Comparing construction technologies of single family housing with regard of minimizing embodied energy and embodied carbon

Arkadiusz Węglarz[1,*],*Michał* Pierzchalski[2]

[1]Faculty of Civil Engineering, Warsaw University of Technology, Warsaw, Poland
[2]Faculty of Architecture, Warsaw University of Technology, Warsaw, Poland

Abstract. This article concerns the Life Cycle Assessment method of evaluation and the ways in which it can be applied as a tool facilitating the design of buildings to reduce embodied energy and embodied carbon. Three variants of a building were examined with the same functional ground plan and usable floor area of 142.6 m^2. Each variant of the building was designed using different construction technologies: bricklaying technology utilizing autoclaved aerated concrete popular in Poland, wooden frame insulated with mineral wool, and the Straw-bale technology. Using digital models (Building Information Model) the building's energy characteristics was simulated and the embodied energy and embodied carbon of the production stage (also called cradle-to-gate) were calculated. The performed calculations were used to compare the cumulative energy and embodied carbon of each variant for a 40 year long life cycle.

1 Life Cycle Assessment (LCA) methodology

Life Cycle Assessment (LCA) is an environmental method of evaluating a process or production during the entire cycle of existence, or in other words, "cradle-to-gate". It includes analysis of the possible influences of the process or product on the natural environment. The analysis takes into account all influence factors (input and output streams) from resources acquisition to all the processes connected to product disposal.

The first mention of the life cycle evaluation method of products date back to 1969 and was presented by Harold Smith at the World Energy Conference[1]. The oil crises of the 70's, the increased price of resources, and issues with waste were some of the reasons for increased interest in improving energy efficiency and reducing the negative impact of human activity on the environment.

In 1992, at a conference in Rio de Janeiro, the International Organization for Standardization (ISO) undertook commitments to support sustainable development. A standards group (group 14000) was created along with the Technical Committee 207 (TC 207), whose role was the continuous development of ISO standards regarding, among others, the LCA method.

---

[*] Corresponding author: a.weglarz@il.pw.edu.pl

Currently it is one of the few tools, which takes into consideration all factors, which can have an effect on the environment connected to a particular product or process. The amount of natural resources and energy used during production, transport, utilization, and the amount of waste produced is defined for each product or process analyzed. It is followed by an evaluation of the effect of these elements on the natural environment. The evaluation of effects is included under three categories of impact: quality of the ecosystem, human health, and use of resources [1, 2].

LCA is a reliable source of information concerning each material and construction product at the cradle-to-gate – that is from resource extraction to production. It can also be used as a tool for evaluating the effects on the environment of the entire building.

LCA method consists of the following stages[2, 3]:

- Definition of the aim and scope of the analysis(ISO 14041),
- Analysis of the input and output – LCI (Life Cycle Inventory),e.g. input – resources and energy, output – waste (ISO 14041),
- Evaluation of the life cycle impact (evaluation of effect) – LCIA Life Cycle Impact Assessment) (ISO 14042),
- Life Cycle Interpretation(ISO 14043).

For the practical application of the LCA method in the ecological evaluation of buildings some key and necessary elements are the databases containing data (indicators for each category of impact and use of resources) concerning the environmental impact of each component, material and construction products. Out of the databases and tools for performing LCA analyses currently being used or developed in the European market it is necessary to name: Environmental Profiles Database[1] (BRE, United Kingdom), SBK nationalemilieudatabase[2] (Netherlands), Ökobau.dat – LCA database[3] (Germany), Generic construction LCA data[4] (Austria), Generic construction LCA data[5] (Switzerland), probas - ProzessorientierteBasisdatenfürUmweltmanagementsysteme (Germany), Ecoinvent[6] (Switzerland), Baubook[7] (Austria) or the European database ELCD, the ESUCO LCA database or the EPLCA[8] (European Platform on Life Cycle Assessment – a European platform using ELCD <European reference Life Cycle Database> resources, ILCD <the International reference Life Cycle Data System> and z LCDN <Life Cycle Data Network>, or the Polish database created for the “Innovative measures and effective methods of improving the security and lifespan of buildings and the transport infrastructure under sustainable development”[3]. Type III environmental product declarations can also be used to develop databases. The final evaluation of impact in the LCA method consists of a number of impact categories employing the coefficients of the ELCD (European reference Life Cycle Database). Table 1 shows the list of categories and their respective parameters.

For this work concerning the environmental evaluation concerning the energy used and embodied carbon connected to the construction of a building, it was necessary to acquire two indicators for each material or construction product used in the project:

- Total use of renewable and non-renewable primary energy (embodied energy) expressed as MJ/kg of the product, and
- Global warming potential (embodied carbon) expressed as kg CO_2 e./kg of the product (see Table1).

---

[1] http://www.bre.co.uk
[2] https://www.milieudatabase.nl/
[3] http://www.oekobaudat.de/
[4] http://www.ibo.at/de/oekokennzahlen.htm
[5] http://www.ecoinvent.org/database/database.html
[6] https://www.ecoinvent.org/
[7] http://www.baubook.info
[8] http://eplca.jrc.ec.europa.eu/ELCD3/

Table 1. Categories of impact in the LCA method along with their parameters and units per functional unit, e.g. piece, kg, or m^3 of product. Own elaboration based on PN EN 15804+A1:2014-04 [4].

Category of impact - Parameter	**Unit**
GWP (Global Warming Potential)	kg CO2 e.
ODP (Ozone Depletion Potential)	kg CFC 11 e.
AP (Acidification Potential)	kg SO_2 e.
EP (Eutrophication Potential)	kg PO_4 e.
POCP (Photochemical Ozone Creation Potential)	kg C_2H_4 e.
ADP-minerals (Abiotic Depletion Potential) – for non-fossil resources. Pertains to all non-renewable resources with the exception of fossil fuels.	kg Sb e.
ADP-fossil fuels (Abiotic Depletion Potential) – for fossil fuels.	MJ

The evaluation of the remaining categories of impact was not performed as not all databases contained the full range of LCA impact categories. This is the case of the ICE v.2.0 database (Inventory of Carbon & Energy) [5], which contains only the above mentioned two categories – embodied energy and embodied carbon.

The analyses conducted included the most energy intensive stages of a building's life cycle [6–8]:

- production stage, or 'cradle-to-gate', designated as A1-A3 (Table 2),
- operational stage in terms of energy use, designated as B6 (Table 2).

The production stage (A1–A3) concerns all the processes connected to producing construction products, while the operational stage in terms of energy use (B6, operational energy use) concerns equipment integrated with the building and its internal installations e.g. central heating, ventilation, cooling, lighting, domestic hot water, powering pumps and others. The use of energy during the B6 stage is connected to the emission of greenhouse gases.

Table 2. Stages of a building's life cycle. * - stages included in the analysis. Source: Own elaboration based on 15804+A1:2014–04 [6].

Building Life cycle stages																
Product stages			**Construction process stage**		**Use stage**							**End-of-life stage**				**Info**
A1*	**A2***	**A3***	A4	A5	B1	B2	B3	B4	B5	**B6***	B7	C1	C2	C3	C4	D
Raw material supply	**Transport**	**Manufacturing**	Transport	Construction / Installation process	Use[9]	Maintenance	Repair	Replacement	Refurbishment	**Operational Energy use**	Operational Energy use	De-construction / Demolition	Transport	Waste processing	Disposal	Reuse, recovery, recycling potential

---

[9] B1 pertains to the use and utilization of a built in product. During this stage all environmental impacts not included in B2–B7, e.g. release of substances from the materials used, should be included

2 Single family housing using three technologies

A single family residential building was designed with a minimal operational programme for a family of four. The body and the floor plan of the building was designed in accordance with design rules for energy efficient buildings. The body was designed to be simple, tight, and compact. Living quarters with large windows were placed on the southside, the unheated antechamber and the roofing were designed as expansion jointed constructions independent from the building. The building contains 142.60 m^2 of usable area and 139.85 m^2 of heated area. A natural gas condensing boiler was designed for heating and preparing domestic hot water. The design includes floor heating and a mechanical supply and exhaust ventilation with recovery.

The floor plan of the building is shown in Fig. 1.

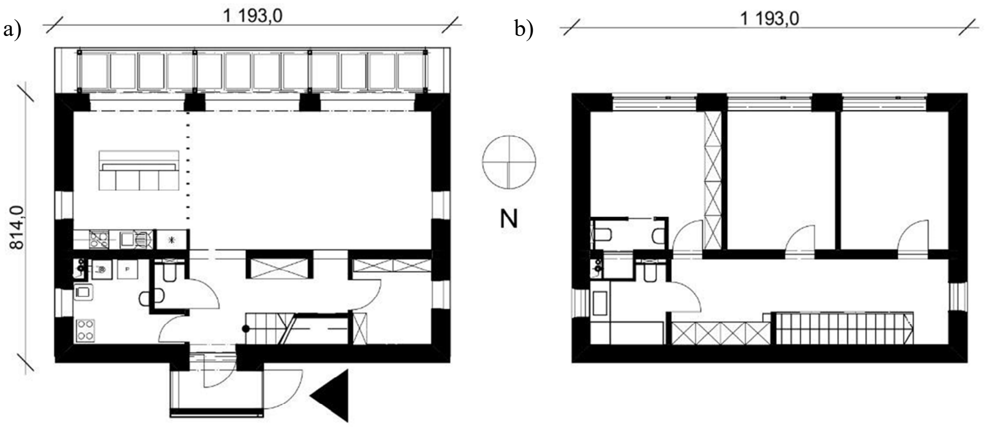

Fig. 1. Floor plan of the building, a) ground floor, b) first floor. Source: Own elaboration.

ARCHICAD was used to prepare building information models (BIM). The building was designed in three different technologies, with different energy standards. All buildings use a reinforced concrete foundation plate. The parameters of each variant is shown in Table 3.

Table 3. The parameters of each variant of buildings. Source: Own elaboration.

Type	Technology	Energy standard
Passive House	Traditional brickwork. Walls from autoclaved aerated concrete with styrofoam insulation. Beam-and-block floors, flat room additionally insulated with styrofoam aligned at an incline.	According to the PassivHausInstitut[10] standard
Wooden frame	Construction on a wooden frame filled with mineral wool. Wooden construction floors. Ventilated flat roof using wooden lattice girders.	In accordance with Polish Regulation[11]. U coefficient of the partitions below the required values.
Straw bale	Wooden construction filled with blocks of pressed staw. Wooden construction floors.Ventilated flat roof using wooden lattice girders.	In accordance with Polish Regulation[12]. U coefficient of the partitions significantly below the required values.

---

[10] http://www.passiv.de/

[11] Regulation of the Minister of Infrastructure and Construction from 14 November 2017, changing the regulation on the technical conditions which buildings should fulfill and their status with later changes

Visually there are few differences between the buildings. In buildings with a wooden construction the external roofing was also designed using wood, while the roof of the passive building was designed using a steel construction. A view of each building is shown in Fig. 2.

Fig. 2. Perspective view of each building, a) passive building, b) wooden frame building, c) straw bale. Source: Own elaboration.

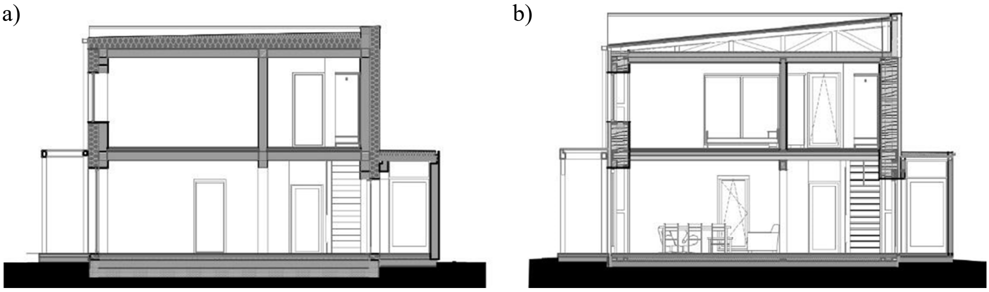

Fig. 3. Comparison between the cross sections of a passive building (a) and a straw bale building (b). Source: Own elaboration.

3 Straw bale

The most popular construction technology of single family houses in Poland is bricklaying technology. Wooden frame technology is also well known, but less popular. Straw bale technology is considered unusual and little known. However, increased interest in these types of ‘low-tech’ technologies (earth buildings or hempcrete) has been observed. A number of straw-bale technology buildings were built in Poland over the last couple of years. The author of this article also designed a building using this technology. Photographs from the building’s construction are shown in Fig. 4.

Fig. 4. Construction of the “Dobry Dom” Straw bale building in Werstok. Construction of the wooden with connector plates, straw bales being laid before clay plastering, a wall constructed from light clay compacted into shoring. Photos: KamilSyller.

Most often wheat or rye straw pressed to a density of around 90 kg/m^3 is used for construction. Straw is laid between wooden construction elements, additionally compressed using belts or tensioners and plastered on both sides about 3 cm thick. The clay inside should have a higher diffusion resistance than the clay used on the outside to minimize the risk of condensation of water vapour inside the partition. To increase the diffusion resistance of the internal layers additives lowering the diffusion can be added to the clay e.g. linseed varnish. The width of straw bales produced in Poland is about 45 cm. According to different sources the thermal conductivity coefficient λ of straw bale is between 0.038 [9, 10] and 0.080 [11], depending on the straw, density and alignment. Straw in which the stalks are aligned perpendicular to the direction of thermal flow achieve better parameters. During a study on 10 samples conducted by the Building Research Institute, the lowest λ coefficient was 0.06958 W/(mK) and the highest was 0.0708 W/(mK) [12]. Further calculation assume λ=0.070 W/(mK).

4 Energy performance

It was assumed that the building is located in Warsaw. Calculations of energy performance used weather data from the Warsaw-Okęcie meteorological station. Energy simulations were performed using the EcoDesigner Star programme.

The U coefficient of each partition can be found in table 4. The passive building uses a recuperator with a 93% temperature efficiency, higher than in the other buildings where it is 84%. For the passive building a n_{50}=0.6 airtightness was assumed, while for the others n_{50}=1.0 (recommended by the Regulation [13].

Table 4. Coefficients of thermal conductivity of partitions U [W/(m^{2}K)]. Source: Own elaboration.

Partition	Passive building	Wooden frame building	Straw-bale
External walls	0.091	0.15	0.159
Flat roof	0.078	0.14	0.14
Floor at foundation	0.1	0.18	0.18
Windows	0.76–0.96	0.8–0.9	0.8–0.9

Results of energy performance calculations are shown in Table 5.

Table 5. Final energy demand of the buildings for heating and ventilation $Q_{k,\,H+W}$ [kWh/a].

	Passive building	Wooden frame building	Straw-bale
Demand for energy of a A2P (passivestandard) building for heating and ventilation $Q_{k,\,H+W}$ [kWh/a]	1649	3229	2764

5 Embodied energy and embodied carbon

The embodied energy and embodied carbon for the building products used was calculated on the basis of numerical models developed using the ARCHICAD programme. The calculations included the production stage A1–A3 (C2G, cradle-to-gate). Data used for calculating the embodied energy and the embodied carbon came from the British ICE v2.0 (Inventory of Carbon and Energy database, the German Ökobau.dat database, and data from Type III Environmental Product Declarations for particular products. It is important to note that not all elements of the buildings were included, e.g. electrical wiring, light fittings, pipers, or trim fittings (excluding flooring/ and equipment). The CO_2 capture of wooden products during the growth of the tree was not included in calculating the embodied carbon in the production stage. According to an opinion by ICE [5] and information included in Product Category Rules for environmental declarations [14] capture (sequestration) of CO_2 can be taken into account only when the analysis takes into account all stages of the life cycle. The results of the calculations are presented in Table 6.

Table 6. Embodied carbon and embodied energy for the building products used during the production stage of the product (C2G).

	Passive building	**Wooden frame building**	**Straw-bale**
Embodied Energy (C2G) [MWh]	231.5	141.77	131.68
Embodied carbon (C2G) [Mg CO_2] e.	63.33	37.20	35.68

Table 7. Embodied carbon and embodied energy of the use stage in a 40 year building use cycle.

	Passive building	**Wooden frame building**	**Straw-bale**
Embodied Energy (use stage in a 40 year cycle) [MWh]	542.08	611.60	591.14
Embodied carbon (use stage in a 40 year cycle) [Mg CO_2] e.	119.30	131.96	128.24

Table 8. Cumulated embodied carbon and embodied energy of the production stage (C2G) of the product and the use stage in a 40 year building operation cycle.

	Passive building	**Wooden frame building**	**Straw-bale**
Embodied Energy (C2G) [MWh]	773.58	753.37	722.82
Embodied Carbon (C2G) [Mg CO_2] e.	182.63	169.16	163.92

As seen in the table above and the graphs below (Fig. 4 and Fig. 5) the biggest share in the embodied energy and embodied carbon in a 40 year (and beyond) cycle comes from energy use during the building's operation. This is energy used for heating, preparing domestic hot water, and powering additional appliances.

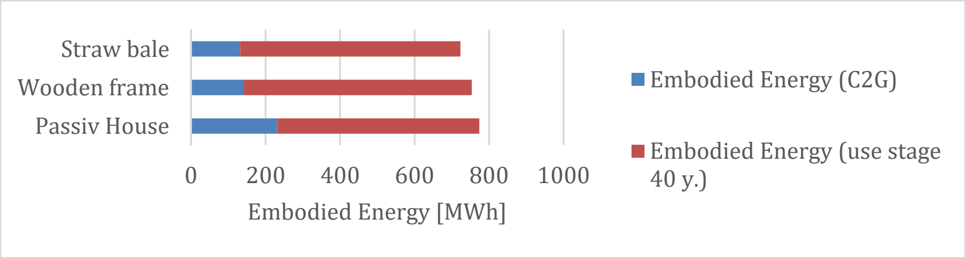

Fig. 5. The cumulated embodied energy of the production stage (C2G) and the use stage in a 40 year building operation cycle.

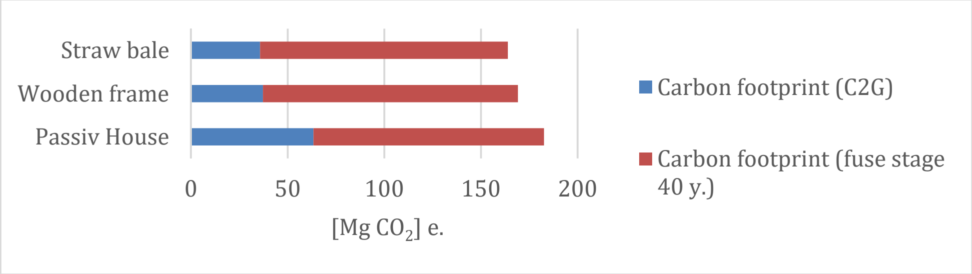

Fig. 6. Cumulated embodied carbon of the production stage (C2G) and the operation stage in a 40 year building operation cycle.

6 Summary and conclusions

The most energy intensive stage of a building's life cycle is its operation stage, however the contribution of the product's production stage in the entire life cycle is significant. In the cases analyzed it contributed between 19% and 30% of all embodied energy in a 40 year building use cycle. In the case of embodied carbon its contribution was 22–35% in a 40 year building use cycle. These figures justify enacting measures for the reduction of embodied energy and embodied carbon during the production stage of a product.

Despite higher energy uses in a 40 year life cycle, the Star-bale technology building turned out to be the most ecological solution. The results of the wooden frame building were not much worse. This result comes from replacing concrete with wooden construction elements, and in the case of straw-bale, replacing the mineral wool thermal insulation with locally sourced straw.

A gradual reconstruction of traditional templates can be seen in energy efficient, harmonious, passive, etc. architecture. Modern, passive methods for acquiring solar energy, its storage, and managing its flow in buildings have their sources in traditional solar architecture [15]. Using straw-bale type products is a return to an organic architecture tradition.

In times of observable climate change and the risk of depleting conventional energy sources, fresh water, and other resources, the idea of creating buildings which harmoniously coexist with their environment, or could amend the losses caused by human activity seems very justified.

References

1. Z. Kowalski, J. Kulczycka, and M. Góralczyk, *Ekologiczna ocena cyklu życia procesów wytwórczych (LCA)*. (Warsaw, Polish Scientific Publishers PWN, 2007)
2. ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework
3. K. Żmijewski, A. Węglarz, and M. Jarzemska, *PT7.1 Metody komputerowej optymalizacji projektowania budynków przyjaznych dla środowiska z wykorzystaniem oceny LCA* (Baza danych o wartościach emisji CO$_2$ i wartościach energii skumulowanej dla głównych technologii budowlanych w Polsce, Warsaw 2011)
4. EN 15804:2012+A1:2013 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products
5. P. G. Hammond and C. Jones, Inventory of Carbon & Energy (ICE), *Mech. Eng.*, **161**, 1–49 (2006)

6. I. Sartori and A. G. Hestnes, *Energy Build.*, vol. 39, no. **3**, pp. 249–257, (2007)
7. M. M. Khasreen, P. F. G. Banfill, and G. F. Menzies, *Sustainability*, 1, no. **3**, 674–701 (2009)
8. S. L. Hsu, Life cycle assessment of materials and construction in commercial structures : variability and limitations, (2010)
9. F. D’Alessandro, F. Bianchi, G. Baldinelli, A. Rotili, and S. Schiavoni, *J. Build. Eng.*, **11**, no. October 2016, 56–68 (2017)
10. J. Munch-Andersen and B. M. Andersen, Straw Bale Houses -design and material properties, Danish Building and Urban Research.
11. G. Minke and B. Krick, *Podręcznik budowania z kostek słomy, podstawy, konstrukcje, przykłady*.(Łódź, Fundacja Cohabitat (2015)
12. The Building Research Institute (ITB), “*Badanie współczynnika przewodzenia ciepła kostek słomy, Nr pracy: 02236/15/Z00NG* (LFS00-02236/15/Z00NF),” Warsaw, 2015)
13. Ministry of Infrastructure, Ordinance on technical conditions to be met by buildings and their location of 12 April 2002. (Journal of Laws of 2002, No. **75**, item 690, consolidated text (2002), (in Polish)
14. FPInnovations, Product Category Rules (PCR) for Preparing an Environmental Product Declaration (EPD) for North American Structural and Architectural Wood Products, (2011)
15. S. Wehle-Strzelecka, *Energia słońca w kształtowaniu środowiska mieszkaniowego – ewolucja koncepcji na przestrzeni wieków*, (Kraków, Wydawnictwo Politechniki Krakowskiej, 2014)