Life Cycle Assessment Benchmark for Wooden Buildings in Europe

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Abstract Climate change and other environmental problems from the production of raw materials, construction, and end of life of buildings are serious concerns that need to be solved urgently. Life cycle assessment (LCA) and the EU-recommended Environmental Footprint (EF) are well-known and accepted tools to measure a comprehensive set of environmental impacts throughout a product's life cycle. But to assess how good (or bad) a wooden building performs environmentally is still a challenge. In the EU Environmental Footprint [11] pilot phase from 2013 to 2018, an average benchmark for the different product groups was found to be very useful. Based upon the recommendations for a benchmark of all kinds of European dwellings, we developed a scenario of a typical European wooden building. The EU Environmental Footprint method covers 16 recommended impact categories and can be normalized and weighted into one single point for easy and quick comparisons. The results are presented as the average impact per one square meter (m^2) of floor area over 1 year. The developed benchmark for wooden buildings is a suitable comparison point for new wooden building designs. The benchmark can be used by architects and designers early in the planning stages when changes can still be made to improve the environmental performance of wooden buildings or the communication and interpretation of LCA results for customers and other stakeholders.

1 Introduction

According to the European Commission, the construction industry accounts for 15% of all greenhouse gas emissions [1]. During their use phase, buildings use 80% of the total energy consumption [2], which contributes significantly to air pollution and other environmental impacts stemming from energy sourcing, distribution, and transformation. While energy consumption during the use phase is predicted to decrease as efficient buildings, like zero and near zero energy buildings, become more common, climate change and other environmental problems from the production of raw materials, construction, and end of life remain serious concerns that

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need to be solved urgently. This calls for a life cycle-based approach for the assessment of the environmental impacts of a building.

In the EU Environmental Footprint [11] pilot phase from 2013 to 2018, an average benchmark for different product groups was found to be very useful [3–5] as a help for interpretation of the product's life cycle assessment results in scope of the product category.

Spirinckx et al. [6] give recommendations on benchmarks for office buildings, while Lavagna et al. [2] provide the average environmental impacts of existing dwellings in Europe. However, as the European Union has introduced a stricter policy for buildings' use of energy, a benchmark for new buildings to be built is needed. In this work, we provide an environmental benchmark for a near zero energy wooden residential buildings (nZEB) for new buildings in the future (after 2020). The typical (European average) wooden single-family house holds on average 2.36 inhabitants and, in this study, is set to be 100 m^2 large.

2 Data and Method

2.1 Background Data for a Typical (European Average) Wooden Single-Family House

Based on market-based statistics from Eurostat [7], supplemented with national data where necessarily [8], a prevision for where wood-based residential housing is found in Europe today is made (cf Table 1).

The apparent consumption is what is sold in each country and calculated based on production value – export + import (EUR). The apparent consumption is used for weighting the climate data and energy requirement data of the countries investigated to come to an average wooden residential building.

European countries have different climate and, therefore, different heating demand for residential buildings. We took the climatic conditions on a country level into account, represented by the degree heating days, which is a measurement for how much heating is necessary during a year [9, 10]. Table 1 also shows the heating degree days in the countries investigated. The weighted average heating degree days for the European countries according to Table 1 is 3500. We have used 10 years of data for the climate conditions, and not the usual 30 years, for two reasons: (1) prefabricated building statistics are not easily available for 30 years (for weighting the data), and, more importantly, (2) climate is changing to warmer conditions such that an increase in heating degree days can be observed. For example, the reference climate in Germany is 500 heating degree days less (i.e., warmer) in the period 2008–2017 than was used as a reference 20 years ago (3500 heating degree days).

The energy requirements for new residential buildings from 2021 are given in Table 2.

Table 1 Apparent consumption (million EUR) of prefabricated wooden buildings and climate expressed as heating degree days in different countries (average per year, 2008–2017)

Country	Consumption (million EUR)	Heating degree days per year	Country	Consumption (million EUR)	Heating degree days per year
Austria	583	3482	Latvia	5	4046
Belgium	56	2697	Lithuania	65	3854
Bulgaria	5	2494	Luxembourg	7	2906
Croatia	11	2281	Malta	0.1	468
Cyprus	1	691	Netherlands	150	2721
Czechia	27	3309	Norway	544	4113
Denmark	121	3244	Poland	4	3370
Estonia	23	4224	Portugal	14	1201
Finland	414	5466	Romania	30	2924
France	231	2380	Slovakia	10	3173
Germany	1658	3053	Slovenia	25	2785
Greece	2	1546	Spain	143	1742
Hungary	10	2668	Sweden	1126	5221
Ireland	42	2821	United Kingdom	1226	3033
Italy	615	1875	–	–	–

Source: [7–10]

Table 2 Energy requirement for new buildings (nZEB) from 2021

Country	Max kWh/(m^2 year)	Country	Max kWh/(m^2 year)	Country	Max kWh/(m^2 year)
Austria	160.0	Germany	48.3	Norway	97.5
Belgium	45.0	Greece	57.5	Poland	67.5
Bulgaria	40.0	Hungary	61.0	Portugal	57.5
Croatia	37.0	Ireland	45.0	Romania	155.0
Cyprus	100.0	Italy	57.5	Slovakia	43.0
Czechia	57.5	Latvia	95.0	Slovenia	47.5
Denmark	20.0	Lithuania	77.5	Spain	57.5
Estonia	75.0	Luxembourg	57.5	Sweden	52.5
Finland	130.0	Malta	40.0	United Kingdom	44.0
France	52.5	Netherlands	57.5	–	–

Source: Own calculations and estimates based on [12–15]

The weighted average maximum energy requirement (near zero energy building) is 67.5 kWh/(m^2 year).

2.2 Design of a Typical (European Average) Wooden Single-Family House

With the average climate (from Table 1, 3500 degree heating days, which corresponds to approximate climatic conditions in Austria, South Germany, Slovenia and Italy near the alps) and energy requirement, we started the design of the wooden single-family house that would serve as a benchmark; the shape of the house was made according to the most common plans and structures that we found offered from construction firms of prefabricated wooden houses in Austria. It contains three bedrooms, a living room, cabinet, toilet, utility, staircase, and bathroom. The outer measurements of the house are 9.6 m x 6.7 m, and maximum height is 7.72 m above ground floor level. The house has a pitched roof with 35° angle and 1.0 m overhang. Wooden windows (triple glazed) and doors have Uw = 0.8 W/m^{2}K. There is a 25-cm-thick concrete plate for the house's foundation. Walls are made of wooden profiles 16/8 cm and stone wood filling in-between, with additional 10 cm of stone wool on the outer side covered with finishing plaster. The roof structure is made of 16/8 wooden profiles as well, with mineral wool in-between and 10 cm on top. For roof cover, wave fiber cement roof tiles were used. Inner floors were covered with parquet on floating screed; ceramics were used in sanitary rooms. Figure 1 shows two profiles and Fig. 2 the schematic floor plan of the house.

After preliminary drawings were made, load-bearing construction of the building was calculated and drawings were updated; the layers for all building parts were precisely defined and U-values of the building's outer enclosure were calculated with diverse online tools. Afterward, the house's energy consumption was

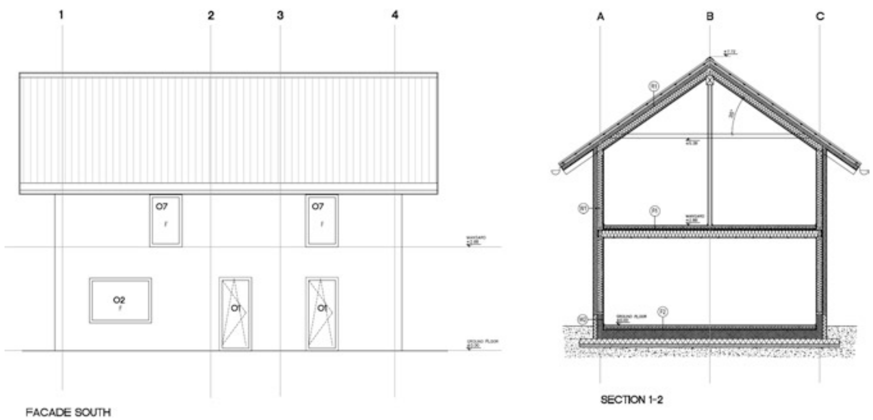

Fig. 1 Façade and section drawings of the house

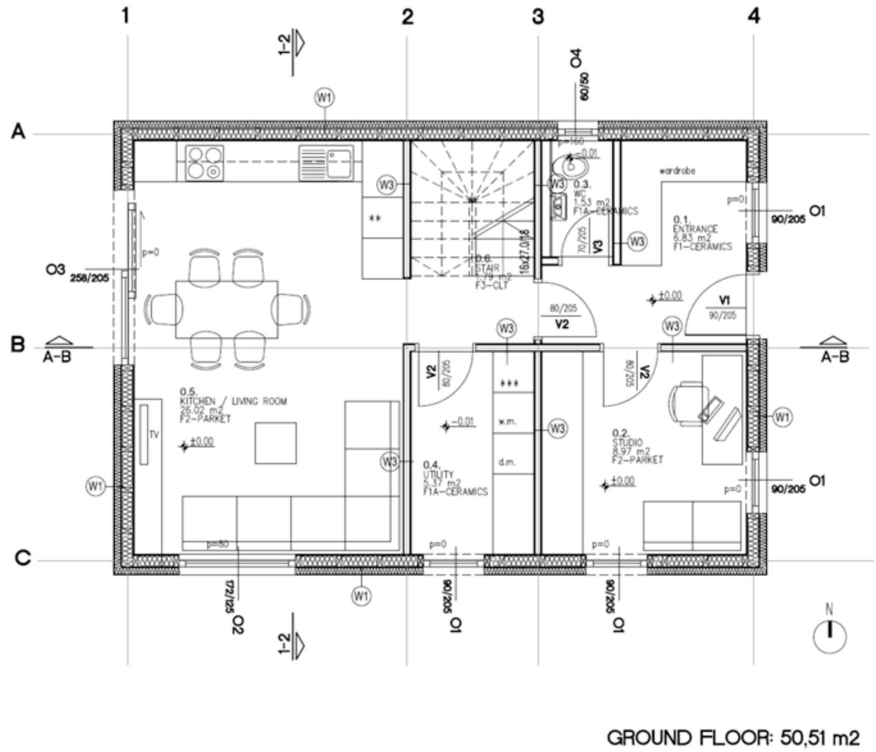

Fig. 2 Ground floor of the house

calculated using a simplified building energy calculation, the Preliminary Passive House Planning Package (PHVP) 2002 [16], which is suitable in the preliminary design phase. Since the shape of the building was made simple and compact, avoiding placement of widows on the northern façade, the energy consumption was calculated to be 26.9 kWh/m^{2}a. This corresponds to nZEB buildings for all countries in Table 2, except for Denmark where there is a stricter requirement.

3 Life Cycle Assessment of a Typical (European Average) Wooden Single-Family House

3.1 Goal and scope

The goal of the life cycle assessment (LCA) for the average wooden one family house is to have a benchmark for wooden buildings suitable as a comparison point for new wooden building designs. The benchmark should be of use for architects and designers early in the planning stages when changes to the building can be made to improve the environmental performance of wooden buildings. Further, a goal of the LCA is to facilitate the interpretation and communication of LCA results for customers and other stakeholders of wooden buildings, for example, when comparing environmental performance of different materials or building elements like the façade.

The functional unit is one dwelling with a 100-year lifetime. Our single-family house has a living area equal to 100 m^2; however, the results are given as per m^2 per year.

The impact categories selected are the EU-recommended Environmental Footprint methods [11], which include 16 impact indicators. Version 2.0 was the newest available at the time of the assessment.

3.2 Life Cycle Inventory

Data collection was based on the detailed architectural drawings of the house (cf. Figs. 1 and 2 for examples). Table 3 shows an example of data collection and calculations for one element of the house, the inner walls (W3).

Table 4 shows an overview of the materials for construction and maintenance of the house.

The life cycle inventory data and modeling follow closely the data and life cycle inventory modeling of the benchmark for environmental impact of housing in Europe – Basket of Products Consumer Footprint indicator for housing [2, 17], where the ecoinvent database is used. We used ecoinvent version 3.5 [18] with allocation, cutoff by classification, as implemented in SimaPro v 9.0 [19] for the background data.

4 Results

The characterized results (cf. Table 5) show that the energy for heating and water use in the operational stage (B6 and B7) of the house is dominating, expect for *land use* and *resource use, minerals, and metals* impact categories, where the product stages (A1–A3), respectively, and maintenance (B2 and B4–B5) are dominating. This is caused by high land use and land transformation for wood products (forest management areas) and high use of materials in the maintenance period, which is quite long (100 years). The *water scarcity* impact category is totally dominated by the operational water use during the use phase. However, both *water scarcity* and *resource use, minerals, and metals* are expected to decrease when the total life cycle, including water and other materials end of life, is included, as these can be cleaned and released into nature or, respectively, become recycled material.

The normalized results in Fig. 3 not only show high *water scarcity* from the use of water in the operational phase but also high *resource use, energy, particulate*

Table 3 Example of data collection, here for inner walls (W3)

W3 – inner walls	Quantity [m^2]	Volume [m^3]	Mass [kg]
Gypsum plasterboards 1.25 cm*2 = 2.5 cm	92.54	2.313	2082.1
Load-bearing construction profiles 6/10 cm – 10 cm	18.5	1.851	777.3
Stone wool (between wooden construction) – 10 cm	92.5	9.254	277.6
Gypsum plasterboards – 1.25 cm*2 = 2.5 cm	92.54	2.313	2082.1

Table 4 Material quantities for construction and maintenance

Material	Quantities for construction [kg]	Quantities for maintenance [kg]
Concrete	57621	0
Gypsum	9922	17186
Wood	12707	5354
Sawnwood	7419	821
Window frame, wood	1681	3122
Oriented strand board	1502	0
Fiberboard	423	987
Glued laminated timber	1258	0
Door, inner, wood	356	356
Door, outer, wood-glass	67	67
Insulation, stone wool	4355	10161
Cement	4342	2466
Gravel	5858	0
Ceramic	1439	1923
Glass	1019	1892
Plastic	660	806
Steel	1286	41
Insulation, polystyrene	288	673
Glue	395	547
Bitumen	591	0
Copper	23	23
Aluminum	12	0

matter, and *climate change*. Here, the use phase is still important, but so are the product stage (A1–A3) and maintenance (B2 and B4–B5) in these three impact categories.

The weighted results (cf. Figure 4) show that *water scarcity* and *climate change* are the most important, followed by *resource use, energy,* and *respiratory inorganics*. The impact category *ozone depletion* is less relevant.

Table 5 Characterized results [per m^2 and year] broken down at different stages

Impact category (unit)	A1–A3 product stages	A4–A5 transport and construction	B2, B4, B5 maintenance	B6, B7 use – operational energy and water
Climate change (kg CO_2 eq)	2.99E+00	3.90E-01	3.73E+00	8.54E+00
Ozone depletion (kg CFC11 eq)	2.60E-07	5.31E-08	5.83E-07	6.52E-07
Ionizing rad. (kBq $U\text{-}^{235}$ eq)	1.42E-01	5.04E-02	1.62E-01	9.40E-01
Photochem. Ozon form. (kg NMVOC eq)	1.24E-02	1.34E-03	1.45E-02	2.68E-02
Respiratory inorg. (disease inc.)	5.35E-07	1.60E-08	6.30E-07	9.76E-07
Non-cancer HH effects (CTUh)	5.09E-07	4.66E-08	5.31E-07	1.77E-06
Cancer HH effects (CTUh)	9.34E-08	3.40E-09	7.56E-08	1.33E-07
Acidification (mol H^+ eq)	1.95E-02	2.52E-03	2.71E-02	6.33E-02
Eutrophication – fresh w. (kg P eq)	1.95E-04	2.94E-05	2.26E-04	7.44E-04
Eutrophication – marine (kg N eq)	3.23E-03	4.38E-04	3.56E-03	8.36E-03
Eutrophication terr. (mol N eq)	4.34E-02	6.67E-03	5.24E-02	1.33E-01
Ecotoxicity freshwater (CTUe)	3.01E+00	3.90E-01	3.56E+00	4.21E+00
Land use (Pt)	7.97E+02	4.07E+00	3.55E+02	3.87E+02
Water scarcity (m3 depriv.)	1.06E+00	8.24E-02	1.34E+00	5.73E+01
Resource use, energy (MJ)	4.13E+01	7.11E+00	5.39E+01	1.41E+02
Resource use, mineral, and metals (kg Sb eq)	3.19E-05	7.82E-07	4.29E-05	9.35E-06

5 Discussion, Outlook, and Conclusion

This contribution shows how we designed an average European wooden residential building and used life cycle assessment (LCA) and, more specific, the EU-recommended Environmental Footprint (EF) to investigate the cradle to gate and use phase of the house suitable for a benchmark. Even with an improved design,

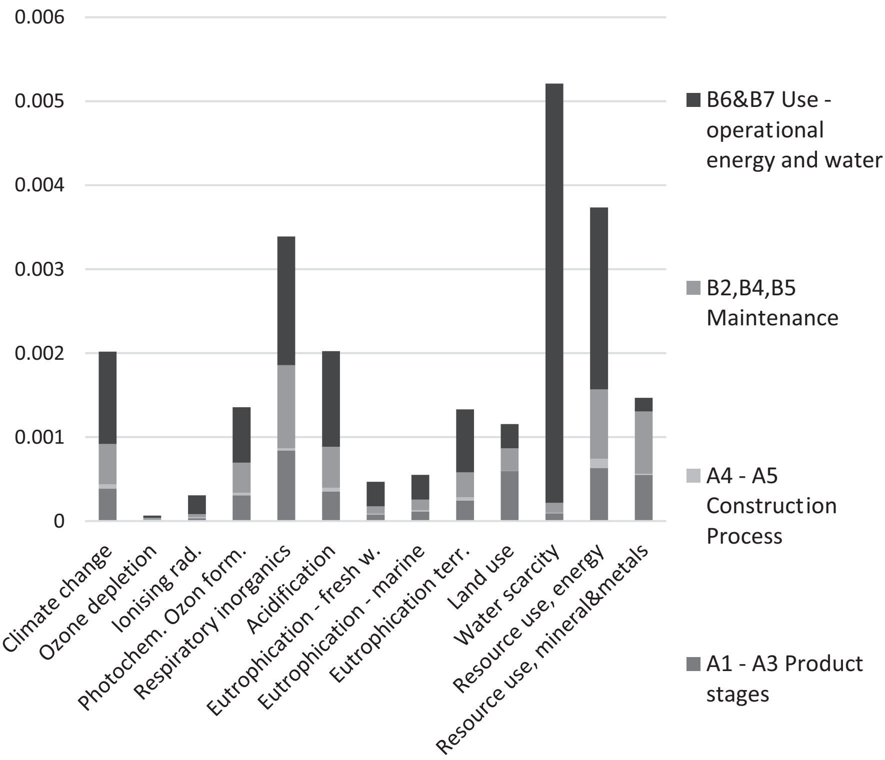

Fig. 3 Normalized results

like better insulation, the use phase is still a major contributor to the environmental impact categories investigated. Climate change, respiratory inorganics (particulate matter), water scarcity, and resource use and energy are the most important impact categories in this study. Waste scenarios, some that happen 100 years into the future, are left for future studies. However, these are believed to include lots of reuse and material recycling. Future studies should also apply the new EU Environmental Footprint method v.3, where the toxicity impact categories have been updated. However, this was not yet implemented in the software used at the time of impact assessment calculation.

The results will be used to compare to existing housing in the Basket of Products for a single-family house and establish and compare the reference houses in specific countries, like Spain. Other building types, like multifamily houses and other buildings made of wood, could be investigated based on the same concept.

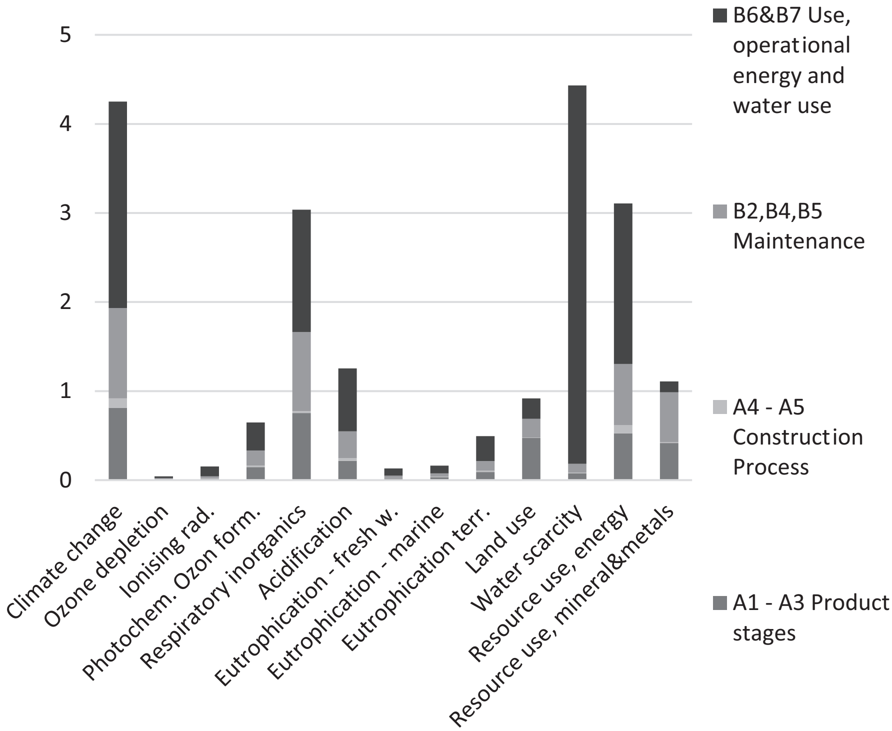

Fig. 4 Weighted results

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