

# Energy and Sustainable Renovation of Building Stock in Europe: The Environmental Benefits of Biobased Insulation Materials

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**Abstract.** Given the long-term renovation strategies implemented at European level to improve the efficiency of existing buildings stock by 2050, the demand for insulation materials will increase significantly. Insulation materials have played a crucial role in energy efficient building design for over 30 years, providing effective solutions for thermal comfort and energy efficiency. They must now align with European goals for ecological sustainability and the circular economy while meeting the carbon neutrality objectives. In renovation process of traditional old buildings, considered as energy-intensive and mainly targeted by those long-term strategies, the choice of insulation is more complex dealing with maintenance and durability of the existing building, respect of heritage value, and specific hygrothermal behaviour. The choice of thermal insulation is even more crucial as these materials provide a variety of types and forms. In this context, with a focus on internal insulation of traditional façade walls, the study investigated biobased insulation materials through a multi-criteria approach, addressing both constructive and environmental considerations. First, three inventories were compiled to establish a more comprehensive understanding of their availability, composition and processing, technical properties and applications, and their potential recovery at the end of life. Then, three insulation scenarios were analysed to determine the reversibility and reuse potential of biobased insulation materials along with an environmental assessment. The findings were compared with four conventional materials. This study has provided a holistic perspective of biobased insulation materials available in the European markets, their life cycle, technical performance, circularity, and environmental impact. It highlighted the effective solutions they provide for the internal insulation of traditional walls.

## 1. Introduction

### 1.1. Context

For over thirty years, insulation materials have played a vital role in building design, driven by evolving energy regulations and stricter thermal insulation standards. The 2018 update of European EPB regulations urged member states to enhance renovation efforts and improve building energy efficiency by 2050. Energy renovation is a major challenge for Wallonia, as for all

European regions, which must address a residential building stock characterized by its diversity—both rural and urban—and a high percentage of old buildings, poorly insulated, and highly energy-intensive. Consequently, the demand for insulation materials is expected to rise significantly (1).

Building energy renovation primarily involves enhancing envelope performance through appropriate insulation materials selection. While these materials enhance comfort and efficiency, they are also required in recent years to align with European goals for sustainable and circular management of resources and waste (2). Therefore, insulation materials can no longer be selected solely for their thermal conductivity; the selection should also consider overall impacts on the existing construction and the broader environment. Moreover, many insulation techniques used in new construction cannot be directly applied to old traditional buildings, which interact with their climatic environment and rely on the hygrothermal behaviour of their materials to manage the water vapor (3). Non adapted insulation options can significantly compromise this characteristic, leading to material and structural degradation. It can also affect summer comfort by reducing the ability of insulated walls to store heat. In addition, it can result in the loss of a building's identity or cultural value, which contributes to the architectural character of a region and the built heritage that should be preserved for future generations. Furthermore, non-circular insulation materials with irreversible assemblies and limited reuse potential contribute to resource consumption, greenhouse gas emissions and waste production.

The selection of insulation materials during the renovation process, particularly for existing traditional buildings, is crucial. In fact, thermal insulation encompasses a wide range of materials with diverse natures and forms, both of which influence deeply their technical performance, suitability for renovation projects, and environmental impact. The nature of an insulation material depends on the resources used in its production and the manufacturing processes involved. Insulation materials are classified as organic or inorganic (mineral) based on their composition and further categorized as natural or synthetic depending on their type and extent of processing (4). Biobased insulation materials, derived from organic resources, are often considered as “natural” due to their minimal processing. Although the term “biobased” has varying definitions, a previous literature review (5) has supported the following: materials derived from plant or animal origin, produced from renewable biomass resources, and often biodegradable. Given the importance of biobased content, the requirement for the “biobased product” label, which is set at 70% for insulation materials, has also been considered (6).

Scientific literature has extensively studied conventional insulation materials such as mineral and synthetic options, focusing on their thermal, acoustic and mechanical properties (7), and their carbon footprint and embodied energy (8). Some studies have explored the effects of internal insulation on hygro-metric behavior (9), while only a few other studies address specific energy renovation and technical solutions (10). Recently, research on biobased insulation materials has expanded (11) examining their physical properties (12) and comparing their technical, environmental and economic performances with conventional materials (13). However, few studies take an integrated approach, considering not only the physical properties but also practical application in energy renovation and their long-term sustainability and circularity (14).

### *1.2. Aim and focus of the study*

The current study examines biobased insulation materials available on the European market, from technical, constructive and environmental perspectives. It aims to highlight their balanced characteristics and effective solutions for energy renovation, while promoting low-carbon and circular economy principles, with a particular focus on the energy renovation of Walloon

traditional residential buildings constructed before 1919 (12), especially the insulation of their façade walls.

Old traditional buildings represent around 14,3% of the existing European building stock (15), 18% of Brussels' stock and 25% of Wallonia's stock (16). They are characterized by thick façade walls, primarily solid brick or natural stone masonry, both with lime mortar. Walls vary in thickness depending on geographical location, building height, and/or number of floors, ranging from around 54 to 60 cm in the basement to around 24 to 27 cm in the attic. Solid brick masonry is the most prevalent across Brussels and Walloon regions, both in urban and rural areas.

Many traditional buildings and their façades hold cultural or historical significance, even if not officially listed or protected (17). Ensuring their integrity and quality during retrofitting is essential. Therefore, this study focused on internal insulation of the façade walls, exploring three scenarios with different techniques and materials.

## 2. Methodology

### 2.1. Comprehensive inventories

The three inventories were compiled from multiple data sources, including scientific literature, manufacturer technical data sheets and Environmental Product Declarations (EPDs), supplemented by extensive prior research conducted by the two authors (4, 18). The objective was to collect both qualitative and quantitative data to provide a comprehensive overview of biobased insulation materials focusing on their availability, composition, resource origins, technical properties, life cycle, transformations, and end-of-life valorization potential.

The first inventory listed biobased insulation materials available in the European and Belgian markets, categorized by types (e.g., wood, straw, and grass...). For each type, it has detailed material forms (e.g., bulk, flexible mat, rigid panel), potential applications in energy renovation as well as biomass origins, producers, and products. Particular attention was given to ecological labels, the presence of Belgian and French EPDs, and environmental data from the TOTEM database (**Table 1**). Then, to align with the definition proposed above, the percentage of biobased content, additional components, and additives were also identified (**Table 2**).

**Table 1:** Some qualitative data collected in the first inventory for various biobased insulation materials.

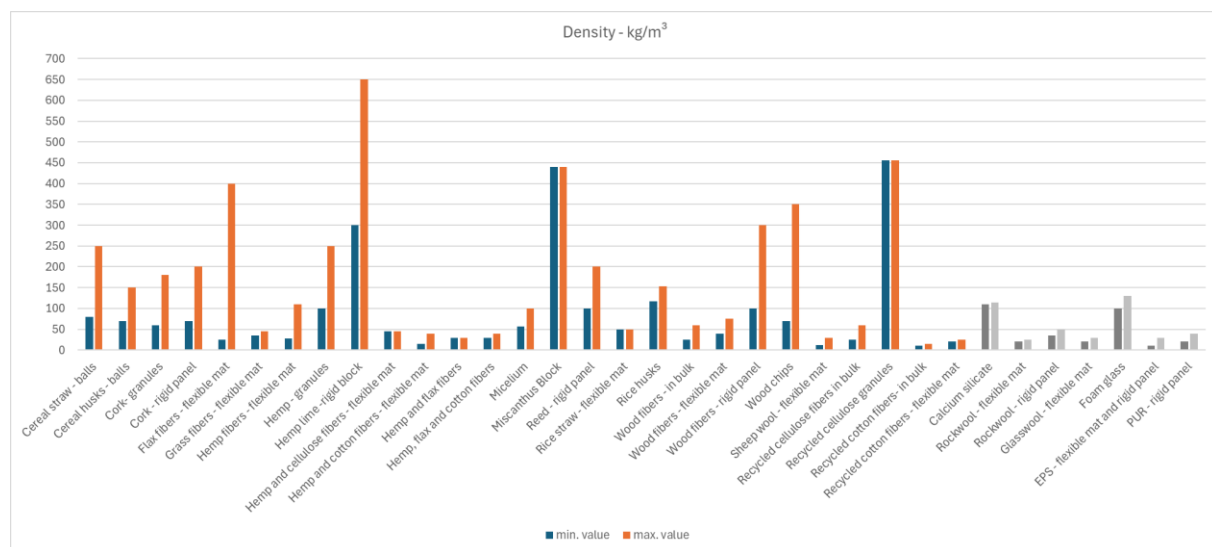
Type of material	Form	Origin of raw materials	Belgian producers	Eco-label	EPD	Data in TOTEM
Cereal straw	In bales	France, Germany	/	NO	NO	Generic data
Cork, recycled	In bulk	Belgium	Recycork	NO	NO	Generic data
Hemp-lime	Block	France, Germany	Isohemp	YES	YES	Generic and EPD data
Grass	Flexible mat	Belgium, Switzerland	Gramitherm	YES	YES	EPD data
Sheepwool	Flexible mat	Austria, Belgium, England	Woolconcept	NO	YES	Generic and EPD data

This inventory has provided a deeper qualitative understanding of the life cycle of biobased insulation materials by identifying products, producers, resources used, as well as their forms, compositions, processing and possible applications.

**Table 2:** Data collected on the composition of biobased insulation materials

Type of material	Form	Biobased content (%)	Additional raw materials	Adjuvants
Cereal straw	In bales	100	Binding wires	NO
Cork, recycled	In bulk	100	NO	NO
Hemp-lime	Block	70 to 90	Lime binder	NO
Grass	Flexible mat	70 Recycled jute (20%)	PET or PLA fibers	Amonium polyphosphate, urea and silica
Sheepwool	Flexible mat	70 to 100	Polyester fibers	Mothproof, flame-retardants

The second inventory focused on the thermal and hygrothermal properties of insulation materials, highlighting their role in improving summer and winter thermal comfort while ensuring the long-term durability of insulated buildings. Insulation materials are typically classified by their thermal conductivity ( $\lambda$ ) and density ( $\rho$ ). However, to tackle the challenges of internal insulation in traditional façade walls, particularly heat retention, overheating, and moisture regulation, the inventory also gathered data on specific heat capacity ( $c$ ), water absorption ( $W$ ), and the water vapor diffusion resistance factor ( $\mu$ ).



**Figure 1:** Minimum and maximum values for density. Twenty-seven biobased insulation materials are presented in the figure followed by seven conventional insulation materials. Source: S. Trachte. Additionally, it compiled data on fire resistance and acoustic absorption, ensuring compliance with the applicable EN standards.

Due to the wide variety of types and forms, the performance of biobased insulation materials varies significantly. To reflect this, the study presented a range of values for each property,

highlighting both the minimum and maximum levels achieved (**Figure 1**). These properties were then compared to those of seven conventional materials, allowing for a performance assessment both among biobased materials and in relation to conventional ones.

The third inventory emphasized the circularity of biobased materials by considering all life cycle stages, focusing on renewability, reusability, and recyclability, in line with resource efficiency and waste prevention principles. It examined secondary materials use and biomass renewal times at the extraction stage, material scrap rates, scrap recovery systems and lifespan at the implementation stage, as well as reuse potential, pretreatment, recycling, and organic recovery potential at the end-of-life stage. For each materials type and their applications in renovation, the inventory then evaluated the reversibility potential of various assembly methods using a qualitative approach based on a graphic scale (**Figure 2**), and four key constructive aspects highlighted in Reversible Design concepts (19).

Type of assembly	Type of insulation material	Reversibility of connection	Simplicity of disassembly	Speed of disassembly	Ease of handling
Connection by glue	Rigid panels or blocks	no reversible	/	/	/
Connection by screw and glue	Rigid panels	no reversible	/	/	/
Mechanical connection with screw	Rigid panel	reversible with small damages		rather slow disassembly	
Mechanical connection with staples between frames	Flexible mats	reversible	simple	speedy but time required for staples removal	very easy to handle manually
By friction between frames	Flexible mats	reversible	very simple	very speedy	very easy to handle manually
By blowing or loose between frames	In bulk	reversible	complex, requires specific tools and/or several workers	rather slow disassembly	can be handled manually, but requires two or more workers

**Figure 2:** Types of insulation materials assembly and assessment of their reversibility. Source: S. Trachte

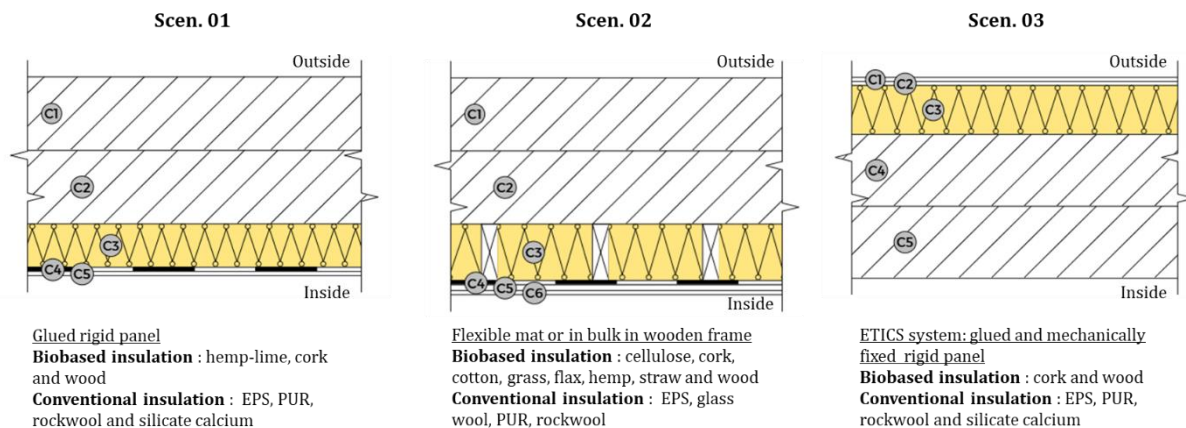
## 2.2. Presentation of Totem tool

This study relied on the TOTEM (Tool to Optimize the Total Environmental impact of Materials), used in Belgium to assess the environmental impact of buildings materials, elements and/or entire buildings. The evaluation follows all indicators defined by the EN 15804-A2 standard and spans a sixty years period, accounting for maintenance and replacement if needed. The tool provides both a unique environmental score based on the Product Environmental Footprint (PEF) weighting method and a detailed breakdown by indicator and life cycle stage. Its database includes generic data adapted to the Belgian context—such as energy mix, and end-of-life scenarios—as well as EPD's data. The tool enables the modeling of various material statuses, allowing for simulations of construction, renovation, demolition scenarios, and also reuse scenarios.

## 2.3. Insulation scenarios for environmental assessment

Based on the options available in the TOTEM database, the study first considered an existing 44 cm-thick solid brick masonry wall, with lime mortar, featuring a U-value of 1.09 W/m<sup>2</sup>K. Exterior and interior layers were excluded, as they are typically removed before renovation works. Two internal insulation scenarios were then selected: one using glued rigid panels (scen.01) and another using flexible mat or bulk materials, implemented within a wooden frame (scen.02). These scenarios were compared to the most common façade insulation method in Wallonia: external insulation with the ETICS system (scen.03).

As illustrated in **Figure 3**, all scenarios comply with the EPB Belgian requirements, achieving a maximum U-value of 0.24 W/m<sup>2</sup>K. For each of them, a selection of biobased materials was prioritized, focusing on those produced in Wallonia and listed in the TOTEM database. This selection was then supplemented by four conventional insulation materials for comparison.



**Figure 3:** The three insulation scenarios used for the environmental assessment of biobased materials.

Source of diagrams: [www.totem-building.be](http://www.totem-building.be)

## 2.4. Evaluation process

The evaluation was conducted on a one-square-meter wall using a three-step modelling approach (Figure 4). The environmental impact of each step was assessed separately to analyse the impact of the selected insulation materials.

Insulation system	Wall composition composition (external to internal)				Status	Modelling
	Layers	Thickness	Percentage	Materials		
	C1	22	100%	Solid brick - fired clay - laid in lime mortar	Existing	Step 01
	C2	22	100%	Solid brick - fired clay - laid in lime mortar	Existing	
	C3	varying	15%	Woodframe - nailed	New	Step 02
			85%	Insulation - flexible mat or in bulk blown on site	New	Step 3
	C4	0,025	100%	Proofing sheet - stapled	New	Step 02
	C5	1,8	100%	OSB board - nailed	New	
C6	1,25	100%	Gypsum plaster board - screwed	New		

**Figure 4:** Presentation of wall composition for scenario 02, materials status and modelling steps.

## 3. Results and discussion

### 3.1. Availability of biobased insulation materials

The study highlighted approximately twenty-five types of biobased insulation materials, available in various forms, along with and fifteen Belgian producers on the Belgian market. Additionally, other biobased materials, though not included in the inventory due to limited data, were identified on the European market. These include jute and hemp mat, flax granules, reed granules mixed with lime, as well as seashells and seaweed flakes or mats. Wood remains the most widely developed biobased insulation material in Europe, available in multiple forms and produced by various manufacturers. In Belgium, the production of biobased insulation includes bulk cellulose, hemp-lime, grass, sheep wool and miscanthus. In comparison, the French market is more diverse, offering materials such as cereal and rice straw and husks, hemp, blends of hemp, cotton, flax, and cellulose, miscanthus, recycled cotton, reed, and wood.

Crucially, the study identified that most of these materials have already acquired a significant level of technical and normative maturity, justified by technical approvals. This allows them to compete effectively with conventional insulation materials.

### 3.2. Composition and processing of biobased insulation materials

The study highlighted that biobased insulation materials are primarily derived from agricultural and forestry byproducts, as well as recycled waste like paper and textiles. Some also originate from natural resources such as mycelium, reeds, and seaweed. However, their renewal cycles vary

significantly, ranging from a few weeks (grass, mycelium) to several months (hemp, flax, miscanthus, reeds, sheep wool, straw) or even decades (cork and wood).

The study found that some materials, such as cereal and rice straw and husks, reeds, mycelium, and minimally processed bulk materials (e.g., miscanthus and hemp granules), consist of 100% biobased content. However, many products, particularly those in flexible mat or rigid panel forms, contain synthetic reinforcing fibers, typically accounting for approximately 10-15% of their composition. Additionally, most biobased insulation products - except for cereal and rice straw and husks, reeds, mycelium, hemp-lime, and cork - also contain fungicides and flame retardants.

Although biobased insulation materials, particularly those in bulk or in flexible mats, undergo minimal processing, mainly mechanical (e.g., grinding) or physical (e.g., heating), the presence of additives can influence their environmental impact and end-of-life recoverability. Additionally, while biobased insulation materials have a lifespan comparable to conventional ones, their long-term durability largely depends on quality of installation works and suitability for application.

### *3.3. Constructive and technical qualities of biobased insulation materials*

The study demonstrated the suitability of biobased materials for internal insulation of old traditional walls. Due to their diversity in types and forms, these materials provide solutions adapted to the specific requirements of the wall in each renovation project. In terms of thermal conductivity, most biobased materials - except straw and hemp-lime - achieve values around approximately 0.04 W/m·K, leading to thicknesses comparable to conventional insulation to meet required U-value. Moreover, several of them exhibit higher density (straw, cork, flax, wood, and cellulose) and heat capacity (grass, hemp, wood, and cellulose) than conventional ones.

Regarding moisture behavior, biobased materials, except cork panels, generally have low water vapor diffusion resistance, ranging from 1 to 5 corresponding to mineral insulation. Due to a lack of available data, a precise comparison of water absorption between biobased and conventional materials was not enough precise. Nonetheless, literature suggests that most biobased materials possess open porosity, acoustic absorption ranging from Class A to C and a "hygrothermal dynamic" process that contributes to moisture regulation. Consequently, biobased insulation materials are considered breathable or open to water vapor, like traditional construction materials. Most of them are also considered hygroscopic and capillary.

However, in terms of fire resistance, most biobased materials, as synthetic insulation, fall into Class E or D, except for hemp-lime.

### *3.4. Circular character of biobased materials*

The study demonstrates that biobased materials contribute effectively to a circular economy, by incorporating high proportions of byproducts or waste recycled content, requiring minimal processing, and offering strong potential for reuse and recovery. However, unlike conventional materials, biobased materials are not currently reintegrated into production cycles due to lack of collect and recovery systems in Belgium and across Europe. This is largely due to the relatively low and variable volumes, making economic feasibility challenging. The assessment of insulation system reversibility further reveals that most rigid panels solution - whether biobased or conventional - are not-reversible, limiting their reuse potential. Currently, only mechanical connection and assemblies by friction or blowing within a frame enable reversibility and quite easy disassembly and handling, as shown in **Figure 5**.

Scen. 02	Materials	Reversibility of connection	Simplicity of disassembly	Speed of disassembly	Ease of handling
	Solid brick - laid in lime mortar	Yellow	Orange	Orange	Green
	Solid brick - laid in lime mortar	Yellow	Orange	Orange	Green
	Woodframe - nailed	Yellow	Orange	Orange	Green
	Insulation - flexible mat	Green	Orange	Orange	Green
	Insulation - in bulk	Green	Orange	Orange	Green
	Proofing sheet - stapled	Orange	Green	Green	Green
	OSB board - nailed	Yellow	Orange	Orange	Green
	Gypsum plaster board - screwed	Yellow	Orange	Orange	Green

Figure 5: Assessment of assemblies' reversibility for materials in scenario 2.

### 3.5. Environmental assessment of biobased materials, beyond carbon footprint

Although the environmental impact of biobased materials was assessed using all the indicators outlined in the EN 15804-A2 standard, the study focused on Global Warming Potential (GWP), Carbon Sequestration, and Abiotic Resource Depletion, to complement the Environmental Global Score provided by TOTEM and align with transition and carbon neutrality objectives.

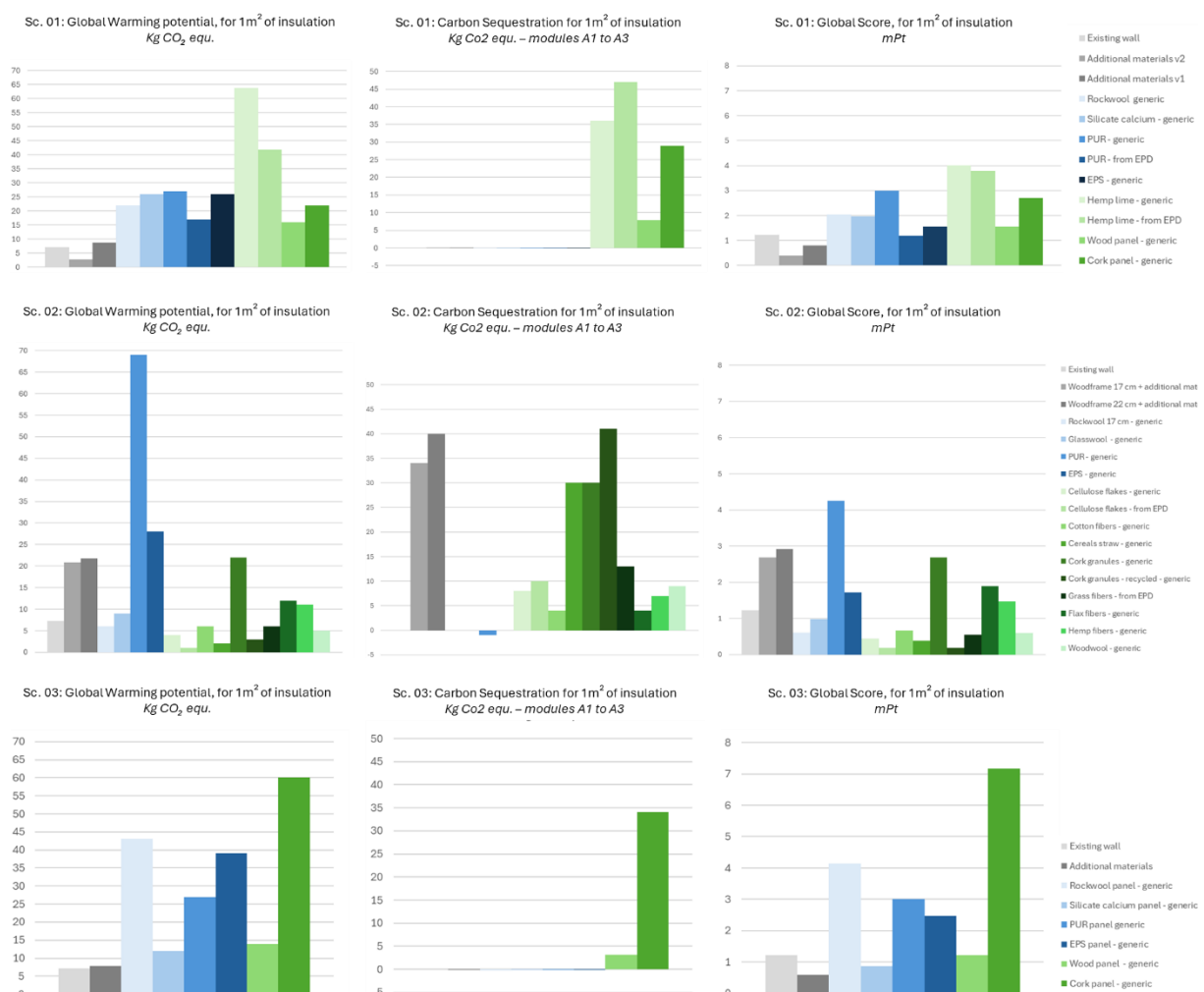


Figure 6: Results for three indicators provided by TOTEM for one square meter of various insulation materials based on three insulation scenarios: Global Warming Potential, Carbon Sequestration and Environmental Global Score. Source: S. Trachte

As illustrated in Figure 6, results indicate that the Global Score varies significantly depending on the insulation technique and material used, partially explained by variations in material density. In fact, while higher densities improve thermal comfort in internal insulation applications, they negatively impact environmental scores, which are calculated based on the

quantity of material required to achieve a specific performance. This effect is particularly evident for hemp-lime, wood and cork panels. However, in Scenario 02, cellulose, recycled cotton, straw, grass, and woodwool exhibit very low global score, largely due to their high recycled content and/or use in flexible mat or bulk form. The environmental impact is further significantly reduced when bulk materials without additional components, or reused materials are incorporated.

The results also highlight the significant carbon sequestration potential of biobased insulation materials, particularly cork, grass, hemp-lime and straw. However, this benefit is not fully exploited, as these materials are predominantly subjected to thermal recovery at end-of-life, substantially increasing their carbon footprint. Regarding the indicators of abiotic resource depletion (fossil fuels), biobased materials -particularly in bulk or flexible mats - generally demonstrates lower impact score than rigid panels. Moreover, some biobased materials, such as cork and wood (in rigid panels form), as well as flax and hemp (in flexible mat form), show environmental scores like or higher than mineral insulation. These findings emphasize that the term "biobased" does not inherently guarantee a lower environmental impact.

Finally, the results reveal substantial difference in the environmental scores between materials based on generic data and those with EPDs. This underscores the importance of producers investing in life cycle analyses and EPDs to better quantify and communicate the environmental benefits of their products, extending beyond just carbon storage.

#### **4. Conclusion**

Achieving European carbon neutrality and circular economy objectives requires rethinking insulation material selection. While insulation effectively improves thermal comfort and energy efficiency for decades, it must now be evaluated through a multi-criteria approach that also considers resource sustainability and environmental impact. This necessitates a balanced selection process integrating these four aspects. In renovation projects, it is especially complex, where additional factors such as building durability, architectural preservation, and specific hygrothermal behavior must also be considered.

By taking all these aspects into account, the study demonstrated that biobased materials could compete with more conventional materials, especially as they are now increasingly visible on the construction market, and they offer technical and normative maturity. First, it highlighted the technical properties of biobased insulation materials, and their multiple available forms enable tailored solutions adapted to the specificities of each wall. Due to their thermal and moisture-regulating characteristics, these materials enhance comfort and energy efficiency in traditional old buildings while ensuring long-term durability. Although their reuse and recovery potential remain largely untapped due to the lack of effective recovery systems, the study then underscored that biobased materials should be regarded as drivers of local and circular economic development by sourcing raw materials and byproducts from diverse natural ecosystems or waste recycling chains, undergoing minimal processing and providing reversible assembly solutions. Finally, the assessment of their environmental impact demonstrated that those materials are a crucial asset in achieving our goals of both carbon neutrality and sustainable resource management. Unlike conventional insulation, biobased materials are made from renewable biomass. Through the process of photosynthesis, they can store a significant amount of carbon for periods of more than 50 years. However, biobased insulation does not automatically guarantee better environmental performance than conventional insulation. Its performance must be assessed by considering the entire life cycle as well as all material flows, including the incorporation of additional raw materials and additives.

Despite their technical, constructive and environmental benefits in energy renovation, biobased insulation materials are still too often unknown. To meet future insulation demands, it is crucial to develop the knowledge and expertise in biobased materials among renovation professionals. This will enable them to actively contribute to what Ph. Madec describes as the "ecological, circular, and social transition of our human settlements"(20).

## 5. Acknowledgements

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