COMPARATIVE LCA STUDY OF THERMAL INSULATION MATERIALS FOR INDUSTRIAL AND CONSTRUCTION APPLICATIONS

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Summary

The purpose of the study is a systematic comparative life cycle analysis (LCA) of the most common thermal insulation materials in the context of residential and industrial construction in Ukraine and the EU countries. The LCA methodology was applied in accordance with ISO 14040/44 standards (including a "cradle-to-grave" assessment with a functional unit, for example, 1 m² of wall with a certain heat transfer resistance). The materials considered were: mineral wool (stone, glass), expanded polystyrene (EPS, XPS), polyurethane foam (PUR/PIR), cellulose insulation, aerogels and other bio- or recycled insulation materials (wood fibers, flax, etc.). The methodology involves comparing environmental indicators (in particular, GWP - global warming potential, ADP - mineral depletion potential, ODP - ozone depletion potential) based on data from literary sources and EPD. The results show that natural and recycled insulation materials (cellulose, wood or hemp fibers) usually have the lowest GWP and CED values due to the use of renewable resources and carbon sequestration, although additives (boron compounds) can increase ADP. Plastic foams (EPS, XPS, PUR) demonstrate the highest environmental impacts (especially GWP and energy consumption) due to petroleum raw materials and energy-intensive production. Mineral wool is an intermediate option: among all insulation materials, it consumes the least primary energy for production, and its emissions are moderate. Aerogels, despite their unique thermal insulation properties, require significant energy resources and chemical precursors during production, which leads to very high GWP and ADP values. The scientific novelty lies in the comprehensive generalization of current LCA studies of insulation materials, including promising materials and the specifics of Ukrainian conditions. Theoretical significance – combining engineering analysis with environmental criteria, forming systematic recommendations for the selection of insulation materials. Practical significance – helping engineers and politicians assess the joint energy and environmental consequences of using different insulation solutions in construction, in particular during reconstruction and reconstruction in Ukraine (taking into account recycling and circular economy).

Key words: Thermal insulation; life cycle assessment (LCA); energy efficiency; global warming potential (GWP); building materials; sustainable development.

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1. Introduction

Thermal insulation of buildings is a key factor in energy saving and reducing CO_2 emissions in the construction sector, since it is through the enclosing structures (walls, roofs, floors) that a significant share of heat loss is formed, which directly affects the amount of fuel and electricity consumption during the operation of buildings. At the level of the European Union, this issue is systemic: buildings account for about 40% of energy consumption in the EU, and therefore increasing the energy efficiency of the existing stock is considered one of the basic tools for achieving climate goals and reducing dependence on fossil fuels *(European Commission, nd).* In addition, the European Commission emphasizes that buildings are also associated with significant greenhouse gas emissions, which are formed not only during use, but also during the construction, reconstruction and dismantling stages *(European Commission, 2020).* Accordingly, the traditional logic of "energy conservation at any cost" is no longer sufficient: increasing thermal insulation must be accompanied by evaluating materials according to environmental and resource criteria in order to avoid a situation where reducing operating energy costs is achieved at the expense of excessive "built-in" environmental load in materials.

That is why modern studies increasingly mention the life cycle assessment (LCA) of thermal insulation materials, which allows you to cover the full chain (from raw material extraction to disposal) and compare alternatives according to a set of standardized impact categories. Unlike indicators of thermal conductivity, layer thickness, price, etc., LCA allows you to assess system effects. These include: carbon footprint of production, energy intensity of technologies, environmental consequences of transportation, installation losses, as well as end-of-life scenarios, etc. The studies that were considered for writing the work show that the results of LCA for different types of thermal insulation materials can differ significantly - primarily due to different methodological assumptions. Despite this, common trends can be traced in many publications. For example, polymer foams (EPS/XPS, PUR/PIR) often exhibit higher environmental impacts at the production stage, while bio-based and recycled materials often have lower GWP values and more favorable profiles across a number of impact categories *(Füchsl et al., 2022).* This shows that it is necessary not to simply choose any insulation material, but to formulate clear criteria for its selection, which simultaneously take into account its thermal efficiency, environmental feasibility and rational use of resources.

For Ukraine, this problem is of particular importance in the context of war and the constant need to rebuild and restore destroyed buildings. And with constant reconstruction, the question of finding high-quality materials and effective solutions for the successful completion of such a long process also arises. On the one hand, energy-efficient solutions are a tool for increasing the resilience of the housing and business sectors to energy risks, and on the other hand, this type of construction creates significant costs due to large volumes of construction materials and waste. That is why in this context, integrated approaches are becoming particularly relevant, within which energy policy, natural resource management and financial security are considered as interrelated components of sustainable development and key guidelines for decisions in the construction sector *(Petrukha et al., 2025).* Accordingly, it is advisable to choose thermal insulation materials not only based on thermal conductivity or technological convenience, but also taking into account their life cycle, circularity potential, availability of recycling, logistical constraints and environmental risks.

This review focuses on a comparative analysis of the most common insulation materials in the context of residential and commercial buildings in Ukraine and the EU. Mineral wool (stone and glass), expanded polystyrene (EPS, XPS), polyurethane foams (PUR/PIR), cellulose insulation, modern biomaterials (wood, flax, hemp fibers) and aerogels are considered. The methodological basis for the assessment is the requirements of ISO 14040/44, which regulate the sequence of LCA performance and the approach to comparative comparisons. Given the different physical and technical characteristics of insulation materials, the principle of comparison by equivalent thermal insulation function (for example, a unit of area of the structure that provides a given heat transfer resistance) was adopted as the functional basis for comparison, since it is this approach that allows us to translate different materials into a common "applied dimension" and form correct conclusions for design practice and thermal modernization policy *(Füchsl, 2022).*

2. Literature Review

The literature shows that LCA results for different insulation materials are mixed. A comprehensive review by Füchsl et al. (2022) analyzed 47 LCA studies of insulation materials and found patterns: EPS, rock wool and glass wool have similar lifetime impacts, while XPS and PUR/PIR have generally higher impacts than most. At the same time, materials based on renewable raw materials (cellulose, wool, wood, etc.) usually show a reduction in impacts (primarily GWP), although this does not guarantee better results for all indicators. *(Füchsl et al., 2022)*

Comparative LCAs from European studies support these findings. Schmidt et al. (2004) compared stone wool, flax and recycled cellulose paper wool for roof insulation. In their analyses, they found that cellulose paper wool had the lowest global and regional impacts, while flax had the highest, with stone wool occupying an intermediate position. In particular, based on the LCA, the authors indicated that stone wool required the lowest total energy to produce, while flax had the highest energy costs. Similar patterns have been observed in more recent studies. Schulte et al. (2021) evaluated “bio” and traditional insulation materials in Germany. They confirmed that wood and grass fibers (e.g., wood fiber, miscanthus) are generally the “greenest”, outperforming EPS and rock wool in most categories (11 out of 18). This is due to lower CO_2 emissions during production and the retention of biogenic carbon. *(Schmidt et al., 2004; Schulte et al., 2021)*

On the other hand, LCA studies of plastic insulations show significantly higher emissions. For example, for EPS, it was found that almost 99.7% of the global warming potential (GWP) is formed precisely at the production stage - through raw materials and energy consumption *(Lim et al., 2021).* Taking into account recycling can significantly reduce the total impact of EPS, but widespread implementation of recycling requires developed infrastructure and economically justified technologies *(Lim et al., 2021).* At the same time, XPS and PUR/PIR usually have an even higher environmental impact, since their production is associated with energy-intensive synthesis from petrochemical raw materials and the use of blowing agents, which can increase ODP and other indicators *(Füchsl et al., 2022; Lim et al., 2021).*

New materials are of particular interest. Aerogels, due to their extremely low thermal conductivity, are promising as ultrathin insulation materials, but their “solvogenic” and supercritical drying technology is energy-intensive. Analysis by Jiang et al. (2023) showed that the GWP of aerogels can range from a few units to several thousand kg CO_2 eq/unit. The main driver is the energy consumption for drying and chemical precursors (e.g. sodium silicate, which significantly increases ADP). Thus, LCAs of aerogels indicate their high environmental “dark bill” in the production phase, which currently limits their widespread use *(Jiang et al.,2023; De Marco et al. 2019).*

For the Ukrainian context, one study highlights the problem of accumulation of insulation materials in construction waste. They note that among the most common materials – EPS, XPS, PUR, mineral wool, glass foam, etc. – a significant part of the complex secondary raw materials can be reused or recycled. In their comparison of products, glass foam turned out to be the most acceptable from an ecological point of view: its processing requires little energy and creates the least pollution. Therefore, in Ukraine and nearby climatic regions, it is worth taking into account not only the thermal, but also the environmental performance of materials *(Khalieiev et al., 2025).*

According to the ISO 14040/44 analysis, the following main impact categories are used to compare insulation materials: global warming potential (GWP), mineral depletion potential (ADP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), and energy consumption (CED). The data from the literature LCA studies vary in detail, but generally confirm the fact that biomaterials have the lowest GWP, foams have the highest, and mineral wools have intermediate values with low energy consumption. *(Valentini et al., 2025; Turhan et al., 2024; Füchsl et al., 2022; Schmidt et al., 2004).*

3. Problem Statement

The main problems of comparative LCA analysis of thermal insulation materials are the lack of a consistent, representative and comparable dataset for Ukrainian and EU conditions, as well as the high variability of results between sources. In practice, different studies use different functional units (FUs), system boundaries (cradle-to-gate, cradle-to-site, cradle-to-grave), transportation scenarios, installation losses, end-of-life modeling approaches and different sets of impact categories. This creates methodological "noise" when materials are compared not by the same function (same thermal resistance/thermal performance), but by mass or thickness, which leads to incorrect conclusions. An additional difficulty is the uneven quality of inventory data (LCI): some works rely on general or outdated databases, do not take into account specific formulations (for example, the type of foaming agent in XPS or the composition of binders in mineral wool), and also use different allocation methods for recycling, incineration and reuse. As a result, even for the same materials, GWP/ADP/ODP indicators can differ significantly, which makes it difficult to form unambiguous rating conclusions and practical recommendations.

For Ukraine, the comparability problem is exacerbated by the lack of localized data. A significant part of insulation is imported or produced from imported raw materials, and the life cycles of such products depend on the technological profile of the country of origin, logistics and customs and warehousing operations. At the same time, the national specifics of the energy mix (including emergency modes of the power system) and differences in heat supply structures and tariff policies can change the "relative profitability" of different materials, taking into account the operational phase and energy saving potential. A separate challenge is the lack of open environmental product declarations (EPDs) made according to the same product category rules (PCR), which limits the ability to form an evidence base for the selection of materials in public procurement and reconstruction projects. Because of this, in practice, decisions are often made on the basis of cost and availability, rather than overall environmental efficiency.

A specific and also very significant factor for Ukraine is the impact of destruction caused by military actions and strikes on construction waste flows and the quality of secondary raw materials. The destruction of buildings increases the volume of mixed waste, in which thermal insulation materials are often contaminated with plasters, adhesives, structural fragments and combustion products. This significantly complicates sorting, reduces the share of material suitable for recycling, and increases the cost of recovery - because additional energy is required for cleaning, transportation and further processing. Under such conditions, landfilling or incineration of mixed waste streams is most often used. The reason for this is that it can negate the potential benefits of materials that, in theory, have high recyclability. Therefore, for Ukraine, the assessment of the final stage of the life cycle should be based on separate scenarios that reflect real waste management practices and the actual capabilities of the recycling infrastructure *(Khalieiev et al., 2025).*

An additional problem is the integration of changes in energy infrastructure into LCA assessments. In the EU, there is a gradual decarbonization of the electricity sector and an increase in the share of renewable sources, which over time reduces the “carbon footprint” of the production phase of many materials, especially energy-intensive ones (for example, aerogels, mineral wool or polymer insulation). For Ukraine, the energy mix is more unstable, and future trajectories of energy system reconstruction can significantly change the results of the comparison. This emphasizes the need for prospective and scenario LCAs, where the comparison is not “frozen” in one year, but takes into account possible decarbonization trajectories and changes in production technologies. Without such an approach, there is a risk of receiving recommendations that quickly lose relevance or do not reflect the strategic priorities of climate policy.

No less important is the block of issues related to durability, operational characteristics and degradation risks of insulation materials. In many LCA works, the same service life is assumed for different materials, while in practice the resource of the insulation system depends on installation, humidity, freeze-thaw cycles, fire risks and maintainability. If a material requires early replacement or shows a loss of thermal insulation properties, its total impact on the life cycle increases, and a comparison based only on the “built-in” production footprint becomes simplified. In addition, safety and health aspects are important: dust fractions, volatile compound emissions, toxicity of combustion products, which are rarely equally well integrated into typical LCIA kits, but are important for residential and commercial buildings.

4. Methods and Materials

The study was conducted as a review and analytical comparison of existing LCA studies of thermal insulation materials using the ISO 14040 and ISO 14044 standards, which define the general principles, requirements and sequence of LCA implementation *(ISO, 2006a; ISO, 2006b).* The LCA methodology within this review is structured in four basic phases:

1) formulation of the goal and scope, including the definition of the functional unit and system boundaries;

2) life cycle inventory analysis (LCI) – accounting for material and energy flows, as well as initial emissions;

3) impact assessment (LCIA) – conversion of LCI data into impact category indicators;

4) interpretation – matching the results with the purpose of the study, checking sensitivity and drawing conclusions *(ISO, 2006a; ISO, 2006b).*

Given the comparative nature of the review, a key methodological principle was to bring the data to a comparable basis by function: in most cases, a unit of insulated surface area providing a given heat transfer resistance (e.g. 1 m^2 of enclosing structure with equivalent R-value/U-value) was taken as the functional unit. This approach reduces methodological distortions typical of comparisons “per kg of material” or “per m^3” and allows the results to be interpreted from the perspective of the real building function *(Füchsl et al., 2022).* The system boundaries were mainly considered in a cradle-to-grave logic, i.e. they included extraction/production of raw materials, material manufacturing, packaging, transportation, installation (including installation losses), the operational phase as a context (without direct mixing with the comparison results if the initial data were incompatible), and the end of life cycle – dismantling, sorting, recycling, incineration with energy recovery or landfill *(ISO, 2006b; Khalieiev et al., 2025).*

It was separately recorded whether the primary source presented reuse/recycling scenarios as “credits” or as alternative system boundaries, and whether a “cut-off”, “allocation at point of substitution” or other impact allocation rules were applied, as this is what often explains the discrepancies between publications with formally identical materials.

The impact assessment in the selected works was most often carried out according to a set of categories relevant to building materials and consistent with current LCIA practice: global warming potential (GWP), resource depletion potential (ADP), ozone depletion potential (ODP), photochemical ozone creation (POCP), acidity (AP), eutrophication (EP), as well as energy consumption indicators (e.g. CED or gross primary energy). When reconciling materials between sources, particular attention was paid to whether the time horizon for GWP was specified (most often 100 years), which characterisation methods were applied (e.g. CML or ReCiPe), and whether biogenic carbon for bio-based insulation was included in a way that was comparable to other works *(Schulte et al., 2021; Cascione et al., 2025)*. And in order to increase comparability, the results from different sources were brought to a common basis - a single functional unit and agreed assumptions. In particular, the same level of thermal function was assumed, a typical material thickness to achieve a given heat transfer resistance was assumed, and, where possible, the transportation and end-of-life scenarios were agreed. Such a recalculation was only performed when the original sources contained sufficient data and this did not affect the correctness of the comparison. If recalculation was not possible (for example, due to the lack of LCI data, an unknown energy mix or unclear rules for the distribution of impacts during recycling), the results were considered only as qualitative or comparative within the author's assumptions, separately marking such cases at the interpretation stage *(Füchsl et al., 2022)*.

The selection of sources was carried out as a systematic literature review with an emphasis on publications indexed in Scopus/Web of Science and those with an active DOI. The search was performed using combinations of keywords relevant to LCA and insulation (for example: “life cycle assessment”, “thermal insulation”, “mineral wool”, “EPS”, “XPS”, “PUR”, “PIR”, “cellulose insulation”, “bio-based insulation”, “aerogel”), with further selection according to the inclusion criteria: the presence of a clearly defined functional unit or the possibility of its recovery; transparently described system boundaries; the presence of data for at least one key impact category; described end-of-life scenarios or assumptions about them; the presence of a DOI and the suitability for reproducing the conclusions. The exclusion criteria included works without methodological transparency (lack of FO/system boundaries), purely technical and economic articles without an LCA component, as well as sources in which the results cannot be compared due to critically incomplete input data. For each selected study, metadata (country/region, building or structure type, insulation, thickness/density, energy mix, transport shoulders, EoL scenario, LCIA method) and key numerical indicators were extracted. The harmonization of the Ukrainian and European contexts in the methodological part was implemented by fixing the regional parameters that are most sensitive for insulation: the structure of electricity and heat supply, logistics of material supply, as well as realistic scenarios for construction and demolition waste management, including limited recycling capacity and a high share of mixed waste streams *(Khalieiev et al., 2025)*. Where necessary, operational effects related to energy savings during the use of the building were taken into account as a context and possible “credit” at the interpretation stage. At the same time, the main comparison was focused on the materials themselves, so as not to confuse “built-in” impacts (related to production and supply) with “operational” impacts (related to operation), especially when the primary sources used different and incompatible assumptions regarding climatic conditions, heating regimes and service life of building solutions. The biogenic carbon sequestration by biomaterials and the contribution of energy savings to the total balance were considered mainly qualitatively and through scenarios, since these components are the most sensitive to accounting approaches (in particular to dynamic biogenic carbon accounting methods) and often explain the differences between the results of different authors *(Cascione et al., 2025; Schulte et al., 2021).*

5. Results and Discussion

The results of comparative LCA studies show that the environmental profile of thermal insulation materials is largely determined by their origin (mineral, polymer or bio-based), the energy intensity of the technologies, the type of raw material and the chosen end-of-life scenario. Review works covering dozens of LCA analyses demonstrate a fairly stable pattern: insulation materials of petrochemical origin and materials requiring energy-intensive synthesis (EPS/XPS and PUR/PIR) are more often characterized by higher values of global warming potential (GWP) and cumulative energy consumption. In contrast, secondary insulation materials or insulation materials based on bio-materials, in particular cellulose and wood fiber, usually have lower GWP values and a more favorable impact index. However, their advantages may be less pronounced according to individual indicators (for example, ADP). The reason for this is the use of functional additives and the characteristics of production chains *(Füchsl et al., 2022; Schulte et al., 2021; Cascione et al., 2025).*

For mineral wool (rock and glass wool), the results are more "average" compared to other material groups. In a number of works, this material is considered as a compromise between environmental impact and practical advantages (fire safety, dimensional stability, durability). Comparative assessments on a functional basis (e.g. 1 m² of a structure with a given thermal resistance) show that mineral wool often has a moderate GWP and relatively controlled energy consumption in the production phase. A classic comparison of stone wool, cellulose (paper) wool and flax shows that stone wool can be competitive in terms of energy costs of production, while cellulose wool often has an advantage precisely in the climatic aspect due to the origin of the raw material and the potential "storage" of biogenic carbon in the material *(Schmidt et al., 2004).* At the same time, mineral wool has limitations in terms of end-of-life scenarios: it is difficult to "energy recycle", and mechanical recycling and reuse in practice depend on the purity of the waste, logistics and the availability of appropriate infrastructure.

Expanded polystyrene (EPS) and extruded polystyrene (XPS) are assessed in many LCAs as materials with a relatively high share of impact precisely at the production stage, which is associated with petroleum raw materials and process energy. It is significant that for EPS in detailed assessments almost the entire contribution to GWP is formed by the production stage, i.e. the chain "raw material–polymerization–product formation", while transportation and installation remain secondary in most scenarios *(Lim et al., 2021).*

This indicates that the main opportunities for reducing the environmental burden for EPS/XPS are primarily related to the decarbonization of electricity, increasing the efficiency of production processes, increasing the share of secondary raw materials and the real development of recycling infrastructure. If in practice there are no sustainable and scalable collection and processing flows capable of accepting significant volumes of insulation waste, then the claimed benefits of circular scenarios are mostly not realized and remain rather calculated.

Polyurethane insulation (PUR/PIR) is often considered to have a higher total environmental impact in comparative reviews, especially in the categories of fossil fuel use, energy intensity of production and chemical input. Despite existing regulations that regulate and limit the use of harmful blowing agents, the production technology of polyurethanes remains resource-intensive, and the dependence on petrochemical supply chains and the difficulty of reprocessing usually lead to higher integrated impact indicators compared to a number of alternatives. However, this does not mean that PUR/PIR should be discarded immediately: these materials can provide high thermal insulation characteristics with a lower layer thickness. However, they should be evaluated through a correct functional comparison and with the obligatory consideration of end-of-life scenarios *(Füchsl et al., 2022).*

Bio-based insulation and materials with a high proportion of secondary raw materials, in particular cellulose, wood fiber and some fiber composites, in most works show more favorable results in terms of GWP and often in terms of energy consumption. An important explanation is the lower intensity of production processes and the possibility of fixing biogenic carbon in the material. Current comparisons emphasize that biomaterials are able to outperform traditional insulation in most impact categories, but this advantage is not universal: for example, flame retardant and biocidal additives can increase individual indicators, and raw material logistics and quality stability affect the reproducibility of results *(Schulte et al., 2021; Cascione et al., 2025).*

A separate group are high-tech insulation materials, in particular aerogels. Although they provide uniquely low thermal conductivity and can be effective where layer thickness is critical, LCA data often indicate a significant environmental burden at the production stage due to energy-intensive drying stages and the use of chemical precursors. Aerogels are characterized by a wide spread of GWP values and resource indicators depending on the technological route, production scale and composition, which makes generalizations cautious: in the current state of technology, the environmental "price" for high performance properties may be too high if optimized processes and "clean" energy mixes are not used *(Jiang et al., 2023).*

In the context of Ukraine, the issues of construction waste management and the real possibilities of recycling thermal insulation materials are becoming more important, which is becoming an increasingly important issue against the background of large-scale destruction and subsequent restoration work. Assessment of the prospects for the further recycling process shows that a significant part of the common insulation materials (EPS/XPS, PUR, mineral wool) form technologically complex waste streams, which are often mixed and contaminated and therefore require specialized solutions for sorting and processing. It is for this reason that interest in glass-based materials, in particular glass foam, is growing - under certain conditions, during reuse or recycling, it can provide more favorable eco-indicators *(Khalieiev et al., 2025).* For Ukraine, this means that it is worth implementing the principles of the circular economy: if collection and recycling are established, even materials with a high "embedded" impact can be generally more environmentally friendly, because the need for primary raw materials is reduced.

Overall, the results confirm that the comparison of insulation materials should be functional (due to the same thermal resistance, durability and usage scenario), and the conclusions should be sensitive to assumptions about the energy mix and end-of-life cycle. The prospective assessments show that the decarbonization of electricity and the increase in the share of recycling can significantly change the ranking of materials and reduce production impacts. This means that for the EU and Ukraine it is important not only "which material to choose", but also "under what systemic conditions" (energy, logistics, recycling) this choice will provide the best environmental outcome *(Valentini et al., 2025).*

6. Conclusions

A comparative LCA study showed that natural and recycled insulation materials (cellulose, wood fibers, hemp, etc.) have the lowest environmental impact, while synthetic materials (EPS, XPS, PUR/PIR) turned out to be the most "heavy" in terms of GWP and energy consumption. Mineral wool occupies an intermediate position: it is inert and durable, with a relatively low specific energy consumption during production. Aerogels, although promising in terms of thermal insulation, currently have high life emissions due to the complex manufacturing process.

In practice, this means that when choosing a heater, one should evaluate not only thermal performance, but also environmental indicators. State policy should encourage the use of materials with a lower carbon footprint (for example, wood fibers or components from secondary raw materials) and support closed cycles of use, in particular the recycling of EPS and mineral wool. For Ukraine, this is especially important in conditions of war destruction: national strategies should provide for effective management of construction waste from heaters - through recycling and, where appropriate, energy recovery.

The proposed systemic approach allows for a more consistent consideration of environmental criteria when choosing building materials. The results obtained confirm that energy and construction issues should be considered comprehensively, and LCA serves as a key basis for assessing sustainability indicators. In further studies, it is worth considering changes in the energy system and detailing scenarios for the use and final disposal of insulation materials.

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