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Insulation materials for building : dealing with climate change along with other challenges yet to come

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Abstract. In France, numerous regulations have been enacted to tackle climate change. The initial ones focused on the use phase of buildings, while the last regulation considered both the construction and use phases. Meanwhile, issues such as energy supply and resource scarcity are becoming increasingly important, but no current regulations address these challenges. To go further than climate change, five impact categories are studied: global warming potential, abiotic depletion potential – fossil fuels, consumption of primary non-renewable energy, transport distances, and abiotic depletion potential – elements. These categories are used to rank 11 insulation materials: polyurethane, expanded polystyrene, extruded polystyrene, rock wool, glass wool, hemp concrete, hemp wool, cellulose wadding, straw, semi-rigid wood fiber, and rigid wood fiber. For this purpose, we analyzed 664 Environmental Product Declarations (EPD) from the French EPD database, using a functional unit of 1 m² of insulation with an R-value of 5 m²·K/W. It appears that bio-based materials generally performed better than conventional ones across all five impact categories. However, the ranking based on the five indicators provided a nuanced view of the ranking solely based on the global warming potential and did not significantly alter the overall ranking.

Keywords: insulation materials, energy supply, climate change, resource scarcity, life cycle assessment

1. Introduction

For the past fifteen years, climate change has increasingly impacted political decisions. In France, this began in the building sector in 2005 with the Thermal Regulation 2005 (RT2005) and later in 2012 with the Thermal Regulation 2012 (RT2012) [1]. These regulations aimed to reduce energy consumption in new buildings and thus greenhouse gas emissions during their use. Subsequently, climate change considerations have also been incorporated into the materials used in construction. For example, since 2015 in France, the Low Carbon Building label (BBCA) has been helping building designers to value the use of materials with lower embodied energy. From 2016 to 2021, the French Energy+Carbon-(E+C-) experiment [2] promoted buildings with a low carbon footprint (construction and use). While RT2005 and RT2012 legally mandated reductions in greenhouse gas emissions in the building sector, the BBCA label and the E+C- experiment were voluntary initiatives to promote sustainable construction. Following the COP21, the French law on ecological transition for green growth [3] initiated the development of the environmental regulation for French buildings (RE2020). This regulation [4], which came into effect on January 1, 2022, requires life cycle assessments for new buildings and sets thresholds



for greenhouse gas emissions during construction and use. The ecological transition law also initiated the works of the tertiary eco-energy decree. This French decree [5] was published in 2019 and mandates the reduction of final energy consumption in tertiary-use buildings with thresholds set for 2030, 2040, and 2050. All these regulations only impose thresholds on greenhouse gas emissions. Furthermore, the regulatory texts are often transpositions of European directives. Some of the regulations mentioned above follow the “Energy Performance of Buildings Directive,” the “Energy Climate Package”, and the 2018 European taxonomy. The “RepowerEU” (2022) and “Fitfor55” programs will also impact future regulations concerning the building sector in EU member countries.

In France, life cycle analyses are carried out to determine greenhouse gas emissions, based on the Environmental and Health Declaration Sheets¹ (FDES), which are the French transposition of the Environmental Product Declarations (EPD). The FDES are included in the French INIES database (Information on Environmental and Health Impacts). This database is managed collaboratively by private and public actors. Other databases for EPDs exist in Europe: ÖKOBAUDAT (Germany), baubook (Austria), EPDIItaly (Italy), Nationale Milieudatabase (Netherlands), DAPconstrucción (Spain), etc.

In addition to climate change, there are many other upcoming challenges or other future disruptions [6]. We will focus on two particular challenges: energy supply and resource depletion.

The use of fossil fuels has increased exponentially since the mid-19th century, and fossil fuels today account for about 80% of the global energy supply [7]. The building sector is no exception. For instance, 21% of European gas is used for heating buildings [8]. It is also heavily dependent on fossil fuels for producing insulation materials and depends on oil for transporting materials throughout its lifecycle [9]. However, this supply is not guaranteed indefinitely. Laherrère et al. [10] predict peaks in global production between 2020 and 2045 under various scenarios and expect that global production will have halved from today's levels by 2100. The Shift Project [11] estimates that the oil peak for the 16 main oil-supplying countries of the European Union will occur before 2030 with a 50% reduction in supply around 2050.

Resource depletion is the last challenge studied in this research. This challenge is also coupled with the resilience of the value chain. As shown by Goldin et Mariathan [12], the resilience of the industrial value chain has greatly decreased in order to optimize costs. Each region, country, or city has its specialization. However, this is only possible with large-scale and low-cost transportation. On the other hand, resource depletion is a topic that has been highlighted by the Club of Rome report [13] and has been making headlines again in recent years. In the building sector, it is mainly the use of aggregates, especially sand for concrete, that is currently under discussion. UNEP has also produced a report [14] on this subject. However, there are not yet many studies in this area on other building materials, particularly insulators.

In sum, the consideration of climate change is now well-established in public policies. This is notably achieved through the life cycle assessment of building materials via data retrieved from the FDES in the INIES database. However, the climate change indicator is the only one studied mandatorily (RE2020) or voluntarily (BBCA label). In contrast, the indicators for energy supply and resource depletion, although calculated in LCAs, are not subject to regulations or valuations. Yet, these challenges will rapidly impact the French or European building sector.

For the climate change indicator, a clear consensus emerges on the performance of insulation materials. Indeed, as shown by the compilation of Oliva and Courgey [15] (based on the Austrian database baubook), but also by the study by Hill et al. [16], bio-based materials are more efficient than conventional materials (Fig. 5). These studies also take into account the embodied energy of insulation materials. Unlike climate change, the results for embodied energy are more nuanced (Fig. 6). However, the results for these two indicators highlight the better performance of bio-based materials compared to

¹ FDES : declaration established under the responsibility of the manufacturers (or professional associations) of the construction product. The EN 15804+A1 and NF 15804/CN standards provide the method of obtaining and the format of these declarations.

conventional materials. These studies focus on two indicators that take into account climate change and part of the energy supply, but do not consider resource depletion and other indicators for energy supply.

Thus, our study seeks to determine if the ranking of the aforementioned studies would remain the same if climate change, energy supply, and resource scarcity were considered. To address this issue, we propose to classify insulators by taking into account the three challenges mentioned just before.

2. Methodology

2.1. Choosing the FDES

The latest annual INIES report [17] provides the following figures for insulation as of December 31, 2022: 1302 FDES and 156 default environmental data² (DED). Moreover, the database hosts data for 20 different insulators distributed across 26 insulation categories.

The first step is to increase the accuracy of the data used. For this purpose, only the Environmental and Health Declaration Sheets (FDES) present in the INIES database are used. Indeed, the environmental impacts of the DEDs are overestimated, making them less precise. Some insulation categories only have DEDs. These categories are therefore excluded from the study's scope (Fig. 1).

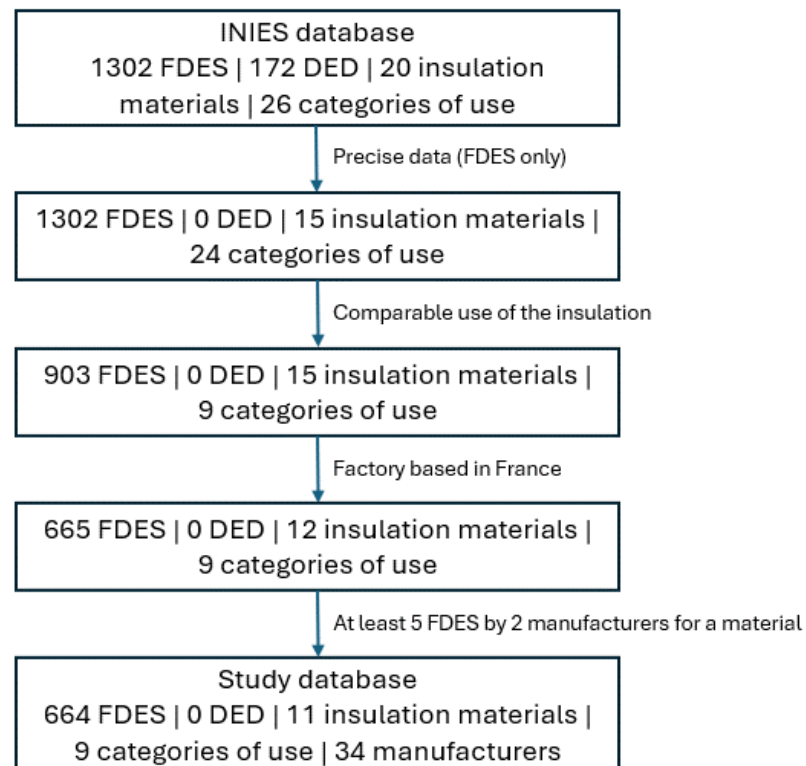


Figure 1. Diagram of the different stages of selecting data extracted from the INIES database. Note that the number of DEDs differs from that of the INIES 2023 barometer due to the addition of data in the meantime.

The second step is the choice of insulation categories to use. This involves enabling valid comparisons between different insulators. To do this, it is necessary to compare insulators that meet similar constraints. Additionally, to facilitate comparisons, we will only compare insulators and not insulation systems (insulator + support).

² DED: substitute data provided by the French ministry in charge of construction in the absence of specific data (FDES/PEP), where the environmental impacts of the product or equipment are increased to cover the uncertainty of the installed product.

The third selection step takes into account two factors (energy mix and resilience of the supply chain) with one characteristic (location of the factory). Indeed, as noted by Hill et al [16], the energy mix is a factor that impacts the calculation of environmental indicators. Additionally, Goldin et Mariathasan [12] explain that the more dispersed the value chain is in the world, the more fragile it is. Thus, only products manufactured in factories located in France will be studied.

The last step is the number of FDES for a material. To have a representative sample, a material must have at least 5 FDES from at least 2 manufacturers. Moreover, to gain precision, it was decided to split the data for "wool and wood fiber" into "semi-rigid wood fiber" and "rigid wood fiber." Similarly, the data for the "hemp" material was split into "hemp concrete" and "hemp wool".

This methodology allows for a total of 667 FDES and 34 manufacturers distributed across 11 materials as follows: polyurethane (114 FDES, 6 manufacturers); expanded polystyrene (35 FDES, 9 manufacturers); extruded polystyrene (20 FDES, 3 manufacturers); rock wool (136 FDES, 3 manufacturers); glass wool (273 FDES, 3 manufacturers); hemp concrete (9 FDES, 6 manufacturers); hemp wool (17 FDES, 3 manufacturers); cellulose wadding (20 FDES, 5 manufacturers); straw (6 FDES, 2 manufacturers); semi-rigid wood fiber (7 FDES, 2 manufacturers); rigid wood fiber (30 FDES, 3 manufacturers).

2.2. Choosing the indicators and the data

As previously explained, the challenges considered in this study are as follows: climate change, energy supply, and resource depletion. It is therefore necessary to propose for each of these challenges one or more performance indicators that will subsequently allow for the classification of insulators (Table 1).

Table 1. Impact categories and indicators according to challenges.

Challenges	Impact categories	Indicators
Climate change	Global warming potential	kgCO ₂ eq/FU
	Abiotic depletion potential – fossil fuel	MJ/FU
Energy supply	Consumption of primary energy, non-renewable	MJ/FU
	Transport distances (A4)	km
Resource scarcity and supply chain resilience	Abiotic depletion potential – elements	kgSbeq/FU ^a
	Transport distances (A4)	km

a : Antimony (Sb) is used as a reference to quantify the impact on the depletion of various mineral elements.

The FDES from the INIES database include "cradle-to-grave" data covering each stage of the life cycle, as described in standards EN 15804/EN 15978. However, many studies cited by Hill et al [16] only provide results for the "cradle-to-gate" life cycle (production module, stages A1-A3, Fig. 2). Hill et al. explain that the "cradle-to-gate" life cycle analysis "potentially represents the most accurate LCA (Life Cycle Analysis) data and does not involve assumptions about lifespan, maintenance, disposal, etc., which can increase uncertainties when comparisons are made." Similarly, Oliva et Courgey [15] only present data for the production stage (A1-A3). Thus, to minimize uncertainties and to be able to compare the results among themselves, only data relating to the production module will be used.

To compare insulators on the same basis, the functional unit of the latter has been modified. The functional unit (FU) used is as follows: "1 m² of insulation with a thermal resistance of R = 5 m².K/W (excluding installation accessories)." For each of the FDES, the results are calculated proportionally to the base thermal resistance of the insulator and the data extracted from the FDES. Only the "Transport Distances A4" indicator is not modified. Indeed, this last one is not proportional to the functional unit but to the location of the factory and the associated transport scenario.

Finally, the last step is the comparison of the data between insulators. For this purpose, the data were averaged for each indicator according to the material.

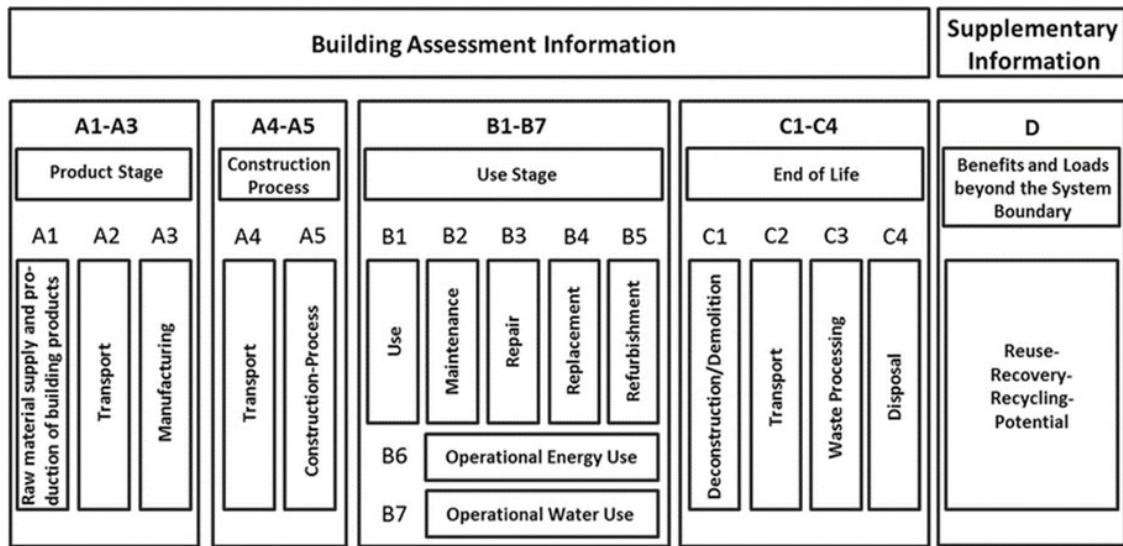


Figure 2. Life cycle stages of a building as taken from the EN 15804/EN 15978 standards.

3. Results

3.1. Results by material

The results for the climate change indicator for polyurethane, expanded polystyrene, extruded polystyrene, and rock wool range between 10 and 20 kgCO₂eq/FU (Fig. 3). Glass wool is at 3 kgCO₂eq/FU. Bio-based materials oscillate between -5 kgCO₂eq/ FU and -40 kgCO₂eq/ FU.

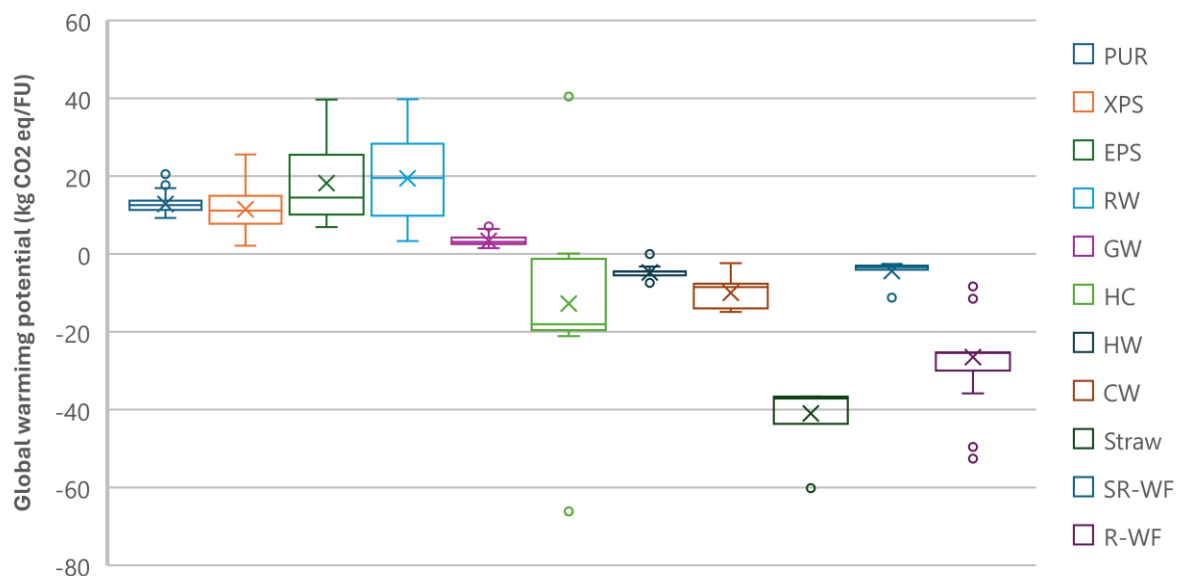


Figure 3. Box and whisker plot of the global warming potential (kgCO₂eq/ FU) of the insulation materials. The cross is the average value, the line in the box is the median value, the whiskers represent the standard deviation, the limits of the box are the 25 and 75 percentile and open circles are the value larger or minor than the 25 and 75 percentile. Abbreviations : polyurethane: PUR; expanded polystyrene: XPS; extruded polystyrene: EPS; Rock wool: RW; Glass wool: GW; Hemp concrete: HC; Hemp wool: HW; cellulose wadding: CW; Straw: Straw; semi-rigid wood fiber: SR-WF; rigid wood fiber: R-WF.

For the depletion of abiotic resources – fossil fuels, polyurethane, expanded polystyrene, extruded polystyrene, rock wool, hemp concrete, and rigid wood fiber are around 300 MJ/FU. Glass wool and other bio-based materials are close to 50 MJ/FU.

For the total use of non-renewable primary energy resources, the results are more disparate. Fig. 4 allows for the identification of 4 categories. Extruded polystyrene, hemp concrete, and rigid wood fiber are around 600 MJ/FU. Polyurethane, expanded polystyrene, and rock wool are at about 300 MJ/FU. Semi-rigid wood fiber is close to 200 MJ/FU. Hemp wool is at 100 MJ/FU. Finally, glass wool, cellulose wadding, and straw are around 50 MJ/FU.

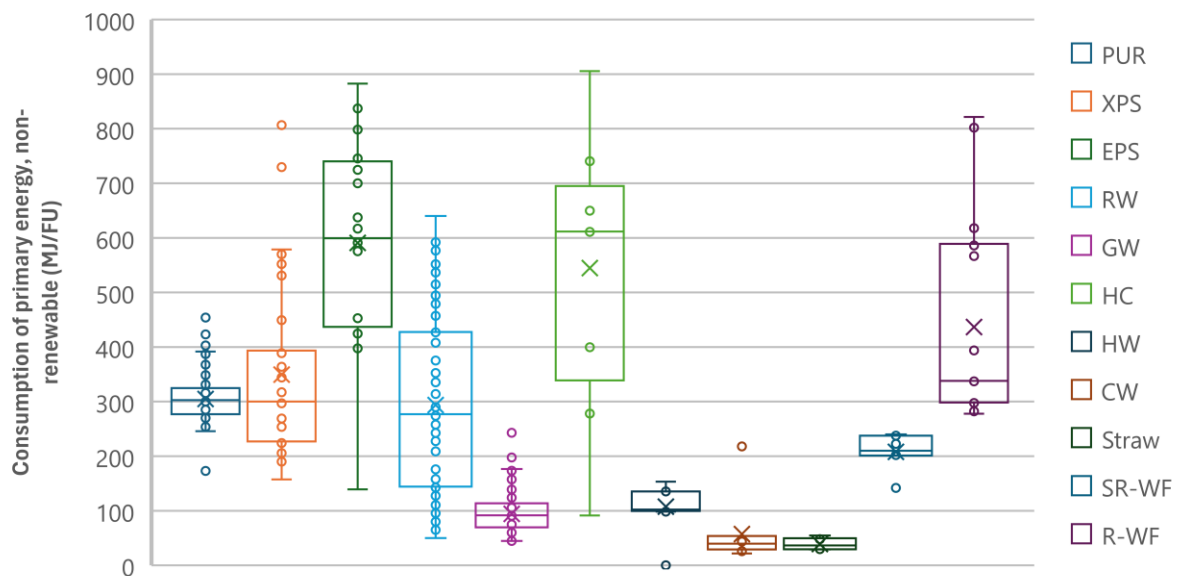


Figure 4. Box and whisker plot of the Consumption of primary energy, non-renewable (MJ/FU) of the insulation materials. Abbreviations as figure 3.

Table 2. Average and standard deviation (*between brackets*) for each indicator according to the insulation.

Insulation	Global warming potential (kg CO ₂ eq/FU)	Abiotic depletion potential – fossil fuel (MJ/FU)	Consumption of primary energy, non-renewable (MJ/FU)	Transport distances A4 (km)	Abiotic depletion potential – elements (x10 ⁻³ kg Sb eq/FU)
Hemp concrete	-12,8 (26,1)	419,6 (193,7)	544,6 (233,5)	299,6 (172,8)	34,5 (45,7)
Hemp wool	-4,8 (1,7)	89,2 (26,9)	107,6 (32,8)	323,2 (108,2)	4,5 (1,5)
Rock wool	19,4 (10,4)	430,5 (477,8)	293,6 (153,0)	472,8 (95,6)	5,4 (8,5)
Glass wool	3,4 (1,1)	69,9 (27,4)	94,4 (33,4)	531,1 (116,8)	12,9 (12,1)
Semi-rigid wood fiber	-4,4 (2,8)	155,6 (25,6)	207,9 (30,6)	345,1 (132,6)	2,3 (0,9)
Rigid wood fiber	-26,5 (12,0)	293,3 (138,5)	436,7 (177,4)	453,3 (86,8)	2,4 (4,4)
Cellulose wadding	-10,0 (3,9)	41,0 (51,2)	57,4 (56,4)	363,7 (36,6)	13,5 (33,8)
Expanded polystyrene	11,5 (4,6)	290,8 (124,3)	349,5 (155,6)	344,5 (227,6)	1,1 (1,4)
Extruded polystyrene	18,2 (9,4)	334,5 (171,4)	590,9 (181,8)	482,3 (102,2)	31,6 (17,5)
Polyurethane	12,8 (2,2)	275,3 (38,3)	304,7 (39,8)	424,4 (85,1)	1,6 (3,0)
Straw	-41,0 (8,6)	38,4 (9,6)	39,1 (10,1)	143,0 (36,8)	1,5 (0,4)
Standard deviation	18,1	141,2	184,3	103,5	11,6

For the transport distance A4, the results oscillate between 300 km and 500 km with an average close to 400 km except for straw at 150 km.

Finally, for the depletion of abiotic resources – elements, a first category of materials including polyurethane, expanded polystyrene, rock wool, hemp wool, cellulose wadding, straw, semi-rigid wood

fiber, and rigid wood fiber has a result close to 2×10^{-5} kgSbeq/FU. The second category oscillates around 3×10^{-4} kgSbeq/FU and includes extruded polystyrene, glass wool, and hemp concrete. Table 2 summarizes the different averages for each of the materials.

3.2. Classification of the materials

The previous results allow for the classification of materials from the most to the least performant for each of the indicators (Table 3). The classification of materials is done through a scoring system. Each of the indicators is scored out of ten. The score corresponds to the division of the minimum value of the impact category by the value of the insulator in that category then the whole is multiplied by 10 (eq. 1). The formula used is as follows:

$$\text{Score} = \frac{\text{Minimum value of the category}}{\text{Value of the insulator's indicator}} * 10 \quad (\text{eq. 1})$$

where *Score*: score out of 10 of the insulator for the calculated impact category;

Minimum value of the category: minimum value of the impact category;

Value of the insulator's indicator: value of the insulator's indicator for the calculated impact category;

Through this calculation, the most performant material in the category is scored 10/10, a material that is twice less performant is scored 5/10, and a material ten times less performant will be scored 1/10. Due to the positive and negative results for the climate change indicator, the formula has been adapted to allow for the calculation.

Table 3. Score out of 10 for each material based on the indicator, total score, and ranking.

Insulation	Global warming potential (kg CO ₂ eq/FU)	Abiotic depletion potential – fossil fuel (MJ/FU)	Consumption of primary energy, non-renewable (MJ/FU)	Transport distances A4 (km)	Abiotic depletion potential – elements (x10 ⁻⁵ kg Sb eq/FU)	Total score /50	Ranking
Straw	10,00	10,0	10,0	10,0	7,1	47,1	1
Cellulose wadding	2,44	9,4	6,8	3,9	0,8	23,4	2
Expanded polystyrene	0,01	1,3	1,1	4,2	10,0	16,6	3
Rigid wood fiber	6,47	1,3	0,9	3,2	4,5	16,4	4
Hemp wool	1,17	4,3	3,6	4,4	2,5	16,0	5
Semi-rigid wood fiber	1,07	2,5	1,9	4,1	4,7	14,3	6
Glass wool	0,03	5,5	4,1	2,7	0,8	13,2	7
Polyurethane	0,01	1,4	1,3	3,4	6,9	12,9	8
Hemp concrete	3,11	0,9	0,7	4,8	0,3	9,8	9
Rock wool	0,01	0,9	1,3	3,0	2,0	7,3	10
Extruded polystyrene	0,01	1,1	0,7	3,0	0,3	5,1	11

4. Discussion

4.1. Discussion on the results

The good results of bio-based materials for the climate change indicator are relatively consistent with what was expected. Indeed, these materials are often minimally processed which limits the direct and indirect emissions of greenhouse gases during production. However, the results for hemp wool and semi-rigid wood fiber are surprising due to their poor performance (respectively 1.17 and 1.07/10). Glass wool is the most performant non-bio-based material. This is explained in particular by the use of recycled materials and a highly optimized process along with a low density. Finally, other insulators are poorly performant (below 1/10) which corresponds to the transformations undergone by these materials during production.

Concerning the depletion of fossil fuel resources, the results are relatively proportional to the climate change indicator due to the close link between the use of fossil fuels and greenhouse gas emissions. However, non-bio-based materials have better results and partly compete with bio-based materials. For example, the case of glass wool (3rd/11 materials). Polyurethane, extruded polystyrene, and expanded polystyrene (rated around 1.3/10) compete with rigid wood fiber (1.1/10) and hemp concrete (0.9/10). This result is explained by the fact that non-bio-based materials have a low density (between 10 and 50 kg/m³) and a good thermal conductivity (below 0.35 W/(m².K)). Therefore, not much material is needed to meet the functional unit (1m² of insulation with R = 5 m².K/W). These observations and explanations are similar for the indicator of total use of non-renewable primary energy resources. Consequently, the choice of the functional unit is questionable. Indeed, thermal resistance is the main indicator when comparing insulators. This indicator takes into account heat losses and thus winter energy consumption but does not allow for a good consideration of other characteristics like phase shift, thermal effusivity, or inertia of a material. However, these indicators allow for an understanding of summer comfort in addition to winter energy consumption. In view of the current and future rise in heat waves, modifying the functional unit to take into account summer comfort could be interesting but also modify the results of this study.

The results for transport distances correspond to the fact that most of the studied materials are manufactured in factories. Therefore, the material must be transported from the factory to the construction site. In this case, the nature of the material does not influence the result. Straw is an exception. Indeed, straw is handmade and often used locally.

Finally, considering these five indicators slightly modifies the result compared to a classification using only the climate change indicator. However, regardless of the classification, bio-based materials remain at the top of the ranking while non-bio-based materials are less well classified. Thus, this study shows that considering other indicators allows for a nuancing of the very good performance of bio-based materials in a single indicator-only ranking.

To conclude, the good ranking of bio-based materials was largely expected. However, we note three surprises in this ranking. The first is the good score of expanded polystyrene (due in particular to its score for the indicator of depletion of abiotic resources – elements). The second surprise is the ranking of hemp concrete. Even though lime (a component of hemp concrete) negatively impacts the rating, hemp concrete is 9th out of 11. The last surprise is the fact of having 6 insulators between 16.6 and 12.9/50. Thus, the ranking does not distinctly discriminate most of the insulators.

4.2. Comparison with the literature

Mostly, the results are consistent with the data from the literature. For the climate change indicator, cellulose wadding, hemp wool, semi-rigid wood fiber, glass wool, expanded polystyrene, and polyurethane have results close to what is found in the literature (Fig. 5). For extruded polystyrene and rock wool, the data from the literature are more disparate but our results fit within them. Our results for straw do not fit in with the data provided by the literature although the order of magnitude is respected (-41 kgCO₂eq/FU vs -29.3 et -27.85 kgCO₂eq/FU). Finally, our results for rigid wood fiber differ from those in the literature. Our value is 7 times greater than that of Oliva and Courgey and 2.2 times greater than The Construction Material Pyramid (respectively -25,7 kgCO₂eq/FU, -3,6 kgCO₂eq/FU et -11,75 kgCO₂eq/FU).

Concerning the total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) (MJ/FU), the results for cellulose wadding, straw, glass wool, polyurethane, expanded polystyrene, rock wool and extruded polystyrene are in agreement with the literature (Fig. 6). The result for hemp wool is lower than Oliva and Courgey. Conversely, semi-rigid wood fiber is almost twice as high (115 MJ/FU vs 208 MJ/FU) and rigid wood fiber is 70% higher (305 MJ/FU vs 518 MJ/FU). For the latter, a first explanation would be some aberrant points significantly increasing the average result.

In general, the discrepancies in results between different studies raise the question of the reliability of the data used for the life cycle analysis of these materials. As well for greenhouse gas emissions as for the embodied energy of materials, the results can vary from single to double.

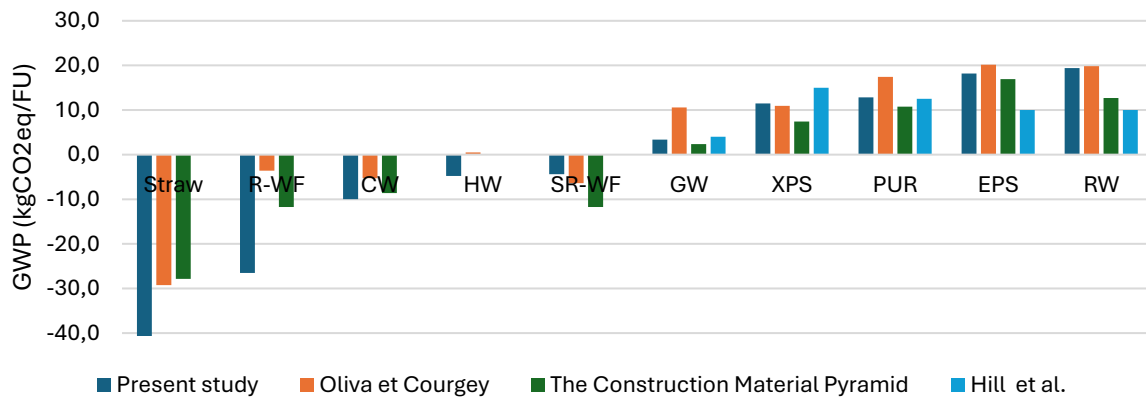


Figure 5. Comparison of different values of the climate change indicator according to the material (kgCO₂eq/FU). A lack of data prevents comparison of hemp concrete. Abbreviations as figure 3.

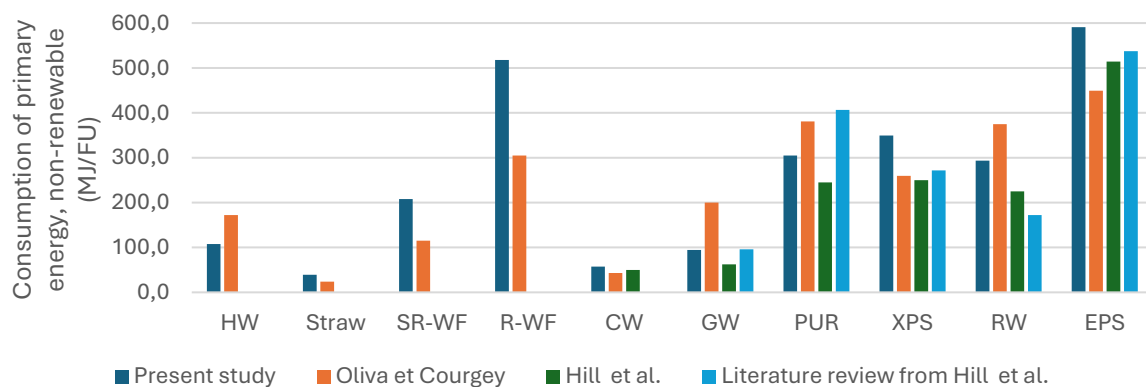


Figure 6. Comparison of different values of the indicator for the total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) (MJ/FU). A lack of data prevents comparison of hemp concrete. Abbreviations as figure 3.

4.3. Limits of the study

As previously mentioned, the low number of FDES for some materials does not allow for the smoothing of extreme data. For example, this is the case with hemp concrete where only one FDES corresponds to a clay-hemp mixture. Thus, the lime-hemp mixture is almost exclusively represented and consequently impacts the results.

The transport data in the production module (A2) of the LCA (Fig. 2) is not quantified in the FDES. However, this indicator is probably as important as the A4 data of the LCA. Indeed, the A2 data would enable for a better understanding of the dependence on fossil fuels but also of the sourcing of raw materials. The more significant the result of the A2 stage, the further the sourcing would be done, which would indicate the dependence on fossil fuels. This indicator could also be the gateway to an indicator on the resilience of sourcing. For example, Ulrich [18] reports a sourcing distance for wood fiber of

about 150 km. This distance should be greater for plastic-based insulators given the location of the extraction of the raw material.

An indicator allowing to determine the resilience of the value chain would be worth studying. Indeed, producing with a raw material close to the construction site (e.g., clay-hemp concrete) or the factory (e.g., wood fiber or cellulose wadding) is much more resilient than manufacturing insulators from raw materials coming from other countries, often located several thousand kilometers from the factory (e.g., oil for plastic-based insulators).

Finally, the study shows a real lack of consideration of the renewable nature of the raw material. The resource depletion indicator in the FDES does not highlight this renewable character. Thus, it would be necessary to add an indicator of resource consumption in terms of renewable material or simply an indicator of the valorization of renewable bio-based material.

5. Conclusion

The objective of this study was to classify insulating materials according to five indicators. These indicators respond to three future challenges: climate change, the reduction in energy supply, and resource depletion. Thanks to the data collected in the FDES from the French INIES database, the insulators were classified according to their performances. These results highlight bio-based materials and show the limits of non-bio-based materials. By taking into account these five indicators, the result is slightly different from a classification using only the climate change indicator. However, in both cases, bio-based materials remain the most performant. This study does not completely question the current classifications using only the climate change indicator but allows for a nuancing and further information of these classifications.

However, this work remains to be deepened. Indeed, certain gaps have been highlighted and deserve to be studied more deeply to confirm the results of this study.

Author Contributions: Conceptualization, methodology, formal analysis, investigation, writing-original draft preparation, writing-review and editing, discussion: MG. Writing-review and editing, discussion, supervision: BL and JPC. All authors have read and agreed to the published version of the manuscript.

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