89	40.00	33.01	5.59	A	A
	XPS	Heat	0.43	30.50	2.32	18.26	43.25	35.69	6.05	B	A	0.43	30.50	2.32	18.35	43.44	35.85	6.07	B	A	0.43	30.50	2.32	18.15	42.98	35.47	6.01	B	A
		Heat + Cool	0.42	29.96	2.28	17.65	41.79	34.48	5.84	A	A	0.42	29.96	2.28	17.73	41.99	34.65	5.87	A	A	0.42	29.96	2.28	17.54	41.52	34.26	5.80	A	A

Table 15. Overall thermal transmittance ($\overline{U}$), in $W/m^2{\cdot}K$; heating energy demand (HED), in $kWh/m^2{\cdot}year$; cooling energy demand (CED), in $kWh/m^2{\cdot}year$; final energy consumption (FEC), 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), in kg $CO_2/m^2{\cdot}year$; non-renewable primary energy consumption rating (R_{NRPEC}); and CO_2 emissions rating (R_{EM}) for climate zone D3 by January climate zone, system used, insulation type and optimization criterion for renovated buildings.

			January Climate Zone X									January Climate Zone Y									January Climate Zone Z								
System	Insulation Material	Optimization Criterion	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
1	EPS	Heat	0.43	29.30	4.49	47.99	59.39	58.32	14.97	B	C	0.43	29.30	4.49	48.66	60.18	59.11	15.18	B	C	0.43	29.30	4.49	45.88	56.89	55.83	14.31	B	C
		Heat + Cool	0.41	27.67	4.24	45.94	56.81	55.81	14.33	B	C	0.41	27.67	4.24	46.61	57.61	56.60	14.54	B	C	0.41	27.67	4.24	43.83	54.32	53.32	13.67	B	C
	MW	Heat	0.39	26.37	4.04	44.32	54.79	53.82	13.83	B	C	0.39	26.37	4.04	44.99	55.58	54.61	14.03	B	C	0.39	26.37	4.04	42.21	52.29	51.34	13.17	B	B
		Heat + Cool	0.37	25.02	3.83	42.62	52.65	51.74	13.29	B	B	0.37	25.02	3.83	43.29	53.44	52.53	13.50	B	B	0.37	25.02	3.83	40.51	50.16	49.25	12.64	B	B
	PUR	Heat	0.41	27.90	4.27	46.23	57.18	56.16	14.42	B	C	0.41	27.90	4.27	46.90	57.97	56.95	14.63	B	C	0.41	27.90	4.27	44.12	54.69	53.68	13.77	B	C
		Heat + Cool	0.39	26.40	4.04	44.35	54.82	53.86	13.83	B	C	0.39	26.40	4.04	45.02	55.61	54.64	14.04	B	C	0.39	26.40	4.04	42.24	52.33	51.37	13.18	B	B
	XPS	Heat	0.43	29.41	4.50	48.12	59.55	58.48	15.01	B	C	0.43	29.41	4.50	48.79	60.34	59.27	15.22	B	C	0.43	29.41	4.50	46.01	57.06	55.99	14.35	B	C
		Heat + Cool	0.41	27.76	4.25	46.06	56.96	55.95	14.37	B	C	0.41	27.76	4.25	46.73	57.75	56.74	14.58	B	C	0.41	27.76	4.25	43.95	54.47	53.46	13.71	B	C
2	EPS	Heat	0.43	29.32	4.49	44.53	55.85	54.71	11.40	B	B	0.43	29.32	4.49	45.15	56.59	55.44	11.56	B	B	0.43	29.32	4.49	42.58	53.52	52.39	10.91	B	B
		Heat + Cool	0.41	27.68	4.24	42.62	53.42	52.34	10.91	B	B	0.41	27.68	4.24	43.24	54.16	53.08	11.06	B	B	0.41	27.68	4.24	40.67	51.09	50.02	10.42	B	B
	MW	Heat	0.39	26.39	4.04	41.12	51.51	50.48	10.52	B	B	0.39	26.39	4.04	41.74	52.25	51.22	10.68	B	B	0.39	26.39	4.04	39.18	49.18	48.16	10.03	B	B
		Heat + Cool	0.37	25.03	3.83	39.54	49.50	48.52	10.12	B	B	0.37	25.03	3.83	40.16	50.24	49.25	10.27	B	B	0.37	25.03	3.83	37.59	47.17	46.20	9.62	B	B
	PUR	Heat	0.41	27.92	4.27	42.90	53.77	52.68	10.98	B	B	0.41	27.92	4.27	43.52	54.51	53.42	11.14	B	B	0.41	27.92	4.27	40.95	51.44	50.36	10.49	B	B
		Heat + Cool	0.39	26.41	4.04	41.15	51.54	50.51	10.53	B	B	0.39	26.41	4.04	41.76	52.28	51.24	10.68	B	B	0.39	26.41	4.04	39.20	49.21	48.19	10.04	B	B
	XPS	Heat	0.43	29.42	4.51	44.65	56.00	54.86	11.43	B	B	0.43	29.42	4.51	45.27	56.74	55.60	11.59	B	B	0.43	29.42	4.51	42.71	53.68	52.54	10.94	B	B
		Heat + Cool	0.41	27.77	4.25	42.73	53.56	52.48	10.94	B	B	0.41	27.77	4.25	43.35	54.30	53.21	11.09	B	B	0.41	27.77	4.25	40.78	51.23	50.16	10.45	B	B
3	EPS	Heat	0.49	33.46	5.12	53.20	62.43	9.31	1.76	A	A	0.49	33.46	5.12	53.87	63.17	9.37	1.77	A	A	0.49	33.46	5.12	51.09	60.08	9.13	1.72	A	A
		Heat + Cool	0.45	30.54	4.68	49.55	58.08	8.58	1.62	A	A	0.45	30.54	4.68	50.21	58.82	8.64	1.64	A	A	0.45	30.54	4.68	47.44	55.73	8.40	1.59	A	A
	MW	Heat	0.44	29.82	4.57	48.65	57.01	8.40	1.59	A	A	0.44	29.82	4.57	49.32	57.75	8.46	1.60	A	A	0.44	29.82	4.57	46.54	54.66	8.22	1.55	A	A
		Heat + Cool	0.40	27.40	4.20	45.61	53.40	7.80	1.48	A	A	0.40	27.40	4.20	46.28	54.15	7.86	1.49	A	A	0.40	27.40	4.20	43.50	51.05	7.62	1.44	A	A
	PUR	Heat	0.47	31.72	4.86	51.02	59.83	8.87	1.68	A	A	0.47	31.72	4.86	51.69	60.58	8.93	1.69	A	A	0.47	31.72	4.86	48.91	57.48	8.70	1.64	A	A
		Heat + Cool	0.43	29.04	4.45	47.66	55.84	8.21	1.55	A	A	0.43	29.04	4.45	48.33	56.58	8.26	1.57	A	A	0.43	29.04	4.45	45.55	53.49	8.03	1.52	A	A
	XPS	Heat	0.49	33.59	5.14	53.36	62.62	9.34	1.77	A	A	0.49	33.59	5.14	54.03	63.37	9.40	1.78	A	A	0.49	33.59	5.14	51.26	60.27	9.16	1.73	A	A
		Heat + Cool	0.45	30.65	4.69	49.69	58.25	8.61	1.63	A	A	0.45	30.65	4.69	50.35	58.99	8.67	1.64	A	A	0.45	30.65	4.69	47.58	55.90	8.43	1.59	A	A
4	EPS	Heat	0.43	29.53	4.52	17.91	42.40	34.99	5.93	A	A	0.43	29.53	4.52	18.13	42.94	35.43	6.00	A	A	0.43	29.53	4.52	17.19	40.71	33.59	5.69	A	A
		Heat + Cool	0.42	28.52	4.37	16.70	39.54	32.62	5.53	A	A	0.42	28.52	4.37	16.92	40.08	33.07	5.60	A	A	0.42	28.52	4.37	15.98	37.84	31.22	5.29	A	A
	MW	Heat	0.39	26.57	4.07	16.49	39.06	32.23	5.46	A	A	0.39	26.57	4.07	16.72	39.60	32.67	5.53	A	A	0.39	26.57	4.07	15.78	37.36	30.83	5.22	A	A
		Heat + Cool	0.38	25.72	3.94	15.44	36.55	30.16	5.11	A	A	0.38	25.72	3.94	15.66	37.09	30.61	5.18	A	A	0.38	25.72	3.94	14.72	34.86	28.76	4.87	A	A
	PUR	Heat	0.41	28.11	4.30	17.23	40.80	33.67	5.70	A	A	0.41	28.11	4.30	17.46	41.34	34.11	5.78	A	A	0.41	28.11	4.30	16.51	39.10	32.27	5.47	A	A
		Heat + Cool	0.40	27.18	4.16	16.09	38.11	31.44	5.33	A	A	0.40	27.18	4.16	16.32	38.65	31.89	5.40	A	A	0.40	27.18	4.16	15.38	36.41	30.04	5.09	A	A
	XPS	Heat	0.43	29.64	4.54	17.96	42.52	35.09	5.94	A	A	0.43	29.64	4.54	18.18	43.06	35.53	6.02	A	A	0.43	29.64	4.54	17.24	40.83	33.69	5.71	A	A
		Heat + Cool	0.42	28.62	4.38	16.74	39.64	32.71	5.54	A	A	0.42	28.62	4.38	16.97	40.18	33.16	5.62	A	A	0.42	28.62	4.38	16.02	37.94	31.31	5.30	A	A

Table 16. Overall thermal transmittance ($\overline{U}$), in W/m^2·K; heating energy demand (HED), in kWh/m^2·year; cooling energy demand (CED), in kWh/m^2·year; final energy consumption (FEC), 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), in kg CO_2/m^2·year; non-renewable primary energy consumption rating (R_{NRPEC}); and CO_2 emissions rating (R_{EM}) for climate zone E1 and January climate zone Z by system used, insulation type and optimization criterion for renovated buildings.

System	Insulation Material	Optimization Criterion	$\overline{U}$	HED	CED	FEC	TPEC	NRPEC	EM	R_{NRPEC}	R_{EM}
1	EPS	Heat	0.40	35.22	0.80	56.21	66.92	66.58	17.49	B	C
		Heat + Cool	0.40	34.90	0.80	55.83	66.47	66.14	17.37	B	C
	MW	Heat	0.36	31.89	0.73	52.25	62.20	61.89	16.26	B	C
		Heat + Cool	0.36	31.63	0.72	51.94	61.83	61.52	16.16	B	C
	PUR	Heat	0.38	33.62	0.77	54.31	64.65	64.33	16.90	B	C
		Heat + Cool	0.38	33.33	0.76	53.97	64.24	63.93	16.79	B	C
	XPS	Heat	0.40	35.34	0.81	56.35	67.08	66.75	17.53	B	C
		Heat + Cool	0.40	35.02	0.80	55.97	66.63	66.30	17.42	B	C
2	EPS	Heat	0.40	35.24	0.80	51.99	62.60	62.17	13.13	B	B
		Heat + Cool	0.40	34.93	0.80	51.64	62.18	61.76	13.04	B	B
	MW	Heat	0.36	31.91	0.73	48.33	58.18	57.79	12.21	B	B
		Heat + Cool	0.36	31.65	0.72	48.04	57.83	57.44	12.13	B	B
	PUR	Heat	0.38	33.64	0.77	50.23	60.48	60.07	12.69	B	B
		Heat + Cool	0.38	33.35	0.76	49.91	60.09	59.69	12.61	B	B
	XPS	Heat	0.40	35.36	0.81	52.12	62.75	62.33	13.17	B	B
		Heat + Cool	0.40	35.04	0.80	51.77	62.33	61.91	13.08	B	B
3	EPS	Heat	0.45	39.95	0.91	61.83	69.39	6.11	1.26	A	A
		Heat + Cool	0.45	39.35	0.90	61.12	68.59	6.03	1.24	A	A
	MW	Heat	0.41	35.81	0.82	56.92	63.86	5.60	1.15	A	A
		Heat + Cool	0.40	35.32	0.81	56.33	63.20	5.54	1.14	A	A
	PUR	Heat	0.43	37.97	0.87	59.47	66.74	5.87	1.21	A	A
		Heat + Cool	0.42	37.42	0.85	58.82	66.01	5.80	1.19	A	A
	XPS	Heat	0.45	40.10	0.92	62.00	69.58	6.13	1.26	A	A
		Heat + Cool	0.45	39.50	0.90	61.29	68.78	6.05	1.24	A	A
4	EPS	Heat	0.40	35.48	0.81	19.48	46.14	38.07	6.45	A	A
		Heat + Cool	0.40	35.30	0.81	19.27	45.64	37.66	6.38	A	A
	MW	Heat	0.36	32.11	0.73	18.10	42.85	35.36	5.99	A	A
		Heat + Cool	0.36	31.95	0.73	17.91	42.41	35.00	5.93	A	A
	PUR	Heat	0.38	33.86	0.77	18.82	44.56	36.77	6.23	A	A
		Heat + Cool	0.38	33.69	0.77	18.62	44.09	36.38	6.16	A	A
	XPS	Heat	0.40	35.60	0.81	19.53	46.25	38.17	6.47	A	A
		Heat + Cool	0.40	35.41	0.81	19.32	45.75	37.75	6.40	A	A

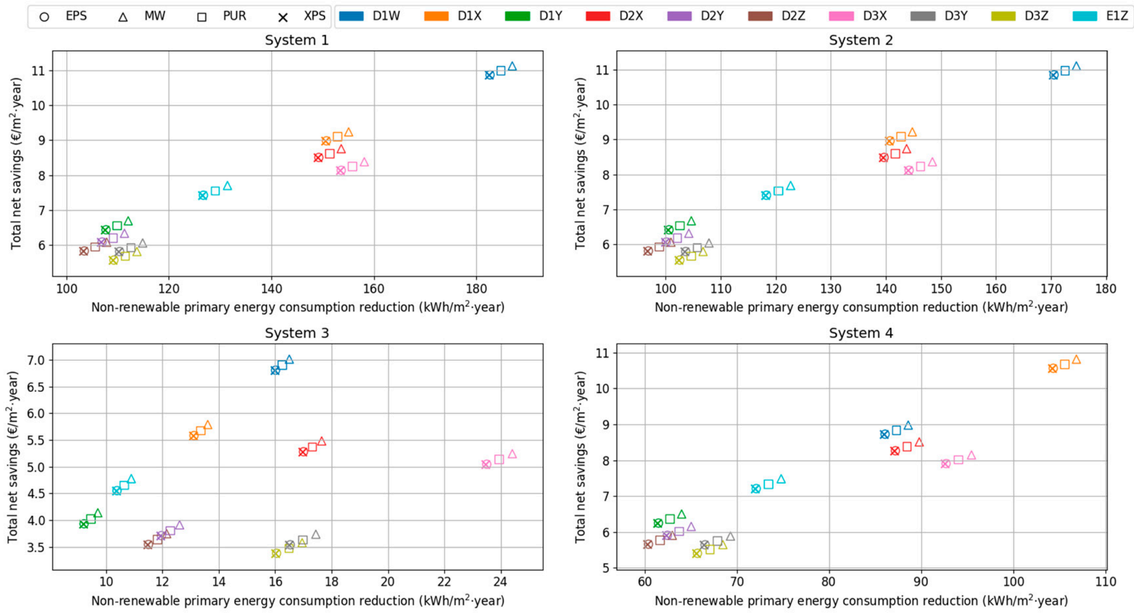

Figure 3. Total net savings, in €/m^2·year, versus non-renewable primary energy consumption reduction, in kWh/m^2·year, for each system used by insulation material and building climate zone (climate zone and January climate zone), with the insulation thickness optimized to minimize the total heating costs.

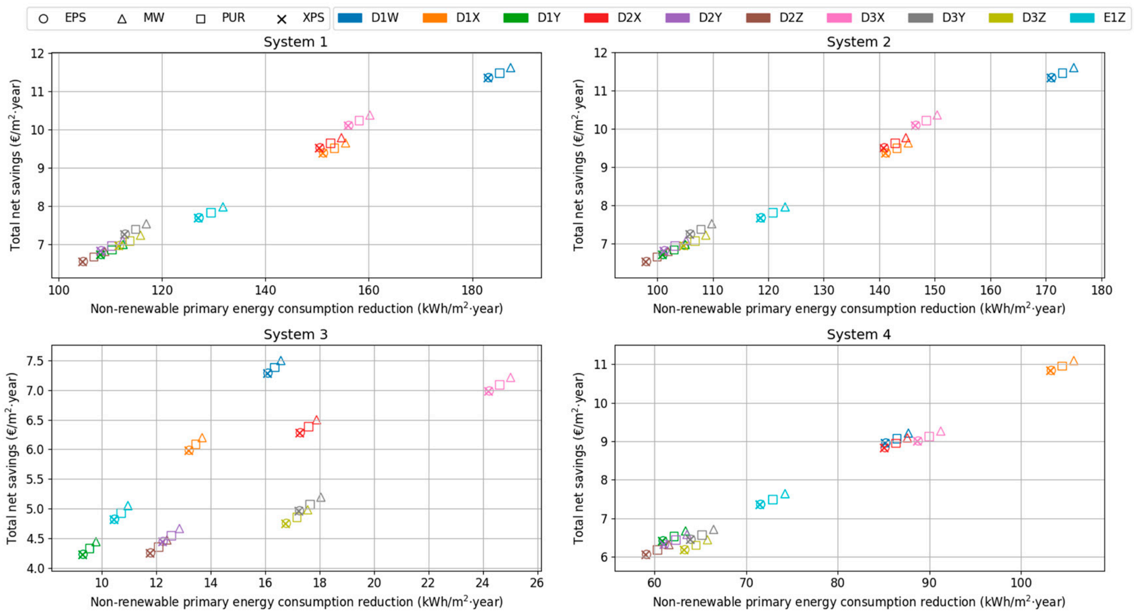

Figure 4. Total net savings, in €/m^2·year, versus non-renewable primary energy consumption reduction, in kWh/m^2·year, for each system used by insulation material and building climate zone (climate zone and January climate zone), with the insulation thickness optimized to minimize the total heating and cooling costs.

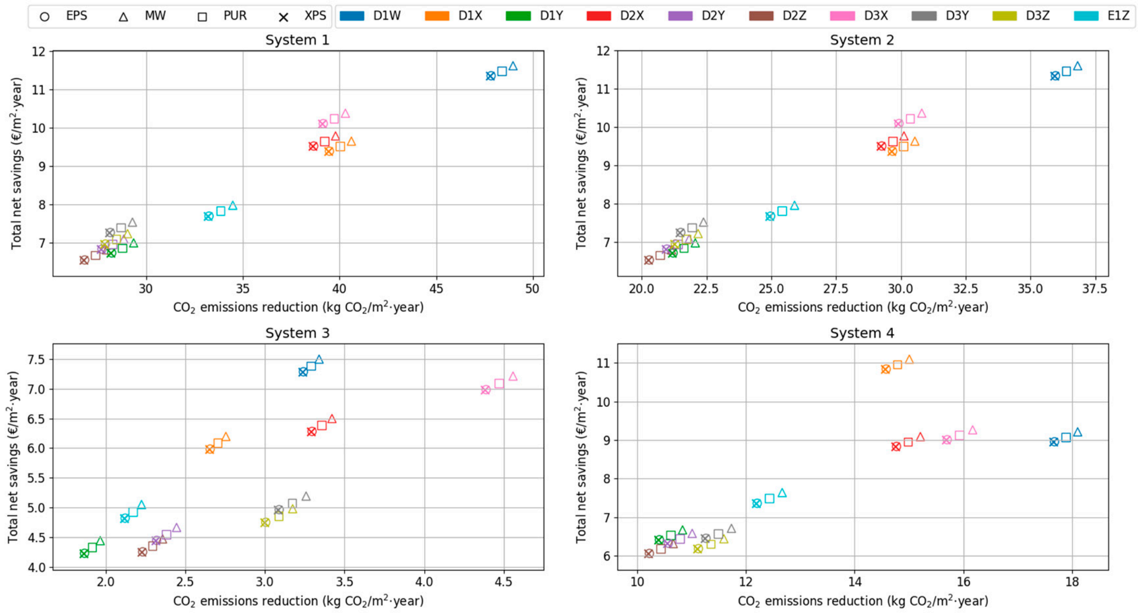

Figure 5. Total net savings, in €/m^2·year, versus CO_2 emissions reduction, in kg CO_2/m^2·year, for each system used by insulation material and building climate zone (climate zone and January climate zone), with the insulation thickness optimized to minimize the total heating costs.

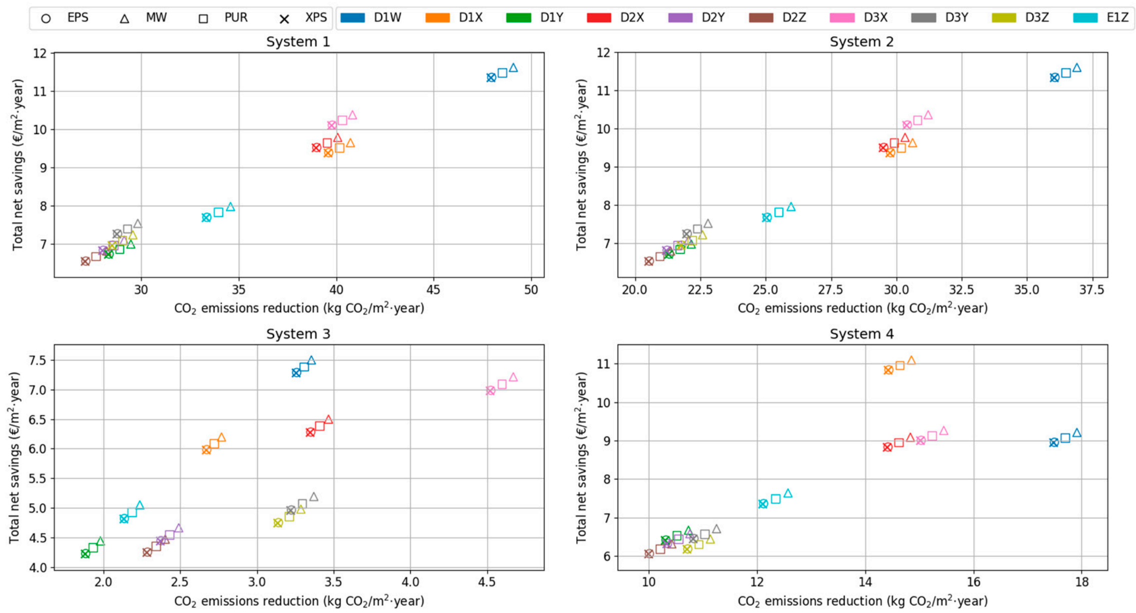

Figure 6. Total net savings, in €/m^2·year, versus CO_2 emissions reduction, in kg CO_2/m^2·year, for each system used by insulation material and building climate zone (climate zone and January climate zone), with the insulation thickness optimized to minimize the total heating and cooling costs.

The average reductions in the overall thermal transmittances of the renovated buildings compared to those of the existing buildings are 80.67% in January climate zone W, 77.47% in January climate zone X, 71.26% in January climate zone Y and 70.67% in January climate zone Z (Tables 12–16). These reductions are achieved by replacing the current openings with new openings in addition to adding, on average, 104 mm of insulation to the walls, roofs and first floor frameworks of the renovated buildings in January climate zone W, 99 mm to those in January climate zone X and 94 mm to those in January climate zones Y and Z (Tables 8–11).

In each of the climate zones and January climate zones, for each system and insulation material, the cost of the energy renovation for the cases in which the insulation thickness is optimized to minimize the total heating costs is less than that of the corresponding cases in which the insulation thickness is optimized to minimize the total heating and cooling costs. The order of the insulation materials from the lowest to the highest cost of energy renovation for each system used is MW, PUR, EPS and XPS; the order of the systems from the lowest to the highest cost of energy renovation for each insulation material used is system 3, system 4, system 2 and system 1. Of all the systems, the system with the lowest cost of energy renovation corresponds to the case in which MW is used as the insulation and the insulation thickness is optimized to minimize the total heating costs. Furthermore, within the same climate zone, the order of the January climate zones from the lowest to the highest cost of energy renovation is Z, Y, X and W; however, within the same January climate zone, the order of the climate zones from the lowest to the highest cost of energy renovation is D3, D2, D1 and E1 with the optimization of the insulation thickness to minimize the total heating costs, and D1, D2, D3 and E1 with the optimization of the insulation thickness to minimize the total heating and cooling costs (Tables 8–11).

In each of the climate zones and January climate zones, for each system and insulation material, the total net savings for the cases in which the insulation thickness is optimized to minimize the total heating and cooling costs is greater than that of the corresponding cases in which the insulation thickness is optimized to the minimize the total heating costs. The order of the insulation materials from the highest to the lowest total net savings for each system used is MW, PUR, EPS and XPS; the order of the systems from the highest to the lowest total net savings for each of the insulation materials used is system 1, system 2, system 4 and system 3. Of all the systems, the system with the highest total net savings corresponds to the case in which MW is used as the insulation and the insulation thickness is optimized to minimize the total heating and cooling costs. Furthermore, within the same climate zone, the order of the January climate zones from the highest to the lowest total net savings is W, X, Y and Z. However, within the same January climate zone, the order of the climate zones from the highest to the lowest total net savings is E1, D1, D2 and D3 when the insulation thickness is optimized to minimize the total heating costs and is E1, D3, D2 and D1 when the insulation thickness is optimized to minimize the total heating and cooling costs (Tables 8–11).

In each of the climate zones and January climate zones, for each system and insulation material, the payback period for the cases in which the insulation thickness is optimized to minimize the total heating and cooling costs is shorter than that of the corresponding cases in which the insulation thickness is optimized to minimize the total heating costs. The order of the insulation materials from the shortest to the longest payback period for each system used is MW, PUR, EPS and XPS; the order of the systems from the shortest to the longest payback period for each insulation material used is system 1, system 2, system 4 and system 3. Of all the systems, the system with the shortest payback period corresponds to the case with MW as the insulation and the insulation thickness optimized to minimize the total heating and cooling costs. Furthermore, within the same climate zone, the order of the January climate zones from the shortest to the longest payback period is W, X, Y and Z; however, within the same January climate zone, the order of the climate zones from the shortest to the longest payback period is E1, D1, D2 and D3 with the optimization of the insulation thickness to minimize the total heating costs and E1, D3, D2 and D1 with the optimization of the insulation thickness to minimize the total heating and cooling costs (Tables 8–11).

The highest total net savings is accompanied by both the greatest reduction in non-renewable primary energy consumption and the greatest reduction in CO_2 emissions in the renovated buildings that use systems 1 and 2 in climate zone D1 and January climate zone W. The greatest total net savings occurs in the renovated buildings that use system 3 in climate zone D1 and January climate zone W, while both the greatest reduction in the non-renewable primary energy consumption and the greatest reduction in the CO_2 emissions occur in those located in climate zone D3 and January climate zone X. Finally, in the renovated buildings that use system 4, the highest total net savings occurs in those located in climate zone D1 and January climate zone X, the greatest reduction in the non-renewable primary energy consumption occurs in those located in climate zone D1 and January climate zone X, and the greatest reduction in CO_2 emissions occurs in those located in climate zone D1 and January climate zone W (Tables 12–16 and Figures 3–6).

Notably, considering the energy demand for heating, the energy demand for cooling and the non-renewable primary energy consumption (Tables 13–16), the renovated buildings that become nearly zero-energy buildings according to the current CTE-DB-HE [31] are as follows:

- Those located in climate zone D1 that use system 1 or 2 and MW insulation and in which the insulation thickness is optimized to minimize the total heating and cooling costs.
- Those located in climate zone D2 that use system 1, 2 or 4 and MW insulation.
- Those located in climate zone D3 that use MW insulation and in which the insulation thickness is optimized to minimize the total heating and cooling costs; those that use system 1, 2 or 4 and PUR insulation and in which the insulation thickness is optimized to minimize the total heating and cooling costs, or that use MW insulation and in which the insulation thickness is optimized to minimize the total heating costs; those that use system 1 or 2 and EPS insulation and in which the insulation thickness is optimized to minimize the total heating and cooling costs, or that use XPS insulation and in which the insulation thickness is optimized to minimize the total heating and cooling costs; and those that use system 1 and PUR insulation and in which the insulation thickness is optimized to minimize the total heating costs.
- Those located in climate zone E1.

In future studies, the methodology developed will be used to evaluate the optimum thermal envelope insulation thicknesses in other cold Mediterranean climate zones and will be improved to (i) customize the optimal energy renovation solution for each city selected; (ii) evaluate the optimized thermal envelope insulation thicknesses to obtain the maximum possible energy performance rating; and (iii) adapt the thermal envelope insulation thickness to hot and temperate Mediterranean climate zones where air conditioning is of great importance.

4. Conclusions

This study assessed the energy, environmental and economic impacts of the energy renovation of the thermal envelope of the existing residential buildings in the 26 provincial capitals in the cold climate zones of Spain. The insulation thickness to be added to the walls, roof and first floor framework was optimized by a life cycle cost analysis, and the replacement of the building openings was assessed. The optimization of the insulation thickness was carried out to minimize both the total heating costs and the total heating and cooling costs using four insulation materials for four different heating and cooling systems.

On average, the overall thermal transmittance in the renovated buildings was reduced by between 70.67% and 80.67% compared to that of the existing buildings. These reductions were achieved by adding, on average, between 94 mm and 104 mm of insulation to the walls, roofs and first floor frameworks of the renovated buildings, in addition to replacing the building openings with new openings.

In each of the climate zones and January climate zones, although the case with the lowest energy renovation cost was that in which system 3 and MW insulation were used and the insulation thickness was optimized to minimize the total heating costs, the case with the highest total net savings and the shortest payback period was that in which system 1 and MW insulation were used and the insulation thickness was optimized to minimize the total heating and cooling costs.

The greatest reductions in non-renewable primary energy consumption occurred in the renovated buildings that used system 1 or 2 in climate zone D1 and January climate zone W, in those that used system 3 in climate zone D3 and January climate zone X, and in those that used system 4 in climate zone D1 and January climate zone X. Additionally, the greatest reductions in CO_2 emissions occurred in the renovated buildings that used system 1, 2 or 4 in climate zone D1 and January climate zone W and in those that used system 3 in climate zone D3 and January climate zone X.

The results obtained in this study will serve as a starting point for proposals of energy renovation solutions for existing residential buildings in order to achieve nearly zero-energy buildings in the cold climate zones of Spain; however, in the future, it would be interesting to evaluate the possibilities for customizing the method developed for each selected city, as well as the optimized thermal envelope insulation thicknesses to obtain the highest energy performance rating possible. Finally, the methodology developed in this study, in addition to being used in other cold Mediterranean climate zones, could be adapted to hot and temperate Mediterranean climate zones where air conditioning is of great importance.

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