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A Comparison of the Environmental Performance between Construction Materials and Operational Energy of Nearly Zero-Energy Wood-Based Educational Building

Jozef Mitterpach [1,*], Rozália Vaňová [2], Přemysl Šedivka [1] and Jozef Štefko [2]

[1] Department of Wood Processing and Biomaterials, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Prague, Czech Republic; sedivka@fld.czu.cz
[2] Department of Wood Structures, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 96053 Zvolen, Slovakia; xvanova@is.tuzvo.sk (R.V.); stefko@tuzvo.sk (J.Š.)
* Correspondence: mitterpach@fld.czu.cz; Tel.: +420-704-533-789

Abstract: This paper focused on the environmental performance of a nearly zero-energy wood-based educational building (NZEB-W) via the life cycle impact assessment (LCIA). It identifies the environmental impacts of construction materials and operational energy demands of the NZEB-W and compares them using the SimaPro 8 software with the IMPACT 2002+ method. The LCIA results from NZEB-W show that the overall environmental impact of construction materials (98.9 Pt) and 45 years operational energy demands (98.6 Pt) will be at the same level. Its overall environmental impact 197.75 Pt for 45 years is relatively small. NZEB-W has the greatest impact on the environment in the category of damage respiratory inorganics (34.5%), 419 kg PM2.5 eq from construction materials, and 271 kg PM2.5 eq from operational energy for 45 years; follows global warming (31.7%), 1.98×10^5 kg CO_2 eq from construction materials, and 4.23×10^5 kg CO_2 eq from operational energy for 45 years; and non-renewable energy (21.8%), 2.82×10^6 MJ primary from construction materials, and 3.73×10^6 MJ primary from operational energy for 45 years. As this environmental assessment shows, the material composition of construction materials compared to the energy consumption in the use phase is an essential element for understanding the life cycle impact of buildings.

Keywords: environmental impact; construction materials; operational energy; wooden building; LCA

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1. Introduction

Collectively, buildings in the EU are responsible for 40% of our energy consumption and 36% of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition. Therefore, improving energy efficiency in buildings has a key role to play in achieving the ambitious goal of carbon-neutrality by 2050, set out in the European Green Deal [1]. In Directive 2010/31/EU [2] are NZEBs, defined as buildings with a very high energy performance, where energy requirements should mostly be covered by renewable energy sources. There is a mandatory introduction in all member states of NZEB for all new buildings or those receiving a significant retrofit from 2020 (from 2018 for public buildings).

One of the methods evaluating the environmental impacts of human activities and identifying potential areas for improvement is the life cycle assessment—LCA [3,4]. This methodology is broadly applied in practice and provides a sound assessment to the understanding of environmental issues and buildings [5–11]. LCA provides a holistic approach that is based on studying the whole industrial system involved in the production, use, and waste management of a product or service [12].

Adalberth [12] proved conformity between energy use and environmental impact during the life cycle of buildings. In both aspects, the use stage constitutes a majority of the life cycle (approximately 85% of the total estimated energy use) and 70–90% of the total environmental impact arises in this stage. Since the distribution of energy use and the environmental impact over the life cycle have a similar pattern, the energy use of a building can be used as one indicator of a building's environmental status. Moreover, the energy requirement of buildings is directly related to the technology of their construction and the type and amount of used construction materials [13,14]. Building operations worldwide account for 28% of energy-related greenhouse gas (GHG) emissions, which mainly come from the energy used for heating and/or cooling, hot water supply, ventilation and air conditioning, lighting, and process-related climate-relevant GHG emissions (i.e., the release of refrigerants and blowing agents) [15,16].

Reduction in environmental demands of the electricity production and the influence of climate change and the electricity mix are being increasingly studied [17–20].

Amongst a number of strategies to reduce energy consumption in buildings, nearly zero energy buildings (NZEB) have the potential to significantly reduce the energy they use while increasing the share of renewable resources [21,22]. Due to the findings of Hernandez and Kenny [23], the main energy consumption in a building is the energy for operation (heating, cooling, lighting, etc.), and they suggest that the amount of consumption can be regulated by technical innovations. However, it has not always been proven that the selected design choices are the most suitable from both an environmental and economic perspective [22,24].

Several studies have shown construction materials to be major contributors to environmental impacts for low energy buildings [25,26]. Each building has a unique structural composition consisting of individual elements forming a separate unit. Of course, all types of building materials have many specific technical [27–29] and environmental properties [7,30,31]. The life cycle impact assessment (LCIA) of buildings is therefore significantly influenced by the specific construction materials used for the construction. Takano et al. [32] showed that a building with a wood envelope has a better score on embodied GHG emissions and on carbon storage than an envelope made with concrete, steel, or brick. Hence, the life cycle of buildings is a complex system, since it involves the aggregate effects of a host of life cycles of their constituent materials, components, and assemblies [25,33–35]. Therefore, analysis of the environmental impact of particular structures may be helpful in selecting construction materials, with regard to the environmental performance of buildings in the early project phase [36].

In light of the above, the aim of this contribution is to evaluate the environmental performance of a nearly zero energy wood-based educational building (NZEB-W) via the LCIA, identify the environmental impacts of construction materials as well as the operational energy demands of the NZEB-W and compare them.

2. Materials and Methods

The system boundaries for LCIA [3,4] of the NZEB-W (Figure 1) are defined from cradle to the end of use with options [7], and activities included in the assessment were divided into construction materials (stage A1–A3), the energy required to operate the NZEB-W for 45 years (stage B6), and construction stage. Stages B1 to B5 and B7 were excluded from the assessment (Table 1).

Figure 1. Visualization of the NZEB-W: (**a**) exterior, (**b**) interior, (**c**) classroom, and (**d**) relaxation area.

Table 1. NZEB-W life cycle system boundaries.

Product stage	Raw material supply	A1	included
	Transport to manufacturer	A2	included
	Manufacturing	A3	included
Construction stage	Transport to construction site and transport on site	A4	excluded
	Construction and installation process	A5	excluded
Use stage	Use	B1	excluded
	Maintenance	B2	excluded
	Repair	B3	excluded
	Replacement	B4	excluded
	Refurbishment	B5	excluded
	Operational energy use	B6	included
	Operational water use	B7	excluded
End of life stage	Deconstruction and demolition	C1	excluded
	Transport	C2	excluded
	Waste processing for reuse, recovery or recycling	C3	excluded
	Waste disposal	C4	excluded
Benefits and loads beyond the system boundaries	Reuse, Recovery, Recycling potential	D	excluded

NZEB-W is a two-story structure with a countertop roof, standing on a flat terrain without a basement, located in Zvolen, Slovakia (Central Europe). Actual location factors, solar radiation, and climatic elements that have a direct impact on the energy performance of the structure were taken into account in all calculations (technical, thermotechnical, and environmental). The ground plan is rectangular with a total area of 19.2 × 29.8 m and a 572.16 m^2 built-up area. The supporting structure consists of wooden (OSB + solid wood column of spruce) box beams 400 × 80 mm, together with straw bale insulation with a bulk density $\rho = 90\ kg/m^3$. The foundations are on reinforced concrete feet. The floor above the terrain is formed by a beam construction with a double beam 150 × 300 mm in the 2000 mm module. Above this construction, the construction of a peripheral wall is also created with straw bale insulation (400 mm thick) and additional mineral insulation (50 mm thick). The construction of windows was designed to be made of A+ triple glazed windows. The proposed NZEB-W complies with the normalized value of the specific heat demand according to EN 73 0540 − 2 + Z1 + Z2 [37] and meets the assumption of achieving energy efficiency QN, EP < 40.7 $kWh/(m^2/year)$ [38]. Base building characteristics and operational energy needs of NZEB-W are listed in Table 2. Construction materials used and their distribution within the NZEB-W components are listed in Table 3.

Table 2. Characteristics of the NZEB-W.

Built-up area	572.16 m^2
Heated area	528.72 m^2
Heated volume	1679.05 m^3
Floor area	550.23 m^2
Load-bearing walls	122.5 m^2
Partitions	267.4 m^2
Window area	121.15 m^2
Door area	23 m^2
Lightning area	544.4 m^2
Electricity consumption for lightning	9.05 kWh /m^2/year
Lightning *	4926.82 kWh/year *
Electricity consumption for technical equipment	1478.05 kWh/year
Energy consumption for hot water preparation	8.60 kWh/m^2/year
Energy consumption for heating	21.59 kWh/m^2/year

* 114 × LED tube 16 W, 38 × LED tube 8 W.

The construction and thermal characteristics of the NZEB-W (Figure 1) were analyzed in detail by Mitterpach et al. [39] and use ultra-low energy building technologies with an intelligent operational management system.

Operational energy demands of NZEB-W (22,366.93 kWh/year) are linked to electricity consumption by the lighting (4926.82 kWh/year) and technical equipment (1478.05 kWh/year) of the building together with heating (11,415.07 kWh/year) and domestic hot water (4546.99 kWh/year). For lighting, the requirement of $\leq$9 kWh/m^2 per year for the energy efficiency of buildings is met. This dataset uses electricity available on the low-voltage public network in the Slovak Republic. For technical equipment, the calculations included electricity consumed by the technical equipment of buildings (computers, vending machines, portable personal equipment, etc.). These values represent 30% of the need for electricity for lighting. The dataset used was the same as for lighting. For the calculation of the specific heat demand for heating, natural ventilation with heat recovery with a normative air exchange number of 0.5/h was considered. As a residential heating system, a detailed model of a wall-mounted natural gas condensing boiler was used with a maximum heat output of 14.9 kW. To produce domestic hot water, wood chips are used in a co-generation plant with a capacity of 6667 kW (referring to fuel input).

The SimaPro 9.0 database software [40] and the IMPACT 2002+ method [41] are used for LCIA. The dataset covers all relevant process steps and technologies over the supply chain of the represented cradle to gate inventory with good overall data quality [42].

For uncertainty analysis, we used a Monte Carlo simulation. Monte Carlo analysis was chosen because it offers fast capability and simplicity to produce probabilistic results and is the most common method. LCA software SimaPro has a built-in Monte Carlo simulation capability [38]. Parameter uncertainty was evaluated for 10,000 simulation runs and 95% confidence intervals of whole NZEB-W.

Table 3. List of construction materials and their distribution into structural units of NZEB-W, OSB—oriented strand board, HDF—high-density fiberboard, CLT—cross-laminated timber, GLT—glued-laminated timber, PU—polyurethane.

Structural Units	Subtitle	m^3	kg/m^3	kg
Foundation	Concrete C 20/25	30	2250	67,500
	Rolled steel 4 mm thick	0.192	7850	1507.2
	Solid wood Spruce C24	15.174	420	6373.08
Flooring—1st floor	HDF fiberboard	7.77	600	4662
	Box beam Spruce short	1.55	420	650.64
	Box beam OSB short	1.15	550	631.14
	Box beam Spruce long	2.09	420	876.19
	Box beam OSB long	1.55	550	849.92
	Straw insulation	108.98	90	9808.56
	Grate Spruce	0.84	420	354.06
	Isover DOMO	28.98	120	3477.60
	Flex glue	4.64	1600	7418.88
	Ceramic paving	6.96	2000	13,910.40
	Exterior stairs	0.35	420	145.15
Flooring—2nd floor	CLT board	104.33	470	49,034.16
	Epoxy resin	1.16	1750	2028.60
	Ceramic paving	0.34	2000	686.88
	Paving BK	2.16	380	821.94
Peripheral walls—1st floor	Facade cladding Larch	3.06	550	1684.38
	Grate Spruce	1.18	420	493.92
	HDF fiberboard	1.84	600	1102.50
	Box beam Spruce	2.57	420	1079.57
	Box beam OSB	1.90	420	799.68
	Straw insulation	49	90	4410
	CLT board	12.25	470	5757.50
	PU lacquer	0.06	950	58.19
Inner walls—1st floor	CLT board	14.42	470	6777.40
	Glazed walls	0.34	2600	891.80
	GLT columns	7.87	420	3306.24
Ceiling beams	GLT	5.03	420	2112.08
Inner walls—2nd floor	CLT board	12.32	470	5790.45
	Glazed walls	0.78	2600	2022.12
	GLT columns	6.74	420	2830.46
Roof	Roof beams GLT	15.98	420	6713.28
	Cement board	4.12	1300	5359.58
	Isover plus	19.24	130	2501.14
	Box beam Spruce	5.24	420	2199.96
	Box beam OSB	3.88	550	2134
	Straw insulation	109.94	90	9894.60
	HDF fiberboard	8.96	600	5374.56
	Grate Spruce	4.59	420	1923.37
	OSB III board	14.28	550	7856.4
	Folded sheet metal roofing	0.32	7140	2308.53

3. Results

A comparison of LCIA between the environmental damage of the construction materials and operational energy demands of NZEB-W (Figure 2) shows that the overall environmental impact of construction materials (98.9 Pt) and 45 years operational energy demands (98.6 Pt) will be at the same level.

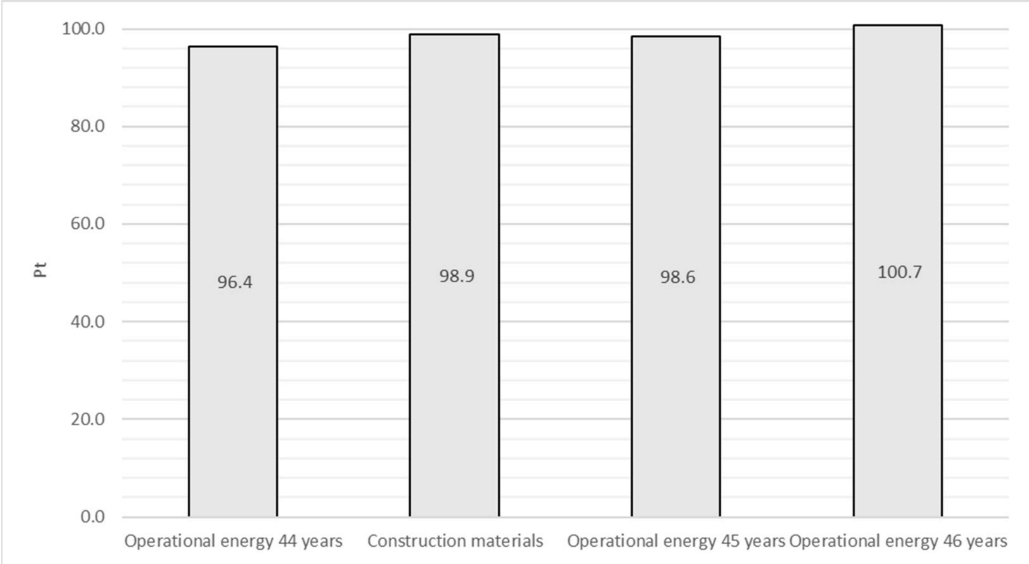

Figure 2. Environmental impact comparison of the construction materials and operational energy demands for 44, 45, and 46 years of the NZEB-W; IMPACT2002+ method; single score Pt (Eco-indicator point).

Figure 3 presents the environmental impact comparison of construction materials and operational energy demands for 45 years of the NZEB-W; IMPACT2002+ method; midpoints single score Pt (Eco-indicator point). This comparison shows a different amount of influence on the individual impact categories (Figure 3, Tables 4 and 5). The total negative impact of NZEB-W had the greatest impact on the environment in the category of damage respiratory inorganics (34.5%), 419 kg PM2.5 eq from construction materials and 271 kg PM2.5 eq from operational energy for 45 years; followed by global warming (31.7%), 1.98×10^5 kg CO_2 eq from construction materials and 4.23×10^5 kg CO_2 eq from operational energy for 45 years; and non-renewable energy (21.8%), 2.82×10^6 MJ primary from construction materials and 3.73×10^6 MJ primary from operational energy for 45 years. These first three impacts on the environment accounted for 88% of the total environmental impact.

Table 4. Environmental impact comparison of the construction materials and operational energy demands for 45 years of the NZEB-W; IMPACT2002+ method; midpoints characterization.

Impact Category	Unit	Total	Construction Materials	Operational Energy 45 Years
Respiratory inorganics	kg PM2.5 eq	6.90×10^2	4.19×10^2	2.71×10^2
Global warming	kg CO_2 eq	6.21×10^5	1.98×10^5	4.23×10^5
Non-renewable energy	MJ primary	6.55×10^6	2.82×10^6	3.73×10^6
Land occupation	m^2org.arable	1.06×10^5	9.78×10^4	8.03×10^3
Terrestrial ecotoxicity	kg TEG soil	1.26×10^7	9.75×10^6	2.89×10^6
Non-carcinogens	kg C_2H_3Cl eq	9.05×10^3	6.94×10^3	2.11×10^3
Carcinogens	kg C_2H_3Cl eq	6.59×10^3	5.07×10^3	1.52×10^3
Terrestrial acid/nutri	kg SO_2 eq	9.67×10^3	5.35×10^3	4.32×10^3
Mineral extraction	MJ surplus	3.97×10^4	3.38×10^4	5.97×10^3
Aquatic ecotoxicity	kg TEG water	3.93×10^7	2.97×10^7	9.63×10^6
Ionizing radiation	Bq C-14 eq	1.67×10^7	1.94×10^6	1.48×10^7
Respiratory organics	kg C_2H_4 eq	1.75×10^2	1.13×10^2	6.23×10^1
Ozone layer depletion	kg CFC-11 eq	4.16×10^{-2}	1.52×10^{-2}	2.64×10^{-2}
Aquatic eutrophication	kg PO_4 P-lim	1.04×10^2	4.00×10^1	6.43×10^1
Aquatic acidification	kg SO_2 eq	2.62×10^3	1.37×10^3	1.26×10^3

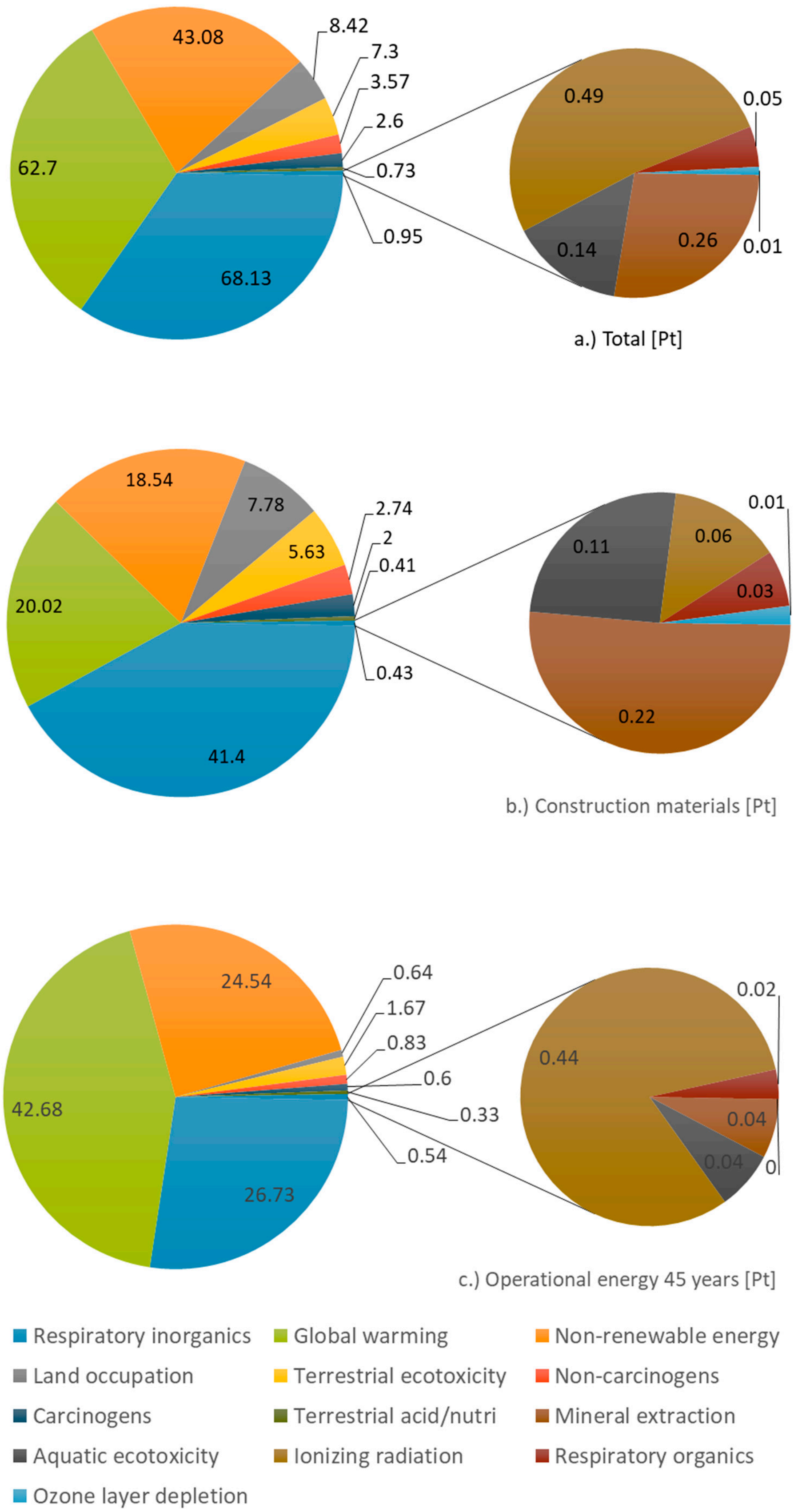

Figure 3. Environmental impact comparison of construction materials and operational energy demands for 45 years of the NZEB-W; IMPACT2002+ method; midpoints single score Pt (Eco-indicator point).

Table 5. Environmental impact comparison of the construction materials and operational energy demands for 45 years of the NZEB-W; IMPACT2002+ method; midpoints characterization.

Impact Category	Unit	Domestic Hot Water	Flooring 1st	Flooring 2nd	Foundations	Heat Energy	Inner Walls 1st	Inner Walls 2nd	Lightning	Peripheral Walls	Roof	Technical Equipment	Windows and Doors
Carcinogens	kg C_2H_3Cl eq	6.7×10^1	7.8×10^2	5.6×10^2	2.6×10^2	6.0×10^2	4.3×10^2	8.1×10^2	6.5×10^2	4.0×10^2	6.9×10^2	2.0×10^2	1.1×10^3
Non-carcinogens	kg C_2H_3Cl eq	1.4×10^2	6.5×10^2	7.6×10^2	3.1×10^2	9.4×10^2	6.7×10^2	1.2×10^3	8.0×10^2	5.2×10^2	1.7×10^3	2.4×10^2	1.1×10^3
Respiratory inorganics	kg PM2.5 eq	8.3	1.4×10^2	64	15	78	31	53	1.4×10^2	26	42	43	43
Ionizing radiation	Bq C-14 eq	9.3×10^3	1.8×10^5	2.3×10^5	8.5×10^4	2.9×10^5	2.1×10^5	3.8×10^5	1.1×10^7	2.5×10^5	3.5×10^5	3.3×10^6	2.6×10^5
Ozone layer depletion	kg CFC-11 eq	2.7×10^{-3}	1.6×10^{-3}	2.1×10^{-3}	9.4×10^{-4}	2.7×10^{-3}	1.5×10^{-3}	2.6×10^{-3}	1.6×10^{-2}	1.7×10^{-3}	3.0×10^{-3}	4.8×10^{-3}	1.8×10^{-3}
Respiratory organics	kg C_2H_4 eq	3.6	9.4	20	6.5	41	7.4	12	14	7.8	17	4.1	34
Aquatic ecotoxicity	kg TEG water	1.2×10^5	2.5×10^6	4.8×10^6	1.1×10^6	1.3×10^5	3.9×10^6	6.3×10^6	7.2×10^6	2.2×10^6	5.8×10^6	2.2×10^6	3.0×10^6
Terrestrial ecotoxicity	kg TEG soil	1.7×10^5	7.6×10^5	1.8×10^6	4.4×10^5	5.2×10^5	9.6×10^5	1.3×10^6	1.7×10^6	6.0×10^5	2.4×10^6	5.1×10^5	1.5×10^6
Terrestrial acid/nutri	kg SO_2 eq	3.1×10^2	4.3×10^2	1.0×10^3	2.6×10^2	1.8×10^3	4.5×10^2	7.8×10^2	1.7×10^3	4.5×10^2	8.3×10^2	5.2×10^2	1.1×10^3
Land occupation	m^2org.arable	6.2×10^3	4.7×10^3	3.4×10^4	4.8×10^3	0.0	1.1×10^4	1.4×10^4	1.4×10^3	1.4×10^4	1.4×10^4	4.2×10^2	1.2×10^3
Aquatic acidification	kg SO_2 eq	42	1.3×10^2	2.1×10^2	59	2.8×10^2	1.3×10^2	2.5×10^2	7.2×10^2	1.3×10^2	1.9×10^2	2.2×10^2	2.6×10^2
Aquatic eutrophication	kg PO_4 P-lim	5.3×10^{-1}	4.0	6.4	1.6	1.2	3.9	7.1	48	3.6	4.7	14	8.7
Global warming	kg CO_2 eq	1.2×10^3	1.9×10^4	2.8×10^4	1.3×10^4	2.8×10^5	1.7×10^4	3.2×10^4	1.1×10^5	1.8×10^4	3.5×10^4	3.3×10^4	3.6×10^4
Non-renewable energy	MJ primary	1.6×10^4	2.5×10^5	5.1×10^5	1.2×10^5	4.4×10^5	2.3×10^5	4.2×10^5	2.5×10^6	2.5×10^5	3.3×10^5	7.6×10^5	7.1×10^5
Mineral extraction	MJ surplus	1.3×10^2	2.6×10^3	1.0×10^3	7.1×10^2	2.4×10^2	2.8×10^3	5.9×10^3	4.3×10^3	2.3×10^3	7.1×10^3	1.3×10^3	1.1×10^4

3.1. LCIA Construction Materials

The major negative impact of construction materials is presented by respiratory inorganics (41.40 Pt), followed by global warming (20.02 Pt), and non-renewable energy (18.54 Pt). The course of environmental damage from construction materials incorporated into structural units (Table 2) as well as damage from the composition of energy requirements (type of energy consumption) NZEB-W are shown in Figure 4 and Table 5.

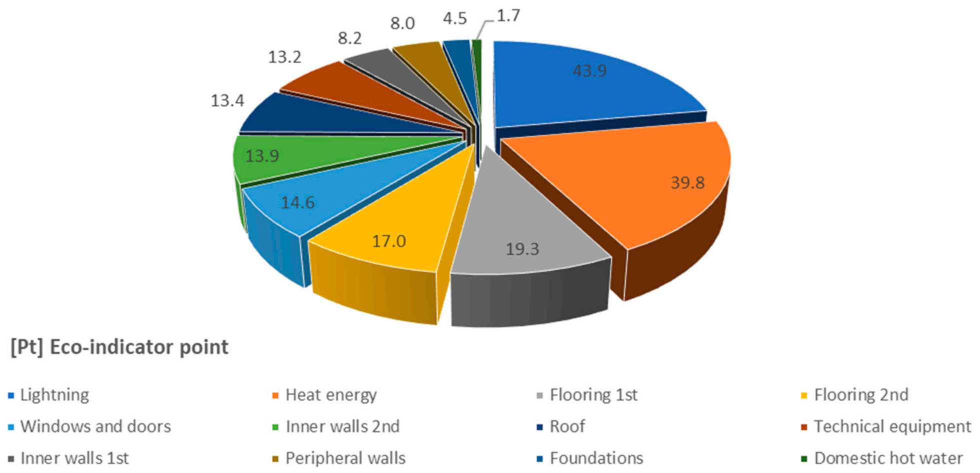

Figure 4. Environmental impact comparison of the construction materials and operational energy demands for 45 years (lightning, heat energy, technical equipment, domestic hot water) of the NZEB-W in structural unit; IMPACT2002+ method; single score Pt (Eco-indicator point).

The greatest damage of construction materials is caused by the first floor materials, second floor, and infill structures (windows and doors). For example, ceramic paving caused first floor flooring had the highest impact (15.8 Pt) among the construction elements mainly affecting respiratory inorganics (133 kg PM2.5 eq), global warming (1.00×10^4 kg CO_2 eq), and non-renewable energy (1.51×10^5 MJ primary). The contribution of wood as a construction material is displayed in second floor flooring where 93.3% of weight came from CLT panel, which was also the second-highest value within the whole construction, representing 20.8% of the total weight. The total impact of CLT (9.76 Pt) was mainly in respiratory inorganics (33.2 kg PM2.5 eq), global warming (1.32×10^4 kg CO_2 eq), and non-renewable energy (2.01×10^5 MJ primary). The third-largest contributors of the structural unit were windows (13.4 Pt) and doors (1.16 Pt), which had a relatively high impact due to the large glass filling area (non-renewable energy 7.08×10^5 MJ primary; respiratory inorganics 43.4 kg PM2.5 eq; and global warming 3.58×10^4 kg CO_2 eq). For example, the influence of inner walls 2nd (13.9 Pt) is largely due to the most filling structures of glazed walls (80.3%). The roof also had a relatively high impact (13.4 Pt) caused by sheet metal roofing, which contained only 6.3% of the weight of the roof and 1% of the total weight of the building.

A whole building assessment was conducted by Tushar et al. [27] and research was conducted to find the contribution to environmental impacts for different building components (e.g., ceiling, wall, and floor) and to compare design options to find the most suitable materials for building components. For example, the most adverse effects of the four paving materials used were ceramic tiles, with an effect on global warming potential of 15,227 CO_2 eq and the primary energy consumption of 255,896 MJ. As in our study (although the buildings were structured differently), floors and walls had the total greatest impact on both global warming potential and primary energy demand. However, a complete and conclusive comparison was not possible because the research used different evaluation methods and the buildings did not have completely comparable characteristics in common.

Najjar et al. [43] suggested a new proposal for a building and compared the potential reduction in energy consumption and environmental impacts. After calculating the quantities of construction materials, a simulation was made to measure the impact categories such as global warming potential. Global warming potential was from 4,537,449 kg CO_2 equivalent to 2,934,501 kg CO_2 equivalent, which corresponds to a decrease of 35.33%. Insights into the results show that all components of building envelopes affect the consumption of energy in buildings, however, exterior walls and windows account the most in these values. For example, Estokova et al. [44] showed that the overall environmental impacts of a residential house, on average, were represented by 220 kg CO_2eq emissions for global warming and 1.03 kg SO_2eq emissions for acidification potential. Related to 1 m^2 of floor area, our NZEB-W reached higher values of 359.9 kg CO_2eq and 12.216 kg SO_2eq. These values should also not be simply compared with each other as the individual studies have different inventory bases and were compared with different evaluation methods.

Generally, embodied emissions of wood-based construction are generally less than conventional masonry constructions [45–47]. According to Vilčeková et al. [48], wooden log houses have a significantly lower negative impact on the environment compared to a wooden house, which is a combination of a wooden frame and other conventional materials. As is shown, the impact of wood constructions can also be influenced by other types of used construction materials.

3.2. LCIA Operational Energy

For the highest impact values of operational energy for 45 years, the global warming (42.68 Pt), followed by respiratory inorganics (26.73 Pt) and non-renewable energy (24.54 Pt) impact categories were responsible.

According to Fouquet et al. [25], NZEB introduces highly energy-efficient systems through renewable energy sources, reducing the energy demand together with adequate regulation of thermal insulation thickness. The results of our study proved the use stage environmental impact of energy-efficient buildings reached a balance in the 45th year of use. In this respect, construction materials are major contributors to environmental impact for low-energy buildings. It was also confirmed that the effects of electricity produced from renewable sources (production domestic hot water, wood chips in a cogeneration plant) had less environmental impacts (1.77%) than the energy used from the public grid (44.5% lighting and 13.4% technical equipment; the energy mix for Slovakia uses electricity mostly from brown coal, lignite combustion, and nuclear energy) and the production of heat from natural gas (40.3%; is the second non-renewable resource). The overall results showed that the highest negative impact connected with operational energy needs came from global warming (4.23×10^5 kg CO_2 eq), respiratory inorganics (271 kg PM2.5 eq), and non-renewable energy (3.73×10^6 MJ primary). The main contributor to global warming remained heat from natural gas. Ionizing radiation is connected to the electricity consumption mix of Slovakia, which widely uses nuclear energy, and the impact on non-renewable energy is from brown coal combustion.

Rodrigues and Freire [49] confirmed that the use phase impacts are highly correlated with electricity use, so changes in the electricity mix may have a significant influence on the results. Pajchrowski et al. [14] stated that the main source of negative environmental impact in the life cycle of buildings is the energy consumption at the stage of long-term building use and the impact categories that are mainly influenced by the negative impact are as follows: respiratory inorganics, global warming, and non-renewable energy. Our study confirmed the substantial impact of these impact categories, but the magnitude of the impact was different. The sequences of construction materials were the same, unlike the 45th year of energy consumption where the order was altered to non-renewable energy, global warming, and respiratory inorganics, respectively (Tables 4 and 5 and Figures 3 and 4). From Luo and Chen's [50] analysis, it can be seen that the total carbon emissions during the building use phase is the highest, and is the focus of reducing carbon emissions. The comparison in our study confirms this finding and specifies that for NZEB-W after the 45th year of using the building, the environmental impact of electricity consumption is higher than the environmental impact of the building materials. Röck et al. [51] showed a clear reduction trend in life cycle GHG emissions due to improved operational energy performance. The analysis revealed an increase in relative and absolute contributions of so-called 'embodied' GHG emissions. Due to the study, the average share of embodied GHG emissions from buildings, following the current energy performance regulations, was approximately 20–25% of life cycle GHG emissions, followed by 45–50% for highly energy-efficient buildings, and surpassed 90% in extreme cases. At the same time, the contribution of embodied GHG emissions increased up to and beyond a ratio of 1:1 (embodied:operational) when we considered a 50-year period. Our study confirmed the validity of these statements. Reduction in environmental demands of the electricity production and the influence of climate change and the electricity mix are being increasingly studied [17–20]. It is expected that electricity mixed with lower GHG intensity leads to a change in the most influential variables due to a reduction in use phase impacts [49,52].

Therefore, given the type of building, its overall environmental impact of 197.75 Pt (Respiratory inorganics 690 kg PM2.5 eq; Global warming 6.21×10^5 kg CO_2 eq; non-renewable energy 6.55×10^6 MJ primary) is relatively small, and when comparing the environmental impacts of construction materials and up to 45 years of energy consumption, the environmental suitability of the construction materials as well as the energy efficiency of NZEB-W is indicated. If public policies requiring decreased energy demands in buildings are to be implemented, one can expect embodied loads in most buildings to become as relevant as (if not more than) operational loads [53].

3.3. Lifespan of Building

According to Mequignon et al. [54], the lifespan of buildings has a significant impact on the environment. Safari and AzariJafari [55] state that most studies have shown that by focusing on the operational phase, which is the longest phase of a building's life cycle, the greatest environmental impact reduction can be achieved and the lifetime of case studies in the literature ranges from 30 to 100 years. Our study further agrees with studies that declare that building materials contribute significantly to the environmental impacts of low-energy buildings [25,26], and a clear definition of the lifetime of buildings and materials should be an important upcoming topic for LCA in the field of buildings [56]. In relation to the above-mentioned information and in order to balance the environmental damage of construction materials and the energy performance of buildings, we propose that the building lifetime (BL) should be limited by the number of years "n" when the environmental damage of the construction materials (EDM) is approximately equal to the environmental damage of the energy needs of the building (EDE) for "n" years: BL = EDM $\approx$ n $\times$ EDE

3.4. Uncertainty Analysis

Uncertainty analysis with a Monte Carlo simulation of the NZEB-W is presented in Figure 5 and Table 6. The results (10,000 simulation runs and 95% confidence intervals) show the details of all the interval variations including the mean, median values, standard error of mean (SEM), standard deviation (SD), and the coefficient of variability (CV).

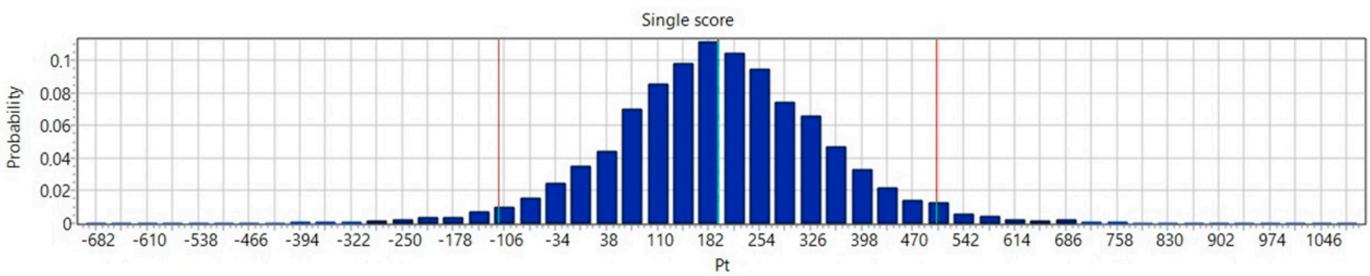

Figure 5. Uncertainty analysis of NZEB-W, method IMPACT 2002+, single score, confidence interval: 95%.

Table 6. Uncertainty analysis of NZEB-W, method IMPACT 2002+, characterization, confidence interval: 95%, standard deviation (SD), coefficient of variability (CV), and standard error of mean (SEM).

Impact Category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
Global warming	kg CO_2 eq	6.21×10^5	6.20×10^5	1.27×10^4	2.05	5.99×10^5	6.49×10^5	1.27×10^2
Aquatic acidification	kg SO_2 eq	2.62×10^3	2.61×10^3	1.39×10^2	5.31	2.37×10^3	2.92×10^3	1.39
Respiratory inorganics	kg PM2.5 eq	6.89×10^2	6.86×10^2	4.54×10^1	6.59	6.11×10^2	7.88×10^2	4.54×10^{-1}
Terrestrial acid/nutri	kg SO_2 eq	9.66×10^3	9.62×10^3	6.84×10^2	7.08	8.42×10^3	1.11×10^4	6.84
Mineral extraction	MJ surplus	3.94×10^4	3.90×10^4	4.42×10^3	1.12×10^1	3.19×10^4	4.91×10^4	4.42×10^1
Respiratory organics	kg C_2H_4 eq	1.75×10^2	1.72×10^2	2.00×10^1	1.14×10^1	1.50×10^2	2.25×10^2	2.00×10^{-1}
Non-renewable energy	MJ primary	6.55×10^6	6.43×10^6	8.02×10^5	1.22×10^1	5.32×10^6	8.48×10^6	8.02×10^3
Carcinogens	kg C_2H_3Cl eq	6.61×10^3	6.41×10^3	1.17×10^3	1.77×10^1	4.94×10^3	9.42×10^3	1.17×10^1
Ozone layer depletion	kg CFC-11 eq	4.16×10^{-2}	4.12×10^{-2}	1.58×10^{-2}	3.79×10^1	1.16×10^{-2}	7.41×10^{-2}	1.58×10^{-4}
Land occupation	m^2org.arable	1.07×10^5	9.40×10^4	5.03×10^4	4.72×10^1	4.79×10^4	2.36×10^5	5.03×10^2
Aquatic eutrophication	kg PO_4 P-lim	1.05×10^2	8.58×10^1	7.10×10^1	6.77×10^1	3.76×10^1	2.86×10^2	7.10×10^{-1}
Ionizing radiation	Bq C-14 eq	1.67×10^7	1.06×10^7	2.21×10^7	1.33×10^2	4.51×10^6	6.50×10^7	2.21×10^5
Non-carcinogens	kg C2H3Cl eq	8.32×10^3	8.44×10^3	7.56×10^4	9.09×10^2	1.44×10^5	1.58×10^5	7.56×10^2
Aquatic ecotoxicity	kg TEG water	3.90×10^7	3.58×10^7	4.97×10^8	1.27×10^3	-9.54×10^8	1.03×10^9	4.97×10^6
Terrestrial ecotoxicity	kg TEG soil	1.10×10^7	8.71×10^6	2.24×10^8	2.04×10^3	-4.43×10^8	4.68×10^8	2.24×10^6

A Monte Carlo simulation on a single score of whole NZEB-W showed a mean of 196.22, median of 193.70, SEM of 1.52, and CV of 77.66%. The major negative impacts were presented in a small CV by respiratory inorganics (CV 6.59%), followed by global warming (CV 2.05%), and non-renewable energy (CV 12.2%). These first three impacts on the environment accounted for 88% of the total environmental impact. Less significant impact categories with a high CV were caused by the uncertainties in the database for the energy country mix, or in the case of materials due to their uncertainty by acting primarily on aquatic ecotoxicity, terrestrial ecotoxicity, non-carcinogens, and ionizing radiation. Similar results were found, for example, by de Souza et al. [57], Robati et al. [58], and Hasan et al. [59].

3.5. Research Limitations

To compare the results of this work with others, it is important to be aware of the parameters that affect the results of the study, in particular, the different types of buildings and their location, functional units, system boundaries, depth of inventory analysis, type of databases used, chosen LCIA test method, and software used. There are many works, however, for example, Safari and AzariJafari [43] also reached these findings after a thorough study of the articles, where 50 articles were included for a comprehensive analysis and classification of the BIM-LCA integration methodology. Owsianiak et al. [60] and Stavropoulos et al. [61] showed that the single score resulting from each LCIA method cannot be directly compared with the other due to differences in characterization, normalization, and weighting factors used in each method. Alyaseri and Zhou [62] preferred to evaluate outcomes from different methods, where the impact or damage categories were used for comparison instead of a comparison based on single scores. From the article by Mitterpach et al. [63], there were also clearly different values of the results in the different methods used for LICA, although the trends of environmental damage were similar. Concerning the databases, the material sensitivity originated from the background data [56]. Sensitivity results found due to database variation are very much in line with the findings from Modahl et al. [64], which showed that using two datasets with different degrees of specificity implies substantial differences. The importance of sensitivity depending on the evaluation method was also confirmed by Röder et al. [65].

The results of this study are bound to a specific structure and region (central Slovakia). Hence, comparison with other buildings should be carried out with care, especially when comparing operational energy needs vastly bound to the energy consumption mix of a specific country. The system boundaries of this LCIA study considered only some phases of the life cycle according to Table 1. It is therefore necessary to take this fact into consideration when comparing the results with other works, with a recommendation to take into account the lifetime of buildings in future works in order to also point out reliable results within extended system boundaries.

4. Conclusions

The paper focused on and compared the environmental performance of an almost zero energy wood-based educational building (NZEB-W) through a life cycle impact assessment (LCIA). It identifies the environmental impacts of building materials and the operational energy intensity of NZEB-W.

Based on this analysis and the deeply studied research cited in this study, it was confirmed that each LCA study is unique in terms of functional unit, system boundaries, inventory analysis, and the content of the impact assessment method. The results of this LCA study assessing the environmental impacts of building materials and the energy performance of a building for wood-based teaching show that it is important to compare the environmental properties of the building materials used and the energy mix consumption. A comparison of the environmental damage of building materials with the energy intensity needs of the NZEB-W operation showed a different impact on individual categories of impacts, depending on the material composition and energy mix. The biggest negative impacts of this NZEB-W were respiratory inorganics, global warming, and non-renewable energy of the building materials and energy consumption. Environmental damage by building materials as well as "n" annual energy consumption represents a significant part of NZEB's environmental impact and therefore the minimum lifetime of a building should be limited to a number of years when the environmental damage to building materials is approximately equal to the environmental damage caused by operational energy needs. Particular attention should be paid to the amount of cement, ceramic, and glass materials, the type of insulation and wood materials, and the amount and type of energy.

A comparison of the environmental damage of building materials with the energy intensity needs also indicated the environmental suitability of building materials as well as the energy efficiency of NZEB-W.

Regarding environmental damage and the above information, the material composition of building materials compared to energy consumption in the use phase is an essential element for understanding the complex life cycle impact of buildings.

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