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Integration of Energy Simulations and Life Cycle Assessment in Building Refurbishment: An Affordability Comparison of Thermal Insulation Materials through a New Sustainability Index

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Abstract: Energy efficiency and greenhouse gas reduction have become two of the most important issues to address in fighting climate change. Focused strategies have been implemented aiming at reducing the energy consumption of buildings since it is one of the most energy-intensive sectors, but they are mainly concerned with energy reduction without considering their environmental impact. The present work therefore aims at assessing the energy and environmental impacts of the use of insulation materials for building envelope refurbishment as the thermal coating. Reference buildings were used to perform energy simulations in representative cities of Italy and energy and environmental impacts of the most common and sustainable insulation materials were thus evaluated. Relevant outcomes have been focused on defining a new Economic and Environmental Sustainability Index (EESI) capable of considering both economic and environmental aspects; particularly, sustainable materials (such as cellulose fiber) can have the same affordability as traditional ones (such as polystyrene foam slab, glass wool, or stone wool) if environmental impact is also taken into account, despite their higher cost. However, according to EESI, the affordability of traditional insulation materials remains evident in the warmest climatic zones because of the lower energy needs of buildings.

Keywords: energy and environmental impact; insulation materials; sustainable materials; energy simulations; economic payback time; carbon payback time; reference buildings; life cycle assessment; Economic and Environmental Sustainability Index

Citation: Scrucca, F.; Palladino, D. Integration of Energy Simulations and Life Cycle Assessment in Building Refurbishment: An Affordability Comparison of Thermal Insulation Materials through a New Sustainability Index. *Sustainability* **2023**, *15*, 1412. https://doi.org/10.3390/su15021412

Academic Editor: Chi-Ming Lai

Received: 1 December 2022
Revised: 4 January 2023
Accepted: 7 January 2023
Published: 11 January 2023

1. Introduction

Energy demand and, consequently, greenhouse gas (GHG) emissions, are significantly increasing worldwide, posing the global challenge of properly addressing climate change in the framework of a sustainability transition. Energy-focused strategies aimed at reducing the use of fossil fuels and increasing energy efficiency, giving priority to actions in the most energy-intensive and environmentally impacting sectors, are crucial in this context. Particularly, carbon neutrality is the new international and European goal to be reached by 2050, representing a very ambitious target since it requires manifold strategies in all sectors [1].

The building sector is one of the most relevant, since buildings account for 36% of total energy consumption and around 37% of energy-related CO_2 emissions [2,3]; therefore, it plays a strategic role in decarbonization and in pursuing climate change mitigation targets.

Unlocking the energy and carbon savings potential of the building sector is closely linked with boosting the performance of new and existing buildings through a series of energy efficiency strategies. Since the biggest environmental impact is associated with the buildings' operational phase due to energy consumption for air conditioning (heating and cooling), efficient and sustainable technologies (such as, for instance, ground-source heat pumps [4]) represent promising solutions in this regard, but thermal insulation is certainly the widely recognized main strategy to reduce the overall energy demand. The strong correlation between the energy consumption of a building and its envelope characteristics is well known [5], as well as the contribution of insulated buildings in reducing air pollution and impacts on the environment [6].

Accordingly, manifold energy strategies were put in place in Europe to improve energy efficiency and to achieve important energy savings, increasing the total investment in the building sector by more than 10% in 2020 alone [3]. The importance of reaching energy efficiency and savings in the building sector was also underlined by the International Energy Agency (IEA), which provided useful recommendations to take into account in the building renovation process [7]. According to the IEA, renovators should consider: zero emissions and energy efficiency targets, use of renewable energy systems, and cost effectiveness. Furthermore, pointing out the importance of focusing on the renovation of buildings that need to be renovated "anyway", i.e., buildings with poor energy performance, IEA developed a method for cost-effective energy and carbon emissions optimization [8] and a tool to support decision-making [9] in the building renovation process. The developed method aims at defining, assessing, and comparing energy renovation activities, optimizing the energy use and the carbon emissions reduction [10].

As highlighted in [7–10], energy issues related to buildings are particularly felt in Europe as a whole as well as in Italy, where more than 85% of structures were built before the 1990s, and many energy strategies have been developed to improve their quality. Currently, buildings are accountable for more than 30 Mtep of national energy consumption, and thanks to the adopted national strategies, a cumulative energy saving of around 1.3 Mtep has been achieved (considering all the energy strategies implemented from 2014 to 2020) [11].

In this context, the energy calculation method plays a key role in both the evaluation of energy strategies and energy savings and, at the same time, the use of reliable and accurate tools such as life cycle assessment (LCA) is strategic; in fact, integrating LCA with energy saving calculation would allow taking into account not only the operating energy consumption but rather the life cycle impact of insulation materials used for building refurbishment.

On one hand, the current and regulated energy calculation method at the European level consists of a monthly calculation to produce Energy Performance Certificates (EPCs), based on standard boundary conditions and conventional climatic data. This method is widely used at the national level also for checking energy savings and requirements through energy incentives, such as in the Superbonus 110% strategy, where the standard calculation (EPC) is used for checking the energy improvement of at least two classes of all the adopted energy measures [12].

In Italy, the monthly calculation method is mandatory by Interministerial Decree 26 June 2015 [13] and it is detailed by technical standards UNI TS 11300 [14–18]. Moreover, it allows the evaluation of the following energy services for residential buildings: space heating, cooling, hot water production, and ventilation. Although the calculation method does not provide reliable results for cooling, it seems able to return comparable outcomes for space heating [19,20], allowing its use for energy incentive assessments. Many studies have highlighted the low accuracy of the calculation method, particularly when compared to the actual energy consumption of buildings [21], but EPC remains the simplest and most regulated calculation method capable of orienting national energy policy [22] although it can lead to less reliable outcomes and its consistency can be poor [23]. More complex tools can be used, such as dynamic tools that allow assessing more reliable outcomes taking into account the fluctuation of all the variables over time [9], but they are generally time-consuming and require more detailed information.

On the other hand, LCA allows the evaluation of potential environmental impacts of products or services throughout their entire life cycle, providing comprehensive and reliable results describing the whole environmental performance. LCA in buildings is usually performed at the envelope scale to provide in-depth analyses of energy and environmental performances and mainly to compare several sample solutions to identify the ones that perform best and are suitable for sustainable building construction [24].

Focussing on building thermal insulation materials, the market leaders (such as EPS, XPS, stone wool, and glass wool) are the most studied in terms of LCA in the literature [25–27], but natural and renewable materials also attract attention for life cycle evaluations [28–30], with LCA that is generally used to compare different materials as well as to identify environmental hotspots in their life cycle. LCA is therefore considered and used as a powerful tool to support decisions for the choice of more environmentally friendly thermal insulation materials. Its strategic relevance in this regard is related to the possibility of comprehensively assessing resource consumption and environmental impacts of each stage in the life cycle, avoiding the shift from one to another, and covering a wide range of impact categories [31].

According to this background, the integration of energy assessment and environmental analysis of insulation materials can represent an added value in the renovation process of buildings [32]. Against this background, the present paper represents a further investigation of the key research problem addressed by previous studies of the International Energy Agency [7–9] and Almeida and Ferreira [10], by considering three important aspects of the building renovation process: primary energy need, environmental impact of insulation materials, and economic analysis. This study, in fact, aims at evaluating the energy, environmental, and economic impacts of several insulation materials used for the thermal coating of building envelopes by using the standard energy calculation method adopted at the national level, i.e., the monthly calculation method with asset rating (standard evaluation). To achieve this goal, according to the national background, several reference condominiums representative of the national buildings built before the 1990s were defined and used to perform thousands of energy simulations in compliance with the calculation method provided by technical regulations [14–18]. The most representative cities in the country were thus chosen based on previous work carried out by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) [33], and the primary energy need of each reference building in each climatic zone was assessed by adopting the standard monthly calculation method. This method was preferred to dynamic tools since it is the simplest available calculation method, but also the one mandated by national regulations for energy performance assessment of buildings. Furthermore, it is also adopted for checking and assessing the current national energy incentives.

Refurbishment measures of the building envelope were thus considered, using several insulation materials and setting the normative energy requirements for all the selected materials. The costs (and savings) of each refurbishment option, as well as their environmental impacts (and benefits), were then estimated, and simple economic and carbon payback times were calculated. Finally, a new index, namely the Economic and Environmental Sustainability Index (EESI), able to combine energy, economic, and environmental impacts, was defined. Considering the studies of IEA [7–9], the EESI could be considered as a further development based on both the monthly calculation method for primary energy need assessment and LCA analysis.

2. Materials and Methods

2.1. Research Procedure

To achieve the goal of the work, a detailed research procedure (Figure 1) was planned. Firstly, several reference buildings with thermal properties typical of existing buildings were defined as representative of the national building stock; this kind of analysis was based on data provided by the National Institute of Statistics [34] and on a recent study carried out by ENEA [33].

The most commercial insulation materials used for thermal coat application were thus chosen and compared to natural and renewable ones that, on the one hand, are less used for this kind of application because of their greater cost, but on the other, are more sustainable.

Energy simulations were thus performed in each climatic zone in compliance with the EPC calculation method, considering the most representative cities of the country. Two configurations were investigated overall: (1) ante-operam, representing the energy consumption of existing buildings, and (2) post-operam, corresponding to the energy performance of buildings after envelope refurbishment with a thermal coat by adopting the chosen insulation materials. Therefore, the operating CO_2 emissions and costs of reference buildings were estimated. At the same time, the overall costs and the environmental impact in terms of life cycle embodied carbon were investigated for each material. Based on these parameters, economic and environmental paybacks were calculated and combined in a synthetic Economic and Environmental Sustainability Index (EESI).

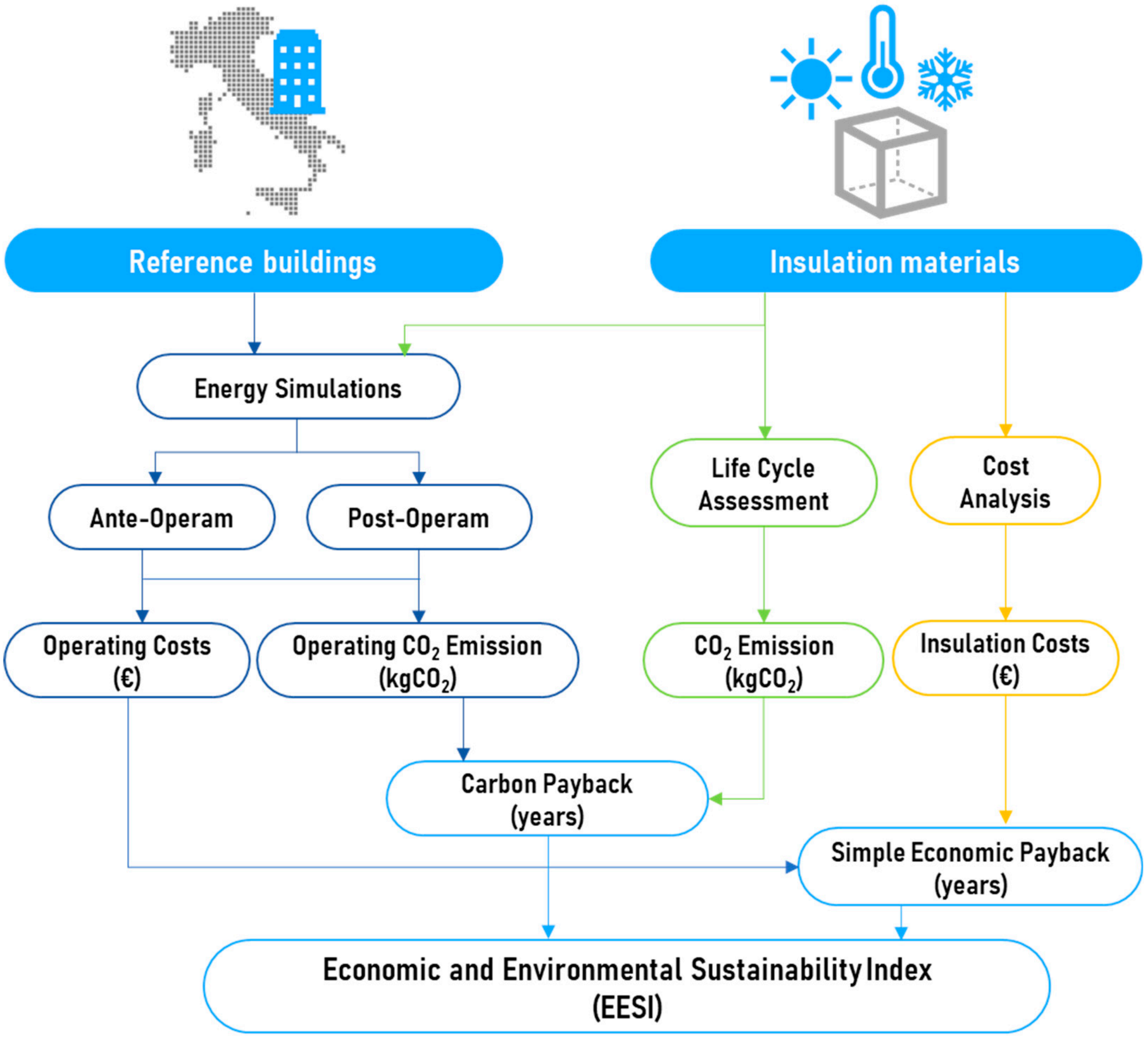


Figure 1. Research procedure adopted in the present work for the Economic and Environmental Sustainability Index (EESI) assessment for different insulation materials.

In the remainder of the paper, after an energy consumption overview of reference buildings with and without thermal coating, the costs and environmental impact analyses of the chosen materials are presented, highlighting the economic and environmental paybacks, and the properly introduced index EESI is discussed.

2.2. Reference Buildings Definition and Energy Simulations

Based on data provided by the National Institute of Statistics [34], it was possible to define the national building stock background and introduce several reference condominiums to be used for the present energy simulations.

In Italy, the number of building units (B.U.) amounts to more than 31 million and around 79% of them are in multi-family house (MFH) building types, i.e., small or large condominiums. More than 87% of B.U. are located in buildings built before 1991, i.e., before the second more important energy regulation at the national level, and around 67% before 1976, i.e., before the first energy regulation on energy containment and requirements of buildings. Therefore, the energy performance of the national building stock is comprehensively poor, and it has required important and focused energy strategies.

Considering the national climatic breakdown provided by Decree of the President of the Republic (D.P.R.) n.412/93 in six climatic zones, it has been possible to highlight (Figure 2) that the great number of B.U. (around 48%) are located in the coldest climatic zones, i.e., E and F zones, about 45% in moderate zones (25% and less than 19% in zone D and C respectively), while less than 9% are located in the warmest climatic zones such as in B (more than 8%) and A. Besides, data from the National Institute of Statistics provided only limited and even less detailed information on building type; as shown in Figure 2, it divides buildings into two, three, and four or more floors, with three (42% of the sample) and four or more floors (45% of the sample) being the most likely configurations.

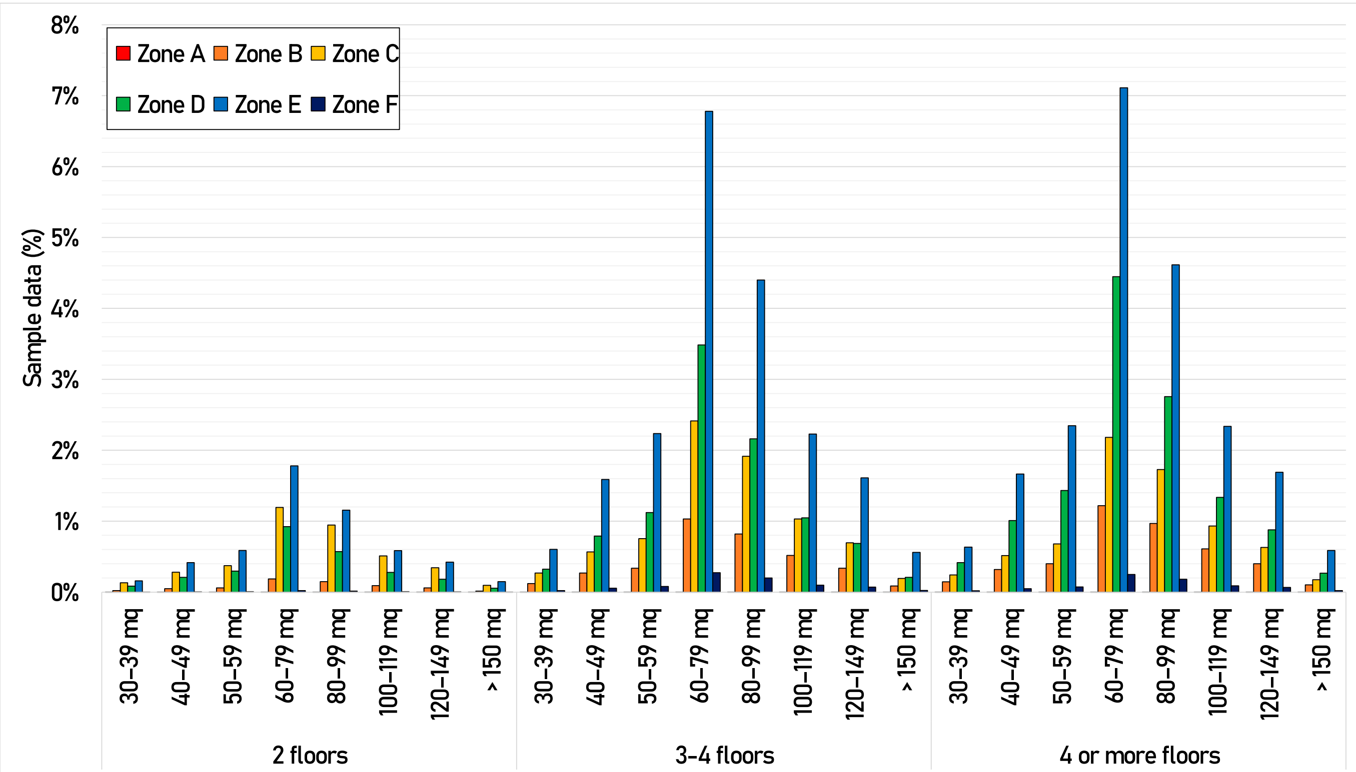


Figure 2. Building unit distribution in each climatic zone for some type of MFH elaborated from sample data of the National Institute of Statistics: distribution based on the height of buildings (from two floors up to four or more floors) and on the net surfaces of units.

The mean representative net surface of building units in MFH is around 85 m^2, calculated as the average value weighted on the distribution of the net surface in ranges provided by [34] and reported in Figure 2. Most of the sample falls in the 60–79 m^2 (around 33%) and in the 80–99 m^2 (around 23%) ranges, while higher (around 130 m^2) or smaller (around 45 m^2) values represent the minority.

No detailed information on heating systems can be taken from data made available by the National Institute of Statistics; however, a recent study carried out by ENEA [33] gave a more detailed picture on existing Heating, Ventilation and Air Conditioning (HVAC) systems, thanks to the integration of several data sources with the Informative System on Energy Performance Certificates (SIAPE in Italian). According to this report, the most representative building heating system is standard (around 58%) or condensing (around 30%) boilers with natural gas as the main energy source (more than 70% of the sample). Other heating systems or energy sources are less common across the country, such as the heat pump, which is the most common solution in new construction (fewer than 2% of building units).

Furthermore, the same study carried out by ENEA [33] has provided a detailed analysis of the thermal properties of the building envelope, which are mainly dependent on the building construction technology. Particularly, the study has highlighted that buildings built before 1991 are generally masonry or reinforced concrete structures, and their envelope thermal transmittance can significantly vary from a minimum value of 0.75 W/m^2 K up to 3.5 W/m^2 K based on both materials and wall thickness. The same trend was found for ceilings and roofs but with a smaller range of values (between 0.63 W/m^2 K and up to 2.72 W/m^2 K). Transparent surfaces have smaller variations in thermal transmittance values, falling predominantly in the 2.0–2.7 W/m^2 K range, instead.

Based on these premises, a reference building unit was considered with rectangular planimetry, a net surface of 85 m^2, and a window surface of 10.8 m^2 (according to national regulation it has to be greater than or equal to 1/8 of the net surface). A standard boiler powered by natural gas with a nominal power of 26.3 kW and an energy efficiency of 0.93 was also set as a heating system operating at high temperature (i.e., considering radiators as the heating emission system). Several condominiums were thus defined, considering four reference building units per floor and varying the number of floors from three to eight based on both the National Institute of Statistics and the authors' experiences. Geometrical characterization of each defined reference building is detailed in Table 1 in terms of net surfaces, heated volume, and dispersant surfaces of walls; the latter represents the vertical surface where the thermal coating can be applied, and it was used for LCA analysis.

Table 1. Net geometrical characterization of reference condominiums.

Number of Floors (-)	Number of Building Units (-)	Net Surfaces (m^2)	Heated Volume (m^3)	Dispersant Surface (m^2)
3	12	1020	3315	572
4	16	1360	4386	751
5	20	1700	5457	930
6	24	2040	6528	1109
7	28	2380	7599	1289
8	32	2720	8670	1468

To achieve the goal of the present paper, ante-operam configuration was defined considering mean thermal properties (Table 2) assessed as the mean value of the thermal transmittances of all opaque surfaces without thermal insulation studied in [33]. Thermal coating on external walls was thus finally hypothesized and set for post-operam configuration by considering different insulation materials (Table 3) and thicknesses depending on thermal properties of chosen materials and climatic zone. The thermal transmittance standard based on the climatic zone was used for windows, instead. Therefore, refurbishment configuration consists of windows replacement and thermal coating on the external walls of buildings varying the thickness of insulation materials based on climatic zone. The thicknesses to be used for each material in each climatic zone are detailed in Table 4. All the other opaque surfaces were kept as in the ante-operam configuration. This assumption is justified by the analysis of the most common energy interventions in recent years across the country to assess the national incentives; particularly, the 2021 annual report of ENEA [35] highlighted that more than 65% of energy interventions have concerned thermal coating on external vertical walls.

Table 2. Mean thermal transmittance values set for the ante-operam configuration.

Components	Thermal Transmittance (W/m^{2}K)
Wall	2.13
Ceiling/floor	1.47
Roof	1.63
Windows	2.00

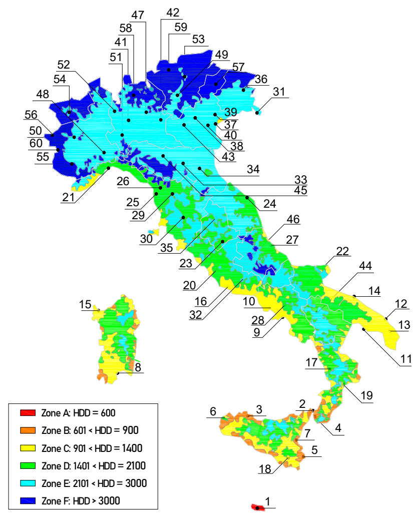
Table 3. Thermal properties of insulation materials investigated in this work.

Materials		λ (W/mK)	ρ (kg/m^3)
Polystyrene foam slab with graphite, 6% recycled	EPS-1	0.031	20
Polystyrene foam slab	EPS-2	0.033	33
Glass wool	GW	0.034	25
Stone wool	SW-1	0.035	40
Stone wool high-bulk density	SW-2	0.036	100
Cellulose fiber	CF	0.038	45

Table 4. Thicknesses (in meters) of the thermal insulation materials adopted in each climatic zone.

Thermal Insulation Materials	Climatic Zone					
	A	B	C	D	E	F
EPS-1	0.07	0.07	0.09	0.11	0.12	0.13
EPS-2	0.08	0.08	0.10	0.12	0.13	0.14
GW	0.08	0.08	0.10	0.12	0.14	0.14
SW-1	0.08	0.08	0.11	0.13	0.14	0.15
SW-2	0.08	0.08	0.11	0.12	0.14	0.15
CF	0.09	0.09	0.11	0.13	0.15	0.16

Finally, energy simulations were performed for each climatic zone by taking into account the most representative cities: 60 cities were chosen and uniformly distributed across the country as shown in Figure 3 (cities were sorted with increasing heating degree days (HDD) value). Except for Bellino, Bardonecchia, and Cusio, which were chosen solely for the severity of their climatic conditions, they represent the most representative cities in the country in terms of number of building units, population, and climatic outdoor conditions.



n.	city	HDD	n.	city
1	Lampedusa e Linosa	568	31	Trieste
2	Messina	707	32	Frosinone
3	Palermo	751	33	Modena
4	Reggio di Calabria	772	34	Bologna
5	Siracusa	799	35	Perugia
6	Trapani	810	36	Udine
7	Catania	833	37	Venezia
8	Cagliari	990	38	Vicenza
9	Salerno	994	39	Treviso
10	Napoli	1034	40	Padova
11	Taranto	1071	41	Milano
12	Brindisi	1083	42	Brescia
13	Lecce	1153	43	Verona
14	Bari	1185	44	Potenza
15	Sassari	1185	45	Parma
16	Latina	1220	46	L'Aquila
17	Cosenza	1317	47	Bergamo
18	Ragusa	1324	48	Alessandria
19	Catanzaro	1328	49	Trento
20	Roma	1415	50	Torino
21	Genova	1435	51	Pavia
22	Foggia	1530	52	Varese
23	Terni	1650	53	Bolzano
24	Ancona	1688	54	Aosta
25	Pisa	1694	55	Cuneo
26	Lucca	1715	56	Bardonecchia
27	Pescara	1718	57	Belluno
28	Avellino	1742	58	Cusio
29	Firenze	1821	59	Bormio
30	Siena	1943	60	Bellino

Figure 3. Geographical distribution of selected cities over the county and climatic zone identification based on heating degree day (HDD) values.

Two configurations were thus simulated overall: the first one, namely ante-operam, corresponds to condominiums with poor thermal properties, the second one, post-operam, corresponds to the refurbishment configuration of the building envelope with all the selected thermal insulation materials.

2.3. Economic Analysis

In order to carry out the economic analysis, an average cost was considered for each insulation material (Table 5). The cost was defined considering a fixed cost for all the activities required for thermal coating realization (common phase for all the materials) and a variable cost; that is, the specific cost of each insulation material; all these costs were estimated based on the national price list.

Table 5. Insulation materials and cost for thermal coat realization adopted in this work.

Insulation Materials	Common Activities (€/m^2)	Insulation Materials (€/m^3)
EPS-1	75.0	105.3
EPS-2	75.0	72.9
GW	75.0	99.4
SW-1	75.0	98.0
SW-2	75.0	159.3
CF	75.0	222.2

The economic payback time (EPBT), intended as the number of years to match the initial cost, was estimated as the ratio between the initial cost for thermal coating realization (Table 5) and the savings resulting from the energy savings calculated with the simulations described in Section 2.2, considering the following price for each energy carrier (data provided by Italian Regulatory Authority for Energy, Networks and Environment (ARERA) [36]): electric energy: 0.501 €/kW h; natural gas: 0.835 €/Sm^3.

2.4. Environmental Analysis

Considering reference buildings, that are representative of the Italian building stock, and their energy performance in the different climatic zones, as described in previous sections, an LCA was carried out to evaluate the environmental impact of the commonly used material for external thermal insulation, according to ISO standards 14040 [37] and 14044 [38].

Referring to the standard stages of an LCA, the details of the performed study are given in the following:

- Goal and scope definition: the goal of this research was to perform a comparative LCA of different materials generally used for external thermal insulation of buildings, in order to highlight their life cycle environmental impacts in the various climatic zones of the Italian territory and, therefore, to enable the identification of the ones to be recommended for the environmentally friendly renovation of buildings in each of these zones. The considered conventional and natural materials are the ones described in the previous sections. All the "downstream" phases of the building life cycle were excluded from the system boundaries since, due to the expected long life of the insulation materials and the building itself after refurbishment, they are considered not relevant for the aim of the study, while among the "upstream" phases, the building refurbishment activities (including all the related materials, such as for instance anchoring systems and plaster) were neglected since they can be considered comparable for all the studied insulation materials (Figure 4). Since taking into account the desired function and the different physical properties of the materials is crucial for a proper comparison, the choice of the functional unit (FU) is particularly relevant to limit the uncertainty and avoid inaccurate/not reliable/not understandable results [39]. The FU was therefore defined as 1 m^2 of the wall surface with a thermal transmittance compliant with the Italian legal limit for the reference climatic zone;
- Life cycle inventory (LCI): both primary and secondary inventory data, coupled with the background dataset of the Ecoinvent v3.8 [40] included in the SimaPro v9.3 software [41], were used to carry out the study. In particular, data regarding the materials flows as well as data resulting from energy modeling referred to the selected FU were used as primary LCI data, while secondary data were used for all the other phases/processes included in the system boundaries (Figure 4);
- Life cycle impact assessment (LCIA): the environmental impacts associated with the investigated materials were evaluated focusing on the climate change impact category, using the Intergovernmental Panel on Climate Change (IPCC) 2021 method [42,43] and thus expressing their significance in terms of carbon dioxide equivalents (CO_2eq).

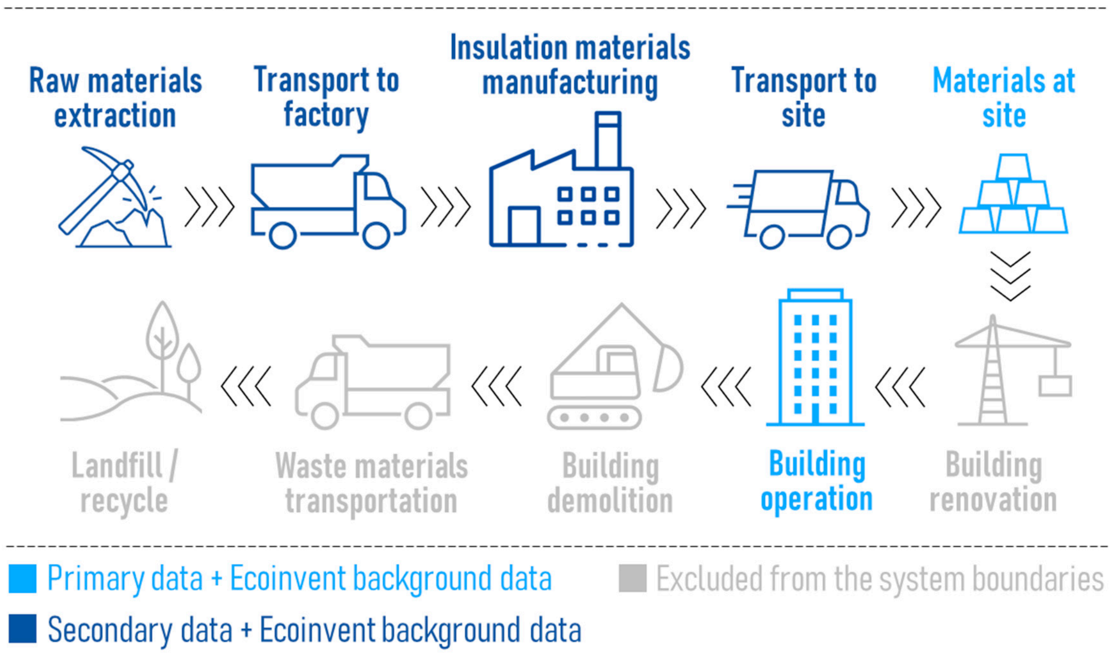


Figure 4. LCA study details and system boundaries.

Starting from the embodied carbon resulting from the LCA analysis, the carbon payback time (CPBT) of the different thermal insulation materials was calculated, intended as the number of years required to offset the negative environmental impact from the production of materials (i.e., embodied carbon) through the avoided CO_2eq emissions associated with the energy consumption reduction due to thermal insulation.

2.5. Economic and Environmental Sustainability Index (EESI)

After energy simulations, economic, and environmental analysis, a new index was introduced in this work, namely the Economic and Environmental Sustainability Index (EESI), aimed at highlighting the affordability of insulation materials on the basis of overall assessment results. The smaller the EESI value, the higher the affordability of the investigated insulation materials. The EESI was defined by considering and combining EPBT and CPBT through normalization and weighting. In particular, average values of EPBT and CPBT estimated on the basis of previous literature [44–54] were used for normalization (3.20 years for EPBT and 3.65 years for CPBT) and each payback was properly weighted through two coefficients varying in the range 0–1 (w_{EPBT} and w_{CPBT}) that take into account the importance given to economic and environmental aspects in insulation material choice. It is evident that a value of the weighting coefficient equal to 0 means neglecting the specific aspect, while a value equal to 1 means a 100% significance given to the specific aspect and also that the coefficients can be arbitrarily varied within the range 0–1 to reflect the relevance given to each one of the aspects in the choice.

This new index EESI was thus assessed as follows:

$$\text{EESI} = \frac{\text{EPBT}}{\text{EPBT}_{\text{average}}} \cdot w_{\text{EPBT}} + \frac{\text{CPBT}}{\text{CPBT}_{\text{average}}} \cdot w_{\text{CPBT}} \tag{1}$$

3. Results and Discussion

As already stated, reference buildings were simulated in all the 60 selected cities, both in ante-operam and post-operam configurations. Primary energy needs for heating, assessed as the average of outcomes obtained in all the cities falling in the same climatic zone, are shown in Figure 5. As expected, the worse the climatic conditions, as well as the greater number of floors, the greater the energy savings. The lowest energy savings were obtained in zone A and for smaller buildings (three floors), whereas the greatest savings were obtained for buildings with eight floors in the coldest zone. In the warmest climatic zone (A), a mean energy saving of around 133 MWh was obtained, while it rose to 704 MWh for the coldest one (F); on average, a mean energy saving around of 318 MWh can be highlighted. More detailed energy outcomes are shown in Tables A1–A3 reported in Appendix A.

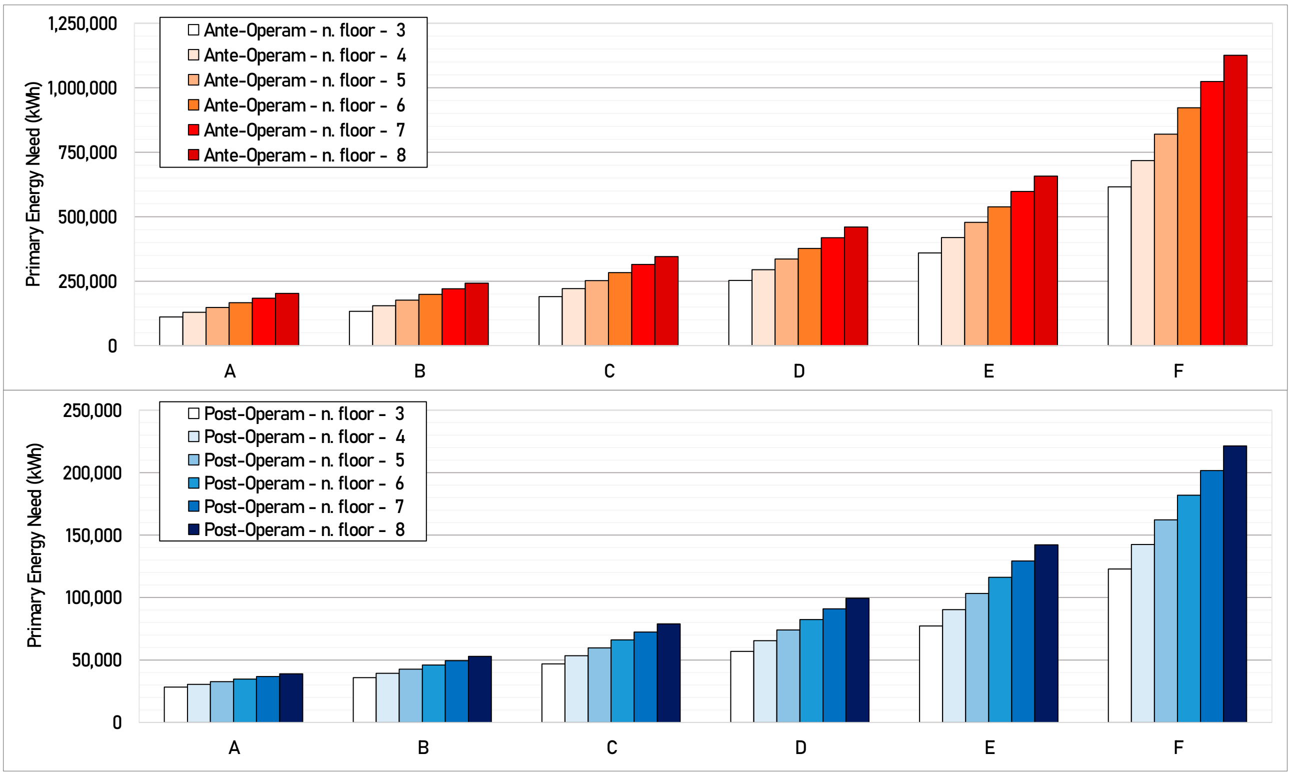


Figure 5. Mean primary energy needs for reference condominiums: ante-operam (**above**) and post-operam (**below**) configurations.

Figure 6 shows the calculated EPBT for all the insulation materials and each reference building; as expected, CF has the highest EPBT in each climatic zone because of its highest initial cost. It is worth noting that the colder the climatic zone, the more EPBTs converge, indicating that the affordability of natural materials increases with increasing energy need of buildings. Except for SW-2, which has a higher initial cost (about twice that of the others), all other mineral- or fossil-fuel-based materials followed the EPBT trend.

LCA analysis was thus performed on the basis of the energy needs of reference buildings and the gross dispersant surfaces of each reference condominium, i.e., considering both the net dispersant surface (Table 1) and the thickness of the insulation materials used for the thermal coat (Table 3).

LCA showed interesting results in terms of embodied carbon in the different studied materials (Table 6). It is worth noting that apart from CF, which is characterized by a very low-impact value in terms of CO_2eq/m^2, the other materials present similar characteristics whether being mineral (natural)- or fossil fuel-based. In particular, EPS-1, GW, and SW-1 showed a very comparable embodied carbon value (in the order of about 4–10 kg CO_2eq/m^2 depending on climatic zone), that was almost halved compared to the quite similar values associated with EPS-2 and SW-2 (in the order of about 10–22 kg CO_2eq/m^2).

Considering the embodied carbon values in Table 6 and the annual avoided emissions resulting from energy savings, reported in Appendix A, the results shown in Figure 7 were obtained.

The increasing trend of CPBT versus the number of building floors is quite evident for all the climatic zones, with a CPBT related to 8 floors buildings that is 31–41% higher than that of 3 floors buildings for the various materials considered. On the other hand, moving from climatic zone A to climatic zone F, the CPBT significantly decreases, confirming the high environmental benefits associated with building thermal insulation in colder climates, i.e., in those climatic zones where heating has great relevance in the building total energy demand.

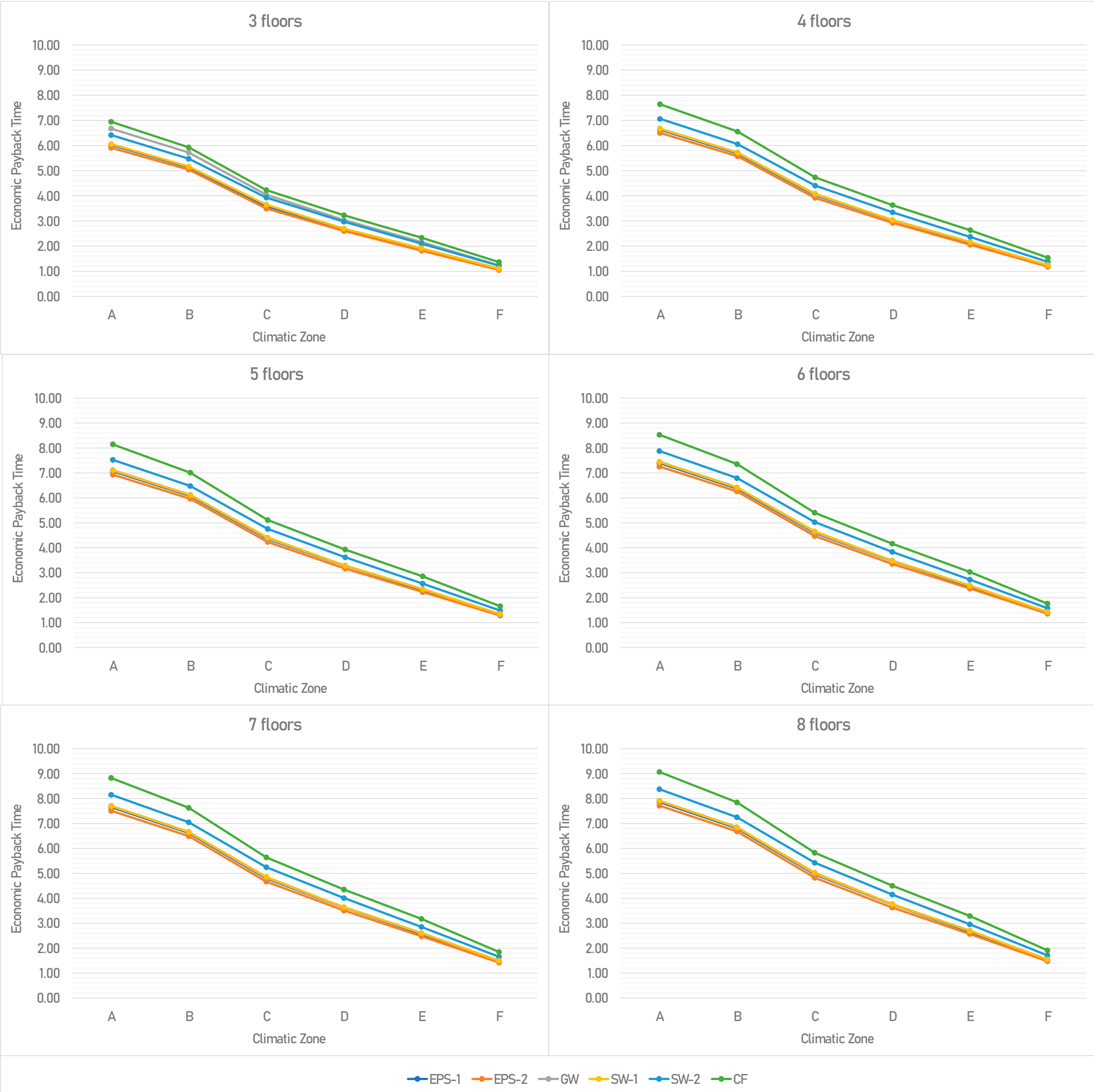


Figure 6. Economic payback time (EPBT) for the chosen insulation materials.

Table 6. Embodied carbon in the different thermal insulation materials and in each climatic zone.

Thermal Insulation Materials	Climatic Zone					
	A	B	C	D	E	F
EPS-1	5.09	5.09	6.55	8.01	8.73	9.46
EPS-2	12.19	12.19	15.24	18.29	19.81	21.34
GW	5.30	5.30	6.62	7.95	9.27	9.27
SW-1	4.35	4.35	5.98	6.52	7.61	8.16
SW-2	10.41	10.41	14.32	16.92	18.22	19.52
CF	1.24	1.24	1.51	1.78	2.06	2.20

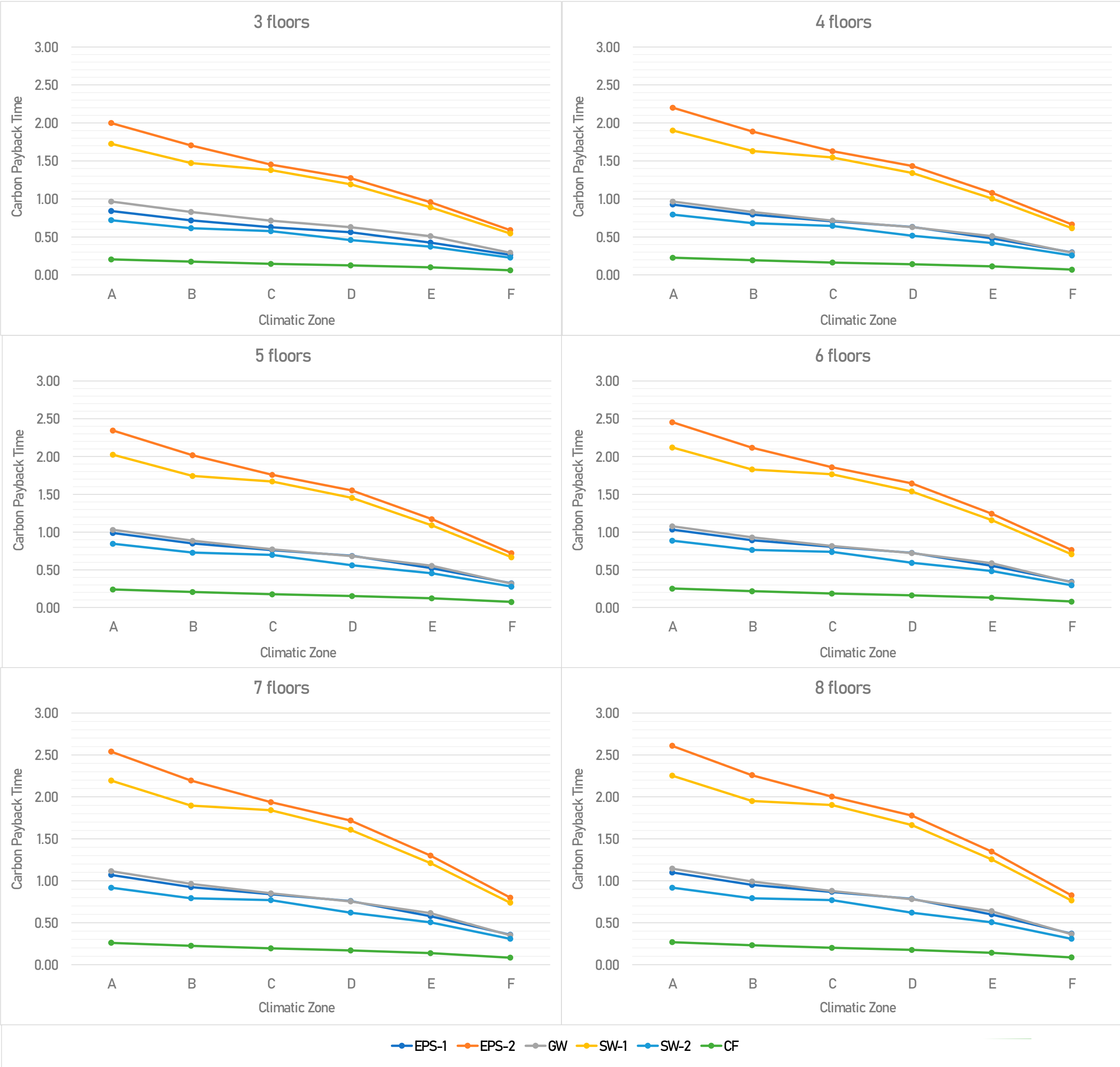


Figure 7. Carbon payback time (CPBT) for the chosen insulation materials.

Figure 7 also shows that, moving from climatic zone A to climatic zone F, there is an appreciable reduction of the difference between the CPBTs of the different materials, thus highlighting that in colder climates, mineral- and fossil fuel-based thermal insulation materials tend to be quite comparable in terms of environmental convenience. In detail, comparing the materials with similar embodied carbon (EPS-1 versus SW-1, EPS-2 versus SW-2, and GW versus EPS-1 and SW-1), the reduction between the CPBTs calculated for climatic zone A and the CPBTs calculated for climatic zone F is in the order of 70–80% for all the building configurations.

EESI was thus calculated considering two possible scenarios:

1. Scenario 1: This scenario represents the current situation when insulation materials are chosen, i.e., at the same energy performance of buildings, the choice is solely based on economic considerations. Therefore, in this scenario w_{EPBT} was set equal to 1 and w_{CPBT} equal to 0;

2. Scenario 2: This represents the ideal conditions, i.e., at the same energy performance of buildings, the choice depends on both economic and environmental aspects. Therefore, in this ideal scenario, w_{EPBT} was set equal to 0.5 and w_{CPBT} equal to 0.5.

These scenarios were chosen just as an example to show how the "current method of choice" of insulation materials (choice of the cheaper material, given the same performance) and an "ideal method of choice" (given the same performance, choice made giving the same weight to economic and environmental aspects) affect the EESI.

EESI results are shown in Figures 8 and 9 for the two analyzed scenarios respectively.

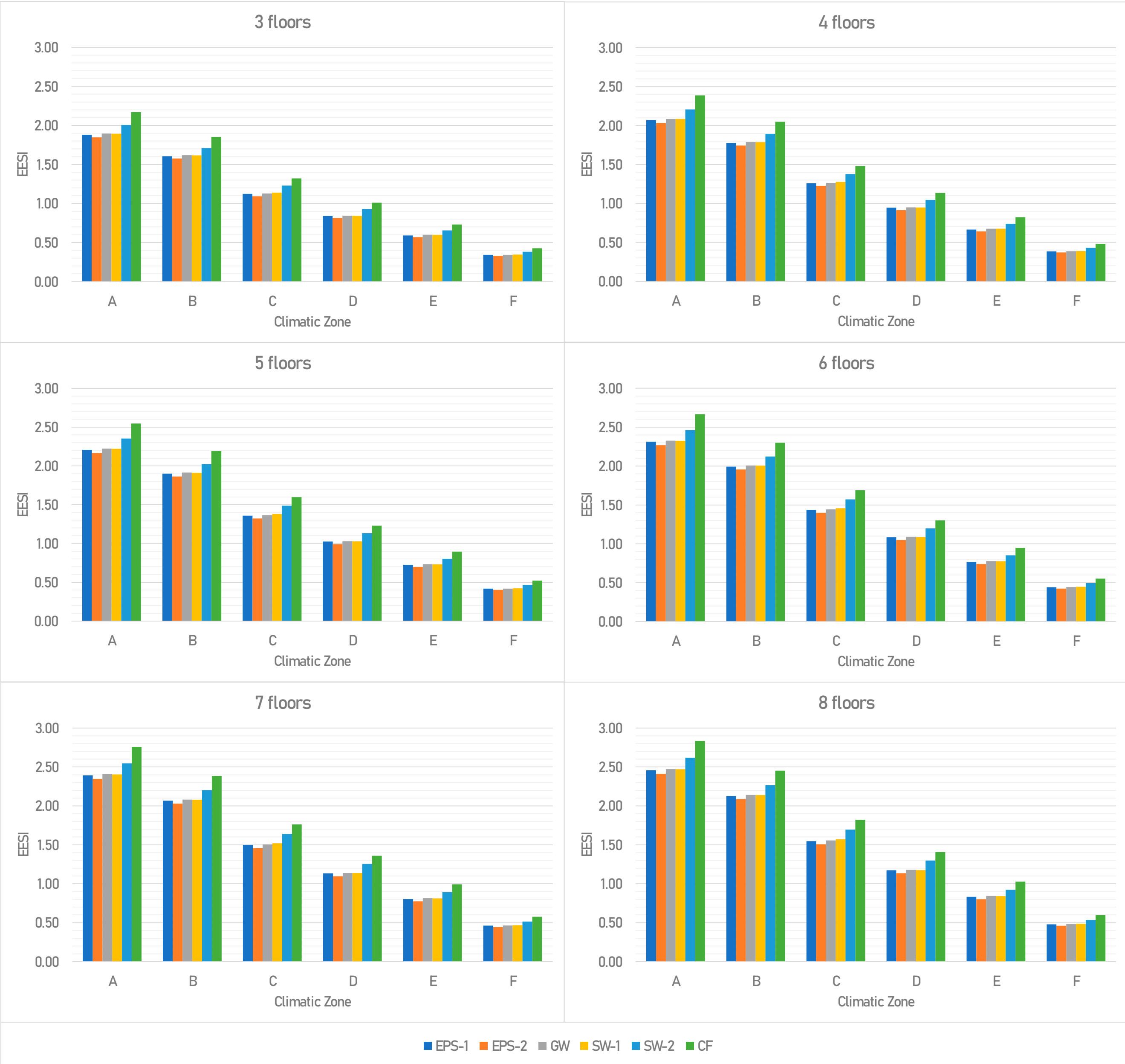


Figure 8. Economic and Environmental Sustainability Index (EESI): scenario 1.

The EESI of scenario 1 (Figure 8) mainly shows the lower affordability of natural and renewable materials compared to traditional and more widespread insulation materials. In the warmest climatic zone, the EESI tends to significantly diverge, indicating the greater affordability of traditional materials, but in the coldest one, it seems to be more comparable (even if still higher for natural materials), thus suggesting a suitable use of natural materials in these zones.

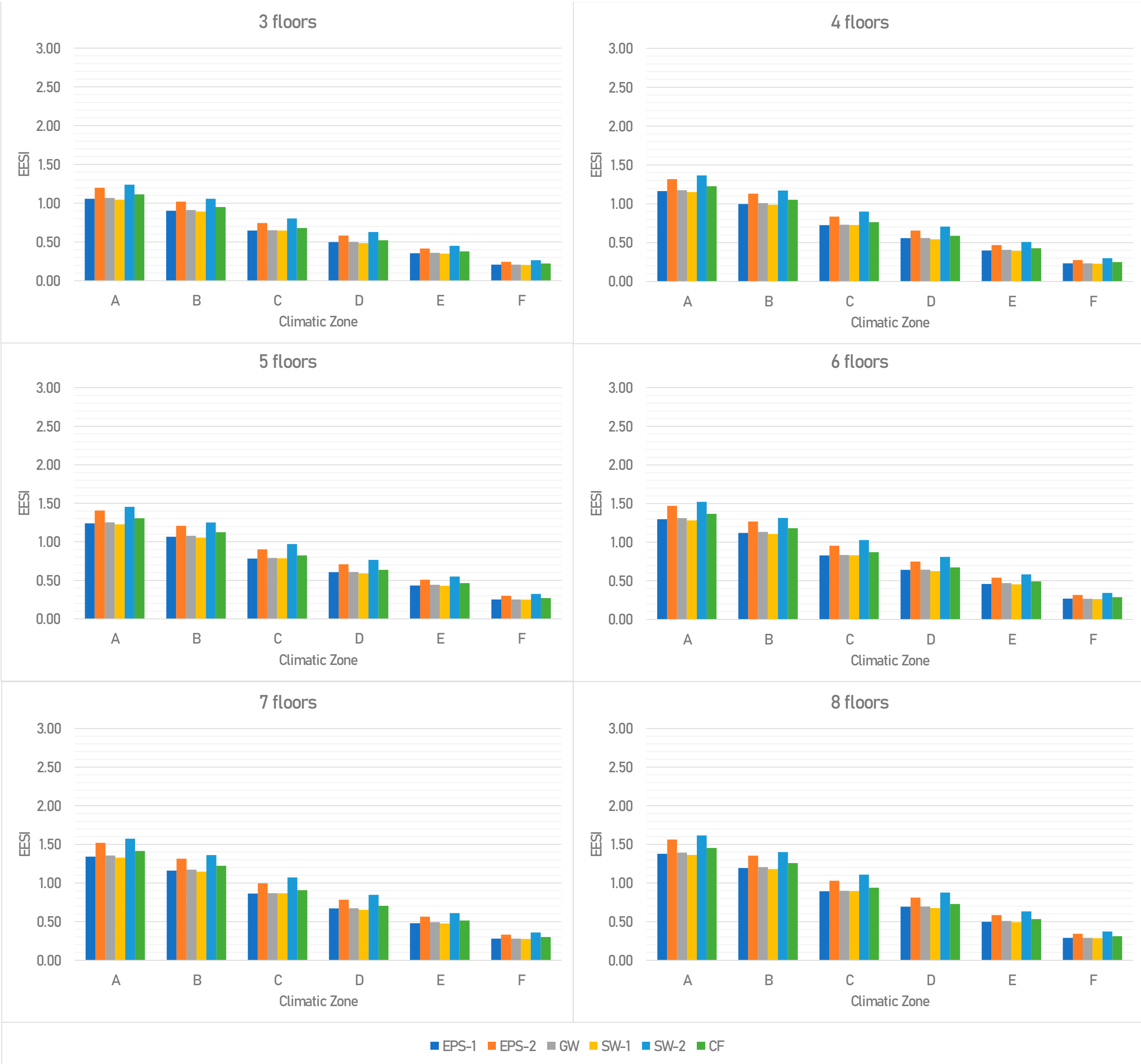


Figure 9. Economic and Environmental Sustainability Index (EESI): scenario 2.

If the environmental impact was also taken into account (scenario 2—Figure 9), the affordability of natural materials would become relevant in all the climatic zones, instead. In fact, in this scenario, the EESI of natural materials is comparable with other EESI values, assuming a lower value than EPS-2 and SW-1. It is worth noting that if different weights in EESI were assumed, the affordability of traditional materials tended to change, such as for SW-1 and SW-2, whose affordability significantly changed from scenario 1 to scenario 2.

According to these results, it is evident that energy, economic, and environmental aspects have to be taken into account in the choice of insulation materials since a comprehensive evaluation can lead to the choice of natural materials despite their higher initial cost. Anyway, the affordability of natural and renewable materials, such as CF, seems to be greater in the coldest climatic zones (such as in E and F) both in scenario 1 and in scenario 2, while in the warmest (mainly A and B) having the highest cost still makes them unaffordable compared to conventional materials.

The study represents a preliminary attempt to evaluate energy, economic, and environmental aspects of different insulation materials through a synthetic sustainability index aimed at simply showing their affordability. However, due to the assumptions made in this work, it has some limitations although interesting applications can be already highlighted.

First of all, the energy simulations were performed in compliance with the current energy calculation method provided by national regulations, i.e., by adopting the monthly calculation method, which is also adopted for energy incentive assessments. As known, this method is not able to return the actual energy consumption of buildings due to: (1) standard user profile, (2) standard heating profile, (3) conventional boundary conditions, and (4) standard outdoor conditions. Although it is less reliable, it remains the easiest calculation method available and the mandatory one to carry out in calculating the energy performance of buildings.

This simplification represents the first limitation of the work. Other calculation methods, such as dynamic tools or the hourly calculation method, could be used as future development but they require more information on building systems as well as model validation through experimental data or energy carrier bills.

Focusing on the environmental analysis instead, the one carried out in the framework of the study can be considered as a partial LCA, since some phases of the building life cycle were excluded from the system boundaries. Beyond the "downstream" phases that were not considered, the main exclusion is related to the refurbishment materials/activities. Specifically, all the materials other than insulation materials, such as for instance anchoring systems and plaster, as well as all the building site activities, were excluded from the study, since they can be considered comparable for all the studied configurations. Even if a partial limitation of the study, it represents an acceptable simplification for a comparative LCA (the overall impact values slightly change, but do not change the relationships between them).

Moreover, the LCA study used secondary data to model a key aspect in the use of insulation materials, i.e., the transportation, that was approximated with secondary data from LCA databases (in particular, Ecoinvent) which can be considered as average representative data. Even if a relevant simplifying assumption, it can be considered reasonable and consistent with the aim of the study; in fact the building site and the factory location were not known (hypothetical case study) and also varying them, the supply distances can be in general considered of the same order of magnitude for a typical building refurbishment worksite.

Lastly, in the definition of the EESI, the weighting coefficients w_{EPBT} and w_{CPBT} were assumed to vary in the range 0–1 and were arbitrarily assigned to exemplify how the importance given to economic and environmental aspects in insulation material choice affects the index evaluation. These arbitrary assumptions were only made as an example just to show how the "current method of choice" of insulation materials (choice of the cheaper material, given the same performance) and an "ideal method of choice" (given the same performance, and choice made giving the same weight to economic and environmental aspects) affect the results.

4. Conclusions

The present work aimed at showing the affordability of different insulation materials, taking into account energy, economic, and environmental aspects. Currently, when buildings are refurbished with thermal coating, the choice of insulation materials is only based on economic analysis, such as on the economic payback time, addressing use of cheaper materials.

The present analysis focused on the importance of carrying out not only energy and economic assessments but also environmental analyses of insulation materials since it can significantly show the affordability of natural and renewable materials, which are generally more expensive.

Based on energy simulations performed in 60 representative Italian cities, the new Economic and Environmental Sustainability Index (EESI) was defined as capable of indicating the affordability of analyzed insulation materials by considering both economic and environmental impacts. Particularly, we found the smaller the index, the higher the affordability of the investigated insulation materials. When the environmental impact is taken into account, the analysis shows that natural materials, such as cellulose fiber, can represent a valuable alternative solution despite their high cost. Particularly, if only the economic aspect is considered in the EESI assessment, the affordability of natural materials seems to be already comparable with mineral (natural)- or fossil fuel-based materials in the coldest climatic zone, although the EESI assumes higher values. On the other hand, the affordability of natural materials significantly increases if EESI is assessed considering both economic and environmental aspects, assuming values close to those of glass wool or polystyrene foam slab with 6% recycled graphite, and lower than those of traditional polystyrene foam slab and stone wool.

It has to be highlighted that the achieved results are specific to the considered case study, i.e., strictly related to the assumptions/selected parameters to model it (climatic conditions, building characteristics, energy performance calculation method, energy prices, insulation materials prices, etc.) and, therefore, that they cannot be directly compared with the ones from other studies.

This work represents a first attempt at a combined energy, economic, and environmental assessment of thermal insulation materials and, even if potentially improvable, it showed the greater importance of considering all these aspects in the building refurbishment process since they can significantly affect the affordability of each material.

The present study allows highlighting interesting future developments such as: (1) carrying out more reliable energy assessment by means of dynamic tools or energy audits, (2) studying the variation of EESI with different weighting coefficients (w_{EPBT} and w_{CPBT}) in order to establish the most appropriate values, (3) upgrading EESI by using a more accurate economic index such as the net present value instead of payback time.

Author Contributions: Conceptualization, D.P. and F.S.; methodology, D.P. and F.S.; energy software and validation, D.P.; LCA analysis and software, F.S.; formal analysis, D.P. and F.S.; investigation, D.P. and F.S.; resources, D.P. and F.S.; data curation, D.P. and F.S.; writing—original draft preparation, D.P. and F.S.; writing—review and editing, D.P. and F.S.; visualization, D.P. and F.S.; supervision, D.P. and F.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are from an ENEA study (2019) [34] and from a new design analysis carried out consistent with the aim of the study. All the data are available under request to the corresponding author.

Acknowledgments: The authors wish to warmly thank F. Pagliaro, M. Morini, and G. Murano for kindly inviting them to publish in the journal's Special Issue "Construction of Green Building and Energy Assessment Using a Life Cycle Approach", of which they are guest editors, and two anonymous reviewers for their invaluable review comments on an earlier version of this manuscript.

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

Nomenclature

ARERA	Italian Regulatory Authority for Energy, Networks, and Environment
BU	Building units
CPBT	Carbon payback time
CF	Cellulose fiber
DPR	Decree of President of Republic
EESI	Economic and Environmental Sustainability Index
ENEA	Italian National Agency for new Technology Energy and Sustainable Economic Development
EPBT	Economic payback time
EPC	Energy Performance Certificate

EPS	Polystyrene foam slab
FU	Functional unit
GHG	Greenhouse gas
GW	Glass wool
HDD	Heating degree days
HVAC	Heating ventilation air conditioning
IEA	International Energy Agency
LCA	Life cycle assessment
MFH	Multi-family house
s	Thickness
SIAPE	Informative System on Energy Performance Certificates
SW	Stone wool
w	weight
XPS	Extruded expanded polystyrene
λ	Thermal conductivity
ρ	Density

Appendix A

Table A1. Energy consumption results: natural gas per gross dispersant surface (Sm^3/m^2).

Materials (-)	Climatic Zone (-)	Gas Natural Consumption per Gross Dispersant Surface (Sm^3/m^2)											
		Ante-Operam						Post-Operam					
		3	4	5	6	7	8	3	4	5	6	7	8
EPS-1	A	17.8	15.8	14.5	13.7	13.1	12.6	4.5	3.7	3.2	2.9	2.6	2.4
	B	21.3	18.9	17.4	16.3	15.6	15.1	5.7	4.8	4.2	3.8	3.5	3.3
	C	30.4	26.9	24.8	23.3	22.3	21.5	7.5	6.5	5.9	5.4	5.1	4.9
	D	40.4	35.8	33.0	31.0	29.7	28.6	9.1	8.0	7.3	6.8	6.4	6.2
	E	57.5	51.0	47.0	44.3	42.4	40.9	12.4	11.0	10.1	9.6	9.2	8.9
	F	98.5	87.4	80.5	75.9	72.6	70.0	19.6	17.3	15.9	15.0	14.3	13.8
EPS-2	A	18.0	15.9	14.6	13.8	13.2	12.7	4.6	3.7	3.2	2.9	2.6	2.4
	B	21.5	19.0	17.5	16.5	15.7	15.2	5.8	4.8	4.2	3.8	3.5	3.3
	C	30.6	27.1	25.0	23.5	22.5	21.7	7.6	6.5	5.9	5.5	5.2	4.9
	D	40.7	36.1	33.2	31.3	29.9	28.8	9.2	8.0	7.3	6.8	6.5	6.2
	E	57.9	51.4	47.4	44.6	42.7	41.2	12.4	11.1	10.2	9.6	9.2	8.9
	F	99.2	88.0	81.1	76.5	73.1	70.6	19.8	17.5	16.1	15.1	14.4	13.9
GW	A	17.8	15.7	14.5	13.7	13.0	12.6	4.5	3.7	3.2	2.8	2.6	2.4
	B	21.3	18.8	17.3	16.3	15.6	15.0	5.7	4.8	4.2	3.8	3.5	3.3
	C	30.3	26.8	24.7	23.3	22.2	21.4	7.5	6.5	5.8	5.4	5.1	4.9
	D	40.3	35.7	32.9	31.0	29.6	28.5	9.1	7.9	7.2	6.8	6.4	6.2
	E	57.3	50.9	46.9	44.2	42.3	40.8	12.3	11.0	10.1	9.5	9.1	8.8
	F	98.2	87.1	80.3	75.7	72.4	69.9	19.6	17.3	15.9	14.9	14.3	13.7
SW-1	A	17.8	15.7	14.5	13.6	13.0	12.6	4.5	3.7	3.2	2.8	2.6	2.4
	B	21.3	18.8	17.3	16.3	15.6	15.0	5.7	4.8	4.2	3.8	3.5	3.3
	C	30.3	26.8	24.7	23.2	22.2	21.4	7.5	6.5	5.8	5.4	5.1	4.9
	D	40.3	35.7	32.8	30.9	29.5	28.5	9.1	7.9	7.2	6.8	6.4	6.2
	E	57.3	50.8	46.8	44.1	42.2	40.7	12.3	10.9	10.1	9.5	9.1	8.8
	F	98.1	87.0	80.2	75.6	72.3	69.8	19.6	17.3	15.9	14.9	14.2	13.7
SW-2	A	17.8	15.7	14.5	13.6	13.0	12.6	4.5	3.7	3.2	2.8	2.6	2.4
	B	21.3	18.8	17.3	16.3	15.6	15.0	5.7	4.8	4.2	3.8	3.5	3.3
	C	30.3	26.8	24.7	23.2	22.2	21.4	7.5	6.5	5.8	5.4	5.1	4.9
	D	40.3	35.7	32.8	30.9	29.5	28.5	9.1	7.9	7.2	6.8	6.4	6.2
	E	57.3	50.8	46.8	44.1	42.2	40.7	12.3	10.9	10.1	9.5	9.1	8.8
	F	98.1	87.0	80.2	75.6	72.3	69.8	19.6	17.3	15.9	14.9	14.2	13.7
CF	A	17.7	15.7	14.5	13.6	13.0	12.5	4.5	3.7	3.2	2.8	2.6	2.4
	B	21.2	18.8	17.3	16.3	15.5	15.0	5.7	4.8	4.2	3.8	3.5	3.3
	C	30.2	26.8	24.7	23.2	22.2	21.4	7.5	6.5	5.8	5.4	5.1	4.9
	D	40.2	35.6	32.8	30.9	29.5	28.5	9.1	7.9	7.2	6.8	6.4	6.2
	E	57.2	50.7	46.8	44.1	42.1	40.7	12.3	10.9	10.1	9.5	9.1	8.8
	F	98.0	86.9	80.1	75.5	72.2	69.7	19.5	17.3	15.9	14.9	14.2	13.7

Table A2. Energy consumption results: electric energy per gross dispersant surface (kWh/m^2).

Materials (-)	Climatic Zone (-)	Electric Energy Consumption per Gross Dispersant Surface (kWh/m^2)											
		Ante-Operam						Post-Operam					
		3	4	5	6	7	8	3	4	5	6	7	8
EPS-1	A	37.1	32.9	30.3	28.5	27.2	26.3	9.4	7.7	6.7	5.9	5.4	5.0
	B	44.4	39.3	36.2	34.0	32.5	31.3	11.9	9.9	8.7	7.9	7.3	6.8
	C	63.3	56.0	51.6	48.6	46.4	44.8	15.6	13.5	12.2	11.3	10.7	10.2
	D	84.1	74.5	68.6	64.6	61.8	59.6	19.0	16.6	15.1	14.1	13.4	12.9
	E	119.6	106.1	97.9	92.2	88.2	85.1	25.7	22.9	21.1	19.9	19.1	18.4
	F	205.0	181.9	167.7	158.0	151.1	145.8	40.9	36.1	33.2	31.2	29.8	28.7

Table A2. *Cont.*

Materials (-)	Climatic Zone (-)	Electric Energy Consumption per Gross Dispersant Surface (kWh/m^2)											
		Ante-Operam						Post-Operam					
		3	4	5	6	7	8	3	4	5	6	7	8
EPS-2	A	37.4	33.1	30.5	28.7	27.4	26.5	9.5	7.8	6.7	6.0	5.5	5.1
	B	44.7	39.6	36.4	34.3	32.8	31.6	12.0	10.0	8.8	7.9	7.3	6.9
	C	63.8	56.5	52.0	48.9	46.8	45.1	15.7	13.6	12.3	11.4	10.8	10.3
	D	84.8	75.1	69.1	65.1	62.2	60.0	19.1	16.7	15.2	14.2	13.5	13.0
	E	120.5	107.0	98.6	93.0	88.9	85.8	25.9	23.0	21.3	20.1	19.2	18.6
	F	206.6	183.3	168.9	159.2	152.2	147.0	41.2	36.4	33.4	31.4	30.0	28.9
GW	A	37.0	32.8	30.2	28.4	27.1	26.2	9.4	7.7	6.6	5.9	5.4	5.0
	B	44.3	39.2	36.1	34.0	32.4	31.3	11.9	9.9	8.7	7.9	7.3	6.8
	C	63.1	55.9	51.5	48.5	46.3	44.6	15.6	13.5	12.2	11.3	10.7	10.2
	D	83.9	74.3	68.5	64.5	61.6	59.4	18.9	16.5	15.1	14.1	13.4	12.8
	E	119.3	105.9	97.6	92.0	88.0	84.9	25.7	22.8	21.1	19.9	19.0	18.4
	F	204.5	181.4	167.2	157.6	150.7	145.5	40.8	36.0	33.1	31.1	29.7	28.6
SW-1	A	37.0	32.8	30.1	28.4	27.1	26.2	9.4	7.7	6.6	5.9	5.4	5.0
	B	44.2	39.2	36.0	33.9	32.4	31.2	11.9	9.9	8.7	7.9	7.3	6.8
	C	63.0	55.8	51.4	48.4	46.2	44.6	15.6	13.5	12.2	11.3	10.7	10.2
	D	83.8	74.2	68.4	64.4	61.5	59.3	18.9	16.5	15.1	14.1	13.4	12.8
	E	119.2	105.7	97.5	91.9	87.9	84.8	25.6	22.8	21.0	19.9	19.0	18.4
	F	204.3	181.2	167.0	157.4	150.5	145.3	40.8	36.0	33.1	31.1	29.6	28.6
SW-2	A	37.0	32.8	30.1	28.4	27.1	26.2	9.4	7.7	6.6	5.9	5.4	5.0
	B	44.2	39.2	36.0	33.9	32.4	31.2	11.9	9.9	8.7	7.9	7.3	6.8
	C	63.0	55.8	51.4	48.4	46.2	44.6	15.6	13.5	12.2	11.3	10.7	10.2
	D	83.8	74.2	68.4	64.4	61.5	59.3	18.9	16.5	15.1	14.1	13.4	12.8
	E	119.2	105.7	97.5	91.9	87.9	84.8	25.6	22.8	21.0	19.9	19.0	18.4
	F	204.3	181.2	167.0	157.4	150.5	145.3	40.8	36.0	33.1	31.1	29.6	28.6
CF	A	36.9	32.7	30.1	28.3	27.1	26.1	9.4	7.7	6.6	5.9	5.4	5.0
	B	44.2	39.1	36.0	33.9	32.3	31.2	11.9	9.9	8.7	7.8	7.3	6.8
	C	63.0	55.8	51.3	48.3	46.2	44.5	15.6	13.4	12.1	11.3	10.6	10.2
	D	83.7	74.2	68.3	64.3	61.4	59.3	18.9	16.5	15.0	14.1	13.3	12.8
	E	119.1	105.6	97.4	91.8	87.8	84.7	25.6	22.8	21.0	19.8	19.0	18.3
	F	204.0	181.0	166.8	157.2	150.3	145.1	40.7	35.9	33.0	31.0	29.6	28.5

Table A3. Energy consumption results: CO_2 emission per gross dispersant surface ($kgCO_2/m^2$).

Materials (-)	Climatic Zone (-)	CO_2 Emission per Gross Dispersant Surface ($kgCO_2/m^2$)											
		Ante-Operam						Post-Operam					
		3	4	5	6	7	8	3	4	5	6	7	8
EPS-1	A	8.1	7.2	6.6	6.2	5.9	5.7	2.1	1.7	1.5	1.3	1.2	1.1
	B	9.7	8.6	7.9	7.4	7.1	6.9	2.6	2.2	1.9	1.7	1.6	1.5
	C	13.8	12.2	11.3	10.6	10.1	9.8	3.4	3.0	2.7	2.5	2.3	2.2
	D	18.4	16.3	15.0	14.1	13.5	13.0	4.1	3.6	3.3	3.1	2.9	2.8
	E	26.2	23.2	21.4	20.2	19.3	18.6	5.6	5.0	4.6	4.4	4.2	4.0
	F	44.8	39.8	36.6	34.5	33.0	31.9	8.9	7.9	7.3	6.8	6.5	6.3
EPS-2	A	8.2	7.2	6.7	6.3	6.0	5.8	2.1	1.7	1.5	1.3	1.2	1.1
	B	9.8	8.7	8.0	7.5	7.2	6.9	2.6	2.2	1.9	1.7	1.6	1.5
	C	13.9	12.3	11.4	10.7	10.2	9.9	3.4	3.0	2.7	2.5	2.4	2.3
	D	18.5	16.4	15.1	14.2	13.6	13.1	4.2	3.7	3.3	3.1	3.0	2.8
	E	26.3	23.4	21.6	20.3	19.4	18.8	5.7	5.0	4.7	4.4	4.2	4.1
	F	45.2	40.1	36.9	34.8	33.3	32.1	9.0	8.0	7.3	6.9	6.6	6.3
GW	A	8.1	7.2	6.6	6.2	5.9	5.7	2.1	1.7	1.5	1.3	1.2	1.1
	B	9.7	8.6	7.9	7.4	7.1	6.8	2.6	2.2	1.9	1.7	1.6	1.5
	C	13.8	12.2	11.2	10.6	10.1	9.8	3.4	2.9	2.7	2.5	2.3	2.2
	D	18.3	16.2	15.0	14.1	13.5	13.0	4.1	3.6	3.3	3.1	2.9	2.8
	E	26.1	23.1	21.3	20.1	19.2	18.6	5.6	5.0	4.6	4.3	4.2	4.0
	F	44.7	39.7	36.6	34.5	32.9	31.8	8.9	7.9	7.2	6.8	6.5	6.3
SW-1	A	8.1	7.2	6.6	6.2	5.9	5.7	2.1	1.7	1.4	1.3	1.2	1.1
	B	9.7	8.6	7.9	7.4	7.1	6.8	2.6	2.2	1.9	1.7	1.6	1.5
	C	13.8	12.2	11.2	10.6	10.1	9.7	3.4	2.9	2.7	2.5	2.3	2.2
	D	18.3	16.2	14.9	14.1	13.4	13.0	4.1	3.6	3.3	3.1	2.9	2.8
	E	26.1	23.1	21.3	20.1	19.2	18.5	5.6	5.0	4.6	4.3	4.2	4.0
	F	44.7	39.6	36.5	34.4	32.9	31.8	8.9	7.9	7.2	6.8	6.5	6.2
SW-2	A	8.1	7.2	6.6	6.2	5.9	5.7	2.1	1.7	1.4	1.3	1.2	1.1
	B	9.7	8.6	7.9	7.4	7.1	6.8	2.6	2.2	1.9	1.7	1.6	1.5
	C	13.8	12.2	11.2	10.6	10.1	9.7	3.4	2.9	2.7	2.5	2.3	2.2
	D	18.3	16.2	14.9	14.1	13.4	13.0	4.1	3.6	3.3	3.1	2.9	2.8
	E	26.1	23.1	21.3	20.1	19.2	18.5	5.6	5.0	4.6	4.3	4.2	4.0
	F	44.7	39.6	36.5	34.4	32.9	31.8	8.9	7.9	7.2	6.8	6.5	6.2
CF	A	8.1	7.1	6.6	6.2	5.9	5.7	2.0	1.7	1.4	1.3	1.2	1.1
	B	9.7	8.5	7.9	7.4	7.1	6.8	2.6	2.2	1.9	1.7	1.6	1.5
	C	13.8	12.2	11.2	10.6	10.1	9.7	3.4	2.9	2.7	2.5	2.3	2.2
	D	18.3	16.2	14.9	14.1	13.4	13.0	4.1	3.6	3.3	3.1	2.9	2.8
	E	26.0	23.1	21.3	20.1	19.2	18.5	5.6	5.0	4.6	4.3	4.1	4.0
	F	44.6	39.6	36.5	34.4	32.9	31.7	8.9	7.9	7.2	6.8	6.5	6.2

Table A4. Economic and carbon payback time (years).

Materials (-)	Climatic Zone (-)	Payback Time (years)											
		Economic						Carbon					
		3	4	5	6	7	8	3	4	5	6	7	8
EPS-1	A	6.02	6.63	7.07	7.40	7.65	7.86	0.84	0.93	0.99	1.03	1.07	1.10
	B	5.14	5.68	6.08	6.38	6.62	6.81	0.72	0.79	0.85	0.89	0.92	0.95
	C	3.59	4.02	4.35	4.59	4.79	4.95	0.63	0.70	0.76	0.80	0.84	0.87
	D	2.69	3.03	3.28	3.47	3.63	3.75	0.56	0.63	0.68	0.73	0.76	0.78
	E	1.89	2.13	2.31	2.45	2.57	2.66	0.43	0.48	0.52	0.55	0.58	0.60
	F	1.09	1.23	1.34	1.42	1.48	1.53	0.26	0.30	0.32	0.34	0.36	0.37
EPS-2	A	5.91	6.51	6.93	7.26	7.51	7.71	2.00	2.20	2.34	2.45	2.54	2.61
	B	5.04	5.58	5.97	6.26	6.49	6.68	1.71	1.89	2.02	2.12	2.20	2.26
	C	3.50	3.92	4.23	4.47	4.67	4.82	1.45	1.63	1.76	1.86	1.94	2.00
	D	2.60	2.93	3.17	3.36	3.51	3.63	1.27	1.43	1.55	1.64	1.72	1.78
	E	1.82	2.05	2.23	2.37	2.47	2.56	0.96	1.08	1.17	1.24	1.30	1.35
	F	1.05	1.18	1.28	1.36	1.42	1.47	0.59	0.66	0.72	0.76	0.80	0.83
GW	A	6.07	6.68	7.12	7.45	7.71	7.92	0.88	0.97	1.03	1.08	1.11	1.15
	B	5.18	5.72	6.12	6.42	6.66	6.85	0.75	0.83	0.89	0.93	0.96	0.99
	C	3.61	4.05	4.37	4.62	4.82	4.98	0.64	0.71	0.77	0.82	0.85	0.88
	D	2.70	3.04	3.29	3.49	3.64	3.77	0.56	0.63	0.68	0.72	0.75	0.78
	E	1.92	2.16	2.35	2.49	2.60	2.70	0.45	0.51	0.55	0.59	0.62	0.64
	F	1.10	1.24	1.34	1.42	1.48	1.54	0.26	0.29	0.32	0.34	0.35	0.36
SW-1	A	6.42	7.06	7.53	7.88	8.15	8.37	1.73	1.90	2.03	2.12	2.19	2.25
	B	5.48	6.06	6.48	6.80	7.05	7.25	1.47	1.63	1.74	1.83	1.90	1.95
	C	3.93	4.41	4.76	5.03	5.25	5.42	1.38	1.55	1.67	1.77	1.84	1.90
	D	2.98	3.35	3.62	3.84	4.01	4.15	1.19	1.34	1.45	1.54	1.61	1.66
	E	2.10	2.37	2.57	2.72	2.85	2.95	0.89	1.00	1.09	1.16	1.21	1.25
	F	1.22	1.37	1.49	1.58	1.65	1.71	0.55	0.62	0.67	0.71	0.74	0.77
SW-2	A	6.06	6.67	7.11	7.44	7.70	7.91	0.72	0.79	0.85	0.89	0.92	0.94
	B	5.17	5.72	6.11	6.42	6.65	6.84	0.62	0.68	0.73	0.76	0.79	0.82
	C	3.65	4.09	4.41	4.66	4.86	5.03	0.58	0.65	0.70	0.74	0.77	0.80
	D	2.70	3.03	3.28	3.48	3.63	3.76	0.46	0.52	0.56	0.59	0.62	0.64
	E	1.91	2.16	2.34	2.48	2.60	2.69	0.37	0.42	0.46	0.48	0.51	0.52
	F	1.11	1.25	1.35	1.43	1.50	1.55	0.23	0.26	0.28	0.30	0.31	0.32
CF	A	6.95	7.65	8.15	8.53	8.83	9.07	0.20	0.23	0.24	0.25	0.26	0.27
	B	5.93	6.56	7.01	7.36	7.63	7.85	0.17	0.19	0.21	0.22	0.23	0.23
	C	4.23	4.74	5.12	5.41	5.64	5.83	0.15	0.16	0.18	0.19	0.19	0.20
	D	3.23	3.63	3.93	4.17	4.35	4.51	0.13	0.14	0.15	0.16	0.17	0.18
	E	2.34	2.64	2.86	3.03	3.17	3.29	0.10	0.11	0.12	0.13	0.14	0.14
	F	1.36	1.54	1.67	1.77	1.85	1.91	0.06	0.07	0.08	0.08	0.08	0.09

Table A5. Economic and Environmental Sustainability Index (EESI) (-).

Number of Floors (-)	Materials (-)	Economic and Environmental Sustainability Index (EESI) (-)											
		Scenario 1						Scenario 2					
		A	B	C	D	E	F	A	B	C	D	E	F
3	EPS-1	1.88	1.61	1.12	0.84	0.59	0.34	1.06	0.90	0.65	0.50	0.35	0.21
	EPS-2	1.85	1.58	1.09	0.81	0.57	0.33	1.20	1.02	0.75	0.58	0.42	0.25
	GW	1.90	1.62	1.13	0.84	0.60	0.34	1.07	0.91	0.65	0.50	0.36	0.21
	SW-1	1.89	1.62	1.14	0.84	0.60	0.35	1.05	0.89	0.65	0.48	0.35	0.20
	SW-2	2.01	1.71	1.23	0.93	0.66	0.38	1.24	1.06	0.80	0.63	0.45	0.27
	CF	2.17	1.85	1.32	1.01	0.73	0.43	1.11	0.95	0.68	0.52	0.38	0.22
4	EPS-1	2.07	1.78	1.26	0.95	0.67	0.39	1.16	1.00	0.73	0.56	0.40	0.23
	EPS-2	2.03	1.74	1.23	0.91	0.64	0.37	1.32	1.13	0.84	0.65	0.47	0.28
	GW	2.09	1.79	1.26	0.95	0.68	0.39	1.18	1.01	0.73	0.56	0.41	0.23
	SW-1	2.08	1.79	1.28	0.95	0.67	0.39	1.15	0.99	0.73	0.54	0.39	0.23
	SW-2	2.21	1.89	1.38	1.05	0.74	0.43	1.36	1.17	0.90	0.71	0.51	0.30
	CF	2.39	2.05	1.48	1.14	0.82	0.48	1.23	1.05	0.76	0.59	0.43	0.25
5	EPS-1	2.21	1.90	1.36	1.02	0.72	0.42	1.24	1.07	0.78	0.61	0.43	0.25
	EPS-2	2.17	1.86	1.32	0.99	0.70	0.40	1.40	1.21	0.90	0.71	0.51	0.30
	GW	2.22	1.91	1.37	1.03	0.73	0.42	1.25	1.08	0.79	0.61	0.44	0.25
	SW-1	2.22	1.91	1.38	1.03	0.73	0.42	1.23	1.06	0.78	0.59	0.43	0.25
	SW-2	2.35	2.02	1.49	1.13	0.80	0.47	1.45	1.25	0.97	0.77	0.55	0.32
	CF	2.55	2.19	1.60	1.23	0.89	0.52	1.31	1.12	0.82	0.64	0.46	0.27
6	EPS-1	2.31	1.99	1.44	1.09	0.77	0.44	1.30	1.12	0.83	0.64	0.46	0.27
	EPS-2	2.27	1.96	1.40	1.05	0.74	0.43	1.47	1.27	0.95	0.75	0.54	0.32
	GW	2.33	2.01	1.44	1.09	0.78	0.44	1.31	1.13	0.83	0.64	0.47	0.27
	SW-1	2.32	2.00	1.46	1.09	0.78	0.45	1.28	1.11	0.83	0.62	0.45	0.26
	SW-2	2.46	2.12	1.57	1.20	0.85	0.49	1.52	1.31	1.03	0.81	0.58	0.34
	CF	2.67	2.30	1.69	1.30	0.95	0.55	1.37	1.18	0.87	0.67	0.49	0.29
7	EPS-1	2.39	2.07	1.50	1.13	0.80	0.46	1.34	1.16	0.86	0.67	0.48	0.28
	EPS-2	2.35	2.03	1.46	1.10	0.77	0.44	1.52	1.32	0.99	0.78	0.56	0.33
	GW	2.41	2.08	1.51	1.14	0.81	0.46	1.36	1.17	0.87	0.67	0.49	0.28
	SW-1	2.41	2.08	1.52	1.14	0.81	0.47	1.33	1.15	0.87	0.65	0.48	0.28
	SW-2	2.55	2.20	1.64	1.25	0.89	0.52	1.57	1.36	1.07	0.85	0.61	0.36
	CF	2.76	2.38	1.76	1.36	0.99	0.58	1.42	1.22	0.91	0.70	0.51	0.30
8	EPS-1	2.46	2.13	1.55	1.17	0.83	0.48	1.38	1.19	0.89	0.69	0.50	0.29
	EPS-2	2.41	2.09	1.51	1.13	0.80	0.46	1.56	1.35	1.03	0.81	0.59	0.34
	GW	2.47	2.14	1.56	1.18	0.84	0.48	1.39	1.21	0.90	0.70	0.51	0.29
	SW-1	2.47	2.14	1.57	1.18	0.84	0.48	1.36	1.18	0.89	0.68	0.49	0.29
	SW-2	2.62	2.27	1.70	1.30	0.92	0.53	1.62	1.40	1.11	0.88	0.63	0.37
	CF	2.83	2.45	1.82	1.41	1.03	0.60	1.45	1.26	0.94	0.73	0.53	0.31

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