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THE ENVIRONMENTAL ANALYSIS OF INSULATION MATERIALS IN THE CONTEXT OF SUSTAINABLE BUILDINGS

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Abstract. Sustainable building means constructing structures using processes that are environmentally responsible and resource-efficient through the various stages of a building's life-cycle, namely design, construction, operation, maintenance, restoration, and demolition. Insulation materials are used to minimize energy loss from buildings, and are therefore generally considered to be “green” materials. Nevertheless, it is still important to take into consideration the environmental impact caused by their production in order to make the building environmentally and people friendly. The production of the insulation materials, like every production process, entails a consumption of energy and raw materials as well as the release of pollutants. Furthermore, the impacts related to some life cycle phases (e.g. installation) are sometimes neglected or not adequately investigated. The importance of environmental analysis of insulation materials is crucial in the context of sustainable buildings because it can help to confirm or change the direction of the development of new technologies.

This article compares three types of insulation (mineral-wool, glass-wool, and polystyrene) using the LCA methodology. The Ecoinvent database was used to evaluate the environmental impact of insulation material production. Moreover, the investigation of energy savings was added to make the comparison more complete.

Keywords: Thermal insulation, insulation, environmental analysis, LCA, sustainable buildings, sustainable development.

1. Introduction

The introduction to the concept of sustainable development was the “Our Common Future” report. This report describes the idea of sustainability as a development concept which meets the present day requirements of society and does not limit future societies in meeting their needs (Hull, 2007; Ikerd, 2008; Pawłowski, 2009). Considering the above mentioned, the need to introduce the idea of sustainability into all aspects of people’s lives becomes essential. Sustainable development is nowadays one of the major assumptions for the future and most countries apply legal measures to put this into effect.

From the sustainability point of view, construction is an area whose origin dates back to the dawn of civilisation. It is one of the most permanent evidence of our ancestors’ performances. This sustainability is driven mostly by the materials used in the construction and the scale of the projects. The essence of construction has not changed much over the centuries. Modern structures must also comply with the established functions, appear aesthetic, but at the same time remain one of the most material and energy intensive branches of industry.

The idea of assessing the energy efficiency of buildings grew out of the need to reduce the amount of consumed energy. This idea consists of both economical (higher fuel prices) as well as ecological considerations like the protection of the environment from adverse usage effects.

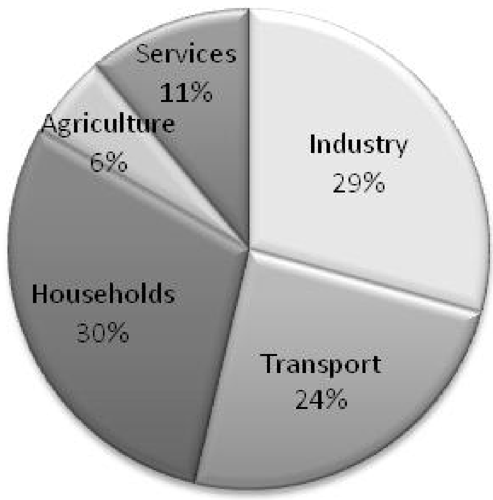

Fig 1. Final energy consumption in Poland, 2007, according European Commission Statistical Pocketbook 2010

The energy sector in Poland, both in the case of heat and electricity generation, is mainly based on the burning of coal. It is widely considered that the effects of extraction and combustion of this fuel are harmful, especially on the atmosphere. Climate changes related to the high emission of greenhouse gases into the atmosphere and the presence of nitrogen oxides and sulphur dioxide as precursors of acid rain are the incentives, which cannot be overlooked (Lindzen, 2010). Moreover, the energy safety of a country is a significant matter. Considering this, the rational use of energy is a key factor that can involve minimizing the above mentioned problems.

From an environmental point of view it is very important to develop and implement new, effective technologies and products with the production process parameters optimized, reduce energy demand and also the consumption of raw materials. These technologies should promote the use of energy from renewable sources, and also facilitate the use of recycled materials. The use of secondary raw materials should, in addition to the environmental benefits, reduce investment costs of the construction phase (Blengini, 2009; Stawicka-Wałkowska, 2001). The above trends are compatible with the principles of a sustainable development (Pawłowski, 2007; Pawłowski, 2008), and so the concept of sustainable building was created.

Sustainable development is also important for the quality of life for the buildings' users. Modern technologies and innovative solutions used in the construction industry can significantly affect the comfort of apartments and offices, and thus the health of the occupants.

For the construction sector, the application of the environmental assessment methods appear to be justified because of its high material and energy consumption. In the western countries, the construction sector represents about 10% of the Gross Domestic Product, which translates into a significant share of the emission of CO_2 (De Meester *et al*.; 2009). The construction industry is the basis on which energy is spent by its main consumers, namely households, services and industry (Figure 1). It is estimated that in the industrialised countries the construction sector is responsible for about 40% of the total energy consumption and for 36% of CO_2 emissions connected with this consumption. These details concern the current consumption associated with the everyday running of buildings and do not take into account the energy costs of exploration, production and transportation of materials (Nassen *et al*.; 2007).

The awareness of the problem of energy consumption in the building industry exists in most countries of the world (Monstvilas *et al*, 2010). There is a great economic potential which could be used to reduce the greenhouse gas (GHG) emissions in the world over the next few decades (Ginevicius *et al*.; 2008).

2. LCA in construction sector

According to the European Environment Agency, Life Cycle Assessment (LCA) is a "process of evaluating the effects that a product has on the environment over the entire period of its life thereby increasing resource-use efficiency and decreasing liabilities. It can be used to study the environmental impact of either a product or the function the product is designed to perform". LCA is commonly referred to as a "cradle-to-grave" analysis (Kowalski *et al*.; 2007).

LCA's main elements are:

- identifying and quantifying the environmental loads, for example the energy and raw materials consumed, the emissions and wastes generated,
- evaluating the potential environmental impacts of these loads,
- assessing available options for reducing environmental impacts.

The methodology of Life Cycle Assessment in reference to the construction sector is described in detail in the final report of the REGENER project, formed by the representatives of the five member countries of the European Union in order to implement the life cycle assessment technology in this field. This report was published in January 1997 and contains a detailed description of the common framework for applying LCA analysis, an overview of the tools used in the analysis, a description of the databases and the creation of model dependencies in addition to the impact assessment of the life cycle of buildings.

In the report, the fact that the LCA method in its application to buildings should take into account their special characteristics, was underlined. The main properties are:

- Buildings have the longest life cycle amongst all industrial products;
- The cost of energy consumption throughout the life cycle operation phase is typically greater than the cost of the investment;
- There are some relationships between the initial investment cost and current operational costs, depending on the type of occupancy, maintenance strategy, the utilisation of the building etc.;
- There are difficulties in comparing buildings because of their heterogonous nature;
- The design process is iterative, the same data is used repeatedly to achieve the required degrees of accuracy;
- Many individuals with different environmental perceptions are involved in the life cycle of the building.

In the matter of the duration of the life cycle period, most of the buildings can be seen as long-term objects. Life cycle periods for observation and analysis using LCA techniques have been identified in the REGENER report as follows:

- 1 – 3 years: design and construction;
- 3 – 5 years: short-term day-to-day maintenance and usage;
- 10 – 15 years: mid-term usage and partial renovation;
- 30 – 50 years: long-term usage and comprehensive renovation;
- 80 – 120 years: estimated time for the life cycle for today's buildings;
- 150 years: the expected life time for monuments.

In addition to those mentioned above, the analysis of the life cycle of a building should also take into account: extraction processes and the transportation of raw materials, the production and transportation of construction materials, creating the concept of the building. The final phase of the life cycle, that is the demolition and disposal of, or the recycling of building materials, is also important (Nassen *et al*.; 2007; Zhuguo *et al*.; 2006).

Studies on the topic of the application of LCA in the environmental assessment of buildings were conducted simultaneously in different parts of the world, mainly because of the need to meet new legal requirements. Most of the results show that the operational phase of the building life cycle is essential and responsible for more than 80% of the total environmental impact (Sartori *et al*.; 2007; Scheuer *et al*.; 2003; Verbeeck *et al*.; 2010; Sobotka, Rolak, 2009).

3. Building energy standards in Poland

The building energy standard can be defined by E_o – a factor of the seasonal energy demand for heating. This value is the amount of energy supplied per unit area of the building per year. Table 1 below compares the E_o values between Poland and Germany

There is a big discrepancy in the energy standards between the two countries. However, there is also the tendency, in both countries, to design buildings with diminishing heating requirements. This trend is supported by governments who create legislation to improve the energy efficiency in the construction industry.

For example, new buildings and objects constructed in Poland must have a thermal transmission factor of less than 0,30W/(m^2·K) for walls and 0,25W/(m^2·K) for roofs. These values mean that it is necessary to use insulation materials during the construction phase.

Table 1. Comparison of E_o values for Poland and Germany (Wnuk, 2006)

Country	Period	E_o [kWh/(m^2·a)]
Poland	1967 – 85	240 - 290
	1985 – 93	160 - 200
	After 1993	120 - 160
	Currently	90 - 120
Germany	After 1995	50 - 100
	Planned	30 - 70

In order to encourage owners and end users to undertake appropriate action and thus lead to greater energy efficiency in buildings in Poland, The Thermomodernization Fund was established. It is possible to obtain renovation grants for improving the building's energy efficiency. These grants can be up to 80% of the value of the current investment and include a premium which is 25% of this value. These grants are highly favourable for the investor, however, for their achievement, it is necessary to submit the required documents. The most important document is the building's energy audit, which determines the scope and technical and economical parameters of the thermomodernization plan of action and is the optimal solution from the cost of the improvements and energy savings point of view.

Moreover, according the European Union requirements, since 2009, every building which is built or sold, has to have an energy certificate, which is a document grading the building or dwelling from the viewpoint of energy efficiency. The consumption of energy generates costs during the operational phase of building's life cycle. Certification aims at reducing the expenses on the operation of buildings, and in the long term, its aim is the global reduction of energy consumption, thereby reducing GHG emissions.

4. Insulation materials

In order to minimize the building's energy consumption by means of thermal protection of its shell, insulation materials with low conductivity values, usually less than 0.040W/(m·K), are used in construction. The European market for insulating materials is characterised by predominantly two groups of products. The two main categories which cover 90% of the insulation materials market are inorganic fibrous (glass-wool and stone-wool) and organic foam (expanded and extruded polystyrene, polyurethane). The remaining 10% of the market is mainly wood-wool. The rest of the materials, like those sourced from agriculture, have found limited access to the market place because of their high cost (Papadopoulos, Giama, 2007).

In the European market, the most widely used insulation materials are mineral-wools, in the forms of stone-wool and glass-wool, which account for 60% of the market. Organic foam materials, expanded and extruded polystyrene, and polyurethane account for some 27% of the market (Papadopoulos, 2005).

There are about 250 companies producing insulation materials, of which nine account for more than 50% of the total production (Bribián *et al*.; 2010).

Glass-wool and stone-wool consist of quartz sand, dolomite, resovit and limestone. Adhesive materials and water-repellent oils are added to glass-wool, in order to increase its mechanical strength, though the use of these elements must be kept within limits in order to achieve a high fire-resistance. The main differences between stone-wool and glass-wool are the higher melting temperatures during the production process of stone-wool and the different size of the fibres. Stone-wool is heavier, with a higher melting point, which means that it is better suited for high temperature applications.

Expanded polystyrene (EPS) is produced from polymerised polystyrol (1.5 – 2%) and air (98,5 – 98%). In the expansion process, pentane is used as a propellant gas and in addition, 5 – 7% (by volume) of hexabromocyclododecane (HBCD) is used as a fire-retardant additive (Papadopoulos, 2005).

All the above mentioned materials have similar insulation properties. Their thermal conductivity values in the range 0.038 – 0,040W/(m·K) make them a very important element of construction, considering both ecological and economical issues. Moreover, if we focus on all the basic elements of sustainable development, the use of insulation materials can also affect people's comfort. As insulation materials are used to diminish the energy consumption in buildings, they are generally considered to be "green" materials. Nevertheless, it is still important to take into consideration the environmental impacts caused by their production. The production of the insulation materials, like every production process, entails a consumption of energy and raw materials as well as the release of pollutants. The importance of the environmental analysis of insulation materials is crucial in the context of sustainable buildings. However, the economical factor is still the most important in the market.

5. Results of analysis of selected materials

The most popular insulation materials: glass-wool, stone-wool and polystyrene were selected to assess their environmental impacts. To make the analysis more comparable, the amounts of materials were calculated based on the thermal conductivity value to ensure the same thermal properties for a $10m^2$ shelter. The density of the material was taken into consideration ($40kg/m^3$ for the glass-wool, $80kg/m^3$ for the stone-wool, $30kg/m^3$ for the polystyrene). Thus 40kg of glass-wool, 80kg of stone-wool and 28,5kg of polystyrene were used in the analysis. The conductivity value of polystyrene is 0.038 W/(m·K), for both types of mineral-wool it was assumed to be 0,040W/(m·K).

In addition to the environmental analysis, an investigation into the heating costs was undertaken. The building selected for analysis was a family house situated in Poland, near Lublin. It has a heated surface of $250m^2$ and external walls made of clinker bricks. The difference in the seasonal energy demand for this building, in the case of one wall ($10m^2$) being insulated, compared to the case where there was no insulation was 20,5GJ. Considering different energy sources, the annual savings are calculated in Table 2. The energy prices from the various sources were accepted as according to Stolarski (Stolarski *et al*.; 2011).

Table 2. The comparison of annual savings from the investigated insulation

Energy source	Price in €/GJ	Annual savings, €
Hard coal	6,24	128,1
Natural gas	10,35	212,5
Heating oil	17,55	360,3

The basis for the analysis was the Ecoinvent database using the SimaPro application. The analysis is for the production processes only; the installation phase was neglected. The techniques used for result comparison were the Global Warming Potential and EcoIndicator'99 methods.

The results obtained by the Global Warming Potential method show that the glass-wool has the lowest CO_2 equivalent production per selected unit, whereas the stone-wool and polystyrene productions release similar amounts of CO_2 into the environment. The results are shown in Table 3 below.

Table 3. Results of analysis by GWP 100a method

Impact category	Unit	Glass wool	Stone wool	Polystyrene
GWP 100a	kg CO_{2eq}	60,1	120	109

The EcoIndicator'99 method is a damage-oriented LCA technique that focuses on three categories of end-point damage: human health, ecosystem quality, and resources. The results for these categories can be presented either as a single score using default weighting factors, or as categorised indicators. Standard Eco-indicators are numbers that express the total environmental load of a product or process.

Table 4 shows the results of the EcoIndicator'99 method analysis when comparing glass-wool, stone-wool and polystyrene. Just like in the GWP 100a results, the total index for glass-wool is the lowest, which makes it the most "environmentally friendly". For polystyrene, the greatest importance is its position in the fossil fuel consumption impact category, with a value which is more than twice that for glass-wool. In the case of stone-wool, the respiratory inorganics impact category is the most significant. This category's index defines the lowest point for stone-wool in this comparison which means that this type of material is the least environmentally friendly.

Table 4. Results of analysis by EcoIndicator'99 method

Impact category	Unit	Glass wool	Stone wool	Polystyrene
Total	Pt	4,3596	10,4925	9,0364
Carcinogens	Pt	0,0733	0,08938	0,0389
Respiratory organics	Pt	0,0019	0,00231	0,0113
Respiratory inorganics	Pt	0,6198	4,69678	0,8363
Climate change	Pt	0,2427	0,44043	0,4730
Radiation	Pt	0,0277	0,01177	0,0039
Ozone layer	Pt	0,0002	0,00010	6,8E-05
Ecotoxicity	Pt	0,1260	0,15314	0,2068
Acidification / Eutrophication	Pt	0,1633	0,32698	0,1276
Land use	Pt	0,0865	0,58173	0,0100
Minerals	Pt	0,1005	0,40767	0,0118
Fossil fuels	Pt	2,9174	3,78219	7,3163

Considering the price of insulation materials in the Polish market, the situation is quite favourable because glass-wool is the cheapest, whilst stone-wool is the most expensive. However, one needs to remember that the applications for these materials are not identical, and their individual properties, like the fire resistance of stone-wool, can affect their share in the market.

6. Conclusions

The results obtained from the analysis show that glass-wool has the lowest environmental impact compared to stone-wool and polystyrene. However, the applications for these materials are not identical, so for example, the similarity between stone wool and polystyrene can be more adequate for walls. Different technologies used in shelter construction can make the use of special materials obligatory. An example is the use of glass-wool for roof insulation, and stone-wool or polystyrene used typically for walls. In fact, the demand for individual materials mostly results from their prices and application possibilities (e.g. fire resistance).

As a result of literature research and analysis, the author can state that in the case of insulation materials, their usage is necessary to achieve future energy savings at the highest level. LCA analysis shows that the operational phase is responsible for about 80% of the total environmental impact. Considering this, utilisation of insulation materials is still essential, even if their damage indicators are not zero.

In the context of sustainable buildings, the Life Cycle Assessment method seems to be a useful tool for the evaluation of environmental costs of buildings performance and operation. The basic LCA can be treated as tool of environmental sustainability assessment, and partially can lead to the evaluation of social issues, from the viewpoint of human health risks. Life Cycle Costing, financial modification to the basic LCA, can be used to evaluate economic issues connected with construction. The holistic perspective of analysis makes the LCA technique appropriate for the evaluation of almost all dimensions of sustainable development.

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