IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: Z Zimele *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **660** 012042

IOP Conf. Series: Materials Science and Engineering **660** (2019) 012042 doi:10.1088/1757-899X/660/1/012042

Life cycle assessment for masonry exterior wall assemblies made of traditional building materials

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Abstract. Building materials contribute a significant amount of CO_2 to overall greenhouse gas emissions and this environmental impact should be reduced to improve the sustainability of the construction industry. Although new and low-carbon materials are emerging, the majority of materials used are still traditionally produced and are highly carbon intensive, such as masonry blocks and insulation slabs – rock wool or expanded polystyrene. To assess which of the traditionally used building materials are more sustainable, in this paper, wall models of the most widely used masonry blocks and insulation materials were analysed using life cycle assessment. The wall models were created to fulfil the requirements of nearly-zero energy buildings. The assessment showed that the lowest impact on the environment is from aerated concrete blocks and expanded polystyrene insulation, which is mostly due to low weight and raw materials consumption compared to other materials. On the other hand, expanded polystyrene insulation poses more danger to humans and the environment in its use phase than other materials due to emissions during fire and degradation, thus should be used with caution.

1. Introduction

The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy [1,2]. The European Union has a number of official documents and guidelines aimed at reducing CO_2 emissions by up to 20% by 2020 [3], up to 40% by 2030 [4] and the energy performance of the Buildings Directive requires all new buildings to be nearly zero-energy by the end of 2020 [4]. In this study traditionally used material assemblies for exterior wall construction are analyzed using Life cycle assessment (LCA) to assess their impact on the environment, mostly focusing on greenhouse gas (GHG) emissions.

This study examined outer wall construction models consisting of a traditional masonry wall with a thermal insulation layer according to nearly zero-energy building requirements. Aerated concrete, hollow ceramic blocks, and expanded clay concrete were chosen as constructive materials, as they are equally suitable for use in exterior walls because of their physical properties – lower thermal conductivity than concrete and greater compressive strength amongst other types of lightweight concrete. To reach the requirements defined for nearly zero-energy buildings, rock wool and polystyrene foam slabs were chosen as a thermal insulation material.

In this study, the main focus was to analyze the impact on the environment by calculating LCA of the selected wall models using SimaPro software to find a solution for construction with the least impact on the environment.

2. Methodology

2.1. Methods: Life cycle assessment

All buildings have an impact on the environment at all stages of their life cycle - materials must be quarried, mined or harvested, transported to factories and manufactured. The building products have to be transported to the site, lifted into place and fixed into position. The finished buildings have to be operated, heated and cooled. All of those listed stages have an impact on the environment that can be calculated and analyzed using the life cycle assessment software SimaPro. As the factors of building operation, in the scope of this study, are considered identical for all chosen materials, the “cradle to gate” system is analyzed.

The main value for comparing different outer wall constructions is the thermal transfer coefficient which is defined as U=0.105 (W/m^2K). The examined area (unit) of the outer walls made of different constructions is $1m^2$. The main environmental impact category which is compared is the *Global Warming Potential (GWP)*, which expresses climate change by the emission of greenhouse gases like carbon dioxide (CO_2) and methane (CH_4) and it is measured in *CO_2 equivalents*. Additionally other impact category are considered - acidification potential (views gases that cause acid deposition, measured in kg SO_2 eq), abiotic depletion potential (the consumption of non-biological and biological resources , MJ and kg Sb eq), human toxicity potential (calculated index of a chemical released in the environment such as arsenic, sodium dichromate, and hydrogen fluoride, which are dangerous to human health, kg 1,4-DB eq), ozone layer depletion potential (the damage of various gases into stratospheric compounds reduce ability to prevent ultraviolet light entering the atmosphere, kg CFC-11 eq), photochemical oxidation (pollution of photochemical ozone, kg C2H4 eq), eutrophication (chemical nutrient concentration in ecosystems which lead to abnormal productivity, kg PO_4^{3-} eq), eco-toxicity (tolerable concentrations for ecosystems caused by heavy metals, kg 1,4-DB eq), that is divided into fresh-water aquatic ecosystems, marine ecosystems and terrestrial ecosystems [5,6].

2.2. Materials

The outer wall constructions of the buildings are designed with different constructive materials - lightweight concrete blocks (200 mm thickness), hollow ceramic blocks (250 mm thickness), and aerated concrete blocks (300 mm thickness), with variations of thermal insulation material - rock wool or polystyrene slab of different thickness. The outer wall constructions are designed to achieve the thermal transfer coefficient U=0.105 (W/m^2K).

2.2.1. Lightweight concrete blocks. The lightweight concrete blocks contain expanded clay aggregates mixed with cement. Lightweight expanded clay aggregates are artificial, and their manufacturing involves heating clay particles at a temperature of 1150 -1250 °C in a rotary kiln. After heat treatment, the clay particles expand and become about four to five times larger compared to their original size and take the shape of pellets. A hard-sintered crust is formed on the outer surface, while quite light and highly durable aggregates with a porous clinker-like structure may be produced inside it [7]. The lightweight concrete block manufactured by *Weber* (as hereinafter *Fibo*) with a density of 740 kg/m^3 and thermal conductivity is 0.22 W/mK [8] is used.

2.2.2. Hollow ceramic blocks. The hollow ceramic blocks are produced using clay - forming, then drying at a temperature of 50-150°C and sintering at 900-1000 °C [9]. The hollows in the structure of ceramic blocks increase their thermal performance. Hollow ceramic blocks are lighter compared with traditional clay bricks, easier to handle due to their dimensions and usually, single-block wall constructions are made. The density of the hollow ceramic blocks "*Keraterm*" manufactured by *Lode* (as hereinafter *Keraterm*) is 783 kg/m^3 and thermal conductivity is 0.13 W/mK [10].

2.2.3. Aerated concrete blocks. The aerated concrete blocks are produced using cement, lime, fly ash, and a foam formation agent (aluminum powder). It is a high-efficiency constructive thermal insulating material made through the molding and steam curing processes. The apparent density of the aerated concrete manufactured by *Bauroc* (as hereinafter *Bauroc*) is low (375±25 kg/m^3) and the thermal conductivity of it is even lower than that of the hollow ceramic blocks - 0.09 W/mK [11].

2.2.4. Rock wool. Two types of rock wool are examined in this study - Paroc Linio 15 and Paroc Linio 80. The difference between Paroc Linio 15 and Paroc Linio 80 is density and thermal conductivity. Paroc Linio 15 density is 120 kg/m^3 and thermal conductivity is 0.037 W/mK while Paroc Linio 80 density is 85 kg/m^3 and thermal conductivity is 0.04 W/mK [12].

2.2.5. Polystyrene foam slab. Polystyrene foam slab *Tenapors NEO EPS 100* (as hereinafter *EPS*) with a density of 20 kg/m^3 and thermal conductivity of 0.03 W/mK [13] is used. The main component of a polystyrene foam slab is styrene (C_8H_8), which is derived from petroleum or natural gas and formed by a reaction between ethylene (C_2H_4) and benzene (C_6H_6), benzene is produced from coal or synthesized from petroleum. Styrene is polymerized either by heat or by an initiator such as benzoyl peroxide [14].

2.3. Exterior wall models.
The outer wall construction models design are of Fibo and Paroc Linio 15 (as hereinafter *Fibo-Paroc 15*); Fibo and EPS (*Fibo-EPS*); Keraterm and Paroc Linio 80 (*Keratem-Paroc 80*); Keraterm and EPS (*Keratem-EPS*); Bauroc and Paroc Linio 80 (*Bauroc-Paroc 80*) and Bauroc and EPS (*Bauroc-EPS*) Table 1. For all models the same indoor and outdoor finishing is used – stucco (2 mm thick stucco for indoors and 10 mm thick stucco for outdoors).

Table 1. Exterior wall models.

	Fibo-Paroc15, mm	**Fibo-EPS, mm**	**Keraterm-Paroc 80, mm**	**Keraterm-EPS, mm**	**Bauroc-Paroc 80, mm**	**Bauroc-EPS, mm**
Stucco, 1750 kg/m^3 [15]	12	12	12	12	12	12
Fibo, 740 kg/m^3	200	200	-	-	-	-
Keraterm, 783 kg/m^3	-	-	250	250	-	-
Bauroc, 400 kg/m^3	-	-	-	-	300	300
Cement mortar for Fibo and Keraterm, 1800 kg/m^3 (16,6 kg/m^2)	2	2	2	2	-	-
Cement mortar for Bauroc, 1400 kg/m^3 (9 kg/m^2)	-	-	-	-	2	2
Adhesive mortar, 1670 kg/m^3 [15]	2	2	2	2	2	2
Paroc Linio 15, 120 kg/m^3	350	-	-	-	-	-
Paroc Linio 80, 85 kg/m^3	-	-	340	-	300	-
EPS, 20 kg/m^3	-	300	-	280	-	240
Thickness of wall, mm	**564**	**514**	**604**	**542**	**614**	**554**

3. Results

The LCA calculation is made using SimaPro8 software. Outer wall models with an area of 1m^2 are analyzed taking into account all manufacturing stages of the building materials used. For LCA the environmental impact is calculated using the CML-IA baseline V3.04 method. This CML method was created by the University of Leiden in the Netherlands in 2001 and contains more than 1700 different flows. The CML-IA baseline being the most common impact categories used in LCA [5]. The outer wall's component emissions impact on the environment was analyzed separately in GWP impact category Table 2.

Table 2. GWP by 1m^2 of outer wall.

	Fibo-Paroc15, kg CO_2 eq	**Fibo-EPS, kg CO_2 eq**	**Keraterm-Paroc 80, kg CO_2 eq**	**Keraterm-EPS, kg CO_2 eq**	**Bauroc-Paroc 80, kg CO_2 eq**	**Bauroc-EPS, kg CO_2 eq**
Stucco	1.47	1.47	1.47	1.47	1.47	1.47
Fibo	65.06	65.06	-	-	-	-
Keraterm	-	-	57.16	57.16	-	-
Bauroc	-	-	-	-	53.20	53.20
Cement mortar for Fibo and Keraterm	11.76	11.76	11.76	11.76	-	-
Cement mortar for Bauroc	-	-	-	-	1.57	1.57
Adhesive mortar	7.98	7.98	7.98	7.98	7.98	7.98
Paroc Linio 15	60.43	-	-	-	-	-
Paroc Linio 80	-	-	39.59	-	36.69	-
EPS	-	24.78	-	23.13	-	19.42
Wall kg CO_2 eq	**146.71**	**111.06**	**117.96**	**101.50**	**100.91**	**83.41**

The results in Table 2 show that *Fibo-Paroc 15* (area 1 m^2) produces 146.71 kg CO_2 eq, the biggest impact of emissions is made by the Fibo masonry wall –65.06 kg CO_2 eq, the insulation material contributes - kg 60.43 CO_2 eq. The constructive model made of *Fibo-EPS* (1 m^2) gives 111.06 kg CO_2 eq in GWP. The highest impact comes from the Fibo masonry wall, but the thermal insulation layer gives only 24.78 kg CO_2 eq. The CO_2 emissions of *Fibo-EPS* are about 24% less compared with the same structural wall construction made with Paroc Linio 15.

1 m^2 of *Keraterm-Paroc 80* wall in the GWP impact category makes 117.96 kg CO_2 eq, the biggest impact is made by Keraterm masonry wall -57.16 kg CO_2 eq, which is about 12% less than from Fibo. The GWP from thermal insulation Paroc Linio, 80 is 39.59 kg CO_2 eq, which is 33% of all CO_2 emissions. Comparing *Fibo-Paroc 15* and *Keraterm-Paroc 80*, the results of CO_2 emissions differs depending on the insulation, the PAROC Linio 15 gives a bigger impact than Paroc Linio 80 because of its density, Paroc Linio 15 density is 120 kg/m^3 but Paroc Linio 80 is only 85 kg/m^3 [12]. Facade rock wool CO_2 emissions from 1 kg of material are 1.44 kg CO_2 eq by Paroc Linio 15 and 1,37 kg CO_2 eq by Paroc Linio 80. The GWP of the rock wool production is dominated by the direct emissions during the fabrication of the rock wool, which contribute over 60 % to the total greenhouse gas emissions amount to 1.01 kg CO_2-eq/kg rock wool, other material emissions are from briquette fabrication, hard coal and phenol in the supply chain [16].

The wall of *Keraterm-EPS* makes 101.50 kg CO_2 eq of GWP emissions, the main impact is made by Keraterm, while EPS makes 23.13 CO_2 kg eq, which is 23% of all emissions.

According to the GWP impact category the *Bauroc-Paroc 80* wall contributes 100.91 kg CO_2 eq, where the highest impact is by Bauroc masonry wall – 53.20 kg CO_2 eq, which is about 7% less compared to Keraterm (1 m^2 Keraterm of 250 mm thickness makes 57.16 kg CO_2 eq, while 1 m^2 Bauroc of 300 mm thickness makes 53.20 kg CO_2 eq). The GWP emissions for Paroc Linio 80 is 36.69 kg CO_2 eq, which is 37% of total CO_2 emissions. In this case, comparing models of *Keraterm-Paroc 80* and *Bauroc-Paroc 80*, obtained results of CO_2 emissions are similar because the same insulation material (Paroc Linio 80) is used.

The wall with lowest greenhouse gas emissions is *Bauroc-EPS*, it contributes only 83.41 kg CO_2 eq, where the highest impact is made by Bauroc masonry wall -53.20 kg CO_2 eq, while thermal insulation EPS makes 19.42 kg CO_2 eq, which is 23% of total CO_2 emissions.

The choice of insulation material plays a major role in CO_2 emissions, as the LCA calculations show that reducing the thickness of the polystyrene foam slab by 40 mm reduces CO_2 emissions by 16% (3.71 kg CO_2 eq), which is better compared with rock wool (7% or 2,9 kg CO_2 eq).

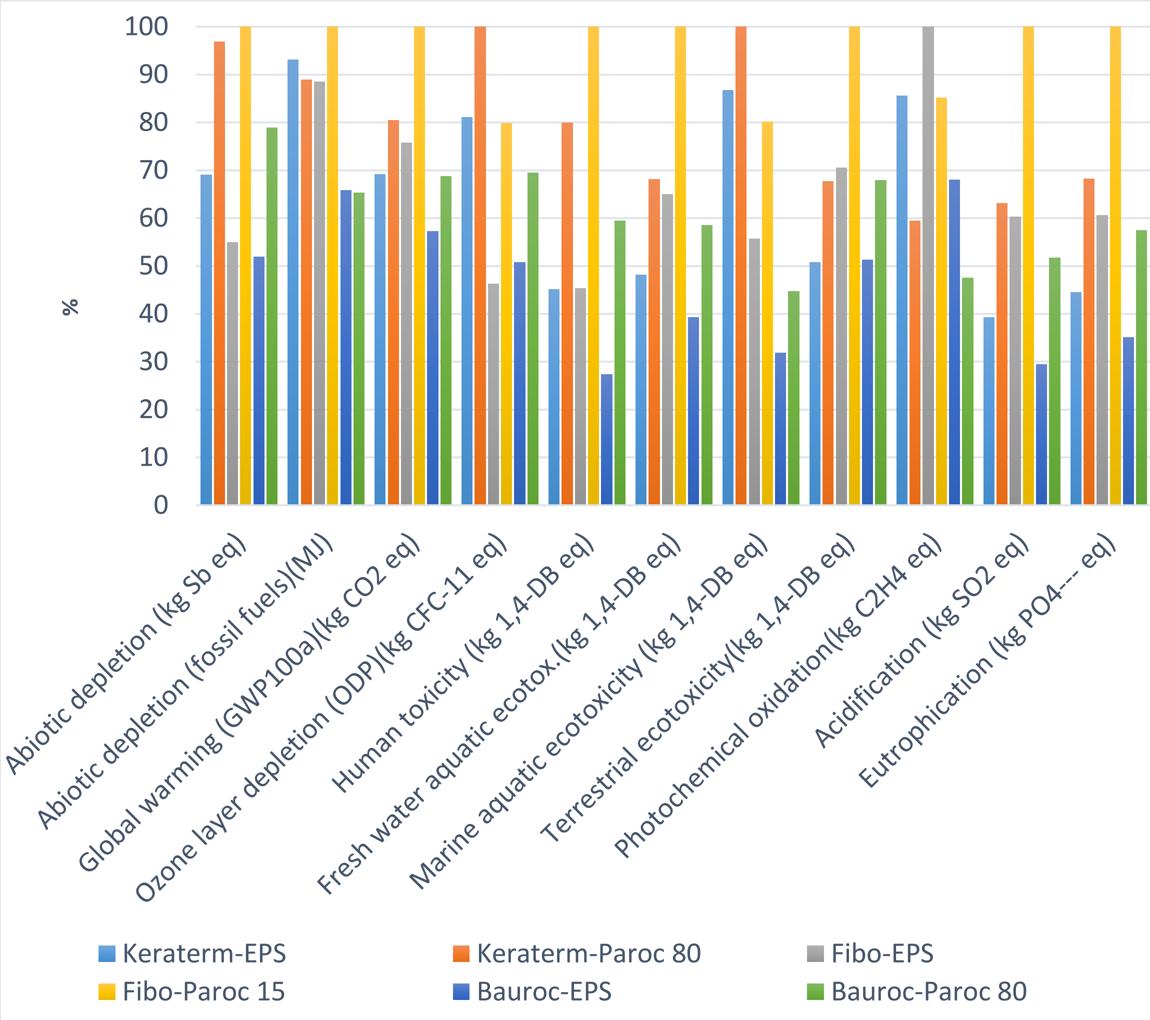

Figure 1. Impact of masonry walls (1m^2) according to the method: CML-IA baseline V3.04.

From the results showed in Figure 1. the biggest impact is made by the wall model *Fibo-Paroc 15*, except in impact category ozone layer depletion and marine aquatic ecotoxicity, where the biggest impact is made by *Keraterm-Paroc 80,* in photochemical oxidation the biggest impact is by *Fibo-EPS.* In photochemical oxidation the biggest emissions come from EPS which is 62% of total emissions, while Fibo makes 31% of all emissions. The results of *Bauroc-EPS* show lower impact in almost all of the impact category, except in the category of photochemical oxidation, where the highest impact is given by EPS (approximately 75% from total emissions).

4. Discussions

As shown in the results, masonry wall construction *Bauroc-EPS* has a lower impact on global warming emissions (CO_2 emissions - 83.31 kg CO_2 eq) compared with the other wall models. The highest emissions are by *Fibo-Paroc 15* - 146.71 kg CO_2 eq, which is 43% more compared to *Bauroc-EPS*. The total CO_2 emissions are higher for all models consisting of a rock wool insulation layer than with a polystyrene foam slab. The reason is the fact that the insulation layer used has a higher density – the density for rock wool is 85-120 kg/m^3, but for polystyrene foam slabs - 20 kg/m^3.

It should be noted, that the highest impact of abiotic depletion (fossil fuels), ozone layer depletion and human toxicity is caused by construction materials, not by thermal insulation materials. The highest impact of the photochemical oxidation emissions comes from masonry walls with EPS, it is because of the polystyrene foam slabs used in the models.

This study is based on the LCA report of different building exterior wall models to find a suitable wall model with less impact on GWP according to nearly zero-energy building conditions. The achieved results of 1m^2 of external walls with the lowest impact are summarized in Table 4.

Table 3. Outer wall results according to the Global warming potential (GWP100a), kg CO_2 eq for 1m^2.

External wall	**Global warming potential (GWP100a), kg CO_2 eq for 1m^2**	**Essential Impact contributor**
Keraterm-EPS	101.5	Hollow ceramic block.
Keraterm-Paroc 80	117.96	Hollow ceramic block.
Fibo-EPS	111.06	Lightweight concrete block.
Fibo-Paroc 15	146.71	Lightweight concrete block and rock wool (Paroc Linio 15) – equally makes the impact. Paroc Linio 15 makes more CO_2 emissions than Paroc Linio 80.
Bauroc-EPS	83.31	Aerated concrete block.
Bauroc-Paroc 80	100.91	Aerated concrete block makes the biggest impact (53% from all emissions), and 37% emissions are from used rock wool (Paroc Linio 80).

In Table 4 it can be seen that there are wall models that can be improved – for the masonry wall like *Fibo-Paroc 15* - thermal insulation replacement to Paroc Linio 80 can reduce CO_2 emissions.

The best results comparing masonry wall constructive solutions by GWP according to nearly zero-energy building is *Bauroc-EPS*, which is also the most popular masonry wall form in a single-family house building in Latvia, because the aerated concrete block has better thermal insulation properties than the hollow ceramic block and lightweight concrete block, as a result, there is a need for a thinner layer of thermal insulation.

5. Conclusions

From the results obtained from the LCA it can be concluded that the masonry wall construction *Bauroc-EPS* has the lowest impact on global warming by CO_2 emissions - 83.31 kg CO_2 eq which is 10-43% lower compared to other wall models. From masonry wall constructive materials Bauroc showed the lowest impact in GWP, yet much of the raw materials used in aerated concrete blocks production may consist of recycled materials, including copper mine tailings and fly ash, a byproduct of coal-fired power plants, thus reducing CO_2 emissions [17].

All examined wall models with polystyrene foam slab (EPS) thermal insulation showed lower CO_2 emissions than walls with rock wool, contrary to what was expected, as EPS is considered to have the highest environmental impact of traditional insulation materials. If the reference functional unit in LCA calculation would be 1kg of material instead of 1 m^2, then the claim that EPS has higher environmental impact would be justified, because 1 kg of EPS material contributes 4.1 kg CO_2 eq/kg, while from1 kg of Paroc is 1.37 – 1.44 kg CO_2 eq/kg (by SimaPro calculation). Obviously, EPS is a better thermal insulation according to CO_2 emissions in the stage of production, but this material is a petroleum-based non-biodegradable foam material, which when for long periods is exposed to UV rays photodegrades. By this process EPS can to get into the food chain causing pollution in fauna (for animal it causes starvation or death) [14]. Biodegradation of EPS does occur but at a very slow rate in the natural environment - EPS biodegradation in mixed microbial soil (including silt loam, cow manure, activated sludge, decaying plastics, etc.) ranged from 0.04 to 0.57% after 11 weeks [18]. By biodegradation EPS persists for long periods of time as a solid waste increasing the amount of plastic waste [19], because of its high resistance to water, mould, fungi, and bacteria. The burning of EPS is more toxic than rock wool [20]. EPS consist of three precursors - benzene, pentane and styrene - that impact on human health through various means of exposure, both in the production and the use of polystyrene foam products (packaging and disposable tableware) [14]. The benzene is carcinogenic to humans, with long-term exposure increasing the risk of leukemia. The pentane in EPS is in low levels, is a highly flammable gas which may evaporate from EPS during processing and storage, thus creating a fire hazard when the product is exposed to ignition sources or high heat. Styrene in EPS is reasonably anticipated to be a human carcinogen [14]. The environmental impact of the product listed above is a reason for reducing the production and use of EPS products, despite the fact that this insulation material is better by comparing wall models according CO_2 emissions in LCA calculation of material production stage.

Acknowledgement
The financial support of the European Regional Development Fund Project No. 1.1.1.1/16/A/192 "Development, optimization and sustainability analysis of smart solutions for nearly zero- energy buildings under natural climate condition" is acknowledged.

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