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# Strategies for reducing energy consumption in existing buildings through ecological renovation

## Strategii de reducere a consumului de energie în clădirile existente prin renovare ecologică

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**Abstract.** *This paper presents an original approach to energy-efficient renovation of existing buildings by evaluating thermal insulation materials and their impact on energy consumption and $CO_2$ emissions. Five insulation scenarios were analyzed using simulation software, focusing on both environmental and economic performance. The results highlight the effectiveness of innovative and sustainable solutions, providing guidelines for optimizing thermal insulation in line with the European Green Deal and EPBD 2024 requirements.*

***Key words:*** *energy-efficient renovation, thermal insulation, $CO_2$ emissions, existing buildings, simulation, European Green Deal, EPBD 2024*

**Rezumat.** *Articolul prezintă o abordare originală a renovării eficiente energetic a clădirilor existente prin evaluarea materialelor termoizolante și a impactului acestora asupra consumului de energie și emisiilor de $CO_2$. Au fost analizate cinci scenarii de izolație folosind software de simulare, concentrându-se pe performanța de mediu și economică. Rezultatele evidențiază eficiența soluțiilor inovative și durabile, oferind ghiduri pentru optimizarea izolației termice conform Green Deal-ului European și cerințelor EPBD 2024.*

***Cuvinte cheie:*** *renovare eficientă energetic, izolație termică, emisii $CO_2$, clădiri existente, simulare, Green Deal European, EPBD 2024*

## 1. Introduction

The present article addresses a critically important and timely topic in the context of global climate change and the urgent need to reduce $CO_2$ emissions:

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strategies for enhancing energy efficiency in existing buildings through ecological renovation. By conducting a comparative analysis of both conventional and ecological thermal insulation materials, this study aims to provide practical, sustainable, and scalable solutions for improving the energy performance of the existing building stock.

The selection of this topic is motivated by the authors' professional expertise in building installations, combined with a strong commitment to environmental protection.

Buildings account for approximately 40% of global energy consumption and a similar share of greenhouse gas emissions 37% in 2021 [1], highlighting the pressing need for effective interventions. In this context, ecological renovation of office buildings represents one of the most impactful approaches to reduce carbon footprint and support the European Union's sustainability agenda.

In the current context of climate challenges and increasingly strict energy-efficiency regulations in the construction sector, the choice of thermal insulation materials has become crucial, not only in terms of performance but also from a long-term sustainability perspective. Life Cycle Assessment (LCA) is a key tool in this evaluation, quantifying environmental impacts from raw material extraction to end-of-life. Recent studies illustrate this multidimensional approach: Valentini et al. (2025) [18] show that combining high-performance insulation with recycling strategies can significantly reduce carbon footprints in Italy; Kilis, Ploskas, and Panaras (2025) [19] propose a framework integrating LCA, economic, and technical criteria to optimize insulation type and thickness, highlighting trade-offs between thermal efficiency, environmental impact, and cost; and Ramakrishnan and Jambunathan (2025) [20] demonstrate that EPS-enhanced concrete provides both improved thermal insulation and lower greenhouse gas emissions. Collectively, these works emphasize that insulation selection should balance thermal performance, sustainability, and lifecycle considerations

This research is driven by the aspiration to contribute to a healthier built environment for future generations through the implementation of ecological solutions capable of significantly reducing $CO_2$ emissions. Practical experience in the field has revealed the potential of sustainable insulation materials, as well as the necessity for rigorous scientific evaluation of their performance in comparison with traditional alternatives.

The novelty and relevance of this study are reinforced by the evolving European legislative and normative framework. The European Level framework, launched by the European Commission in 2017, provides a standardized methodology for assessing building sustainability throughout their life cycle, incorporating energy performance, environmental impact, occupant health and comfort, and climate resilience. [2]

International initiatives such as BREEAM, LEED, and the Passivhaus standard further emphasize the growing importance of ecological renovation. Moreover, the European Green Deal and the objective of climate neutrality by 2050 position energy-efficient renovation at the core of sustainable construction strategies. [3] [4]

The originality of this research lies in the comprehensive comparative evaluation of five insulation materials: expanded and extruded polystyrene (conventional solutions) versus basalt wool, sheep wool, cellulose, wood fibers. Both energy performance and environmental impact are analyzed to achieve the following objectives:

- Perform a comparative assessment of the energy efficiency of conventional versus ecological insulation materials in the context of renovating an existing office building;
- Quantify the environmental impact of each insulation material, with a focus on $CO_2$ emissions throughout their life cycle;
- Demonstrate the viability of ecological materials as sustainable alternatives to conventional solutions;
- Provide practical recommendations for industry professionals to facilitate widespread adoption of ecological insulation;
- Contribute to the application of Level principles and other international sustainability standards in Romanian construction practice.

This study adopts a mixed-methods approach, integrating theoretical analysis with a practical case study. The methodology includes:

- Quantitative comparison of the thermophysical properties of the studied insulation materials;
- Energy modeling of a selected office building using specialized software (DesignBuilder v7.3.1.003);
- Life Cycle Assessment (LCA) to evaluate the environmental impact of each material using DesignBuilder v7.3.1.003 and One Click LCA;
- Integration of Level(s) principles in the overall assessment of renovation interventions.

Grounded in the principles of sustainable architecture, building physics, and European energy efficiency standards, this study applies its methodology to a real office building, yielding concrete and actionable results. Ultimately, this research aims to advance knowledge in ecological renovation and equip construction professionals with the tools required to implement sustainable solutions that align with environmental protection and $CO_2$ reduction objectives.

## 2. Building description and characteristics

### 2.1 Building Description

#### 2.1.1 Geometric characteristics

The analyzed building is an office building with a P+1 height, a total usable area of 850 $m^2$, and a usable volume of 2,978 $m^3$. The building geometry has been optimized to ensure efficient use of interior space while complying with local urban regulations. Location: Bucharest, Romania, climate zone II, characterized by warm summers and moderate winters, which is crucial for the design of heating, cooling, and ventilation systems.

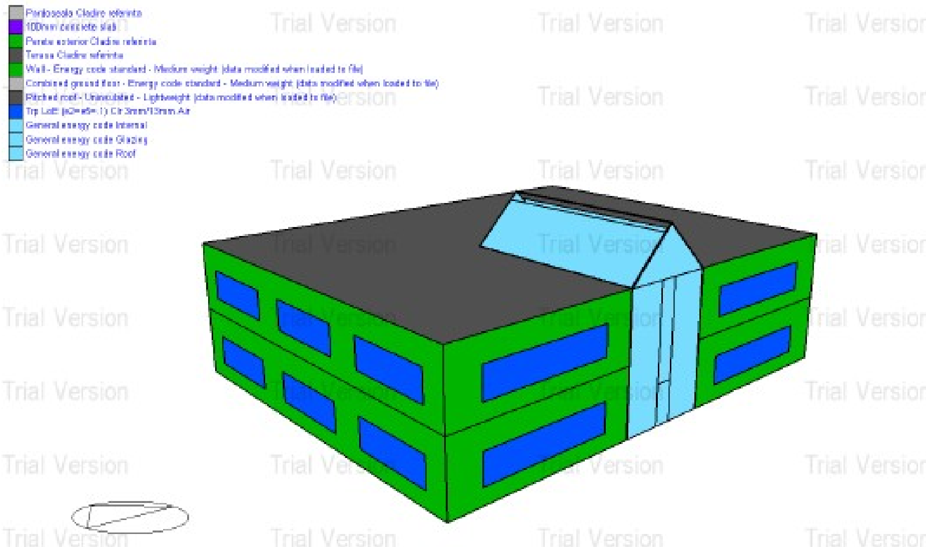


Fig. 2.1 – Front view in DesignBuilder

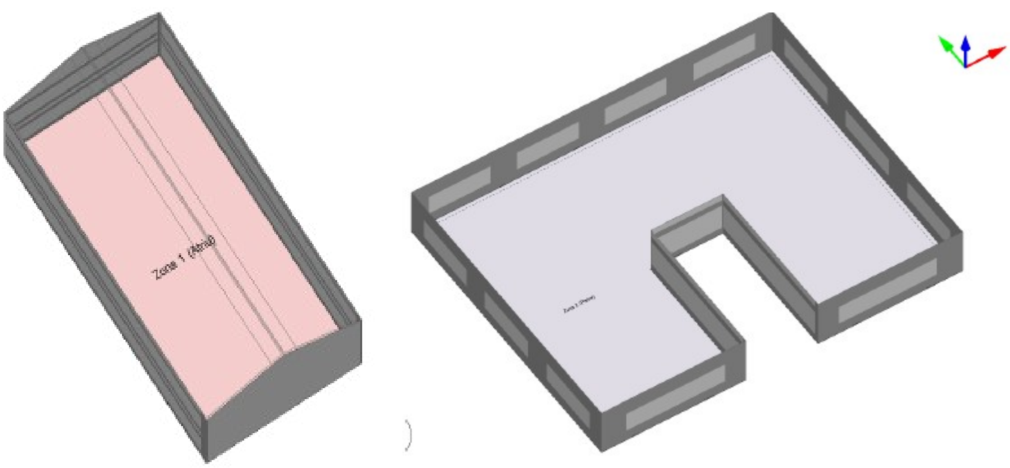

Fig. 2.2 – Top view of thermal zone 1 (Atrium) and thermal zone 2 (Ground Floor)

### 2.1.2 Occupancy and requirements

The building has an occupancy density of 12 m² per person, which results in a maximum of 70 people. The activity carried out by the occupants corresponds to sedentary office work. The working schedule follows a standard pattern, with 21 days of annual leave excluded from the operating period.

The daily domestic hot water demand is estimated at 5 liters per person, which corresponds to a total of 350 liters per day at a reference temperature of 60°C. The indoor temperature during the heating season is maintained at 20°C, with a setback temperature of 12°C outside working hours. In the cooling season, the setpoint is

25°C, with a setback temperature of 30°C. The acceptable relative humidity range is set between 35% and 70%, ensuring comfort and compliance with indoor air quality standards.

The minimum fresh air supply is 4,000 $m^3/h$, designed in accordance with I5/2022 requirements for category IDA 2. The infiltration rate is assumed at 0.1 $h^{-1}$, reflecting the air exchange due to building envelope permeability.

Artificial lighting is provided to achieve an average illuminance level of 300 lux in occupied spaces.

### 2.2 Building Envelope

The vertical opaque elements consist of a multilayer wall with the following structure: 3 cm lime-cement plaster, 10 cm insulation (five variants considered: EPS, basalt wool, sheep wool, cellulose, or wood), 30 cm hollow brick, and 1.3 cm gypsum plaster. This configuration ensures thermal resistance while allowing comparison between conventional and bio-based insulating materials.

The horizontal opaque elements are represented by two cases. For the roof terrace, the buildup includes 3 cm gravel, 1.5 cm waterproofing, 3 cm cement screed, 20 cm insulation (XPS, basalt wool, sheep wool, cellulose, or wood), 0.8 cm vapor barrier, 5 cm lightweight concrete screed, 10 cm reinforced concrete, and 1.5 cm lime plaster. For the ground floor slab, the composition includes 3 cm lime-cement plaster, 15 cm insulation (EPS, basalt wool, sheep wool, cellulose, or wood), 10 cm reinforced concrete, 5 cm leveling screed, and 2 cm wooden parquet.

The transparent elements are defined by exterior joinery with triple glazing of the type Clr 3 mm / 13 mm air gap. This solution ensures a low thermal transmittance, contributing to reduced heat losses in winter and minimized heat gains in summer.

All materials sourced from DesignBuilder v7.3.1.003 library, except manually input thermal insulation properties

### 2.3 Building Systems

#### 2.3.1 Heating System

The heating system is based on an air-to-water heat pump with a nominal capacity of 72.70 kW and a coefficient of performance (COP) of 4.33. This indicates that for every unit of electricity consumed, the system can provide more than four units of thermal energy, ensuring both high efficiency and reduced operating costs.

Heat distribution is primarily achieved through underfloor heating, which ensures uniform temperature levels, improved thermal comfort, and low supply water temperatures that are well-suited to heat pump operation. To cover peak load conditions or sudden variations in demand, the system is supplemented with fan coil units. The integration of underfloor heating and fan coil units allows the heat pump to operate closer to its optimal efficiency range, avoiding oversizing and ensuring adaptability to varying thermal loads.

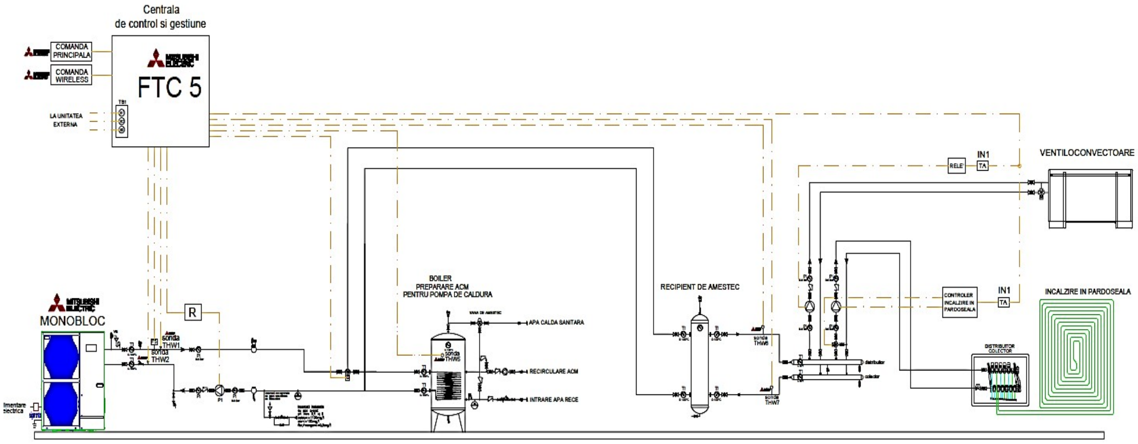


Fig. 2.3 – Heating system schematic [5]

### 2.3.2 Ventilation and Air Conditioning System

The cooling and ventilation system relies on a reversible air-to-water heat pump with a nominal cooling capacity of 61.50 kW and an energy efficiency ratio (EER) of 3.12. This performance ensures efficient operation during the cooling season, with the ability to switch to heating mode when required.

Fresh air supply is provided through an Air Handling Unit (AHU) with a capacity of 4,000 m³/h. The AHU is equipped with a heat recovery system, capable of recovering between 50% and 85% of the exhaust air energy, thereby reducing the overall cooling and heating demand and improving indoor air quality.

Thermal energy is distributed via fan coil units, each equipped with individual control for every office. This setup allows occupants to adjust temperature according to their comfort needs while enabling zone-level energy management.

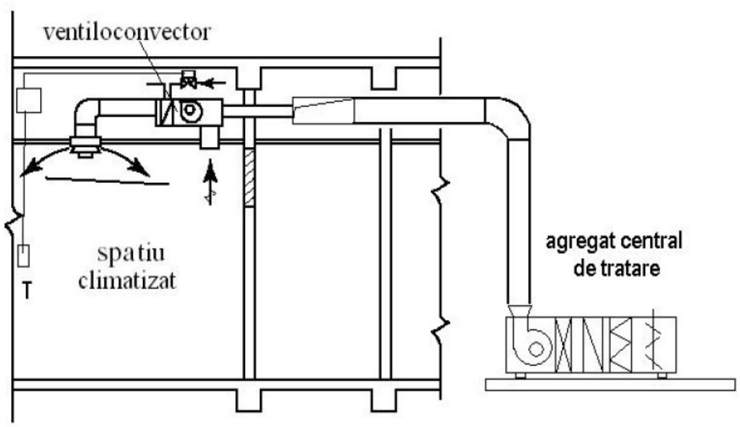


Fig. 2.4 – Centralized fresh air system to fan coils [6]

#### 2.3.3 Domestic Hot Water System

A 500 L storage boiler, connected to the heat pump via an extended coil, maintains water at 60°C and ensures continuous domestic hot water availability during the working day.

## 3. Energy and Environmental Analysis Methodology

### 3.1 Software Tools

DesignBuilder is used for dynamic energy simulation, comfort evaluation, lighting performance, energy use, and operational emissions assessment. [7]. One Click LCA supports whole-life environmental impact analysis from "Cradle-to-Grave," with BIM integration and access to a verified database. [8].

### 3.2 Simulation Parameters

The simulation uses a meteorological file for Bucharest, containing hourly data for a typical year. This ensures that both heating and cooling loads are accurately calculated under local climatic conditions.
The occupancy profile is defined at 12 m² per person, consistent with a standard office schedule. This setting reflects typical workplace density and usage patterns.
Internal gains are considered as 120 W per person from occupants, 15 W/m² from equipment, and 10 W/m² from lighting. These inputs capture the main sources of internal heat load in office environments.
The Life Cycle Assessment (LCA) is based on a building lifespan of 50 years. Replacement cycles are included: HVAC systems every 25 years, exterior joinery every 30 years, and the structure and envelope every 50 years. This approach allows for a comprehensive evaluation of environmental impacts across the full life cycle of the building.

### 3.3 Life Cycle Assessment and $CO_2$ Emissions

The evaluation covers the full life cycle of the building according to EN 15804, including:

- **A1–A3 (Product stage):** raw material extraction, transport, manufacturing
- **A4 (Construction stage):** transport to site, construction processes
- **B4–B5 (Use stage – replacements and renovations):** HVAC systems (25 years), joinery (30 years), generating additional emissions
- **C1–C4 (End-of-life stage):** demolition, waste transport, recycling/recovery, final disposal

DesignBuilder calculates operational emissions and allows manual input for construction and demolition stages. One Click LCA provides full life-cycle $CO_2$-equivalent emissions per m² of usable floor area, using verified datasets and including $CO_2$, $CH_4$, and $N_2O$ equivalences based on IPCC AR5/AR6 methodology.

### 3.4 Analysis Scenarios

The comparative study evaluates **5 insulation materials** applied to the building envelope, assessing their thermal performance, energy consumption, and life cycle $CO_2$ emissions. *The analysis combines results from DesignBuilder simulations, and One Click LCA for a comprehensive "Cradle-to-Grave" assessment (A1–C4).*

#### 3.4.1. Scenario 1 - Expanded and Extruded Polystyrene (EPS & XPS)

Scenario 1 evaluates a combined thermal insulation system using EPS ($\lambda$ = 0.04 W/mK, 16 kg/m³ [9], embodied carbon 4.205 $kgCO_2e/kg$) and XPS ($\lambda$ = 0.037 W/mK, 32 kg/m³ [10], embodied carbon 5.84 $kgCO_2e/kg$) in an 850 m² office building. [11] The difference in embodied carbon reflects the more complex manufacturing process and use of blowing agents for XPS. The thermal resistance achieved is R = 2.67 m²K/W for walls and R = 3.74 m²K/W for the floor. The building's heating demand is 62.66 kW and cooling demand is 57.02 kW (DesignBuilder).

Annual final energy consumption: 68.388 MWh/year, with specific final energy 80.46 kWh/m²·year and specific primary energy 201.14 kWh/m²·year.

Energy breakdown:

- Heating: 29.051 MWh
- Cooling: 24.531 MWh
- Domestic hot water: 1.305 MWh
- Ventilation: 5.628 MWh
- Lighting: 7.872 MWh

Auxiliary pumps: Heating 1.072 kWh, Cooling 715 kWh

Operational $CO_2$ emissions were calculated using $fCO_2 = 0.107$ $kgCO_2/kWh$ (electricity from SEN). Annual $CO_2$: 21.52 $kgCO_2/m^2$·year and thus 50-year operational $CO_2$: 914.70 $tCO_2e$. Distribution by system: Heating 388.56 $tCO_2e$, Cooling 328.11 $tCO_2e$, Auxiliary systems 198.03 $tCO_2e$

Life Cycle Assessment (LCA) calculated with the software One Click LCA 53.4 $tCO_2e$

- Building LCA (phases A1–A4, B4–B5, C1–C4): 2,169.772 $tCO_2e$
- Total LCA including operational use: 3,084.47 $tCO_2e$
- Specific LCA emissions: 3.63 $tCO_2e/m^2$

**Most contributing materials (Global warming)** — Compare data (1)

| No. | Resource | Cradle to gate impacts (A1-A3) | Of cradle to gate (A1-A3) | Sustainable alternatives | |
|---|---|---|---|---|---|
| 1. | Wood plastic composite products, 23.24 kg/m2, 1180 kg/m3 ? | 26 tonnes $CO_2e$ | 13.7 % | Show sustainable alternatives | Add to compare |
| 2. | Bricks, 226x104x60, 226x85x60 mm ? | 24 tonnes $CO_2e$ | 12.5 % | Show sustainable alternatives | Add to compare |
| 3. | EPS insulation, L=0.038 W/mK, R=4.59 m2K/W, 120 mm, 5.44 kg/m2, 45.33 kg/m3, Lambda=0.038 W/(m.K) ? | 22 tonnes $CO_2e$ | 11.2 % | Show sustainable alternatives | Add to compare |
| 4. | Levelling screed for floor heating, 1.7 kg/m2/mm, 1700 kg/m3 ? | 17 tonnes $CO_2e$ | 8.6 % | Show sustainable alternatives | Add to compare |
| 5. | Ready-mix concrete, 50 MPa, 2301 kg/m3 ? | 16 tonnes $CO_2e$ | 8.1 % | Show sustainable alternatives | Add to compare |
| 6. | Ready-mix concrete for foundations and infrastructure for aggressive soils, C45 XF1 CEM III/A, [A4 = 0 km] ? | 15 tonnes $CO_2e$ | 8.0 % | Show sustainable alternatives | Add to compare |
| 7. | XPS Insulation board, L=0.035 W/mK , R=1 m2K/W, 150 mm, 600 mm x 1200-2400 mm, 5.4 kg/m2, 36 kg/m3 ? | 13 tonnes $CO_2e$ | 6.5 % | Show sustainable alternatives | Add to compare |
| 8. | Ready-mix concrete, 25 Mpa, 2400 kg/m3 ? | 9,9 tonnes $CO_2e$ | 5.1 % | Show sustainable alternatives | Add to compare |
| 9. | Aluminium frame window triple glazed, non-operable, 50% recycled aluminium, 1.48 m x 2.18 m, 30.7 kg/m2 ? | 9,9 tonnes $CO_2e$ | 5.1 % | Show sustainable alternatives | Add to compare |
| 10. | Argon gas filled insulating glass unit (IGU) with clear float glass panes, triple glazed, 4-14-4-14-4, 30 kg/m2 ? | 9 tonnes $CO_2e$ | 4.7 % | Show sustainable alternatives | Add to compare |
| 11. | Autoclaved concrete block, 425 kg/m3 ? | 8,7 tonnes $CO_2e$ | 4.5 % | Show sustainable alternatives | Add to compare |
| 12. | Heat pump, 14 kW, 226 kg/unit ? | 8,7 tonnes $CO_2e$ | 4.5 % | Show sustainable alternatives | Add to compare |
| 13. | Reinforcement steel, French average, ? | 8,1 tonnes $CO_2e$ | 4.2 % | Show sustainable alternatives | Add to compare |
| 14. | Solidwood flooring, multiple species, thickness range: 8 - 22mm, 4.38kg/m2, 548 kg/m3 oven-dry, moisture content < 13% ? | 1,8 tonnes $CO_2e$ | 0.9 % | Show sustainable alternatives | Add to compare |

Figure 3.1: One Click LCA overview of embodied carbon. - (EPS & XPS)

### 3.4.2. Scenario 2 - Basalt Wool

Scenario 2 evaluates the use of basalt wool as thermal insulation, a mineral product with $\lambda$ = 0.035 W/mK, density 40 kg/m³ [12], and embodied carbon 1.12 $kgCO_2e/kg$ [13]. The lower embodied carbon compared to plastics reflects the manufacturing process based on melting volcanic rocks. Thermal resistance achieved: R = 2.98 m²K/W for Walls, 4.91 m²K/W for roof and 4.22 m²K/W for the floor Heating demand: 61.68 kW; Cooling demand: 56.12 kW (DesignBuilder).

Annual final energy consumption: 62.969 MWh/year, with specific final energy 74.08 kWh/m²·year and specific primary energy 185.21 kWh/m²·year. Energy breakdown:

- Heating: 25.847 MWh
- Cooling: 22.317 MWh
- Domestic hot water: 1.306 MWh
- Ventilation: 5.628 MWh
- Lighting: 7.872 MWh

Auxiliary pumps: Heating 1.072 kWh, Cooling 715 kWh

Operational $CO_2$ emissions were calculated using $fCO_2$ = 0.107 $kgCO_2/kWh$ (electricity from SEN). Annual $CO_2$: 19.82 $kgCO_2/m^2$·year and 50-year operational $CO_2$: 842,22 $tCO_2e$. Distribution by system: Heating 345.7 $tCO_2e$, Cooling 298,49 $tCO_2e$, Auxiliary systems 198.03 $tCO_2e$

Life Cycle Assessment (LCA) calculated with the software One Click LCA was 8,44 $tCO_2e$

- Building LCA (A1–A4, B4–B5, C1–C4): 2,124.815 $tCO_2e$
- Total LCA (including operational use): 2,967.04 $tCO_2e$
- Specific LCA emissions: 3.49 $tCO_2e/m^2$

### 3.4.3. Scenario 3 - Sheep Wool insulation

Scenario 3 evaluates sheep wool as a natural insulation material with $\lambda = 0.038$ W/mK, density 18 $kg/m^3$ [14], and embodied carbon of only 0.14 $kgCO_2e/kg$ [13] , the lowest value among all previously analyzed materials. This performance results from its natural origin and minimal processing, wool being a by-product of the textile and food industries. Thermal resistance achieved: R = 2.79 $m^2K/W$ for Walls, 4.55 $m^2K/W$ for roof and 3,92 $m^2K/W$ for the floor Heating demand: 62.4 kW; Cooling demand: 56.92 kW (DesignBuilder). Sheep wool also provides additional benefits such as natural humidity regulation and the ability to absorb and neutralize air pollutants Annual final energy consumption: 67.257 MWh/year, with specific final energy 79.13 $kWh/m^2\cdot year$ and specific primary energy 197.82 $kWh/m^2\cdot year$.

Energy breakdown:

- Heating: 28.400 MWh
- Cooling: 24.051 MWh
- Domestic hot water: 1.306MWh
- Ventilation: 5.628 MWh
- Lighting: 7.872 MWh

Auxiliary pumps: Heating 1.072 kWh, Cooling 715 kWh

Operational $CO_2$ emissions were calculated using $fCO_2 = 0.107$ $kgCO_2/kWh$ (electricity from SEN). Annual $CO_2$: 19.82 $kgCO_2/m^2\cdot year$ and 50-year operational $CO_2$: 842,22 $tCO_2e$

Distribution by system: Heating 345.7 $tCO_2e$, Cooling 298,49 $tCO_2e$, Auxiliary systems 198.03 $tCO_2e$

Life Cycle Assessment (LCA) calculated with the software One Click LCA was 6.28 $tCO_2e$ (One Click LCA)

- Building LCA (A1–A4, B4–B5, C1–C4): 2,122.655 $tCO_2e$
- Total LCA (including operational use): 3,022.22 $tCO_2e$
- Specific LCA emissions: 3.56 $tCO_2e/m^2$

### 3.4.4. Scenario 4 - Cellulose Insulation

Scenario 4 considers cellulose as the insulation material, with a thermal conductivity of $\lambda = 0.039$ W/mK and a density of 40 $kg/m^3$ [15]. The embodied carbon is negative, at -0.39 $kgCO_2e/kg$ [15], reflecting its origin from recycled paper and recovered wood fibers. Thermal resistance achieved: R = 2.73 $m^2K/W$ for Walls, 4.45 $m^2K/W$ for roof and 3.83 $m^2K/W$ for the floor

Heating demand: 62.73 kW; Cooling demand: 57.27 kW (DesignBuilder).

Annual final energy consumption: 68.298 MWh/year, with specific final energy 80.35 kWh/m²·year and specific primary energy 200.88 kWh/m²·year.

Energy breakdown:

- Heating: 29.0 MWh
- Cooling: 24.491 MWh
- Domestic hot water: 1.306 MWh
- Ventilation: 5.628 MWh
- Lighting: 7.872 MWh

Auxiliary pumps: Heating 1.072 kWh, Cooling 715 kWh

- Operational $CO_2$ Emissions

Operational $CO_2$ emissions were calculated using $fCO_2$ = 0.107 $kgCO_2/kWh$ (Mc 001-2022) [21] (electricity from SEN).

- Annual $CO_2$: 21.49 $kgCO_2/m^2$·year
- 50-year operational $CO_2$: 913.49 $tCO_2e$

Distribution by system: Heating 387.89 $tCO_2e$, Cooling 327.57 $tCO_2e$, Auxiliary systems 198.03 $tCO_2e$

Life Cycle Assessment (LCA) calculated with the software One Click LCA was 2.80 $tCO_2e$ (One Click LCA)

- Building LCA (A1–A4, B4–B5, C1–C4): 2,119.17 $tCO_2e$
- Total LCA (including operational use): 3,032.66$tCO_2e$
- Specific LCA emissions: 3.57 $tCO_2e/m^2$

### 3.4.5. Scenario 5 -Wood Fibers Insulation

- Insulation System Characteristics

Scenario 6 evaluates wood fibers as an insulation material, with a thermal conductivity of $\lambda$ = 0.038 W/mK and a high density of 110 kg/m³ [16]. The embodied carbon is negative, at -1.05 $kgCO_2e/kg$ [17], reflecting the long-term carbon storage capability of wood.

- Thermal Performance

Thermal resistance achieved: R = 2.73 m²K/W for Walls, 4.55 m²K/W for roof and 3.92 m²K/W for the floor

Heating demand: 62.4 kW; Cooling demand: 56.92 kW (DesignBuilder).

Annual final energy consumption: 67.257 MWh/year, with specific final energy 79.13 kWh/m²·year and specific primary energy 197.82 kWh/m²·year.

Energy breakdown:

- Heating: 28.4 MWh
- Cooling: 24.051 MWh
- Domestic hot water: 1.305 MWh
- Ventilation: 5.627 MWh
- Lighting: 7.872 MWh

Auxiliary pumps: Heating 1.072 kWh, Cooling 715 kWh

Operational $CO_2$ emissions were calculated using $fCO_2$ = 0.107 $kgCO_2$/kWh (Mc 001-2022 [44]). Annual $CO_2$: 21.17 $kgCO_2/m^2$·year and 50-year operational $CO_2$: 899.57 $tCO_2e$. Distribution by system: Heating 379.85 $tCO_2e$, Cooling 321.69 $tCO_2e$, Auxiliary systems 198.03 $tCO_2e$

Life Cycle Assessment (LCA) calculated with the software One Click LCA was 5.32 $tCO_2e$ (One Click LCA)

- Building LCA (A1–A4, B4–B5, C1–C4): 2,121.696 $tCO_2e$
- Total LCA (including operational use): 3,021.26 $tCO_2e$
- Specific LCA emissions: 3.57 $tCO_2e/m^2$

## 4. Results summary

From Table 1 we can see that EPS & XPS record the highest embodied emissions with 2,169.77 $tCO_2e$, while basalt wool and natural materials remain slightly lower, around 2,120 $tCO_2e$. When operational use is included, total life-cycle emissions reach 3,084.47 $tCO_2e$ for EPS/XPS and only 2,967.04 $tCO_2e$ for basalt wool, the lowest among all cases. Natural materials fall in between, with values around 3,021–3,033 $tCO_2e$. Specific emissions per square meter confirm this trend: EPS/XPS has the highest value at 3.63 $tCO_2e/m^2$, while basalt wool achieves the best performance at 3.49 $tCO_2e/m^2$. Natural options remain slightly higher, 3.56–3.57 $tCO_2e/m^2$, but still perform better than EPS/XPS. Overall, basalt wool offers the most favorable balance between energy efficiency and environmental impact, while natural materials provide ecological benefits yet show slightly higher operational contributions. EPS/XPS, although cheaper, ranks lowest in sustainability.

*Table 1*

**LCA indicators**

| | EPS & XPS | Basalt Wool | Sheep Wool | Cellulose | Wood Fibers |
|---|---|---|---|---|---|
| Building LCA (phases A1–A4, B4–B5, C1–C4) $tCO_2e$ | 2169,772 | 2124,815 | 2122,655 | 2119,17 | 2121,69 |
| Total LCA including operational use: $tCO_2e$ | 3084,47 | 2967,04 | 3022,22 | 3032,66 | 3021,26 |
| Specific LCA emissions: $tCO_2e/m^2$ | 3,63 | 3,49 | 3,56 | 3,57 | 3,57 |

The comparative graphs show that basalt wool consistently performs best, with the lowest specific primary energy (185.21 $kWh/m^2$·year), the lowest total LCA emissions (2,967.04 $tCO_2e$), and the lowest specific LCA emissions (3.49 $tCO_2e/m^2$). Natural materials such as sheep wool, cellulose, and wood fibers provide intermediate results, slightly higher in total and specific emissions but still significantly better than EPS/XPS. EPS/XPS achieves the lowest cost but performs worst environmentally, with the highest specific final energy (80.46 $kWh/m^2$·year), highest total LCA emissions (3,084.47 $tCO_2e$), and highest specific LCA emissions (3.63 $tCO_2e/m^2$). Overall, basalt wool offers the most balanced and sustainable solution, while natural materials represent viable ecological alternatives, and EPS/XPS remains the least sustainable despite its cost advantage.

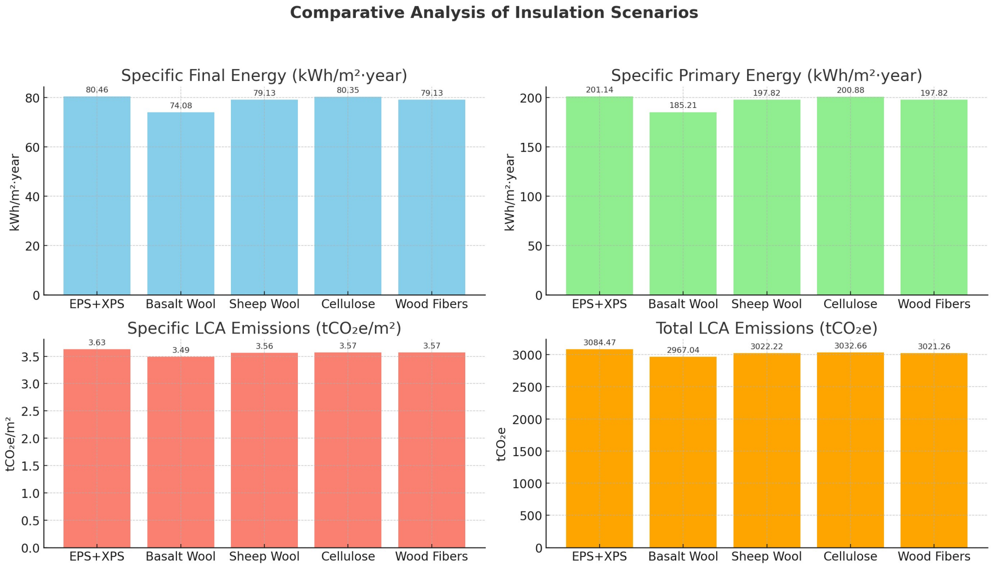


Figure 3.2: Comparison between the different insulation materials

## 5. Conclusions

This study comparatively evaluated five thermal insulation solutions for an office building, integrating energy, environmental, and economic perspectives. Results indicate that no single material is universally optimal; rather, choices depend on specific priorities and constraints.

Basalt wool delivers the best overall performance, with the lowest primary energy demand (185.21 $kWh/m^2 \cdot year$) and life-cycle $CO_2$ emissions (2,967 $tCO_2e$). It reduces energy use by 7.9% compared to EPS/XPS and ensures stable thermal comfort.

Natural insulation materials (cellulose, hemp, wood fibers, sheep wool) achieve intermediate energy performance (197.82–200.88 $kWh/m^2 \cdot year$). Their major advantage is negative embodied carbon, acting as carbon sinks and offsetting operational emissions.

From a cost perspective, EPS/XPS has the lowest investment (29.33 kRON) but the highest environmental burden. Cellulose provides the best balance at 71.20 kRON, while sheep wool and wood fibers exceed 200 kRON, positioning them as premium solutions.

Overall, basalt wool ranks highest in energy and environmental performance, natural materials add value through sustainability and comfort, while EPS/XPS ranks lowest despite its low cost.

Energy performance converges across materials, with differences below 8%, highlighting that careful design and material thickness can be as influential as material selection itself. In contrast, environmental impact varies significantly, with natural materials offering carbon storage that transforms buildings into temporary $CO_2$ sinks. Economic analysis reveals a wide range of initial costs, reflecting market maturity and adoption challenges for emerging materials. Hybrid strategies that combine different insulation types emerge as the most promising approach, optimizing thermal efficiency, cost, and sustainability simultaneously. Overall, the research demonstrates the value of a holistic methodology that integrates life-cycle assessment, dynamic energy simulations, and real-market economic data, pointing toward innovative, resilient, and sustainable solutions for the building sector.

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