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Assessment of Retrofit Strategies and Material Selection for Sustainable Building Practices: A Life Cycle Assessment of a Residential Building

TESI DI LAUREA MAGISTRALE IN
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Abstract

The thesis presents a critical analysis of the energy refurbishment design choices made for ALER assets, focusing on a residential building in Milan. It analyses the environmental impact of the proposed energy efficiency interventions over a sixty-year life cycle, employing relevant tools and inputs for the assessment.

Nowadays mitigating CO₂ emissions throughout the building lifecycle is crucial, including stages such as extraction, manufacturing, transportation, construction, maintenance, energy consumption and disposal. This comprehensive method, known as Life Cycle Assessment (LCA), is crucial for understanding and minimizing a building's environmental impact from cradle to grave.

The analysis highlights the need to consider mechanical system improvements due to the building's substantial energy consumption. However, the aim of the study is to explore and demonstrate how strategic selection of materials can significantly influence the building's environmental footprint. This approach underscores the critical role of material choice in promoting sustainable development, reducing emissions, and enhancing energy efficiency.

The study offers an in-depth comparison of alternative insulation materials compatible with the ETICS system, highlighting their carbon contributions.

The results underscore the importance of choosing durable, long-lasting insulation materials to reduce refurbishment and environmental impacts. Adopting advanced recycling strategies, using biodegradable materials, prioritizing locally produced materials, and employing efficient transportation methods are essential for minimizing the environmental impact over the building life cycle.

Future studies should explore a broad range of materials, assessing their insulative qualities, environmental advantages, and potential to lower global warming, to identify the most sustainable insulation options available.

Key-words: Life Cycle Assessment (LCA), Sustainable Development, Energy Efficiency, Carbon Footprint, Material Selection, Insulation Materials

Abstract in lingua italiana

La tesi presenta un'analisi critica delle scelte progettuali per l'efficientamento energetico degli appartamenti ALER, concentrandosi su un edificio residenziale a Milano. Essa analizza l'impatto ambientale degli interventi di efficientamento energetico proposti su un ciclo di vita di sessant'anni, impiegando strumenti e input pertinenti per la valutazione.

Oggi è fondamentale ridurre le emissioni di CO₂ in tutto il ciclo di vita dell'edificio, includendo fasi come l'estrazione, la produzione, il trasporto, la costruzione, la manutenzione, il consumo energetico e lo smaltimento. Questo metodo comprensivo, noto come Valutazione del Ciclo di Vita (LCA), è cruciale per comprendere e minimizzare l'impatto ambientale di un edificio dalla culla alla tomba.

L'analisi evidenzia la necessità di considerare miglioramenti ai sistemi meccanici, dato il sostanziale consumo energetico dell'edificio. Tuttavia, lo scopo dello studio è indagare e dimostrare come la selezione strategica dei materiali possa influenzare significativamente l'impronta ambientale dell'edificio. Questo approccio sottolinea il ruolo critico della scelta dei materiali nel promuovere lo sviluppo sostenibile, ridurre le emissioni e migliorare l'efficienza energetica.

Lo studio offre un confronto approfondito tra materiali isolanti alternativi compatibili con il sistema ETICS, evidenziando i loro contributi in termini di carbonio.

I risultati sottolineano l'importanza di scegliere materiali isolanti a lunga durata per ridurre la necessità di ristrutturazioni e gli impatti ambientali. Adottare strategie di riciclo avanzate, utilizzare materiali biodegradabili, dare priorità a materiali prodotti localmente e impiegare metodi di trasporto efficienti sono essenziali per minimizzare l'impatto ambientale durante il ciclo di vita dell'edificio.

Studi futuri dovrebbero esplorare una vasta gamma di materiali, valutando le loro qualità isolanti, vantaggi ambientali e il potenziale per ridurre il riscaldamento globale, per identificare le opzioni di isolamento più sostenibili disponibili.

Parole chiave: Valutazione del ciclo di vita, Sviluppo Sostenibile, Efficienza Energetica, Impronta Carbonica, Selezione dei Materiali, Materiali Isolanti

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Introduction

Background

The increasing mean atmospheric temperature, predominantly resulting from the release of greenhouse gases (GHGs), is a critical factor of global warming, significantly modifying the earth's climate and weather patterns. Human activities are the principal source of these emissions, with carbon dioxide (CO₂) being the most impactful anthropogenic greenhouse gas [1]. Its abundance and long atmospheric lifespan, spanning thousands of years, make CO₂ particularly problematic [2]. Emissions arise from both natural processes and human activities, with urbanization being a notable contributor.

Rural landscapes are transformed into urban regions through urbanization, which is characterized by higher population densities and the extension of the built environment in both horizontal and vertical directions. The built environment, which consists of surroundings created by humans and used for different purposes, is essential to the economic and social development of a country. The building sector's expansion significantly raises CO₂ emissions as metropolitan areas grow. This sector is divided into residential and non-residential sectors, covering everything from building construction to building operations [3]. It is responsible for significant environmental impacts, including ecosystem disruption and the consumption of natural resources. The building sector is a major energy consumer and a source of various emissions, including GHGs, particulate matter, sulfur dioxide, carbon monoxide, and nitrogen oxides [4].

The energy demands of the building sector, from the production and transportation of materials to construction and maintenance, contribute immensely to CO₂ emissions [5]. Buildings are responsible for almost 39% of yearly global CO₂ emissions, a startling statistic that highlights their significance for both wealthy and developing nations. Consequently, implementing CO₂ emission mitigation strategies in the building sector is essential [6].

Mitigation efforts should focus on energy conservation and the implementation of strategies to reduce emissions. Exploring the issues, impacts, and potential mitigation strategies in the building sector should be the main priorities to control and reduce CO₂ emissions [7].

According to the National Oceanic and Atmospheric Administration (NOAA) Global Climate Summary, the combined land and ocean temperature has risen at an average

rate of 0.07 °C per decade since 1880, with a more rapid increase of 0.18 °C per decade since 1981. These phenomena have far-reaching consequences, impacting environmental conditions, food and water availability, weather patterns, and sea levels. CO₂ also contributes to acid rain, causing physical damage to vegetation and infrastructure [8].

The impacts of CO₂ emissions are evident today, extending beyond temperature rise to affect ecosystems and communities worldwide. Understanding and addressing these challenges is crucial for sustainable development and the health of our planet.

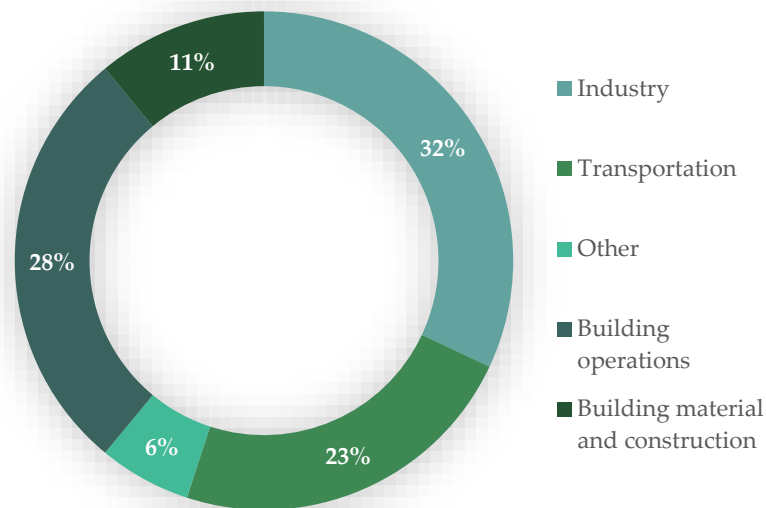


Figure 1. Global CO₂ emissions by sector [9].

Strategies of CO₂ emissions

The challenge in making building practices more sustainable is the huge amount of CO₂ they release. This is mostly because we rely on energy sources that aren't good for the environment, like fossil fuels. Right now, sustainable energy only makes up a small part of the energy used in this sector.

Most of the CO₂ in buildings comes from using fossil fuels for energy-intensive purposes such as heating, which is the major concern as it contributes significantly to global greenhouse gas emissions.

One way to use more sustainable and efficient strategies is to break down the whole building process, from putting up the structure to maintaining it, and look closely at each step. This detailed look can help us find better, more efficient ways to build and maintain buildings.

In the last twenty years, there has been a global movement among governments and policymakers to address CO₂ emissions across various industries.

These methods are designed to be effective at different levels in reducing CO₂ emissions covering the building sector [6].



Figure 2. Strategies of CO₂ emissions in building sector

Low carbon technologies

Low carbon technologies in the building sector refer to methods, materials, and innovations that minimize carbon dioxide and other greenhouse gas emissions.

Notable examples include sustainable energy technologies such as evaporative cooling, passive ventilation, solar photovoltaics, dehumidification, and energy recovery systems. These technologies not only aim to minimize greenhouse gas emissions, particularly CO₂, but also bring a multitude of benefits [10].

The most significant advantage is the substantial reduction in energy consumption. Buildings equipped with technologies such as solar photovoltaic systems, energy-efficient HVAC systems, and smart building technologies consume far less energy compared to traditional buildings. This not only leads to a smaller carbon footprint but also translates into lower operational costs over time. The energy savings achieved often compensate for the initial investments in these technologies [11].

Furthermore, buildings that incorporate low carbon technologies offer enhanced comfort and healthier living environments. Green roofing, for instance, not only insulates but also purifies the air [12]. Smart systems optimize indoor temperature and air quality, contributing to a more comfortable and productive environment. There's also the aspect of resilience and sustainability. Buildings that are less dependent on conventional energy are more resilient to fluctuations in energy prices and supply, making them sustainable in the long term [13].

However, integrating low carbon technologies is not without its challenges [14]. The initial investment in such technologies can be significant. The cost barrier often makes it difficult for stakeholders to commit to these solutions, despite the long-term savings [15]. Additionally, implementing these technologies, especially in existing buildings, requires a certain level of technical expertise and can pose integration challenges [16]. Maintenance and reliability of new technologies are other concerns that need to be addressed.

The involvement of policy and market is crucial in managing these issues. Government incentives like subsidies, tax breaks, and grants can make low carbon technologies more accessible and financially viable. Furthermore, the adoption of low-emission and energy-efficient technologies is enforced by strict building norms and requirements [17]. Public awareness and the growing demand for sustainable living spaces further drive the market, creating a virtuous cycle of innovation, implementation, and improvement.

Low carbon technologies represent a vital pathway for the building sector to reduce its environmental footprint, enhance efficiency, and contribute to global climate goals. While challenges exist, the long-term benefits and evolving innovations make these technologies a key focus for sustainable development.

Building process and materials

Mitigating CO₂ emissions in the building process is crucial and involves understanding various stages such as extraction, manufacturing, transportation, construction, maintenance, and disposal. Sustainable sourcing practices, such as utilizing recycled materials, significantly lower the overall carbon footprint. This comprehensive evaluation, known as Life Cycle Assessment (LCA), is significant in understanding and reducing a building's environmental footprint from cradle to grave [16].

Choosing the right sustainable building materials can lead to a reduction of up to 30% in embodied CO₂ emissions throughout the building's lifetime. Studies have shown that materials like reinforced concrete and clay bricks are significant contributors to carbon emissions, accounting for about 60% to 70% of a building's total embodied carbon [18] [11]. This emphasizes the need for careful material selection in sustainable construction practices to minimize environmental impact.

Construction techniques and the machinery used play a crucial role in determining the environmental impact [13]. Energy-efficient construction methods, coupled with optimal waste management strategies, substantially reduce the ecological footprint. Additionally, the transportation of materials to construction sites and the ensuing emissions are critical factors [19]. Utilizing local materials and optimizing logistics are effective strategies to mitigate this impact.

Post-construction, the focus shifts to the building's operational energy efficiency. This phase examines the efficiency of systems like heating, cooling, and lighting [20]. Integrating renewable energy sources and employing smart technologies to optimize energy usage are key to reducing the operational carbon footprint [21].

An important aspect of LCA is the end-of-life stage of building materials. Strategies for deconstruction, recycling, and repurposing materials play an essential role in minimizing the environmental impact at this stage [22].

The regulatory landscape significantly shapes these assessments. Governments and international bodies are formulating guidelines and regulations to standardize environmental impact assessments in the building sector. Certification programs like LEED and BREEAM further incentivize sustainable practices by recognizing and certifying environmentally responsible buildings [23].

Although standardizing assessment methods remains a challenge, efforts are being made to develop universal standards. Innovations in material science promise the development of new, environmentally friendly materials. Furthermore, architects and builders are increasingly embedding life cycle thinking into their designs, aiming for sustainability throughout the building's lifespan.

The impact assessment of building processes and materials is a dynamic field, crucial for driving the building sector towards sustainable practices. By considering every stage of a building's life cycle, from material sourcing to end-of-life management, the environmental footprint of our built environment can be significantly reduced.

Objective

The primary goal of this research is to conduct an examination of the energy refurbishment design decisions discussed in a prior analysis. Centered on a residential structure in Milan, it aims to evaluate the environmental impact of suggested energy efficiency measures.

The study reveals that the adoption of new, energy-efficient technologies plays a crucial role in reducing energy consumption compared to traditional buildings. Nonetheless, the study's core intention is to investigate and demonstrate the profound impact that strategic material selection can have on a building's environmental footprint, highlighting the pivotal role of material choice in fostering sustainable development.

Furthermore, this research aims to provide an in-depth comparison of alternative insulation materials that are compatible with the ETICS system, employing the life cycle assessment (LCA) methodology. This comparison is essential for understanding how the selection of alternative insulation options can decrease the environmental impact throughout the building's lifecycle.

Boundary Conditions

The study of the residential building has been done over 60-year life cycle.

In the first part of the analysis, which includes the environmental evaluation of the refurbishment design choices, it was important to carefully select the inputs to add in the IES and One click software to perfectly conduct the analysis.

When calculating the embodied and operational carbon is essential to consider the geographic location, as this affects the building energy consumption and the material availability and transport distances.

However, the process faced challenges due to limitations in the OneClick database, which sometimes lacked detailed Environmental Product Declarations (EPDs). This lack of information made it difficult to fully assess the sustainability of products and their fit for specific project requirements. Thus, an updated and detailed database, including comprehensive EPDs, is essential. It enables informed choices, ensuring products are not only energy-efficient but also environmentally sustainable.

Research Question

The main question was:

- How can we achieve zero carbon?
- Is it more advantageous to demolish and rebuild or should I opt for refurbishment practices?
- What contribution can I give if reaching zero carbon goes beyond my capability?

The analysis of the case study highlighted the necessity of focusing on systems and opting for more renewable choices due to the high energy consumption emissions identified. A minimal reduction was achieved by switching from a boiler to a heat pump, but it's also crucial to understand the contributions made through the building envelope, such as the design of the External Thermal Insulation Composite System (ETICS) and the choice of windows. However, the primary goal of the study is to explore how much it's possible to reduce emissions by selecting appropriate materials, without considering interventions to the systems.

Approach and Methodology

First, a comprehensive investigation of the case study features, and location is necessary, focusing on understanding the building's envelope properties, occupant schedules and ventilation profiles. Then, an environmental analysis of the building is useful to understand the baseline performance so that the refurbishment scenarios can be compared over a 60-year period of service life.

These analyses are carried out using the software IESVE to evaluate the energy consumption in kWh for each scenario depending on the type of intervention choice. The calculation of operational carbon involved the conversion of energy requirements into carbon emissions while the determination of embodied carbon has been conducted using the software OneClick LCA.

Exploring the OneClick database is useful for selecting materials and products aligned with the physical requirements of the proposed refurbishment choices. The calculation of operational carbon involved the conversion of energy requirements into carbon emissions while the determination of embodied carbon has been conducted using the software OneClick LCA.

Following this, various types of alternative insulation materials have been investigated based on literature review and market products compatible with ETICS system. These insulation materials are compared to the insulation material chosen in the last refurbishment scenario proposed in terms of embodied and operational carbon. An

analysis has been undertaken to evaluate the tradeoff among different scenarios and the limit of the evaluation.

1. State of the art

1.1 Thermal comfort in building sector

In contemporary societies, individuals typically spend about 90% of their time in indoor settings like offices, commercial and industrial buildings, and vehicles, engaging in daily activities [24] [25]. The quality of indoor air and thermal conditions in these spaces is crucial, as exposure to pollutants and extreme temperatures can negatively impact human productivity and health [26]. According to Ole Fanger, a Danish scientist whose doctoral thesis in the 1960s has been widely accepted, an in-depth study was conducted considering all relevant physical factors to enhance understanding of individuals' thermal comfort. Fanger's research under laboratory steady-state conditions posited that the main determinants of thermal comfort include mean radiant temperature (T_r), air temperature (T_a), air velocity around the human body (V_a), and ambient water vapor pressure or relative humidity (RH). These factors, in conjunction with the activity level (M) and the thermal resistance of the clothing worn by individuals (I_{cl}), were identified as crucial in assessing thermal comfort [27]. In residential buildings, maintaining a safe and comfortable indoor environment is essential. Climate change effects, such as overheating, not only impair residents' productivity and health, leading to heat-related illnesses but also strain electricity generation, increasing the risk of power outages due to heightened cooling and heating demands [28].

1.1.1 Thermal comfort regulatory documents

Regulations and standards across many countries ensure thermal comfort in buildings, impacting both commercial and residential sectors. Comfortable living and working conditions improve occupant satisfaction, which is vital for tenant retention and property value enhancement.

The evaluation of thermal comfort often focuses on temperature as the primary parameter accommodating regional and contextual variables such as the thermophysical properties of building materials, climatic conditions, age of occupants and activity levels [29].

Standards like EN-ISO 7730, EN 15251, ASHRAE 55 and ASHRAE 62.1 are essential addressing aspects of comfort like thermal comfort, air quality, acoustic and visual comfort. The ASHRAE 62.1 provides procedures and methods for meeting minimum

ventilation and IAQ requirements acceptable to human occupants and that minimizes adverse health effects [30]. The European standard EN 15251 provides indoor environmental input parameters for designing and assessing the energy performance of buildings. It addresses factors such as thermal comfort, indoor air quality and lighting [31].

The ASHRAE 55 provides guidelines for the indoor thermal environment to achieve acceptable thermal comfort for occupants. It specifies conditions for thermal comfort, including temperature, humidity, air speed, and personal factors like clothing and metabolic rate. [32] The ISO 7730 standard presents methods for predicting the general thermal sensation and degree of discomfort of people exposed to moderate thermal environments. It involves the calculation of the predictive mean vote (PMV) and the predicted percentage of dissatisfied (PPD) index to determine an acceptable range of thermal conditions for human occupancy [33].

Following the regulations mentioned, researchers conducted full-scale evaluations through case studies. Huang Zhijun and his team [34] utilized 221 temperature sensors to assess the thermal environment inside a gymnastics stadium across summer, winter, and transitional seasons. Similarly, Krüger and Givoni [27] analyzed the year-round thermal behavior of a residential home, highlighting the interaction between indoor and outdoor temperatures and how this interplay is influenced by climate and building materials. These investigations have paved the way for further advancements using computer-aided techniques, yielding more precise and comprehensive findings. For example, Hashimoto and Yoneda [35] explored the impact of different ceiling heights on thermal comfort, discovering that buildings with taller ceilings tend to maintain temperatures closer to the comfort zone. AlOtaibi [27] employed computational fluid dynamics (CFD) software to study thermal comfort in an office setting, finding significant improvements in temperature distribution and overall comfort by lowering the ceiling to 2.4 meters and integrating an underfloor air distribution system.

Research highlights the significant influence of design elements and environmental conditions on thermal comfort within buildings. Studies using both traditional methods and advanced computational simulations have shown that variables such as indoor and outdoor temperatures, ceiling heights, and air distribution systems are crucial in maintaining comfort levels. These findings emphasize the need for thoughtful architectural design that incorporates both climatic considerations and innovative technology to optimize building performance for human comfort and energy efficiency. This evolving research area continues to offer valuable insights for improving the built environment in response to the challenges of climate and sustainability.

1.1.2 Evolution of constructive solutions and thermal comfort

The pursuit of thermal comfort in buildings has been an enduring quest, reflecting a convergence of architectural innovation, technological progress, and a deepening understanding of human comfort needs.

Initially, buildings relied on their design for thermal comfort [36]. Ancient civilizations used materials like thick stone walls and high ceilings to regulate indoor temperatures, an approach that changed significantly as societies transitioned to more universally available materials such as brick and cement [37]. This shift, while economically favorable, often compromised the thermal inertia that traditional materials provided, leading to variations in thermal comfort [27].

The Industrial Revolution catalyzed the first major shift, introducing active heating systems for greater control over indoor temperatures, and later, the development of energy-efficient HVAC systems [38]. The 20th century saw innovations like central heating and the proliferation of air conditioning after the advent of electricity, revolutionizing building design and occupant comfort. As materials science advanced, better insulation techniques emerged, enhancing the energy performance of building envelopes which is a crucial determinant in achieving and maintaining thermal comfort [39].

The energy crises of the 1970s prompted a re-evaluation of energy-intensive practices. Recent years have paid attention on the building sector's energy consumption and carbon footprint, with projections indicating a potential 50% increase in global energy consumption and CO₂ emissions from buildings by 2050 [40]. This scenario has prompted the initiation of various energy efficiency programs and the adoption of carbon pricing policies [41]. Sustainable building practices are increasingly recognized as crucial for reducing energy demands and mitigate climate change [42]. Strategies like bioclimatic design, which includes glazing systems [43], thermal insulation [44], natural ventilation [45], green roofs, facades [45], sun shading [46], and evaporative cooling [47], are being proposed.

Despite the potential of these strategies, their cost-effectiveness varies by region due to differences in initial investment costs, operational and maintenance expenses, energy savings, and energy prices [48]. Energy affordability tailors approaches that align with local energy pricing and climatic conditions, ensuring that investments in sustainable building designs are both economically and environmentally beneficial.

Dauletбек and Zhou's [49] research showed that upgrading an existing building to meet passive house standards through technologies like thermal insulation, sun shading, green roofs, and enhanced glazing systems could significantly reduce its heating and cooling needs by up to 100% for heating and 22% for cooling. Despite the clear energy benefits of these passive strategies, they found the economic return over a 50-year building lifespan to be negative, ranging between a 26% to 28% unprofitability rate, largely due to the high costs of materials required for the refurbishment. Passive design strategies, while effective in reducing energy demand, often lead to longer payback periods when compared to active energy systems [50].

However, a blend of passive and active strategies could offer up to 13.5% in cost savings [51]. The study underscores passive techniques' role in reducing operational costs over time, particularly as energy needs grow—highlighting their economic advantage despite initial investment hurdles [52]. The effectiveness and economic viability of these bioclimatic strategies can vary greatly depending on local climate conditions, impacting their overall benefits. It's also essential to consider the costs of materials, energy prices, and local weather conditions.

Luo et al. [53] highlighted that utilizing 7.5 cm thick sheep wool for roofing insulation and a 2 cm thick insulation board for walls yielded considerable cost benefits over alternative insulation methods. However, despite its effectiveness in lowering energy consumption, the triple-glazed window system's financial viability was less favorable. The high upfront costs led to a payback period that exceeded the system's expected lifespan, making it a less economically attractive option despite its energy-saving potential. Naji and colleagues [54] utilized a life cycle cost (LCC) analysis to evaluate enhancements to the thermal envelope of prefabricated homes across six Australian climate regions. By improving insulation in roofs and walls, choosing better glazing materials and sizes, and refining shading, they discovered potential LCC reductions of 27% to 31%. This indicates significant cost savings over the building's lifespan by upgrading to the improved envelope design. Harkouss and colleagues [55] analyzed the impact of passive design elements such as glazing systems, thermal insulation, blinds, and natural ventilation on minimizing both thermal loads and life cycle costs (LCC) across various climates. Their study showed that integrating these elements could lead to significant LCC reductions, ranging from 52% to 87%, when compared to standard designs without these energy-efficient features.

Vargas and Hamui [56] investigated the impact of employing passive energy-saving techniques within a residential building in Mexico. Their findings highlighted a significant reduction in electricity use, approximately 23.5%, and determined that the investment in these passive solutions would pay for itself in just under six years, marking a notable 5.8-year payback period.

Ike et al. [57] highlighted the significant impact of energy prices on CO₂ emissions, emphasizing that higher energy prices lead to reduced CO₂ emissions.

In reflecting on the adoption of passive building technologies and bioclimatic design strategies, it becomes evident that while these approaches offer significant potential to reduce heating and cooling demands, their implementation is not without challenges. The initial high costs and complex maintenance requirements associated with these technologies can pose barriers to their widespread adoption, despite their proven benefits in energy efficiency and lifecycle cost reductions. The effectiveness of these strategies is also heavily influenced by specific local factors, such as climate conditions and energy pricing, underscoring the importance of tailoring solutions to individual contexts.

The diverse outcomes revealed by studies across various regions highlight the critical need for a thorough analysis of bioclimatic strategies within different economic and climatic scenarios. Such detailed examination is essential for informing policymakers

and designers in their efforts to develop buildings that strike a balance between cost-efficiency and environmental sustainability. Progress in this area of research is crucial for advancing the adoption of energy-efficient and sustainable practices in the building sector, ultimately contributing to the sector's transition towards a lower-carbon future.

1.1.3 Enhancing Building Energy efficiency through Thermal Insulation

Cooling and heating in buildings significantly impacts global energy use, contributing to almost 40% of total consumption [58]. This energy demand not only raises local environmental concerns but also contributes to global greenhouse gas emissions, with natural gas and electricity being key contributors [59]. To mitigate these effects, reducing energy use in the building sector is highly advised [60]. Among the multiple strategies that can be adopted to reduce the energy consumption, the improvement of thermal performance of building envelopes through the application of thermal insulation materials is a widely applied strategy. Enhancing insulation can significantly lower the energy demand of buildings thereby reducing both the environmental impact and the costs associated with energy production and consumption. This approach needs an investment and carries an environmental footprint related to the production, installation, dismantling, and disposal of the insulation materials [61].

Rosti and their team [62] explored the most effective thermal insulation setups for buildings utilizing an earth-air heat exchanger to optimize HVAC systems. Their study revealed that configurations featuring a single layer of insulation on the exterior and another with two layers positioned in the middle have the best efficiency. Kayfeci and colleagues [63] conducted a study on the economic impacts of insulation thickness in cooling systems, finding that as insulation thickness increases, so does the cost of insulation. However, they also discovered that fuel expenses diminish when the insulation thickness reaches its optimal level, highlighting the balance between initial investment and long-term savings.

Dlimi et al. [64] conducted a study comparing bio-based insulation materials with traditional ones in building walls, focusing on optimal insulation thickness, energy savings, and payback periods through a Life Cycle Cost (LCC) analysis. Their findings suggested that walls facing east and west benefit from slightly thicker insulation (approximately 5mm more) than those facing north and south due to the differing solar exposure.

Most of the referenced studies primarily utilized single-objective optimization to minimize economic parameters like payback periods or total costs. Although economic considerations are crucial, the decision to implement insulation in buildings also encompasses environmental benefits.

1.1.3.1 External Thermal Insulation Composite System (ETICS)

In EU countries, the most prevalent approach for energy efficiency in buildings involves the use of External Thermal Insulation Composite Systems (ETICS) [65].

ETICS enhances the energy efficiency of the envelope for both new constructions and renovations by serving as external insulation and rendering for walls. This system typically includes an insulation board mounted on the substrate through adhesive, mechanical fasteners, or both, covered by one or two layers of reinforced render. Employing ETICS for external insulation significantly reduces thermal bridges, diminished risk of surface condensation, enhanced indoor thermal comfort during both winter and summer, improved facade permeability, reduced consumption of energy and greenhouse gasses emission.

Various combinations of components within External Thermal Insulation Composite Systems (ETICS) are possible, with insulation often being the primary differentiator among the systems analyzed in numerous studies. The environmental impacts vary significantly based on the insulation material chosen and the building's location, especially when considering the building's entire lifecycle [66]. Research comparing different types of insulation frequently highlights the advantages of EPS (Expanded Polystyrene) or styrene-based insulations over other materials, considering their low material consumption and weight across most environmental impact categories [67]. Additionally, some studies have explored the environmental implications of innovative materials like cork and wood fiber insulation, offering insights into their sustainability profiles [68].

Jaoek Michalak [69] evaluated nine environmental impacts for 1 m² of ETICS across five different insulation thicknesses using either EPS or MW.

In terms of Global Warming Potential (GWP), the production of 1 m² of ETICS with MW resulted in almost three times the CO₂ equivalent emissions for insulation thicknesses of 10 cm and nearly four times higher for thicknesses of 25 cm compared to EPS. Josè D. Silvestre [70] compares the environmental impacts of using Insulating Corkboard (ICB) and Expanded Polystyrene (EPS) within ETICS. The analysis reveals that ETICS incorporating ICB offers environmental benefits over EPS in terms of Global Warming Potential (GWP) and the consumption of non-renewable primary energy (PE-NRe) during the production phase of the construction materials.

When evaluating ETICS with ICB and EPS at equal thicknesses, the EPS alternative demonstrates lower energy requirements for heating and cooling needs due to its superior insulation performance.

However, when comparing solutions that achieve similar insulation performance (U-values) but require different thicknesses (owing to ICB's higher thermal transmittance, necessitating thicker boards), the energy consumption for heating and cooling becomes nearly identical between the two options. Despite this similarity in operational energy use, the energy and resources required to produce the materials, differ significantly between the two solutions, underscoring the need to consider both

initial environmental impacts and ongoing energy consumption in selecting materials for ETICS.

Tajda Potrc [71] indicates that ETICS systems with EPS insulation perform better across most environmental impact categories. EPS has a lighter weight compared to the other ETICS options. Wood fiber board offers benefits in terms of global warming potential because is a carbon sequestering material, reducing the global warming effects. Conversely, mineral wool exhibits a higher environmental impact in categories such as Acidification Potential (AP), Eutrophication Potential (EP), and Global Warming Potential (GWP) when compared to the other two systems.

1.1.3.2 The use of Thermal Insulation Materials

The demand for sustainable insulation products, characterized by lower embodied energy and diminished environmental emissions, is on the rise, leading to a continuous influx of innovative insulation solutions into the market.

The thermal properties of insulation materials, crucial for regulating heat transfer in buildings, are largely determined by thermal conductivity. This property is affected by operating temperature, moisture content, density, and other factors like material thickness and aging, emphasizing the need for careful selection based on environmental conditions to ensure optimal energy efficiency [72].

Thermal insulation materials broadly fall into four categories: inorganic, organic, composite, and advanced materials, available in various forms such as porous, blanket or batt, rigid, natural, and reflective [73].

Inorganic materials like glass wool and rock wool dominate the market, making up 60% of it, while organic insulation materials hold a 27% share. Traditional materials including polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), and expanded polystyrene (EPS) remain popular in construction and thermal energy storage for their effective thermal insulation properties and affordability [74].

Mineral wool encompasses several inorganic insulation types, including rock wool, glass wool, and slag wool, offering a range of options for thermal management in buildings.

Mineral wool, with thermal conductivity typically ranging from 0.03 to 0.046 W/(m·K) for both glass and rock wool, offers low thermal conductivity, non-flammability, and moisture resistance [75]. In contrast, organic insulation materials, sourced from natural, renewable resources, are gaining popularity in construction for their environmental benefits, recyclability, and lower manufacturing energy requirements compared to conventional materials [76].

Gnip et al. [77] analyzed the influence of temperature on the thermal conductivity of expanded polystyrene (EPS) material. By calculating the λ -value at varying temperatures from 0°C to 50°C, based on the thermal conductivity value at 10°C, they observed a modest increase in thermal conductivity with rising temperatures.

Empirical studies on insulation materials such as expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR) have demonstrated the effect of temperature on their effective thermal conductivity. The findings reveal that the relationship between thermal conductivity values (λ -values) and temperature follows a linear pattern [78].

To enhance thermal resistance in building envelopes, several advanced insulation materials have been developed, including vacuum insulation panels (VIPs), gas-filled panels (GFPs), aerogels, and phase change materials (PCMs). VIPs, known for their exceptionally low thermal conductivity (below $0.004 \text{ W/(m}\cdot\text{K)}$) and durability exceeding 50 years, use a super-insulated core to minimize material thickness. However, over time, their thermal efficiency may diminish due to air and moisture permeation. [79] Fantucci et al. [80] explored how temperature affects the thermal conductivity of fumed silica-based vacuum insulation panels (VIPs), highlighting the benefit of their relatively low thermal conductivity, even with a complete vacuum loss. Their experiments on two samples with varying thicknesses revealed a thermal conductivity increase of up to 45% as temperatures rose from 2°C to 50°C . Further studies observed a 53% rise in thermal conductivity for raw VIPs from 0.0049 to $0.0075 \text{ W/(m}\cdot\text{K)}$, and from 0.0021 to $0.0028 \text{ W/(m}\cdot\text{K)}$ in fumed silica, across a temperature range of -7.5°C to 55°C .

Aerogels, recognized for their outstanding insulation properties with thermal conductivity between 0.013 and $0.014 \text{ W/(m}\cdot\text{K)}$ and density ranging from 70 to 150 kg/m^3 , are limited in commercial use by high production costs [75]. Liu et al.'s [81] research demonstrated that silica aerogels exhibit an effective thermal conductivity range from 0.014 to $0.044 \text{ W/(m}\cdot\text{K)}$, revealing a nonlinear increase as temperatures rise from 28° to 108 K . Similar findings were observed in three silica aerogel samples of varying densities across temperatures from 300° to 700 K . In aerogel blankets, thermal conductivity increased from 0.0135 to $0.0175 \text{ W/(m}\cdot\text{K)}$ as temperatures ranged from -20° to 80°C , showing a nearly linear relationship.

GFPs and PCMs represent the future of insulation, with thermal conductivities of $0.013 \text{ W/(m}\cdot\text{K)}$ and $0.004 \text{ W/(m}\cdot\text{K)}$, respectively. GFPs utilize a reflective structure with gas insulation, while PCMs adjust to temperature changes by alternating between solid and liquid states, efficiently storing, and releasing heat [79].

Thermal conductivity values for inorganic, organic, and advanced insulation materials vary widely, with inorganic materials ranging from 0.03 to $0.07 \text{ W/(m}\cdot\text{K)}$, organic materials from 0.02 to $0.055 \text{ W/(m}\cdot\text{K)}$, and advanced materials exhibiting values lower than $0.01 \text{ W/(m}\cdot\text{K)}$. Porous materials typically show thermal conductivities between 0.02 and $0.08 \text{ W/(m}\cdot\text{K)}$, whereas natural fiber-based insulations have values between 0.04 and $0.09 \text{ W/(m}\cdot\text{K)}$. Traditional options like mineral wool and foamed polystyrene are favored in thermal energy systems for their durability and affordability.

Materials derived from agricultural waste, such as coconut husk, rice straw, and bagasse, offer eco-friendly insulation solutions but tend to absorb water, which can increase their thermal conductivity. [82] To combat energy loss and enhance cost-efficiency, utilizing vacuum insulation panels (VIPs) or polyurethane-

polyisocyanurate (PUR-PIR) foams, known for their lower thermal conductivities, offering the significant advantage of minimizing the thickness needed for insulation layers in comparison to traditional insulation materials. [74] Innovations also include creating insulation from wood waste, which requires moisture protection for external use [74].

Emerging materials like aerogels and VIPs, with thermal conductivities as low as 0.017–0.021 W/(m·K) and 0.002–0.008 W/(m·K) respectively, offer superior insulation performance [75]. The effectiveness of fibrous materials is influenced by fiber fineness and orientation, whereas in foam insulations, thermal performance is affected by the cell size, distribution, and the gases contained within those cells.

This comprehensive analysis of insulation materials emphasizes the critical role of thermal properties, particularly thermal conductivity, in enhancing building energy efficiency. It underscores the influence of environmental factors like temperature, moisture, and material density on the effectiveness of various insulation types, ranging from inorganic to organic and advanced materials. These findings suggest a pressing need for careful selection and application of insulation materials tailored to specific climatic conditions, aiming for optimal energy savings and reduced carbon emissions in the construction sector.

1.1.3.3 Environmental Impact of Thermal Insulation Materials

In the spectrum of insulation materials, there's a discernible pattern among inorganic, organic non-renewable, and renewable types. Specifically, inorganic materials like stone wool and glass wool exhibit their highest environmental impacts during the manufacturing stage, primarily due to the energy-intensive processes of melting and spinning glass or rock into fibers. [83] Bribián et al. [84] also highlighted that the use of binders and additives significantly contributes to these materials' environmental footprint.

The primary organic non-renewable insulation materials, including EPS, XPS, and PUR, consistently exhibit significant environmental impacts primarily due to their raw materials [85]. It is noted that 40% to 50% of the non-renewable energy utilized for EPS and PUR production is directly linked to these materials. Furthermore, Gomes et al. [86] identified that up to 90% of the Global Warming Potential (GWP) for EPS originates from raw material usage. This pattern is similarly observed in PIR, PF, and PET materials [87]. Specifically, the production phase of EPS is responsible for 98% of its Ozone Depletion Potential (ODP) and 69% of its Photochemical Ozone Creation Potential (POCP) impacts [86].

Current research distinctly highlights that the insulation materials predominantly present in today's market are divided between inorganic materials, which undergo more energy-intensive manufacturing processes, and organic non-renewable materials, characterized by the significant environmental impacts of their raw material production. When it comes to insulation materials based on renewable resources, the

environmental impact hotspots tend to vary more widely. This variability stems largely from the diverse product systems associated with renewable insulation options, with binders and additives most cited as the primary contributors to environmental impacts.

For cellulose insulation, studies by Dickson and Pavía and Mattoni et al. [88] highlight the advantageous use of recycled paper as the primary raw material. However, the incorporation of additives like fire retardants and anti-fungal agents is identified as the leading cause of environmental impacts.

Rocchi et al. [89] found that for wood fibers, binders and additives account for 30% to 40% of environmental impacts. Conversely, Nakano et al. [90] attribute the primary impacts to the production process, especially the wood boilers that provide heat for drying, which contribute between 74% to 98% of the impacts.

Yildirim [91] considers electricity use during manufacturing as the primary factor affecting environmental impact. The discrepancies among studies stem from the diversity in product systems examined. Nakano et al. [90] focused on insulation boards derived from wood fibers, Rocchi et al. [89] on panels made from pruning remnants, and Yildirim [91] on nano insulation panels also based on wood fibers. Despite all employing wood-based materials, each study investigated distinct methods of production.

For cork-based insulation, the most significant environmental impacts arise during the manufacturing process, particularly from the boiling and agglomeration stages of the cork. Nonetheless, the sourcing of raw materials also plays a critical role in several environmental categories. Sierra-Pérez et al. [92] and Demertzi et al. [93] pinpointed the extraction of raw materials as the primary factor for the abiotic depletion potential (ADP). Moreover, Demertzi et al. [93] highlighted that raw materials could also predominantly influence both global warming potential (GWP) and ozone depletion potential (ODP).

The environmental impact of other renewable insulation materials, such as hemp, also centers around the use of binders and additives. Arrigoni et al. [94] and Zampori et al. [95] indicate that these components account for approximately 60% of the global warming potential (GWP) impacts.

A significant environmental benefit of renewable materials is their ability to sequester carbon during the biomass growth phase. This carbon uptake means bio-based materials generally show excellent performance in reducing GWP, according to most studies [88].

The delineation of study boundaries plays a crucial role, particularly when considering carbon uptake, which is essentially a form of temporary carbon storage; eventually, this stored carbon is released back into the atmosphere at the end of the product's life cycle. To circumvent this complexity, certain studies, for example, Nakano et al. [90], opt to exclude the sequestration or emission process, assuming the raw material to be inherently carbon neutral. However, this method overlooks the nuances of temporary storage and the consequential delayed emissions, which can significantly influence the global warming potential (GWP) outcomes in life cycle assessment (LCA) models. In

the realm of advanced insulation materials, both the production techniques and the raw materials emerge as pivotal factors influencing environmental impacts. For instance, in vacuum insulation panels (VIP), the core material's production is the critical factor [96], whereas in Aerogel, both the manufacturing process and the materials are deemed significant. [87] Schlanbusch et al. [97] pinpointed the silica coating process as a primary environmental impact factor in their study on nanomaterials for insulation.

This analysis highlights that for traditional inorganic materials, enhancements in manufacturing processes are necessary to mitigate environmental impacts. Conversely, organic non-renewable materials require a shift towards more sustainable raw materials to enhance their environmental profiles. Renewable insulation materials like hemp, cellulose, or wood fiber present the most promising avenues for environmental improvement. Modifying additives and binders to more eco-friendly alternatives could substantially enhance the sustainability of these insulation options. In sum, the evolution of thermal comfort strategies represents the ingenious human capacity to adapt and innovate. From passive designs aligned with nature's rhythms to intelligent, technology-driven systems, the relentless pursuit of thermal comfort continues to spur innovation. Moving forward, the seamless integration of sustainable practices, smart technology, and adaptive design is set to redefine thermal comfort in the buildings of the future, creating environments that are not only comfortable but also conducive to the health, well-being, and productivity of occupants.

1.2 Building Energy Modelling

Over the last few decades, there has been a notable increase in the energy consumption of buildings, driven by factors like population growth, economic development, and the increasing demand for a higher quality of life. However, it's crucial to recognize that significant energy savings can be achieved through proper building design, construction, and operation [10]. A central strategy in achieving this is Building Energy Modeling (BEM), a technology that has become essential in the building design process. [98] BEM is essentially a digital simulation that is used to analyze mechanical and architectural designs and to evaluate building performance. It predicts energy usage based on parameters such as climate data, building geometry, material properties, occupant behavior, and mechanical systems, thereby estimating the energy consumption and efficiency of buildings.

Although BEM is a critical tool in the architectural and construction industry, contributing to the creation of energy-efficient and sustainable buildings, it does have its limitations. The effectiveness of BEM heavily depends on the accuracy of the input data. Inaccurate or incomplete data can lead to misleading outcomes, highlighting the importance of precise and comprehensive data collection, which can often be challenging in practice [99]. This complexity can present a barrier, especially for practitioners who lack the necessary expertise in BEM. Significant training and

experience are crucial for accurate modeling and interpretation of building energy performance, potentially limiting the accessibility of BEM to a wider audience. These challenges underline the need for careful data management, the development of more user-friendly BEM tools, and the creation of training programs to enhance the expertise of practitioners in the field [100]. This approach will ensure that BEM continues to play an integral role in addressing the modern challenges of rising energy demands and environmental concerns.

1.2.1 Thermal Modeling Process with IESVE

Thermal modelling tools have been widely used in the construction industry at the design stage, either for new build or retrofitting existing buildings, providing data for informed decision-making.

The primary objective is to evaluate the effectiveness of passive design strategies in improving thermal performance, regulating indoor temperatures, and reducing the cooling load of residential buildings.

A software-based method for evaluating building performance is referred to as the Integrated Environmental Solutions-Virtual Environment (IES-VE).

Several works of literature are referenced in this context to confirm the validity of using the IES-VE software. IES-VE has been used by Salameh et al. [101] as a simulation tool in the study to determine the feasibility of incorporating passive design strategies into residential buildings to diminish reliance on active load systems. Crawley et al. [102] recognized the IES-VE software as a leading tool for assessing the environmental performance of buildings. Hammad et al. [103] notes that the software popularity stems from its precision and user-friendly interface. Additionally, the software offers a range of building assessments, including energy consumption and sun exposure analysis [101].

Building Energy Modeling (BEM) plays a significant role throughout these stages. It begins with creating a detailed digital representation of the building, incorporating its geometry, orientation, and architectural features. This model factors in the thermal properties of construction materials, along with environmental and operational conditions like climate data and occupancy patterns. BEM involves dynamic simulations of thermal performance, including heat transfer analysis and HVAC system performance. This helps estimate the building's energy consumption, identify areas of thermal discomfort, and enables design optimization for better thermal performance.

Through BEM, designers can perform comparative analysis of different design alternatives and 'what-if' scenarios. This ensures the building design complies with local building codes and achieves sustainability certifications. BEM thus becomes a critical tool in both conventional and integrated design processes, aiding in the comparison of various design options and technological systems for optimized decision-making.

1.3 Life Cycle Assessment

The construction and long-term use of buildings significantly affect both human health and the environment. Life Cycle Assessment (LCA) is a developing science that helps to quantify these impacts in terms of quality, severity, and duration. [104] This assessment covers the entire life cycle of a building, which includes:

Stage A (Production and Construction): This stage encompasses the energy and resources used in extracting raw materials, transporting them to manufacturing facilities, and producing building products. It also involves the transportation of materials to the construction site, energy used in construction equipment, supporting materials, and waste disposal.

Stage B (Use Stage): This covers the impacts of using a building over its lifetime, including lighting, heating, water usage, and materials for maintenance, repairs, and replacements.

Stage C (End-of-Life Stage): This involves demolition and disposal of the building, along with waste processing. If the building is not repurposed or improved for further use, this stage also deals with those aspects.

Stage D (Externalized Impacts): This final stage includes all the different effects of reusing, recycling, or recovering materials, energy, or water from the project. These are termed externalized impacts because they occur outside the system boundary of the LCA study.

Emissions and pollutants are released into the environment at each stage of a building's life cycle [105]. Table 1 visually represents where these emissions may occur.

LCA boundaries		Life-Cycle Stages/LCA Information Modules		Life-Cycle Stage Designation and Description	
Cradle to Cradle	Cradle to Grave	Cradle to Gate	Product Stage (A1-A3)	A1	Raw material extraction and processing, processing of secondary material input
				A2	Transport to the manufacturer
				A3	Manufacturing
		Gate to Grave	Construction process stage (A4-A5)	A4	Transport to the building site
				A5	Installation in th ebuilding
			Use stage - information modules related to the building fabric (B1-B5)	B1	Use or application of the installed product
				B2	Maintenance
				B3	Repair
				B4	Replacement
				B5	Refurbishment
			Use stage - information modules related to the operation of the building (B6-B7)	B6	Operational energy use
				B7	Operational water use
			End-of-life stage (C1-C4)	C1	Deconstruction, demolition
				C2	Transport to waste processing
				C3	Waste processing for reuse, recover and/or recycling
				C4	Disposal
			Benefits and loads beyond the system boundary (D)	D	Reuse, recovery and/or recycling potential

Table 1. Life-cycle stages of building and building materials.

Furthermore, the life cycle begins with the “cradle” (the start of the cycle), passes through the “gate” (the exit point of manufacturing), and ends with the “grave” (the conclusion of the life cycle). Hence, terms like “cradle-to-gate” and “cradle-to-grave” describe different portions of the life cycle.”

Life Cycle Assessment (LCA) is a method that examines a building's emissions, focusing on a wide array of greenhouse gases. It quantifies all components in terms of kilograms of carbon dioxide equivalent (kgCO₂e), encompassing both embodied and

operational carbon emissions. The whole life carbon includes emissions from the construction, operation, maintenance, and demolition phases of a building [104].

A building achieving whole life net zero carbon status not only meets the operational zero carbon balance but also achieves 100% circularity [106]. This means all its materials and products are composed of reused materials, and the building is designed for disassembling 100% of its materials and products to be reused in future constructions. When activities like construction, transport, and disassembly use renewable energy, there are no carbon emissions associated with the embodied carbon. Operational energy refers to the energy consumed by a building for heating, hot water, cooling, ventilation, lighting, and operating equipment like fridges, washing machines, TVs, computers, lifts, and cooking appliances. Reducing operational energy is crucial for achieving scalable zero carbon.

Embodied carbon, on the other hand, encompasses the 'upfront' emissions related to building construction. This includes the extraction and processing of materials, as well as the energy and water used in production, assembly, and construction. It also covers the 'in-use' stage (maintenance, replacement, and emissions from refrigerant leakage) and the 'end of life' stage (demolition, disassembly, and disposal of building parts or products), along with any related transportation [107]. As operational carbon reduces, the significance of embodied carbon in achieving overall carbon reduction goals becomes increasingly important.

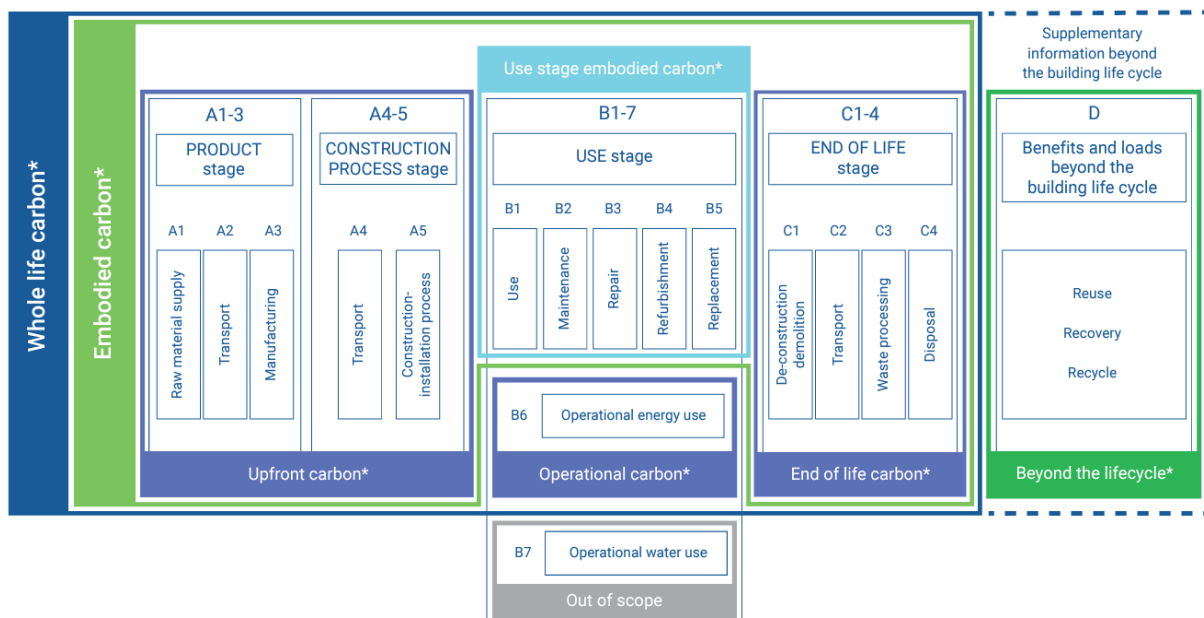


Figure 3. Whole life carbon, embodied carbon, and operational carbon across life-cycle stages [108].

1.3.1 Life Cycle Assessment Process

Life Cycle Assessment (LCA) is a detailed process, guided by various international standards, designed to be both methodical and transparent. The LCA process involves a series of steps, often requiring iterative refinement as new information becomes available or goals and scopes are reassessed [109]. Here's a summarized overview of the five key steps in conducting an LCA for a building:

Define Goal and Scope: This initial step involves establishing the purpose and the extent of the LCA. The goals can vary, such as aiding decision-making, complying with legal requirements, documenting environmental performance, or supporting policy development. Defining the scope includes outlining the functional description of the building, setting the reference study period, and determining the system boundaries, which include the building and site scopes, and the life cycle stages to be considered [110].

Collect Inventory: This step involves gathering detailed information about the building, akin to a comprehensive 'bill of activities and materials'. It includes data on materials used, transportation details, construction processes, operational energy and water consumption, and end-of-life considerations. The inventory is crucial for accurate analysis and is supported by LCA tools designed to estimate material quantities and activities [111].

Perform Impact Assessment: After defining the goal and collecting the inventory, the next phase is to calculate the environmental impacts. This is typically done using specialized software tools that track materials, scenarios, impacts, and organize results. Common environmental impact categories assessed include Global Warming Potential, Ozone Depletion Potential, Eutrophication Potential, Acidification Potential, and Smog Formation Potential [112].

Interpret Results: This involves understanding and analyzing the LCA results to draw meaningful conclusions. The interpretation includes error checking, breaking down environmental impacts by components and life cycle stages, and performing sensitivity and uncertainty analyses to determine the reliability and significance of the results [111].

Report Results: The final step is to compile and communicate the findings. This includes detailing the goal and scope, building inventory, environmental impact results, and the interpretation of these results. If the LCA is to be shared externally, it may undergo verification for consistency, data accuracy, representativeness of scenarios, and completeness [109].

Throughout these different stages of building design and construction, it's possible to significantly contribute to more environmentally conscious building practices.

1.3.2 Combining BEM and LCA

Integrating Building Energy Modeling (BEM) and Life Cycle Assessment (LCA) is key to optimizing thermal comfort strategies in buildings, combining energy efficiency with environmental sustainability [113].

Numerous studies have demonstrated that passive design strategies and the orientation of buildings significantly impact energy efficiency, occupant comfort, and safety [114]. Research efforts have been dedicated to exploring the adoption of passive approaches to lower energy consumption in buildings [115]. According to Gagliano et al. [116] effective passive design encompasses various elements of architectural design, including the orientation of principal façades and windows, selection of suitable materials for walls, thermal insulation, and the window-to-wall ratio (WWR). Perez et al. [117] involved the design of shading devices and the incorporation of natural ventilation methods.

Energy simulation tools play a critical role in passive design, offering significant advantages in enhancing building performance. These tools consider various factors, including building geometry, thermo-physical properties of the façade, air leakage mitigation, and building layout [114]. Consequently, this study has conducted energy simulations on developed models to investigate the impact of passive design elements on energy consumption. It is widely recognized that the requirements for passive design differ according to climatic conditions. Harkouss et al. [118] conducted simulations across 25 distinct climates, undertaking an extensive analysis of passive design strategies for residential buildings.

Their research aimed to identify optimal practices for minimizing energy consumption in these structures.

The fields of BEM and LCA are evolving with innovative approaches:

Renewable Energy Integration in BEM: Modern tools now integrate renewable energy sources more accurately into the building's energy model.

Dynamic Simulation Tools: Advanced BEM tools offer dynamic simulations for detailed thermal comfort analysis over time.

Comprehensive LCA Databases: Enhanced databases provide detailed environmental impact data for a wide range of materials.

Net Zero Energy Buildings: A key research area is developing strategies for net-zero energy buildings, balancing on-site energy generation with consumption.

Building Automation and IoT: The use of IoT in BEM enables real-time monitoring and control of building systems for peak efficiency.

AI and Machine Learning: These technologies are increasingly used in BEM and LCA tools for predictive optimization of building performance.

Holistic and Bioclimatic Design: Integrating bioclimatic design principles into BEM enhances thermal comfort using natural solutions.

The journey to optimal thermal comfort involves several challenges such as balancing energy efficiency with comfort needs, adapting designs for climate change, managing costs, and catering to diverse occupant preferences. Future trends point towards

smarter, more adaptive, and sustainable buildings, utilizing emerging technologies like AI, innovative materials, and bioclimatic design principles. These advancements will revolutionize how buildings achieve and maintain thermal comfort, prioritizing both energy efficiency and occupant well-being.

2. Method

2.1 Case of study

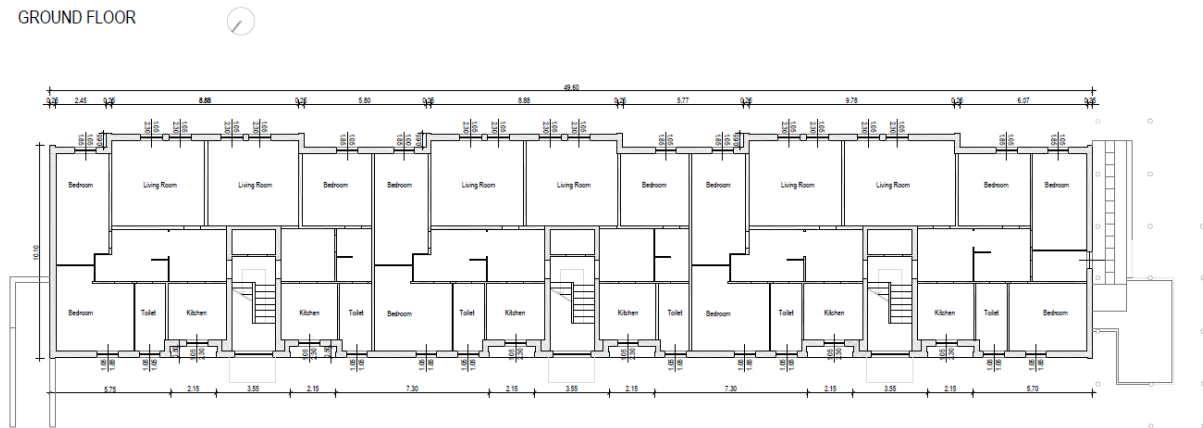
The case study is part of an energy efficiency program for ALER assets, financed by the PINQuA (Programma Innovativo Nazionale per la qualità dell’Abitare), which is an investment plan included in the National Recovery and Resilience Plan and promoted by the Ministry of Infrastructure and Sustainable Mobility. The program aims to carry out social housing and urban regeneration interventions throughout Italy. PINQuA's goal is to build new public housing to reduce housing issues, rehabilitate degraded areas, and promote sustainability by reducing environmental impacts. The main impacts of the PINQuA, as reported in the report presented in April 2022, can be summarized as follows:

- 2.8 billion euros in funding, allocated to 159 selected projects and 16,500 housing units.
- Rehabilitation of 9.8 million square meters of public spaces
- Target of 8.4 million square meters of vegetated surface and 1.3 million square meters of public residential surface
- Monthly rent savings of €479 per household, thanks to a 38% reduction in annual primary energy consumption
- Reduction of 31% in annual carbon dioxide emissions (kgCO₂/m² per year)

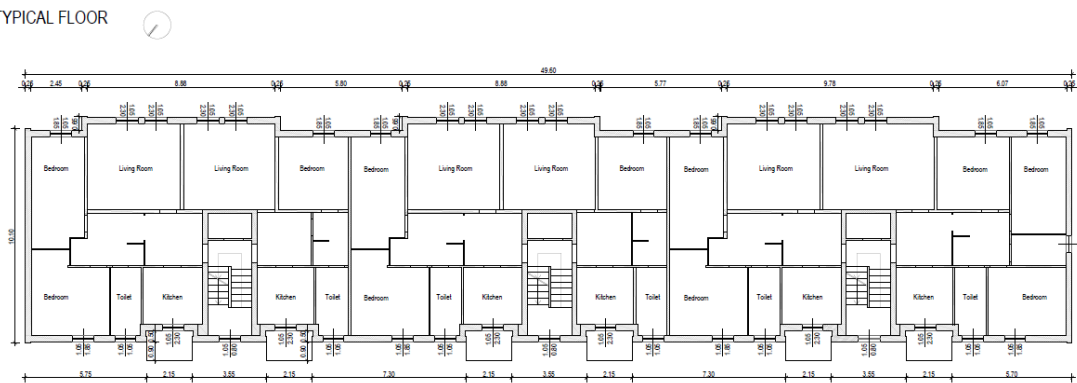
The project under consideration refers to the building complexes located in the Gratosoglio district in the southern suburbs of Milan, essentially divided into two sections: the south, with 27 buildings and 1898 apartments, and the north, with 25 buildings containing 2091 apartments. The planned energy efficiency interventions are aimed both at improving thermal comfort conditions, acting on the thermal dispersion of the vertical and horizontal building envelope through the application of thermal insulation and the replacement of existing windows and installation of point mechanical ventilation systems with heat recovery, and at improving system efficiency, by replacing domestic hot water generators with more efficient heat pumps; furthermore, interventions for the redevelopment of adjacent external spaces and the refurbishment of entrances to stairwells are planned.

The building under analysis has a residential function characterized by 10 floors above ground and a partially underground floor with technical spaces and cellars, is located at via Costantino Baroni n.200-204, Milan (MI). The building, with a footprint area of 505.5 m², mainly faces the Northwest and Southwest directions; each floor is divided into six apartments served by three stairwells, for a total of 60 apartments with usable surfaces ranging from 50-90 m².

GROUND FLOOR



TYPICAL FLOOR



ROOF

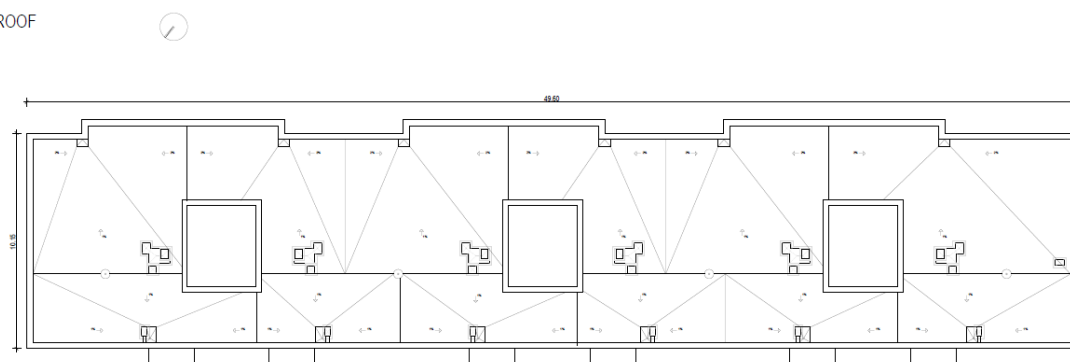


Figure 4. Case study plans.



Figure 5. Case study elevations.

2.1.1 Baseline Construction

The construction system of the buildings built during the construction years of the analyzed building, between 1962-1965, is a prefabricated typology, both for closing and partitioning elements, both horizontal and vertical. Generally, such systems were planned to use concrete or steel combined with hollow brick elements for lighting the structure, or polystyrene panels for thermal insulation. The manufacturing process of the closing and partitioning elements, both vertical and horizontal, is based on the use of rigid steel sheet formworks, dismantled after the concrete has dried and matured

through heating with a coil or via an insulating dome placed over the formwork itself. The window frames consist of double glazing without any treatment, with air inside the gap, and are equipped with external shading such as shutters.

The main characteristics of the assumed materials of the envelope are summarized in the following tables.

The thermal transmittances of opaque and transparent elements were calculated considering Table 2 and Table 3 of UNI EN ISO 6946:2008, where the values of conventional surface resistances and the thermal resistances of conventional cavities are reported, depending on the direction of heat flow.

Resistenza superficiale m^2K/W	Direzione del flusso termico		
	ascendente	orizzontale	discendente
R_{si}	0,10	0,13	0,17
R_{se}	0,04	0,04	0,04

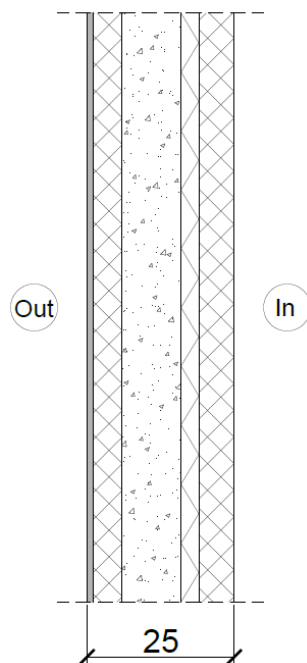
Table 2. Conventional surface resistances from UNI EN 6946:2008.

Spessore dell'intercapedine d'aria (mm)	Resistenza termica (m^2K/W) a seconda direzione del flusso di calore		
	ascendente	orizzontale	discendente
0	0,00	0,00	0,00
5	0,11	0,11	0,11
7	0,13	0,13	0,13
10	0,15	0,15	0,15
15	0,16	0,17	0,17
25	0,16	0,18	0,19
50	0,16	0,18	0,21
100	0,16	0,18	0,22
300	0,16	0,18	0,23

Table 3. Thermal resistance of conventional cavities (unventilated cavity and high emissivity surfaces) from UNI EN ISO 6946:2008. Intermediate values can be obtained by linear interpolation.

The thermal transmittance calculated for the vertical enclosures exclude the impact of thermal bridges. The transmittance values that account for thermal bridges are detailed in the document [119].

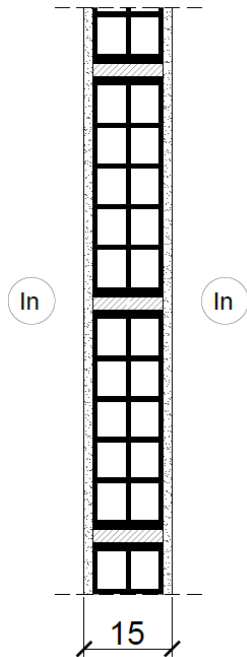
External Wall – EW00



Corrected Uvalue (to include thermal bridges losses) = 2,57 W/m²K

Layer	t [m]	λ [W/mK]	R [m ² K/W]	ρ [kg/m ³]	U [W/m ² K]
Outdoor					1.133
Ceramic stoneware tiles	0.01	1.3	0.008	2300	
Reinforced concrete with welded wire mesh	0.05	2	0.025	2400	
Pozzolanic concrete	0.1	2	0.050	2400	
Expanded Polystyrene Sheet (EPS)	0.03	0.05	0.600	40	
Reinforced concrete with welded wire mesh	0.06	2	0.030	2400	
Indoor					

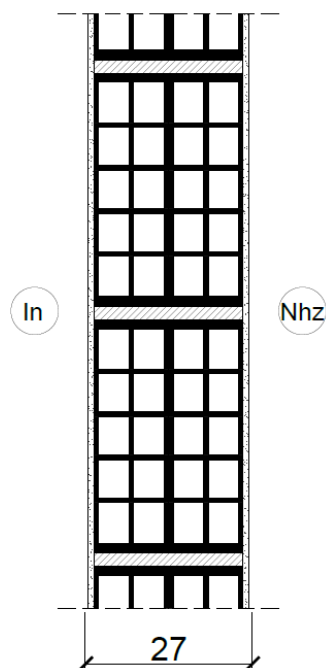
Table 4. Baseline – External Wall

Internal Wall – IW00

Layer	t [m]	λ [W/mK]	R [m ² K/W]	ρ [kg/m ³]	U [W/m ² K]
Outdoor					1.631
Lime and cement plaster	0.015	0.7	0.021	1800	
Perforated bricks	0.12	0.387	0.310	717	
Lime and cement plaster	0.15	0.7	0.021	1800	
Indoor					

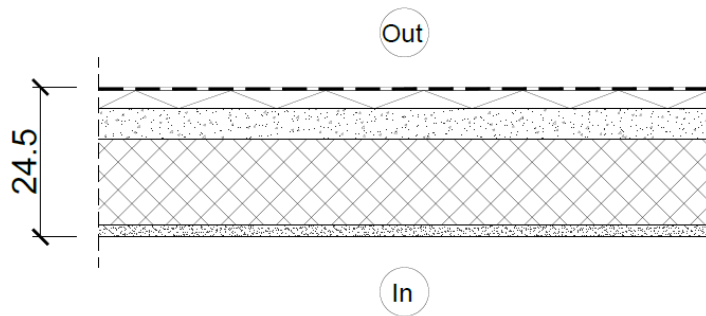
Table 5. Baseline – Internal Wall

Staircase Wall – SW00



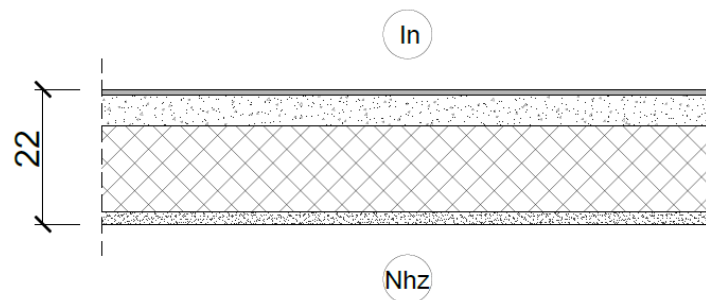
Layer	t [m]	λ [W/mK]	R [m ² K/W]	ρ [kg/m ³]	U [W/m ² K]
Indoor					1.519
Lime and cement plaster	0.01	0.7	0.014	1800	
Semi-solid bricks	0.25	0.676	0.370	1516	
Lime and cement plaster	0.01	0.7	0.014	1800	
Indoor					

Table 6. Baseline – Staircase Wall

Roof – R00

Layer	t [m]	λ [W/mK]	R [m ² K/W]	ρ [kg/m ³]	U [W/m ² K]
Outdoor					1.070
Waterproofing membrane	0.005	0.17	0.029	1200	
Expanded Polystyrene Sheet (EPS)	0.03	0.05	0.600	40	
Cement mortar	0.05	0.7	0.071	1600	
Reinforced concrete slab with welded wire mesh	0.14	2.15	0.065	2400	
Lime and cement plaster	0.02	0.7	0.029	1800	
Indoor					

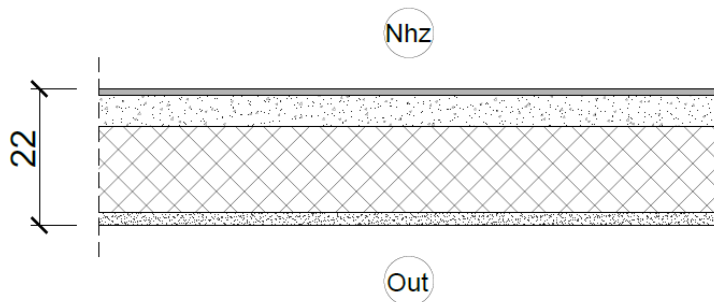
Table 7. Baseline – Roof

Internal Slab - IS00

Layer	t [m]	λ [W/mK]	R [m ² K/W]	ρ [kg/m ³]	U [W/m ² K]
Indoor					2.754
Ceramic stoneware tiles	0.01	1.3	0.008	2300	
Cement mortar	0.04	0.7	0.057	1600	
Reinforced concrete slab with welded wire mesh	0.15	2.15	0.070	2400	
Lime and cement plaster	0.02	0.7	0.029	1800	
Indoor					

Table 8. Baseline – Internal Slab

Ground Floor Slab - GFS00



Layer	t [m]	λ [W/mK]	R [m2K/W]	ρ [kg/m3]	U [W/m2K]
Indoor					2.680
Ceramic stoneware tiles	0.01	1.3	0.008	2300	
Cement mortar	0.04	0.7	0.057	1600	
Reinforced concrete slab with welded wire mesh	0.15	2.15	0.070	2400	
Lime and cement plaster	0.02	0.7	0.029	1800	
Outdoor					

Table 9. Baseline – Ground Floor Slab

Window - W00

The windows consist of double glazing without any treatment, with air inside the cavity, and an aluminum frame. g value = 0.75.

Layer	t [m]	λ [W/mK]	R [m2K/W]	τ	U [W/m2K]
Outdoor					
Outer pane	0.004	1	0.004	0.8	2.538
Cavity	0.012	-	0.173	-	
Inner pane	0.004	1	0.004	0.9	
Indoor					

Table 10. Baseline – Window

Additionally, for the underground portion of the building, the calculation of the correct thermal transmittance for external walls and the ground floor slab was carried out in accordance with ISO 13370:2017. Figure 5

R _{se}	Thermal transmittance of the external surface	0.04 m ² K/W
R _{w,b}	Thermal resistance of the basement wall	0.78 m ² K/W
R _{f,b}	Thermal resistance of the floor slab	0.16 m ² K/W

2.1.1.1 Internal gains and Natural Ventilation inputs

Internal gains are defined as the sum of heat flows generated within thermal ones due to the presence of people, lighting, equipment, etc. Various international standards provide standard values, typically expressed in power per square meter (W/m²), already divided by type and associated with a usage profile characteristic of the thermal zone. Among these, ISO 17772-1:2017 provides the following peak values with their respective usage profiles for thermal zones with residential use.

Internal gain	Value [W/m ²]
People	2.8
Equipments	3
Lighting	-

Table 12. Peak values for internal gains typology (ISO 17772-1:2017)

Based on these mentioned values, it has been possible to develop detailed hourly profiles for each hour and day of the week, as highlighted in the document [119]. These profiles were then used in the IES model to conduct energy analyses.

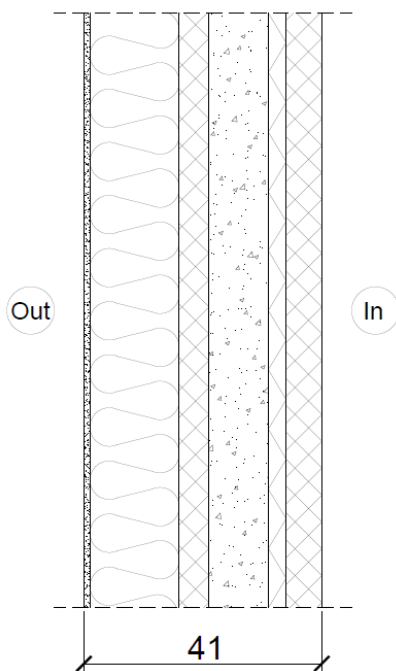
Natural ventilation profile has been proposed for the baseline scenario during the whole year considering standards like UNI/TS 11300-1:2014. Each apartment has a consistent ventilation rate seasonally variable: 0.3 1/h during heating season and between 0.5 to 10 1/h during other times, depending on indoor and outdoor temperatures. For unheated spaces, ISO 13789:2017 is applied, setting an infiltration rate at 1 1/h for stairwells and cellars, assuming windows and doors are mostly closed. A deeper evaluation is reported in the document [119].

2.1.2 Refurbishment – Scenario 1

The refurbishment scenario proposed for the building envelope involves reducing the losses of both opaque and transparent envelopes, by applying an external insulation layer both for vertical and horizontal elements and replacing the windows. The design choices proposed also include the installation of a mechanical ventilation system with heat exchanger (flow rate 37 m³/h, recovery efficiency 70%) to reduce ventilation losses through the building envelope. The mechanical ventilation profile changes depending

on the internal CO₂ concentration. Details are provided in the document [119]. The natural ventilation profile remains the same as previously presented for the building. The characteristics of the refurbishment scenario are reported in the following tables.

External Wall - EW01

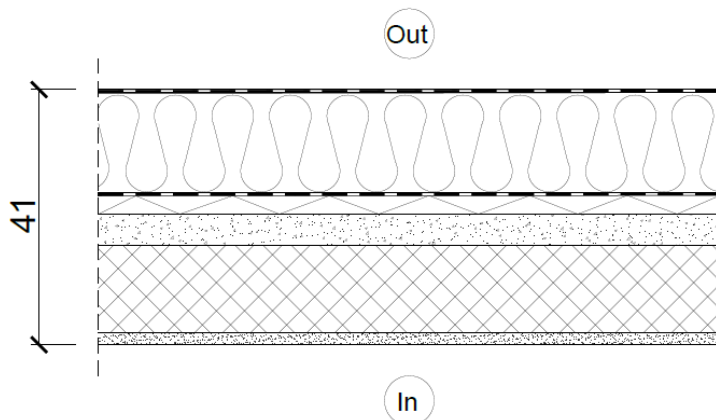


Corrected Uvalue (to include thermal bridges losses) = 0,54 W/m²K

Layer	t [m]	λ [W/mK]	R [m2K/W]	ρ [kg/m3]	U [W/m2K]
Outdoor					0.193
Plaster	0.01	0.54	0.007	1600	
Rock wool insulation panel	0.15	0.035	4.286	70	
Reinforced concrete with welded wire mesh	0.05	2	0.025	2400	
Pozzolanitic concrete	0.1	2	0.050	2400	
Expanded Polystyrene Sheet (EPS)	0.03	0.05	0.600	40	
Reinforced concrete with welded wire mesh	0.06	2	0.030	2400	
Indoor					

Table 13. Scenario 1 – External Wall

Roof - R01



Layer	t [m]	λ [W/mK]	R [m2K/W]	ρ [kg/m3]	U [W/m2K]
Outdoor					1.181
Waterproofing memebrane	0.005	0.17	0.029	1200	
Rock wool insulation panel	0.16	0.035	4.571	70	
Waterproofing memebrane	0.005	0.17	0.029	1200	
Expanded Polystyrene Sheet (EPS)	0.03	0.05	0.600	40	
Cement mortar	0.05	0.7	0.071	1600	
Reinforced concrete slab with welded wire mesh	0.14	2.15	0.065	2400	
Lime and cement plaster	0.02	0.7	0.029	1800	
Indoor					

Table 14. Scenario 1 – Roof

Window W – 01

The windows consist of triple glazing with optimized glass pane, with krypton inside the cavity, and a PVC frame. g value = 0.23.

Layer	t [m]	λ [W/mK]	R [m ² K/W]	τ	U [W/m ² K]
Outdoor					0.776
Outer pane	0.006	1	0.006	0.362	
Cavity	0.014	-	0.211	-	
Internal pane	0.006	1	0.006	0.362	
Cavity	0.014	-	0.8638	-	
Inner pane	0.006	1	0.006	0.362	
Indoor					

Table 15. Scenario 1 – Window

2.1.3 Refurbishment – Scenario 2

Despite the refurbishment scenario led to a significant reduction in the building transmission and ventilation losses, an alternative scenario has been proposed to evaluate further improvements of the building energy performance.

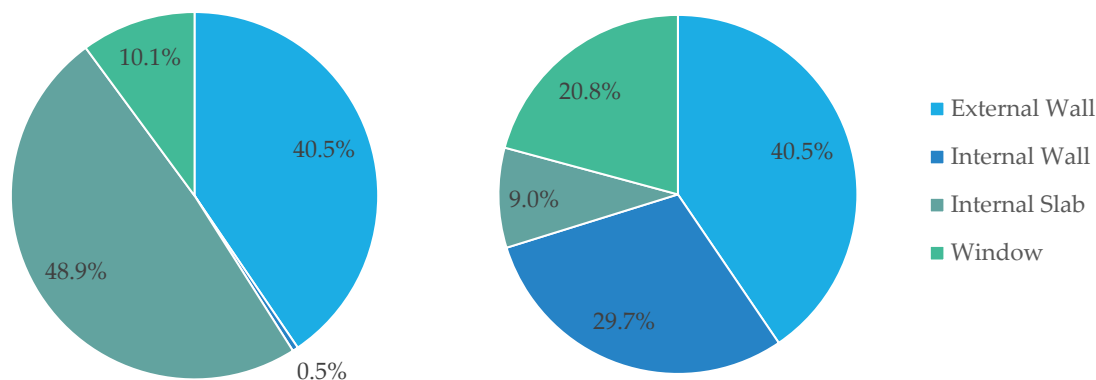
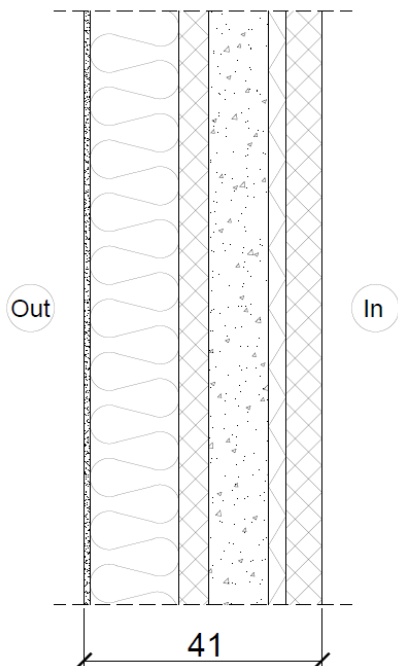


Chart 1. Average winter conduction losses (15th October – 15th April) for coolest room (left) and the warmest room (right).

Based on the energy analyses conducted in the document [119], the winter transmission losses in the two thermal zones examined show a significant impact from the building's unheated areas, specifically the stairwells and basement, which have not yet been addressed with energy efficiency measures. Scenario 2 proposes design choices for these envelope components, such as the internal partitions of the stairwells and the ground floor slab in direct contact with the cellars, by adding an insulating layer to reduce their transmittance.

Furthermore, the report highlights that the building's vertical closures exhibit high thermal transmittance values, surpassing regulatory maximum limits. To address this, a reduction in thermal transmittance is proposed, aiming for a minimized impact of thermal bridges to ensure compliance with regulatory standards. Additionally, to enhance internal comfort conditions, it is suggested to replace the previously selected windows. Due to their low solar factor, these windows potentially reduce the free solar gains. The mechanical ventilation system, along with natural ventilation during the intermediate and summer periods, retains the characteristics defined in the project status.

External Wall - EW02



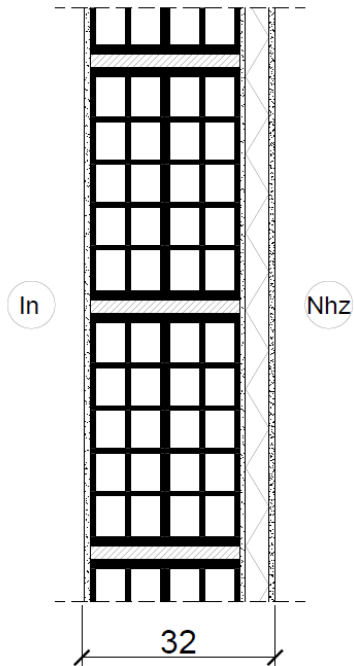
Layer	t [m]	λ [W/mK]	R [m2K/W]	ρ [kg/m3]	U [W/m2K]
Outdoor					0.245
Plaster	0.01	0.54	0.007	1600	
Rock wool insulation panel	0.15	0.047	3.192	70	
Reinforced concrete with welded wire mesh	0.05	2	0.025	2400	
Pozzolanic concrete	0.1	2	0.050	2400	
Expanded Polystyrene Sheet (EPS)	0.03	0.05	0.600	40	
Reinforced concrete with welded wire mesh	0.06	2	0.030	2400	
Indoor					

Table 16. Scenario 2 – External Wall

The thermal conductivity value of the mineral wool panel was adjusted from the 0.035 W/mK used in scenario 1, to 0.047 W/mK to account for residual thermal bridge values, especially concerning the window-to-wall connection. The thickness was maintained at 15 cm.

The thermal conductivity value of the EPS insulation panel was adjusted from 0.033 W/mK to 0.05 W/mK to approximate the considerations that it is not only an aged, prefabricated panel but also a concrete panel with several thermal bridges.

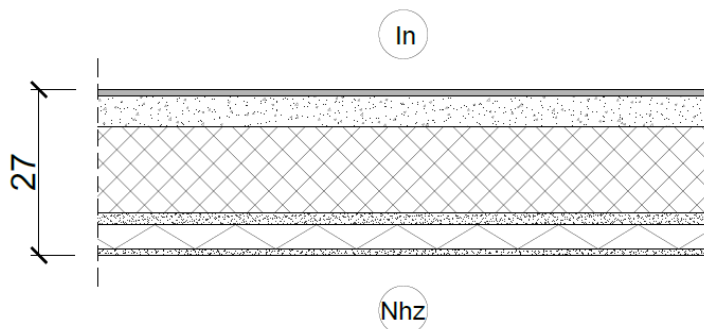
Staircase Wall - SW02



Layer	t [m]	λ [W/mK]	R [m ² K/W]	ρ [kg/m ³]	U [W/m ² K]
Indoor					0.679
Lime and cement plaster	0.01	0.7	0.014	1800	
Semi-solid bricks	0.25	0.676	0.370	1516	
Lime and cement plaster	0.01	0.7	0.021	1800	
EPS insulation panel	0.04	0.05	0.800	40	
Lime and cement plaster	0.01	0.7	0.014	1800	
Indoor					

Table 17. Scenario 2 – Staircase Wall

Internal Slab - IS02



Layer	t [m]	λ [W/mK]	R [m2K/W]	ρ [kg/m3]	U [W/m2K]
Indoor					0.849
Ceramic stoneware tiles	0.01	1.3	0.008	2300	
Cement mortar	0.04	0.7	0.057	1600	
Reinforced concrete slab with welded wire mesh	0.15	2.15	0.070	2400	
Lime and cement plaster	0.02	0.7	0.029	1800	
EPS insulation panel	0.04	0.05	0.800	40	
Lime and cement plaster	0.01	0.7	0.014	1800	
Indoor					

Table 18. Scenario 2 – Internal Slab

Window - W02

The windows consist of double glazing with optimized glass pane, with krypton inside the cavity, and an aluminum frame. g value = 0.61.

Layer	t [m]	λ [W/mK]	R [m2K/W]	τ	U [W/m2K]
Outdoor					
Outer pane	0.006	1	0.006	0.844	0.905
Cavity	0.01	-	0.173	-	
Inner pane	0.005	1	0.005	0.516	
Indoor					

Table 19. Scenario 2 – Window

2.2 Energy Analysis

The dynamic energy analysis was conducted with IES VE (Integrated Environmental Solutions – Virtual Environment), a software used for carrying out climate, lighting, energy, CFD simulations, etc. The created model (Figure 6) consists of 68 thermal zones, divided as follows:

- 60 thermal zones dedicated to apartments.
- 2 thermal zones dedicated to the basement (one for the underground portion and one for the above-ground portion, necessary for modeling reasons because they are characterized by different thermal performances due to the presence of the ground)
- 6 thermal zones dedicated to stairwells and elevator (3 stairwells entirely contained within the building, from the basement to the top floor, and 3 zones located on the roof of the same)

However, given the model's complexity due to such a high number of thermal zones, a reduction of these was proposed through the definition of clusters containing apartments with similar energy performances. In this way, the final model consists of a total of 26 thermal zones (18 containing apartments and 8 containing unheated areas), whose calculation methodology is reported in the document [119]. The climate file chosen for the simulations is "ITA_LM_Milano-Linate.AP.160800_TMYx.2007-2021" (source: <https://climate.onebuilding.org/>), containing climate data collected between 2007 and 2021.



Figure 7. IESVE model.

For the energy analysis, the following modeling and simplification assumptions were made:

- Each room is characterized by a gross height of 3.1 m and a net height of 2.85 m, derived from the design documents and architectural drawings.
- The stairwells are considered unheated zones, devoid of any internal contribution due to people, lighting, or equipment. For this reason, each stairwell has been modeled as a single thermal zone, from the basement to the top floor.
- The basement, also considered an unheated zone and devoid of any internal contribution, has been modeled without any type of window, given their modest area (about 6% of the gross area of the above-ground walls of the basement for the two main facades) and therefore influence on the building's energy performance. Furthermore, the partitions of these have not been modeled, as they are unheated zones.
- The balconies have been modeled as solar screens, to consider the reduction of solar gains in the apartments. However, the effect of the balcony railings, given their modest influence, was neglected.

2.2.1 Energy Consumption Scenarios

The assessment of energy consumption was carried out through the IESVE building model. This evaluation encompassed the three distinct scenarios, each incorporating the refurbishment design choices along with internal gains and factors inputs related to both natural and mechanical ventilation. It's important to highlight the substantial impact of the chosen thermal generation system on the building's energy consumption. The initial scenario utilizes an LTHW boiler in its baseline setup, subsequently transitioning to an air-source heat pump for the next two scenarios, marking a significant shift in energy strategy.

Scenario	Generator	Seasonal efficiency	Energy consumption	
			Electricity use [kW]	Natural gas [kWh]
Baseline	Boiler	0.65	379986	220330
Scenario 1	Heat pump (electric): air source	2.00	174297	20753
Scenario 2	Heat pump (electric): air source	2.00	159884	6720

Table 20. Energy consumption from IESVE.

The energy consumption values obtained from each of the scenarios will be used as inputs for One Click to provide a global prospective on the environmental impact of the building subjected to the proposed energy measures. The following analyses will offer a more detailed explanation of the variations in these values across the scenarios.

2.3 Life Cycle Assessment

After implementing energy efficiency measures, an environmental impact analysis was conducted to quantify the equivalent CO₂ emissions attributable to both the amount of material used for the efficiency improvements and the energy consumed during the building's use. This evaluation considered all stages, from A to C₄, identifying those that have a greater environmental impact.

During the analyses, certain categories, such as B1, B3, and B7, were not considered due to the specific nature of the evaluated elements and their relevance to the study's focus. B1, which considers the emissions related to the environment from the use of products, is marked as zero in this analysis because none of the materials under consideration emit during their use phase. Similarly, B3, which is related to the repairs of a broken product, is also assigned a value of zero because the analysis does not involve any repairs. Lastly, B7, which concerns the water use of building systems and the building envelope, is considered zero since there is no water consumption associated with the aspects being analyzed.

The concept of "embodied carbon" refers to the carbon dioxide emissions associated with all phases of a building material's life cycle, including its production, transport, maintenance, and disposal. This metric is crucial for understanding the environmental impact of materials used in enhancing a building's energy efficiency. The OneClick software facilitates the analysis of embodied carbon, allowing for the evaluation of different options and highlighting the importance of life cycle assessment. When calculating a building's embodied carbon, it's essential to account for its geographic location, as this affects material availability and transport distances. OneClick LCA can adjust embodied carbon figures based on the building's location. Moreover, it utilizes the product Environmental Product Declarations (EPDs) to detail the embodied carbon across all life cycle stages. The software also adjusts emissions based on the material's lifespan, as stated in the EPDs, ensuring they align with the building's intended service life. Operational carbon encompasses the carbon emissions resulting from the energy used for heating, cooling, and lighting within a building. It includes the carbon impact of district heating systems for heating requirements and electricity for cooling and lighting. To align with the data on embodied carbon, the calculation of operational carbon emissions will cover a projected period of 60 years.

2.3.1 OneClick Input

For the proposed energy efficiency interventions, products have been selected directly from the OneClick database, aiming to find those that best matched the preliminary assumptions of the interventions. The selection was guided by specific criteria such as thermal conductivity, density, and thermal transmittance. This approach aimed to ensure that the chosen products met the necessary physical characteristics to achieve maximum energy efficiency.

In addition to physical parameters, significant attention was also paid to environmental aspects, favoring products with a low environmental impact. This choice was motivated by the desire to reduce the ecological footprint of the interventions, in line with sustainability principles.

In some instances, despite selecting a product from OneClick that appeared to fulfill the required physical characteristics for the proposed interventions, limitations have been encountered selecting from the database. Crucial details such as the material's origin, its expected lifespan, and information related to the end-of-life scenario depend entirely on the Environmental Product Declaration (EPD) of the chosen product.

This means that, even though a product may seem suitable based on its physical specifications, the lack of complete data in the EPD or the absence of such declarations in the "One Click" database can limit our ability to fully assess the environmental impact of the product and its adherence to sustainable criteria or specific project requirements. Therefore, the importance of an updated database rich in detailed information, including EPDs, is crucial for making informed and responsible choices.

This approach allows overcoming the encountered limitations and selecting products that are not only energy-efficient but also sustainable.

2.3.2 Life Cycle Assessment – Baseline

The baseline reflects the current condition of the building without any interventions, the only significant data obtained concerns phase B6, which corresponds to the use of the building, with particular attention to energy consumption. The energy consumed by a building throughout its life, especially if sourced from fossil fuels, has a significant impact on its overall CO₂ emissions. Operational energy use, which includes the energy required for heating, cooling, ventilation, lighting, and equipment, typically constitutes a major portion of the total life-cycle energy consumption and, consequently, the CO₂ emissions of buildings. Assessing operational energy consumption due to its large impact on the building's overall environmental footprint. This focus is also aligned with global efforts to reduce energy consumption and greenhouse gas emissions in the built environment. Buildings powered by renewable energy sources will have significantly lower CO₂ emissions compared to those relying on fossil fuels, highlighting the importance of considering energy sourcing in the LCA.

Result category	Global warming [kg CO ₂ e]
B6 Energy consumption	14313503.92

Table 21. Baseline – energy consumption.

In the initial setup proposed by the document [119], a LTHW boiler powered by natural gas is designed for low-temperature water heating in heating systems. While natural gas boilers can be considered cost-efficient in terms of operational expenses, their environmental sustainability is influenced by the source of the gas and the efficiency of the boiler system. In subsequent scenarios, replacing the boiler with a heat pump was considered.

The following analysis compares three different thermal generation systems to assess the environmental impact resulting solely from the replacement of the generation system. The comparison includes a traditional natural gas boiler, an air-to-water heat pump, and a geothermal (water-source) heat pump.

Air-to-water heat pumps, which extract heat from the outside air for heating, cooling environments, and hot water production, prove to be much more efficient than traditional boilers and have the potential to significantly reduce the carbon footprint, especially when powered by electricity from renewable sources. However, this scenario was not considered in the analysis. On the other hand, geothermal heat pumps utilize heat from the ground or water bodies, offering superior energy efficiency. Despite the higher initial cost, this type of heat pump provides benefits in terms of lower operational costs and reduced environmental impact.

	Seasonal Efficiency	OneClick Input Data	
		Electricity use [kW]	Natural gas [kWh]
Boiler	0.65	379985.50	220329.60
Heat pump (electric): air source	2.00	249470.40	89238.10
Heat pump (electric): ground or water source	2.55	230221.90	69989.60

Table 22. Electricity use and natural gas among different generators.

The seasonal efficiency values presented in the Table 22 are default data provided by IESVE during the selection of the generator. Although these values are below average, they are considered adequate for comparison purposes since the systems are not the focus of the thesis analysis. The data on electricity and natural gas consumption were obtained through energy simulation on IESVE and subsequently entered One Click to calculate the kg of CO₂eq in the B6 phase of energy consumption.

Global warming [kgCO ₂ e]			
	Boiler	Heat pump (electric): air source	Heat pump (electric): ground or water source
B6 - Energy consumption	14313503.92	8565978.46	7719602.66

Table 23. Energy consumption among different generators.

The obtained values confirm the initial hypothesis that the ground or water source heat pump exhibits a significantly lower energy consumption compared to the other two categories.

The boiler records the highest energy consumption value, primarily because it conventionally burns fuel to generate heat, which is translated into substantial CO₂ equivalent emissions.

Air source heat pumps are typically more energy-efficient than traditional boilers, using the external air as a heat source. However, their efficiency may diminish under extremely cold conditions.

The ground or water source heat pumps demonstrate the lowest energy consumption among the three. These systems are often more effective than air source alternatives due to the relatively stable temperatures found underground or in bodies of water, which allows them to operate more efficiently, particularly in the colder months.

Given the analysis, the selection of an air source heat pump represents a strategic choice for reducing environmental impact of the forthcoming scenarios. While it is not as energy efficient as the ground or water source heat pump, it still offers a significant improvement over traditional boilers and supports the goal of a more sustainable energy system.

2.3.3 Life Cycle Assessment – 1 Scenario

For the LCA analysis of the proposed scenario, interventions designed to enhance the building's energy efficiency were input into the software. This refurbishment scenario includes improving the insulation of both opaque and transparent building envelopes by applying an external insulating layer to exterior walls and roofs, as well as replacing window frames. The replacement of the old boiler with an electric heat pump air source was also considered. The inputs added to the software for the analysis consist of materials added to the structure to reduce thermal losses, as well as data related to energy consumption, specifically regarding electricity and gas, calculation period and service life.

Energy consumption [kWh]		Calculation period [years]	Building area [m2]
Electricity use	Natural gas		
174297	20753	60	5055

Table 24. Scenario 1 – OneClick inputs.

Intervention	Area [m2]	Material Origin	Distance from the construction site [km]	Service Life [years]	End of Life
Triple glazed window	699.42	Ireland	2188	50	Recycled/Landfilled
Mineral Wool Insulation Panel	3677.64+505.37	France	851	50	Landfilled
Plaster	3677.64	United Arab Emirates	5902	20	Landfilled
Waterproofing membrane	505.37	Germany	1043	20	Landfilled

Table 25. Scenario 1 – Building materials OneClick inputs.

The data presented in the Table 24 and Table 25 are the inputs required for running simulations in OneClick. Initially, information related to the building was entered, including the energy consumption of the electric heat pump, the building's required service life, and the gross internal floor area. Subsequently, a selection of building materials was made, with details sourced from Environmental Product Declarations (EPDs) for each material used in the interventions.

Every detail is crucial as it can significantly impact the results. This includes the origin of the material, indicating the location where the material is produced. Such information is vital for calculating the distance from the manufacturing site to the construction site, which affects transportation emissions. Highlighting the service life of each product is also important. The service life is the estimated period during which a product, material, or system is expected to fulfill its intended function without significant degradation or the need for excessive maintenance. End of life denotes the concluding phase in the life cycle of a product, material, or system, covering all

processes related to the disposal, recycling, or recovery of the product following the completion of its designated usage period.

Intervention	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
Triple glazed window	53 tonnes CO ₂ eq	59.2%
Mineral Wool Insulation Panel	24 tonnes CO ₂ eq	27.0%
Plaster	9.3 tonnes CO ₂ eq	10.3%
Waterproofing membrane	3.2 tonnes CO ₂ eq	3.5%

Table 26. Scenario 1 – GWP most contributing materials.

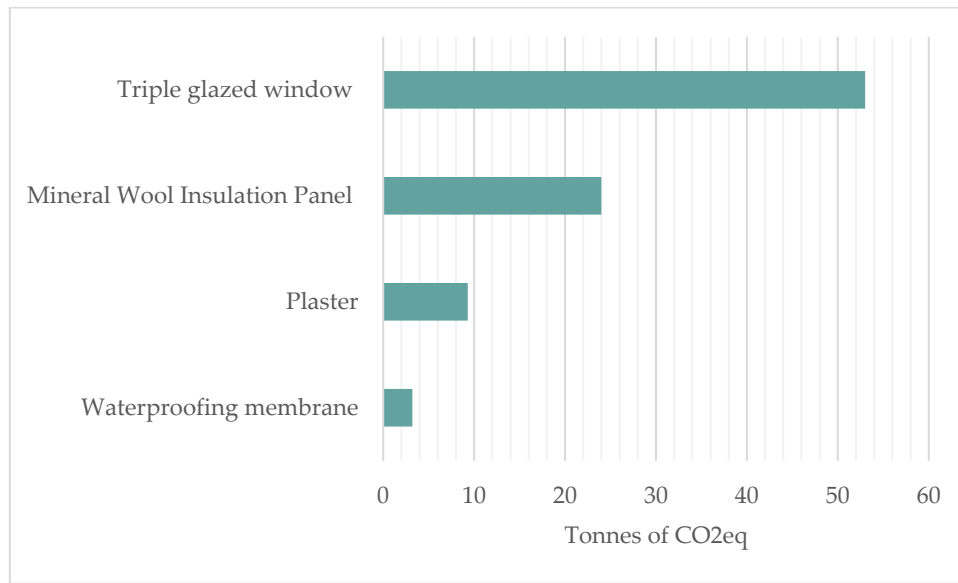


Chart 2. Scenario 1 – GWP most contributing materials across A1-A3 life-cycle stages.

The rockwool insulation panels used, sourced from France, are produced from volcanic rocks through a process of melting and fiberizing that requires significant heat, or from recycled materials, which may mitigate the initial energy consumption over time.

PVC, a synthetic polymer, is made from ethylene and chlorine. Ethylene, derived from fossil fuels, is produced through cracking processes that release substantial CO₂ emissions. Chlorine production involves electrolyzing salt water, consuming a significant amount of energy.

Transportation data for all materials suggest that procuring materials closer to the construction site could lower transport-related emissions. Considering the service life and wastage rates of materials offers insights into reducing environmental impacts, for instance, by enhancing durability or optimizing construction practices to decrease waste.

Rockwool panels are utilized for insulation in walls and roofs, markedly improving the building's energy efficiency. Despite its effectiveness, rockwool's energy-intensive production contributes notably to its global warming potential (GWP). Adding an

extra insulation layer to the roof diminishes heat loss but increases the GWP due to the materials' production. Triple-glazed PVC windows offer superior insulation; however, the carbon-intensive production of PVC significantly affects the GWP.

The considerable CO₂e emissions from the window unit highlight an opportunity for enhancement, possibly through alternative materials or by refining the manufacturing process to cut emissions.

Result category		Global warming kgCO ₂ eq
A1-A3	Construction Materials	89590.01
A4	Transportation to site	15837.2
A5	Construction/installation process	1974.26
B1	Use phase	0
B3	Repair	0
B4-B5	Material replacement and refurbishment	132955.76
B6	Energy consumption	5360857.89
B7	Water use	0
C1-C4	End of life	1328.07

Table 27. Scenario 1 – LCA results.

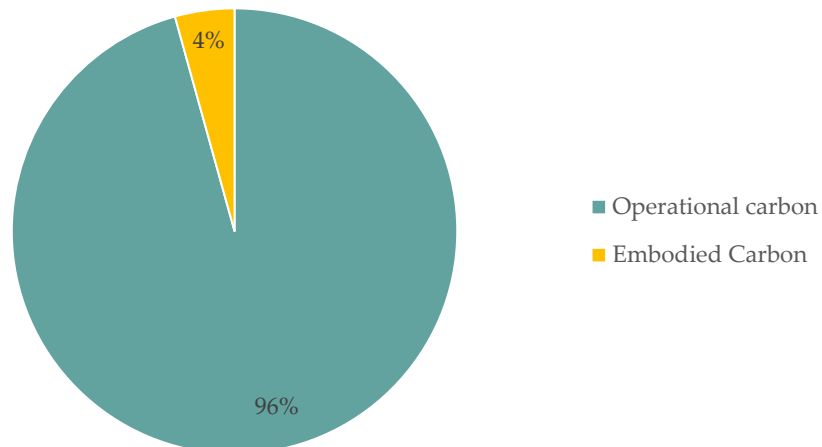


Chart 3. Scenario 1 – Contribution of Embodied and Operational kgCO₂eq emissions.

The Chart 3 reveals that the operational carbon contribution related to the B6 stage has the highest rate 96% compared to the other stages 4%.

From the LCA analysis it's possible to notice a significant amount of non-renewable energy in the Construction Stage (A1-A3) that is used in the construction material phase, which includes the extraction, production, and manufacturing of materials. This is reflected in the high total use of primary energy (36680,76 MJ) and a

considerable amount of non-renewable primary energy used (483879,37 MJ). Renewable energy is (72100,11 MJ), indicating a potential area for improvement by increasing the use of renewable resources in material production.

External walls and façade	
Global warming [kgCO ₂ eq]	
Mineral Wool Insulation Panel	69,46%
Plaster	30,54%
Section Share	33,84%
Floor slabs, ceilings, roofing decks, beams, and roof	
Mineral Wool Insulation Panel	49,25%
Waterproofing membrane	50,75%
Section Share	7%
Windows and doors	
Triple glazed window	100%
Section Share	59,17%

Table 28. Scenario 1 – Materials contribution to A1-A3.

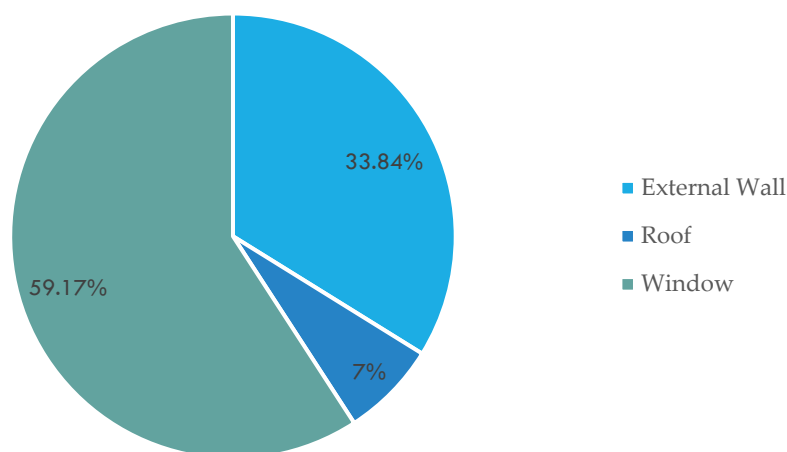


Chart 4. Scenario 1 – Building parts contribution to A1-A3.

From Table 28 it's possible to notice that the highest impact (59,17%) is due to the triple glazed window due to the manufacturing process of the glass and the frame, as well as the materials used, but a strong contribution is also given by the production of rockwool with 69,46% over the 33,84% of the section share.

External walls and façade	
Global warming [kgCO ₂ eq]	
Mineral Wool Insulation Panel	4,15%
Plaster	95,85%
Section Share	87,60%
Floor slabs, ceilings, roofing decks, beams, and roof	
Mineral Wool Insulation Panel	41,05%
Waterproofing membrane	58,95%
Section Share	1,30%
Windows and doors	
Triple glazed window	100%
Section Share	11,10%

Table 29. Scenario 1 – Transportation contribution A4.

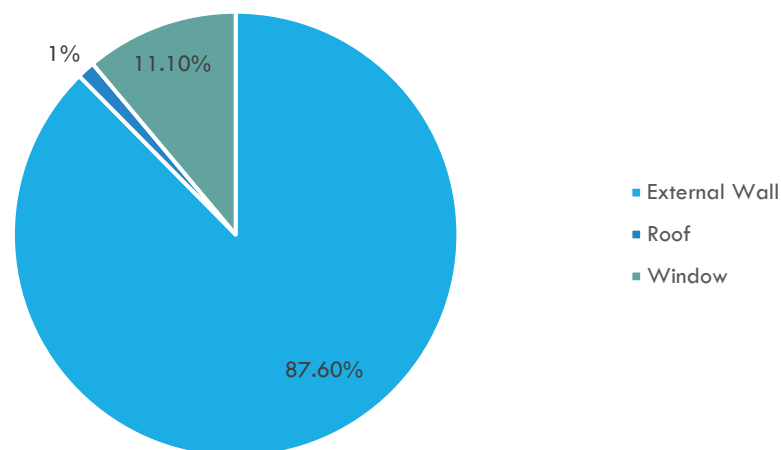


Chart 5. Scenario 1 – Building parts contribution to A4.

Most of the impact related to the transportation to the construction site (A4) is given by the plaster, directly shipped from United Arab Emirates.

During Construction and installation process (A5) both renewable and non-renewable energy use increases, with non-renewable energy being predominant. The emissions related to this stage are mostly due to the waste produced in the construction site generated from the installation of plaster. During its installation and construction, 5% of the material amount is estimated to be wasted through excess preparation and cleaning processes. The losses are considered as landfilled.

The B4 and B5 show material replacement and refurbishment as significant contributors to primary energy use, indicating that maintenance activities and material lifespans are critical factors in the building's overall energy profile. Each material

selected for the interventions has a service life shorter than the building's calculated lifespan. The analysis underscores that a substantial portion of emissions are due to the maintenance of plaster for ETICS system. To preserve the plaster's quality over time, regular monitoring and preventive maintenance are crucial. Therefore, the plaster's projected lifespan is established at 20 years. Similarly, the waterproofing membrane plays an important role, necessitating maintenance. Consequently, its lifespan has also been assessed at 20 years, significantly impacting the project's overall emissions.

The energy consumption (B6) is the largest contributor to non-renewable primary energy use, and it highlights the importance of energy efficiency measures and the potential impact of renewable energy sources on reducing the building's carbon footprint. Comparing Scenario 1 with the Baseline, the switch from a boiler to an electric heat pump revealed significant differences especially in the reduction of the 61% in primary energy. This change underscores the importance of the system selection and demonstrates the potential environmental benefits (-63% of kgCO₂eq). The switch to an electric heat pump changes the type of energy consumed from direct combustion of fuels in a boiler to electrical energy reducing the use of non-renewable energy to -63%.

External walls and façade	
Global warming [kgCO ₂ eq]	
Mineral Wool Insulation Panel	23,08%
Plaster	76,92%
Section Share	31,83%
Floor slabs, ceilings, roofing decks, beams, and roof	
Mineral Wool Insulation Panel	46,04%
Waterproofing membrane	53,96%
Section Share	2,34%
Windows and doors	
Triple glazed window	100%
Section Share	65,83%

Table 30. Scenario 1 – End of life contribution C1-C4.

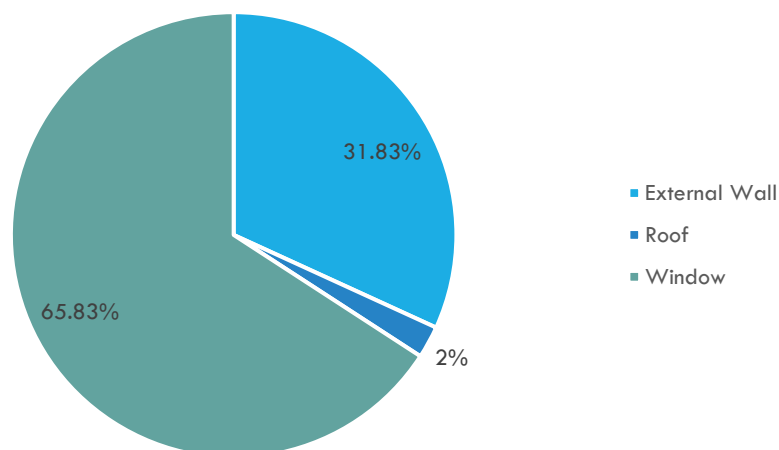


Chart 6. Scenario 1 – Building parts contribution to C1-C4.

The End of Life (C1-C4) phase includes deconstruction, waste transport, processing, and disposal. The most significant impact in this category is attributed to triple-glazed windows with PVC frames, of which only a portion is recycled, while the remainder is disposed of in landfills. Another part of the contribution comes from rock wool, which is disposed of in a storage facility for non-inert and non-hazardous waste. The plaster is also expected to be disposed of in landfills without any reuse, recovery, or recycling.

2.3.4 Life Cycle Assessment – Scenario 2

This refurbishment scenario includes improving the insulation of both opaque and transparent building envelopes by applying an insulating layer to the staircases wall, to the internal slab dividing heated zone from non-heated zone as well as replacing window frames. The electric heat pump has not been changed to the previous intervention. The inputs added to the software for the analysis consist of materials added to the structure to reduce thermal losses, as well as data related to energy consumption, specifically regarding electricity and gas.

Energy consumption [kWh]		Calculation period [years]	Building area [m2]
Electricity use	Natural gas		
159884	6720	60	5055

Table 31. Scenario 2 – OneClick inputs.

Intervention	Area [m2]	Material Origin	Distance from the construction site [km]	Service Life	End of Life
Double glazed window	699.42	France	876	50	Recycled/Reused
Mineral Wool Insulation Panel	33677.64+505.37	France	851	50	Landfilled
EPS Insulation Panel	1461.60+518.28	Italy	65	As building	Landfilled
Waterproofing membrane	505.37	Germany	1043	20	Landfilled
Plaster	3677.64	United Arab Emirates	5902	20	Landfilled
Lime cement plaster	1461.60+518.28	United Arab Emirates	5902	50	Landfilled

Table 32. Scenario 2 – Building materials OneClick inputs.

The Table 31 and Table 32 display the input data added to OneClick. The measures implemented exceed those of the initial scenario, including, for example, the insulation of the stairwell and the floor that separates heated from unheated areas. These modifications help reduce the building's thermal losses, thereby decreasing the required energy consumption.

Intervention	Cradle to gate impacts (A1-A3)	Of cradle to gate (A1-A3)
Double glazed window	49 tonnes CO ₂ eq	46.5%
Mineral Wool Insulation Panel	24 tonnes CO ₂ eq	23.0%
EPS Insulation Panel	15 tonnes CO ₂ eq	13.9%
Plaster	9.3 tonnes CO ₂ eq	8.8%
Lime cement plaster	5 tonnes CO ₂ eq	4.7%
Waterproofing membrane	3.2 tonnes CO ₂ eq	3.0%

Table 33. Scenario 2 – Most contributing materials.

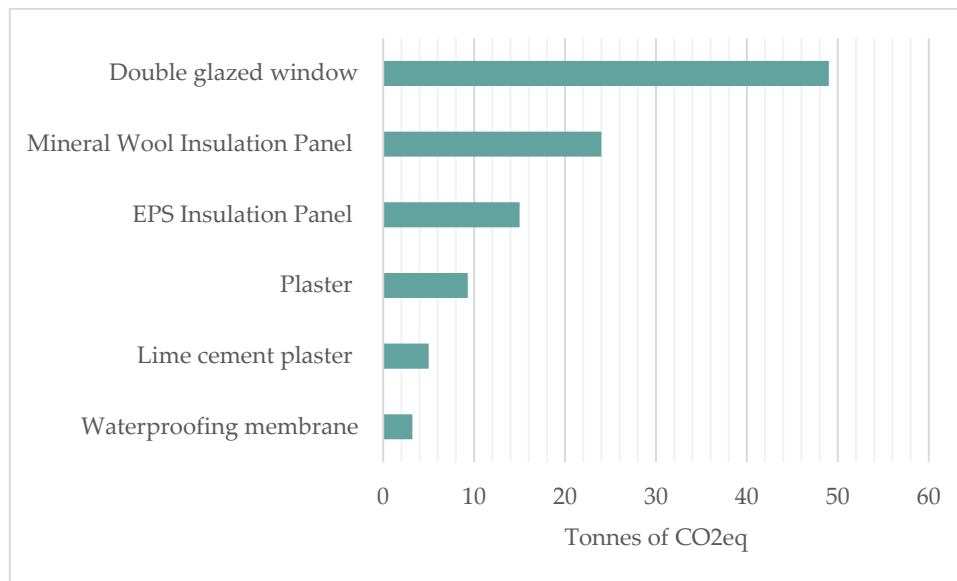


Chart 7. Scenario 2 – GWP most contributing materials across A1-A3 life-cycle stages.

The triple-glazed windows with PVC frames have been replaced with double-glazed windows with aluminum frames, shipped from France, reducing the environmental impact of the building's transparent envelope by approximately 4 tons. A significant factor influencing the results in this scenario is the EPS, whose production process is particularly energy-intensive, contributing significantly to the environmental impact.

Result category		Global warming kgCO ₂ eq
A1-A3	Construction Materials	104903.79
A4	Transportation to site	21802.27
A5	Construction/installation process	2586.19
B1	Use phase	0
B3	Repair	0
B4-B5	Material replacement and refurbishment	138954.45
B6	Energy consumption	4732806.66
B7	Water use	0
C1-C4	End of life	645.22

Table 34. Scenario 2 – LCA results.

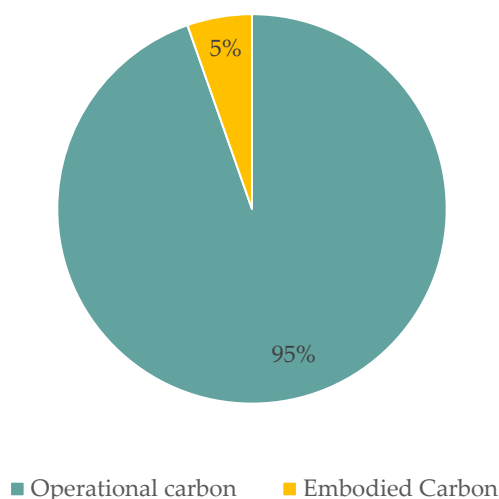


Chart 8. Scenario 2 – Contribution of Embodied and Operational kgCO₂eq emissions.

The Chart 8 reveals that the operational carbon contribution related to the B6 stage has the highest rate 96% compared to the other stages 4%.

Based on the provided analysis of the construction materials stage (A1-A3), the switch from triple-glazed PVC windows to double glazed aluminum frame windows has significantly reduced the contribution to global warming. Double glazing is beneficial for insulation, but the manufacturing process still results in significant CO₂ emissions, like the production of aluminum.

The comparison between scenario 1 and scenario 2 reveals an increase in the construction phase due to the addition of EPS and plaster for insulating the staircase wall and internal slab. The comparison of the two proposed scenarios has resulted in a +17% increase in emissions during the A1-A3 stage, attributable to the escalation of interventions and, consequently, the increased production of materials.

The energy consumption for transportation (A4) experiences a +38% increase in the second scenario, primarily due to the transportation of additional materials, including both types of plaster shipped from the United Arab Emirates. The construction and installation processes (A5) an increase (+31%) given especially by the 2% of rockwool wasted at the construction site and to the packaging of the insulation panels which are partly recycled and partly incinerated. The most significant contribution comes from both types of plaster, which account for a 5% material loss during the preparation and cleaning processes.

The B4 and B5 stages highlight material replacement and refurbishment as significant factors in the building's primary energy consumption, emphasizing that maintenance practices and material lifespans play an important role in the building's energy footprint. The analysis reveals that a significant number of emissions are due to the maintenance of plaster in the ETICS system. To ensure the plaster remains in prime condition, it is essential to conduct regular inspections and carry out preventive maintenance. As such, the lifespan of the plaster is projected at 20 years. In a similar

way, the waterproofing membrane is critical, requiring ongoing maintenance, with its lifespan also estimated at 20 years, markedly influencing the project's total emissions. Moreover, a slight increase of 2% is noted compared to scenario 1, attributed to the environmental impact increased from the replacement of the double-glazed window and the plaster used for the staircase walls and internal slab finishes.

The energy consumption (B6) during the use phase is substantial and represents the highest contributor, despite this, the decrease in energy consumption (B6) impact in Scenario 2 (-12%) might seem to be given by the addition of EPS. This could be due to improvements in heating/cooling technology, shifts to renewable energy sources, or the building requiring less energy despite less effective insulation used for external walls. Total use of non-renewable primary energy in the energy consumption phase (B6) of Scenario 2 decreases (-12%), which can be attributed to the interventions such as improved insulation and window replacements that lead to reduced energy demand for heating and cooling.

The end of life (C1-C4) (-51%) shows a decrease in the waste disposal category primarily attributed to windows. According to the Environmental Product Declarations (EPDs), both plasters are landfilled without reuse, recovery, or recycling. Similarly, EPS is disposed of entirely in landfills, a fate that the waterproofing membrane also shares. The double-glazed window, on the other hand, doesn't contribute to the end-of-life stage, as the window frame can be reused for its original purpose. The aluminum profiles are fully recyclable. During dismantling or renovation, the glazing is separated from the window frame right at the construction site and then directed to the glass industry's return system for recycling.

The final values from the LCA highlight the importance of reducing CO₂e emissions throughout the building's lifecycle to mitigate climate change and its associated social costs. The analysis highlights that operational energy use, particularly electricity, is the dominant factor in the building's global warming potential. This suggests a need for strategies to reduce energy consumption or shift towards renewable energy sources. Materials like PVC in windows and insulation have a significant environmental impact. This suggests that choosing materials with a lower carbon footprint could reduce the building's overall emissions. The construction process itself has a lower impact on global warming potential compared to the use phase. However, material replacement and refurbishment are still significant and should be minimized through durable design choices.

2.4 Insulation Materials Analysis

The objective of the project is to demonstrate a reduction in the embodied carbon of the primary materials used within the project scope, compared to a baseline scenario of equivalent building size, function, and energy performance.

Using a baseline is essential to illustrate the individual reduction strategies implemented compared to the initial design.

The project may achieve a benefit by substituting a carbon-sequestering product for one that produces carbon. Eligible embodied carbon reduction strategies fall into one of three categories: a reduction in material quantity, a material alternative, or a product alternative:

Reduction Type	Example Strategies
Material quantity reduction	Building or material reuse
	Prefabrication for material reduction
	Structural design for material efficiency
Material alternative	Structural assembly alternative
	Wall assembly alternative
	Natural or carbon-sequestering alternative
Product Alternative	Salvaged product alternative
	Locally sourced product alternative
	Sustainability harvested product alternative
	Product manufactured from renewable energy

Table 35. Embodied carbon reduction categories and examples strategies.

Beginning with the initial premise, scenario 2 is identified as the baseline, with all its characteristics and implemented interventions fully preserved. The analysis involves substituting the mineral wool insulation, as suggested by the document [119], with insulation materials that are compatible with the external thermal insulation composite system (ETICS). These materials may either be carbon sequestering or emit carbon producing, with the goal of investigating the potential to lower the building's total CO₂ emissions by employing alternative materials.

The alternative insulation materials selected for further analysis include:

- Cork
- Wood Fiber
- Expanded Polystyrene
- Polyurethane

Examples of insulation materials capable of sequestering carbon include cork and wood fiber insulation. Cork, harvested from the bark of cork oak trees without damaging the tree, is a renewable resource that is naturally resistant to moisture and

mold. It is biodegradable and can be composted at the end of its life, reducing landfill waste, depending on its application. Cork can also be recycled into new insulation products or other cork-based materials, providing a sustainable end-of-life scenario. Wood fiber insulation panels are produced using sawmill residues, thereby reducing industrial waste. This makes them an ecological and sustainable choice, derived from a natural source with the capacity to store carbon.

On the other hand, materials known for producing carbon include Expanded Polystyrene (EPS), Polyurethane (PU), which are commonly used in External Thermal Insulation Composite Systems (ETICS) due to their high thermal resistance. The production of EPS involves petrochemicals and can be energy-intensive, contributing to its carbon footprint. PU is produced through chemical processes that are carbon intensive.

While carbon-producing insulation materials offer excellent thermal properties, significantly reducing the need for heating and cooling in buildings, their embodied carbon, resulting from production, is higher compared to natural alternatives. However, these natural alternatives may have less insulative efficiency.

2.4.1 OneClick Input Data

For the comparison of alternative insulation materials to mineral wool, products have been selected directly from the OneClick database. The selection was driven by specific criteria such as the compatibility of the insulation with the ETICS system. This approach aimed to ensure that the chosen products met the necessary physical characteristics to achieve maximum energy efficiency and the same thermal transmittance as the system designed for scenario 2. In addition to physical parameters, great attention was also paid to environmental aspects, favoring products with a low environmental impact. This choice was motivated by the desire to reduce the ecological footprint of the interventions, in line with sustainability principles. In some cases, even when choosing a product from "One Click" that seemed to meet the necessary physical characteristics for the planned interventions, limitations related to the wide software's database have been faced. Crucial details such as the material's origin, its expected lifespan, and end-of-life scenario information depend entirely on the Environmental Product Declaration (EPD) of the chosen product. This means that, although a product may appear suitable based on its physical specifications, the lack of complete data in the EPD or the absence of such declarations in the "One Click" database can limit our ability to fully assess the product's environmental impact and its adherence to sustainable criteria or specific project requirements. Therefore, the importance of an updated database rich in detailed information, including EPDs, is crucial for making informed and responsible choices. This approach allows overcoming the encountered limitations and selecting products that are not only energy-efficient but also sustainable.

To preserve the building's thermal performance, it was decided to choose an insulation thickness that matched the thermal resistance of the mineral wool in the ETICS system proposed by the document [119] for scenario 2. However, during the calculations, it emerged that the thickness derived from the thermal conductivity of each material (according to their technical data sheets) often did not align with the thicknesses commercially available. This discrepancy led to variations in the calculated thermal resistances compared to the expected values for mineral wool, altering the system's total thermal transmittance. Consequently, this adjustment affected the building's energy consumption.

Material	Required Thickness [m]	Required Resistance [m ² K/W]	Market Thickness [m]	Market Resistance [m ² K/W]	λ [W/mK]	ρ [kg/m ³]
Cork	0.124	3.191	0.120	3.077	0.039	110
Wood Fiber	0.121	3.191	0.120	3.158	0.038	110
Expanded Polystyrene	0.109	3.191	0.100	2.941	0.034	24
Polyurethane	0.083	3.191	0.080	3.077	0.026	35

Table 36. Required and market thicknesses and thermal resistances of alternative insulation materials.

Data related to the calculation period and the building area have not been modified; therefore, the calculation period remains 60 years, and the building gross internal floor area is 5055 m².

To gather data regarding the building's energy consumption, simulations were performed with IESVE, integrating the properties of alternative insulation materials (as detailed in Table 35) as replacements for the mineral wool formerly utilized in the insulation system of the external walls. The settings related to additional interventions in scenario 2 remained unaltered.

Material	Energy consumption [kWh]	
	Electricity use	Natural gas
Cork	161444	6980
Wood Fiber	161254	6790
Expanded Polystyrene	162684	7342
Polyurethane Foam	163212	6983

Table 37. Alternative materials – Energy consumption.

With the reduction in thermal resistance of each material used as an alternative to mineral wool, there was an increase in energy consumption for both electricity and natural gas (Mineral Wool: electricity use 159884 kWh, natural gas 6720 kWh).

It is crucial to note the difference in energy consumption between cork and polyurethane foam, despite them having identical thermal resistance.

This indicates that energy consumption is influenced by various factors, such as the heat conduction properties of each material, which impacts the total energy needed to maintain a specific temperature. The insulation thickness contributes to the building's overall thermal mass, which can affect how the building retains heat or cools down.

Material	Weight [kg]	Material Origin	Distance from the construction site [km]	Service Life [years]	End of Life
Cork	48545	Portugal	2145	50	Recycled/Landfilled
Wood Fiber	48545	Germany	528	50	Landfilled
Expanded Polystyrene	8826	Czech Republic	976	50	Recycled/Landfilled
Polyurethane	10297	Italy	238	50	Landfilled

Table 38. Alternative materials – OneClick inputs.

The values in the Table 37 represent additional input data required for running simulations in OneClick. These data are essential as they will influence the calculation of the environmental impact.

Starting from the provided inputs, an analysis of the environmental impact resulting from the replacement of mineral wool with an alternative insulation material was conducted. The results obtained from the OneClick simulations were compared with those from simulations related to scenario 2.

In the comparison, the interventions applied remained unchanged, except for the thermal insulating material used in the ETICS (External Thermal Insulation Composite System). Thus, the primary distinction between the scenarios was the insulation choice: mineral wool in scenario 2 versus an alternative material in scenario 1.

The comparative assessment focused on analyzing the effect of replacing the thermal insulating material on the energy performance and environmental impact assessing the embodied carbon over a of 1m² of façade and the operational carbon over 1m² of gross internal floor area.

This comparison aimed to identify the differences in terms of thermal insulation, energy efficiency, and overall environmental impact (calculated through indicators such as embodied energy, CO₂ emissions, and other LCA impact factors) between the two insulation options.

2.4.2 Cork Insulation

Expanded Insulation Corkboards exhibit lower thermal conductivity ($\lambda=0,039$ W/mK) compared to mineral wool, suggesting that to achieve the same thermal performance it requires less material. The cork insulation, produced in Portugal, is located 2145km from the construction site. Information obtained from Environmental Product Declarations (EPDs) includes the material's service life of 50 years, which impacts the

B4-B5 stage. Additionally, the EPD provides details on the end of life, indicating that part of the material will be recycled while the one remaining will be sent to landfill.

Result Embodied Carbon		Global warming kgCO ₂ e/m ²	Comparison with Mineral Wool
A1-A3	Construction Materials	10.50	-23%
A4	Transportation to site	1.13	+217%
A5	Construction/installation process	0.23	-17%
B1	Use phase	0	0%
B3	Repair	0	0%
B4-B5	Material replacement and refurbishment	4.63	-67%
B7	Water use	0	0%
C1-C4	End of life	0.03	-63%

Table 39. Cork Insulation – Embodied kgCO₂eq emission results over 1 m² of façade.

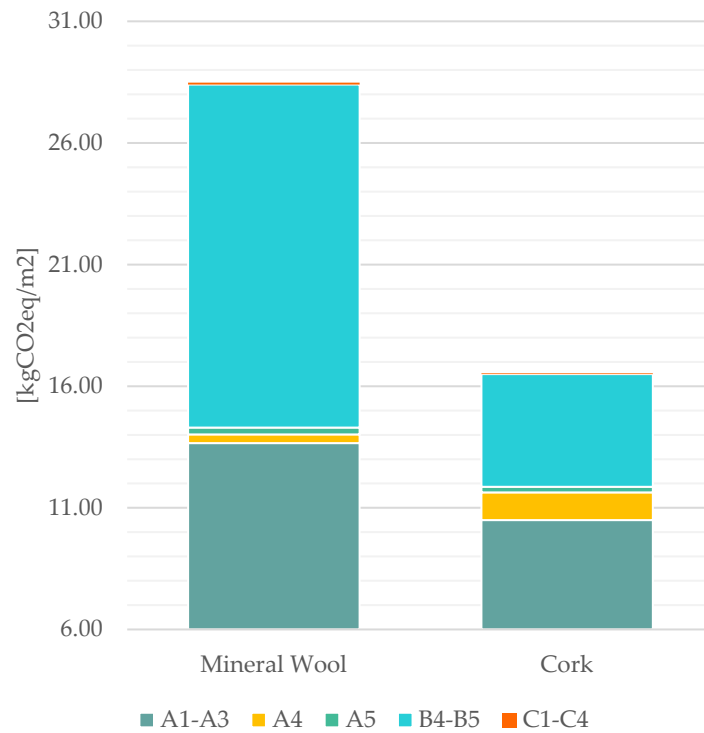


Chart 9. Cork Insulation – Comparison of embodied life-cycle stages among mineral wool and cork insulation over 1 m² of façade.

	Result Operational Carbon	Global warming kgCO ₂ e/m ²	Comparison with Mineral Wool
B6	Energy consumption	945.98	+1%

Table 40. Cork Insulation – Operational carbon results over 1 m² of gross internal floor area.

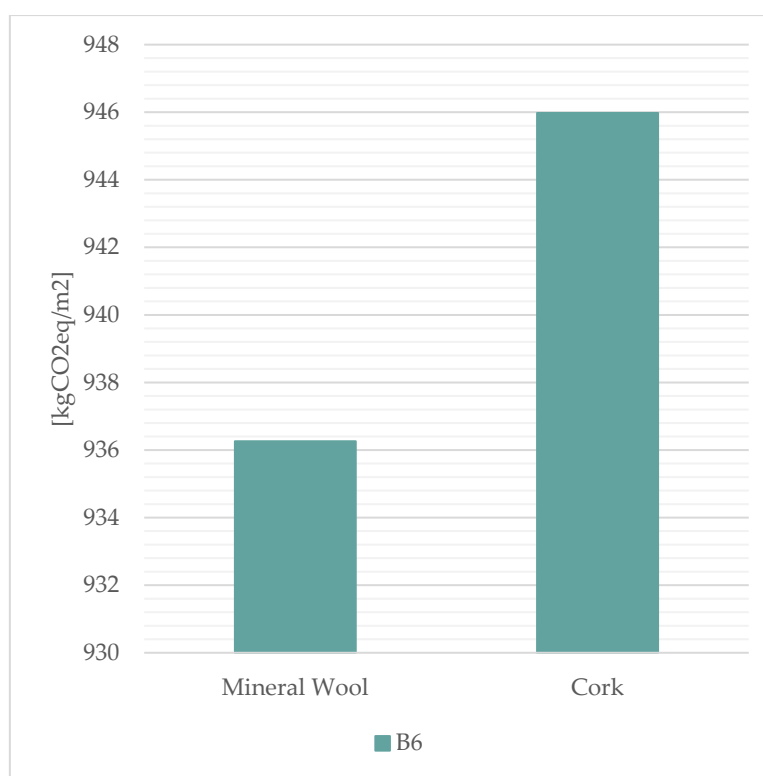


Chart 10. Cork Insulation – Comparison of operational life-cycle stages among mineral wool and cork insulation over 1 m² of gross internal floor area.

The EICB scenario shows a -23% reduction in kgCO₂eq/m² emissions for construction materials phase (A1-A3). The production of expanded cork insulation generally requires less energy than rockwool, leading to lower emissions associated with the manufacturing phase and might generate less waste. The reduction reflects the fact that only one raw (and natural) material is used in ICB production.

There is an increase of +217% in the transport (A4) for the EICB scenario. This is due to the cork being sourced from further away.

EICB scenario has a -17% reduction of kgCO₂eq emissions during construction and installation (A5). This could be due to the lower energy required to produce cork as compared to mineral wool. Cork doesn't require extensive processing like mineral wool, which is typically manufactured at high temperatures. The decrease of the construction site materials in the EICB scenario is due to the presence of less cork needed to achieve the same insulation efficiency.

In the B4-B5 category, a decrease of -67% is observed, with a specific reduction in material replacement. Given a building lifespan of 60 years, mineral wool and cork

may require at least one replacement. The decrease in environmental impacts can be attributed to cork's recyclable and biodegradable nature, which means that it generates fewer emissions in the B5 stage compared to mineral wool, due to the latter's more complex disposal processes.

In the energy consumption category (B6), a +1% increase is observed. This results from replacing mineral wool with an alternative material, necessitating the selection of a commercially available thickness to achieve a thermal resistance comparable to the mineral wool used in Scenario 2. This adjustment has led to decreased thermal resistances, resulting in a more thermally dispersive envelope. Although the increase is only 1%, it is attributed to the mass of the envelope, given by cork insulation, which influences the ability to retain heat.

The substitution of mineral wool insulation with expanded cork insulation is expected to also influence the end-of-life (C1-C4) emissions positively. Based on the analyses it's possible to notice a decrease of -67% in the end-of-life phase. According to the EPD, 60% of the ICB is recycled into Expanded Cork Granules, the remaining 40% is deposited in landfill. This recycling process proposes the cork for further use minimizing waste. The remaining 40% of cork sent to landfill still has a lower environmental impact compared to mineral wool because cork is biodegradable causing less long-term damage to the environment. Mineral wool, on the other hand, is entirely sent to landfills without any portion being recycled. Landfilling contributes to environmental degradation through the emission of greenhouse gases.

In conclusion, while cork's biodegradable nature contributes to reductions across all embodied carbon stages, significantly enhancing its environmental profile, the assessment faces substantial penalties due to transportation distances. Cork production is centralized in Portugal, meaning that if the cork is used in projects located far from Portugal, the environmental benefits gained from its biodegradable properties and reduced waste in landfills may be offset by the emissions associated with transporting it over long distances. This underscores the critical importance of considering the entire lifecycle and supply chain process when evaluating the sustainability of building materials.

This situation highlights the complexity of achieving sustainability in construction and the necessity of a holistic view that encompasses the entire process from material production through to end-of-life disposal, including all intermediary steps like transportation. It emphasizes that sustainable material selection involves balancing various factors, including material properties, production processes, recyclability, biodegradability, and the logistics of getting the material from the source to the site. Only by considering all these aspects can a truly sustainable decision be made, illustrating the importance of local sourcing where possible and the need for a comprehensive approach to assessing environmental impacts.

2.4.3 Wood Insulation

Wood fiber insulation panels represent an eco-friendly choice, featuring lower thermal conductivity ($\lambda=0,038$ W/mK) compared to mineral wool. These insulation panels are manufactured in Germany, located 528 km from the construction site. Information obtained from the Environmental Product Declaration (EPD) includes the material's service life, which is 50 years, and details about its end-of-life options, indicating that the wood insulation can either be incinerated or disposed of in a landfill. For this analysis, it has been assumed that the wood insulation will be sent to a landfill.

Result Embodied Carbon		Global warming kgCO ₂ e/m ²	Comparison with Mineral Wool
A1-A3	Construction Materials	7.28	-47%
A4	Transportation to site	0.27	-25%
A5	Construction/installation process	0.38	+35%
B1	Use phase	0	0%
B3	Repair	0	0%
B4-B5	Material replacement and refurbishment	7.62	-46%
B7	Water use	0	0%
C1-C4	End of life	0.07	-11%

Table 41. Wood Insulation – Embodied carbon results over 1 m² of façade.

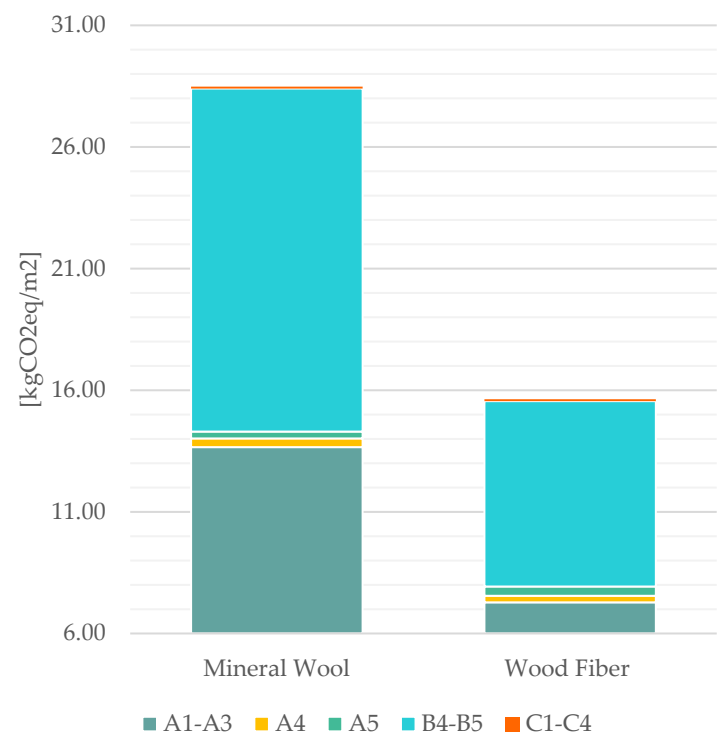


Chart 11. Wood Insulation – Comparison of embodied life-cycle stages among mineral wool and wood insulation over 1 m2 of façade.

Result Operational Carbon		Global warming kgCO2e/m2	Comparison with Mineral Wool
B6	Energy consumption	944.32	+1%

Table 42. Wood Insulation – Operational carbon results over 1 m2 of gross internal floor area.

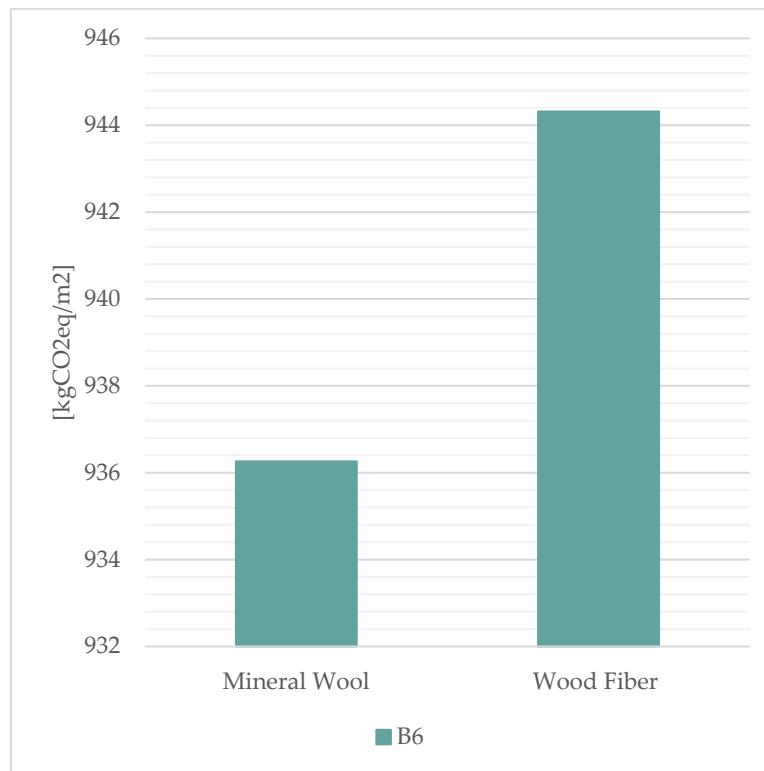


Chart 12. Wood Insulation – Comparison of operational life-cycle stages among mineral wool and wood insulation over 1 m² of gross internal floor area.

In the construction materials phase (A1-A3) there is a -47% reduction in global warming potential. This highlights the natural processes involved in the wood fibers manufacturing. From EPD a significant reduction is due to the use of wood waste from carpentry to produce wood fiber insulation panels, which are then treated and transformed. By recycling this wood waste, the insulation not only helps to reduce the amount of waste that would otherwise end up in landfills but also decreases the need for new wood resources.

In stage A4 is recorded a decrease of -25% in kgCO₂eq/m² associated with the transport which might be due to the need to transport the wood fiber insulation over a smaller distance than the mineral wool.

In the A5 construction and installation stage is recorded an increase of +35% of kgCO₂eq/m² indicating that there is more waste material associated with wood fiber compared to mineral wool. Based on the Environmental Product Declarations (EPDs) for both materials, it is estimated that the product waste during the construction and installation process of mineral wool accounts for 2% of the produced material. Regarding wood, the assumed product waste during the installation process is 5%, which accounts for the increase observed in the A5 category. Additionally, this increase can be attributed to the higher density of wood fiber insulation compared to mineral wool, making it heavier and thus increasing the total emissions associated with material handling.

Both wood fiber and mineral wool insulation share the same service life of 50 years, yet there is a recorded decrease of -46% in the B4-B5 category for wood fiber. This

reduction may be connected to the production process of wood fiber insulation, which could be more energy-efficient and utilize less carbon-intensive energy sources compared to mineral wool.

In the energy consumption category (B6), a +1% increase is observed. This increase is due to the decrease of thermal resistances, resulting in a more thermally dispersive envelope. Although the increase is only 1%, it is attributed to the mass of the envelope, given by wood fiber insulation, which influences the ability to retain heat.

In the end-of-life scenario (C1-C4), a decrease of -11% is observed. The Environmental Product Declaration (EPD) indicates that the insulation will not be recycled but will be completely sent to landfill. This reduction could be attributed to the biodegradable nature of wood fiber insulation, resulting in a lower environmental impact in the end-of-life category.

In the context of Life Cycle Assessment (LCA) impact, wood fiber insulation offers environmental benefits such as carbon sequestration and the potential for lower emissions during production. This underscores the necessity of evaluating the entire supply chain to accurately assess the environmental performance of building materials. The ability of wood fiber to capture and store carbon dioxide during its growth phase, coupled with possibly reduced emissions in its manufacture, positions it as a preferable option from an environmental standpoint.

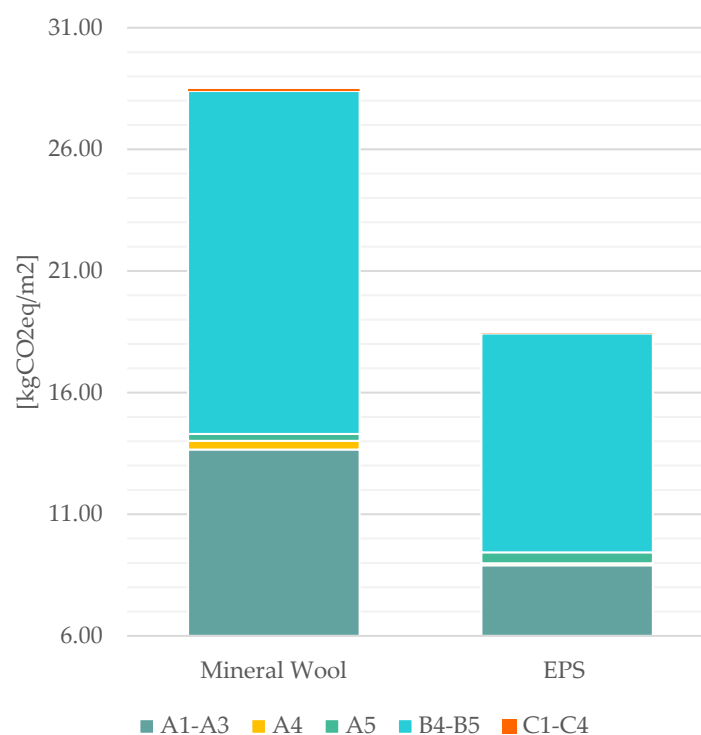
However, this analysis also brings to light the significance of considering different stages of a material's life, including end-of-life scenarios. Had a different service life been assumed, incorporating the potential for recycling rather than disposal, the emissions attributed to this phase might have been significantly reduced. The assumption that wood fiber insulation would be sent to a landfill, as informed by the Environmental Product Declaration (EPD), plays a crucial role in determining the overall environmental impact of the material.

This situation illustrates how producer-provided information can shape the assessment of a product's lifecycle scenario. The EPD, which details the environmental impact of a product across its entire life, from production to disposal, influences the final evaluation of its sustainability. Therefore, the EPD's accuracy and the assumptions made based on its data are important in understanding a material's true environmental footprint.

2.4.4 EPS Insulation

The Expanded Polystyrene (EPS) insulation panels ($\lambda=0,034$ W/mK) are lighter than rockwool due to their low density. EPS is manufactured in the Czech Republic, located 976km from the construction site. According to its Environmental Product Declaration (EPD), EPS has a service life of 50 years. At the end of its life, some of the material will be recycled, while the one remaining will be sent to a landfill.

Result Embodied Carbon		Global warming kgCO ₂ e/m ²	Comparison with Mineral Wool
A1-A3	Construction Materials	8.90	-35%
A4	Transportation to site	0.08	-77%
A5	Construction/installation process	0.45	+60%
B1	Use phase	0	0%
B3	Repair	0	0%
B4-B5	Material replacement and refurbishment	9.00	-36%
B7	Water use	0	0%
C1-C4	End of life	0.01	-85%

Table 43. EPS – Embodied carbon results over 1 m² of façade.Chart 13. EPS Insulation – Comparison of embodied life-cycle stages among mineral wool and EPS insulation over 1 m² of façade.

Result Operational Carbon		Global warming kgCO ₂ e/m ²	Comparison with Mineral Wool
B6	Energy consumption	954.15	+2%

Table 44. EPS – Operational carbon results over 1 m² of gross internal floor area.

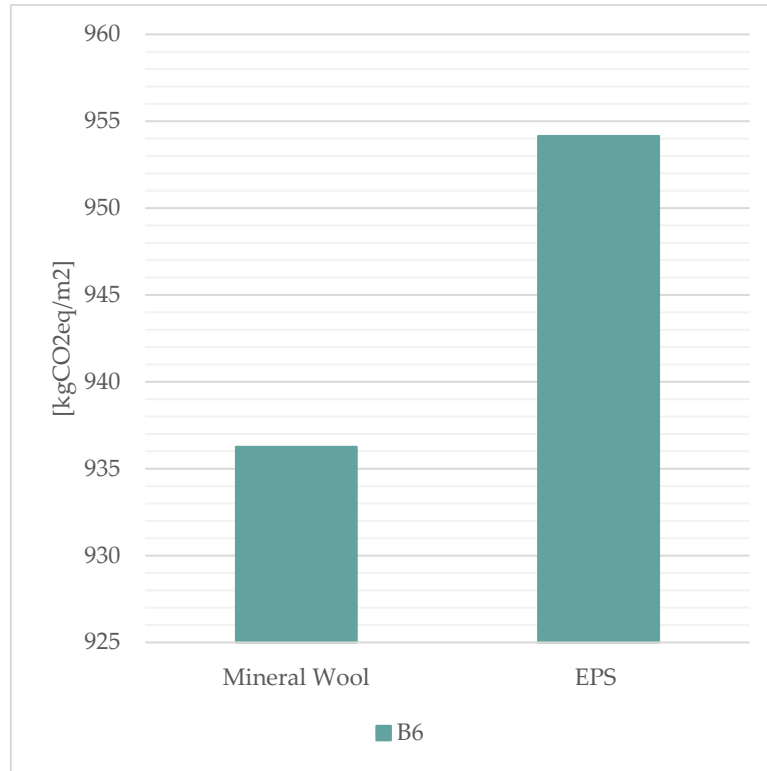


Chart 14. EPS Insulation – Comparison of operational life-cycle stages among mineral wool and EPS insulation over 1 m² of gross internal floor area.

There is a -35% reduction in kgCO₂eq emissions with EPS during the construction material phase (A1-A3). This reduction could be attributed to the fact that less EPS material is required to achieve the same insulating properties, leading to a smaller carbon footprint over the product's entire lifecycle.

The -77% decrease in transportation to the site (A4) might suggest that despite EPS being transported from a greater distance, its lighter weight compared to mineral wool contributes to a reduction in impact. An increase of +60% in the construction and installation process (A5) is related to the waste during the process which is 5% of the product installed compared to the 2% of the mineral wool.

In the B4-B5 category, a decrease of -36% is observed, despite both materials having the same service life. This is because EPS requires less material to achieve the same level of insulation performance, thanks to its superior insulating properties. This efficiency leads to the use of fewer resources throughout the lifecycle, resulting in a lower environmental impact in terms of repair, replacement, and maintenance.

In the energy consumption phase (B6), a +2% increase is observed, despite the materials offering similar thermal resistances. The marginally lower thermal resistance of EPS indicates that it is slightly less effective at inhibiting heat flow. This minor discrepancy can result in slightly increased heat losses, thereby raising energy consumption. Furthermore, the reduced thermal mass associated with EPS may result in less heat storage, necessitating more frequent heating or cooling to maintain comfortable indoor temperatures. Consequently, this leads to higher energy consumption, even when compared to wood fiber insulation.

The decrease (-85%) in the end-of-life (C1-C4) emissions reflects the lower weight of EPS needing to be transported to waste processing facilities or landfills. The reduction is also attributable to the fact that, according to the Environmental Product Declaration (EPD), the EPS used has a high recycling potential. 40% of the products will be returned to the production plant or recycling center, while 60% will end their life in a landfill. Mineral wool, on the other hand, is entirely sent to landfills without any portion being recycled. Landfilling contributes to environmental degradation through the emission of greenhouse gases.

These results underscore that the benefits associated with EPS compared to mineral wool, while notable, are given by the more energy-intensive production process of EPS. However, these findings are intricately linked to an initial assumption made at the outset of these simulations: to consider the same thermal resistance for each insulation material evaluated as a potential replacement for mineral wool. This basis for comparison considers that materials like EPS and polyurethane, which exhibit lower thermal conductivity, require less material volume to achieve the same thermal performance as mineral wool. Consequently, this leads to decreases across the LCA stages due to the lesser volume of material considered.

2.4.5 Polyurethane Insulation

Polyurethane has exceptionally low thermal conductivity ($\lambda=0,026$ W/mK) and is significantly lighter than rockwool. This insulation material is produced in an Italian city located 238 km from the construction site in Milan. Utilizing the Environmental Product Declaration (EPD), the service life of the material has been determined to be 50 years, with its end-of-life options including incineration or landfill disposal. For the purposes of this analysis, it is assumed that the material will be sent to a landfill.

	Result Embodied Carbon	Global warming kgCO ₂ e/m ²	Comparison with Mineral Wool
A1-A3	Construction Materials	7.87	-42%
A4	Transportation to site	0.02	-93%
A5	Construction/installation process	0.08	-72%
B1	Use phase	0	0%
B3	Repair	0	0%
B4-B5	Material replacement and refurbishment	7.91	-44%
B7	Water use	0	0%
C1-C4	End of life	0.01	-82%

Table 45. Polyurethane Insulation – Embodied carbon results over 1 m² of façade.

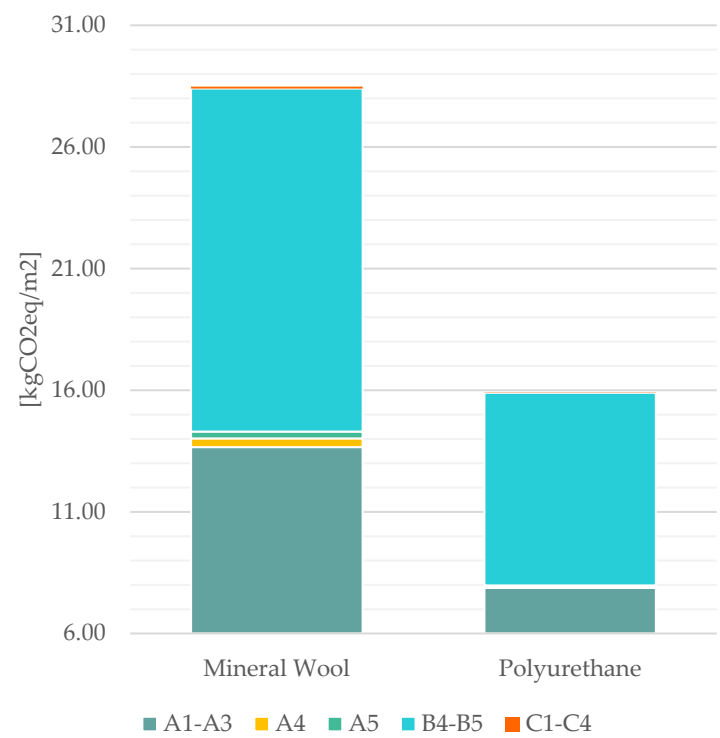


Chart 15. Polyurethane Insulation – Comparison of embodied life-cycle stages among mineral wool and polyurethane insulation over 1 m2 of façade.

Result Operational Carbon		Global warming kgCO2e/m2	Comparison with Mineral Wool
B6	Energy consumption	956.12	+2%

Table 46. Polyurethane Insulation – Operational carbon results over 1 m2 of gross internal floor area.

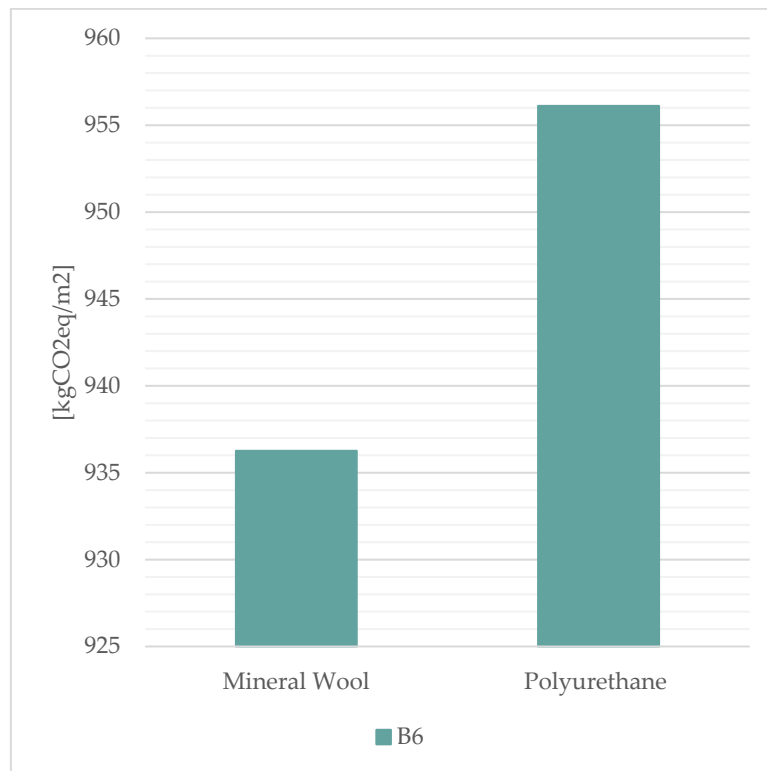


Chart 16. Polyurethane Insulation – Comparison of embodied life-cycle stages among mineral wool and polyurethane insulation over 1 m2 of gross internal floor area.

The use of polyurethane reduces the global warming potential by -42% in the construction process (A1-A3) this might be due to the less thickness used for the polyurethane panel to guarantee the same thermal insulation, influencing positively the impact. Transportation (A4) results in a -93% decrease in emissions because the product, being lighter than mineral wool, was shipped from Italy.

The construction/installation phase (A5) shows a decrease of -72%, primarily attributed to the reduced quantity of material required for installation.

In the B4-B5 category, a decrease of -44% is observed, despite both materials having the same service life. This is because polyurethane foam requires less material to achieve the same level of insulation performance, thanks to its superior insulating properties. This efficiency leads to the use of fewer resources throughout the lifecycle, resulting in a lower environmental impact in terms of repair, replacement, and maintenance.

In the energy consumption phase (B6), a +2% increase is observed, despite the materials offering similar thermal resistances. The marginally lower thermal resistance of polyurethane foam indicates that it is slightly less effective at inhibiting heat flow. This minor discrepancy can result in slightly increased heat losses, thereby raising energy consumption. Furthermore, the reduced thermal mass associated with polyurethane foam may result in less heat storage, necessitating more frequent heating or cooling to maintain comfortable indoor temperatures.

In the end-of-life scenario (C1), there is a noticeable decrease in impact, with a -82% reduction in transportation-related emissions. This reduction suggests a shorter distance to the landfill and less volume to transport, even lower respect to EPS insulation.

This approach highlights how selecting insulation materials based on their thermal efficiency can impact environmental assessments. The reduced volume needed for EPS and polyurethane materials to match the thermal resistance of mineral wool results in lower environmental impacts in various LCA stages, primarily due to decreased material use and associated production, transportation, and disposal impacts.

However, this comparison brings to light a critical aspect of material selection and its implications on sustainability assessments. It would be interesting to analyze what could happen if emissions from these carbon-intensive materials were considered using the same volume as more sustainable options like cork and wood fiber insulation. Such an analysis would potentially offer a deeper understanding of the environmental trade-offs involved. By comparing materials with identical volumes, rather than adjusting for thermal resistance, the evaluation could reveal different insights into the overall sustainability of using high-performance insulations like EPS and polyurethane versus natural, less energy-intensive materials. This could further highlight the importance of considering not just the functional performance of insulation materials but also their comprehensive environmental impacts throughout their lifecycle.

3. Results and discussion

3.1 Building Scenarios

This analysis begins with an environmental impact assessment across three distinct scenarios: the baseline, Scenario 1, and Scenario 2. The objective is to identify the subject of comparison and observe how the results vary across these scenarios. Subsequently, the focus on Scenarios 1 and 2, both of which incorporate specific interventions related to material use. This phase analyzes the impact of these material choices, highlighting the environmental implications of each intervention. Finally, attention is directed towards the most significant interventions between Scenario 1 and Scenario 2, exploring the differences in emissions outcomes. This comparison highlights the trade-offs between energy efficiency and sustainability, offering insights into the effectiveness of each intervention in contributing to a more environmentally friendly and sustainable building design.

3.1.1 Environmental Impact Implications across the three scenarios

The comparison of environmental impacts across the three scenarios reveals a notable reduction in kgCO₂eq per square meter of gross internal floor area. Moving from the Baseline to Scenario 1 and then to Scenario 2, there is a marked decrease, which corresponds with the enhancements in energy consumption and efficiency that have been implemented.

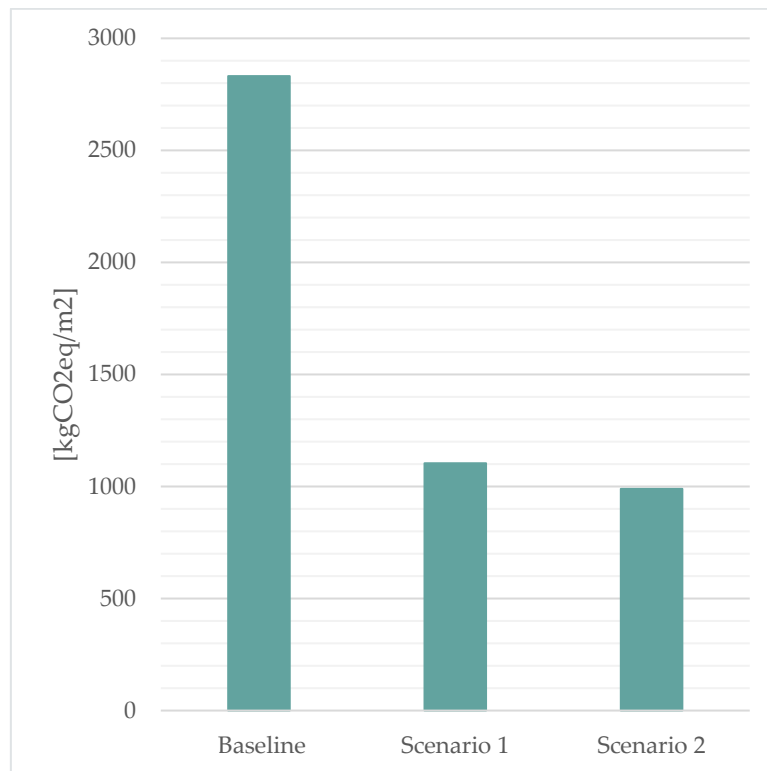


Chart 17. GWP among the three scenarios over 1 m² of gross internal floor area.

The Chart 3 reveals a significant reduction in the environmental impact of the building when transitioning from the baseline to scenario 2. However, a direct comparison between the different stages is not possible, as the baseline depicts the building's current state without any interventions. Scenarios 1 and 2 incorporate interventions from a technological perspective. The only significant information derived from the baseline concerns the energy consumption category B6 in the Life Cycle Assessment.

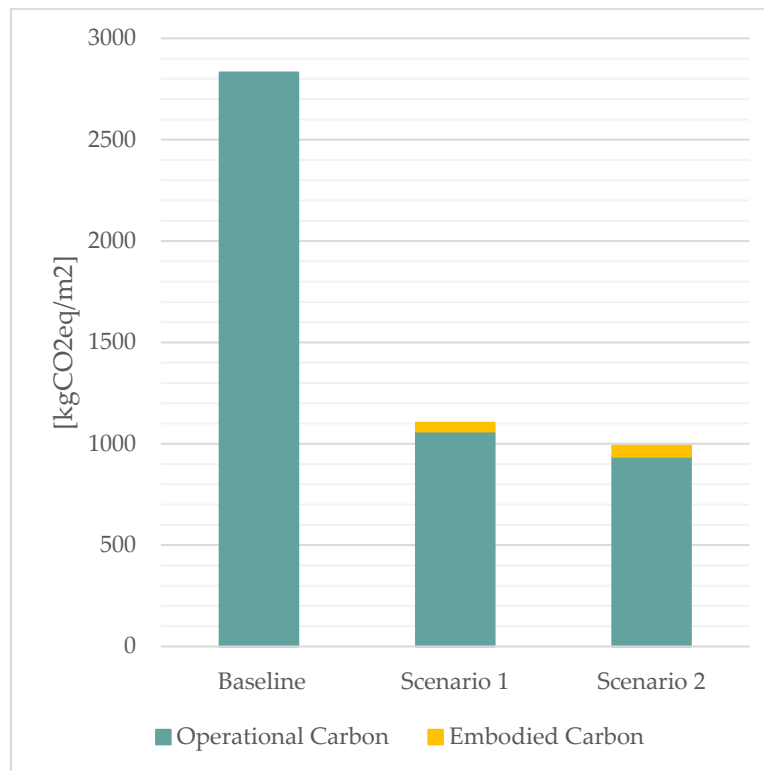


Chart 18. Embodied and Operational kgCO₂eq emissions comparison among the scenarios over the gross internal floor area.

This Chart 4 provides a clear comparison between operational and embodied carbon by focusing on the environmental impact in terms of kgCO₂eq/m². It highlights that the B6 stage, which accounts for operational energy use, has the most significant environmental impact across all scenarios. Compared to the baseline scenario, which uses a boiler, the impact is considerably lower in scenarios that employ an air source heat pump. This reduction, emphasized in both scenario 1 and scenario 2, demonstrates that switching to a heat pump significantly reduces energy consumption and associated emissions. In contrast, using a boiler, which burns fuel to generate heat, results in direct greenhouse gas emissions throughout the building's lifetime. Furthermore, even when analyzing electric heat pumps, if the electricity is sourced from non-renewable resources, it contributes to the carbon footprint. The energy required to run these systems often exceeds the embodied energy and emissions associated with the manufacturing, transportation, installation, maintenance, and disposal of building materials. Consequently, operational energy use (B6 stage) emerges as the most impactful factor over the building's life cycle.

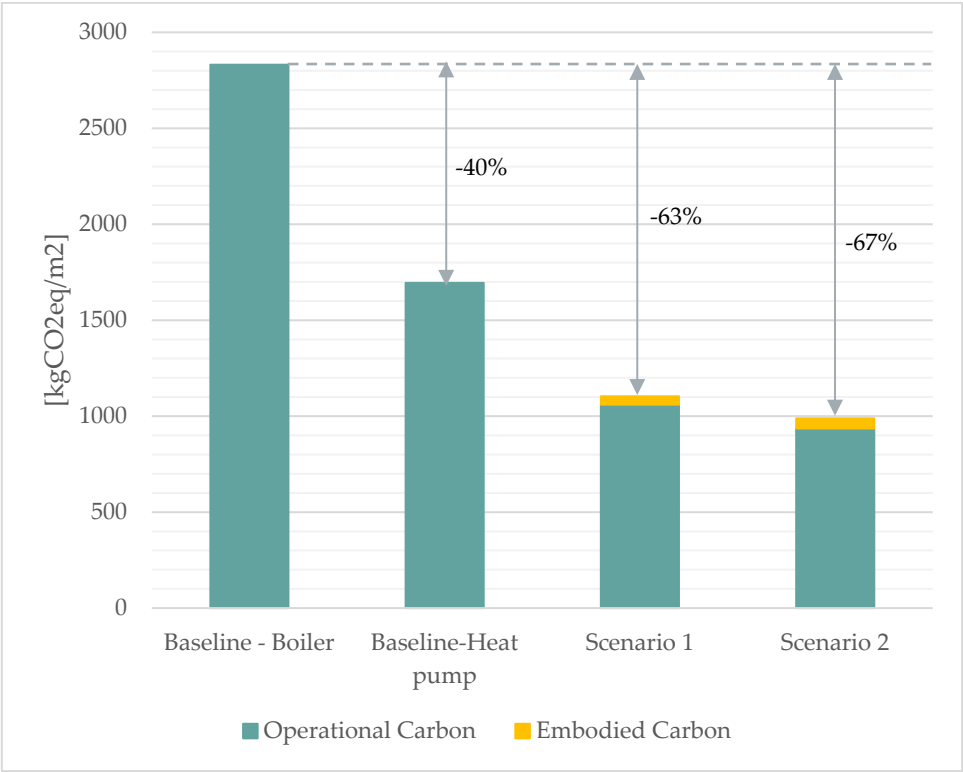


Chart 19. Reduction in energy consumption among scenarios over 1 m2 of gross internal floor area.

The Chart 5 provides a focused comparison on the B6 stage, highlighting the shift in environmental impact due to changes in the heating system and the contribution of materials across various scenarios. Initially, the baseline scenario is characterized by a boiler with a high environmental impact, attributed to its low seasonal efficiency (0.65) and the emissions from fuel combustion for heating. The introduction of an air source heat pump, with a higher seasonal efficiency of 2.00, significantly reduces (-40%) the boiler's impact in comparison to the baseline.

The following analysis shows the installation of the heat pump in both scenarios 1 and 2, leading to further reductions in energy consumption impact: -63% in scenario 1 and -67% in scenario 2 respect to the boiler configuration. These reductions are attributed to interventions aimed at implementing energy-saving solutions, such as the use of materials and technologies that enhance insulation. This improved insulation reduces the demand on the heat pump, thereby lowering overall energy consumption and associated emissions. The contribution of these materials effectively offsets the energy consumption caused by the heat pump, demonstrating a beneficial trade-off, and highlighting the importance of considering both operational and embodied impacts in environmental strategies.

3.1.2 Environmental Impact across Scenario 1 and Scenario 2

Focusing on the interventions planned for both Scenario 1 and Scenario 2, the implementation of technological measures has led to a decrease in energy consumption during the life cycle assessment.

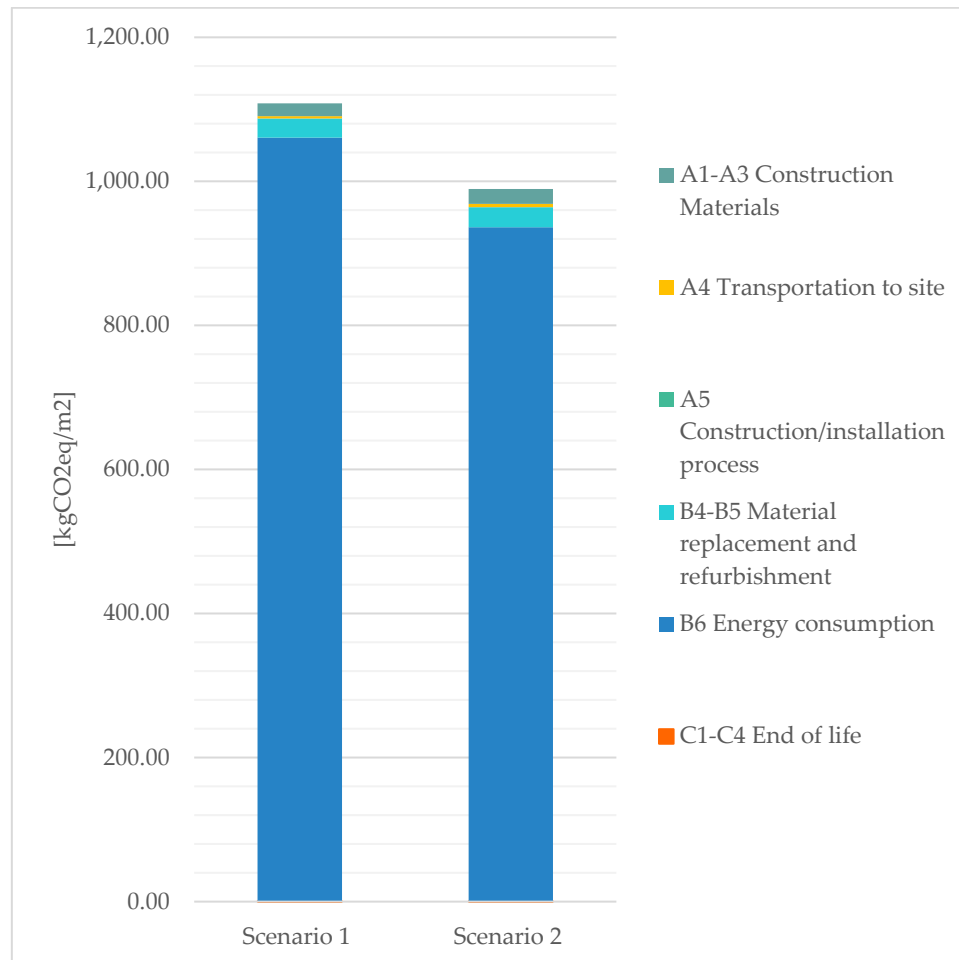


Chart 20. GWP of Scenario 1 and Scenario 2 over 1 m2 of gross internal floor area.

Based on the Chart 6, Scenario 1 exhibits a total global warming potential of 1108.32 kgCO₂eq/m², whereas Scenario 2 shows a reduction to 989.46 kgCO₂eq/m². However, examining the contributions outside of the B6 category, Scenario 2 demonstrates a higher impact (53.19 kgCO₂eq/m²) compared to Scenario 1 (47.81 kgCO₂eq). This indicates that the additional interventions in Scenario 2, which involve increased material usage, have led to a rise in environmental impact. Despite this, Scenario 2, with its higher number of interventions, strategically aims to reduce energy consumption compared to Scenario 1. This approach integrates sustainability measures that lead to lower long-term operational costs and environmental impacts, achieving an energy-efficient outcome.

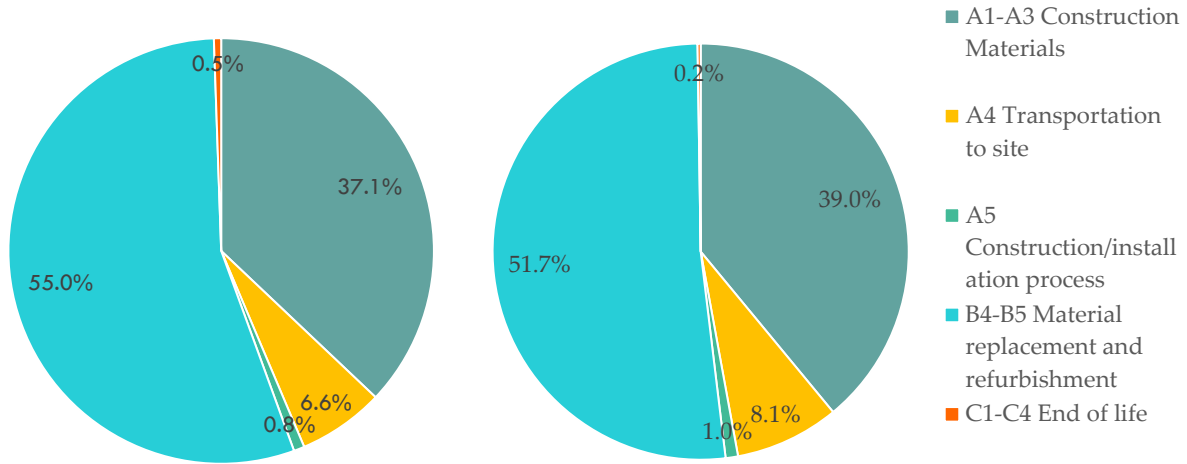


Chart 21. Life Cycle stages contribution of Scenario 1 (left) and Scenario 2 (right) without B6 stage.

Regarding the total emissions expressed in $\text{kgCO}_2\text{eq/m}^2$, the contributions from categories other than B6 account for 4.31% in Scenario 1 and 5.32% in Scenario 2.

By examining this Chart 7, the contribution of each specific category can be estimated using pie charts. These charts highlight the emissions associated with the materials' lifecycle, including their production, transportation to the construction site, installation, and replacement based on their service life, as well as their end-of-life scenarios.

3.1.3 Comparison of Technological Interventions

The materials used in the interventions for Scenario 1 and Scenario 2 exhibit notable differences.

In Scenario 1, mineral wool, with specific plaster, was selected due to its critical role in the ETICS technology for external walls. Additionally, a layer of mineral wool with a waterproofing membrane was applied to the roof, and the existing windows were replaced with triple-glazed windows featuring PVC frames.

In contrast, Scenario 2 also employed mineral wool for the external wall as part of the ETICS system, EPS insulation was applied to the staircase walls and the internal slab to enhance thermal efficiency completed with the respective plaster. The final intervention involved replacing the triple-glazed PVC-framed windows with double-glazed windows that have aluminum frames, aiming for improved thermal performance and sustainability. Examining the environmental impact of technological interventions in both scenarios for the LCA analysis, interventions aimed at enhancing the building's energy efficiency were proposed.

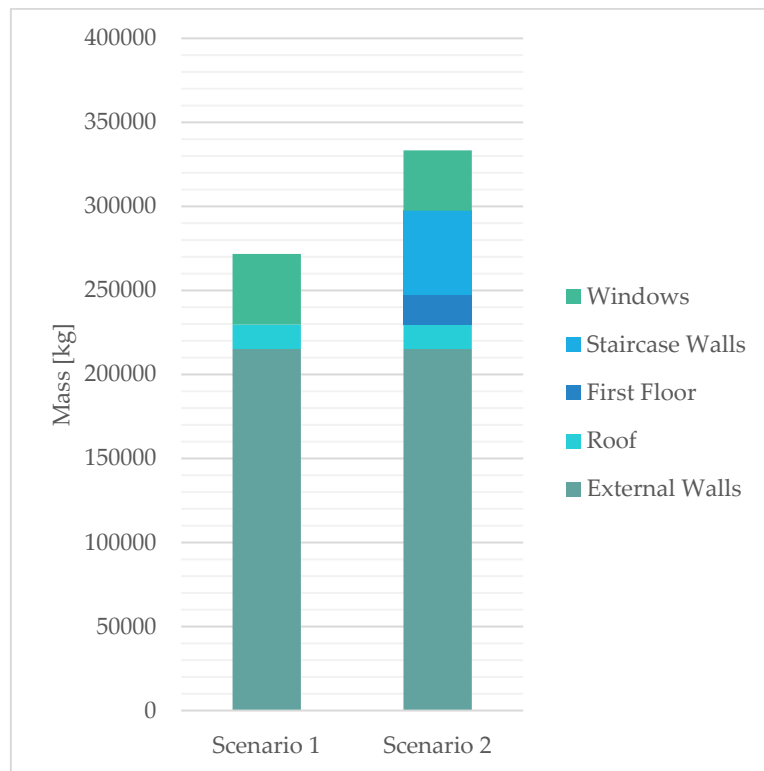


Chart 22. Mass comparison [kg] among Scenario 1 and Scenario 2.

The comparison of the interventions' mass in Chart 8 indicates that heavier interventions could lead to higher impacts during both the embodied and operational phases of the building's lifecycle, due to changes in thermal mass. However, these interventions, despite affecting the building's mass, significantly contribute to its overall sustainability and energy efficiency. This demonstrates the strategic importance of such enhancements in reducing long-term environmental impacts and improving the building's performance.

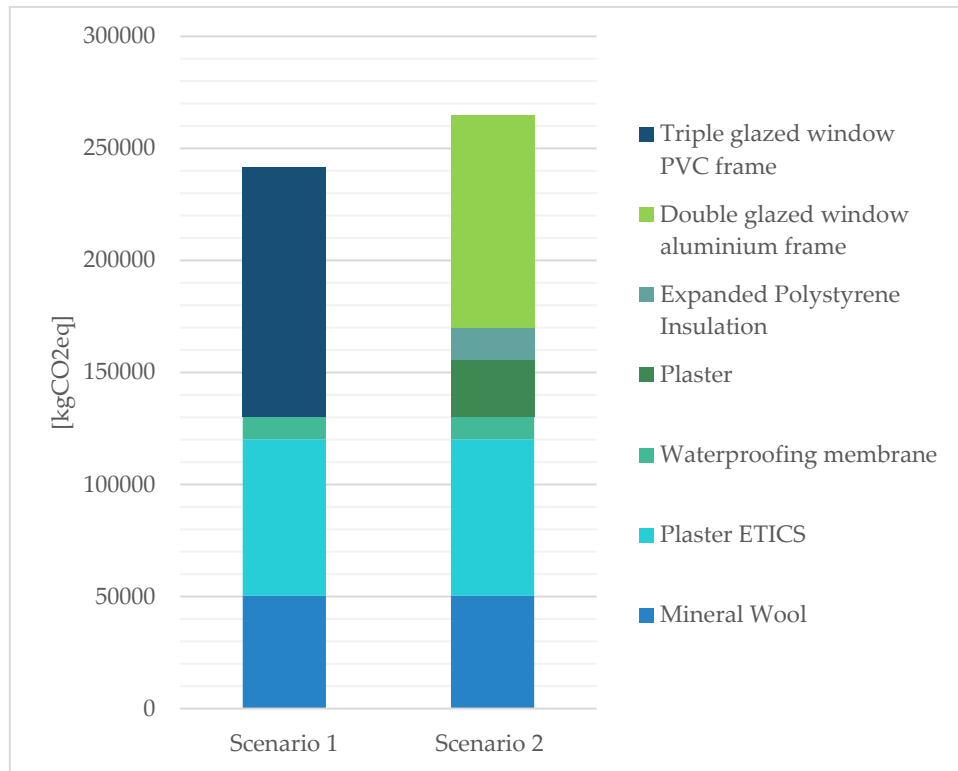


Chart 23. GWP contribution of each intervention element in Scenario 1 and Scenario 2.

According to Chart 9, it becomes clear that the most significant contributor to emissions is the triple-glazed window with a PVC frame. While triple-glazed windows provide superior insulation compared to double-glazed ones, they are also more expensive and heavier. Conversely, double-glazed windows offer a balance between initial costs and long-term savings, with aluminum frames providing greater durability and recyclability than PVC.

The introduction of Expanded Polystyrene (EPS) in Scenario 2 represents a strategic choice for its lightweight nature, ease of installation, and effective insulation properties. With its lower thermal conductivity, EPS enhances the building's thermal efficiency, especially in areas benefiting from a material that combines performance with practical application.

The consistent emission levels from the use of plaster in the ETICS across both scenarios suggest unchanged roles and applications, despite substantial contributions to emissions. Notably, the high emission contributions from plaster in both scenarios are influenced by the distance it is transported from the manufacturing site to the construction site, affecting their overall environmental impact. Maintenance practices for ETICS plastic and the waterproofing membrane are significant sources of emissions. Regular inspections and preventive maintenance are crucial to keep the plaster in optimal condition, projecting its lifespan to 20 years. Similarly, the waterproof membrane demands continuous controls and is also expected to last 20 years, significantly impacting the project's emissions. This situation underscores the importance of material replacement and refurbishment in the building's energy

consumption, highlighting the vital role of maintenance routines and material lifespans in shaping the building's energy profile.

For the proposed energy efficiency interventions, it has been selected products directly from the OneClick database, aiming to identify those that best match the refurbishment design choices.

The selection focused on key properties like thermal conductivity, density, and thermal transmittance, aiming to ensure the selected items met the physical requirements to achieve the energy efficiency required.

It has been also prioritized environmental considerations choosing products to minimize environmental impact. This choice was motivated by the desire to reduce ecological footprint of the interventions, in line with sustainability principles.

However, selecting products that seemed physically suitable for our intervention sometimes revealed limitations related to the limited software's database. Crucial details like the material's origin, its expected lifespan, and end-of-life scenario information relies entirely on the product's Environmental Product Declaration (EPD).

This means that, although a product may appear suitable based on its physical specifications, the lack of complete data in the EPD or the absence of such declarations in the "One Click" database can limit our ability to fully assess the product's environmental impact and its adherence to sustainable criteria or specific project requirements. Therefore, the importance of regularly updating the database, including EPDs, is crucial for facilitating informed and responsible choices. Adopting this approach, it's possible to overcome these limitations, selecting products that are both energy efficient and environmentally suitable.

3.1.3.1 Façade Openings Comparison

Replacing the triple-glazed window with a PVC frame with a double-glazed window featuring an aluminum frame has led to a significant reduction in emissions related to the facade opening, achieving a -8% decrease compared to Scenario 1.

This underscores the importance of comparing these two elements based on their characteristics, which is crucial for understanding their contributions to various life cycle stages. By evaluating the emissions of each option across the total window area of 699.42 m², it's possible to gain deeper insights into the environmental impact of these choices.

Element	Material Origin	Distance from the construction site [km]	Service Life [years]	End of Life
Triple glazed window	Ireland	2188	50	Recycled/Landfilled
Double glazed window	France	876	50	Recycled/Reused

Table 47. Windows – OneClick inputs.

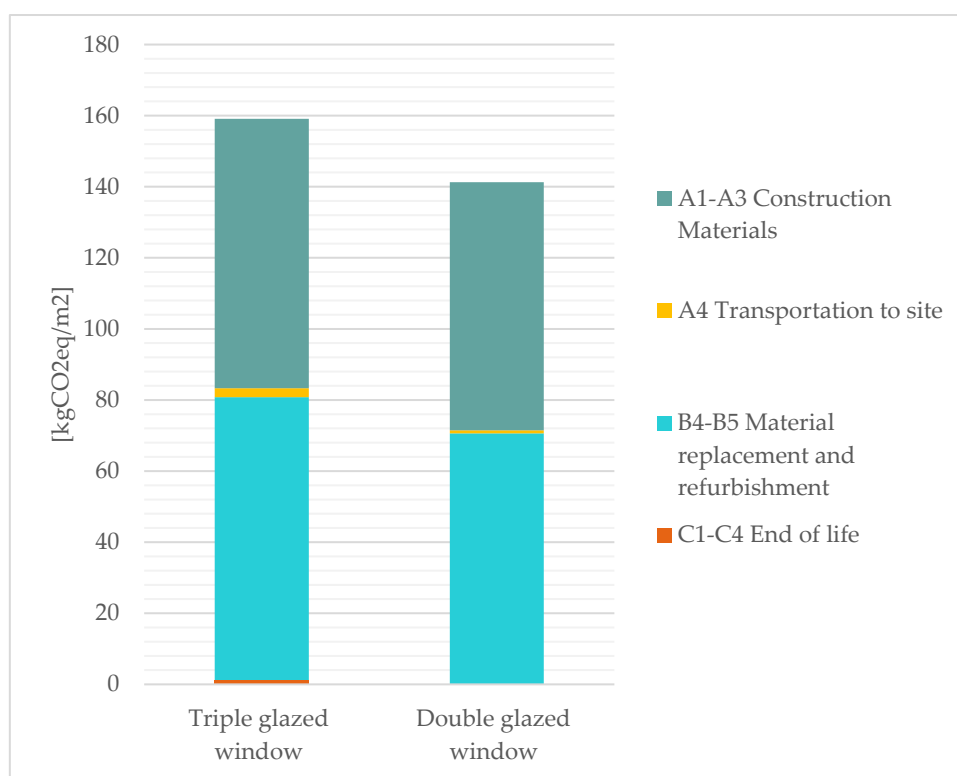


Chart 24. Windows – Embodied kgCO₂eq emissions over 1 m² of window.

The Chart 10 presents the kgCO₂eq/m² emissions for triple and double-glazed windows across various LCA stages, with the building's calculation period set at 60 years.

The triple-glazed window, with its manufacturing process involving glazing and PVC frame production, exhibits a higher initial impact in the construction phase (A1-A3) at 75.79 kgCO₂eq/m². This is attributed to the extensive manufacturing processes, including extrusion, mixing, cutting, assembly, packing, and internal transportation, all of which consume electricity, fuels, and auxiliary materials.

Conversely, the double-glazed window shows a slightly lower impact in the A1-A3 category at 69.77 kgCO₂eq/m². This reduction is due to the assembly process of the glazed unit with an aluminum frame, which, despite being energy-intensive, benefits from the use of recycled aluminum (as noted in the EPD), thereby reducing manufacturing emissions.

This concept highlights that although the production process of PVC is less energy intensive compared to the extraction and refinement process of aluminum, the recyclability potential of aluminum offset the high emissions due to its production.

Transportation emissions (A4) stand at 2.51 kgCO₂eq/m² for the triple-glazed window and 0.86 kgCO₂eq/m² for the double-glazed window. The latter's reduced impact reflects the shorter transportation distance from France, compared to the triple-glazed window's longer journey from Ireland.

No data are shown for the installation stage (A5) for either window type, indicating that the pre-assembled units are manually installed on-site without requiring machinery or additional energy-intensive processes that significantly contribute to emissions.

The refurbishment stage (B4-B5) shows that both the options, with a 50-year service life, need at least one replacement during the building's 60-year calculation period, resulting in emissions of 79.55 kgCO₂eq/m² for the triple-glazed unit and 70.62 kgCO₂eq/m² for the double glazed one.

End-of-life stage (C1-C4) emissions are minimal for both windows, at 1.25 kgCO₂eq/m² for the triple-glazed window, likely due to efficient recycling processes for both glass and PVC. For the double-glazed window, emissions data in this category are not provided, as the window's components are reused, with aluminum profiles being 100% recyclable and glazing units sent to the glass industry for recycling.

In conclusion, the transition to a double-glazed window with an aluminum frame was a decision for both energy efficiency and sustainability. It brought down the initial construction phase emissions, thanks to the utilization of recycled aluminum, which has a lower carbon footprint. Additionally, the lower transportation emissions due to the proximity of France, as the extended service life that aligns with the building's life, eliminate the need for replacement.

The reduction in environmental impact, achieved by replacing a triple-glazed window with a PVC frame with a double-glazed one with an aluminum frame, was achieved based on the products selected through the OneClick database. This decision was made to keep the thermal transmittance of the glazed unit unchanged, selecting products that, although meeting these criteria, showed significant differences in other aspects. From the Environmental Product Declarations (EPD) of both elements, crucial information such as the material's origin, useful life, and end-of-life process was gathered. This information was then used as input for OneClick, leading to a noted - 8% reduction in environmental impact.

However, it's important to highlight that this figure might not fully reflect reality, as a more accurate comparison would have required identical inputs for both products to ensure greater consistency in the results. Differences in basic information, like material origin and end-of-life practices, can significantly influence the calculated environmental impact.

Therefore, although the cited example indicates a reduction in environmental impact, the reliability of this result strongly relies on the precision and comparability of the data employed in the analysis. This emphasizes the importance of conducting detailed and comparable environmental analyses to ensure reliable and representative evaluations of the real impact of such material and technological choices.

3.1.3.2 Windows Alternative Comparison

Addressing the limitations of the OneClick database regarding product selection, it has been explored an alternative that meets the physical specifications required by the proposed interventions, while not considering the detailed information provided by Environmental Product Declarations (EPD). This alternative assessment used standard parameters including the assumption of materials being transported over 1000km to the construction site, the consideration of a 50-year lifecycle for materials, and the projection that the 80% of the glass surface would be recycled at the end of its life. Additionally, the period of calculation of the building was shortened to 30 years.

Element	Distance from the construction site [km]	Service Life [years]	End of Life
Triple glazed window	1000	50	Recycled/Landfilled
Double glazed window	1000	50	Recycled/Landfilled

Table 48. Windows comparison – OneClick inputs.

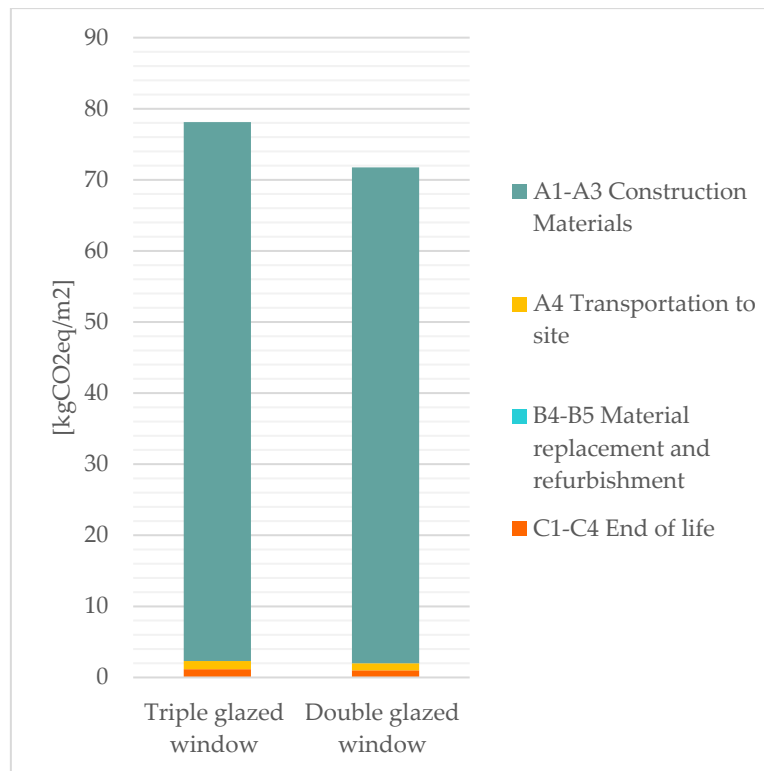


Chart 25. Windows comparison – Embodied kgCO2eq emissions over 1 m2 of window.

According to the Chart 11, in assessing the transportation emissions for the triple glazed unit with PVC frame versus the double-glazed unit with an aluminum frame, we notice a slight difference. The triple glazed option generates 1.15 kgCO2eq/m2, while the double-glazed option emits a slightly lower 0.98 kgCO2eq/m2. Similarly, for the end-of-life emissions, the triple glazed has 1.17 kgCO2eq/m2 and the double glazed

has 1.0 kgCO₂eq/m². Though these differences are modest, they are significant enough to distinguish the environmental impacts of the two window systems when considering identical input parameters.

No data are reported for the B4-B5 stage due to the service life of both systems exceeding the building's assessment period, indicating no requirement for refurbishment or replacement within that calculation period.

The A1-A3 stage, which includes material production and construction, showcases the most considerable environmental impact, and underscores the disparity between the two systems. The gap isn't substantial, and it reflects the higher emissions linked to aluminum production. The usage of aluminum, which is often praised for its high recyclability, could potentially lower the environmental impact of the double-glazed unit when compared to the PVC-framed triple glazed unit. However, the production processes and the qualities of the materials must be thoroughly considered. Aluminum's production is energy-intensive, but its long-term sustainability might be favorable due to its potential for recycling.

This methodology was adopted with the aim of generating evaluations that would approximate a general average, without referring to a specific product. The goal was to obtain estimates that could be considered representative for a wide range of products with similar physical performance, avoiding the limitation of a single product whose specifications might not be fully representative of the market.

This is an approach which allows overcoming some of the restrictions imposed by the lack of detail in the OneClick software, providing a broader basis for evaluation. However, it is important to highlight that, while simplifying the selection process and making it potentially more flexible, this strategy might not fully capture the overall environmental impact of the products. EPDs offer a detailed overview of a product's environmental impact throughout its lifecycle, and not considering this information can lead to an incomplete understanding of the sustainability of the selected materials.

3.2 Alternative Insulation Materials

The building overview sets the foundation for a deeper analysis of the embodied and operational carbon impact associated with the replacing of mineral wool insulation. This examination considers alternative materials that are either carbon sequestering or carbon producing, compatible with ETICS system. The primary objective is to explore their potential in reducing the overall CO2 emissions of the building.

Providing a comprehensive overview of the building’s emission, the analysis compares the environmental impacts of alternative insulation materials highlighting a significant shift in kgCO2eq per square meter of gross internal floor area. Transitioning from Scenario 2, which is used as the baseline for this comparison, variations are marked due to the contributions from the different stages of the Life Cycle Assessment (LCA).

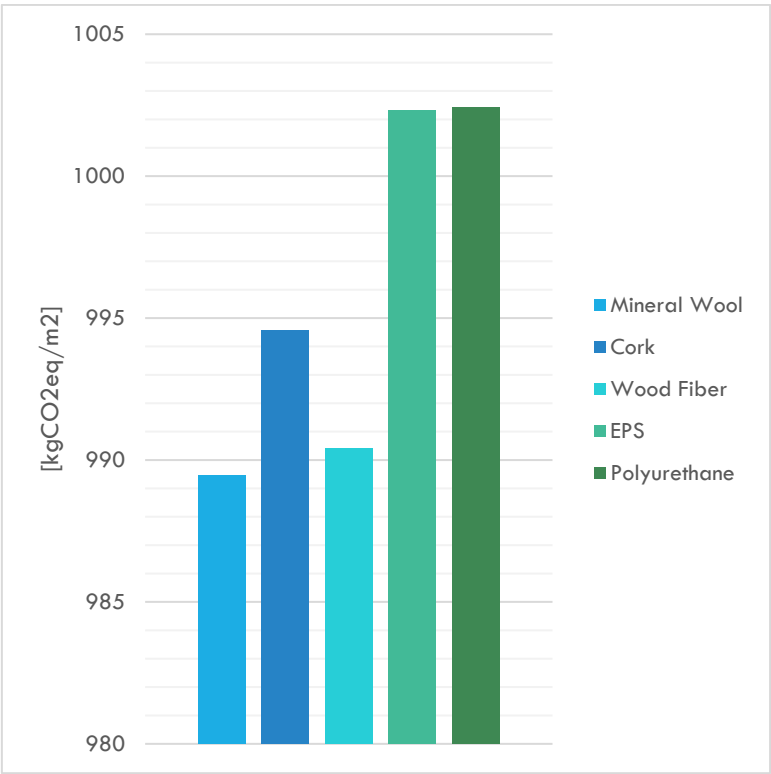


Chart 26. GWP (from A1 to C4) of alternative insulation materials over 1 m2 gross internal floor area.

When examining the Chart 12, is evident that mineral wool exhibits the best performance in terms of impact. To truly understand the significance of this outcome, it's crucial to deep dive into the distinctions between the operational and embodied carbon emissions provided by each of the alternative materials selected.

The operational carbon refers to the carbon dioxide emissions associated with the use of the building, primarily from heating, cooling, lighting, and other energy uses. Insulation materials play a critical role in reducing operational carbon by enhancing

the building's energy efficiency. The effectiveness of insulation in minimizing heat loss or gain directly impacts the amount of energy required to maintain comfortable indoor temperatures, thereby affecting the building's operational carbon footprint.

The embodied carbon encompasses all the CO₂ emissions associated with the production, transportation, installation, maintenance, and disposal of building materials. For insulation materials, this includes the emissions from extracting raw materials, manufacturing processes, transporting the materials to the site, installing them, and eventually their end-of-life processes, such as recycling or landfilling.

3.2.1 Building Operational Emissions Contribution

The operational carbon emissions related to alternative insulation materials are linked to the energy required to operate the building, assessed in the B6 stage, referred to energy consumption. This evaluation of energy consumption is conducted by examining emissions across the entire building, evaluating the results in kgCO₂eq per square meter of gross internal area.

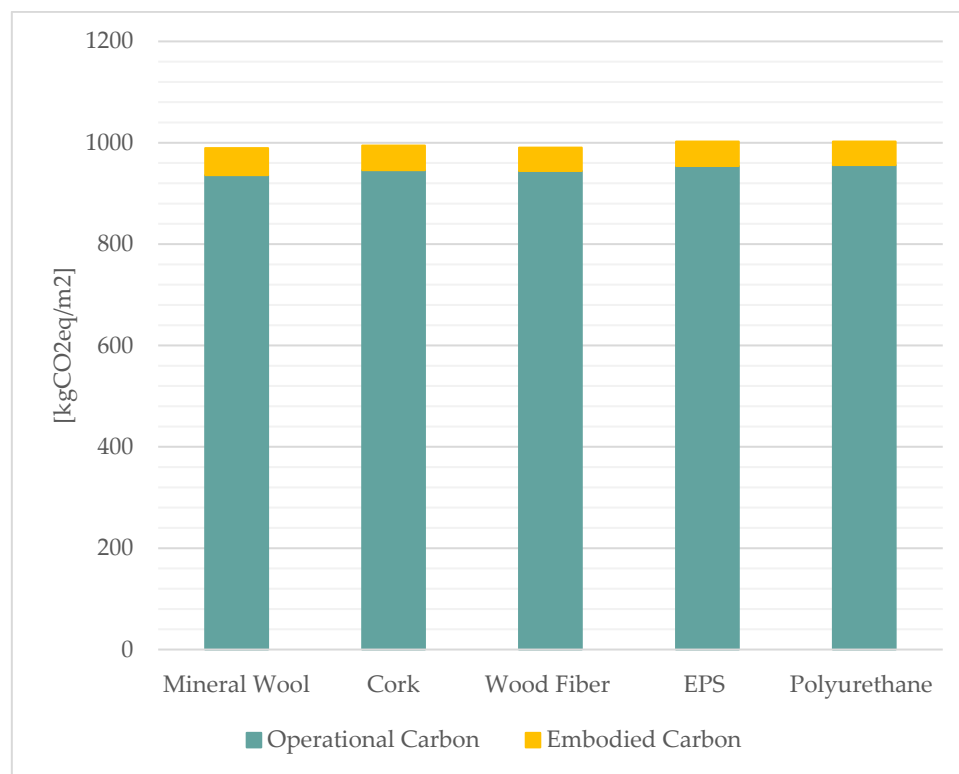


Chart 27. Alternative insulation materials – Embodied and Operational kgCO₂eq emissions comparison over 1 m² of gross internal floor area.

The Chart 13 shows that, since the heat pump in Scenario 2 remained unchanged, this element continues to contribute significantly to emissions. Therefore, to achieve a substantial difference in energy consumption, it is necessary to switch to a more efficient and sustainable generator. This approach aims to find a balance between the two primary objectives: efficiency and sustainability.

While changing the generator would reduce energy emissions, it's equally important to consider the impact of the materials used in the construction and insulation of the building. Analyzing the environmental contributions of these alternative materials can offer a deeper insight into how material choices alone, independent of mechanical systems, can enhance a building's overall environmental performance.

This approach encourages a comprehensive view of sustainability, emphasizing the concept of material selection in reducing emissions and improving energy efficiency.

3.2.1.1 Life Cycle Assessment – B6 Stage

To preserve the building's thermal performance, it was decided to choose an insulation thickness that matches the thermal resistance of the mineral wool in the ETICS system proposed by the document [119] for scenario 2. However, during the calculations, it emerged that the thickness derived from the thermal conductivity of each material (according to their technical data sheets) often did not align with the thicknesses commercially available. This discrepancy led to variations in the calculated thermal resistances compared to the expected values for mineral wool, altering the system's total thermal transmittance. Table 49.

To collect data on the building's energy usage, simulations were conducted using IESVE, incorporating the properties of alternative insulation materials as replacements for mineral wool.

Material	Market Thickness [m]	Market Resistance [m ² K/W]	λ [W/mK]	ρ [kg/m ³]
Cork	0.120	3.077	0.039	110
Wood Fiber	0.120	3.158	0.038	110
Expanded Polystyrene	0.100	2.941	0.034	24
Polyurethane	0.080	3.077	0.026	35

Table 49. Alternative insulation materials – Market thicknesses and thermal resistances.

The reduced thermal resistance of materials chosen as alternatives to mineral wool (3.191 m²K/W) leads to higher energy consumption, affecting both electricity and natural gas usage.

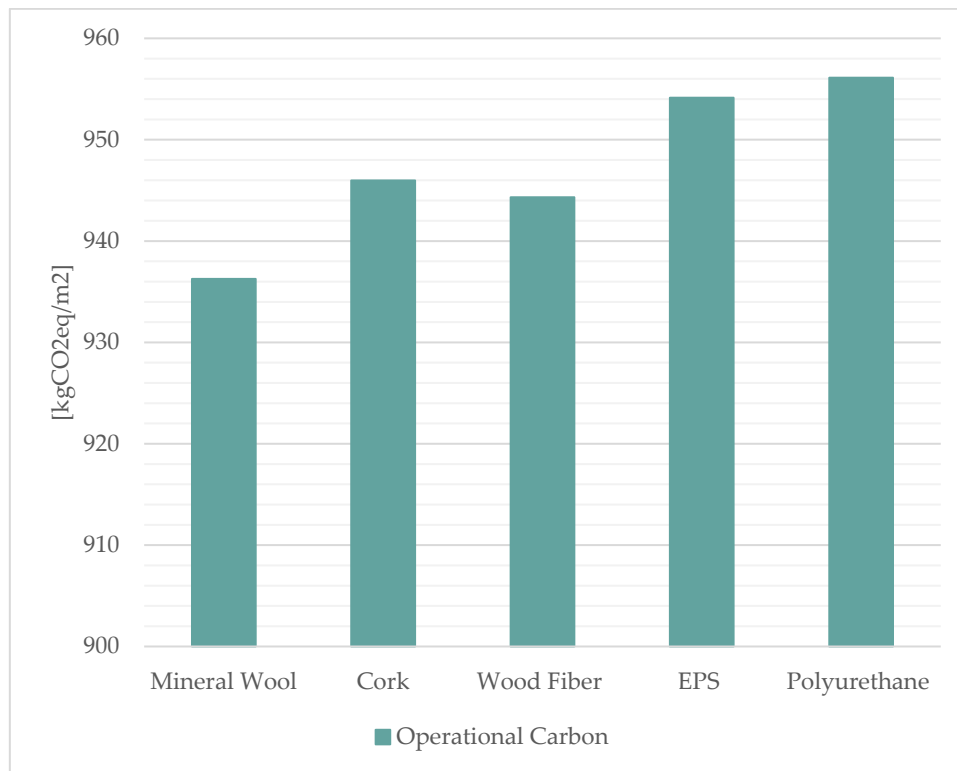


Chart 28. Alternative insulation materials – Operational kgCO₂eq emissions over 1 m² of gross internal floor area.

The necessity of selecting commercially available thicknesses to match the thermal resistance of mineral wool has resulted in a more thermally dispersive envelope. Carbon-sequestering materials exhibit a slight increase in emissions due to the mass of the envelope (+1%), which affects heat retention capabilities. Conversely, carbon-producing materials, despite offering thermal resistances like mineral wool, present a less effective solution in inhibiting heat flow (+2%). This leads to increased heat losses and, consequently, higher energy consumption compared to cork and wood fiber insulation. Additionally, the lower thermal mass associated with carbon-producing materials may lead to reduced heat storage within the building, requiring more frequent heating and cooling to maintain comfortable indoor conditions.

This concept is illustrated by the comparison between cork and polyurethane. Despite having identical thermal resistance, they have different energy consumption outcomes. This discrepancy indicates that energy consumption is influenced by various factors, including the material's heat conduction properties, which affect the total energy required to maintain a specific temperature. Furthermore, the thickness of the insulation contributes to the building's overall thermal mass, influencing how the building retains heat or cools down.

3.2.2 Embodied Emissions across Insulation Materials

The embodied carbon emissions linked to the alternative insulation materials, evaluated across various stages such as construction and production (A1-A3), transportation (A4), installation (A5), replacement and refurbishment (B4-B5), and end of life (C1-C4), have been analyzed over the external wall area of 3677.64m².

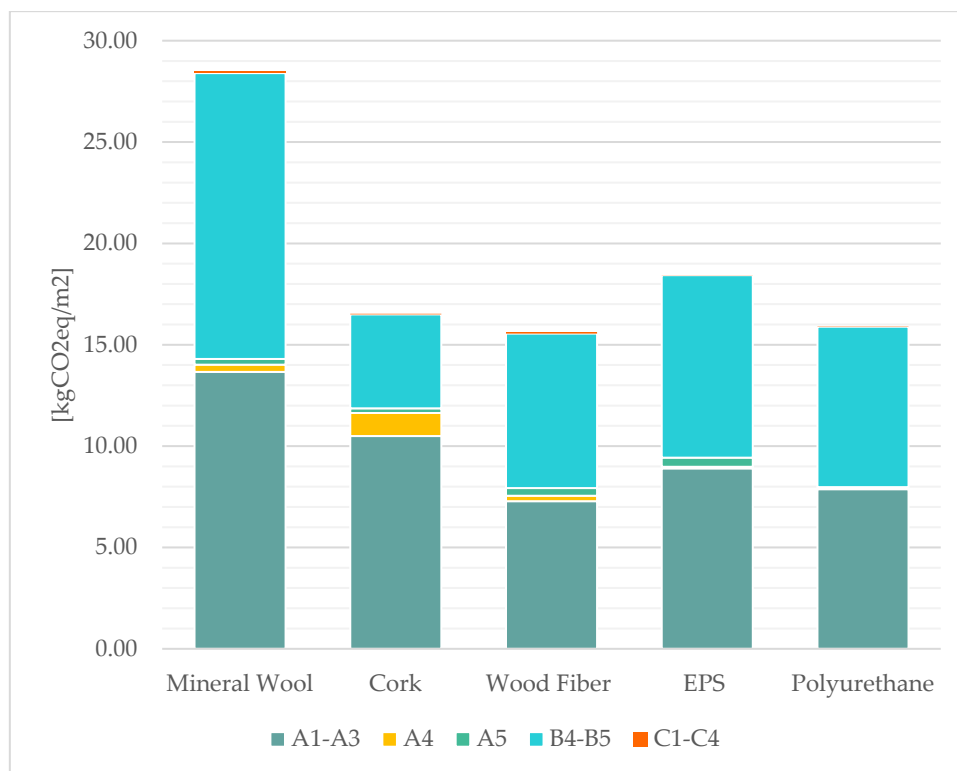


Chart 29. Alternative Insulation materials – Embodied kgCO₂eq emissions over 1 m² of façade.

For the comparison of alternative insulation materials to mineral wool, products have been selected directly from the OneClick database. The selection was driven by specific criteria such as the compatibility of the insulation with the ETICS system. This approach aimed to ensure that the chosen products met the necessary physical characteristics to achieve maximum energy efficiency and the same thermal transmittance as the system designed for scenario 2. In addition to physical parameters, great attention was also paid to environmental aspects, favoring products with a low environmental impact. This choice was motivated by the desire to reduce the ecological footprint of the interventions, in line with sustainability principles. In some cases, even when choosing a product from "One Click" that seemed to meet the necessary physical characteristics for the planned interventions, limitations related to the wide software's database have been faced. Crucial details such as the material's origin, its expected lifespan, and end-of-life scenario information depend entirely on the Environmental Product Declaration (EPD) of the chosen product. This means that, although a product may appear suitable based on its physical specifications, the lack

of complete data in the EPD or the absence of such declarations in the "One Click" database can limit our ability to fully assess the product's environmental impact and its adherence to sustainable criteria or specific project requirements. Therefore, the importance of an updated database rich in detailed information, including EPDs, is crucial for making informed and responsible choices. This approach allows overcoming the encountered limitations and selecting products that are not only energy-efficient but also sustainable.

3.2.2.1 Life Cycle Assessment – A1-A5 Stages

Switching from mineral wool to alternative insulation materials has resulted in a reduction in emissions during the A1-A5 stages of the Life Cycle Assessment (LCA). This highlights the significance of evaluating these materials based on their unique characteristics, which are essential for understanding their impacts across different life cycle stages.

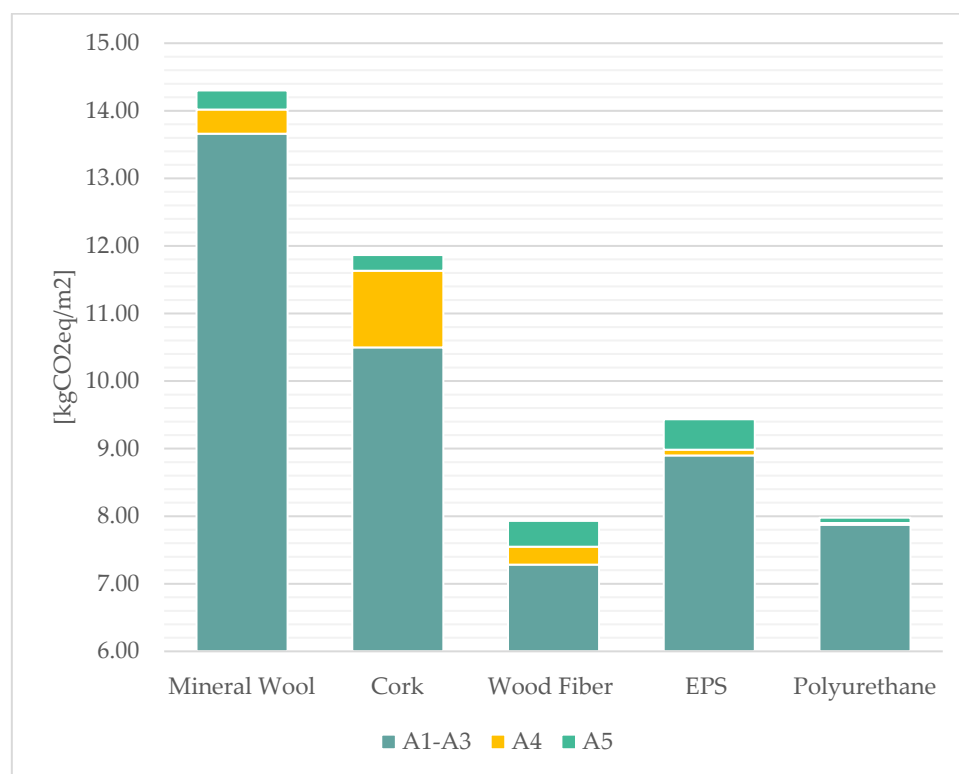


Chart 30. Alternative Insulation materials – kgCO2eq emissions from A1 to A5 over 1 m2 of façade.

Looking at the Chart 16, it's evident that choosing any of these alternatives over mineral wool could result in a lower environmental impact during the A1-A3 stages. However, this initial impression is somewhat misleading. A detailed examination of the A1-A3 stages, which contribute significantly to overall emissions, shows that cork and wood fiber insulation produce emissions of 10.50 kgCO2eq/m2 and 7.28 kgCO2eq/m2, respectively. Being carbon-sequestering materials, their manufacturing

largely involves natural materials. In contrast, carbon-producing materials such as EPS and polyurethane insulation exhibit reduced emissions (8.90 kgCO₂eq/m²; 7.87 kgCO₂eq/m²), respectively attributable to their chemically intensive, energy-demanding production processes. The chart clearly demonstrates that the A1-A3 stage emissions from carbon-producing materials are lower than those from carbon-sequestering materials, except from cork. This discrepancy is due to the lower thermal conductivity of these materials, requiring less volume to match the insulating properties of mineral wool, the baseline. Consequently, a reduced thickness leads to a smaller carbon footprint throughout the product's lifecycle.

The material origin and its distance from the construction site also play a crucial role, affecting transportation emissions (A4). Cork, originating from Portugal, 2145km away, and polyurethane, produced in Italy, 238km distant, incur transportation emissions of 1.13 kgCO₂eq/m² and 0.02 kgCO₂eq/m², respectively.

In the A5 stage, which encompasses construction and installation, wood fiber insulation has the most substantial impact at 0.38 kgCO₂eq/m². This impact is due to the need for pre-installation processing or treatment and the emissions-intensive transportation of panels to the site, caused by the weight of the wood fiber. Similarly, EPS stands out for its higher contribution compared to other insulation materials, necessitated by the energy-intensive tools or processes required for its correct installation.

Carbon-sequestering materials like cork exhibit higher contributions in the A1-A3 stages (covering raw material extraction, material processing, and manufacturing) compared to carbon-producing materials like EPS and polyurethane. This might seem counterintuitive at first, as one would expect materials that absorb carbon during their growth, like cork, to have a lower environmental impact. However, this can be attributed to the fact that EPS and polyurethane require less material volume to achieve the same insulation effectiveness due to their lower thermal conductivity. This reduced material use in production and manufacturing processes leads to decreased emissions for these materials in the A1-A3 stages.

When examining wood's contribution, despite having similar physical characteristics to cork, such as density, it shows a decrease in emissions during the A1-A3 stages. This discrepancy between cork and wood, despite their similarities, could be due to the inputs selected by OneClick and the methodology it employs for running simulations upon selecting the material. The difference might stem from how OneClick accounts for the lifecycle emissions of these materials, potentially incorporating factors like the energy used in harvesting, processing, and manufacturing, as well as differences in the efficiency of raw material utilization.

This anomaly underscores the importance of the assumptions and data used in lifecycle assessments. The choice of inputs and the specific parameters used in simulation software like OneClick can significantly influence the outcomes of environmental impact assessments. It highlights that while lifecycle assessment tools

are invaluable for making sustainable material choices, the results are highly dependent on the underlying data and assumptions. Thus, a comprehensive understanding of these factors is crucial when interpreting LCA results and making decisions based on sustainability criteria.

In conclusion, although carbon-sequestering materials such as cork and wood fiber show higher emissions in the initial stages (A1-A3) compared to carbon-producing materials, a holistic view of the building's entire lifecycle reveals a nuanced narrative. These natural materials offer significant long-term advantages, including the ability to sequester carbon and potentially reduce emissions during the usage phase.

3.2.2.2 Life Cycle Assessment – B4-B5 Stages

The assessment of emissions in the B4-B5 stages, which encompasses refurbishment and replacement of materials, underscores the significance of considering the service life of each selected material over the calculation period of the building set at 60 years.

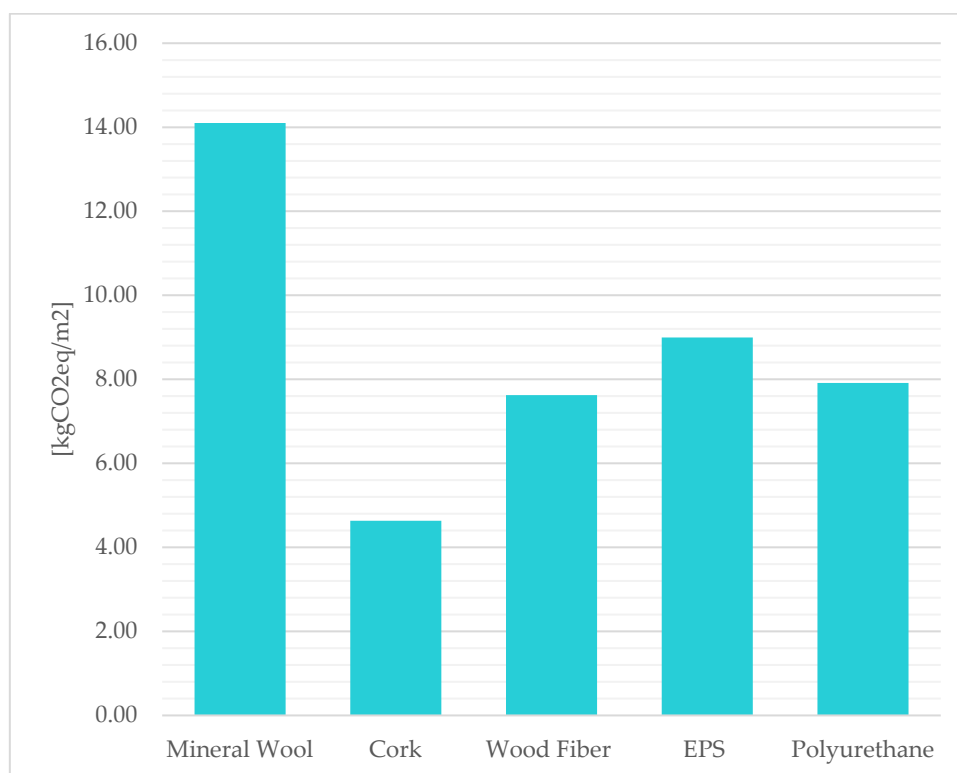


Chart 31. Alternative Insulation materials - kgCO₂eq emissions B4-B5 over 1 m² of façade.

The Chart 17 provides a comparison at the B4-B5 stage, reflecting the impact of setting a 50-year service life for each insulation material.

Cork and wood fiber insulation contribute the least emissions, with respective values of 4.63 kgCO₂eq/m² for cork and 7.62 kgCO₂eq/m² for wood fiber insulation. Their biodegradability at the end of their lifecycle significantly benefits the replacement and

refurbishment stage, diminishing the environmental impact in comparison to synthetic materials such as EPS and polyurethane. The variation in emissions can also be attributed to the inherent properties of the materials, their durability against degradation, and the complexities involved in their replacement.

The comparison highlights the importance of selecting durable materials with long service lives for insulation. Using such materials can avoid or minimize the need for refurbishment, thereby reducing the environmental impact. These choices not only reduce the frequency of resource-intensive refurbishments but also contribute to the overall reduction of the building's carbon footprint over time.

3.2.2.3 Life Cycle Assessment – C1-C4 Stages

The evaluation of emissions in the C1-C4 stages, focusing on the end-of-life of materials and their impacts from processing to landfilling, underscores the importance of considering how materials are managed at the end of their lifecycle. This assessment highlights the significance of end-of-life processing methods and their environmental implications.

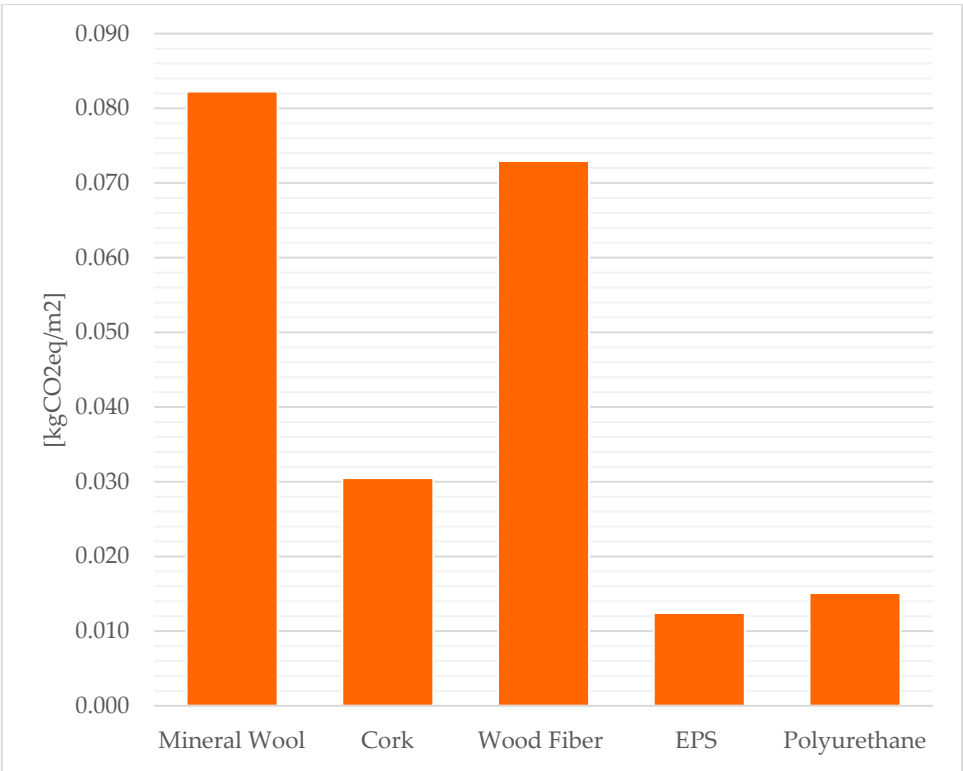


Chart 32. Alternative Insulation materials - kgCO₂eq emissions from C1 to C4 over 1 m² of façade.

The Chart 18 indicates that materials known for carbon sequestration, such as wood fiber insulation, demonstrate higher emissions at the end-of-life stage, showing emissions of 0.073 kgCO₂eq/m², in contrast to carbon-emitting materials like EPS

(0.012 kgCO₂eq/m²) and polyurethane (0.015 kgCO₂eq/m²). Notably, 60% of cork undergoes recycling into expanded cork granules via grinding, leaving 40% to be disposed of in landfills, accounting for its relatively low emissions (0.031 kgCO₂eq/m²). Wood is predominantly directed to landfills, and its lower emission levels can be attributed to the biodegradable nature of wood fiber insulation, which lessens environmental impact in comparison to mineral wool. The higher emission figures for wood are partly due to the environmental impact of transporting this heavier material to landfills.

EPS showcases a significant recycling capacity, with 40% being reused in production or sent to recycling centers, while the remaining 60% is relegated to landfills. Polyurethane, typically consigned to landfills, exhibits lower emission levels among carbon-producing materials, partly due to its lighter weight relative to carbon-sequestering alternatives. The superior thermal efficiency of materials like EPS and polyurethane means that less material is needed to achieve the same insulating effect, which in turn leads to reduced emissions from transport to waste processing facilities or landfills.

In conclusion, recycling materials or choosing biodegradable options plays a crucial role in reducing the environmental impact during the end-of-life stage. As illustrated by cork and wood's higher end-of-life emissions due to recycling processes or biodegradation, utilizing such materials still presents a more sustainable choice. These processes often have a lower carbon footprint compared to the production of new materials, contributing to resource conservation and waste reduction. Moreover, the use of biodegradable materials that can break down naturally helps mitigate long-term pollution, making them favorable for sustainable building practices.

3.2.2.4 Volume Comparison

Conducting an analysis that compares emissions from carbon-intensive materials using the same volume as more sustainable options like cork and wood fiber insulation could provide valuable insights into environmental trade-offs. By setting a uniform volume for comparison, rather than focusing only on thermal resistance, this approach might offer new perspectives on the overall sustainability of using high-performance insulations such as EPS and polyurethane versus natural, less energy-intensive materials.

This comparative analysis would give a more holistic understanding of how material choice affects not just energy efficiency but also the carbon footprint associated with production, use, and disposal stages.

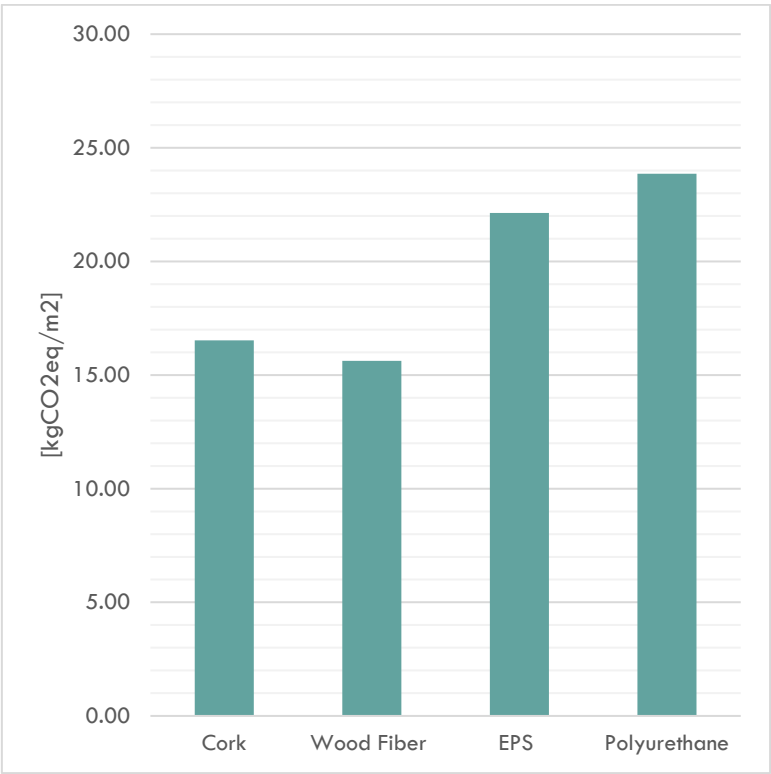


Chart 33. Alternative Insulation Materials – Embodied kgCO₂eq emissions comparison having the same volume over 1 m² of façade.

Using the same volume for EPS and polyurethane results in an increase in embodied carbon compared to carbon-sequestering materials like cork and wood fiber. This outcome emphasizes the environmental benefits of carbon-sequestering materials over those that are carbon-intensive.

3.3 Final Solution

Considering the global warming emissions for the building with different insulation materials, the chart reflects the slight differences in emissions per square meter of the gross internal floor area across the building when replacing the initial insulation in Scenario 2 with alternative materials.

Material	Global warming emissions	
	[kgCO ₂ eq]	[kgCO ₂ eq/m ²]
Mineral Wool	5001699	989.46
Cork	5027560	994.57
Wood Fiber	5006586	990.42
Expanded Polystyrene	5066658	1002.31
Polyurethane	5067263	1002.43

Table 50. Results – GWP in kgCO₂eq and kgCO₂eq/m² over 1 m² of gross internal floor area.

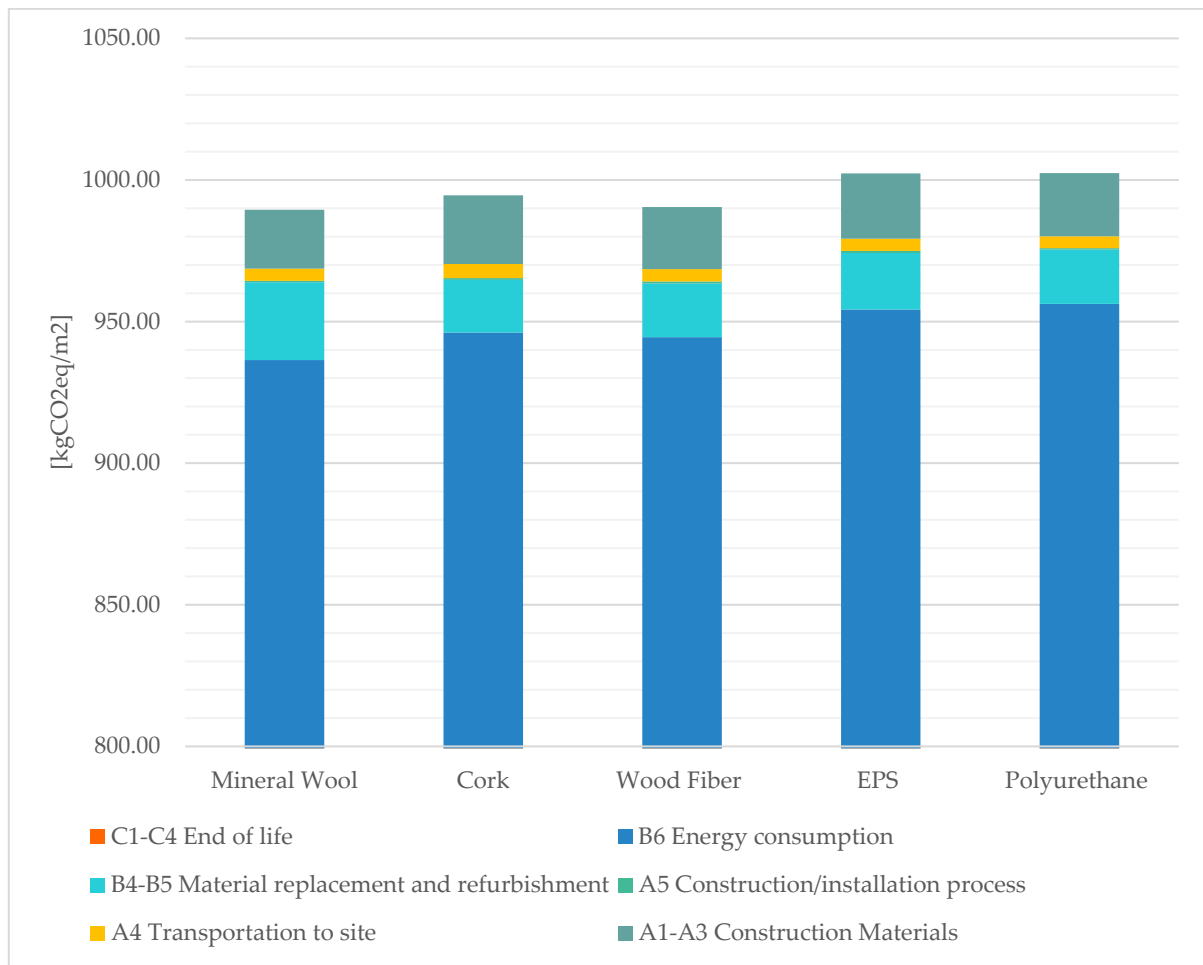


Chart 34. Results – GWP among the life cycle stages over 1 m2 of gross internal floor area.

The Chart 20 reveals that cork and wood fiber show very similar emissions, 994.57 kgCO₂eq/m² for cork and 990.42 kgCO₂eq/m² for wood fiber insulation.

Emissions for expanded polystyrene and polyurethane are closely matched, being between 1002.31 to 1002.43 kgCO₂eq/m².

The mineral wool has the lowest emissions at 989.46 kgCO₂eq/m², making it a strong baseline for comparison.

However, a thorough evaluation of both operational and embodied carbon is crucial for better understanding the impact that each of the insulation materials has in terms of both embodied and operational carbon.

The chart shows that a significant portion of the building's energy emissions are given by operational carbon, which is affected not just by the selection of insulation materials but also by the systems chosen for the building. This suggests the importance of considering both aspects to effectively reduce the building's carbon footprint.

From the discussion of the results mineral wool appears to be the best choice. This means that despite the advantages of carbon sequestering insulation materials, as demonstrated through the embodied carbon assessment, they have higher energy consumption due to the slightly lower thermal resistance selected for both cork and wood fiber insulation compared to mineral wool.

This led to a 1% increase in energy consumption emissions associated with each insulation choice, establishing mineral wool as the optimal selection.

The aim was to provide alternative insulation materials insights into how choices affect a building's environmental performance beyond mechanical systems, underscoring the importance of selecting materials that lower emissions and improve energy efficiency, contributing to sustainability.

The result obtained highlights the importance of evaluating also the contribution given by the system, opting for more renewable solutions. Such an approach can lead to further reductions in energy consumption emissions, highlighting the complex tradeoff between material choice and system design in their impact on environmental footprint.

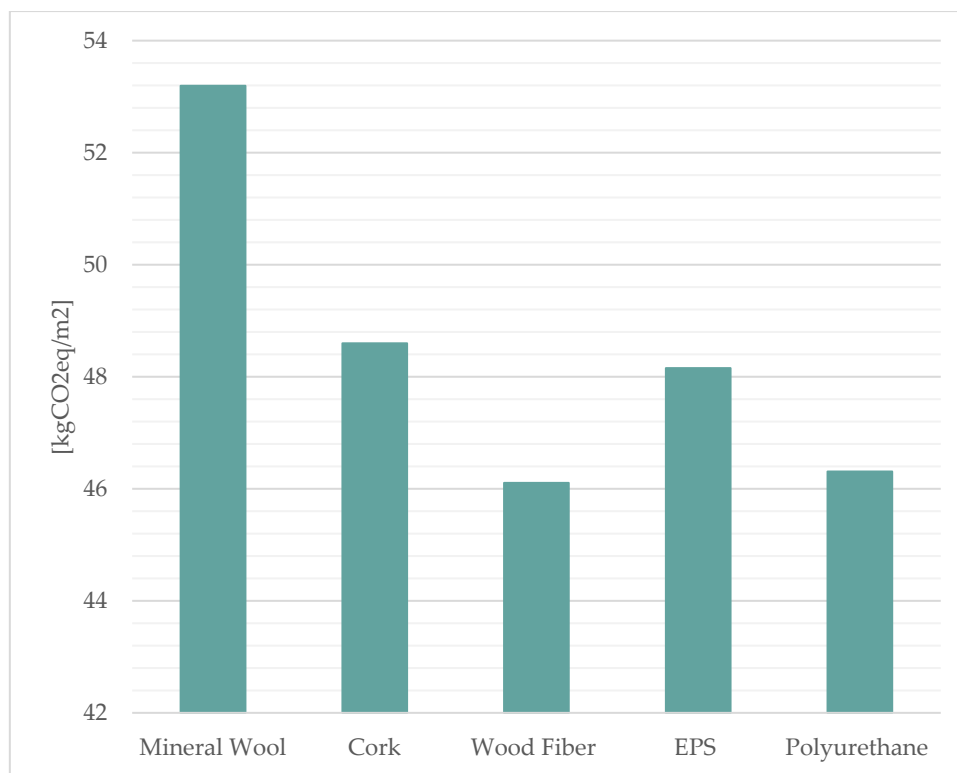


Chart 35. Results – Embodied kgCO₂eq emissions over 1 m² of gross internal floor area.

From the evaluation of the embodied carbon, it has been possible to understand the environmental benefits given by each of the alternative materials chosen giving an overall consideration of them.

EPS and polyurethane insulation are characterized by more energy intensive production processes. However, their observed reduction in embodied carbon compared to mineral wool is attributed to an initial decision to keep unchanged the thermal resistance across all the alternative insulation materials. This basis for comparison considers that EPS and polyurethane, due to their lower thermal conductivity, need a reduced volume of material to achieve comparable thermal

performance to mineral wool. Consequently, this leads to decreases across the LCA stages due to the smaller volume of material considered.

This approach highlights how selecting insulation materials based on their thermal efficiency can impact environmental assessments. The reduced volume needed for EPS and polyurethane to match the thermal resistance of mineral wool results in lower environmental impacts in various LCA stages, primarily due to decreased material use and associated production, transportation, and disposal impacts.

By comparing materials with respect to the volume rather than thermal resistance, the analysis highlights significant environmental considerations involved in selecting high-performance synthetic materials versus natural, more sustainable options.

The lifecycle emissions associated with cork are significantly lower due to its natural origin, capacity for being recycled, and less energy-intensive processing.

Its biodegradability nature contributes to reductions across all embodied carbon stages, significantly enhancing its environmental profile. The assessment faces substantial penalties due to transportation distances, being cork production centralized in Portugal. This factor meaning that if the cork is used in projects located far from Portugal, the environmental benefits gained from its biodegradable properties and reduced waste in landfills may be offset by the emissions associated with transporting it over long distances. This underscores the critical importance of considering the entire lifecycle and supply chain process when evaluating the sustainability of building materials.

Similarly, wood fiber insulation offers environmental benefits such as carbon sequestration and the potential for lower emissions during production.

The ability of wood fiber to capture and store carbon dioxide during its growth phase, coupled with possibly reduced emissions in its manufacture, makes it an environmentally preferable choice. However, assumptions about the disposal for landfilling as indicated by its Environmental Product Declaration (EPD), significantly influence its overall environmental impact. This situation demonstrates how the information provided by manufacturers can influence the lifecycle assessment of a product, with the EPDs in the OneClick database.

The analysis also highlights the importance of selecting durable materials with long service lives for insulation to minimize the need for frequent refurbishments, thus lowering the impact.

In conclusion, the role of recycling or selecting biodegradable materials is vital in diminishing environmental impacts at the end-of-life stage.

Cork and wood represent the best choice, since employing natural and biodegradable materials help in mitigating long-term pollution, making them favorable for sustainable building practices.

4. Conclusion and future development

The analysis evaluates the environmental impact of different building scenarios aimed at improving the efficiency of the building located in Milan. This includes an evaluation of alternative insulation materials through an in-depth life cycle assessment (LCA). It highlights the importance of considering both operational and embodied carbon emissions to enhance the overall environmental performance of buildings. The interventions in Scenarios 1 and Scenario 2 demonstrate that energy-saving solutions, like the use of efficient materials and technologies, can significantly reduce the energy demand and emissions.

Opting for double-glazed windows with aluminum frames was a strategic choice aimed at enhancing energy efficiency and sustainability. This switch significantly reduced emissions during the initial construction phase, primarily due to the use of recycled aluminum, which led to a decrease in carbon footprint.

The analysis further considers the importance of material choice in construction and insulation for reducing energy emissions. A detailed examination of the environmental impacts of various alternative materials, compatible with ETICS system, provides valuable insights. It demonstrates that strategic material selection, even without changes to mechanical systems, can significantly enhance the building's environmental performance.

This approach encourages a future development on sustainability, emphasizing the concept of material selection in reducing emissions and improving energy efficiency. A detailed examination of each insulation material's specific lifecycle stages provided a more understanding of their respective carbon contributions.

The analysis underscores the importance of selecting durable, long-lived materials for insulation to minimize the need for refurbishment, thereby reducing environmental impacts. Materials that align with the building's service life help in avoiding additional emissions from replacements, highlighting the vital role of durability in sustainable construction practices.

Furthermore, adopting advanced recycling strategies and using biodegradable materials are key to lower the environmental impact at the end-of-life stage. Cork and wood demonstrate how employing biodegradable materials that naturally decompose can mitigate long-term pollution, favoring sustainable practices. Recycling processes, by reducing waste production and the carbon footprint compared to new material production, contribute significantly to resource conservation and waste reduction.

The impact of transportation distances on the overall environmental footprint must be considered. The carbon footprint of materials is significantly influenced by the

distance they are transported from production to the construction site. Opting for locally produced materials or using efficient transportation methods can substantially mitigate environmental impacts, underscoring the complexity of sustainability in construction materials that involves their production, use, durability, and transportation.

Investigating the synergy between material selection and overall building design and mechanical systems is another crucial area for future research. This exploration could reveal how strategic material choices can enhance building efficiency and sustainability without necessitating changes to existing mechanical systems.

Comparing carbon-sequestering materials like cork and wood fiber with carbon-producing materials highlights their potential as good alternatives to mineral wool.

While the evaluation primarily focused on Global Warming Potential (GWP), it's important to recognize that there are numerous other impact categories, such as ozone depletion, acidification, eutrophication, and more, that play a significant role in determining the sustainability of building materials. These categories assess various environmental impacts beyond just the greenhouse gas emissions contributing to climate change. For instance, ozone depletion potential measures a substance's capacity to deteriorate the ozone layer, which protects life on Earth from harmful ultraviolet radiation. Other categories, like acidification potential, evaluate the impact of pollutants that can lead to the acidification of ecosystems, affecting soil and water quality and biodiversity.

Future research should incorporate a wide range of impact categories in environmental assessments to allow for a balanced approach to sustainability, where choices are informed by a thorough understanding of their ecological implications. This comprehensive view is crucial for advancing sustainable building practices that not only reduce carbon emissions but also minimize other forms of environmental damage, contributing to the overall health of the planet and its inhabitants.

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