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Life cycle assessment of a wooden single-family house in Sweden☆

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HIGHLIGHTS

- Global warming potential and primary energy as impact categories are analyzed.
- The case study demonstrated the total environmental impact.
- The sources of CO_2e emissions for this single-family house is investigated.
- Using wood-based building materials result in low CO_2e emissions.

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ABSTRACT

To understand the reasons behind the large environmental impact from buildings the whole life cycle needs to be considered. Therefore, this study evaluates the carbon dioxide emissions in all stages of a single-family house in Sweden from the production of building materials, followed by construction and user stages until the end-of-life of the building in a life cycle assessment (LCA). The methodology applied is attributional life cycle assessment (LCA) based on 'One Click LCA' tool and a calculated life span of 100 years. Global warming potential (GWP) and primary energy (PE) are calculated by using specific data from the case study, furthermore the data regarding building materials are based on Environmental Product Declarations (EPDs). The results show that the selection of wood-based materials has a significantly lower impact on the carbon dioxide emissions in comparison with non-wood based materials. The total emissions for this single-family house in Sweden are 6 kg CO_2e/m^2/year. The production stage of building materials, including building systems and installations represent 30% of the total carbon dioxide equivalent emissions, while the maintenance and replacement part represents 37%. However, energy use during the in-use stage of the house recorded lower environmental impact (21%) due to the Swedish electricity mix that is mostly based on energy sources with low carbon dioxide emissions. The water consumption, construction and the end-of-life stages have shown minor contribution to the buildings total greenhouse gas (GHG) emissions (12%). The primary energy indicator shows the largest share in the operational phase of the house.

1. Introduction

The building sector accounts for about 40% of primary energy use and one third of greenhouse gas (GHG) emissions emitted at the global level [1]. Primary energy uses a significant proportion of fossil fuels, around 80%, which contributes to two thirds of GHG emissions in the world [2]. Substantial savings can be achieved by more efficient construction and use of buildings. These savings could lead to a reduction of 42% of the total energy consumption, 35% of GHG, 50% of the extracted raw materials and, in some areas, 30% of water use according to the Roadmap to Resource Efficient Europe [3]. Life Cycle Assessment (LCA) is a method to assess potential environmental impact from material extraction and production, through the construction and user stages to the waste treatment and end-of-life of the product [4]. The building sector can become more resource efficient through incorporating (LCAs) to decrease the environmental impacts from the buildings' whole life cycle [5]. By using LCA sub-optimization can be avoided and it may have an impact on the design and choice of construction materials. In the context of sustainable buildings, energy efficiency and renewable energy are covered by EU policy as the main

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Nomenclature

CO_2e	carbon dioxide equivalent
EN	european standard
EPD	environmental product declaration
GHG	greenhouse gas
GWP	global warming potential
ISO	international organization for standardization
PE	primary energy

keys in promoting resource efficiency in the building sector by using LCA [3]. The European Commission has established an objective to decrease CO_2 emissions from the building sector by 90% by 2050 [6,7]. To achieve the goal of reducing CO_2 emissions, a life cycle approach is required to detail the carbon emissions for buildings for a feasible carbon reduction strategy [7]. The European Commission has come to the conclusion that LCA is one of the best tools for evaluating environmental impacts through all stages of the building [8]. LCA in the building sector is characterized by: (1) long lifespan of the buildings (usually more than 50 years) and the difficulty in predicting the whole life cycle; (2) significant changes with many stakeholders involved during the buildings life span. Hence, there is a need to perform LCA and to estimate the relationship between various materials and the energy performance of the buildings [9]. The benefits of using LCA to help assess sustainability in the building sector are environmental, followed by comparing of alternative products and providing information about environmental impact to help stakeholders to make informed decisions. Economic benefits are based on promotion of products for the green market, lower costs for constructions [10], operation and maintenance and decreased costs because of reduced negative environmental impacts. Furthermore, LCA methodology follows ISO standards and uses a long term perspective [11].

As most buildings have a long life span, energy use and emissions occur over different life cycle stages. Reduced energy use in low energy buildings is achieved by increasing insulation and glazing with reduced U-values in terms of better thermal performance and air-tightness. In low energy buildings, the embodied energy can represent a large part during the lifetime [12]. In another study, the use phase accounts for the largest part of total life cycle energy use over a 50 years life span [13]. The reduction of operational energy consumption have to be followed in parallel with embodied impact. Annex 57 has some recommendations to define templates for system boundaries, inventory of data and also strategies to decrease embodied impacts [14].

In recent years, Nordic countries have shown increased interests in the use of LCA for analysis of environmental performance in the building sector [15]. The Nordic countries are strong actors in providing deep collaboration and a common network for the innovative use of LCA in sustainable building and construction [15]. Boverket (The Swedish National Board of Housing, Building and Planning) has been commissioned by the Swedish government to propose methods for reporting climate impacts, taking into account a life cycle perspective. Sweden's national target is to become carbon neutral by the year 2045. The proposal for the climate declaration shall follow LCA according to the European Standard EN 15987, which proposes that LCA in buildings have to be implemented [16].

A number of studies using LCA in Scandinavia have been made for single-family houses and multi-family residential buildings. A LCA was performed for eight design alternatives based on four-storey building in Växjö in Sweden [17]. The study used data from the Environmental Product Declarations (EPDs) of building products, where global warming potential and primary energy demand were analyzed. Two studies analyzed LCA of wood products in Sweden [18]. Similarly, LCAs have also been carried out for a single-family residence built to conventional or passive house standard [19], multi-family residence [20] and a Danish single-family house [21]. In the Danish study, three buildings were evaluated with respect to life cycle embodied and operational energy for a period of 100 years. Taking into account the whole lifetime of the building, the Danish single-family house was recognized by the importance of embodied primary energy in relation to operational energy caused by more insulation and technical systems needed for buildings. In the study case of Norwegian office building, the large amount of wood using in the construction lead to GWP reduction [22]. Bribián et al shown results of an LCA using three different environmental impact categories. The study showed the importance of using more eco-efficient products in the production stage with encouragement to use EPDs [23] in order to get the information about the environmental impacts of products. Sharma et al in their review found that all life cycle stages of buildings have large environmental impacts with the emphasis on operational energy use (80–85%). Additionally, it has been concluded that the operational phase contributes to 50% of the CO_2e [24]. Furthermore, Sartori and Hestnes in their review showed that the in-use stage for residential buildings and new office contributed to 62–98% energy use during the lifetime, while low energy buildings show 54–91% during the in-use stage [25].

The LCA results from 15 single-family houses and 15 multi-family houses evaluated in France showed reinforced concrete as the largest contribution to environmental impact. For the same study the insulation materials and non-structural wood demonstrated uncertainties for both type of buildings [26]. In typical Brasilian residential buildings the largest contribution to environmental impacts is found in construction processes and building materials. Due to their results, concrete, ceramic tiles and steel have the largest contributions [27].

Ramesh analyzed 73 case studies within 13 countries and found that embodied energy accounted for 10–20% of total impacts [28]. Zabalza studied low energy buildings in Spain, recorded 46% energy use in the production and construction stage of a building with a 50 years lifespan [29]. Greater reduction of the carbon footprint in sustainable building materials and construction installations have been found by Monahan and Powel [30]. In other similar case in Australia, wood products compared with other alternative materials reduce GHG emissions [31]. Building materials consume more energy for their production and emit high amounts of CO_2 emissions. Doodoo states that emphasis on material choice is needed in the construction industry [32]. According to the recent review "The embodied carbon", some countries set up regulations based on limited values for the carbon footprint of different building types [33].

Single-family houses often have different construction components compared to multi-family buildings. A large share of wood as a construction material is important for an eco-based single-family house compared to a conventional house based on concrete as the main construction material. None of the previous studies found have addressed overall LCA for a single-family house in a Nordic climate scenario. Furthermore, there has been no standardized tool for LCAs for buildings, which makes it difficult to compare results of various scenarios. In policies, the main focus on energy saving is mostly given to low energy buildings. However, in Sweden a large share of all dwellings are heated by district heating or heat pumps using electricity, where both heat and electricity is mostly based on renewable energy sources. Therefore, the argument for estimating GHG in a life cycle perspective is that not only the energy use in the in-use stage should be considered but the emphasis should be on the production stage of the buildings [34].

The goal of the study is to present carbon footprint and primary energy of a wooden single-family house in Sweden. The rationale for doing this is because there is no previous comprehensive LCA study of such building. Special attention is given to various construction materials to guide decision makers in the building and construction sector to improve their selection of suitable materials as to decrease the environmental impact. The structure of this paper is given in brief as below: section 2 describes the main methodology; section 3 illustrates the studied case; results and discussion are further given in section 4; section 5 discusses limitations and future work and finally, section 6 summarizes the main conclusion.

2. Methodology

LCA is a method for assessing environmental impacts from the production stage of a building, through the construction stage, the in-use stage up to and including the end-of-life stage according to ISO 14040. The method is used to estimate impacts linked to each material and process, systematically. In this study the LCA methodology framework has been used. It consists of four main phases: goal and scope definition; life cycle inventory analysis; life cycle impact assessment and life cycle interpretation (Fig. 1). The goal and scope definition covers functional unit, system boundary and impact categories. The life cycle inventory analysis includes inventory flows with collection of data based on material and energy flows that occur in the product life cycle. The life cycle impact assessment is based on inventory data that evaluates environmental impacts within different environmental impacts categories, the weighting factors are used to provide common equivalence units. Finally, interpretation presents evaluated results by life cycle inventory and life cycle impact assessment [35,24].

The software One Click LCA was used for simulating the impact of different building materials and cover the whole life cycle assessment of the building. One Click LCA has been developed by Bionova Ltd and is compatible with EN 15978 standard [37]. It is a standardized platform for performing Life Cycle Cost Analysis as well as Life Cycle Assessment with the possibility of estimating costs and reducing environmental impacts. The software consists of using different data from the production and construction stages through the in-use-stage until the end-of-life “grave” stage. In their database, One Click LCA uses Environmental Product Declarations (EPDs) based on the ISO 14044 and EN 15804 standards. An EPD is an externally verified, detailed and standardized description of the environmental profile of any product. It includes transparent information on the environmental impact of the product during its whole lifetime. In comparison with European-level data for building products in the report: “Carbon footprint for building products” by VTT [38], some predictions of CO_2 emissions for building materials are given with EPDs datasets available in the software One Click LCA. By using this software, it is possible to calculate a whole LCA with a standardized database. Furthermore, within One Click LCA it is possible to change and choose building materials and simulate how to reduce carbon emissions [37].

The system boundary of this study is the life cycle assessment including (A1-C4) stages according to EN standards. The LCA results are presented within each life cycle stage in chronological order (Fig. 2) and finally the overall LCA results are presented.

It begins with the production stage by selecting building materials from certain manufacturers based on EPDs. Production process of building installations such as photovoltaic (PV) panels, the ventilation system and the heat pump in the building were also considered under the production stage. Furthermore, under the construction stage, transportation distances from manufacturers to the building site were entered manually by adding the type of transportation. Moreover, water, electricity and waste generated on the site were also calculated. In the in-use stage: application of the installed product, maintenance, repair, replacement and refurbishment were considered together as (B1-B5) modules, while operation energy use and water energy use were calculated separately. Under the end-of-life stage: deconstruction, transport from the building site to waste processing for reuse, recovery and recycling, and disposal were estimated together. The functional unit is defined as building a single-family house, considering 1 m^2 living area in a 100 years perspective.

Therefore, the environmental impacts were presented in two main impact categories: global warming potential and primary energy.

2.1. Energy simulations

Energy calculations were done with TMF Energy 7.11, a program developed by the Research Institute of Sweden (RISE). The program calculates energy use based on the building physics, climate, heating and ventilation systems and occupancy. All used parameters are given within input data in Table 1. Energy data was transferred to ’One Click LCA’ to calculate GHG emissions during the operational phase (B6). The energy use for the house was based on electricity alone with an assumed emission level of 40 g CO_2e/kWh according to the Swedish electricity mix. The requirement level for primary energy is based on The Swedish National Board of Housing, Building and Planning [39].

3. The single-family house

“Dalarnas Villa” is a single-family demonstration house located in the Dalarna region, Sweden, financed by the insurance company Dalarnas Försäkringsbolag. The aim was to build a sustainable house, not only focusing on energy use in the operation phase, but also achieving low environmental impact in a life cycle perspective. The expected lifetime of the building is 100 years. The total gross floor area is 180.4 m^2 (house 150.4 m^2 and garage 30 m^2), distributed over a ground floor and upper floor. In order to show the environmental impacts through all stages of the single-family house, the project evaluates environmental impact from the production stage of building materials until the end-of-life of the house. Fig. 3 presents the drawings for Dalarnas Villa provided by the company Fiskarhedenvillan AB, Sweden.

The input data for Dalarnas Villa are given in the Table 1. Some of data are general and based on regulations and some of them are specific for the case study.

4. Results and discussion

The LCA stages are divided into modules. Fig. 4 displays the impact ratio of each stage to the total carbon emissions. The in-use stage dominates the impact at about 64% while the production stage follows at around 30%. The construction stage and the end-of-life stage have less impact ratio at only 4% and 2%, respectively.

4.1. Production stage

4.1.1. Overall view

The production stage of the building includes three modules according to EN standards. Modules A1, A2 and A3 are defined as one aggregated module (A1-A3). Module (A1) includes raw material extraction and processing; Module (A2) includes transport distance to the manufacturer and internal transport; Module (A3) includes manufacturing of products and packaging. All these modules include supply

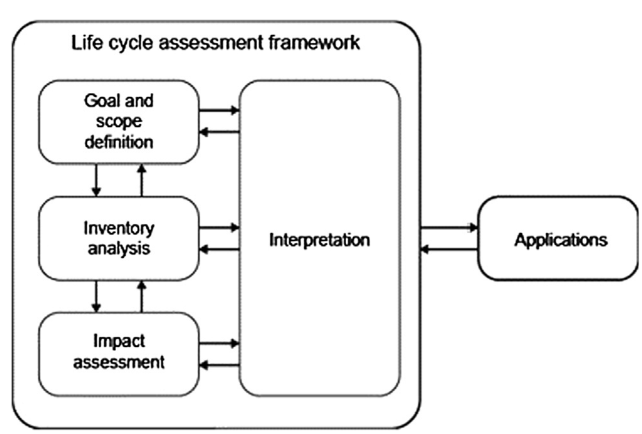

Fig. 1. The framework for life cycle assessment processes different phases [36].

Product Stage			Construction Process Stage		Use Stage							End-of-Life Stage			
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4

Fig. 2. The four life cycle stages and 16 sub-stages according to EN 15804:2012; modified [37].

Table 1
Input data on building, climate conditions and installations in the house.

General information	Data	Unit	Reference
Indoor temperature	21,0	°C	[1]BEN 2
People	3,5	–	[1]BEN 2
Metabolic rate	80	W/person	[1]BEN 2
Attendance time:	14	h/day	[1]BEN 2
Warm water cons., specific	20	$kWh/m^2/y$	[1]BEN 2
Household electricity	30	$kWh/m^2/y$	[1]BEN 2
Building			
Living area	150,4	m^2	[2]Dalarnas Villa
Garage	30,0	m^2	[2]Dalarnas Villa
Building envelope (A_{om})	446,5	m^2	[2]Dalarnas Villa
Mean U-value (U_m)	0,269	$W/K\ m^2$	[2]Dalarnas Villa
U_mA_{tot}	120,1	W/K	[2]Dalarnas Villa
Airtightness (q_{50})	0,18	$l/s\ m^2$	[2]Dalarnas Villa
Time constant	62	H	[2]Dalarnas Villa
Climate conditions			
Outdoor temp. average	5,0	°C	[3]SVEBY
Design outdoor temp.	−19,7	°C	[4]TMF
Ventilation			
Exhaust fan (demand control)	42	W	[5]BBR 25
Design air flow	52,6	l/s	[5]BBR 25
Heating			
Ground source heat pump	5,3	kW	[6] EN 14,511
COP/P heat, nom 0/35 °C	4,62/6070	–/W	[6] EN 14,511
COP/P heat, nom 0/45 °C	3,44/5280	–/W	[6] EN 14,511
COP/P heat, nom 0/55 °C	2,64/4740	–/W	[6] EN 14,511
Solar energy			
PV panels	5074	kWh/y	[2]Dalarnas Villa

Notes:

[1] Normal use of household appliances for new houses and years according to BEN 2 "Boverket regulations and general advice on determining the energy consumption of the building for normal use and a normal year (BFS 2017: 6)".

[2] Data based on specific case "Dalarnas Villa".

[3] SVEBY (Industry standards for energy in buildings) climate data based on SMHI (Swedish Meteorological and Hydrological Institute).

[4] TMF-program for energy simulation.

[5] BBR 25-Boverket building regulations.

[6] Heat pump COP-coefficient performance and nominal heat production at the test points according to EN 14511.

of all materials, products and energy, as well as waste processing up to the disposal of final residues during the product stage. Materials based on EPDs from different manufacturers have been chosen based on what has been found in the software. Building materials with recommended replacement periods and transport distances of materials are presented in Table 2. It can be noted that the production of concrete has the highest CO_2e (the amount of CO_2, which has the equivalent Global Warming Impact (GWP)). Wood as the main material used for framework and panel facade as well cellulose insulation have low carbon emissions. The other materials that also have contributed to high environmental impacts are: steel, gypsum, doors and triple glazed windows. During the lifetime of the building it is assumed based on best practice in Sweden and results provided by the software that: (1) wood panel facade, roof and windows could be replaced once; (2) doors could be replaced twice; (3) thermo-wood for external use and parquet for the floor inside the house could be replaced three times. The CO_2e emissions are separated and visible for each stage regarding building materials. The software gives the possibility of adjusting the total amount of CO_2e emissions from each product with local compensation based on the local energy mix used. The total amount for the production of building materials including transportation distance, maintenance and replacement, and end-of-life is 32 t CO_2e or 30% of total impacts.

CO_2e emissions from production of building materials showed that the concrete for foundations accounts for the largest impact. Furthermore, glass, gypsum and steel gave the next highest emissions.

Cellulose insulation was used for the external walls, ceiling and roof while for the internal walls wood fiber insulation was used. Both have only approximately 2% of the total impact. In the software One Click LCA it is possible to exchange building materials with different emission level. Table 3 presents the span between four materials mainly used in the building industry, regarding their CO_2e emissions in two different units. In comparison with our base case, Dalarnas Villa, it is evident that cellulose and wood are "low carbon" materials. Wood based products could have a key role in reducing energy use and carbon emissions [40]. Some studies demonstrated that wooden materials binds CO_2 [41], that otherwise would have been released to the atmosphere and need less energy use [42] in their production compared to other alternative materials [43] that, for instance, use fossil fuels [44,45]. Therefore, using wood as a construction material can be a design strategy that can reduce the carbon dioxide emission substantially [34] with studied average reductions in GWP of 60% [46]. Emissions from wood per cubic meter are 100 times lower than for concrete (Table 2). But it should be noted that cross laminated timber, commonly used in multi- storey timber building [47], only gives 10 times lower emissions than concrete (Table 2). Other environmental impacts linked to the use of wood, such as local environmental conditions, deforestation/land use change, impact on ecology, ecosystem services, wild life and biodiversity, are not included in this analysis. From a sustainability perspective it is important to use wood from well-managed sustainable forestry with investment in replanting. Today it is estimated that 38% of the total wood removal is used for building and construction [48,49]. Furthermore, a benefit of wood construction products is that they can be re-used, recycled as wood plastic composites or fiberboard panels or down-cycled into pulp or fuel at their end of life [49].

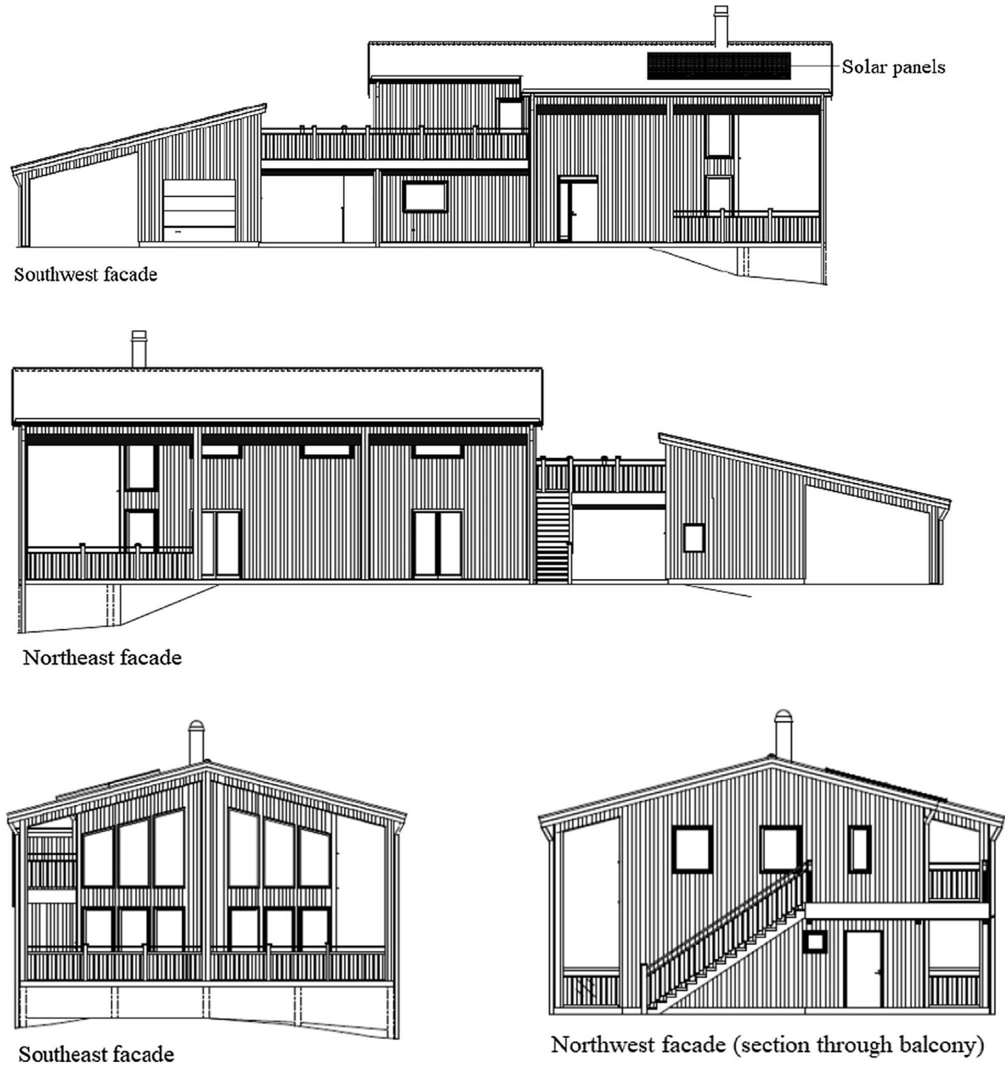

Fig. 3. Facade drawings of Dalarnas Villa.

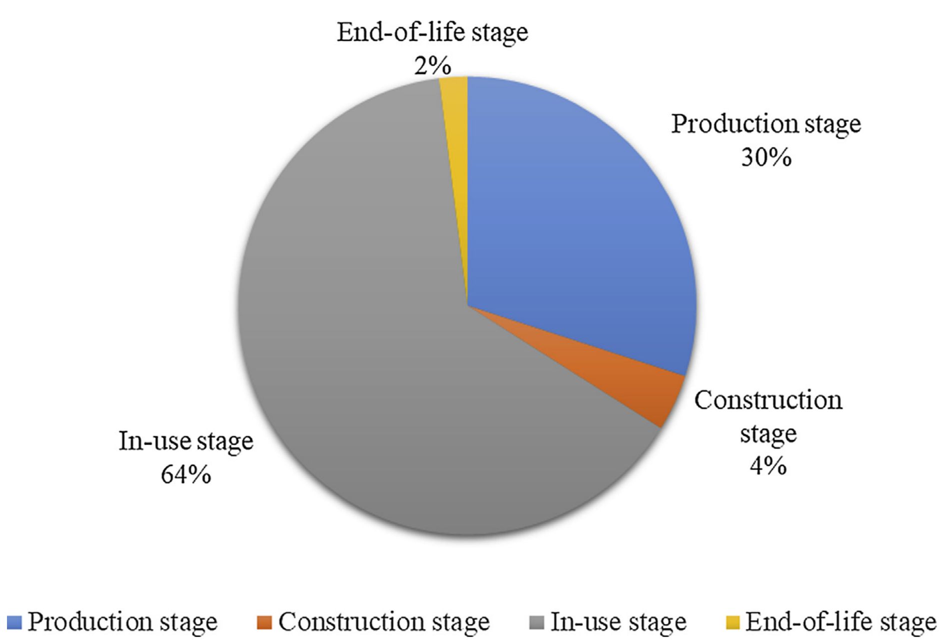

Fig. 4. The buildings stages relative impact on the total emissions of the buildings total life cycle.

Table 2
Data on materials and products quantity, carbon dioxide emissions, transport distance, maintenance and replacement data and end-of-life emissions.

Material	Quantity	kg CO_2e/unit	Material (A1-A3)	Transportation distance (A4)		Maintenance and replacement (B4-B5)		End-of-life (C1-C4)	Total CO_2e	
			Tons CO_2e	km	Tons CO_2e	Times	Tons CO_2e	Tons CO_2e	Tons CO_2e	[%]
Concrete	21.8 m^3	270.6/m^3	5.9	19	0.05	0	0	0.15	6.1	19
Wood framework (internal + external)	23.4 m^3	2.6/m^3	0.06	264	0.02	0	0	0	0.08	0
Wood panel facade	15.6 m^3	3.2/m^3	0.05	264	0	1	0.05	0	0.10	0
CLT (cross-laminated timber)	5.4 m^3	27.8/m^3	0.15	264	0.09	0	0	0.02	0.26	1
Thermo-wood external (heat treated wood)	4.4 m^3	79.5/m^3	0.35	264	0.09	3	1.05	0.01	1.50	5
Cellulose insulation	114.2 m^3	1.5/m^3	0.17	212	0.02	0	0	0	0.19	1
Wood fiber insulation	5.7 m^3	75.4/m^3	0.43	212	0	0	0	0	0.43	1
Expanded Polystyrene (EPS) insulation	21.8 m^3	50/m^3	1.09	380	0	0	0	0.02	1.11	3
Gypsum	1306.2 m^2	2.1/m^2	2.77	220	0.16	0	0	0.03	2.96	9
Floor internal	132 m^2	4.5/m^2	0.59	215	0.02	3	1.77	0.12	2.50	8
Plastic details	1521.8 m^2	0.4/m^2	0.64	200	0.07	0	0	0	0.71	2
Windows-triple glazed	25 pieces	116/piece	2.90	400	0.03	1	2.90	0.07	5.90	18
Doors	15 pieces	117/piece	1.75	470	0.09	2	3.50	0.16	5.50	17
Roof- steel	155 m^2	11.6/m^2	1.80	410	0	1	1.80	0	3.60	11
Total			18.65		0.64		11.07	0.58	31.91	100

Table 3
Variations in carbon dioxide emissions from different building materials. Numbers based on EPDs provided by One Click LCA database.

Global warming potential kg CO_2e/unit			
Materials		m^3	kg
Cellulose	Base case	1.5	–
Glass wool	Highest	97.37	2.79
	Lowest	11.4	0.25
Stone wool	Highest	356	3.09
	Lowest	15.7	0.38
Wood	Base case	2.6	–
Bricks	Highest	539.79	0.55
	Lowest	96.06	0.16
Concrete	Highest	626.28	0.63
	Lowest	41.5	0.05

The cellulose insulation used for Dalarnas Villa has 1.5 kg CO_2e/m^3. It has about 7 times less CO_2e compare than the lowest glass wool and about 10 times less than the stone wool insulation. The mostly used glass insulation in the building industry according to European level data gives about 3.15 kg CO_2e/kg based on VTT report [38].

To compare different facade constructions based on various materials was outside of the scope of the paper. However, the difference in CO_2e emissions between materials such as bricks and concrete are shown in Table 3. For instance, Börjesson and Gustavsson compared primary energy use and GHG emissions between wood and concrete frame buildings. They found significantly increased primary energy for concrete frame building (60–80%) compared to the wood frame. The wood frame building also showed lower GHG emissions in most cases [50].

4.1.2. Building systems and installations

The production stage of building systems and installations: solar (PV) panels, different pipes (PP, PVC, copper), electric heat pump, ventilation, electrical cables, emit about 12 (11.55) t CO_2e (Table 4). Solar (PV) panels are installed on the south-east facade covering 32 m^2 of the cladded area. Installed solar panels (20 modules) of 275 W, produce 5074 kWh solar energy annually. However, solar panels within building installations emit the largest impact 23 (22.8) t CO_2e in total emissions. Their production gives about 6 (5.8) t CO_2e. Thus, with a service life of approximately 30 years, the maintenance and replacement emit 17 tons CO_2e for the whole lifetime of the building. To produce and maintain different pipes (PP, PVC, copper pipes) including water supply piping system, underfloor heating system and electricity cables gives approximately 7 (7.4) t CO_2e. An electric heat pump (brine-water) has to be replaced after every 20 years, while the ventilation system has to be replaced once per lifetime of the building. The pipes, ceramics, heat pump and ventilations system, however, showed only minor emissions to the environment.

A closer look at the production stage of the building materials, including taking the building installations into consideration, can be seen on Fig. 5. The production processes of concrete and solar (PV) panel systems have a significant influence on the total CO_2e emissions.

4.2. Construction process stage

The construction stage includes A4 and A5 modules and emits approximately 4,5 t CO_2e or 4% of the total impacts. Module (A4) is based on the transport distance from the material manufacturer to the building site, added manually by specific data from the suppliers in Table 2. For delivering the large amount of wood the large truck (9 ton capacity, 50% fill rate) is used. For other building materials and installations, trailers and small trucks (12–14 ton capacity) were used for the transportation. The module (A5) includes manufacture and transportation of ancillary materials, energy and water required for installation or operation of the construction site. The construction stage also considers on-site work on the product as well as different wastes generated on the site. Both activities include all impacts and aspects related to any losses during this construction process stage. The energy used during the construction stage of the house is the Swedish electricity mix consumption based on IEA and the total amount is 49518 kWh. Water consumption utilized on-site is 2 m^3. Moreover, mixed waste generated on the building site, including wood waste, steel waste

Table 4
Emissions share for production stage and replacement sub-stage of building installations.

Building installations [t CO_2e]	Production	Replacement
Solar panel system	5.8	17
Pipes (PP, PVC, copper)	1.66	0
Water supply piping system	1.2	1.2
Underfloor heating system	1.2	1.2
Electric heat pump	0.6	2.4
Ventilation system	0.62	0.62
Electricity cables	0.47	0.47
Total	11.55	22.89

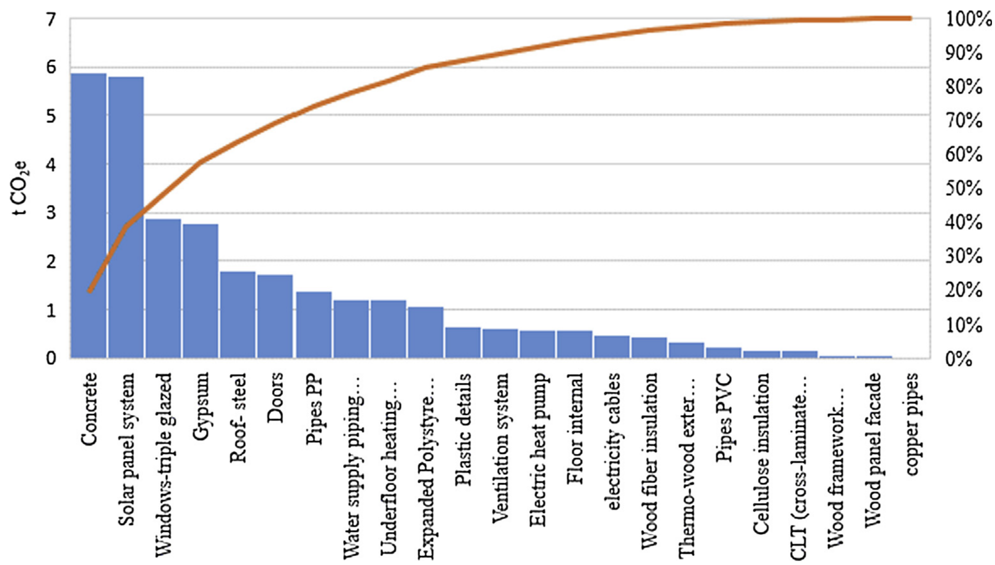

Fig. 5. Production stage of building materials including installations into consideration.

and gypsum waste, were assessed and amounts 12 tons.

The total CO_2e emissions from the materials transportation stage is calculated to be 0.64 t CO_2e. For all building materials from Table 2, the transportation distance is added from specific manufacturer to the building site with estimated CO_2e emissions by the software. The gypsum materials have the highest impact at 0.16 t CO_2e, corresponding to 25% of the total CO_2e emissions at the A4 module. CO_2e emissions from CLT (cross-laminated timber), thermo-wood external (heat-treated wood) and doors account for 0.09 tons equivalently, leading to 14% of the total CO_2e emissions at the material transportation stage, respectively.

In the on-site construction stage, CO_2e emissions are estimated at 4 t CO_2e. Energy use based on Swedish electricity mix contributes with 2 t CO_2e, as well waste generated in the on-site has the same share of CO_2e emissions. The water consumption used on-site gives nearly zero emissions. CO_2e emissions from these work types corresponds to 4% of the total CO_2e emissions in the on-site construction stage, which indicates that the energy consumption due to the use of various construction equipment according to work methods in the construction process results in low CO_2e emissions.

The waste treatment process can be divided depending on the physical property of wastes: (1) discharge, transport, demolition/incineration or treatment, recycling step; and (2) discharge and landfill step [51]. The total amount of waste generated during the evaluation period was 12 tons, and the total CO_2e emissions from the waste generated on the on-site emit around 2 t CO_2e. Of the wastes discharged from the construction process, the materials with physical properties that require crushing, grinding, and incineration at the intermediate treatment company include construction sludge, gypsum waste, waste wood and mixed waste. Mixed waste contributes to high emissions and gives around 1.8 t CO_2e of the total emissions, while construction sludge, gypsum waste and wood waste show negligible CO_2e emissions.

It should be noted that at the construction stage, the waste treatment is taken into consideration in term of end of life scenario, which is a default definition as 'material properties and regional scenario' in One Click LCA tool. In such scenario, the waste handling processes are considered between regions. This assumption of this scenario is based on compensation methodology, which is a peer-reviewed methodology implementing the guideline from CEN/TR 15941 for making product data locally adaptable [37]. The assumption is also in consistence with our practical project, in which we activate the use of local compensation, enabling the overall building impacts more representative of the local context.

4.3. In-use stage

4.3.1. Overall view

The in-use life cycle stage involves: (B1) - use or application of the installed product, (B2) - maintenance, (B3) - repair, (B4) - replacement, (B5) - refurbishment, (B6) - operational energy use and (B7) - operational water use. The in-use stage emit about 65 t CO_2e which is an almost two third (64%) share. In the software, modules (B1-B5) are considered together and provided impacts are calculated based on the service life of the construction materials and life span of the building. They emit about 38 t CO_2e or 37%. Module (B6) involves operational energy use during the in-use stage of the building. The calculation is based on the total annual energy consumption and service life period of the building. The total purchased energy emits about 21 t CO_2e or 21% of the total amount. The share becomes relatively much lower in Sweden compared to most other countries as the electricity mix is mostly based on hydropower and nuclear energy. Module (B7) incorporates water consumption during the operation of the building with a total impact of 6 t CO_2e or about 6%. The estimate is based on 3,5 people living in the house with a total annual water consumption of 200 m^3 obtained on the basis of official annual consumption per capita in Sweden. Operational energy use (B6) and operational water use (B7) also includes ~~also~~ provision and transport of all materials, as well as energy and water provisions, waste processing up to the end-of-waste of final residues during this part of the in-use stage.

4.3.2. Operational energy

Table 5 presents the energy use and primary energy use simulated

Table 5
Data on energy use estimated in Swedish scenario.

Output on energy use	Value	Unit
Specific energy use (bought energy excl. household/A_{temp})	31,5	$kWh/m^2/y$
Primary energy (PE)*	45,3	$kWh/m^2/y$
Primary energy (PE) requirement level BBR 25 (BFS 2017:5)	90	$kWh/m^2/y$
Energy level BED 9 (BFS 2016:14)	B	–
Total energy demand including household electricity	26 331	kWh/y
Energy savings: heat pump	16 562	kWh/y
Energy savings: PV system (solar cells)	5 074	kWh/y
Total purchased energy (electricity), net	4 695	kWh/y

* Note: the primary energy is calculated based in the Swedish scenario with the primary energy factor of about 1.6 $kWh/m^2/y$.

by TMF Energy. The specific energy use is calculated as the amount of electricity net supplied to the building's technical installations for building services during the operational phase, i.e purchased energy excluding household electricity. It was influenced by the heat pump system and solar PV panel system. The demand controlled heating and ventilation systems were operated based on occupancy according to the latest building regulations [39]. It can clearly be seen that the heat pump saves relatively much more energy (16562 kWh/y) compared to solar cells (5074 kWh/y), especially in relation to their environmental impact for the production. Overall, the building almost reached energy performance level A, which is half of the energy requirement. It can clearly be seen that the heat pump saves relatively much more energy compared with solar cells, especially in relation to their environmental impact for the production (also see Fig. 4).

4.4. End-of-life stage

The end-of-life stage consists of these modules: (C1) - deconstruction, (C2) - transport to waste processing, (C3) - waste processing for reuse, recovery and recycling, and (C4) - disposal. The total impact is very low (1,5 t CO_2e or 2%). All (C) modules are aggregated as one including provision of all materials and transport, also products and related energy and water use. Therefore, deconstruction, transportation of the discarded products, waste processing and disposal related emissions are assessed together. The stage end-of-life is considered as marginal for (C1-C4) modules. The data are default.

4.5. Overall LCA

The LCA results of Dalarnas Villa are presented in the Table 5. The study investigates the environmental impacts during all life cycle stages. The total impact of all life cycle stages is about 102 tons CO_2e for a study period of 100 years calculated in the global warming potential indicator. The carbon dioxide equivalent emissions from the project for the scope calculated in this GWP indicator divided by the assessment period and gross internal floor area is 6 kg CO_2e/m^2/year. In Table 6, values are given in different units.

Table 6 shows that nearly 30% of the CO_2e emissions were generated during the production of building materials and installations. In addition, the maintenance and replacement of building materials and installations accounted for nearly 37% of the global warming. In relation, the operational energy is 21% of total impacts, while, the water consumption (5%), the construction (5%) and deconstruction stages (1,5%) have contributed to significantly low environmental impacts. It is obvious that more emphasis must be set on production and maintenance of building components as the operation of buildings becomes more environmental friendly. In comparison with other study with sample of 40 single-family houses in France, the results demonstrates 8.4 kg CO_2e/m^2/year [52]. In another case study, pilot project in Norway, they have developed an LCA with emphasis on GHG emissions. Their results show 21.2 kg CO_2e/m^2/year and emissions embodied in materials has 56% of total emissions [53].

Primary energy shows the highest level within operational energy use (64%), while the production stage is 10%, maintenance and replacement parts (16%) and other stages have minority contribution of the primary energy use. The main reason why the operation phase stand out is because of a high primary energy factor for electricity and the fact that heating of the house is based on electricity use alone.

The LCA estimated in the case study, Dalarnas Villa, facilitates the comparison and further discussion on different considerations of environmental impacts within life cycle stages. The CO_2e emissions could be further reduced by finding some more sustainable solutions in the early stage of building design. For instance, ready-mix concrete with a high proportion of cement, clinker and other aggregates that emit high CO_2e in their production could be replaced by "green" ready mix concrete with recycled binders. Imbabi at al pointed out that concrete is the material, which contributes most to GHG emissions due to cement production. Green cement alternatives could reduce emissions by up to 95%. Therefore, cutting emissions from concrete could lead to significant reduction of embodied emissions [54]. Thus, a large amount of fly ash as a substitute for cement could be considered to give an alternative sustainable concrete [55]. Other fossil-based materials such as: steel, glass and gypsum could be replaced by sustainable alternatives. Using low carbon appropriate materials that need less energy in their production processes leads to lower environmental impact. As the life span of a single-family house with a wood-frame could be more than 100 years, the emphasis could be on the long service life of building materials with reduced environmental impacts.

The case study shows, the production of installations for the house with maintenance and replacement included, produces high CO_2e emissions. The solar (PV) panels contributed a great deal compared to other installations. Thus, solar panels include rare earth metals and mining of metals is energy consuming. Besides a high "energy footprint" fossil fuels are used in energy supply. This means that manufacture of solar panels have a considerable carbon footprint. In the assessment, attributional approach is used meaning solar panels substitute Swedish power mix with a moderate carbon footprint. In most assessments, electricity from solar panels is valuated using a consequential approach by substituting marginal electricity with a high carbon footprint. Another factor contributing to this result is the fact that solar panels have an estimated life span of approximately 30 years, meaning they have to be replaced 3 times during the 100 year period. In all, this means the use of solar panels is not clearly favorable to decrease environmental impact. This is in line with the current discussion on batteries for electric cars where the batteries themselves make a large contribution to CO_2 emissions from the car over the lifetime. This study emphasizes the need to reduce energy use in manufacture by using non-virgin resources, decarbonize energy supply in manufacture, extend life lengths of solar panels, and improve and increase capacity in recycling of green technologies such as solar panels. If panels to a high share can be reused or recycled, it will benefit the assessment both in terms of low impact of new panels and also the impact form end-of-life will be lower.

The Swedish electricity mix contribute to very low GHG emissions. As houses in Sweden become more energy-efficient the environmental

Table 6
LCA results showing the Global warming potential and primary energy use from different life cycle stages.

Life cycle stages:	Life cycle modules:		Global warming potential:				Primary energy:			
			kg CO_2e	kg CO_2e/m^2	kg CO_2e/m^2/y	Total%	MJ	MJ/m^2	MJ/m^2/y	Total%
Production stage	A1-A3	Construction materials	30569	169.8	1.7	30	542106	3011.7	30.1	10
Construction stage	A4	Transportation to the building site	487	2.7	0.03	0	13407	74.5	0.7	1
	A5	Construction	4105	22.8	0.23	4	371897	2 066	20.7	7
Use stage	B1-B5	Maintenance and material replacement	38122	211.7	2.12	37	869281	4829.3	48.3	16
	B6	Operational energy use	21022	116.8	1.17	21	3495718	19420.6	194.2	64
	B7	Operational water use	6018	33.4	0.33	6	127230	706.8	7.1	2
End-of-life stage	C1-C4	Deconstruction	1687	9.4	0.09	2	8355	46.4	0.5	0
Total			102009	566.7	5.7	100	5427994	30155.5	301.6	100

impact from the operational phase becomes very low as a consequence, while the production and construction phases become dominant in the life-cycle perspective. In Sweden the emphasis is shifting towards the production of sustainable building materials instead of the operational energy use. This trend will probably occur elsewhere as well, as more renewable energy sources are introduced in the energy mix.

The software frequently updates and improves the database. However, within material assessment and energy calculations some errors could be possible without these leading to different conclusions in the end. There is uncertainty when calculating the amount of CO_2e emissions due to the adjustment of emissions for “local compensation” based on the energy grid and other data.

More studies regarding overall LCA in the building sector are needed in the future. Thus, benchmarking between different building designs is needed to establish targets within different life cycle stages in the building industry. Furthermore, it could be valuable to compare different building designs at different stages and make a minimum carbon footprint for new buildings. Until now “The embodied carbon review” [33] reports the results of embodied carbon by building materials globally. Some countries in Europe (Norway, Netherlands, Austria and France) have been able to create some regulations limiting the carbon footprint values and make the environment for LCA in the building industry. For instance, France has primary legislation for the carbon footprint of new buildings. The method they used covers the entire building and an estimated 50-year period life span for different building types. The embodied carbon limit for single-family houses is set up to 650 kg CO_2e/m^2 as a good performance level [33].

5. Limitations and future work

5.1. Primary energy factors

In this study GHG emissions during the operation phase was based on the Swedish electricity mix with 40 g CO_2e/kWh. Other European countries may have emissions up to ten times higher than Sweden. In reality the electricity net is connected to neighboring countries and electricity is flowing over the borders all the time. One could argue that the environmental impact of operational energy use should be based on the real origin of the electrons in the power lines, not only considering Sweden. In that case the GHG emissions from operational energy use would be much higher, probably dominant, better reflecting the situation around the world where energy transition to renewable energy production is the most crucial aspect. This effect was not captured in the present work due to limitations of the software. Furthermore, there is incapability of One Click LCA to apply consequential approach when comparing different designs.

Another aspect, which is interesting to reflect on, is how changes in electricity demand affect the environmental impact of buildings. Local changes in the electricity demand, for example due to implementation of solar cells, have an impact on the energy production in a wide perspective. Usually, the renewable energy production is always kept at maximum everywhere, while changes in demand affects electricity production based on fossil fuel far away. Even in Sweden, electricity savings push away fossil fuel production elsewhere in Europe. That is why implementation of solar cells should be encouraged even in countries with renewable energy production.

5.2. End of life PV panels

Lifecycle impacts of PV panels are of great importance in our project, as PV panels contain several carbon-intensive processes except operation stage, such as mining, transportation (I), manufacturing, equipment, transportation (II), construction, transportation (III), and disposal. We have included the basic estimations from mining to operation stage. However, the end-of-life phase has been neglected, mainly because there are only few PV panels that reached the disposal yet and we lack data about their end of life in the tool at the moment.

But the disposal of PV panels will become a relevant environmental issue soon since many PV panels will achieve their end of lives. The disposal stage will affect the total estimation of both carbon emission and energy. According to Latunussa et al. [56], recycling of 1000 kg of silicon PV panels, it has equivalent GWP at 370 kg CO_2e and gross energy ratio (GER) at 2780 MJ throughout their life span. The majority of the impacts for the recycling process of PV panels are related to the transport of PV waste to the site, the plastic incineration processes, and the further treatments (including sieving, acid leaching, electrolysis, and neutralization) for the recovery of metals (including silver) from the bottom ash [56].

In our future work, we will include above figures of EOL of PV panels into the tool to better support estimation, which will enable a different EOL scenario and then result in a change on the related impacts of different segments.

As the LCA of our case study is finished and the environmental impact of single-family house in Sweden is investigated, the next part of our study will analyze and calculate costs of the whole process within Life Cycle Costing including future trends. The integration of LCA and LCC results could give interesting answers to Swedish building industry based on environmental and economic approach.

6. Conclusions

This case study presents the total environmental impacts of one single-family house in a 100 years life cycle perspective. Indicators chosen for this paper are global warming potential and primary energy. The results demonstrate 6 kg CO_2e/m^2/y and a total of 102 t CO_2e, respectively. LCA results show that the highest impact was found to be in the in-use stage of the building. Production of building materials and installations (30%) with maintenance and replacement parts (37%) contribute to the highest level of CO_2e emission in total. As the Swedish electricity mix mainly consists of renewable energy sources, the operational energy consumption stand for only 21% of the CO_2e emissions. The transportation distance, water consumption and waste treatment do not contribute significantly to the environment.

The building industry can place the emphasis on materials with a low environmental impact in their life cycle. The case study shows that cellulose insulation has dramatically low CO_2e emissions in comparison with other materials mainly used in building industry, such as glass wool and stone wool. Furthermore, wood used for the framework and the facade of the house is also a “carbon friendly” material in comparison with other mainly used materials such as bricks and concrete. In recent study done by [22], the strong focus is given to the materials embodied energy and emissions.

As countries move towards fossil free regarding low energy buildings, the wider debate will significantly increase regarding the production stage of building materials as well installations. In our case, the production of concrete and solar (PV) panels showed the greatest amount of CO_2e for the reference time of 100 years. Other materials such as gypsum, steel and glass have a large share of CO_2e emissions. However, in comparison between life cycle stages, the in-use stage (replacement and maintenance of building materials and installations, operational energy use and water consumption) still shows the highest rate. Similarity in results is found in recent case studies for Norwegian and French buildings with emphasis on emissions embodied in materials.

When the house has a 100 years reference time some uncertainties can occur during its lifetime. For example, regarding to some changes in installations or the addition of other appliances into the building during the lifetime the total impact of the building could be changed.

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