

COMPARATIVE LIFE CYCLE ASSESSMENT OF EMBEDDED MATERIALS IN THE COMMON WALL TYPES: CASE OF THE CONTEMPORARY SERBIAN BUILDING PRACTICE

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ABSTRACT

Sustainable construction, in addition to meeting energy efficiency requirements, requires reducing the environmental impact of building materials. In this context, the production stage plays a crucial role in determining the overall sustainability of building materials. This study analyzes the environmental and energy aspects of the initial phase of the life cycle of building materials predominantly used in modern construction and building renovation in Serbia. The research focuses on materials used for external walls, as external walls constitute the largest portion of a building's overall structure and significantly influence its energy efficiency and sustainability. The most commonly used materials for the core of the external wall construction, such as hollow clay blocks, autoclaved aerated concrete blocks, and cast reinforced concrete, form the basis for the comparative analysis. The study assesses the environmental and energy characteristics of these materials as they are embedded in wall systems. The study examines wall assemblies with an insulation layer and plaster finishing layers, while varying the basic structural component of the wall. The thickness of the thermal insulation layer depends on the basic part of the wall, ensuring that approximately the same thermal transmittance coefficients are achieved while meeting the requirements of the applicable Rulebook on Energy Efficiency in Serbia. Using the Life Cycle Assessment (LCA) methodology, the research focuses on two key indicators: Global Warming Potential (GWP) and Cumulative Energy Demand (CED) from fossil sources. The results provide detailed insights into the differences in the environmental impact and energy efficiency of these materials. The study highlights significant advantages and disadvantages of different materials regarding greenhouse gas emissions, cumulative energy demand as indicators of achieved sustainability.

KEYWORDS _ *Life Cycle Assessment (LCA), Cradle-to-Gate, Global warming potential (GWP), Cumulative energy demand, External walls*

INTRODUCTION

According to Eurostat statistics, the construction sector is the largest energy consumer in Europe, accounting for 40% of total energy consumption and 36% of greenhouse gas emissions. Through the European Green Deal strategy, the European Commission has defined legislative frameworks aimed at reducing energy consumption and greenhouse gas emissions, with a focus on achieving climate neutrality across the entire economy by 2050 at the latest and reducing net greenhouse gas emissions by at least 55% compared to 1990 levels by 2030 (DIRECTIVE (EU) 2018/844, EPBD (EU) 2024/1275).

The vision for the decarbonization of the building stock by 2050 goes beyond current targets, which are limited to reducing greenhouse gas emissions caused by operational energy - the energy required for a building's functioning. Instead, it focuses on the entire life cycle of buildings, considering both embedded and operational energy throughout the building's lifespan. Performance assessment is conducted using the Life Cycle Assessment (LCA) methodology, which evaluates the environmental impact of a product, process, or service over its entire life cycle (ISO 14040:2006). According to EN 15804, the life cycle is divided into stages (modules) from A to D (Fig.1).

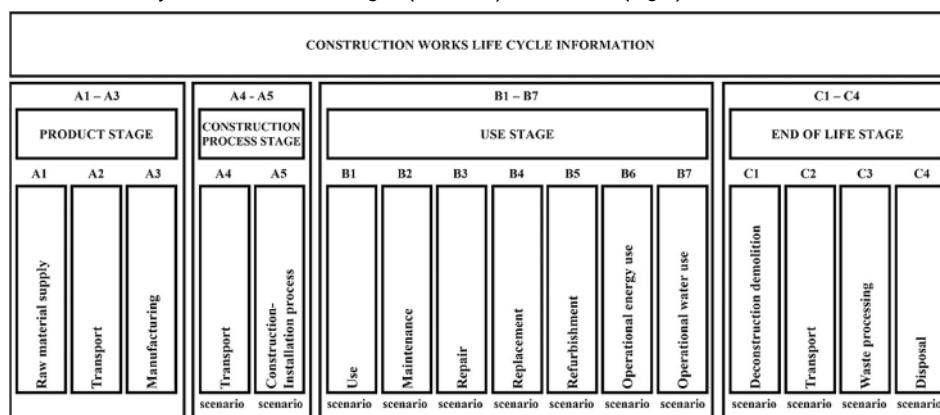


Figure 1: Life cycle stages and modules according to EN 15804 (EN 15804:2020)

This study focuses only on modules A1-A3, or the “cradle-to-gate” processes, as the research is specifically directed at the embedded materials used in typical external wall structures in residential new construction. External walls constitute the largest portion of the overall building structure and significantly influence energy efficiency and sustainability. This study does not consider the end-of-life phase of the installed materials, nor does it examine their potential for recycling and reuse.

International standards ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) define the fundamental methodology for conducting life cycle assessments. The goal of this research is to analyze the environmental impacts of embedded materials in typical external walls of newly constructed residential buildings. The study scope is limited to modules A1-A3, the inventory analysis includes the primary structural wall assembly and thermal insulation material, and two environmental impact indicators related to decarbonization potential are assessed—CML v4.8 2016, climate change, GWP 100a, and cumulative energy demand, fossil, non-renewable energy resources.

Global Warming Potential (GWP)

Global Warming Potential (GWP), commonly referred to as carbon footprint (CF), calculates the radiative forcing over different time horizons. It assesses the potential impact of various gaseous emissions on climate change (IPCC 2021). The impact of emitting one kilogram of a greenhouse gas is compared

to the impact of emitting one kilogram of CO₂, expressed as kg CO₂-equivalents (kg CO₂-eq). The gases with the highest global warming impact are CO₂, CH₄ (methane), and N₂O (nitrous oxide) (GHG Management Institute). Global warming potentials can be determined over different time horizons; however, the 100-year period is most commonly used in research and is adopted in this study as well.

Cumulative Energy Demand (CED)

Cumulative Energy Demand (CED) describes the total consumption of fossil, nuclear, and renewable energy sources over the life cycle of a product or service. This includes both direct energy use and indirect (or “gray”) energy consumption, which results from using materials such as plastic or wood as construction or raw materials (Frischknecht et al. 2015). In this study, the CED, non-renewable (MJ-eq.) – fossil indicator is used as a resource indicator.

METHODS AND MATERIALS

The research focuses on analyzing the selected environmental impacts of typical external walls in newly constructed residential buildings in Serbia. Wall types are determined based on the primary material used for wall construction, and two types of thermal insulation are then varied in the study: mineral rock wool and XPS (extruded polystyrene). The thickness of the insulation is calculated using the Knaufterm software,¹ ensuring compliance with the Regulation on Energy Efficiency of Buildings, which defines the maximum allowable thermal transmittance (U-value) for external walls in new construction as 0.3 W/m²K (Ministry of Environmental Protection, Government of the Republic of Serbia, 2011). Subsequently, the Ecoinvent database,² version 3.8, is used to retrieve inventory data, i.e., materials used in the study. The Activity Browser software is applied to access data from the Ecoinvent v.3.8 database, using the selected model “allocation, cut-off by classification”.³ The chosen impact categories for this research are:

- CML v4.8 2016, climate change, GWP 100a
- Cumulative Energy Demand, fossil, non-renewable energy resources

A **comparative analysis** of the obtained results is performed, assessing the **environmental impacts** and **energy performance** of different wall systems for 1 square meter of a wall.

Energy performance of typical external walls in newly constructed residential buildings

In modern residential construction, external walls are most commonly built using hollow clay blocks, autoclaved aerated concrete blocks, or cast-in-place reinforced concrete. Based on this, three wall types were selected for the study. The thickness of the primary wall layer is typically 20 cm. On the interior side, walls are plastered with lime-cement mortar, while on the exterior side, thermal insulation is applied—most commonly XPS (extruded polystyrene) or mineral rock wool. The final exterior layer consists of plaster applied over a reinforcing mesh. Since the interior and exterior finishes are identical for all wall types, they are not considered in this study. The thickness of the thermal insulation is defined to meet the requirements of the Regulation on Energy Efficiency of Buildings in Serbia, while also aligning with standard insulation thicknesses available on the market. Based on energy performance calculations for external walls in new construction, considering the climatic conditions of Belgrade, the following values for the thermal transmittance (U-value) and insulation thickness were obtained:

¹ Knaufterm is the commercial software that is the most used calculation tool for calculating energy performance and determining the energy class of a building in Serbia.

² Ecoinvent v3 is an LCI database with global spatial coverage regionalized by country or continent (Weidema B P et al., 2012).

³ The Activity Browser (AB) is an opensource software for Life Cycle Assessment (LCA) that builds on Brightway2 (<https://github.com/LCA-ActivityBrowser/activity-browser>)

Table 1: Thermal transmittance coefficients for typical external walls in newly constructed residential buildings

Type	Materials	d [cm]	U [W/m²K]
1A	Hollow clay blocks + adhesive mortar	20	0.293
	Mineral stone wool	10	
1B	Hollow clay blocks + adhesive mortar	20	0.276
	Extruded polystyrene XPS	12	
2A	Autoclaved aerated concrete blocks + adhesive mortar	20	0.281
	Mineral stone wool	10	
2B	Autoclaved aerated concrete blocks + adhesive mortar	20	0.265
	Extruded polystyrene XPS	12	
3A	Cast-in-place reinforced concrete	20	0.265
	Mineral stone wool	12	
3B	Cast-in-place reinforced concrete	20	0.293
	Extruded polystyrene XPS	12	

Table 1 shows that the wall with a base layer of autoclaved aerated concrete blocks has the best thermal performance, followed by the wall made of hollow clay blocks. Mineral stone wool has better thermal performance than XPS. Mineral stone wool is 10 cm thick in wall subtypes 1A and 2A, while XPS is 12 cm thick in all subtypes. The wall with a base layer of cast-in-place reinforced concrete has the weakest thermal performance, so the mineral stone wool had to be 12 cm thick to comply with the maximum allowable thermal transmittance according to the Energy Efficiency Regulation.

Environmental impacts of typical external walls in newly constructed residential buildings

The assessment of the environmental impact of embedded materials is typically expressed in units such as kilograms or cubic meters, meaning it depends on the total quantity of materials. This quantity is directly related to the specific density of the materials, which further emphasizes the importance of material selection in the context of sustainable construction.

Table 2 shows the environmental impacts of embedded materials in typical walls per kilogram of material. XPS has significantly higher values compared to the other materials, followed by reinforcing steel, adhesive mortar, and mineral stone wool. The lowest environmental impacts for the given indicators are associated with concrete, followed by autoclaved aerated concrete blocks and hollow clay blocks. Additionally, it is important to emphasize that in the Ecoinvent database, the environmental impact assessment for concrete is expressed in cubic meters, whereas the other embedded materials in this study are given in kilograms, necessitating an equalization of the data.

Table 2: Environmental impacts of GWP and CED for 1kg of embedded material

Material	CML v4.8 2016 climate change GWP 100a	Cumulative energy demand fossil non-renewable energy resources, fossil
Hollow clay block	0.31	3.42
Autoclaved aerated concrete block	0.44	2.91
Adhesive mortar	1.28	19.24
Concrete	0.11	0.79
Reinforcing steel	2.08	22.97
Mineral stone wool	1.35	16.76
XPS	9.53	93.27

Table 3 presents relevant properties of the materials embedded in the typical walls and their environmental impacts for two selected indicators. When considering individual materials, reinforced steel has the highest environmental impact, which is a result of its extremely high specific density and relatively large quantity within the wall structure. It is followed by hollow clay blocks and autoclaved aerated concrete blocks, which are present in large quantities within the wall structure. Since hollow clay blocks have a higher specific density than autoclaved aerated concrete blocks, their environmental footprint is also greater. It is important to note that adhesive mortar also has a very high environmental impact, despite its small quantity in the typical wall.

When comparing only the base layer of the wall, concrete has the lowest environmental impact, while the hollow clay block has the highest due to the clay firing process at high temperatures. Mineral stone wool, although having a higher density than XPS, has significantly lower environmental impacts (Fig. 2). If the environmental impacts are analyzed according to wall types, the highest impacts are observed in wall 1B, followed by wall 1A, then walls 3B and wall 2B, while the lowest impacts are found in walls 2A and 3A (Fig. 3). It can be concluded that the primary material in walls plays a significant role in the overall environmental impact of the wall. The wall made of hollow clay blocks performed the worst, followed by the reinforced concrete wall, while the best performance was observed in the wall made of autoclaved aerated concrete blocks. Additionally, it can be concluded that walls with XPS insulation have a higher environmental impact than walls with mineral wool insulation.

Table 3: Environmental impacts of GWP and CED for one square meter of typical external walls in newly constructed residential buildings

Type	Material	ρ [kg/m ³]	d [m]	[kg/m ²]	Amount	Unit	CML v4.8 2016 climate change GWP 100a	CED fossil non-renewable energy resources, fossil	CML v4.8 2016 climate change GWP 100a	CED fossil non-renewable energy resources, fossil
1A	Hollow clay blocks	1400	0.2	280	266	kg	83.37	910.63	121.09	1448.69
	Adhesive mortar	2100	0.2	420	21	kg	26.90	403.95		
	Mineral stone wool	80	0.1	8	8	kg	10.81	134.12		
1B	Hollow clay blocks	1400	0.2	280	266	kg	83.37	910.63	148.01	1683.92
	Adhesive mortar	2100	0.2	420	21	kg	26.90	403.95		
	Extruded polystyrene XPS	33	0.12	3.96	3.96	kg	37.73	369.35		
2A	Autoclaved aerated concrete blocks	800	0.2	160	152	kg	67.22	442.35	104.93	980.41
	Adhesive mortar	2100	0.2	420	21	kg	26.90	403.95		
	Mineral stone wool	80	0.1	8	8	kg	10.81	134.12		
2B	Autoclaved aerated concrete blocks	800	0.2	160	152	kg	67.22	442.35	131.85	1215.64
	Adhesive mortar	2100	0.2	420	21	kg	26.90	403.95		
	Extruded polystyrene XPS	33	0.12	3.96	3.96	kg	37.73	369.35		

3A	Concrete	2500	0.2	500	500	kg	56.24	397.25	119.16	1109.42
	Reinforcing steel	7800			24 ⁴	kg	49.95	551.23		
	Mineral stone wool	80	0.12	9.6	9.6	kg	12.97	160.94		
3B	Concrete	2500	0.2	500	500	kg	56.24	397.25	143.92	1317.83
	Reinforcing steel	7800			24	kg	49.95	551.23		
	Extruded polystyrene XPS	33	0.12	3.96	3.96	kg	37.73	369.35		

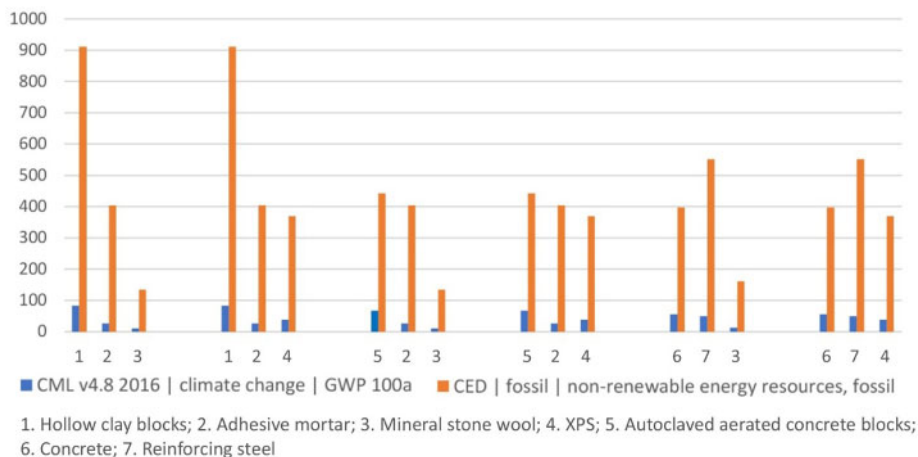


Figure 2: Diagram of environmental impacts of embedded materials in one square meter of typical walls for selected indicators CML v4.8 2016 – climate change – GWP 100a and CED – fossil – non-renewable energy resources, fossil

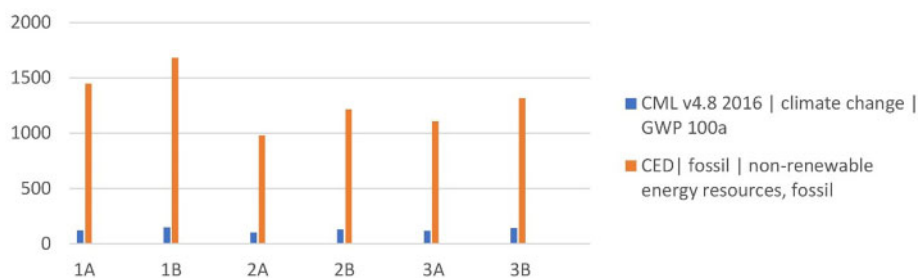


Figure 3: Diagram of environmental impacts in one square meter of typical walls for selected indicators CML v4.8 2016 – climate change – GWP 100a and CED – fossil – non-renewable energy resources, fossil

⁴ The amount of reinforcement in 1 m² of a reinforced concrete wall with a thickness of 20 cm depends on design requirements, load type, and the specified reinforcement ratio. Typical reinforcement values for walls are:

- Minimally reinforced walls: 70–100 kg/m³
- Load-bearing walls with higher loads: 100–150 kg/m³ (<https://oneclicklca.zendesk.com/hc/en-us/articles/360020943800-Average-Quantities-of-Reinforcement-in-Concrete>)

For load-bearing walls, with an average reinforcement value of 120 kg/m³, the amount of reinforcement in 1 m² of a reinforced concrete wall is 24 kg.

CONCLUSIONS

The findings of this study emphasize the importance of material selection in achieving energy-efficient and environmentally sustainable buildings. The research shows that the quantity and specific density of embedded material in the wall are crucial for determining the environmental footprint. Autoclaved aerated concrete blocks demonstrate the best results in terms of both energy efficiency and selected environmental impacts. This is followed by walls made of reinforced concrete in terms of environmental impacts, while the wall made of hollow clay blocks has the poorest performance from an environmental perspective. However, from an energy efficiency perspective, the wall made of hollow clay blocks ranks second after the autoclaved aerated concrete block wall, while the reinforced concrete wall has the weakest energy performance. Additionally, the use of mineral stone wool instead of XPS can enhance both energy efficiency and environmental sustainability. The key takeaway is that material selection should consider both thermal performance and environmental impacts throughout the entire life cycle. Future studies should further investigate these materials through other environmental impact indicators. Additionally, future research should focus on assessing all stages of life cycle. Furthermore, refining environmental impact assessments by standardizing measurement units across different material types would improve comparability and enhance decision-making in sustainable building practices. In addition, future research should focus on establishing a national life cycle inventory (LCI) database to enhance data reliability. It is also important to emphasize that the data used in this study were downloaded from the Ecoinvent database. Due to the absence of a relevant national database on the impact of materials on the environment, the version 3.8 of the Ecoinvent database was used. This is important to be emphasized since the environmental impact of materials depends on the local, i.e. national circumstances regarding the production process, used transportation services, distances, used energy sources, etc. Overall, the study highlights the necessity of integrating energy performance and environmental criteria into material selection processes to optimize both short-term building efficiency and long-term environmental sustainability.

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