TU Berlin
Whole Life Civil Systems Analysis

Assignment 2
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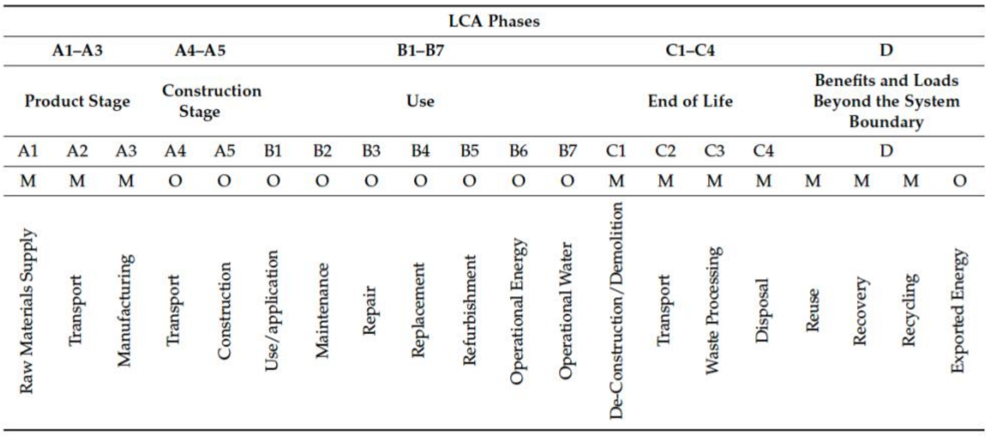
1. Introduction

The building industry plays an important role in reaching national and international sustainability goals. According to the European Commission (2012), approximately 40% of the EU's total energy use and 35% of its greenhouse gas emissions are attributed to the construction industry and building. In this context, insulation materials have grown in importance, as thermal insulation is essential in reducing the energy required for heating and cooling the buildings. This contributes to an overall reduction in energy need in the use phase of buildings (Schiavoni, et al., 2016).

Meanwhile, life cycle assessment (LCA) serves as a tool to assess the potential environmental impacts and resources utilised throughout a products life cycle from raw material acquisition, via production, use phase and waste management to the recycling stage (Liu, et al., 2024). As external thermal insulation composite systems (ETICS) are extensively adopted (Li, et al., 2014), it becomes clear that there is a growing need to understand how the choice of insulation materials impact the environment.

Table 1: Complete phases of a LCA analysis. M = mandatory, O = optional (Table from Asdrubali et al. (2023))



LCA Phases																			
A1–A3			A4–A5		B1–B7							C1–C4				D			
Product Stage			Construction Stage		Use							End of Life				Benefits and Loads Beyond the System Boundary			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D			
M	M	M	O	O	O	O	O	O	O	O	O	M	M	M	M	M	M	M	O
Raw Materials Supply	Transport	Manufacturing	Transport	Construction	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational Energy	Operational Water	De-Construction/Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Exported Energy

2. Goal and Scope of the Assignment

In this assignment, three different types of insulation materials are examined within an ETICS. All other system components are assumed to remain the same, that is, each system is attached to a masonry brick wall using an adhesive, with a base coat applied over the insulation layer followed by a finishing coat, as illustrated in Figure 2.

In the LCA, only the insulation materials were considered in order to isolate and better understand the specific environmental implications of material choice. A cradle-to-grave LCA approach was used, covering raw material extraction, production, transportation, installation, and end-of-life phases. From Module B (use phase), only maintenance and repair activities were included in this assignment to examine how their impacts accumulate when such interventions occur. There was not enough reliable data on the other parts of Module B—such as operational energy use or long-term degradation behaviour—to incorporate them meaningfully into the analysis.

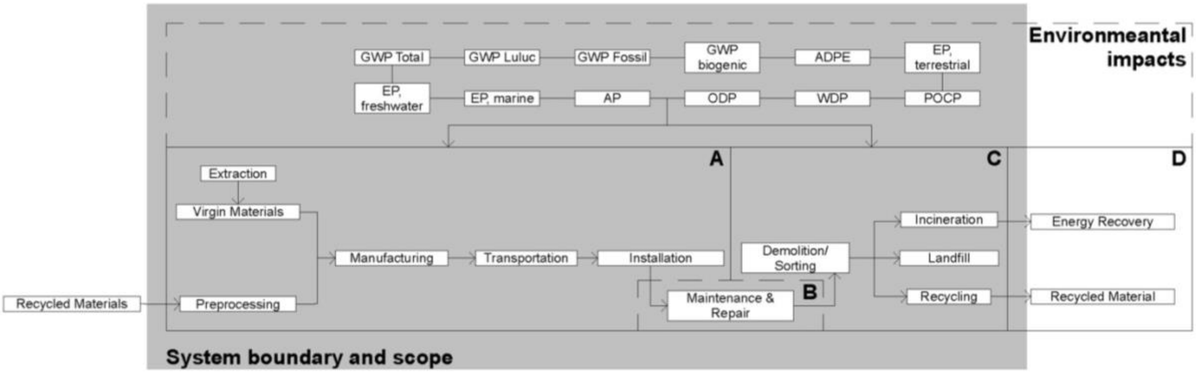


Figure 1: System boundary for insulation material and scope of assignment. Grey hatching defines system boundary (Data adapted from Cassione et al. (2025) and modified by author to include additional information relevant to this assignment)

For the LCA, the environmental performance of the insulation materials was assessed by analysing twelve environmental impact categories. These metrics provide a broad overview of each material's environmental impact. The table below summarises the categories and includes a brief explanation of what each one measures.

Table 2: Environmental impact categories, abbreviations, units and explanation (Data adapted from Baubook, Tingley et al. (2014) and Casione et al. (2025))

Impact category		**Unit**	**Explanation**
Global Warming Potential (GWP$_{100}$), Total	GWP Total	kgCO2$_{eq}$	The indicator "GWP-total" is the sum of GWP-fossil, GWP-biogenic and GWP-uluc. It is calculated automatically in baubook. The global warming potential is given for a time horizon of 100 years.
Global Warming Potential (GWP$_{100}$), Land Use and Land Use Change	GWP Luluc	kgCO2$_{eq}$	The GWP luluc takes into account greenhouse gas emissions and bonds (CO2, CO and CH4) that arise in connection with changes in the specified carbon stock as a result of land use and land use change. The contributions of greenhouse gases are given over a time horizon of 100 years.
Global Warming Potential (GWP$_{100}$), Fossil	GWP Fossil	kgCO2$_{eq}$	The GWP fossil indicator takes into account the GWP of greenhouse gas emissions and sequestration in all media resulting from the oxidation or reduction of fossil fuels or fossil carbon containing substances (e.g. combustion, landfilling, etc.). This indicator also includes the binding or emission of greenhouse gases in inorganic materials (e.g. calcination, carbonation of cement- or lime-based building materials). The contributions of greenhouse gases are given over a time horizon of 100 years.
Global Warming Potential (GWP$_{100}$), Biogenic	GWP biogenic	kgCO2$_{eq}$	The 'GWP-biogenic' indicator takes into account the amount of CO2 absorbed from the atmosphere during the growth of biomass and bound over the lifetime of the material, as well as biogenic emissions into the air through oxidation or decomposition of biomass (e.g. combustion). Transitions of biogenic carbon from previous product systems to the product system under investigation or transitions to subsequent product systems (e.g. in wood recycling) must also be taken into account.
Abiotic Depletion Potential for Elements	ADPE	kg Sb eq	Abiotic depletion potential (ADP) is defined as a measure of the use of nonrenewable sources for energy production, assessed in LCAs. It quantifies the life cycle use of antimony and its equivalents per capita per year relative to the annual sustainable allocation of antimony.

Eutrophication, Terrestrial	EP terrestrial	molc N eq	Based on accumulated exceedance, assessment of soil and atmospheric conditions and accounts for sensitivities of biodiversity in different areas.
Eutrophication, Freshwater	EP freshwater	kg P eq	Estimates nutrient concentrations that have transferred to a freshwater aquatic environment, focussing on phosphorous.
Eutrophication, Marine	EP marine	kg N eq	As above, but focuses on marine aquatic environments, assessing nitrogen equivalent concentrations.
Acidification	AP	molc H+eq	Based on accumulated exceedance, this includes atmospheric transportation and deposition of emissions whilst accounting for vulnerabilities of different ecosystems.
Ozone depletion	ODP	kg CFC11 eq	Ozone depletion potentials (ODPs) from the World Meteorological Organisation used to convert gases to CFC-11 equivalent.
Water Use	WPD	m^3	Considers water use and relates this to local scarcity.
Photochemical ozone formation	POCP	kg NMVOC eq	Emissions that cause increasing ozone concentration in the troposphere are characterised to Non-Methane Volatile Organic Compounds eq. Low level ozone can damage vegetation and cause impacts on human health.

3. Design Options

For the evaluation, a functional unit of 1 m × 1 m was defined, with a target thermal transmittance (U-value) of 0.15 W/m²K for the insulation layer. The thickness of each insulation material was adjusted accordingly to achieve equivalent thermal performance across all three variants, ensuring that the comparison focuses solely on environmental impacts rather than differences in energy efficiency. The environmental impact data (Casione, et al., 2025) used in the assessment are therefore based on these adjusted thicknesses, providing a consistent basis for comparison between the materials.

The three insulation materials investigated are mineral wool (MW), expanded polystyrene (EPS) and wood fibre insulation. As mentioned before,

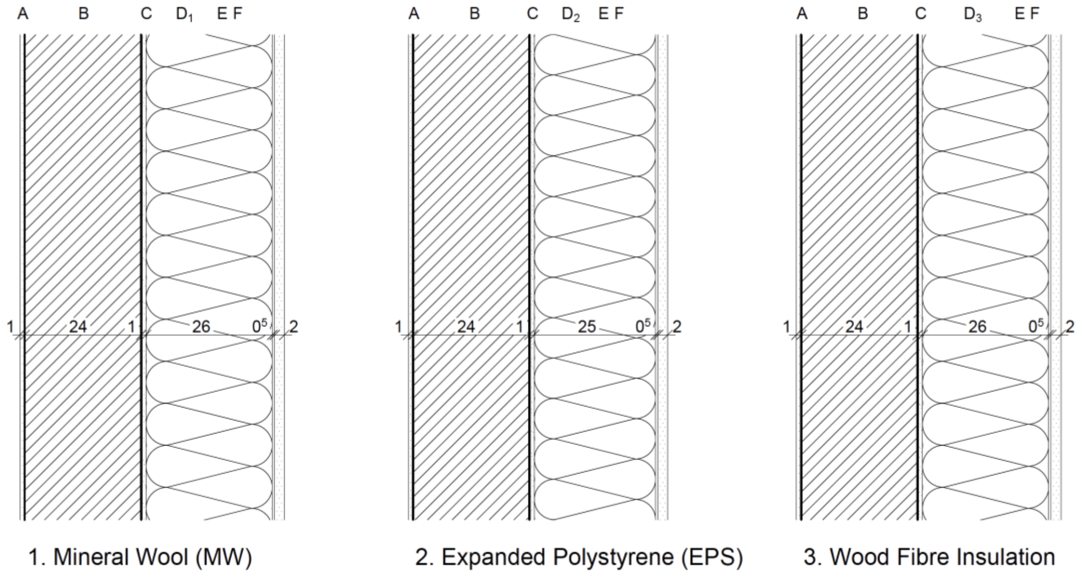


Figure 2: Three design options of ETICS

Table 3: Cross section of ETICS design options

Design Option		Material	Thickness [m]
	A	Interior Plaster	0.01

	B	Masonry	0,24
	C	Adhesive	0,01
Option 1	D_1	Mineral Wool (MW)	0,16
Option 2	D_2	Expanded Polystyrene (EPS)	0,14
Option 3	D_3	Wood Fibre Insulation	0,20
	E	Base Coat	0,005
	F	Finishing Coat	0,02

4. Life Cycle Inventory

In the study by Casione et al. (2025), several scenarios were developed for each material to account for factors such as manufacturing location and end-of-life treatment, both of which can significantly influence the overall environmental impact. Longer transport distances between the production site and installation increase emissions and energy consumption, while the chosen end-of-life pathway, whether 100% recycling, 100% incineration, or 100% landfill, introduces its own distinct environmental implications. Maintenance and repair influences were not included in their analysis due to inconsistent data regarding installation practices, repair cycles, and maintenance requirements.

In this assignment, two scenarios were evaluated, a best-case and a worst-case scenario while including additional emissions and imacts due to maintenance, to capture the range of possible environmental impacts. The best-case scenario represents optimal conditions, while the worst-case scenario was used to assess the upper bound of environmental impacts and to better understand potential trade-offs and limitations of each insulation material produced in less favorable conditions.

Table 4: Worst Case: environmental impacts for the insulation material of each design option (Data adapted from Casione (2025))

Material	**GWP Total**	**GWP Luluc**	**Gwp Fossil**	**GWP biogenic**	**ADPE**	**EP, terrestrial**	**EP, freshwater**	**EP, marine**	**AP**	**ODP**	**WDP**	**POCP**
Unit	kgCO2$_{eq}$				kg Sb eq	molc N eq	kg P eq	kg N eq	molc H+eq	kg CFC11 eq	m^3	kg NMVOC eq
MW	193.5E+0	41.2E-3	193.1E+0	467.1E-3	1.7E-3	3.6E+0	20.6E-3	303.6E-3	1.2E+0	34.6E-6	985.8E+0	956.0E-3
EPS	110.2E+0	12.0E-3	109.6E+0	631.7E-3	241.5E-6	1.1E+0	5.2E-3	103.2E-3	368.1E-3	9.5E-6	330.4E+0	336.1E-3
Wood Fibre Insulation	371.8E+0	248.5E-3	342.1E+0	35.3E+0	1.8E-3	6.1E+0	34.4E-3	633.7E-3	1.8E+0	60.0E-6	1.2E+3	1.7E+0

Table 5: Best case: environmental impacts for the insulation material of each design option (Data adapted from Casione (2025))

Material	**GWP Total**	**GWP Luluc**	**Gwp Fossil**	**GWP biogenic**	**ADPE**	**EP, terrestrial**	**EP, freshwater**	**EP, marine**	**AP**	**ODP**	**WDP**	**POCP**
Unit	kgCO2$_{eq}$				kg Sb eq	molc N eq	kg P eq	kg N eq	molc H+eq	kg CFC11 eq	m^3	kg NMVOC eq
MW	1.09E+01	4.00E-03	1.09E+01	3.16E-02	8.35E-05	1.63E-01	3.40E-03	9.30E-03	1.00E-01	8.22E-07	1.90E+03	4.89E-02
EPS	1.70E+01	1.10E-03	1.68E+01	1.68E+01	6.05E-05	9.47E-02	8.95E-04	8.90E-03	5.69E-02	3.97E-07	1.40E+03	5.11E-02
Wood Fibre Insulation	2.16E+01	3.29E-02	2.14E+01	9.63E-02	2.92E-04	2.63E-01	1.21E-02	2.59E-02	1.42E-01	1.40E-06	1.20E+03	8.92E-02

According to a report by the Fraunhofer Institute for Building Physics (IBP) (Krus, et al., 2023), an inspection of ETICS is recommended every 10 years. In their field study, coating maintenance, typically involving the application of a new paint layer, was carried out around 30 years after the initial installation. In some cases, ETICS systems also received an additional or doubled insulation layer. When this occurred, a new outer coating was required as well, meaning both measures were performed simultaneously. These interventions were implemented less frequently and on a case-by-case basis, usually to improve energy performance or meet updated regulatory requirements.

Table 6: Frequency of intervention and service life of each ETICS design option (Data adapted from Krus et al. (2023))

Material	Event	Frequency	Service Life
Mineral Wool (MW)	Inspection	10	60
Mineral Wool (MW)	Additional Insulation	30	60
Mineral Wool (MW)	Coating Maintenance	30	60
Expanded Polystyrene (EPS)	Inspection	10	60
Expanded Polystyrene (EPS)	Additional Insulation	30	60
Expanded Polystyrene (EPS)	Coating Maintenance	30	60
Wood Fibre Insulation	Inspection	10	60
Wood Fibre Insulation	Additional Insulation	30	60
Wood Fibre Insulation	Coating Maintenance	30	60

Based on the table, the following graphs were illustrated.

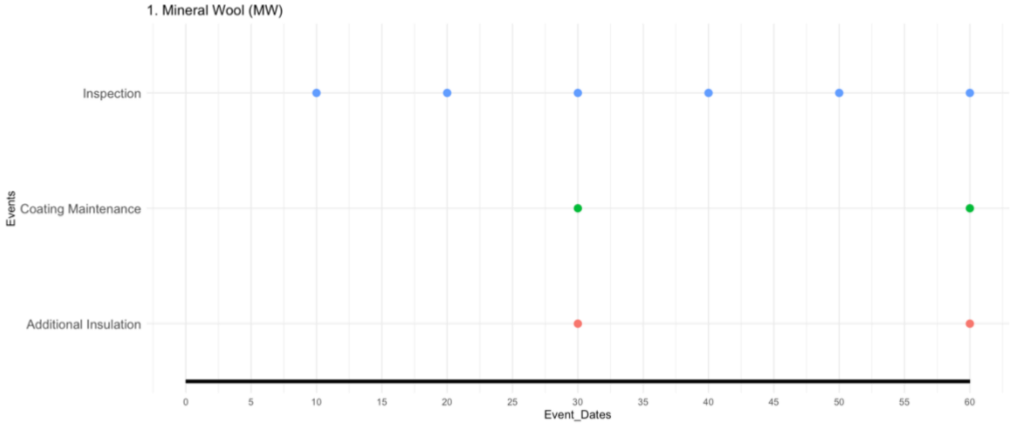


Figure 3: Service life, frequency of maintenance of the ETICS design option 1, mineral wool (MW)

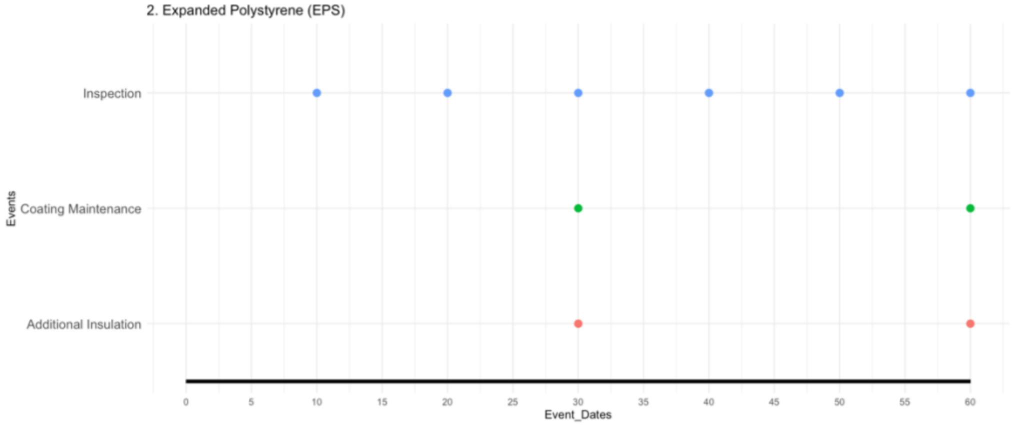


Figure 4: Service life, frequency of maintenance of the ETICS design option 2, expanded polystyrene (EPS)

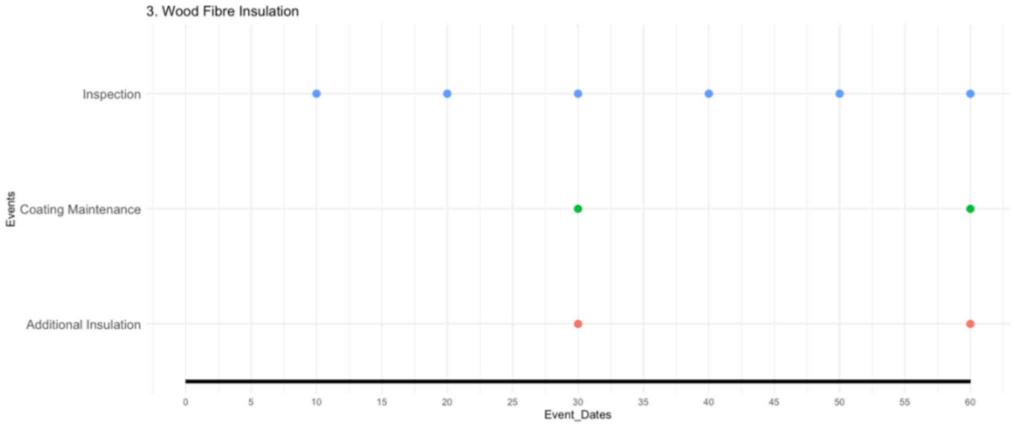


Figure 5: Service life, frequency of maintenance of the ETICS design option 3, wood fibre insulation

5. Life Cycle Results and Analysis

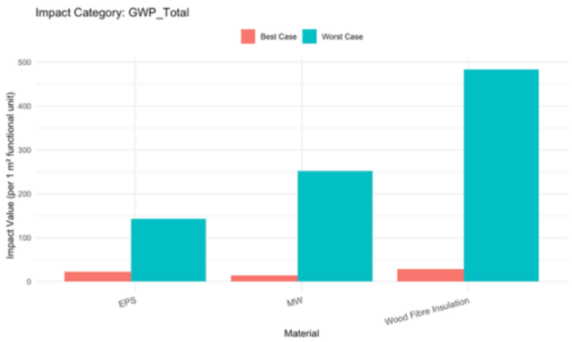
After taking into consideration the impacts of maintenance and repair, the following graphs illustrate the best- and worst-case results for each individual environmental impact category and design option. For this assignment, a 30% increase in emissions was added as an assumption to account for maintenance interventions at the 30 year time point. This reflects the idea that additional insulation layers do not require the same material thickness as the original installation. It can be observed that the differences between the two scenarios vary significantly across the impact categories. As discussed earlier, these variations are largely influenced by several factors, including the geographical origin of production, density of raw materials, transportation distances, and the type of energy used in processing and manufacturing.

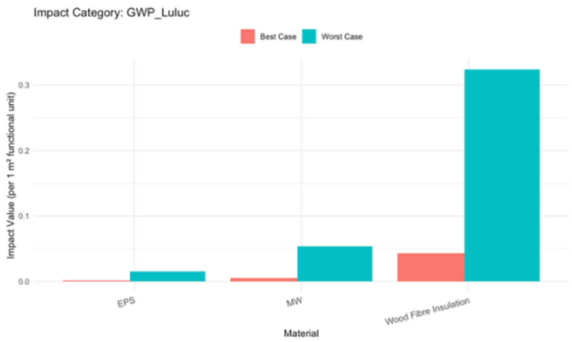
The density of the materials plays a particularly important role, as higher-density products generally require greater quantities of raw materials and higher energy input during production. For instance, in the case of the Global Warming Potential (GWP Total), the worst-case scenario for wood fibre insulation shows a higher impact than that of mineral wool (MW) and expanded polystyrene (EPS). Although this may initially appear counterintuitive, it can be explained by the relatively high density of timber-based boards, which increases the amount of raw resources and energy required during their manufacture (Casione, et al., 2025) to transform into low density insulation material.

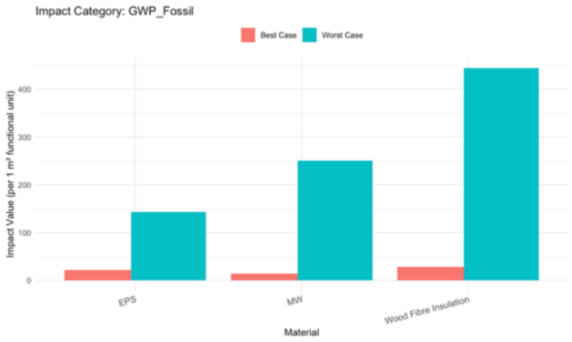
Transportation distance and mode also have a major influence on the results. Shipping typically has the lowest impact due to the large quantities of goods that can be transported per trip compared to other means. However, depending on the origin and distance to the construction site, transportation can significantly affect all impact categories. Similarly, the composition of the local energy grid plays a critical role, as different modes of electricity generation carry varying levels of fossil carbon emissions.

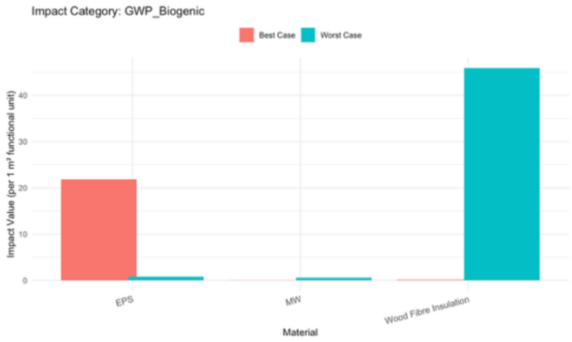
End-of-life treatment further contributes to the overall environmental performance. For example, EPS exhibits a much higher impact when incinerated rather than landfilled, due to the combustion of the polymer component, which releases carbon dioxide and nitrous oxide. In contrast, mineral wool has the lowest end-of-life impact, as it is inert and does not emit gases.

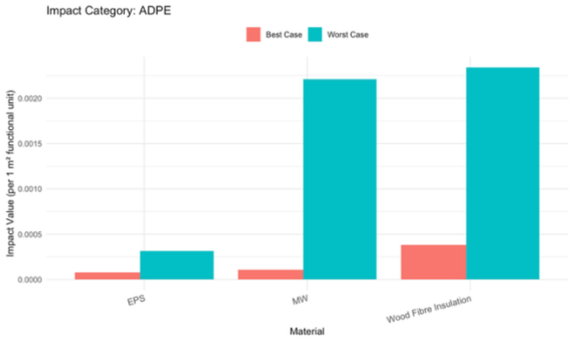
On the other hand, the benefits of wood fibre insulation are not fully reflected in the results. According to EN 15084 (2012) + A2 (2019), all sequestered biogenic carbon is assumed to be released back into the environment at the end of life, regardless of whether the material is disposed of or recycled. In the calculation of GWP Total, biogenic carbon storage is therefore set to zero across Modules A to C and released entirely at the end-of-life stage. As a result, the carbon temporarily stored in wood fibre is not accounted for in the assessment, which means that its potential advantages are not captured. This causes wood fibre insulation to appear less favourable on paper compared to the other materials, despite its renewable origin and carbon-storage capacity.

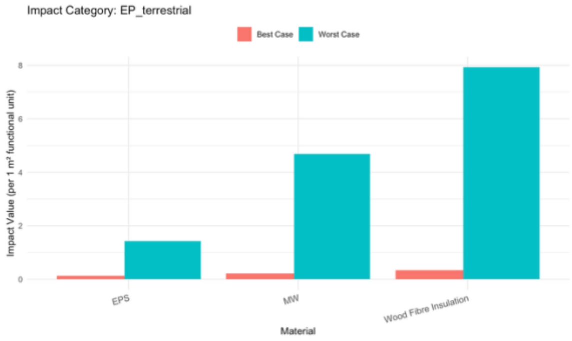

Impact Category: GWP_Total

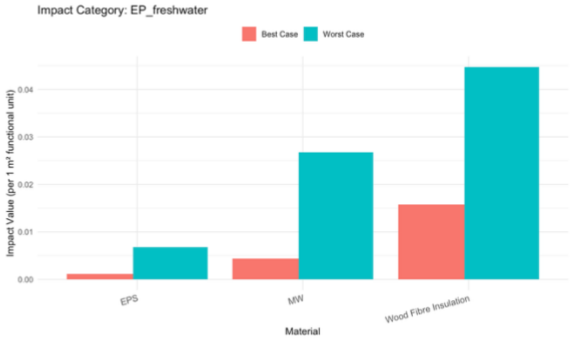

Impact Category: GWP_Luluc

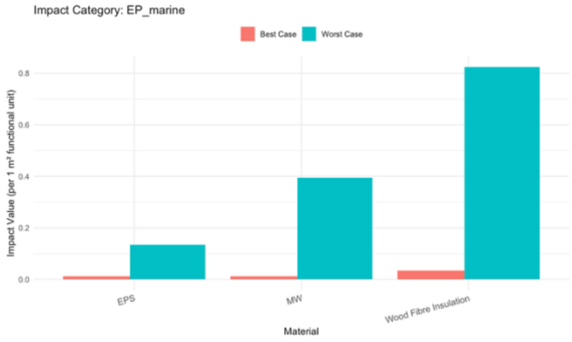

Impact Category: GWP_Fossil


Impact Category: GWP_Biogenic


Impact Category: ADPE


Impact Category: EP_terrestrial


Impact Category: EP_freshwater


Impact Category: EP_marine

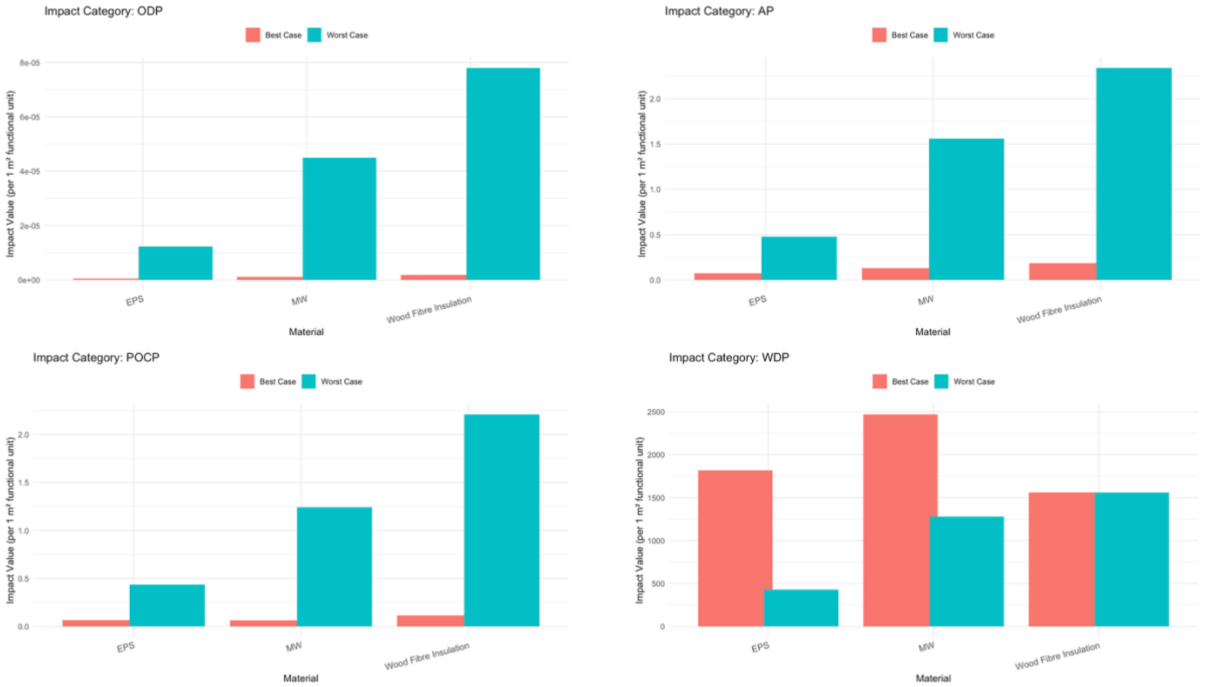


Figure 6: Environmental impact categories of the three insulation materials

Eutrophication potential (EP) is noticeably higher for wood fibre insulation in the worst-case scenario, primarily due to the use of fertilisers during the cultivation of the raw materials. Agricultural processes involved in growing timber or other biomass contribute nutrients such as nitrogen and phosphorus to soil and water systems, which can lead to eutrophication in surrounding ecosystems. Similarly, the Water Depletion Potential (WDP) for wood fibre insulation is also elevated, as the cultivation and processing of bio-based materials often require substantial amounts of water for irrigation, cleaning, and pulp preparation. While wood fibre offers advantages in terms of renewable sourcing and carbon storage, these results highlight that bio-based materials are not free from environmental trade-offs. Their life cycle impacts extend beyond carbon emissions and must also account for land and water resource use.

6. Other Metrics to Consider

Highlighted by Cassione et al. (2025), considering the temporal distribution of environmental impacts also allows for a more realistic understanding of a material's long-term influence on the environment. Wood fibre, due to its bio-based nature, can initially offset fossil carbon emissions from manufacturing through carbon sequestration. This gives wood-based insulation an advantage in the short term, as it temporarily stores carbon that would otherwise contribute to atmospheric greenhouse gases.

However, the benefits of carbon sequestration depend heavily on what happens at the end-of-life stage. If the carbon stored in wood fibre insulation is released during disposal, such as through incineration, the long-term advantage diminishes. Cassione et al. showed that when sequestration is retained through recycling or reuse, the long-term radiative forcing and temperature impacts remain lower than those of non-renewable materials.

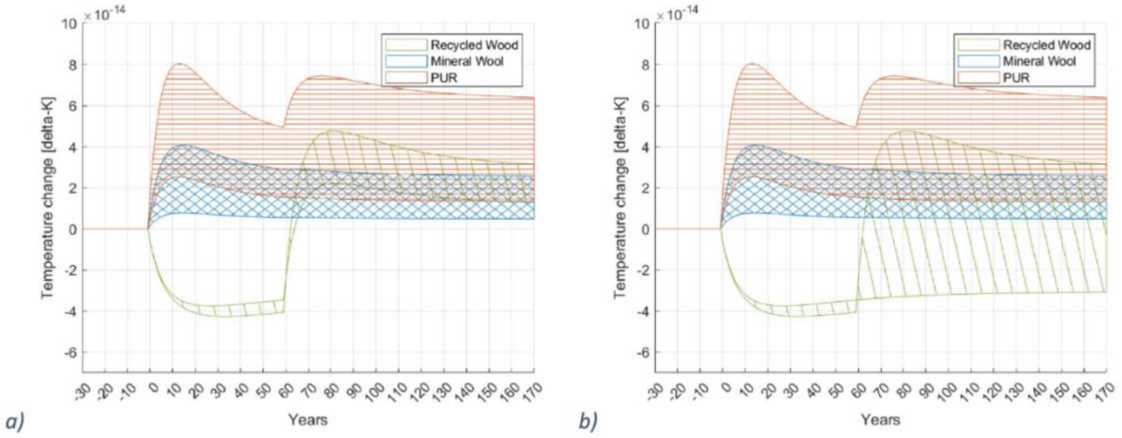


*Figure 7: Comparison of the temperature change of recycled wood fibre, mineral wool, and PUR **a** without carbon sequestration and **b** with carbon sequestration (Figure from Casione et al. (2025))*

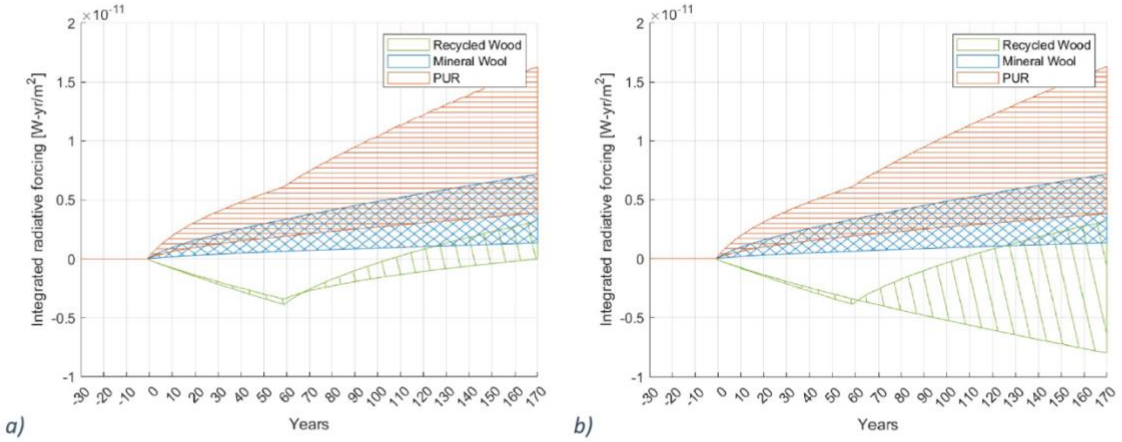


*Figure 8: Comparison of the radiative forcing of recycled wood fibre, mineral wool, and PUR **a** without carbon sequestration and **b** with carbon sequestration (Figure from Casione et al. (2025))*

In contrast, EPS and MW show different temporal patterns. EPS, being a fossil-based material, contributes more directly to greenhouse gas emissions, particularly during end-of-life incineration, which significantly increases temperature forcing due to CO_2 and N_2O release. Mineral wool, on the other hand, remains more stable over time, with low end-of-life impacts since it is largely inert and does not release gases after disposal.

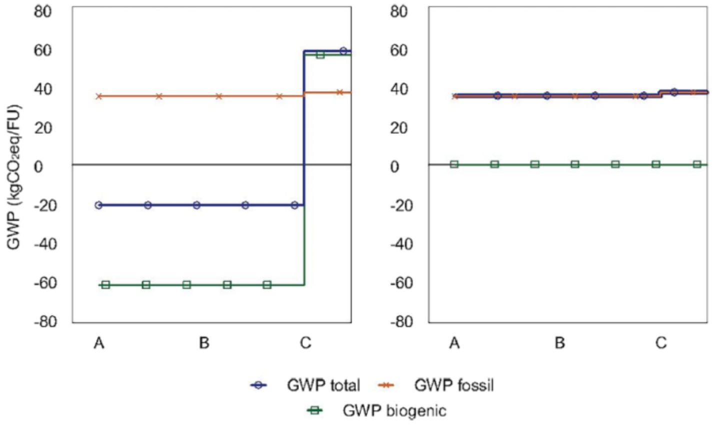


Figure 9: Cumulative GWP distribution over time for recycled wood (left) and PUR (right) (Figure from Casione et al. (2025))

Looking at the temporal distribution of environmental impacts, wood fibre insulation performs best in the short term due to its capacity for carbon storage, its long-term environmental performance largely depends on sustainable end-of-life management. Although the figures presented in the study do not exactly correspond to the design options analysed here, they effectively illustrate the significant differences between bio-based and non-renewable insulation materials.

7. AHP Analysis

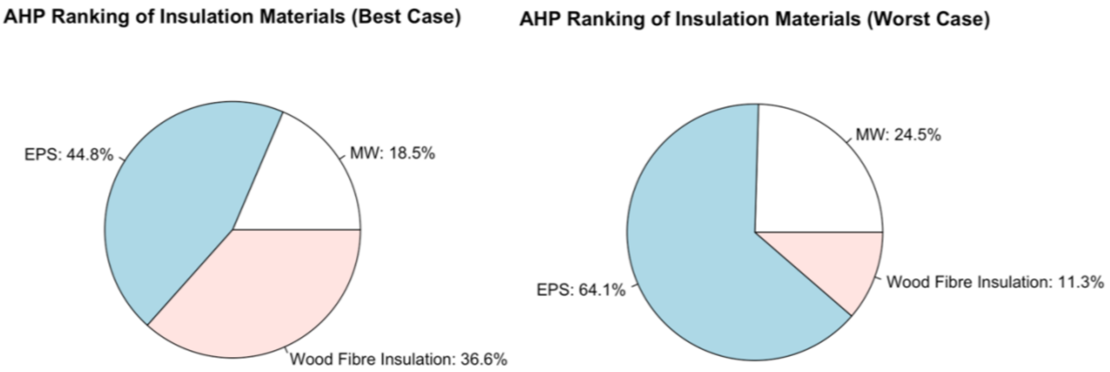


Figure 10: Comparison of AHP ranking of ETICS design options for best- and worst-case

For the AHP analysis, all environmental impact categories were given equal weight (value of 1), meaning each category was treated as equally important. Only the 12 environmental impact categories were included in the assessment. The results show a clear difference between the best- and worst-case scenarios. In the worst case, EPS ranked highest with a score of 64.1%, while wood fibre insulation performed the worst at 11.3%. Under the best-case scenario, EPS remained the top option at 44.8%, but wood fibre insulation followed closely at 36.6%, with MW ranking last at 18.5%. These findings highlight the complexity of comparing environmental performance, as the relative ranking of materials can change significantly depending on assumptions such as production conditions, energy sources, and end-of-life treatment.

8. Conclusion

According to the AHP results, EPS and MW appear to perform better than wood fibre insulation across the selected impact categories. However, this outcome is strongly influenced by the structure of the LCA and the assumptions that underpin it. As discussed earlier, the advantages of bio-based materials, such as carbon sequestration are not fully captured in conventional LCA methodologies. Current calculation rules and standards typically treat stored biogenic carbon as being released at end-of-life, which limits the visibility of long-term environmental benefits in bio-based options like wood fibre.

The final ranking is also highly dependent on the criteria selected for the analysis. Depending on which environmental indicators are prioritised, whether global warming potential, resource depletion, water use, or toxicity, the relative performance of materials can shift noticeably. Weighting these categories differently, or reducing the importance of certain impacts, can substantially influence the AHP outcome. This shows that sustainability assessments inevitably include value-based decisions: what we choose to measure, and how much importance we assign to each metric, directly shapes the result.

Adjusting the weighting to reflect project-specific priorities could therefore lead to a different ranking and potentially highlight other materials as more favourable.

In this analysis, EPS performed best across the twelve equally weighted impact categories, followed by MW. When temporal dynamics or carbon storage are not considered, wood fibre consequently appears less favourable. However, once long-term effects and sequestration are accounted for, the comparative advantage of fossil-based insulation materials becomes less clear, suggesting that regulatory frameworks and methodological boundaries can significantly influence the perceived sustainability of different materials.

From a design and decision-making perspective, these results underscore the importance of not only comparing numerical outcomes but also understanding the context in which they are produced—how materials are sourced, manufactured, transported, and assessed. As Füchsl et al. (2022) note, transparency in assumptions and system boundaries is essential to ensure that LCA results are interpreted correctly and support genuinely sustainable material choices.

9. Works Cited

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