Bauhaus-Universität Weimar
06. / 07. März 2024
BAUPHYSIKTAGE IN WEIMAR 2024
WBA

LIFE CYCLE ASSESSMENT OF THE PROTOTYPE OF A NOVEL ENERGY GENERATION AND HEAT STORAGE SYSTEM

Mahnoor Khawaja, Svenja Carrigan, Oliver Kornadt
Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau (RPTU)
E-Mail: mahnoor.khawaja@rptu.de

Abstract

Life cycle assessment (LCA) is a useful method to quantify the environmental impacts of a product or system for different life cycle stages. In the design stage, it can help decision makers to find the most sustainable material choices. A novel energy generation and heat storage system is under development at Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau (RPTU). A prototype of this system has been developed and installed at RPTU for testing and validation purposes. This paper depicts the significance of the LCA application for the design stage of the prototype. By use of LCA, hotspots have been identified and it could be shown that potential replacement with better material choices result in a reduction of around 21% of Global warming potential (GWP) and non-renewable primary energy consumption (PENRE) in the design stage.

Keywords

Life cycle assessment, Energy production and storage system

Introduction

Buildings as a result of construction, use and demolition have a share of around 40% of gross energy consumption in the European union (EU) (European Comission, 2020). Likewise, 35% of green house gases emissions in EU are linked to the building sector (European environment agency, 2023). This has given rise to several improved practices and building concepts such as “Passive houses”, “Low energy houses” and “Net zero energy buildings”. In Europe, the “Energy performance of buildings directive EPBD (2010/31/EU)” introduced a concept of “Net zero energy building NZEB” where the operational energy consumption is almost brought down to zero by improving building construction details and the residual energy demand should be met by provision of renewable energy generation (Directive, 2010). On the contrary, research has shown that achieving low consumption in the operational stage is resulting in additional resource consumption in other stages and thus elevated embodied impacts (Crawford and Stephan, 2013). Life cycle analysis (LCA) is one of the widely used methods to assess life cycle environmental impacts (Means and Guggemos, 2015). By using this methodology, the LCA practitioner can get a clear depiction of how much impacts, the design alternative under question, pose to the environment.

The German government plans to reach the goal of a nearly climate neutral building stock by 2050 (Bundesministerium für Wirtschaft und Energie (BMWi, 2019). In addition to heating, cooling is also gaining significant emphasis with respect to the building efficiency. Thus, there is a need to develop new sustainable solutions. The key target of the project “EffKon” at Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau (RPTU) is to research and develop a novel energy generation and thermal storage system for building cooling and heating operations (Schröter et al., 2023). The project is sponsored by the Federal Ministry for Economic Affairs and Climate Action and is being executed along with industrial partners Innogration GmbH, Panco GmbH, CuroCon GmbH and Betonwerk Büchner GmbH & Co. KG. The work presented in this paper is a life cycle analysis of the prototype of the system aimed to be designed under project EffKon.

Prototype description

The Prototype consists of an ‘energy pole’ mounted with the help of a foundation (see section in Figure 1). The outermost layer of the prototype consists of a transparent Plexiglas pipe which is divided by an air gap from the solar absorber copper pipes spiral.

The centre of the pole is insulated by a layer of glass wool. In the centre, two hollow steel pipes can be seen where copper heat exchanger pipes are immersed in an organic wax-based paraffin phase change material (PCM). The innermost core consists of the water, again immersed in copper heat exchanger pipes. Water from the building enters the absorber pipes from the bottom and absorbs the heat from the absorber pipes.

The heated water enters the heat exchanger copper pipes surrounded by the PCM, transferring heat energy. Afterwards, the water flows through the heat exchanger copper pipes surrounded by the water, where more energy can be transferred, and finally exits the prototype.

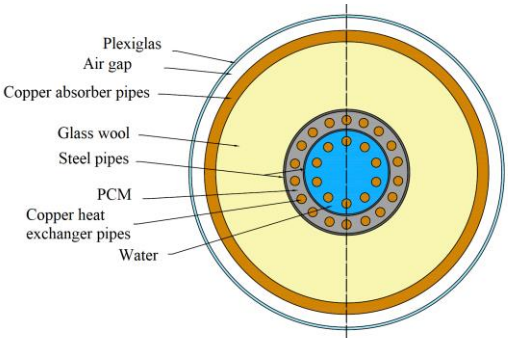


Figure 1. Sectional view of the energy pole

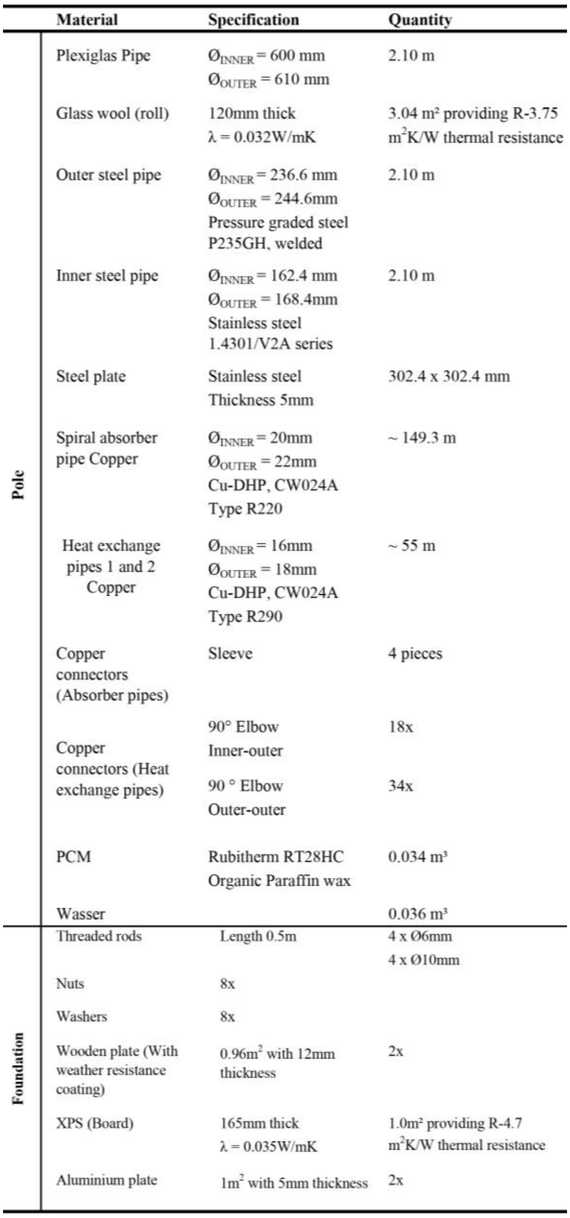
The prototype's foundation consists of wooden plate, followed by Aluminium plate fixed to the Extruded polystrene XPS insulation board with the help of threaded rods. The detailed bill of quantities for prototype is listed in Table 1.

Life cycle analysis of prototype

Life cycle analysis (LCA) is one of the widely used methods to assess the environmental impacts over parts of or while life cycles of materials and products (Means and Guggemos, 2015). By using LCA, different life cycle stages of a product under question can be examined. Eventually, its possible to evaluate different environmental effects caused by the product in its different lifecycle stages, i.e. production, construction, operation, disposal.

This paper reports values for the impact categories global warming potential (GWP) and non-renewable primary energy (PENRE). The system boundary of the LCA is production stage only (A1-A3). Due to lack of data available other impact categories such as Ozone depletion potential or use of net fresh water are not be evaluated. To ensure comparability, only the datasets using EN14025 (DIN, 2011) and EN15804:A1 (DIN, 2019) as core product category rules (PCR) have been selected. Omission of components ≤ 1% by mass is permissible as per EN15804:A1. As the data for small components such as copper connectors and nuts/washers were not available, impacts for these components have been excluded. As evident from Table 2, the major focus has been to shortlist materials relevant to geographical regions relevant to Germany. However, due to unavailability of data for some materials, the impacts have been derived for products from other European countries i.e., Norway, Sweden, Poland etc. Sources of the data inventory have mainly been Ökobaudat (Bundesministerium des Innern, 2018) and Environmental product declarations (EPD). Data for PCM has been derived from literature. Likewise, data for stainless steel in pipe form could not be derived and has only been available for products in sheet form.

Table 1. Bill of quantities for the prototype



	Material	Specification	Quantity
Pole	Plexiglas Pipe	$Ø_{INNER}$ = 600 mm $Ø_{OUTER}$ = 610 mm	2.10 m
	Glass wool (roll)	120mm thick λ = 0.032W/mK	3.04 m² providing R-3.75 m^2K/W thermal resistance
	Outer steel pipe	$Ø_{INNER}$ = 236.6 mm $Ø_{OUTER}$ = 244.6mm Pressure graded steel P235GH, welded	2.10 m
	Inner steel pipe	$Ø_{INNER}$ = 162.4 mm $Ø_{OUTER}$ = 168.4mm Stainless steel 1.4301/V2A series	2.10 m
	Steel plate	Stainless steel Thickness 5mm	302.4 x 302.4 mm
	Spiral absorber pipe Copper	$Ø_{INNER}$ = 20mm $Ø_{OUTER}$ = 22mm Cu-DHP, CW024A Type R220	~ 149.3 m
	Heat exchange pipes 1 and 2 Copper	$Ø_{INNER}$ = 16mm $Ø_{OUTER}$ = 18mm Cu-DHP, CW024A Type R290	~ 55 m
	Copper connectors (Absorber pipes)	Sleeve	4 pieces
	Copper connectors (Heat exchange pipes)	90° Elbow Inner-outer	18x
		90 ° Elbow Outer-outer	34x
	PCM	Rubitherm RT28HC Organic Paraffin wax	0.034 m³
	Wasser		0.036 m³
Foundation	Threaded rods	Length 0.5m	4 x Ø6mm 4 x Ø10mm
	Nuts	8x	
	Washers	8x	
	Wooden plate (With weather resistance coating)	$0.96m^2$ with 12mm thickness	2x
	XPS (Board)	165mm thick λ = 0.035W/mK	1.0m² providing R-4.7 m^2K/W thermal resistance
	Aluminium plate	$1m^2$ with 5mm thickness	2x

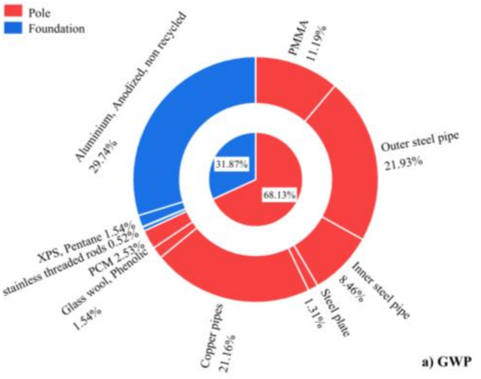
Results and discussion

Figure 2 shows the resulting environmental profile of the prototype production. GWP and PENRE both are almost in similar proportions for all the materials. In the pole, copper pipes and the outer steel pipe are the major hotspots followed by PlexiGlas or Polymethyl methacrylate (PMMA) pipe and inner stainless-steel pipe. Whereas, in the foundation, Aluminium has a major impact share. An overview of the impacts is listed in Table 3. The GWP and PENRE from the pole amounts to be 701 kg-CO_2 and 10136 MJ, respectively, while the foundation causes GWP and PENRE of 326 kg-CO_2 and 4719 MJ, respectively.

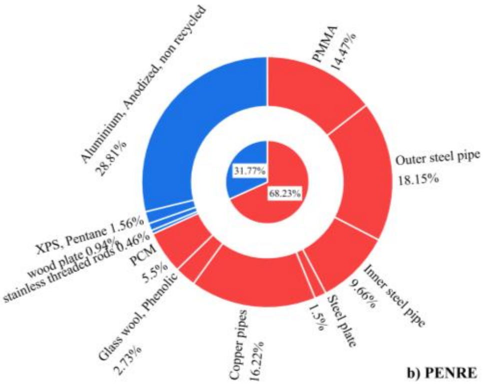
After the evaluation of impacts and identification of hotspots, the next step has been to explore material alternatives with lesser impacts for different components. Figure 3 shows an overview of possible sustainable alternatives and to what extent of impact

Table 2. Data inventory for production stage of the prototype

Part	Material	Sub category	ID	Source	EPD program	Plant location	Reference unit	GWP	PENRE
Pole	Plexiglas (sheet)		795ab193-fc50-463d-a5f8-e37d5336ee78	Okobaudat	-	DE	$1m^3$	6291	107500
			41b8a86d-5d44-49fb-a9b8-de2a9041f1fd	Okobaudat	-	DE	$1m^3$	5757	99870
			EPD-EVO-20180023-IAD4-EN	EPD	IBU	DE	1kg	1190	103.4
	Pressure steel (pipe)		EPD-ARC-20220192-CBA1-EN	EPD	IBU	FR RO PL CZ	1tonn	2800	28700
			EPD-ERC-20200034-IBC1-EN	EPD	IBU	TR	1tonn	2948	39999
	Stainless steel (sheet)		EPD-OTO-20190002-IBD1-EN	EPD, Okobaudat	IBU	DE , SE , FI , US , MX	1tonn	3390	55900
			EPD-OTO-20190003-IBD1-EN	EPD, Okobaudat	IBU	DE , SE , FI , US	1tonn	2740	37200
			EPD-RFI-20210280-IBD1-EN	EPD	IBU	FI , DE	1tonn	3390	55900
	Copper (pipe)		EPD-KME-20150002-IBE1-DE	EPD	IBU	DE	1kg	1.97	21.8
	Glass wool (Roll)	Phenol resin	EPD-SAR-20200272-CBA1-EN	EPD	IBU	CH	1kg	1.31	33.6
		Biobased resin	S-P-01894	EPD	EPD international	BE , DE , CZ	$1\ m^2$, 240mm thickness	5.71	94.8
			EPD-SAR-20200273-CBA1-DE	EPD	IBU	CH	1kg	1.08	27.1
	PCM		-	Literature	-		1kg	0.995	31.2
	Water		ce3057d1-3371-47b4-a982-a1c42c2c6a85	Okobaudat	-		1kg	0.000128	0.001754
Foundation	stainless threaded rods		EPD-OTO-20190107-IBD1-EN	EPD	-	UK , US , SE	1tonn	2890	37200
	Wood plate (Coated)		205/2021	EPD	Ecoplatform	PL	$1m^3$	-62.4	12100
	XPS (board) with blowing agent options:	CO2 + BMB	EPD-BAS-20190114-IBA1-DE 70199377-9eac-401c-b76b-0bf412291949	EPD, Okobaudat	IBU	DE	$1\ m^2$, 120mm thickness	3.25	158.96
		CO2	EPD-BAS-20190113-IBA1-DE 41e09ab7-0e73-4303-84fd-97cb0809db02	EPD, Okobaudat	IBU	DE	$1\ m^2$, 120mm thickness	9.85	179.09
			EPD-DOW-2-13111-DE	EPD	IBU	DE , EL	$1\ m^2$, 100mm thickness	10.2	146
			EPD-FPX-20190111-IBE1-DE 54b63599-07e3-48b1-b33b-11bcbab9032f	EPD, Okobaudat	IBU	DE	$1\ m^2$, 100mm thickness	9.38	145
		HFO	EPD-JAI-20200164-IBC1-EN a8782644-13be-42ab-93ea-950ad7f0c2a5	EPD, Okobaudat	IBU	DE	$1m^3$	121	1860
		Pentane	43e99b8c-90d8-4fcd-90ce-342fb0b7366e	Okobaudat	-	DE	$1m^3$	96.34	1406
	Aluminium (plate) with surface treatment options:	Coil coated	EPD GDA 130	EPD	IBU	EU-28	1kg	6.39	83.2
			EPD hydro	EPD	EPD norge	NO	1kg	1.32	16.6
		Anodized	EPD3–COIL-2017	EPD	European Aluminium	BE	m2, 0.5mm thick, anodic layer 8um	15.3	214



a) GWP

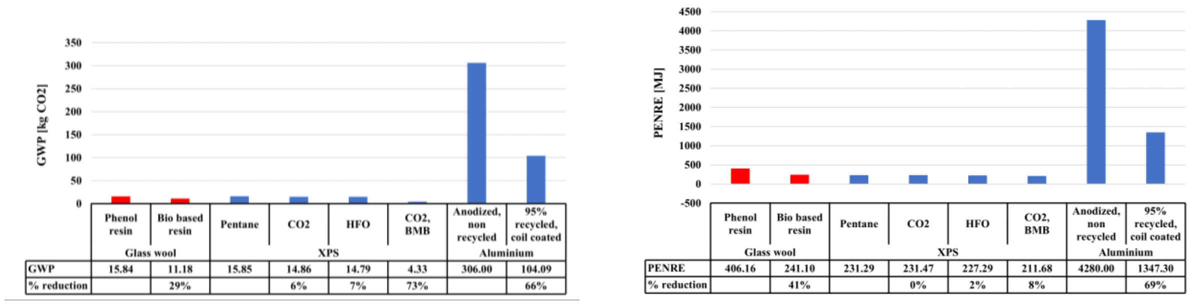


b) PENRE

Figure 2. Environmental profile of prototype (Original scenario)

Table 3. Impact values for prototype (Original scenario)

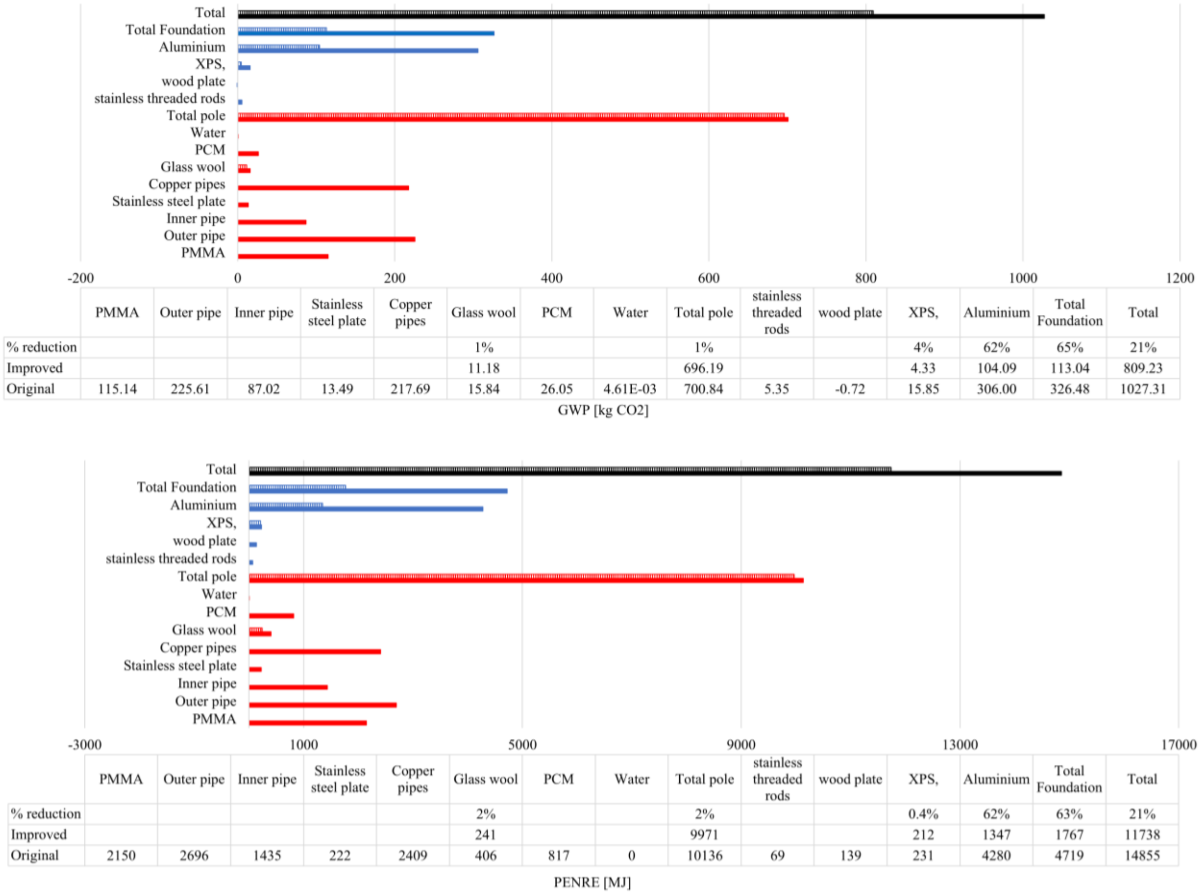
Part	Components	GWP [kg-CO2]	PENRE [MJ]
Pole	PMMA pipe	115	2150
	Outer pressure graded steel pipe	226	2696
	Inner stainless steel pipe	87	1435
	Stainless steel plate	13	222
	Copper pipes	218	2409
	Glass wool	16	406
	PCM	26	817
	Water	4.61E-03	6.31E-02
	Total $_{\text{pole}}$	**701**	**10136**
Foundation	stainless threaded rods	5	69
	wood plate	-1	139
	XPS, Pentane	16	231
	Aluminium, Anodized, non recycled	306	4280
	Total $_{\text{Foundation}}$	**326**	**4719**
	Total	**1027**	**14855**



	Glass wool		XPS				Aluminium	
	Phenol resin	Bio based resin	Pentane	CO2	HFO	CO2, BMB	Anodized, non recycled	95% recycled, coil coated
GWP	15.84	11.18	15.85	14.86	14.79	4.33	306.00	104.09
% reduction		29%		6%	7%	73%		66%

	Glass wool		XPS				Aluminium	
	Phenol resin	Bio based resin	Pentane	CO2	HFO	CO2, BMB	Anodized, non recycled	95% recycled, coil coated
PENRE	406.16	241.10	231.29	231.47	227.29	211.68	4280.00	1347.30
% reduction		41%		0%	2%	8%		69%

Figure 3. Effects of possible material alternatives



	PMMA	Outer pipe	Inner pipe	Stainless steel plate	Copper pipes	Glass wool	PCM	Water	Total pole	stainless threaded rods	wood plate	XPS,	Aluminium	Total Foundation	Total
% reduction						1%			1%			4%	62%	65%	21%
Improved						11.18			696.19			4.33	104.09	113.04	809.23
Original	115.14	225.61	87.02	13.49	217.69	15.84	26.05	4.61E-03	700.84	5.35	-0.72	15.85	306.00	326.48	1027.31

	PMMA	Outer pipe	Inner pipe	Stainless steel plate	Copper pipes	Glass wool	PCM	Water	Total pole	stainless threaded rods	wood plate	XPS,	Aluminium	Total Foundation	Total
% reduction						2%			2%			0.4%	62%	63%	21%
Improved						241			9971			212	1347	1767	11738
Original	2150	2696	1435	222	2409	406	817	0	10136	69	139	231	4280	4719	14855

Figure 4. Improved environmental profile after substitution.

reduction, their substitution causes on a material level. The components for pole and foundation are depicted by red and blue color respectively. The possible alternative in the pole for the glass wool is ‘phenol’ bonded glass wool with a glass wool manufacturer using a ‘biobased’ binder. The latter has GWP and PENRE 11.18 kg-CO_2 and 241 kg-CO2 on material level which is 29% and 41%, respectively, lesser than the former one.

In the foundation, XPS has several alternative options available. In the past, XPS blowing agents consisted of chlorofluorocarbons CFCs with a high ozone depletion potential and have been eventually discouraged especially in the EU. Several innovative blowing agents such as Pentane, CO_2 and hydrofluoroolefin HFO etc. have thus been introduced to the market. However, as apparent from Figure 3, all blowing agents have almost similar impact on GWP and PENRE and cause no significant reduction by substitution. However, if the manufacturing of XPS is done via Biomass balanced method (BMB), it can cause a significant reduction of 73% and 8% GWP and PENRE, respectively, on the material level.

This is because BMB manufacturing involves utilization of renewable resources i.e., bio-Naptha Biogas along with conventional non-renewable resources sourced from the fossil materials. Similarly in the foundation, the substitution of Aluminium brings down the impact by 66% and 69% GWP and PENRE, respectively, on a material level. This is because the alternative consists of 95% recycled Aluminium. The substitution of the primary aluminium with a recycled one has a significant influence because extraction of Aluminium from

Bauxite ore is an impact intensive process. Likewise, the substituted material has coil coating instead of an anodized coating, which also further improves the environmental profile.

Figure 4 shows the influence of substitution on the product level. The components for pole and foundation are represented by red and blue color respectively. The black color shows impacts on whole product level. The solid line stands for impacts before substitution while the hashed line shows the improved impacts after substitution .In the pole, as glass wool is not a hotspot and it's used in a small amount in the pole, there is almost no improvement in pole i.e. 1% GWP and 2% PENRE reduction. Similarly, in foundation XPS contributes a small amount of 4% and 0.4% reduction to GWP and PENRE, repectively. However, Aluminium is a hotspot and its replacement results in 62% decrease in both GWP and PENRE of foundation. So, switching to more sustainable options result in 1% and 65% GWP reduction in pole and foundation, respectively. On the whole prototype level, this GWP reduction is 21%. Similarly, replacement generates 2% and 63% PENRE decline in pole and foundation, respectively. On the whole prototype level, this reduction is 21%.

Conclusion

In this paper, the significance of LCA has been demonstrated by its application on a prototype. The impacts of the production stage (A1-A3) were evaluated, and hotspots were identified. Finally, substitution with alternative material choices improved the GWP and PENRE profile of the prototype by 21%. Due to the lack of data available other impact categories such as Ozone depletion potential or use of net fresh water are not evaluated. In this paper, only the production impact stages have been reported. The authors want to emphasize the importance on conducting LCA to evaluate the environmental impact of a product.

Acknowledgements

The research work has been presented as a part of project 01218514/1-Effkon funded by "Bundesministerium für Wirtschaft und Klimaschutz (BMWK.IIC6)". The authors would also like to thank "Deutscher Akademischer Austauschdienst" for partially funding the research.

Bundesministerium für Wirtschaft und Klimaschutz

DAAD Deutscher Akademischer Austauschdienst German Academic Exchange Service

References

Bundesministerium des Innern, für B. und H., 2018. Ökobaudat–Informationsportal nachhaltiges Bauen.

Bundesministerium für Wirtschaft und Energie (BMWi, 2019. Zweiter Fortschrittsbericht zur Energiewende 'Die Energie der Zukunft' Berichtsjahr 2017,.

Crawford, R.H., Stephan, A., 2013. The significance of embodied energy in certified passive houses. Int. J. Archit. Environ. Eng. 7, 427–433.

DIN, E., 2019. 15804: 2020-03 Sustainability of construction works-Environmental product declarations-Core rules for the product category of construction products. Ger. Version EN 15804, A2.

DIN, E., 2011. 14025: Umweltkennzeichnungen und-deklarationen-Typ III Umweltdeklarationen-Grundsätze und Verfahren (ISO 14025: 2006). Dtsch. Engl. Fass. EN ISO 14035.

Directive, E.C., 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

European Comission, 2020. URL https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en (accessed 12.5.23).

European environment agency, 2023. URL https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy#:~:text=The%20buildings%20sector%20is%20a,related%20EU%20emissions%20in%202021. (accessed 12.5.23).

Means, P., Guggemos, A., 2015. Framework for Life Cycle Assessment (LCA) Based Environmental Decision Making During the Conceptual Design Phase for Commercial Buildings. Procedia Eng., Defining the future of sustainability and resilience in design, engineering and construction 118, 802–812. https://doi.org/10.1016/j.proeng.2015.08.517

Schröter, B., Spiegel, J., Carrigan, S., Kornadt, O., Friedrich, T., Wißbach, M., Platzek, D., Büscher, W., 2023. Energiegewinn und Energieeinspeicherung des Prototyps eines neuartigen Wärmespeicher- und Energieerzeugungssystems. Bauphysik 45, 245–251. https://doi.org/10.1002/bapi.202300014