LIFE CYCLE ASSESSMENT OF A SINGLE-FAMILY PASSIVE HOUSE: ENVIRONMENTAL PERFORMANCE COMPARED WITH A CONVENTIONAL RESIDENTIAL MODEL

Maria RATAJCZAK[1*], Jagoda SZOCIK[1], Joanna SINACKA[2]

[1]Institute of Building Engineering, Poznan University of Technology, Poznan, Poland
[2]Institute of Environmental Engineering and Civil Engineering Installations, Poznan University of Technology

Abstract

This paper delves into the critical intersection of sustainable development in terms of the residential building with a particular focus on passive house designs and their environmental impacts. Passive houses are distinguished by their exceptional energy efficiency, relying minimally on active heating and cooling systems, which makes them a leading model in sustainable residential construction. Through this research, this paper aims to shed light on the environmental implications of passive house designs by employing Life Cycle Analysis (LCA) as a key evaluative tool. The primary objective of this study is to conduct a comprehensive Life Cycle Analysis of a single-family passive house, comparing its environmental performance against a more conventional Base model. The analysis specifically targets the stages A1-A3, which focus on materials, and B6-B7, which focus on the operational energy use and water consumption. By concentrating on these crucial stages, this investigation provides a detailed assessment of the long-term environmental benefits and trade-offs associated with passive house construction.

Keywords: sustainable construction, passive house, energy efficiency, Life Cycle Analysis

1. INTRODUCTION

Passive house designs, recognized for their ability to drastically reduce energy consumption and carbon emissions, have gained significant attention as a viable solution for achieving sustainability in residential construction. Sustainable development is a complex idea aiming to satisfy current needs while safeguarding the capacity of future generations to fulfil their own requirements. It involves achieving a cohesive equilibrium between economic advancement, social fairness, and ecological preservation [1].

The discussion about sustainable growth focuses on creating strategies that consider both current practices and future predictions in different areas. Sustainability assessment tools are crucial for bringing together these various factors and making them more practical and resilient. Additionally, these tools need to keep up with technological advancements and be useful at different levels and scales [2].

---

* Corresponding author: Maria Ratajczak, Piotrowo 5, 60-131 Poznan, maria.ratajczak@put.poznan.pl, +48 61 6652165

In the construction sector, sustainable development is pursued through various strategies, including the use of environmentally friendly building materials, energy-efficient designs, and the integration of renewable energy sources. The goal of sustainable construction is to reduce resource consumption, limit waste production, and minimize environmental pollution throughout the entire life cycle of buildings and infrastructure. Moreover, sustainable development in construction extends beyond environmental issues to encompass social and economic dimensions. This involves creating spaces that support the health and well-being of occupants, promoting equity and social inclusion, and fostering economic growth by generating employment opportunities and advancing local communities [3]. By adhering to sustainable development principles, the construction industry can make a meaningful contribution to global efforts aimed at combating climate change, preserving natural resources, and enhancing the quality of life for current and future generations. Additionally, the adoption of sustainable practices can lead to long-term cost savings, greater resilience to environmental challenges, and improved reputations for companies within the sector.

Over the past two decades, life cycle assessment (LCA) studies of single-family houses—both passive and conventional—have evolved significantly. Early research primarily focused on operational energy, while more recent studies have incorporated embodied energy, material impacts, carbon footprint, and economic factors. However, despite this growing body of work, there remains a lack of comprehensive, directly comparable LCAs of passive and conventional houses under the same climate, construction, and regulatory context. The earliest studies, such as one conducted in France in 2008, focused only on operational energy use, without considering the environmental impacts of materials or construction processes, thus offering only a partial picture of the building's overall impact [4]. By 2012, more comprehensive studies began to emerge. In Norway, a comparative LCA evaluated standard and passive single-family timber houses under the Norwegian building code. It showed a 24–38% reduction in cumulative energy demand and nearly 30% lower greenhouse gas emissions in passive houses, particularly when renewable heating systems were used [5]. In 2013, multiple studies contributed to the field. A detailed analysis from Sweden investigated timber-frame passive houses using a full LCA approach [6]. Other studies reported results in gigajoules (GJ) for the entire building life cycle, but did not align with standardized methods, limiting cross-study comparability [7]. Meanwhile, a study from Ireland measured life cycle performance in kWh/m², covering the entire life cycle, which allowed for clearer benchmarking [8]. In 2014, the focus shifted slightly toward economic analyses, particularly regarding energy costs in passive houses, though these often omitted embodied carbon and material impacts, concentrating only on HVAC system variants and operational efficiency [9]. The scope of material assessment expanded in 2016 with a Serbian study that compared different wall structures in terms of their environmental impact through LCA [10]. In 2017, a cradle-to-grave analysis of an energy-efficient house in Romania identified the most impactful building components across human health and ecosystem damage categories [11]. By 2018, the attention turned more seriously to retrofit scenarios. A Swedish study evaluated the cost-effectiveness of upgrading 1970s homes to the Passive House standard, finding that outcomes varied depending on heating systems used [12]. An Austrian LCA of a passive apartment block found only marginal environmental benefits (e.g., 7% lower global warming potential (GWP) over 80 years) compared to a low-energy equivalent, due to factors such as internal heat gains, window opening behaviour, and material intensity [13]. In the same year, Korean research found that passive construction was economically viable, with added costs of 1.85–4.2% and relatively short payback periods [14]. By 2020, studies emphasized the increasing importance of embodied energy and carbon in highly energy-efficient homes. It was shown that up to 30%—and in some cases 50%—of a building's total life cycle energy and emissions may stem from the embodied phase, especially in passive houses, where operational energy is minimized [15]. More sophisticated and diversified approaches appeared between 2022 and 2024. A 2022 study from southern Europe focused only on energy and cost,

again omitting embodied carbon [16], while others expanded into social cost-benefit analyses, incorporating time value of money, NPV, and IRR metrics to compare passive, net-zero, and conventional buildings [17]. In New Zealand, an LCA of alternative envelope materials showed that less conventional materials, such as 3D-printed concrete, offered environmental advantages over traditional masonry [18]. In the same year, studies in China and Europe adopted advanced digital methodologies, using Building Information Modelling (BIM) and Digital Twin (DT) technologies for carbon accounting and real-time emission optimization across residential and industrial buildings [19], [20], [21]. A 2023 case study from Portugal assessed solar thermal system integration in a detached house. It concluded that, under Portugal's climate, such systems could cover the majority of domestic hot water and HVAC needs, with favourable carbon and financial payback outcomes [22]. Finally, in 2024, research deepened the material analysis of passive building envelopes. One study compared five wall systems (timber and masonry) using both thermal performance and LCA indicators. Timber-based walls performed better in terms of embodied energy and GWP, confirming their advantage in passive construction [23]. The evolution of LCA studies reflects a growing awareness of the complexity involved in assessing building sustainability. However, few studies to date provide a truly holistic and standardized comparison between passive and conventional single-family houses within a shared context [5], [10], [18]. Most research either omits material impacts, uses different system boundaries, or applies inconsistent metrics. A comprehensive, comparative LCA—accounting for both operational and embodied impacts, economic viability, and contextual variables such as climate and construction systems—is still needed to support informed decisions in sustainable housing development.

Given the notable lack of recent published case studies on buildings within our specific regional context of Central Europe—particularly at a time when building regulations, energy standards, and LCA methodologies have become more advanced and harmonized—the authors identified a clear research gap. In response, this study presents a basic comparative analysis of a conventional single-family house and its passive house counterpart. The aim is to contribute region-specific data and insights, using a consistent framework, to support more informed decision-making in the transition toward low-carbon, high-performance housing.

2. MATERIALS AND METHODS

The life cycle assessment (LCA) was carried out in accordance with the requirements of EN 15804+A2 [24], which provides the methodological framework for the environmental assessment of construction products and buildings. The calculations were performed using the One Click LCA software (One Click LCA© Version 0.30.0, Database version 7.6), which integrates environmental datasets from Environmental Product Declarations (EPDs) and other verified databases commonly used in building LCA studies. The LCA calculations were based on Environmental Product Declarations (EPDs) of the construction materials used in the analysed building, ensuring that the environmental impact data reflected the characteristics of the specific materials applied in the project.

Within the scope of the study, only selected life cycle stages were considered. The analysis included the product stage (A1–A3), covering raw material supply, transport, and manufacturing of construction materials, as well as the operational stage (B6–B7), which accounts for operational energy use and water consumption during the building's use phase. These stages were selected because they typically represent the most significant contributors to the environmental impacts of residential buildings, particularly in highly energy-efficient buildings such as passive houses.

The calculations were performed over a 50-year reference study period (RSP). This timeframe is commonly adopted in life cycle assessment studies of residential buildings, as it reflects the typical expected lifespan of such structures and enables a comprehensive evaluation of long-term operational

impacts. Moreover, the selected period is consistent with the design working life for building structures specified in Table EC0 of the Eurocodes, which provides recommended design service lives for structural components of buildings.

3. CASE STUDY DESCRIPTION

For the purposes of this paper a single-story house project designed for 4-5 people was selected. The layout comprises a spacious living room with an adjoining open dining area and kitchen, a study, five bedrooms, three bathrooms, a vestibule, and a boiler room.

The building with a usable floor area of over 300 m² was selected as a representative example of a single-family house with a medium-to-high standard, which is typical for projects implemented in the passive house standard. Due to higher design, material, and technological requirements, passive houses are most often developed by investors from the middle or upper market segment, who prioritize high energy performance, indoor comfort, and long-term operational savings. Therefore, adopting this building size allows for the analysis of a model that reflects current trends in passive residential construction and enables a more representative assessment of its environmental performance. The roof is envisioned to be gable-shaped across both segments of the building. The analysed floor plan with the surface summary is depicted in Figure 1.

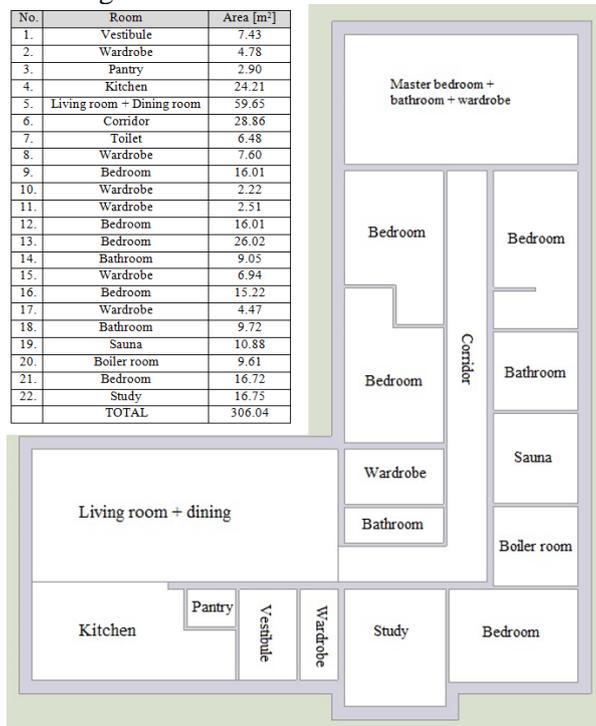| No.	Room	Area [m²]
1.	Vestibule	7.43
2.	Wardrobe	4.78
3.	Pantry	2.90
4.	Kitchen	24.21
5.	Living room + Dining room	59.65
6.	Corridor	28.86
7.	Toilet	6.48
8.	Wardrobe	7.60
9.	Bedroom	16.01
10.	Wardrobe	2.22
11.	Wardrobe	2.51
12.	Bedroom	16.01
13.	Bedroom	26.02
14.	Bathroom	9.05
15.	Wardrobe	6.94
16.	Bedroom	15.22
17.	Wardrobe	4.47
18.	Bathroom	9.72
19.	Sauna	10.88
20.	Boiler room	9.61
21.	Bedroom	16.72
22.	Study	16.75
	TOTAL	306.04

Fig. 1. Floor plan with the surface summary of the analysed building

The building was analysed with the typical structural solution and in the next step adjusted to the passive standard. All significant changes to the building envelope, materials and structural details are described below.

3.1. Three-layer wall

In the initial design, the external walls were built using autoclaved aerated concrete blocks, supplemented with a 20 cm thick layer of Styrofoam insulation. In transitioning to the passive model, a strategic alteration was made to the composition of the walls. Specifically, the original walls were replaced with a three-layered structure comprising autoclaved aerated concrete blocks, PIR board insulation, and clinker bricks serving as the final surface layer.

3.2. Ceiling insulation

Another crucial aspect that arose was the insulation of the roof. Reports indicate that as much as 30% of heat can escape through the roof [25]. Initially, the conventional approach involved insulating the rafters. However, given the presence of an unused attic, a different strategy was adopted for the passive model: insulating the ceiling and sealing the space above it. Consequently, the adjustment in the roof structure resulted in a reduction in the building envelope's area. With a smaller area for heat escape, there is a substantial decrease in the building's heat demand. As a structural solution, a monolith reinforced concrete slab was chosen. Insulation was planned to use two PIR boards, each 20 cm thick. The schemes of the walls and ceilings layering are presented in Figure 2.
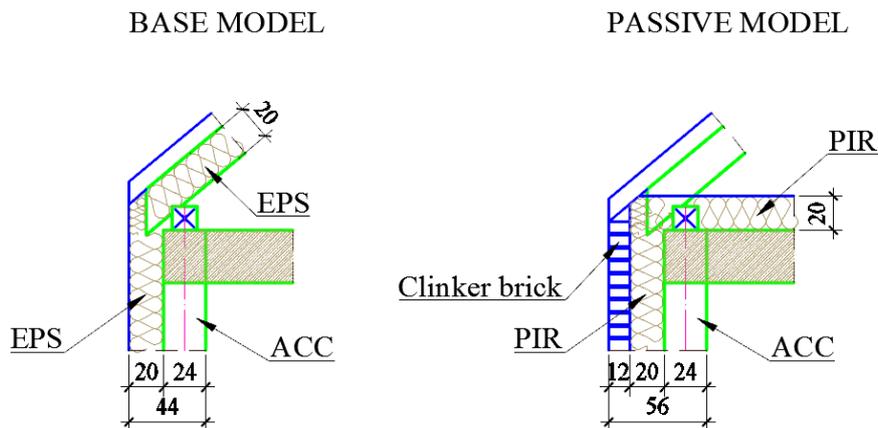

Fig. 2. Scheme of the external walls and ceiling insulation a) Base model, b) Passive model

3.3. Foundation slab

The decision was made to use PIR board as insulation, this time for the foundation slab. PIR board demonstrates comparable compressive strength to XPS polystyrene and EPS polystyrene, rendering it suitable for foundation slab insulation as well.

3.4. Windows

It was determined that certain windows needed to be resized. Some adjustments were made: 3 meters on the south wall were reduced to 2 meters, while 4 meters windows on the west wall were reduced to 3 meters. Additionally, one corner window was removed. This reduced heat demand and allowed a slight reduction in overheating value.

3.5. Bill of materials

For the bill of materials for the base model the following approximations were used:
- Materials in small quantity were omitted from the analysis (i.e., wooden battens and counter-battens, electrical cables (copper with PVC insulation), facade insulation fixing anchors (plastic/steel dowels).
- The amount of concrete and reinforcement has been recalculated proportionally to the elements involved.
- Assumed depth/height of foundation footings: 0.40 m / 0.40 m.
- Assumed depth of concrete floor screed: 0.15 m.
- Assumed height of concrete celling slab: 0.30 m.
- Some materials have been substituted by others with the same environmental indicators.

For the Passive model, as with the Base Model, several modifications and simplifications were made. The baseline model, in which the following changes were made, was adopted as the material bill of materials:
- The fundament footings have been replaced by a fundament slab.
- PIR board was used as insulation for the foundation slab.
- The area of glazing has been reduced.
- Insulating materials on the roof structure have been removed and the correct amount of PIR panels needed to insulate the ceiling has been introduced instead.
- The construction of the exterior walls was based on the same material, so only the insulation material was changed to PIR panels.
- Clinker brick added to finish the walls.

The final bill of materials for both models are presented in Table 1. In both models, the bill of materials consists solely of the building materials required for the structural components of the buildings. In this study, the environmental impact of producing the heating, ventilation, and air conditioning (HVAC) systems was omitted.

Table 1. Bill of materials for the investigated buildings (the differences in material composition between the analysed building variants are highlighted in red in the table for clarity)

No.	Name	BASE MODEL	PASSIVE MODEL
		Quantity	
Foundation, sub-structure, basement, retaining walls			
1.	EPS insulation panels, graphite	63.45 m³	---
2.	Cement mortar	22.84 m³	22.84 m³
3.	Polyethylene vapour barrier membrane	103.05 m²	103.05 m²
4.	Sand	960 kg	240 m³
5.	Aggregate (crushed gravel)	68.56 kg	68.56 kg
6.	Ready-mix concrete, normal strength	24.2 m³	**91.8 m³**
7.	Ready-mix concrete, low strength	45.9 m³	45.9 m³
8.	Reinforcement steel	6655 kg	**9180 kg**
9.	Concrete masonry units	18.15 m³	---
10.	PIR Boards, 300 mm	---	**306 m²**
Vertical structures and facade			
1.	Autoclaved aerated concrete blocks	32219.55 kg	32219.55 kg

2.	Clay brick	4.844 ton	---
3.	Autoclaved aerated concrete	332.06 kg	---
4.	EPS insulation panels, graphite	96.00 m^3	---
5.	Stone wool (mineral wool)	687.52 m^2	---
6.	Fiberglass reinforcing mesh	596.32 m^2	596.32 m^2
7.	Tile grout	689.83 kg	689.83 kg
8.	Stone wool (mineral wool) insulations	23 m^2	23 m^2
9.	Cement plaster, grey, bulk density	23785.86 kg	23785.86 kg
10.	Adhesive mortar	3518.33 kg	3518.33 kg
11.	Plaster mortar	3689.27 kg	3689.27 kg
12.	Adhesive mortar	3113.34 kg	3113.34 kg
13.	Cement mortar, for tile	116.15 kg	116.15 kg
14.	Primers and façade paints	113.91 kg	113.91 kg
15.	Joint grout for tiles	101.28 kg	101.28 kg
16.	Primers and façade paints	0.3050 m^3	0.3050 m^3
17.	Autoclaved aerated concrete blocks- internal walls	12987.63 kg	12987.63 kg
18.	Gypsum plasterboard	53.25 m^2	53.25 m^2
19.	PIR Board, 240 mm	---	**225 m^2**
20.	EPS Insulation panels	---	**120 m^2**
21.	Clinker bricks	---	**16 tons**
Vertical structures and facade – other materials			
1.	Wooden interior doors	13 units	13 units
2.	External wood door	1 unit	1 unit
3.	Balcony security door	101.04 m^2	**90 m^2**
4.	Aluminium clad, wooden frame window	39.41 m^2	**20 m^2**
5.	Balcony door with wooden frame	4 units	4 units
Horizontal structures: beams. floors and roof			
1.	Roofing tile from clay	7.295 ton	7.295 ton
2.	EPS insulation panels	64.43 m^2	---
3.	PIR Boards 300 mm	---	**306 m^2**
4.	Planed and strength-graded timber	38.09 m^3	38.09 m^3
5.	Polyethylene sealing film for slabs	1503.82 m^2	1503.82 m^2
6.	EPDM waterproofing membrane	804.44 m^2	804.44 m^2
7.	Chipboard	332.38 m^2	332.38 m^2
8.	PVC floor covering with foam layer	179.66 m^2	179.66 m^2
9.	Laminate flooring	177.94 m^2	177.94 m^2
10.	Galvanized or organic coated steel	34.090 m^2	34.090 m^2
11.	PVC rain gutters for buildings	104.30 m	104.30 m
12.	Ready-mix concrete, normal strength	92 m^3	92 m^3
13.	Reinforcement steel	10098 kg	10098 kg
Horizontal structures – other materials			
1.	Gypsum mortar	566.02 kg	566.02 kg
2.	Screws, self-tapping	15.31kg	15.31kg
3.	Steel annealed wire and nails	352.93 kg	352.93 kg
4.	Ceramic tiles and plates	251.78 m^2	251.78 m^2
5.	Prefabricated reinforcing steel	39.92 kg	39.92 kg
6.	Asphalt concrete binder course	21.72 kg	21.72 kg
7.	PVC glue	0.23 kg	0.23 kg
8.	Alkyd emulsion-based paint	0.45 m^3	0.450 m^3
9.	Structural steel profiles	30.33 kg	30.33 kg

3.6. Energy demand

Energy performance of buildings was assessed using Passive House Planning Package (version PHPP 9.6a), tool for designing and evaluating which calculates heating and cooling demand, frequency of overheating and annual primary energy consumption. The reliability and accuracy of PHPP has been proved in many completed projects worldwide [26]. Passive House Planning Package is able to calculate heating demand with good precision compared to dynamic simulation tools [27], [28] and predict

overheating frequency in good agreement with measured values [29]. PHPP is widely used for energy analysis of buildings [26], [30 – 35].

Since this is only a house design and analysis assumes the same usage of building, the specific energy demand values for appliances, audio-visual equipment and lighting are unknown. Based on the available data the heating demand and domestic hot water (DHW) demand have been included in both cases. In Figure 3 the final results of specific building parameters with reference to the threated floor area energy for Base model (a) and Passive model (b) are shown.

A) Specific building characteristics with reference to the treated floor area			B) Specific building characteristics with reference to the treated floor area		
	Treated floor area m²	306.00		Treated floor area m²	306.00
Space heating	Heating demand kWh/(m²a)	36.97	Space heating	Heating demand kWh/(m²a)	14.47
	Heating load W/m²	19.00		Heating load W/m²	10
Space cooling	Cooling & dehum. demand kWh/(m²a)	-	Space cooling	Cooling & dehum. demand kWh/(m²a)	-
	Cooling load W/m²	-		Cooling load W/m²	-
	Frequency of overheating (> 25 °C) %	9.54		Frequency of overheating (> 25 °C) %	9.01
	Frequency of excessively high humidity (> 12 g/kg) %	0.00		Frequency of excessively high humidity (> 12 g/kg) %	0.00
Airtightness	Pressurization test result n_{50} 1/h	0.60	Airtightness	Pressurization test result n_{50} 1/h	0.30

Fig. 3. Final results of specific building parameters for: a) Base model, b) Passive model

It was assumed that both buildings are equipped with mechanical ventilation with heat recovery (average air flow: 300m³/h, heat recovery efficiency: 92%) an electrically powered air heat pump with heat storage tank and DHW tank. Space heat and domestic hot water are distributed through insulated pipes. Installation of an air heat pump and mechanical ventilation with heat recovery plays a key role, significantly affecting energy efficiency. For the passive building the final energy demand was calculated to 15.3 kWh/m² per year (heating: 5.9 kWh/(m²·year), DHW: 7.0 kWh /(m²·year)), whereas the final energy demand for the base model was calculated to 24.6 kWh/m² per year (heating: 15.2 kWh/(m²·year), DHW: 7.0 kWh /(m²·year)). The electricity demand of auxiliary devices was assumed to be 2.4 kWh/(m²·year).

Total energy consumption:
- Base model: 24.6 kWh/(m²·year)·306 m² = 7 527.6 kWh/year.
- Passive model: 15.3 kWh/(m²·year)·306 m² = 4 681.8 kWh/year.

The above calculations provide a starting point for further analysis and evaluation of buildings in the context of their environmental impact.

3.7. Water consumption

In Poland, the average water consumption per person is about 100-150 litters per day [36]. For simplicity, an average value of 125 litters per person per day was assumed. Annual water consumption for a 4-person household:
- Daily: 4 people · 125 litters/person = 500 litters per day.
- Annually: 500 litters/day · 365 days = 182 500 litters per year.

3.8. Summary for the house models

Figure 4 shows the visualisations of the analysed buildings the changes applied to the windows and Table 2 presents the basic physical parameters of the buildings.
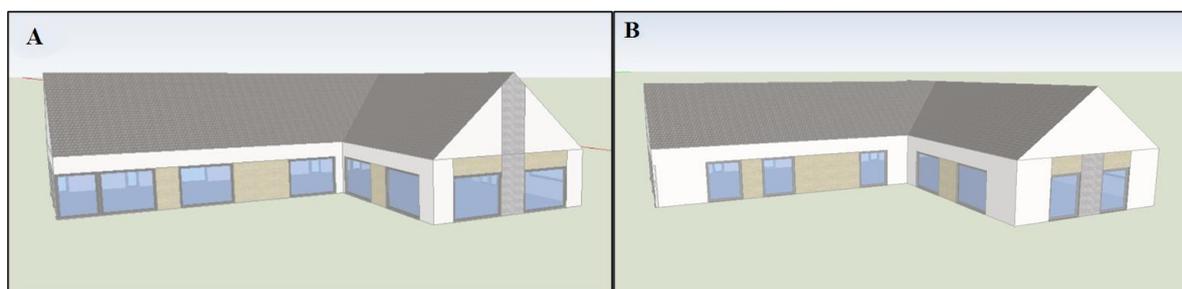
Fig. 4. Visualisation of the analysed buildings: a) Base model, b) Passive model

Table 2. Basic physical parameters of the analysed buildings

	Base Model	Passive Model
U-value [W/m²K]:		
External walls	0.137	0.058
Foundation Plate	-	0.064
Roof	0.12	0.049
Assumed area of roof insulation [m²]:		
-	618.80	370.84
Windows area [m²] according to orientation:		
North	26.40	19.92
East	22.32	24.12
South	24.12	25.80
West	42.12	21.60

4. RESULTS AND DISCUSSION

In environmental impact results of the analysed buildings are presented in Figures 5 and 6. The results clearly demonstrate a significant difference in the Global Warming Potential (GWP) values at the A1–A3 stage between the basic and passive models. This disparity is primarily attributed to the increased material consumption and the use of higher-performance materials required in the passive model in order to achieve improved thermal insulation, airtightness, and overall building performance. Similar observations have been reported in previous LCA studies of passive buildings, where the enhanced building envelope and thicker insulation layers led to higher embodied environmental impacts compared to conventional buildings [15], [23]. Although this results in a higher environmental burden in the early life cycle stages for the passive design, the long-term benefits become apparent when considering the full 50-year service life of the building.

During the use phase, the passive model requires substantially less final energy for heating and cooling, which significantly reduces the GWP contribution associated with operational energy use. Consequently, despite its initially higher embodied emissions, the passive model ultimately demonstrates a lower total GWP over the building's life cycle compared to the basic model. This result is consistent with earlier studies, such as the Norwegian comparative analysis of standard and passive houses, which reported reductions in cumulative energy demand and greenhouse gas emissions when passive design strategies were implemented [5]. The findings also support the conclusions of more recent research indicating that improving operational energy efficiency remains one of the most effective strategies for reducing the life cycle environmental impacts of residential buildings.
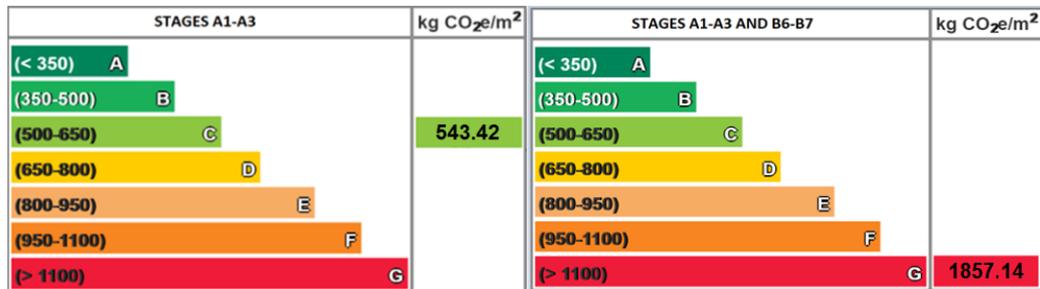
Fig. 5. Total GWP values for the Base model for A1-A3 stage and A1-A3+B6-B7 (50-year service life) stage
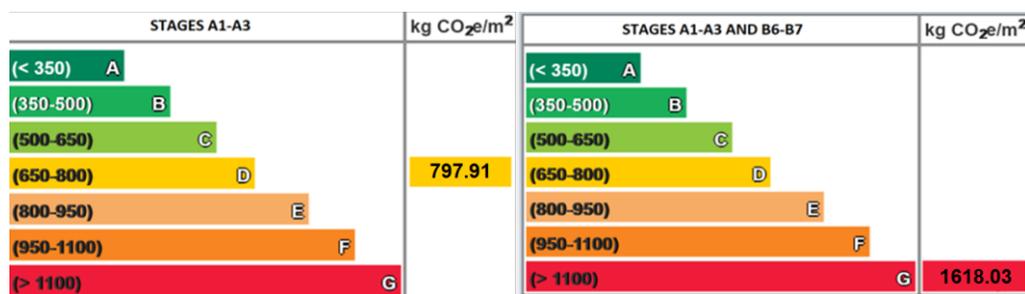

Fig. 6. Total GWP values for the Passive model for A1-A3 stage and A1-A3+B6-B7 (50-year service life) stage

The diagram presented in Figure 7 illustrates the distribution of CO_2 emissions across the different life cycle stages of the building. In both analysed scenarios, the operational phase—specifically stage B6 (operational energy use)—accounts for the largest share of total emissions. However, in the case of the passive model, the contribution of stage B6 becomes almost comparable to that of the material production stage (A1–A3). This shift reflects the significantly reduced operational energy demand typical of passive houses and highlights the growing importance of embodied environmental impacts in highly energy-efficient buildings. Similar trends have been identified in recent LCA studies, which indicate that embodied energy and carbon may account for up to 30–50% of total life cycle impacts in low-energy and passive buildings [15].

The production and supply of construction materials (stages A1–A3) represent 29.26% of the total CO_2 emissions in the basic building model and 49.31% in the passive building model. This substantial increase in the relative contribution of embodied impacts in the passive model reflects the greater material intensity required to achieve higher energy performance standards. Comparable findings were reported in studies investigating the environmental performance of passive building envelopes, where additional insulation layers and more complex building assemblies significantly increased embodied impacts while reducing operational energy demand [23]. Conversely, the contribution from water use (stage B7) remains minimal in both analysed models, indicating that its influence on the overall global warming potential is negligible compared to other life cycle stages.

Figure 8 presents the GWP values for the A1–A3 + B6–B7 stages with respect to the main resource categories, while Figure 9 illustrates the contribution of individual material groups to the embodied environmental impact in stage A1–A3. The results highlight the dominant influence of operational energy consumption in the base model house, which significantly increases its overall life cycle GWP. In contrast, the passive model achieves considerable reductions in operational emissions due to improved thermal performance and lower heating and cooling demand.

However, certain design solutions required to meet the passive house standard—such as the inclusion of a floor slab and the use of thicker insulation layers—contribute to increased embodied emissions in the foundation and external wall systems. The analysis indicates that materials such as PIR (polyisocyanurate) insulation and concrete are among the main contributors to the embodied carbon footprint of the passive design. Similar observations have been reported in previous research, where high-performance insulation materials and structural elements were identified as key contributors to embodied environmental impacts in energy-efficient buildings [10], [23].

Despite their higher environmental burden during the production stage, these materials play a crucial role in achieving the very low operational energy demand required for passive buildings. This highlights an important trade-off between embodied and operational impacts in sustainable building design. The results therefore emphasize the importance of adopting a life cycle perspective when evaluating the environmental performance of buildings. Considering only the construction stage could lead to misleading conclusions, whereas a full life cycle approach demonstrates that investments in higher-performance materials and improved building envelopes can lead to substantial long-term environmental benefits.

Furthermore, the results obtained in this study contribute to addressing the research gap identified in the literature regarding region-specific LCA analyses of passive and conventional residential buildings. By applying a consistent methodological framework and analysing buildings within the Central European context, the study provides additional empirical evidence supporting the environmental advantages of passive house design when evaluated over the entire building life cycle.
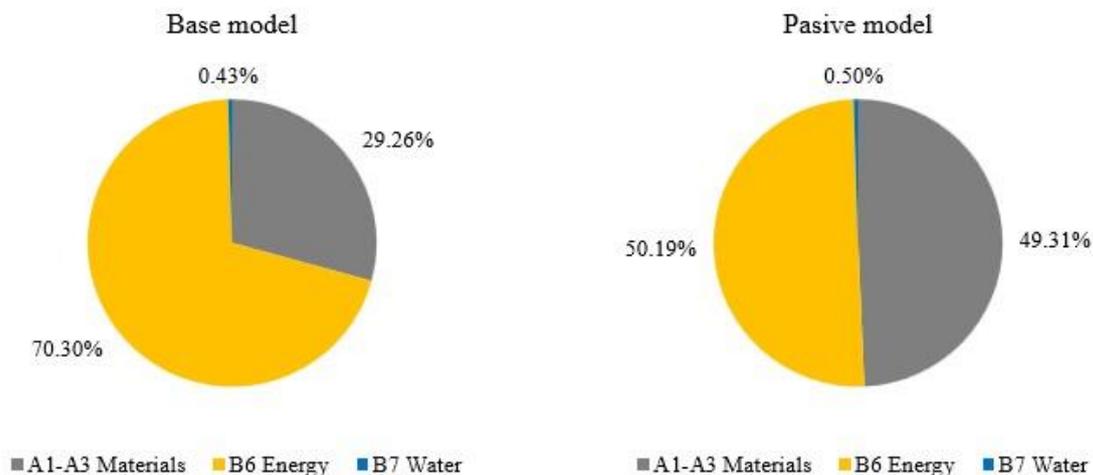

Fig. 7. The impact of the A1-A3, B6-B7 (50-year service life) stages in the Total GWP of buildings
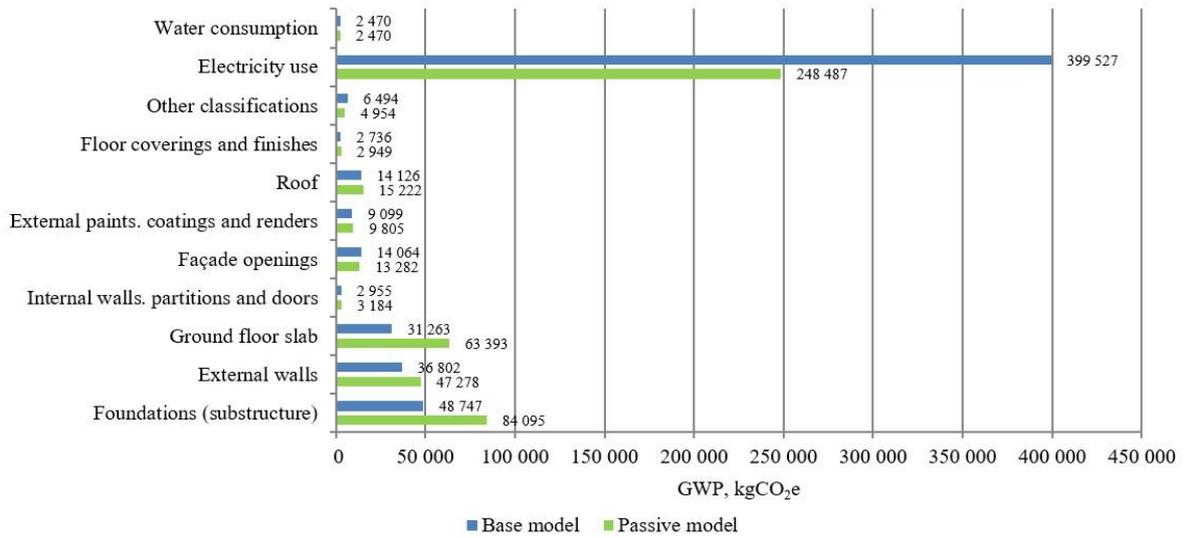
Fig. 8. Total GWP values for the A1-A3+B6-B7 (50-year service life) stage with respect to the resource types
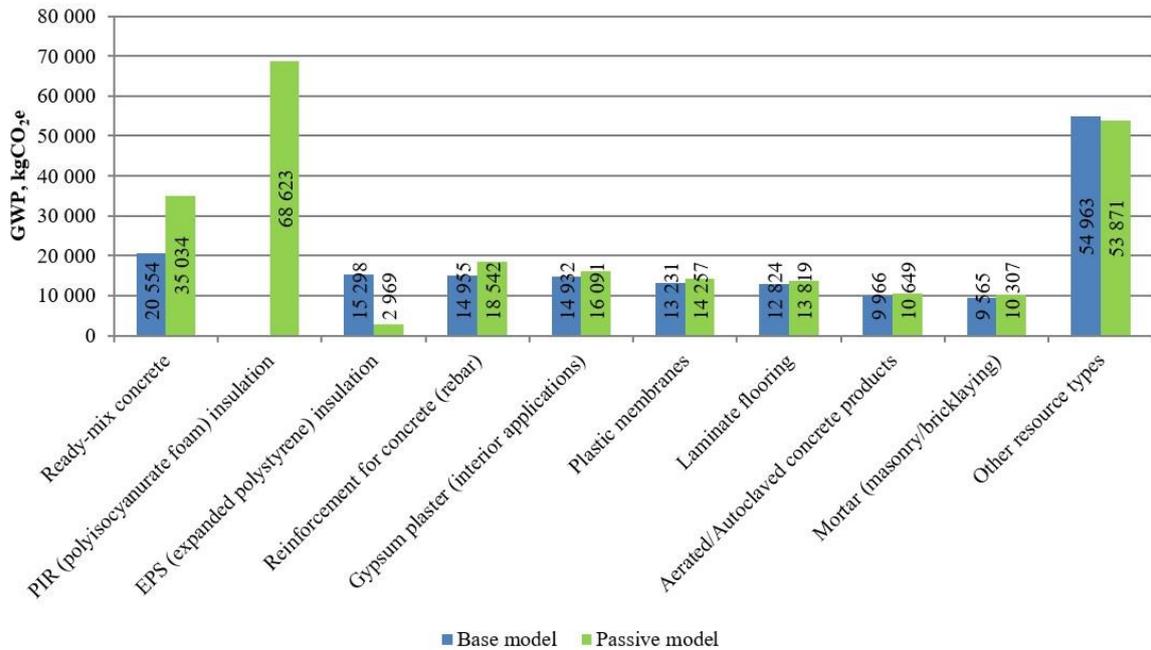

Fig. 9. Total GWP values for the A1-A3 stage with respect to the material types

5. CONCLUSIONS

The comparative analysis of the Life Cycle between the Base model and the Passive model highlights the significant trade-offs and benefits associated with the design and operation of a passive house. The key conclusions drawn from this analysis are as follows:

- The Passive model demonstrates a substantial reduction in Global Warming Potential (GWP) compared to the Base model, with a lower overall carbon footprint during the building's operational phase. This reduction is primarily attributed to the enhanced energy efficiency of the Passive model, which significantly lowers energy-related emissions over time. Despite the higher initial carbon footprint due to the use of specialized materials, the long-term operational savings in carbon emissions make the Passive model more environmentally sustainable.
- The Passive model design, which prioritizes energy efficiency, results in significantly lower energy consumption during the building's lifecycle. This is evidenced by the marked reduction in emissions related to electricity use, highlighting the effectiveness of passive house strategies in minimizing energy demands and contributing to overall sustainability.
- The Passive model incurs higher emissions in several construction-related categories, particularly in materials such as foundations, external walls, and the slab. These increased emissions stem from the use of more energy-intensive materials and construction techniques required to meet the rigorous energy performance standards of passive houses. Although this leads to a higher initial environmental cost, it is a necessary trade-off for achieving long-term sustainability and energy efficiency.
- Both models show identical results in terms of water consumption, indicating that water use does not significantly influence the comparative environmental performance between the Base and Passive models. This finding suggests that water-related impacts are consistent across both designs and do not vary significantly with the adoption of passive house principles.

Passive model emerges as a more sustainable option in the long run, despite the initial higher environmental impact associated with its construction. The significant reduction in operational energy use and associated emissions demonstrates the effectiveness of passive house principles in achieving long-term environmental sustainability. However, careful consideration must be given to the selection of materials and construction techniques to further reduce the initial carbon footprint and address concerns related to ozone depletion and resource use. The findings of this LCA underline the importance of adopting a holistic approach to building design, where short-term environmental costs are balanced against long-term sustainability gains.

ACKNOWLEDGEMENTS

REFERENCES

1. Awdah, O 2017. Sustainability and green building rating systems: LEED, BREEAM, GSAS. *Journal of Building Engineering* **11**, 25–29.
2. Costanza, R and Bernard, CP 1995. Defining and predicting sustainability. *Ecological Economics* **15**, 193–196.

3. Manchanayake, R, Malkanthi, N and Dassanayake, D 2022. *Investigation of Measures for Sustainable Development using Sustainable Construction*. Proceedings of International Conference on Engineering, Jaffna, Srilanka, August, 19, 105–111.

4. Thiers, M and Peuportier, B 2008. Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France. *Solar Energy* **82**, 820–831. DOI: 10.1016/j.solener.2008.02.014.

5. Dahlstrøma, O et al. 2012. Life cycle assessment of a single-family residence built to either conventional- or passive house standard. *Energy and Buildings* **54**, 470–479. DOI: 10.1016/j.enbuild.2012.07.029.

6. Dodoo, A and Gustavsson, L 2013. Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply. *Applied Energy* **112**, 834–842. DOI: 10.1016/j.apenergy.2013.04.008.

7. André Stephan, A, Crawford, R and de Myttenaere, K 2013. A comprehensive assessment of the life cycle energy demand of passive houses. *Applied Energy* **112**, 23–34. DOI: 10.1016/j.apenergy.2013.05.076.

8. Famuyibo, A, Duffy, A and Strachan, P 2013. Achieving a holistic view of the life cycle performance of existing dwellings. *Building and Environment* **70**, 90–101. DOI: 10.1016/j.buildenv.2013.08.016.

9. Badeaa, A et al. 2014. A life-cycle cost analysis of the passive house "POLITEHNICA" from Bucharest. *Energy and Buildings* **80**, 542–555. DOI: 10.1016/j.enbuild.2014.04.044.

10. Maodu, N et al. 2016. Life cycle and energy performance assessment of three wall types in south-eastern Europe region. *Energy and Buildings* **133**, 605–614. DOI: 10.1016/j.enbuild.2016.10.014.

11. Boros, I et al. 2017. Life cycle assessment and life cycle cost analysis of a nearly zero energy residential building - a case study. *Environmental Engineering and Management Journal* **16 (3)**, 695-704.

12. Ekströma, T, Bernardoa, R and Blomsterberga, A 2018. Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s. *Energy and Buildings* **161**, 89–102. DOI: 10.1016/j.enbuild.2017.12.018

13. Kovacic, I, Reisinger, J and Honic, M 2018. Life Cycle Assessment of embodied and operational energy for a passive housing block in Austria. *Renewable and Sustainable Energy Reviews* **82**, 1774–1786. DOI: 10.1016/j.rser.2017.07.058.

14. Shim, J, Song, D and Kim, J 2018. The Economic Feasibility of Passive Houses in Korea. *Sustainability* **10**, 3558. DOI:10.3390/su10103558.

15. Shirazi, A and Ashuri, B 2020. Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta. *Building and Environment* **171**, 106644. DOI: 10.1016/j.buildenv.2020.106644.

16. Vassiliades, C et al. 2022. Assessment of an innovative plug and play PV/T system integrated in a prefabricated house unit: Active and passive behaviour and life cycle cost analysis. *Renewable Energy* **186**, 845–863. DOI: 10.1016/j.renene.2021.12.140.

17. Jayasena, A et al. 2022. Socio-economic and environmental cost-benefit analysis of passive houses: A life cycle perspective. *Journal of Cleaner Production* **373**, 133718. DOI: 10.1016/j.jclepro.2022.133718.

18. Taylor, C et al. 2023. Delivering Sustainable Housing through Material Choice. *Sustainability* **15**, 3331. DOI:10.3390/su15043331.

19. Zhang, S et al. 2023. IFC-enabled LCA for carbon assessment in pumped storage hydropower (PSH) with concrete face rockfill dams. *Automation in Construction* **156**, 105121. DOI: 10.1016/j.autcon.2023.105121.

20. Zhang, A et al. 2024. Carbon emissions accounting and estimation of carbon reduction potential in the operation phase of residential areas based on digital twin. *Applied Energy* **376**, 123155. DOI: 10.1016/j.apenergy.2024.123155.
21. Marrero, M et al. 2022. Life Cycle Assessment of Industrial Building Construction and Recovery Potential. Case Studies in Seville. *Processes* **10**, 76. DOI:10.3390/pr10010076.
22. Mateus, R, Monteiro Silva, S and Guedes de Almeida, M 2019. Environmental and cost life cycle analysis of the impact of using solar systems in energy renovation of Southern European single-family buildings. *Renewable Energy* **137**, 82-92. DOI: 10.1016/j.renene.2018.04.036.
23. Mazur, Ł et al. 2024. External Wall Systems in Passive House Standard: Material, Thermal and Environmental LCA Analysis. *Buildings* **14**, 742. DOI: 10.3390/buildings14030742.
24. EN 15804+A2:2020-03 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products.
25. Filonenko, O 2023. Thermo-Technical Calculation of Combined Roof Structure with Variable Thickness Layers. In: Onyshchenko, V, Mammadova, G, Sivitska, S, Gasimov, A. (eds) Proceedings of the 4th International Conference on Building Innovations. ICBI 2022. Lecture Notes in Civil Engineering, 299. Springer, Cham. DOI: 10.1007/978-3-031-17385-1_9.
26. Han F., et al. 2022. Verifying of the feasibility and energy efficiency of the largest certified passive house office building in China: A three-year performance monitoring study. *Journal of Building Engineering* **46**,103703. DOI: 10.1016/j.jobe.2021.103703.
27. Dermentzis, F et al. 2019. A comprehensive evaluation of a monthly-based energy auditing tool through dynamic simulations, and monitoring in a renovation case study. *Energy & Buildings* **183**, 713–726.
28. Magni, M et al. 2021. Detailed cross comparison of building energy simulation tools results using a reference office building as a case study. *Energy & Buildings* **250**, 111260. DOI: 10.1016/j.enbuild.2021.111260.
29. Ridley, I et al. 2013. The monitored performance of the first new London dwelling certified to the Passive House standard. *Energy and Buildings* **63**, 67–78. DOI: 10.1016/j.enbuild.2013.03.052.
30. Han, F et al. 2022. Exploring solutions to achieve carbon neutrality in China: A comparative study of a large-scale passive House district and a Green building district in Qingdao. *Energy & Buildings* **268**, 112224. DOI: 10.1016/j.enbuild.2022.112224.
31. Sinacka, J and Ratajczak, K 2018. Analysis of selected input data impact on energy demand in office building - case study. *MATEC Web Conf.* **222**, 01015. DOI: 10.1051/matecconf/201822201015.
32. Magni, M, Ochs, F and Streicher, W 2022. Comprehensive analysis of the influence of different building modelling approaches on the results and computational time using a cross-compared model as a reference. *Energy & Buildings* **259**, 111859. DOI: 10.1016/j.enbuild.2022.111859.
33. Schnieders, J et al. 2015. Passive Houses for different climate zones. *Energy and Buildings* **105**, 71–87. DOI: 10.1016/j.enbuild.2015.07.032.
34. Gustafsson, M et al. 2014. Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation. *Energy and Buildings* **82**, 512–519. DOI: 10.1016/j.enbuild.2014.07.059.
35. Ridley, I et al. 2014. The side by side in use monitored performance of two passive and low carbon Welsh houses. *Energy and Buildings* **82**, 13–26. DOI: 10.1016/j.enbuild.2014.06.038.
36. Stelzl, A, Kudaya, F, and Fuchs-Hanusch, D 2025. A GIS-Based and Statistical Approach to Estimate per Capita Water Consumption Based on Different Residential Building Types. *Water* **17**, 1009. DOI: 10.3390/w17071009.