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Life Cycle Environmental and Cost Analysis of Building Insulated with Hemp Fibre Compared to Alternative Conventional Insulations – a Swedish Case Study

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Life Cycle Environmental and Cost Analysis of Building Insulated with Hemp Fibre Compared to Alternative Conventional Insulations – a Swedish Case Study

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Summary

This study presents a comparative life cycle analysis (LCA) and life cycle costing (LCC) assessments of hemp fibre and conventional alternative insulations for the climate shell of a building. The conventional alternative insulations compared to the hemp fibre are cellulose and glass wool. The object of the analysis is a one-story single-family house, in Växjö, Sweden, and the lifetime of the house is set to 50 years. The LCA focuses on the Global Warming Potential (GWP) impact and the LCC during the lifetime of the different insulations for the building are calculated using the net present value method. The results show that the net GWP-impact for hemp fibre insulation is about 10 % lower and the cost is about 20 % higher than the conventional glass wool alternative. Furthermore, the analysis shows that cellulose insulation has slightly lower GWP-impact and nearly the same cost as the glass wool alternative. Sensitivity analyses regarding five different issues were performed and these show that: for cellulose coming from recycled paper, it contributed to less fossil emissions than non-recycled paper. If the data source for glass wool insulation is changed from environmental product declarations (EPD) to generic data, the greenhouse gas emissions increased. By replacing district heating system with geothermal heating system, fossil GWP-impacts also increased while the LCC analysis shows that operating costs is reduced. If the fuel is changed from diesel to electricity, fossil emissions are reduced over the life cycle of the building. If only part A1 – A5 is reported, as required for the Swedish climate declaration, the results point to the outcomes that glass wool insulation gives the least fossil GWP-impact while the hemp fibre gives the least net GWP-impact.

Keywords: life cycle analysis, life cycle cost, climate impact, hemp fibre insulation, cellulose insulation, glass wool insulation, residential building.

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Introduction

With the growing concerns of climate changes, the Paris Agreement and the European Union's net emissions targets have influenced the building sector in Sweden to become more climate neutral (European Commission u.å.a; Europeiska rådet 2021). According to the managing authority Boverket (2021b), the building sector accounted for a fifth of Sweden's total greenhouse gas (GHG) emissions, in 2018. Kosiński, Brzyski, Szewczyk & Motacki (2018) and Zampori, Dotelli & Vernelli (2013) claim that the choice of building materials has a significant effect on emissions of GHG. In addition to the building's operational phase, the production of various building materials causes emissions of GHG, where the emissions vary greatly depending on the material (Boverket 2021a; Treloar, Fay, Ilozor & Love 2001). To facilitate the choice of building materials with less climate impact, from 2022 onwards there will be requirements for a climate declaration in Sweden (Ministry of the environment 2020). Increased environmental awareness and an increased interest in sustainable, ecological and renewable materials means that the use of more environmentally friendly insulation is expected to increase. This is supported by many studies and has led to an increased demand for industrial hemp in the world, especially in Europe (Kymäläinen & Sjöberg 2008; Kallakas, Närep, Närep, Poltimäe & Kers 2018; Bouloc, Allegret, & Arnaud 2013). There are limited studies of hemp fibre as insulation material in the Swedish context, which may be due to the fact that hemp fibre has been illegal to grow in Sweden since the 1970s, but in 2003 certain plants can be approved for cultivation (Kunglig Majestäts kansli 1972). Like the rest of the world, there is an interested in hemp fibre, especially in Europe (Bouloc, Allergret & Arnaud 2013). According to a study conducted by Zampori, Dotelli & Vernelli (2013) in Australia, hemp fibre insulations result in less emissions of CO_2e compared to glass wool, for example.

In addition to different climate impacts, insulation materials also have different costs, which can affect the choice of material (Kymäläinen & Sjöberg 2008). Cellulose is another material which has had a small share in the insulation market, which might be due to limited knowledge of the material's moisture absorption capacity (Tumusiime, Kirabira & Mmusinguzi 2020; Lopez Hurtado, Rouilly, Vandenbossche & Raynaud 2016). Cellulose insulation is interesting to study as it exhibits low environmental impact (Sohn et al. 2017). Presently, the common insulation material in Sweden is mineral wool, which has dominated the market in northen Europe by representing 57 % of the market shares (Sohn et al. 2017). There is an idea that purchase price can be a reason why conventional insulation maintains its market share (Zabalza Bribián, Valero & Aranda Usón 2011). According to Emblemsvåg (2003) the result of an LCC can justify environmental change. By calculating a building's environmental impact with an LCA and complementing this with a life cycle cost (LCC), a more comprehensive picture of the building's climate impact and cost can be made visible and understood.

As we enter a new epoch of great focus on what needs to be done for the good of the planet, the discussion should be about what is required when the decision itself is made. This study investigates which choice of insulation material is most environmentally friendly and what the choice of the most environmentally friendly material will cost in a life cycle perspective. This is a decision that we believe many individuals can face and is crucial for the selection of a sustainable building material.

This study examines the environmental and economic consequences of the decision to choose between three different insulation materials for the construction of a single-family house in Sweden. The purpose of the study is to provide more basis for the choice of insulation material looking into the climate- and cost implication of hemp fibre, cellulose and glass wool insulation.

Case study house

The insulation needed in a standard one-floor Swedish single-family house is analysed to evaluate the implications of the different insulation materials, see Figure 1.

(a) (b)

Fig. 1

An illustration of the house (a) and a drawing of the floorplan (b)

Table 1

Wall thickness [mm], roof thickness [mm], gross floor area [m²], habitable area [m²], ceiling height [mm], roof slope [°] and u-value [W/(m²K)]

	House model		
Building information	Hemp fibre	Cellulose	Glass wool
Wall thickness	375	350	345
Roof thickness	227,7	224,7	224,2
Gross floor area	176,8	175,3	175,0
Habitable area	153,0	153,0	153,0
Ceiling height	2500	2500	2500
Roof slope	24	24	24

Table 2

U-value [W/(m²K)]

U-value of building components	
Building component	U-value
Slab	0.13
Exterior wall	0.14
Window	0.9
Front door	1.3
Front door	1.1
Roof	0.07

The construction consists of a wooden frame with a wooden facade. The design of the construction when calculating and modelling the building follows references for construction in Sweden (Svenskt trä 2014a; 2014b, 2015). In the study, the insulation material in the house are varied between hemp fibre, cellulose and glass wool. The different thermal conductivity of the insulation materials required that in some cases the wall thickness had to be altered to achieve the same U-value in the climate shell, see Table 1 and 2. The study is delimited by looking only at the house model's climate screen. The house's energy use follows Swedish building code's (BBR) requirements for energy use of detached houses located in Växjö, Sweden. The number of residents in the house is calculated as 4 people and thus the house's heat recovery (FTX) ventilation and water use are calculated according to these conditions. In the study, the house is assumed to be heated with district heating (Eriksson, Hult & Karlsmo 2021).

Methodology

The LCA focused on the environmental consequences while the LCC highlighted the economic aspect of the insulations.

LCA

The method used for the study was an attributional LCA. This was carried out according to the normative standard *Sustainability of construction works - evaluation of buildings' environmental performance - calculation method* (SS-EN 15978: 2011). In order to be able to compare, the functional unit was chosen to be kilograms of carbon dioxide equivalents per square meter of habitable area [kg CO_2e / m^2 habitable area], as the habitable area do not change due to increased insulation volume. The goal of the LCA was that the result should be able to facilitate the decision-making process for house manufacturers and house buyers.

The system boundaries of the study are defined as follows:

- The examined materials were those that affects the U-value of the climate screen and eventually affected by a change in wall thickness.
- The study does not include stages that were similar for house models when using the different insulations.
- The environmental impact was limited to emissions of kilograms of CO_2e.
- The time horizon of the analysis was set to 50 years
- The study covers carbon flows in the following stages: product stage (A1 – A3) transport (A4), waste (A5), operating energy (B6), transport of waste (C2), waste management (C3), landfill (C4) and profits outside the system limit (D). Further detailed regarding the study's boundaries is found in Eriksson, Hult & Karlsmo (2021).
- Data on the insulation materials were obtained primarily from EPDs (type III) produced for Sweden and secondarily from generic data. The different building materials from EPDs did not have the same functional unit, therefor the data needed to be recalculated with a comparable unit. Detailed regarding the study's data are documented in Eriksson, Hult & Karlsmo (2021).
- Data on other materials were retrieved primarily for generic data and secondarily from EPDs.
- Data were reviewed and evaluated based on the acquisition method (if the data was credible), age, geographical area, technology of production and method of verification (if the data was complete) in accordance with the methodology of Pedersen Weidema & Suhr Wesnæs (1996).
- In the study, the transports were limited to being calculated with generic data and data from EPD in stage A4. In the remaining stages, the transports with a truck with a maximum load of 26.1 tonnes were calculated.
- Emissions in stage A4a were calculated by multiplying the mass of the materials [kg] by the factor for A4 from the EPD or the generic data. Other transports were calculated with tons of material multiplied by the truck's maximum weight and multiplied by the distance. Per full truck, return only own weight.
- In phase C2, the transports were divided up so that certain materials could be recovered for energy through firing and others ended their life cycle as landfills. For more detailed boundaries see the bachelor thesis (Eriksson, Hult & Karlsmo 2021).

Quantity calculation

The materials which were taken in account are those within the system boundaries: wood, plaster, insulation in loose wool and board form, cellular plastic, concrete 30/37, reinforcement, OSB boards, concrete boilers, baseboard, plastic film and windows and doors. To ensure data quality, Pedersen Weidema & Suhr Wesnæs's (1996) procedure was followed. The operating phase (B6) was calculated in VIP-Energy (version 4) software. The building's energy performance calculations were conducted in accordance with SS-EN 15978 2011. VIP-Energy is validated according to: LEED, BREEAM and ANSI Ashrae-140. Calculation methods in the program for the one-dimensional and two-dimensional building components are valid according to the standard ISO 10211:2007 (StruSoft 2020). Input data for VIP-Energy are presented in Table 3.

Table 4 shows the different analyzes performed in the study, the sensitivity analyzes were done to examine the sensitivity of different parameters by changing key values and assumptions.

Table 3

Input data for the parameters in energy calculation

Input data			
Description	Parameter	Input value	Comments
Climate	Climate data	Växjö (1981 – 2010)	Building location (Kap. 3 Objektbeskrivning in the study by: Eriksson, Hult & Karlsmo 2021))
	Horizontal angle	20 °	To account for shading from nearby objects (Dodoo, Yao Ayikoe Tettey & Gustavsson 2017; StruSoft 2020)
	Wind load that hit the building	70 %	Slightly protected from nearby surroundings (StruSoft 2020)
	Solar reflection against ground	20 %	Share of solar reflected from the ground into building (StruSoft 2020)
Indoor temperature and heat gains	Lightning and appliance	2,06 W/m^2	Building empty mon-fri 7–16/weekends 9–15, other time 4 persons in the building (Sveby 2012)
	Persons	2,4 W/m^2	80 W/person (Sveby 2012)
	Hot water	2,3 W/m^2	Standard (StruSoft 2020)
	Heating	30/21 °C	Highest/lowest (Boverket u.å.)
Ventilation	Supply air	600 Pa/ 55 %	Fan pressure/Fan efficiency (StruSoft 2020)
	Exhaust air	500 Pa/ 55 %	Fan pressure/Fan efficiency (StruSoft 2020)
	Air change rate	0,35/0,1 l/sm^2	Building occupied/empty (BFS 2011:6)

Table 4

Table of completed analyzes

The analysis that was made	Why it was made
Sensitivity analysis: cellulose	To investigate how the recycled raw material affects the result, the cellulose was chosen to be compared. New raw material in relation to recycled.
Sensitivity analysis: glass wool	To investigate whether the type of input data affected the result, the glass wool insulation was replaced. From EPD to the National Board of Housing, Building and Planning's climate database.
Sensitivity analysis: heating system	To investigate the sensitivity in the choice of the heating system, geothermal heat pump (which has a sharply rising popularity in Sweden) was compared with district heating (common in Växjö).
Sensitivity analysis: Fuel	As electric cars are advocated for being more environmentally friendly than diesel cars, a study was conducted to see how the choice of transport of materials affects a building's total emissions.
Sensitivity analysis: Biogenic carbon	As the managing authority Boverket (2021a) does not require biogenic carbon to be included in the climate declaration, an alternative climate declaration was developed without biogenic carbon in stages A1 – A5. To be set against a climate declaration where the biogenic carbon is included.
The climate declaration	Includes: steps A1 – A3, A4 and waste from A5.
LCC	The LCC follows the same stages and system boundaries as the LCA and is finally calculated according to the Procurement Authority's general calculation. For comparison, the functional unit was chosen in Swedish crowns per square meter of habitable area [SEK / m^2 habitable area]. The goal of the LCC was, like the LCA, to be able to facilitate the decision-making process for home builders and home buyers. The prices were retrieved primarily from the Bidcon database Bidcon updates prices twice a year (Consultec ByggProgram AB u.å.). Secondly (hemp and cellulose) from their retailers.

Results

The results of the study are reported in **Table 5** where the mass and GWP emissions for the materials of the different house models during the product phase (A1 – A3) are shown, the biogenic carbon in the material is reported as negative values. The house model with hemp fibre has the largest mass and the house model with glass wool has the smallest mass. During the product phase, the house model with glass wool has the highest net emission and the house model with hemp fibre has the lowest net emission.

Table 5

Mass per square meter habitable area [kg/m^2 habitable area] and Global warming potential per square meter habitable area [CO_2e/m^2 habitable area]

Material		Mass (kg/m^2 habitable area)			GWP (CO_2e/m^2 habitable area)					
		Hemp fibre	Cellulose	Glass wool	Hemp fibre		Cellulose		Glass wool	
					Fossil	Biogenic	Fossil	Biogenic	Fossil	Biogenic
Hemp fibre	Board	7.8	-	-	4.7	-9.5	-	-	-	-
	Loose wool	20.0	-	-	12.4	-25.1	-	-	-	-
Cellulose	Board	-	6.4	-	-	-	4.8	-8.2	-	-
	Loose wool	-	16.3	-	-	-	12.2	-21.1	-	-
Glass wool	Board	-	-	3.4	-	-	-	-	2.7	-
	Loose wool	-	-	8.7	-	-	-	-	7.7	-
Wood		61.2	58.7	59.4	5.3	-96.1	5.1	-92.3	5.1	-93.3
Concrete		331.8	329.4	328.8	48.0	-	47.6	-	47.6	-
Gypsum board		16.6	16.6	16.6	4.7	-	4.7	-	4.7	-
EPS		5.3	5.3	5.3	21.4	-	21.2	-	21.1	-
Rebar		3.7	3.6	3.6	2.7	-	2.7	-	2.7	-
Roof tile		27.5	27.2	27.1	6.2	-	6.1	-	6.1	-
OSB board		5.4	5.4	5.4	2.4	-8.5	2.4	-8.5	2.4	-8.5
Window		5.7	5.7	5.7	14.0	-	14.0	-	14.0	-
Door		0.8	0.8	0.8	4.5	-	4.5	-	4.5	-
Balcony door		0.5	0.5	0.5	1.2	-	1.2	-	1.2	-
PE-foli 20 mm		0.2	0.2	0.2	0.9	-	0.9	-	0.9	-
Asphalt saturated felt		6.0	5.9	5.9	5.1	-	5.0	-	5.0	-
Amount		**491.9**	**481.7**	**471.0**	**133.4**	**-139.2**	**132.3**	**-130.1**	**125.5**	**-101.8**
Net amount		-	-	-	**-5.8**		**2.3**		**23.7**	

LCA

Table 6 shows the LCA of hemp fiber, cellulose, and glass wool that were used as insulation materials in house. The largest emissions came from material production (A1 – A3), followed by the combustion of organic material (waste and building materials) in the final stage (C3). The emissions in C3 correspond to the combustion of the biogenic carbon from A1 – A3 and A5. The largest uptake of biogenic carbon was in the product phase (A1 – A3) and in material waste (A5). The negative value in stage D shows how much emissions the energy recovery (stage C3) com-

Table 6

LCA for the house model [kg CO_2e/m^2 habitable area]

Phase	GWP					
	Hemp fibre		Cellulose		Glass wool	
	Fossil	Biogenic	Fossil	Biogenic	Fossil	Biogenic
A1 – A3	133.4	-139.2	132.3	-130.1	125.5	-101.8
A4	10.9		11.45		11.3	
A5	5.4	-11.1	5.2	-10.4	5.3	-4.9
B6	30.0		30.1		30.0	
C2	3.5		3.5		3.4	
C3	150.2		140.3		111.9	
C4	0.1		0.1		0.1	
D	-54.2		-50.2		-36.8	
Amount	**273.8**	**-150.3**	**270.7**	**-140.4**	**250.6**	**-112.0**
Net amount	**123.5**		**132.3**		**138.6**	

pensated outside the system limit. In steps A4, B6, C2 and C4, there are small differences between the different houses. The house model with glass wool has the highest net emissions during the life cycle and the house model with hemp fibre has the lowest net emissions.

Analysis of cellulose

The results of the sensitivity analysis in the LCA of the different raw materials for cellulose are presented in Table 7. The cellulose production based on unused paper as raw material has the highest net emission compared to the cellulose based on recycled paper. Cellulose with recycled paper has the lowest net emission of all insulation materials in the study.

Table 7

LCA and sensitivity analysis for unused and recycled raw material for cellulose [kg CO_2e/m^2 habitable area]

Phase	Cellulose - Recycle		Cellulose - Unused	
	Fossil	Biogenic	Fossil	Biogenic
A1 – A3	122.4	-146.6	132.3	-130.1
A4	12.0		11.5	
A5	5.1	-10.5	5.2	-10.4
B6	30.1		30.1	
C2	3.5		3.5	
C3	157.0		140.3	
C4	0.1		0.1	
D	-57.9		-50.2	
Amount	**272.2**	**-157.1**	**270.7**	**-140.4**
Net amount	**115.1**		**132.3**	

Sensitivity analysis of glass wool

The results of the emissions over the life cycle of glass wool for changed input data is shown in Table 8. The generic data source results in higher net GHG emissions than the data based on the EPD.

Sensitivity analysis of heating system

The results in Table 9 show how the energy use, the fossil emissions and the operating costs vary between geothermal and district heating as a heat source in the house models during their life-

Phase	Glass wool - Generic data		Glass wool - EPD	
	Fossil	Biogenic	Fossil	Biogenic
A1 – A3	129.7	-101.8	125.5	-101.8
A4	11.4		11.3	
A5	5.4	-10.2	5.3	-10.2
B6	30.0		30.0	
C2	3.4		3.4	
C3	111.9		111.9	
C4	0.1		0.1	
D	-36.8		-36.8	
Amount	**254.9**	**-112.0**	**250.6**	**-112.0**
Net amount	**143.0**		**138.6**	

Table 8

LCA and sensitivity analysis for glass wool [kg CO_2e/m^2 habitable area]

Insulation	Energy consumption [kWh/m²year]		Fossil emission [kg CO_2e/m^2 habitable area]		Operating cost [SEK/m² habitable area]	
	District	Geothermal	District	Geothermal	District	Geothermal
Hemp fibre	63.9	45.8	30.0	107.6	2071	616
Cellulose	64.1	45.6	30.1	107.2	2077	613
Glass wool	63.9	45.8	30.0	107.6	2071	616

Table 9

Energy use, fossil emissions and operating costs for the house models with district heating system or geothermal heating system [kWh /m²year, kg CO_2e/m^2 habitable area, SEK/m² habitable area]

time. The highest energy use is linked to district heating, the largest fossil emissions are linked to geothermal heat and the highest operating cost occurs when using district heating.

Sensitivity analysis of fuel

The results for transport with electricity as fuel are shown in Table 10 and this is compared with. The result shows that the fossil emissions reduced by 5.6 – 5.8 kg CO_2e per m² habitable area depending on which insulation material is used in the house.

Phase	Fuel					
	Hemp fibre		Cellulose		Glass wool	
	Fossil	Biogenic	Fossil	Biogenic	Fossil	Biogenic
A1 – A3	133	-139.2	132.3	-130.1	125.5	-101.8
A4	8.0		8.6		8.5	
A5	5.4	-11.1	5.2	-10.4	5.3	-4.9
B6	30.0		30.1		30.0	
C2	0.7		0.7		0.7	
C3	150.2		140.3		111.9	
C4	0.0		0.0		0.0	
D	-54.2		-50.2		-36.8	
Amount	**268.0**	**-150.3**	**267.1**	**-140.4**	**245.1**	**-112.0**
Net amount	**117.7**		**126.6**		**133.1**	

Table 10

Sensitivity analysis with electric transports [kg CO_2e/m^2 habitable area]

Sensitivity analysis of biogenic carbon (A1 – A5)

The results of the climate declaration (in LCA phases A1 – A5) are shown in Table 11. The house model with glass wool as an insulation material has the highest net emissions and the house model with hemp fiber as an insulation material has the lowest net emissions when the biogenic carbon is included. When only the fossil emissions are considered, the house model with hemp fibre has the highest fossil emissions and the house model with glass wool has the lowest.

Table 11

Climate declaration with and without biogenic carbon (A1 – A5) [kg CO2e/m² habitable area]

	Climate declaration (A1 – A5)	
Insulation	With biogenic carbon	Without biogenic carbon
Hemp fibre	-0.7	149.7
Cellulose	8.5	149
Glass wool	30.1	142.1

LCC

The result of the LCC according to the net present value method is presented in Table 12. This shows that the highest cost during the entire life cycle is borne by the house model with hemp fibre insulation and the lowest cost house is borne by the house model with glass wool insulation.

Table 12

Results from the net present value method [SEK/m² habitable area]

	LCC		
Phase	Hemp fibre	Cellulose	Glass wool
Investment	3906	3267	3302
Operation	2071	2077	2071
Final handling	448	443	443
Total	**5467**	**4830**	**4861**

If only the investment cost is studied, the data shows that hemp fibre is by far the most expensive, see Table 13.

Table 13

Cost of insulation spread over square meters of habitable area [SEK/ m² habitable area]

Cost	Hemp fibre	Cellulose	Glas wool
Wall	300,547	212,517	186,433
Roof	615,600	44,549	139,424
Total amount	**916,147**	**357,066**	**325,857**

Discussion

The most unexpected with the study it was a surprisingly small difference in the energy consumption between the insulation materials during the B-phase. It was also unexpected that the climate declarations do not include biogenic carbon which we shows can have a large impact on the total emissions.

The results of the LCA study show that the house model that is insulated with hemp fibre has the smallest net emissions over the entire life cycle and thus means the best choice for the environment. The results show that due to the increased volume of materials, hemp fibre insulation contributes 9 % more fossil emissions than glass wool insulation. On the other hand, hemp can bind 34 % more CO_2 and thus the net emissions will be 12 % less emissions compared to the choice of glass wool. That insulating materials such as glass wool contribute to higher net emissions than the organic insulating ring materials is confirmed by results from other studies conducted by Zabalza Bribián, Valero & Aranda Usón (2011). This study does not show that cellulose has better environmental performance than hemp, which Dickson & Pavia (2021) study does. The reason is that our study only looks at the carbon flows in LCA, while Dickson & Pavia's study (2021) includes four different parameters for LCA, including acidification. This shows the importance of clarifying what the studies examine, the system boundaries and the scope of the study.

During the product phase (A1 – A3) there are large differences between the different materials, the hemp house stores more carbon dioxide in the organic building materials than what is emitted to produce all other materials in the building. In terms of the total amount of insulation material in the houses alone, hemp fibre insulation contributes to a net emission of -17.46, cellulose with -12.29 and glass wool with 10.34 kg CO_2e / m^2 habitable area. Our results shows like Dickson & Pavia (2021) and Zampori, Dotelli & Vernelli (2013) that plant-based material like hemp has lower GWP than rock wool because the material binds more carbon dioxide and need less energy in the product phase of the material. Despite the high heat capacity of hemp fibre and cellulose, the density is not high enough to store heat in the material, which means that stage B does not differ significantly between the materials. The study shows that the combustion of materials in stage C, contributes to large emissions. It would therefore be good to reuse the material as far as possible, to create a long waterfall effect. None of the insulation materials showed negative net emissions over the entire life cycle in the building. This means that no house became a coal sink. Had the materials been recycled in the final stage instead of being burned as Zabalza Bribián, Valero & Aranda Usón (2011) strongly advocated, it could have had an effect on the result for hemp and cellulose houses, see chapter 6.3.1.2 in our study (Eriksson, Hult & Karlsmo 2021).

The results of the economic analysis, see Figure 2, show that the choice of hemp fibre is 20 % more expensive than the traditional glass wool insulation in Sweden, which is also reported in a study by Dickson & Pavia (2021). The cost of insulation per square meter habitable area showed

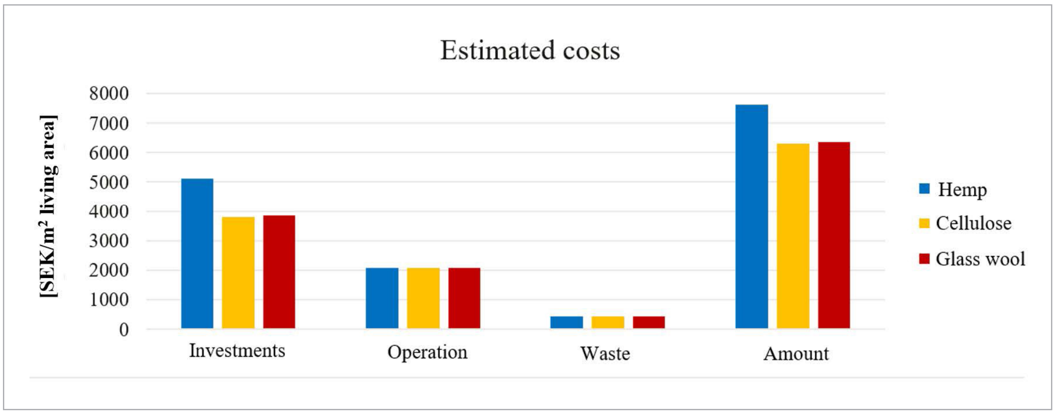


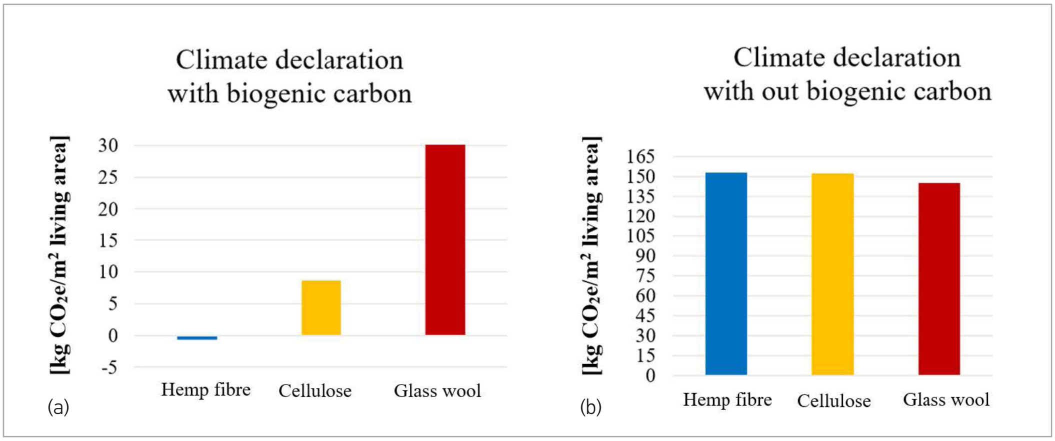
Fig. 2

Differences between EPD and generic data in different designs of the material glass wool

that hemp fibre is 2.8 times more expensive than glass wool and 2.6 times more expensive than cellulose insulation, see Table 13. Cost of insulation based on square meters habitable area [SEK / m^2 habitable area]. Study agrees with Kymäläinen & Sjöberg (2008) study which showed that the bast fibre insulation has double the price compared to conventional insulation. The difference in this study shows that the cost of hemp fibre insulation is almost three times higher. It is in particular the loose wool insulation of hemp that stands out with a 4.4 times higher price than glass wool loose wool. The increase is due to a higher purchase price / volume of materials and the fact that the house with hemp insulation needed thicker walls to achieve the same U-value as the glass

Fig. 3

Climate declaration with (a) the biogenic carbon in the hemp fibre, cellulose and glass wool house in stages A1 A5 and (b) without the biogenic carbon in the hemp fibre, cellulose and glass wool house in stages A1 – A5.



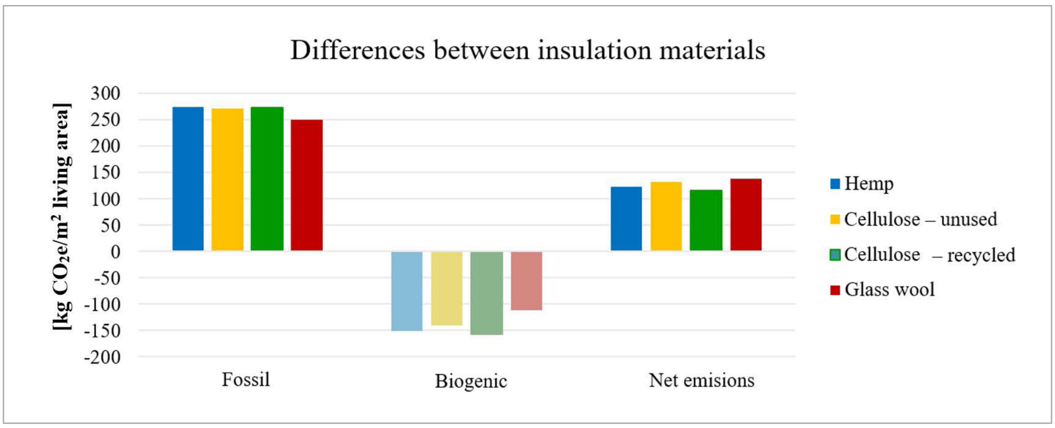
and cellulose house types. The cheapest is the cellulose insulation with 35 SEK / habitable area (approx. 1 %) compared to the glass wool, see Figure 2.

The cellulose in this study had a lower price than those shown in a study done by Kymäläinen & Sjöberg (2008). The price difference may be due to the fact that their input data for costs were from 2005 and 2007, respectively, and this study collected data during April 2021.

The result for the climate declaration, see Figure 3, shows the major impact that the inclusion of biogenic carbon has on the result for the climate declaration. This shows that if the National Board of Housing, Building and Planning or SIS does not introduce guidelines that biogenic carbon must be reported (or if the National Board of Housing, Building and Planning does not publish value of biogenic carbon) in the climate declaration, the organic materials can have high fossil emissions. This means that materials such as hemp fibre insulation will not be seen as an advantageous material. As the National Board of Housing, Building and Planning & the Swedish Environmental

Fig. 4

Different emissions during the life cycle with hemp fibre, cellulose (unused), cellulose (recycled) and glass wool insulation



Protection Agency (2019) point out that the construction sector has great opportunities to become environmentally friendly by using biomaterials such as carbon sinks, it should be of the utmost importance to report the biogenic carbon. The sensitivity analysis shows that the biogenic carbon entails major changes in the result of the materials' climate impact.

Discussion about the impact of input data on the result (Islam, Jollands & Setunge 2015; Pedersen Weidema & Suhr Wesnæs 1996) justified a study of input data in the form of a sensitivity analysis. The sensitivity analysis for the raw material, see Figure 4, to the insulation material reported that cellulose on recycled paper had the lowest net emissions. When comparing all materials over the

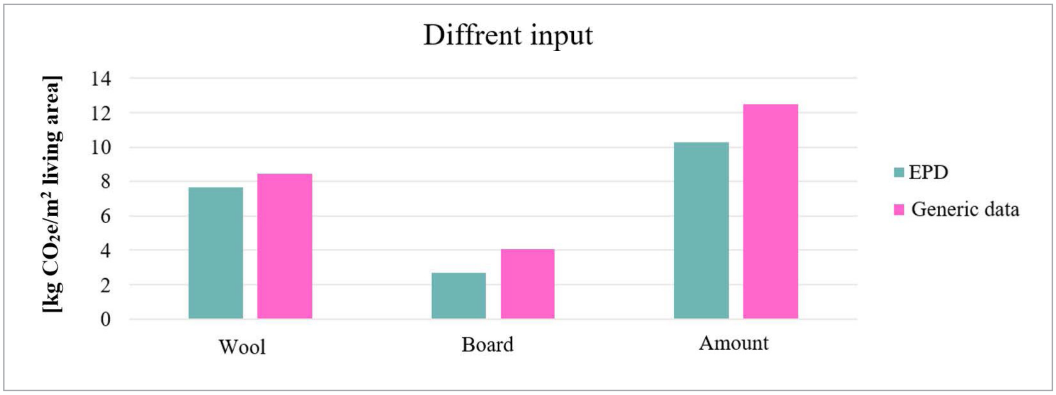


Fig. 5

Differences between EPD and generic data looking at the glass wool insulation

entire life cycle, it can be concluded that cellulose on recycled paper gives the lowest net emissions and would thus have been the material that would have been preferred with regard to the environmental aspect.

The sensitivity analysis for glass wool, see Figure 5, reported that the difference between input data was 3 % for net emissions during the life cycle. The reason may come from the fact that the generic data is based on an average of several EPDs and has a 25 % surcharge on net emissions. SIS (SS-EN 15978: 2011) and the National Board of Housing, Building and Planning (Boverket 2021c) call for the use of EPDs in the first instance. Although there are difficulties in keeping databases up to date, the climate database should be so, as all data comes from a recently published test version (Islam, Jollands & Setunge 2015; Boverket 2021a). One conclusion of this result is that the data source is important for the result.

The results of the sensitivity analysis show that the choice of heating system, see Figure 6, had the greatest impact during the building's life cycle, both net emissions and operating costs varied greatly between the different heating systems. This is due to the low values of net emissions that Veab (u.å.) generated by their district heating production. The values from the rock heat depend on the electric mix used. The electricity mix can vary between different countries and thus give different outcomes on the result depending on in which country the building is located (Trafikverket 2021; Energi företagen 2020; Dixit et al. 2010). As the operation accounts for about 32 % of the total costs, it can be concluded that the operation has a predominant significance of the building's cost of living and the choice of heat source affect this cost.

The sensitivity analysis that studied fuels for the transports shows that the building's net emissions were affected over its life cycle. Transportation powered by electricity instead of diesel reduced net emissions. Most of the transports are carried out in the final stage of the house (C2, C3), which is estimated at 50 years from today. According to Dixit et al. (2010), transport will over time be developed with more fuel-efficient methods and more efficient energy consumption. This means that the result of the sensitivity analysis provides a better picture of how future technology will affect the net emissions for the building during the life cycle.

As the development of both LCA and LCC is complex and extensive, system boundaries were defined to clarify which different parameters the study takes into account. In order to focus on the most important parameters, certain parts of the LCA and LCC were omitted. For example, only carbon flows are studied, which means that other interesting environmental factors are overlooked. Some influence of the system boundaries' assumption that certain stages are equal and should not be examined may have affected the result. For example, the construction phase is assumed to be the same between the different models, technically they are the same, but the density of the materials and the difference in the Gross floor area may have meant that this aspect was important. Through the choice of system boundaries, the result is affected and this can, according to Islam, Jollands & Setunge (2015) and Senga Kiessé et al. (2017) make the result difficult to assess. When the number of elections is reduced, according to Senga Kiessé et al. (2017) that the result becomes more subjective but that it also creates uncertainty as this neglects the sensitive interaction. If the study had been ongoing for a longer period, more parameters could have been included in the study. The time aspect affects the choice of system boundaries. The results of the study can be complicated to compare with other studies as the system boundaries can differ considerably.

Strengths of the study is the sensitivity analyses that shows what happens when the numbers are changed. However, more insulation materials and house models could be considered, in further sensitivity analyses. Notwithstanding, the study is sufficient enough to draw conclusions, to fill gaps in knowledge and hopefully inspires more scientific studies in this field.

Conclusions

If the climate goals are to be achieved, the construction sector must make changes, but it is important to make the right changes. This study shows that the greatest impact on net emissions during the building's life cycle comes from the choice of heating system. The difference between switching from district heating to geothermal heating resulted in an increase in net emissions by 63 %. Although the choice of heat source affects net emissions the most, the study shows that the choice of insulation material has effects in GHG emissions. In the house model, the choice of hemp fibre insulation results in a net emission reduction of 12 % compared with glass wool insulation. Cellulose resulted in a 5 % reduction in net emissions compared to glass wool insulation. Hemp insulation contributes to climate impact with a net emission of 124, cellulose 132 and glass wool 139 CO_2e per m^2 habitable area. The choice of insulation material affects the cost of building the model house. When choosing hemp fibre insulation instead of glass wool, the price increases by 20 %. If cellulose is used instead, the price will be similar (the reduction is 0.01 %). Choosing hemp fibre insulation gives a cost of 5467 SEK per m^2 habitable area, cellulose 4830 and glass wool 4861 SEK per m^2 habitable area.

As biogenic carbon has shown a major impact on the results of this study, and in particular on climate declarations, the concept of biogenic carbon and its entity should be developed and clarified by institutes for standards to create transparency and to take the time aspect of biomaterial renewal time into account biogenic carbon. The system boundaries are central to LCA and LCC studies as these define the scope of the study and thus shape the result. It should be emphasized that the results of this study must always be interpreted within the context of the study.

Declaration of competing interest

This research was supported by Linnaeus University Växjö, Sweden. The authors declare that there is no financial interests for the study and they have no personal relationships that can affect the result.

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References

Bouloc P., Allegret, S. & Arnaud L. (red.) (2013). HEMP: Industrial Production and Uses. Oxfordshire, Boston: Cabi International, ss. 3-25, 238-313.https://doi.org/10.1079/9781845937935.0000

BFS 2011:6. Boverkets byggregler - Allmänna föreskrifter och råd [The national board of housing, Building and Planning's building regulations - General regulations and advice] (consolidated version). Karlskrona: Boverket.

Boverket (2021a). Klimatdeklaration av byggnader [Climate declaration of buildings]. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/klimatdeklaration/ [2021-04-06]

Boverket (2021b). Utsläpp av växthusgaser från bygg-och fastighetssektorn [Emissions of greenhouse gases from the construction and real estate sector]. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/vaxthusgaser/ [2021-03-25]

Boverket (2021c). Om Boverkets klimatdatabas [About the National Board of Housing, Building and Planning's climate database]. https://www.boverket.se/sv/byggande/hallbart-byggande-ochforvaltning/klimatdeklaration/klimatdatabas/om-klimatdatabasen/ [2021-05-07]

Boverket (u.å.). Vilken innetemperatur ska användas vid energiberäkning? [Which indoor temperature should be used for energy calculation?]. https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/fragor--svar/bbr-boverkets-byggregler/avsnitt-9-energihushallning/berakning/vilken-inomhustemperatur-ska-anvandas-vid-energiberakning/ [2021-04-20]
Consultec ByggProgram AB (u.å.). LexCon BYGG: Ett kalkylprogram specialutvecklat

för konstruktionsval och kostnadsoptimering [LexCon BYGG: A spreadsheet program specially developed for design selection and cost optimization]. https://www.elecosoft.se/refDok/produkter/12/Lexinfo02.pdf [2021-04-19]

Dickson, T. & Pavía, S. (2021). Energy performance, environmental impact and cost of a range of insulation materials. Renewable & sustainable energy reviews, 140, p.110752. https://doi.org/10.1016/j.rser.2021.110752

Dixit, M., Fernández-Solís, J., Lavy, S. & Culp, C. (2010). Identification of parameters for embodied energy measurement: A literature review. Energy and buildings, 42(8), pp.1238-1247. https://doi.org/10.1016/j.enbuild.2010.02.016

Dodoo, A., Yao Ayikoe Tettey, U. & Gustavsson, L. (2017). On input parameters, methods and assumptions for energy balance and retrofit analyses for residential buildings. Energy and buildings, 137, pp.76-89. https://doi.org/10.1016/j.enbuild.2016.12.033

Embelmsvåg, J. (2003). Life - Cycle Costing - Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks. New Jersey: John Wiley & son's.

Energiföretagen (2020). Energi i världen [Energy in the world]. Stockholm: Energiföretagen Sverige. https://www.energiforetagen.se/statistik/energi-i-varlden/ [2021-05-10]

Eriksson, Y., Hult, M. & Karlsmo, S. (2021). Life cycle analysis and life cycle cost of building

insulated with hemp fibre compared to alternative insulation. Bachelor's degree, the department of construction technology. Växjö: Linnaeus University.https://www.diva-portal.org/smash/get/diva2:1592444/FULLTEXT02

European Industrial Hemp Association (u.å.). Hemp, a real Green Deal. https://eiha.org/hemp-a-real-green-deal/ [2021-03-23]

European Commission (u.å.a). 2030 climate and energy framework. Bryssel: European commission. https://ec.europa.eu/clima/policies/strategies/2030_en [2021-03-23]

Europeiska rådet (2021). En europeisk klimatlag: rådet och parlamentet når preliminär överenskommelse. [A European climate law: the Council and Parliament reach a preliminary agreement] Brussels: European Commission. https://www.consilium.europa.eu/sv/press/press-releases/2021/05/05/european-climate-law-council-and-parliament-reach-provisional-agreement/ [2021- 05-17]

Islam, H., Jollands, M. & Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings - A review. Renewable & sustainable energy reviews, 42, pp.129-140. https://doi.org/10.1016/j.rser.2014.10.006

Kallakas, H., Närep, M., Närep, A., Poltimäe, T. & Kers,J. (2018). Mechanical and physical properties of industrial hemp-based insulation materials. Proceedings of the Estonian Academy of Sciences, 67(2), pp.183-192. https://doi.org/10.3176/proc.2018.2.10

Kosiński, P., Brzyski, P., Szewczyk, A. & Motacki W. (2018). Thermal Properties of Raw Hemp Fibre as a Loose-Fill Insulation Material. Journal of Natural Fibres, 15:5, 717-730, https://doi.org/10.1080/15440478.2017.1361371

Kunglig Majestäts kansli (1972). Kungl. Maj:ts proposition med förslag till vissa åtgärder mot narkotikamissbruket, m.m. 1972:67 [royal majesty: bill with proposals for certain measures against drug abuse 1972:67]. Stockholm: Kunglig Majestäts kansli

Kymäläinen, H. & Sjöberg, A. (2008). Flax and hemp fibres as raw materials for thermal insulations. Building and environment, 43(7), pp.1261-1269.https://doi.org/10.1016/j.buildenv.2007.03.006

Lopez Hurtado, P., Rouilly, A., Vandenbossche, V. & Raynaud, C. (2016). A review on the properties of cellulose fibre insulation. Building and environment, 96, pp.170-177. https://doi.org/10.1016/j.buildenv.2015.09.031

Miljödepartementet (2020). En samlad politik för klimatet: En sammanfattning av regeringens klimatpolitiska handlingsplan [An overall climate policy: A summary of the Government's climate policy action plan] Stockholm: Miljödepartementet. https://www.regeringen.se/49c770/contentassets/b0f74b9a2a024cfcb1ea42966963abfb/en-samlad-politik-for-klimatet---en-sammanfattning-av-regeringens-klimatpolitiska-handlingsplan.pdf

Pedersen Weidema, B. & Suhr Wesnæs, M. (1996). Data quality management for life cycle inventories-an example of using data quality indicators. Journal of Cleaner Production, 4(3-4) ss. 167-174.https://doi.org/10.1016/S0959-6526(96)00043-1

Senga Kiessé, T., Ventura, A., van der Werf, H. M. G., Cazacliu, B., Idir, R. & Andrianandraina (2017). Introducing economic actors and their possibilities for action in LCA using sensitivity analysis: Application to hemp-based insulation products for building applications. Journal of cleaner production, 142(4), pp.3905-3916. https://doi.org/10.1016/j.jclepro.2016.10.069

Sohn, J.L., Kalbar, P.P., Banta, G. T. & Birkved, M. (2017). Life-cycle based dynamic assessment of mineral wool insulation in a Danish residential building application. Journal of cleaner production, 142, pp.3243-3253. https://doi.org/10.1016/j.jclepro.2016.10.145

SS-EN 15978:2011. Hållbarhet hos byggnadsverk - Värdering av byggnaders miljöprestanda - Beräkningsmetod [Sustainability of construction works - Valuation of buildings' environmental performance - Calculation method]. Stockholm: Svenska institutet för standarder (SIS).

StruSoft (2020). VIP Energy manual version 4. https://www.vipenergy.net/Manual.htm#Tillbaka%20upp%20p%C3%A5%20sidan [2021-04-06]

StruSoft (2021). VIP-Energy. https://strusoft.com/products/vip-energy [2021-10-30]

Sveby (2012). Brukardata bostäder [User data housing]. Stockholm: Sveby.

http://www.sveby.org/wp-content/uploads/2012/10/Sveby_Brukarindata_bostader_version_1.0.pdf [2021-04-06]

Svenskt trä (2014a). Anslutning mot yttervägg [Connection to external wall]. https://www.traguiden.se/konstruktion/konstruktionsexempel/vaggar/lagenhetsskiljandevagg/anslutning-mot-yttervagg/ [2021-04-06]

Svenskt trä (2014b). Vägg med reglar av konstruktionsvirke i två skikt - alternativ 2, horisontalsnitt, rak smyg [Wall with joists of structural timber in two layers - alternative 2, horizontal section, straight stealth]. https://www.traguiden.se/konstruktion/konstruktionsexempel/vaggar/fonster-iyttervaggar/vagg-med-reglar-av-konstruktionsvirke-i-tva-skikt--alt-2-horisontalsnitt-raksmyg/ [2021-04-06]

Svenskt trä (2015). Anslutning mot ytterväggshörn, enkelt regelverk - massivreglar [Connection to exterior wall corner, simple regulations - solid rules]. https://www.traguiden.se/konstruktion/konstruktionsexempel/vaggar/barandeyttervagg/konstruktionsvirke-eller-lattreglar/anslutningrk/ [2021-04-06]

Trafikverket (2021). Miljövarudeklarationer (EPD) [Environmental product declarations (EPD)]. https://www.trafikverket.se/for-digi-branschen/miljo---for-dig-i-branschen/arbetssatt-och-metoder-for-miljo-i-vag--ochjarnvagsprojekt/livscykelanalys-i-anlaggningsprojekt/miljovarudeklarationer-epd/ [2021- 05-10]

Treloar, G., Fay, R., Ilozor, B. & Love, P. (2001). Building materials selection: greenhouse strategies for built facilities. Facilities (Bradford, West Yorkshire, England), 19(3/4), pp.139-150. https://doi.org/10.1108/02632770110381694

Tumusiime, T., Kirabira, J. B. & Musinguzi, W. B. (2020). Performance evaluation of cellulose fibre's effectiveness as a thermal insulation material for productive biogas systems. Energy reports, 6, pp.3390-3398. https://doi.org/10.1016/j.egyr.2020.12.014

Veab (u.å.). Miljövärden [Environmental values]. https://www.veab.se/foretag/fjarrvarme/miljovarden/ [2021-04- 06]

Zabalza Bribián, I., Valero, A. & Aranda Usón, A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and environment, 46(5), pp.1133-1140. https://doi.org/10.1016/j.buildenv.2010.12.002

Zampori, L., Dotelli, G. & Vernelli, V. (2013). Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings. Environmental science & technology, 47(13), p. 7413 - 7420. https://doi.org/10.1021/es401326a

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