Life Cycle Assessment on a KTH Building

Life Cycle Assessment

AG 2800 - 02

(Final) Report

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15.12.2013

Abstract

Buildings require energy in forms of heating, cooling and electricity in order to provide the intended services to their occupants. In order to lower the environmental impacts from the buildings on the KTH campus, the KTH Sustainability Group has initiated the project Zero Emission Campus.

This report focuses on possible improvements of the B building at KTH campus. The methods used are an accounting Life Cycle Assessment (LCA) and additional energy calculations. The LCA is performed using the software SimaPro and the impact assessment method is ReCiPe Midpoint.

To study possible reductions of the environmental impact of the building, additional insulation is applied on the inside of the exterior wall in order to reduce the energy demand for heating. Two cases using different insulation materials – hemp insulation and mineral wool – are compared to the option to do nothing, a zero alternative.

As expected, the results show that both insulation materials significantly can improve the B building's heating performance. Both hemp insulation and mineral wool reduce the building's energy demand by 10% compared to the zero alternative. Due to the reduction in energy use, environmental impacts are reduced in all impact categories. The mineral wool alternative saves slightly more heating energy than the hemp alternative does, but the hemp alternative makes bigger improvements in the impact categories Freshwater eutrophication, Freshwater ecotoxicity and Terrestrial ecotoxicity.

Based on the results of this study, a recommendation to further investigate additional insulation of the walls is made. Both types of insulation materials are recommended, since the differences in environmental impacts are small.

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1 Introduction

This project was initiated by the KTH Sustainability group as a part of a course in Life Cycle Assessment (LCA). The result of the report will be used as a part of the project “Zero Emission Campus” by KTH Sustainability group. One of the main goals of the Zero Emission Campus project is to reduce the energy utilization, (electricity, cooling and heating) from the KTH campus by 5%from 2012-2015 (GreenLeap, ZeroCampus and Miljömål). In this project initiated by the KTH sustainability group they are also trying to reduce the carbon dioxide emissions from transportation that are emitted by different types of travels by people that are working at KTH and people that visit KTH (Miljömål).

The real estate company Akademiska Hus owns and maintains the buildings. It is Akademiska Hus that will implement the improvements, and this report can be seen as a background in the decision making.

According to the ISO standards 14040 and 14044, Life Cycle Assessment (LCA) is defined as “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (p. 8), with a product system being defined as a “collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product” (p.11). So, LCA is a material and energy flow accounting method which sorts environmental impact potentials into the in- and output flows of a product system. This is done in reference to the specific function(s) that this product system has to comply throughout its lifetime.

When conducting a building LCA, the term "product system" naturally refers to the building that is to be analysed. The "inputs" - resources (natural resources, materials and energy) required for the material production - and "outputs" correspond to the caused emissions to air, water and ground as well as solid waste. Usually, the whole building life cycle "from cradle to grave" is considered for a comprehensive building LCA.

Every life cycle phase of a building has to be analysed to descry all different aspects of sustainability and optimize them in all of its life cycle phases. The goal is to reach a higher building quality with a least as possible impact on the environment. Therefore, the lifetime of every single material and its change in the lifetime of the whole building has to be considered.

The following report focuses not on a whole cradle-to-grave analysis of a building. It centers on a life cycle for one improving measure, which is chosen to reduce the consumption of energy. Therefore, two options, a sustainable and a traditional, of one refurbishment procedure will be proposed and compared with each other as well as to the opportunity to do nothing, the zero alternative. This will hopefully also lead to that the information provided by this project will help the KTH sustainability group to reach their goal, reducing the energy utilization from buildings on KTH campus by 5% (GreenLeap, ZeroCampus and Miljömål).

For the proposed improvement methods accounting LCAs were made.

2 Goal and Scope

The aim of the study is to find out how an existing building can be improved and which resources can be influenced to minimize the environmental impact and energy loss. Therefore one building on the KTH Campus is determined as the worst building in energy demand and the main negative hot spot has to be identified. By identifying these hotspots a more efficient energy utilization can be reached by improving the existing building. This goes in line with KTH green leap project; Zero emission campus. The Zero emission campus is an ongoing project that are trying to reduce the energy utilization 5% from 2012 – 2015 since the energy utilization from buildings on KTH campus has steadily increased until 2012 (GreenLeap, ZeroCampus and Miljömål).

After deciding which measure would have the most positive effect on the performance of the chosen building, a life cycle for the whole building over 50 years will be generated. The inventory is seen as an absolute term as we don't take anything out of the existing system.

As far as an advice should be given to Akademiska Hus or KTH Green Leap, there will be given two examples of one refurbishment measure next to the possibility to change nothing. With the result of this study Akademiska Hus can think about improving their buildings in an appropriate way to help KTH Sustainability Group reaching their target to minimize the actual carbon dioxide emission from buildings in KTH campus and provide the users with the best comfort, especially for educational buildings this is important to make good study efforts possible. This report focuses just on one possibility of improvement and other factors influencing the building are set stable and will not be changed. However, several improvements were discussed before the choice to improve the walls was set, see section 4.2.

This chapter is divided into five subchapters to cover the main aspects in the goal and scope definition phase of the LCA procedure.

2.1 Functional unit

The function of the building is to provide an indoor climate of a quality suitable for working and studying. This includes heating, cooling and electricity for achieving the building services. A reduction of the environmental impact from the building could easily be done by shutting all the technical systems down, but for a fair comparison between the zero-alternative and the refurbished buildings a minimum level of indoor climate quality must be provided.

When studying energy use in buildings it's important to take all seasons into account, since most of the heating occurs during the winter, while most of the cooling is needed in the summer. Therefore a year is a good time period for the functional unit.

The functional unit used in this study is: "The use of the building for one year, with a satisfactory indoor climate". A "satisfactory indoor climate" is in this case defined as an indoor climate similar to the current one, in terms of room temperatures and airflows.

2.2 System boundaries

Due to the data provided by Akademiska Hus it is obvious that the B building has the highest loss of energy used for heating (Appendix 1). In Figure 1the total energy use of the B building is specified. An inspection protocol[i] (reference from 2008) illustrated that the walls have worse characteristics than

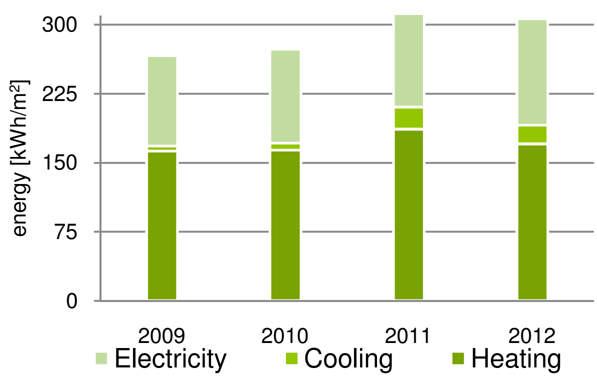

Figure 1.Energy consumption for B Building

other parts of the building and that it is necessary to improve them. The proposed solution is to insulate the walls of the house from the inside. Therefore it is not necessary to take material out of the inventory system and there is no waste scenario before refurbishing. The LCA focuses more on the refurbishment material put in the system. The proposed materials are assumed to have a life time of 50 years, see chapter Assumptions and limitations. After 50 years it is considered that the house has to be improved with better measures. So far, the end-of-life stage or demolition is excluded from the system. It is taken into account that then there is a waste scenario to recycle the proposed materials.

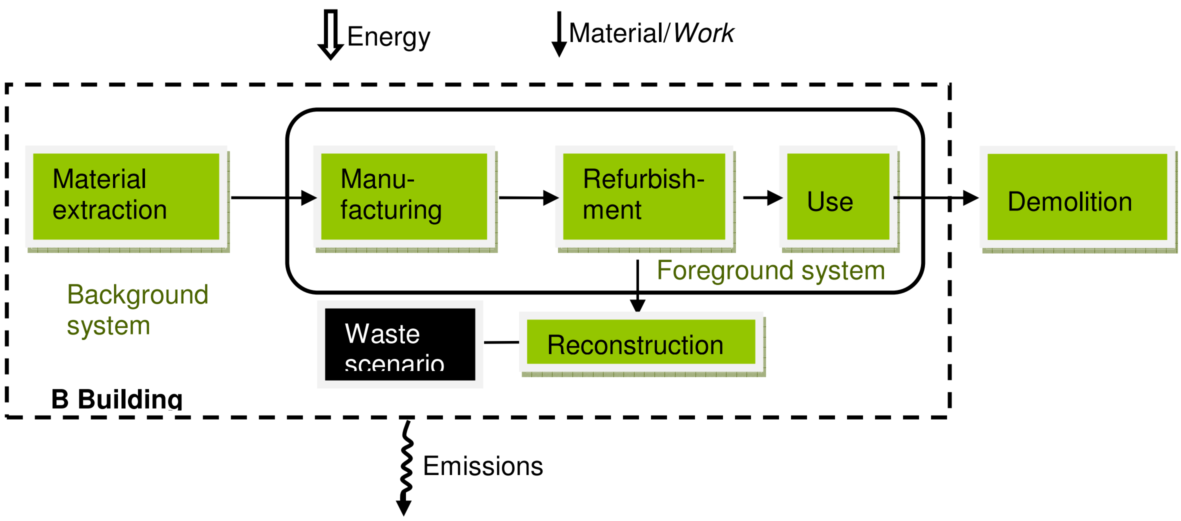

Figure 2.System boundaries in a simplified flow chart

The processes and assemblies which are included in this project are mainly energy utilizations as well as transportation and, of course, the materials used for the refurbishment. As Figure 2 shows for all three possibilities, it is a cradle-to-grave flow.

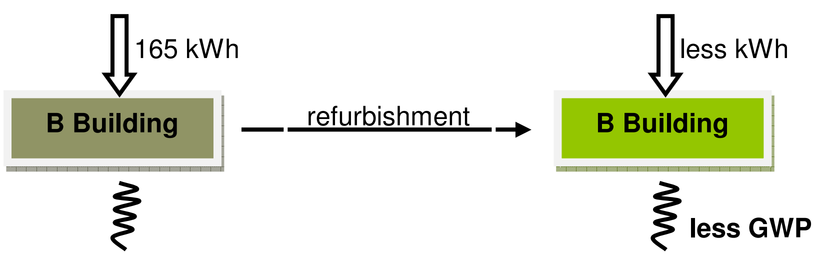

Figure 3. Energy consumption & emissions before & expected

The LCA focuses just on improving the B building by insulating the walls and not by reducing the use of electricity by lighting, computers and similar applications.

So far electricity is a stable point in the modelling process as well as cooling and the inventory parts. They are included in one box called B Building, see Figure 3.

Even though there are more than on process needed for producing heat, all processes are known and can be accounted for, thus there is no allocation problem. One main challenge still exists and that is the energy produced by recovered heat through district cooling. In the calculations with SimaPro this fact was not considered because of missing data.

As we see, there might be an allocation problem due to the presence of more input processes than products. Because of the detailed data the set can be established in SimaPro and the allocation problem is avoided.One main challenge still exists and that is the energy produced by recovered heat through district cooling. In the calculations with SimaPro this fact was not considered because of missing data.

While the KTH is located in Stockholm, the refurbishment material should be produced within Sweden to avoid increasing influences due to transportation.

2.3 Assumptions and limitations

2.3.1 Energy use

The electricity used on KTH Campus is provided by the distribution company Fortum and the source of electricity used in the LCA model is based on average Swedish electricity production and import.

As stated in the previous section,Fortum uses a fuel-mix for their district heat distribution. The mentioned fossil fuels are oil, coal and city gas according to Fortum. Since the proportions of these resources are not known, it is nearby to assume that oil, coal and city gas compose the 13 % of fossil fuels in equal parts.

District cooling is also seen as a stable influence in the system.It is produced out of energy retrieved from lakes and wastewater as well as fromelectricity[I].

Explicitly excluded from the list of investigated processes are craftsman work such asconstruction and maintenance work on site, cleaning services and demolition work, as well asadditional construction or furnishing parts, scraps of materials and energy use on site.

The energy calculations[ii] only consider the heat flows through the walls. All other building parts, like windows, roof and foundation are excluded. For the comparison of the energy performance of the zero alternative and the refurbished buildings a ratio between the U-value – a thermal transfer coefficient - of the insulated wall and the U-value of the original wall was used. This method does not consider thermal bridges. Due to insufficient data regarding the building's structure and technical systems, the heat losses through the walls were assumed to be 30% of the entire building's heat losses, see appendix 5.3.

2.3.2 Area and constitution of the exterior wall

The wall area was estimated by measuring in the blueprints for the B building and by visual inspection of the wall heights. From this a façade area was calculated according to Appendix 5.2 (p.18).For every wall, a percentage of window coverage was estimated. This resulted in average window coverage of 26%. The total window area was then subtracted from the wall area.

The connections between the outer wall and the inner walls and floors were estimated to cover 5% of the exterior walls in the entire building. On this area there will be no insulation.

Altogether, 69% of the façade area or 3206 m^2 can be insulated.

For the U-value calculations the existing walls were assumed to be made out of homogenous construction bricks with interior plastering. Any other interior cladding is unknown and therefore excluded. For the insulated walls, a layer of insulation weighted together with the wooden frame was put on the inside of the brick wall. Double gypsum boards were also taken into account, Appendix 5.3 (p. 19f.). The plastic film used for moisture proofing was neglected in the U-value calculation since its effect on the conductive heat transfer is negligible.

The U-values calculated for the walls are shown in Table 1.

Wall type	**U-value [W/m^{2}K]**
Un-insulated brick wall	1.087
Brick wall insulated with hemp	0.331
Brick wall insulated with glass wool	0.315

Table 1. Calculated U-values

In this report the moisture transfer is neglected, see chapter 4.4.2.

2.3.3 Lifetime and end-of-life of building materials

The expected lifetime of all building materials is assumed to be 50 years. The exception is interior wall paint, which is renewed every ten years. After 50 years, the building might be refurbished with better materials and the old ones should be deconstructed and send to recycling and waste processing.

2.3.4 Transportation distances

The chosen hemp insulation is produced in France[iii] and Germany[iv] and has to be transported to the KTH campus for a maximum distance of 2109[1] km (from France). In this case five lorries with a volume capacity of 81 $m^3$are chosen.

For the second option, insulating with rock wool, the distance amounts just 554[1] km and only two lorries are used. The rock wool insulation can be transported in a compressed way.

Other materials as gypsum boards, paints, plaster and plastic film are delivered by a small truck (3,5 - 7 ton) from the Stockholm area, so a distance of about 50 km is assumed.

2.4 Impact categories and impact assessment method

For this LCA the indicator ReCiPe, the midpoint approach has been applied[v]. The calculations are based on the western European scale. The standardised LCIA method ReCiPe was developed in the Netherlands in 2008 to enable better interpretation of the results from the life cycle inventory analysis, using harmonised category indicators for normalisation. For this purpose, the methods of the most commonly usedimpact categories and indicators (CML, Eco-Indicator 99) were combined in ReCiPe in an attempt to create an improved method which combines the advantages of the different methods in one indicator.

ReCiPe addresses two different levels: The midpoint level, which includes 18 different impact categories, and the endpoint-level, which consists of three major categories to which the midpoint categories are sorted. The results calculated on

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[1] maps.google.com: Cours La Ville (France) and Billeholm(Skåne/Sweden) to KTH Campus

the midpoint level are less uncertain than the ones procured from the endpoint level, as the endpoint results are based on an additional weighting model. Consequently, there can be a significant difference between the results at midpoint and endpoint level. Depending on the goal and scope of an LCA, one level might be preferred over the other.

In this study midpoint level calculations were used. The results of the characterisation and normalisation of the 18 impact categories of ReCiPe are depicted in Appendix 5 and Appendix 6. In both figures in the appendix the values for all three options – the hemp insulation alternative, the mineral wool alternative and the zero alternative - are displayed, so that the efforts and changes are obvious.

Impact categories

- Climate change
- Ozone depletion
- Human toxicity
- Photochemicaloxidant formation
- Particulate matter formation
- Ionizing radiation
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion
- Metal depletion
- Fossil depletion

In this study, the focus of the discussion will be the impact categories Climate change Human toxicity.

2.5 Normalisation and weighting

In LCA normalization is used to compare different impact categories with each other. The results are given as a ratio without unitsto better evaluate the outcome. By applying normalization for the result it is easier to see what type of environmental impact the zero alternative for the building has, compared to the two refurbishment options. In the result it is described which categories have a significant impact in a life cycle perspective for the three alternatives.

In this study weighting is not performed because it is not allowed according by the ISO for comparative assertions (Finnveden, 2012).

3 Life Cycle Inventory Analysis

3.1 Process flowchart

In the Figure 4an example of a flow chart for one refurbishment option (hemp insulation) is given. The cut-off is defined by 0,1% of the impacts. That means that only processes with an impact higher than 0,1% are included.

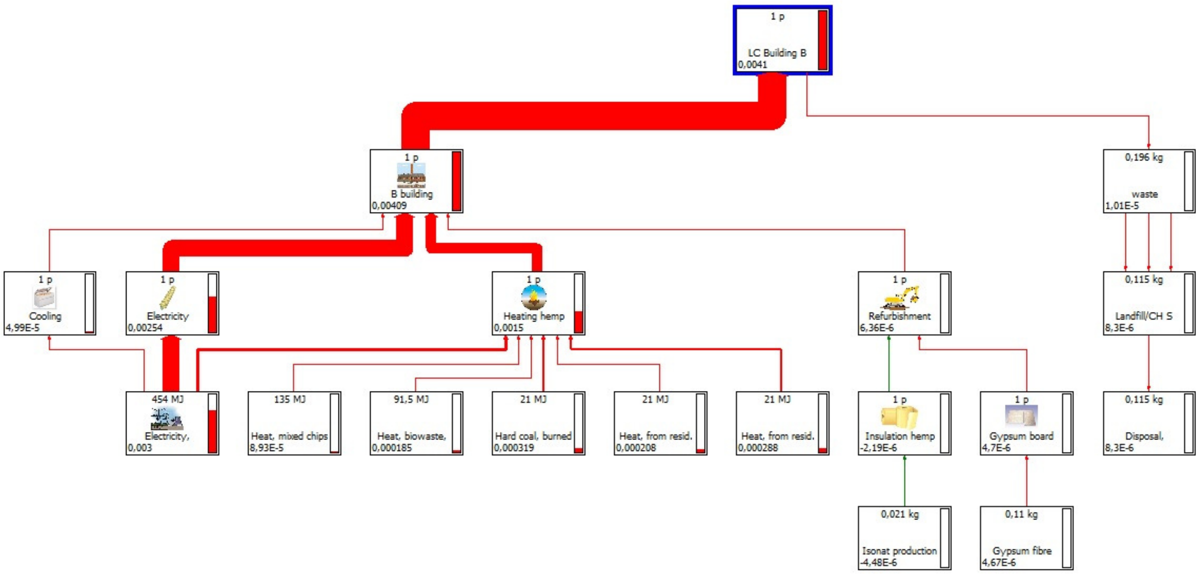


Figure 4. Process flowchart for refurbishment with hemp insulation

3.2 Data

3.2.1 Akademiska Hus

The data on use of electricity, heating and cooling shown in Appendix 1, as well as blueprints, were provided by Akademiska Hus.

3.2.2 Fortum

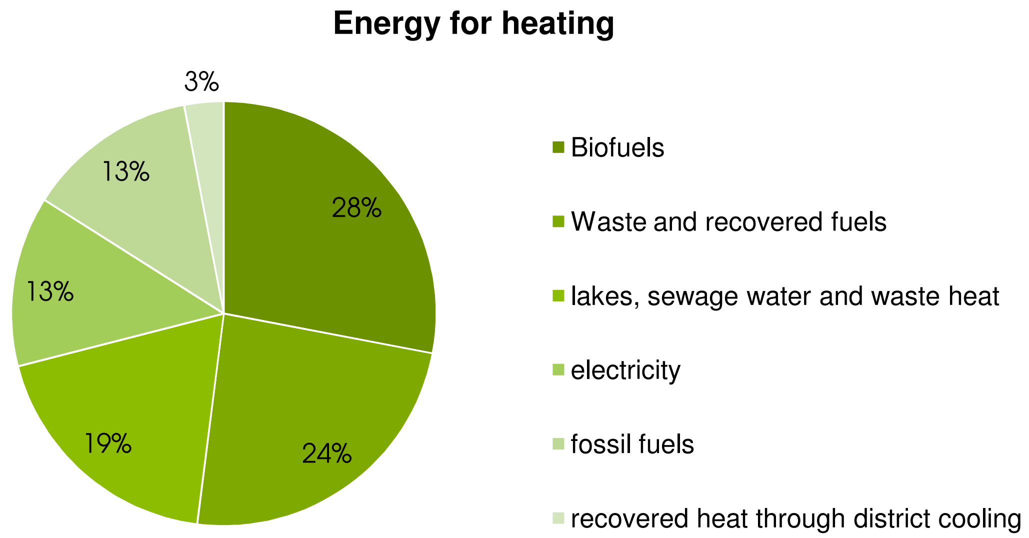


Figure 5.Energy mix provided by Fortum[vi]

The energy provided by Fortum (Figure 5) for the heating in building B is a mixture of; Biofuels 28%, waste and recovered fuels 24%, energy from lakes, sewage water and waste heat 19%, electricity 13%, fossil fuels 13%and recovered heat through district cooling 3%.

3.2.3 Building materials

The different types of insulation materials will cause different impacts on the building's performance and the environment. The detailed information about material dimensions and performance was retrieved from the manufacturers' homepages. To establish a data set for hemp insulation, the important data was taken from a report about "Life Cycle Assessments of Natural Fibre Insulation Materials"[vii].

Information about smaller parts as plastic film, plaster, gypsum boards and so forth was taken from Byggmax's product description[viii].

3.2.4 SimaPro

Data used from SimaPro can be seen in Appendix 2 -Appendix 4. Most of the data used in this study is taken directly from the SimaPro database, except for the hemp insulation material, which is entered manually.

Quantities with volumes have been calculated based on the wallarea that is supposed to be insulated. Furthermore all quantities and transport operations are divided by the total floor area (10830 m^2) of the buildingand the expected lifetime for the usedbuilding materials.

3.3 Results

The calculations on energy demand illustrate the total amount of saved energy per square meter and year is 30 kWh, which is around 18% per year. It is obvious that an insulation with mineral wool has slightly better effects on the energy demand than the hemp insulation.

B Building	Hemp insulation	Mineral Wool insulation	Zero alternative
Total demand [kWh/m^2/year]	135.03	134.27	165,000
Improvement [kWh/m^2]	29.97	30.73	0
Improvement [%]	18.16	18.62	0

Table 2. Compared energy utilization

According toAppendix 5 and Appendix 6 insulating the building decreases the impacts in all categories, see Table 3.The difference between hemp insulation and mineral wool is negligible.

improvement [%] / alternative	Climate change	Human toxicity	Photo-chemical oxidant	Particulate matter form	Ionizing radion	Freshwater euthrophication	Freshwater ecotoxicity	Marine ecotoxicity	Agricultural landoccupation	Fossil depletion	Terrestrial ecotoxicity
Hemp	9,11	13,74	14,35	12,33	4,08	12,05	7,5	11,69	18,67	9,3	16,55
Mineral wool	9,11	13,74	14,35	12,33	4,08	11,65	5,94	11,69	18,67	9,3	14,66

Table 3. Improvements for insulation alternatives by impact category

4 Conclusions and recommendation

4.1 Goal

The heating energy demand after the simulated refurbishment (in both alternatives) dropped by 18%. For the building's total energy use, the improvement is 10%. The goal of this study has clearly been reached, and this result could also be an important part in reaching the KTH Zero emission campus goal of 5% less energy use.The proposal can also provide Akademiska Hus with a sustainable solution to lower energy use and environmental impacts for their buildings at KTH campus.

4.2 Excluded improvement options

There are several ways to lower the energy utilization for the buildings and minimize their impact on the environment. The methods discussed for improving the heating performance were mainly: additional insulation of the walls, roof, cellar and foundation, changing old windows into new and efficient ones, optimizing the ventilation system controls. Minimizing the cooling need by applying solar shading to the windows, and smart control systems to save electricity was also discussed, but these suggestions were discarded because of the focus on heating.

During a first brief inspection of the building, the lack of insulation materials could immediately be determined as an important cause of the high energy use. Many of the windows however, had already been changed to more efficient ones, so therefore the change of windows option wasn't investigated any further.

The roof insulation option was rejected because of the complex geometry and construction of the roof; its many shapes and also roof windows make computer simulations a necessity for such an assessment.

An inspection report commissioned by Akademiska Hus (ref. inspection report) points out the foundation and cellar as the building parts with the most need of improvements. Further investigation into this led to the conclusion that it would be a technically difficult project to insulate the foundation and cellar walls. Furthermore, the risk of having moisture problems was deemed as high and such a solution is therefore not sustainable.

The inspection report above also lists the walls as a priority area for improvement, so additional insulation of the walls became the focus of this project.

The existing walls are mainly built out of bricks, with no interior or exterior insulation. Since brick has a low resistance for heat flowing through, a material with a higher resistance must be added. This study compares insulation with two such materials: Hemp fiber insulation and Mineral wool.

4.3 Impacts

The characterisation and normalisation of the inventory data offered some anticipated results and some surprises. An expected improvement in the category Climate Change could be seen in the characterisation, as well as reduced impacts for all the impact categories, see Appendix 7, Appendix 8and Appendix 9. But after normalisation of the result, the Climate Change impact category was overshadowed by the much more severe impact in the Human Toxicity impact category.

An attempted description of what makes the impact on human toxicity so big can only be done briefly here. For the refurbished building the impact is due to the electricity and the heating in somewhat equal parts, while for the zero alternative the heating has a bigger part in the impact as seen in appendicesAppendix 7, Appendix 8and Appendix 9. The refurbishments' parts of the impacts on most categories are almost negligible, as expected.

The toxic substances visible in the Human toxicity impact category emanates from combustion processes in the heating and electricity production, as seen in Figure 6below. This figure comes from the analysis of the hemp insulation alternative, but the analyses of the other options show similar results. Here, the cut-off is set to 0,1%.

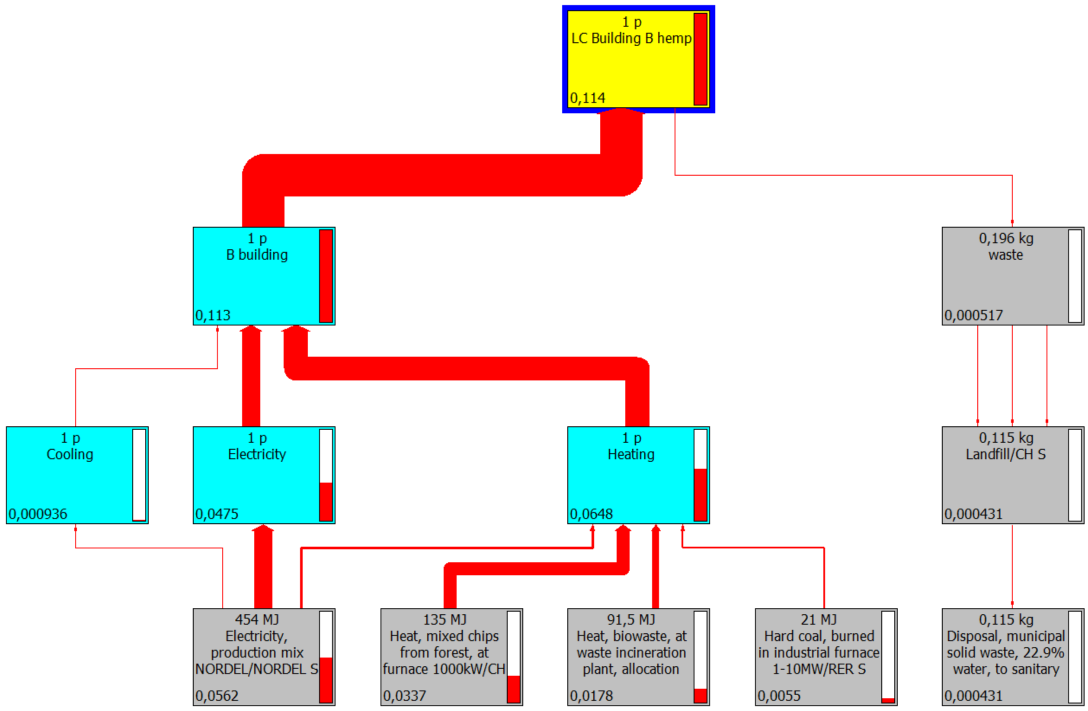


Figure 6. Flow chart on human toxicity impacts for hemp insulation alternative

Another surprising result was the almost equal environmental impacts from the different insulation materials, as seen in the result tables. A lower impact from the hemp alternative was expected in the Climate change category since the hemp functions as a CO2 sink while it remains in the building.

4.4 Important assumption

4.4.1 Energy calculations

When calculating the improvement in the heating performance of the building, some limitations and simplifications were made in the model. If a more accurate and detailed model would be used, the result in terms of energy savings could actually be improved.

One important simplification was that thermal bridges were not at all accounted for, except for the wooden frame that was merged together with the insulation material. Thermal bridges are places where heat can flow more easily from the internal to the external side of the wall. They appear on different places of the exterior wall, for example at exterior wall corners, around the windows, where interior walls and floor slabs connect to the exterior wall, and where screws and bolts go through the wall.

If the thermal bridges were to be taken into account, the result would probably show that the refurbished walls would have less severe thermal bridges than the zero alternative wall, due to the new layer of insulation. That would lead to an additional decrease in the heating demand and therefore save heating energy.

When using the U-value for determining the magnitude of the improvement, only conductive heat transfer is taken into account. But since heat also flows through the building envelope by convection, radiation, air infiltration and exfiltration, the total heat loss is not captured with this method. It is possible that the plastic film used for moisture proofing of the insulated wall would also lower the infiltration and exfiltration flows of air through the wall. Then a lesser volume of air would need heating, and additional savings could be done on the heating energy.

Overall, more accurate modelling is needed to calculate the potential energy savings from the proposed refurbishments. The calculatedlife cycle impact of the refurbished building could then decrease even more.

4.4.2 Moisture

An important discussion that has been left out in this report is about the risk of having condensation in the wall because of the additional insulation. Moisture in the wall could damage the building structure and create an environment which allows the growth of mold and bacteria. A technical solution that creates new problems for the building’s structure and indoor climate is not a sustainable solution. Before applying extra insulation to a building, a closer study of the moisture transfer through the wall must therefore be conducted.

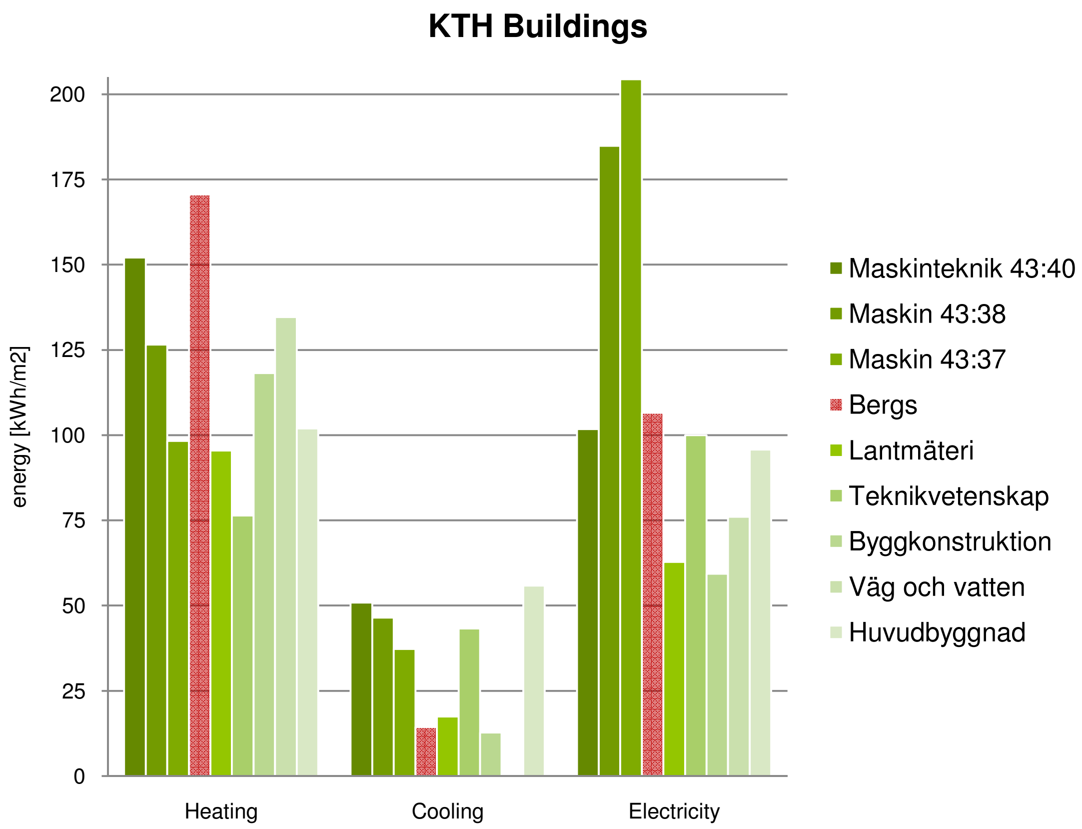
4.5 Recommendation

Additional insulation of the exterior walls with hemp insulation or mineral wool from the inside should be investigated further.

This study shows that the heating performance could be improved by about 20% or even more by additional insulation. A better energy performance will lower the life cycle impacts in all impact categories evaluated.

5 Appendix

5.1 Comparison of energy use - KTH Buildings



Appendix 1.energy use of KTH buildings

Appendix: Area estimations

Area of walls, windows and insulation

The height of the buildning facades and the percentage of glazing have been estimated by visual examination, while the lengths have been measured from the drawings K20.1-111, K20.1-121 and K20.1-131.

$$A_{w1} := 8m\cdot(21.8m + 3.2m) + 5m\cdot 14m + 6m\cdot 43.5m + 8m\cdot 14m + 8m\cdot 6.4m + 25.4m\cdot 4m = 795.8\, m^2$$

$$A_{w2} := 2\cdot 8m\cdot 22.8m + (18 + 10)m\cdot(28.4 + 19.3)m + 8m\cdot 28.5m + 8m\cdot 16m + 7.1m\cdot 16m = 2.17\times 10^3\, m^2$$

$$A_{w3} := 37.1m\cdot 8m + 40m\cdot 18m + 18m\cdot 7.1m + 8m\cdot 5.8m + 40m\cdot 10m = 1.591\times 10^3\, m^2$$

$$A_{wtot} := \left(A_{w1} + A_{w2} + A_{w3}\right) = 4.557\times 10^3\, m^2$$ **Facade area**

$$A_{i1} := 8m\cdot(21.8 + 3.2)m\cdot 0.85 + (5\cdot 14 + 6\cdot 43.5 + 8\cdot 14 + 8\cdot 6.4)m^2\cdot 0.95 + 25.4m\cdot 4m\cdot 0.70 = 710.61\, m^2$$

$$A_{i2} := [2\cdot 8m\cdot 22.8m + (18 + 10)m\cdot(28.4 + 19.3)m]\cdot 0.70 + 28.5m\cdot 8m\cdot 0.85 + 7.1m\cdot 16m = 1.498\times 10^3\, m^2$$

$$A_{i3} := (37.1m\cdot 8m + 40m\cdot 18m + 40m\cdot 10m)\cdot 0.70 + 18m\cdot 7.1m + 8m\cdot 5.8m = 1.166\times 10^3\, m^2$$

$$A_i := A_{i1} + A_{i2} + A_{i3} = 3.374\times 10^3\, m^2$$ **Wall area**

$$A_{wintot} := A_{wtot} - A_i = 1.183\times 10^3\, m^2$$ **Window area**

Adjusting the insulation area by estimating how much of the outer wall area that's connected to the inner walls and floors (and thereby diminishing the insulation area). For the entire house, this is assumed to be 5% of the area.

$$A_{itot} := \left(A_i\cdot 0.95\right) = 3.206\times 10^3\, m^2$$ **Area of insulation needed**

Percentage of windows

An average percentage of windows is used for the entire buiding, i.e. the window area is evenly distributed on the facade model.

$$winratio := \frac{A_{wintot}}{A_{wtot}} = 0.26$$ Average window coverage percentage.

Appendix: calculations for
Heat transfer through insulated V.S. non-insulated walls

The outer walls are assumed to consist of 0.45 m brick and 0.005 m plaster on the inside.
0.10 m of insulation material is used, and wooden studs with c/c distance 0.60 m are used for the monunting of the insulation. The interior cladding consists of double 13 mm gypsum wallboards. The PE-film is neglected in the heat transfer calculation.
The calculation methods are taken from Jóhannesson and Gudmundsson (2011).

Interior and exterior surface resistances are set to 0.13 m2K/W and 0.04 m2K/W respectively (Jóhannesson and Gudmundsson 2011 p 25).

Material data

Heat conductivity	Assumed thickness of layer	
$\lambda_{brick} := 0.60 \frac{W}{m \cdot K}$	$d_{brick} := 0.45m$	
$\lambda_{hemp} := 0.040 \frac{W}{m \cdot K}$	$d_{hemp} := 0.10m$	
$\lambda_{minwool} := 0.036 \frac{W}{m \cdot K}$	$d_{minwool} := 0.10m$	(mineral wool = glass wool)
$\lambda_{wood} := 0.14 \frac{W}{m \cdot K}$	$d_{wood} := 0.10m$	
$\lambda_{gypsum} := 0.25 \frac{W}{m \cdot K}$	$d_{gypsum} := 0.026m$	

(Jóhannesson and Gudmundsson 2011, pp133-134)

The conductivities for insulation and wooden studs are weighted together using the λ-method. This gives a rough approximation of the thermal bridges due to the wooden frame. The studs have a width of 0.060 m in the plane of the wall.

$$\lambda_{hewo} := \frac{\left[\lambda_{hemp} \cdot (600 - 60) + \lambda_{wood} \cdot 60\right]}{600} = 0.05 \cdot \frac{W}{m \cdot K}$$

$$\lambda_{miwo} := \frac{\left[\lambda_{minwool} \cdot (600 - 60) + \lambda_{wood} \cdot 60\right]}{600} = 0.046 \cdot \frac{W}{m \cdot K}$$

Heat resistance factors

$$R_{si} := 0.13\,\frac{m^2K}{W}$$

$$R_{brick} := \frac{d_{brick}}{\lambda_{brick}} = 0.75\cdot\frac{m^2K}{W}$$

$$R_{hewo} := \frac{d_{wood}}{\lambda_{hewo}} = 2\cdot\frac{m^2K}{W}$$

$$R_{miwo} := \frac{d_{wood}}{\lambda_{miwo}} = 2.155\cdot\frac{m^2K}{W}$$

$$R_{gypsum} := \frac{d_{gypsum}}{\lambda_{gypsum}} = 0.104\cdot\frac{m^2K}{W}$$

$$R_{se} := 0.04\,\frac{m^2K}{W}$$

Heat conductive resistances for the different walls

$$R_{wallZ} := R_{si} + R_{brick} + R_{se} = 0.92\cdot\frac{m^2K}{W}$$ Zero alternative

$$R_{wallH} := R_{si} + R_{brick} + R_{hewo} + R_{gypsum} + R_{se} = 3.024\cdot\frac{m^2K}{W}$$ Hemp insulation

$$R_{wallM} := R_{si} + R_{brick} + R_{miwo} + R_{gypsum} + R_{se} = 3.179\cdot\frac{m^2K}{W}$$ Mineral wool insulation

U-values

$$U_{wallZ} := \frac{1}{R_{wallZ}} = 1.087\cdot\frac{W}{m^2\cdot K}$$ **Zero alternative**

$$U_{wallH} := \frac{1}{R_{wallH}} = 0.331\cdot\frac{W}{m^2\cdot K}$$ **Hemp insulation**

$$U_{wallM} := \frac{1}{R_{wallM}} = 0.315\cdot\frac{W}{m^2\cdot K}$$ **Mineral wool insulation**

Estimation of the improvement in energy performance

Because of lacking indata to the energy calculations, an average number of how much of the heat that goes out through the walls is used. In this case we assume 30%.
Sources for input to the assumption:
Lecture by Ivo Martinac, KTH 2013 11 07
http://www.kyotoinhome.info/UK/heat_loss/basic_principles.htm (accessed 2013 12 11)

$$h := 3600s$$

The heating energy bought in 2012 is used as a reference. Since our estimation is that 30 % of the heating energy leaves the building through the walls, the improvement occurs as a decrease of that part.

$$\text{BoughtHeat} := 170.65\,\frac{kW\cdot h}{m^2}$$

$$\text{WallsHeat} := 0.30\cdot\text{BoughtHeat} = 51.195\cdot\frac{kW\cdot h}{m^2}$$

The refurbished walls have higher resistances to convective heat transfer. When the resistances increase, the U-values decrease. The U-values of the refurbished walls are compared to that of the zero alternative.

$$\text{HempRatio} := \frac{U_{wallH}}{U_{wallZ}} = 0.304$$ Hemp insulated wall

$$\text{MineralRatio} := \frac{U_{wallM}}{U_{wallZ}} = 0.289$$ Mineral wool insulated wall

Estimated heating demand after refurbishment

Several simplifications have been made, see the section assumptions and simplifications.

$$\text{HeatHemp} := \text{BoughtHeat} - \text{WallsHeat}\cdot(1 - \text{HempRatio}) = 135.03\cdot\frac{kW\cdot h}{m^2}$$

$$\text{HeatMineral} := \text{BoughtHeat} - \text{WallsHeat}\cdot(1 - \text{MineralRatio}) = 134.27\cdot\frac{kW\cdot h}{m^2}$$

5.4 Data from SimaPro

No	Component name	Amount	Material input	Weight (kg)
1	Isonat production at Buitex, France	1	Hemcore Farming hemp fibre production (29%)	0,35
			Cotton fibres, at farm/US S	0,35
			Polyester resin, unsaturated, at plant/RER S	0,15
			Bitumen sealing, polymer EP4 flame retardant, at plant/RER S	0,15
			Paper, newsprint, at regional storage/RER S	0,00001
			Polyethylene, HDPE, granulate, at plant/RER S	0,028571
			Extrusion, plastic film/RER S	0,028571
2	Hemcore Farming hemp fibre production (29%)	1	Hemcore Farming hemp straw production	3,448
			Dummy_Steel scrap, at plant/US	0,004232
			Electricity, medium voltage, at grid/GB S	1,862 (kWh)
			Polyethylene, HDPE, granulate, at plant/RER S	0,002
3	Hemcore Farming hemp straw production	1	Tillage, rotary cultivator/CH S	1 (ha)
			Application of plant protection products, by field sprayer/CH S	0,625 (ha)
			Haying, by rotary tedder/CH S	2 (ha)
			Baling/CH S	8,57 p
			Combine harvesting/CH S	1 (ha)
			Tillage, rolling/CH S	1 (ha)
			Ammonium sulphate, as N, at regional storehouse/RER S	100
			Ammonium nitrate phosphate, as P2O5, at regional storehouse/RER S	30
			Potassium chloride, as K2O, at regional storehouse/RER S	30
			Polyethylene, LDPE, granulate, at plant/RER S	0,000173
4	Paint	1	Acrylic varnish, 87.5% in H2O, at plant/RER S	0,012
5	Gypsum board	1	Gypsum fibre board, at plant/CH S LCA02	0,12
6	Plaster	1	Base plaster, at plant/CH S LCA02	0,0077
7	Plastic film	1	Packaging film, LDPE, at plant/RER S	0,0012
8	Studs	1	Spruce wood, timber, production mix, at saw mill, 40% water content DE S	0,05
9	Hemcore Farming hemp straw production	1	Carbon dioxide, in air	10054000

Appendix 2.Material input for refurbishment with hemp insulation

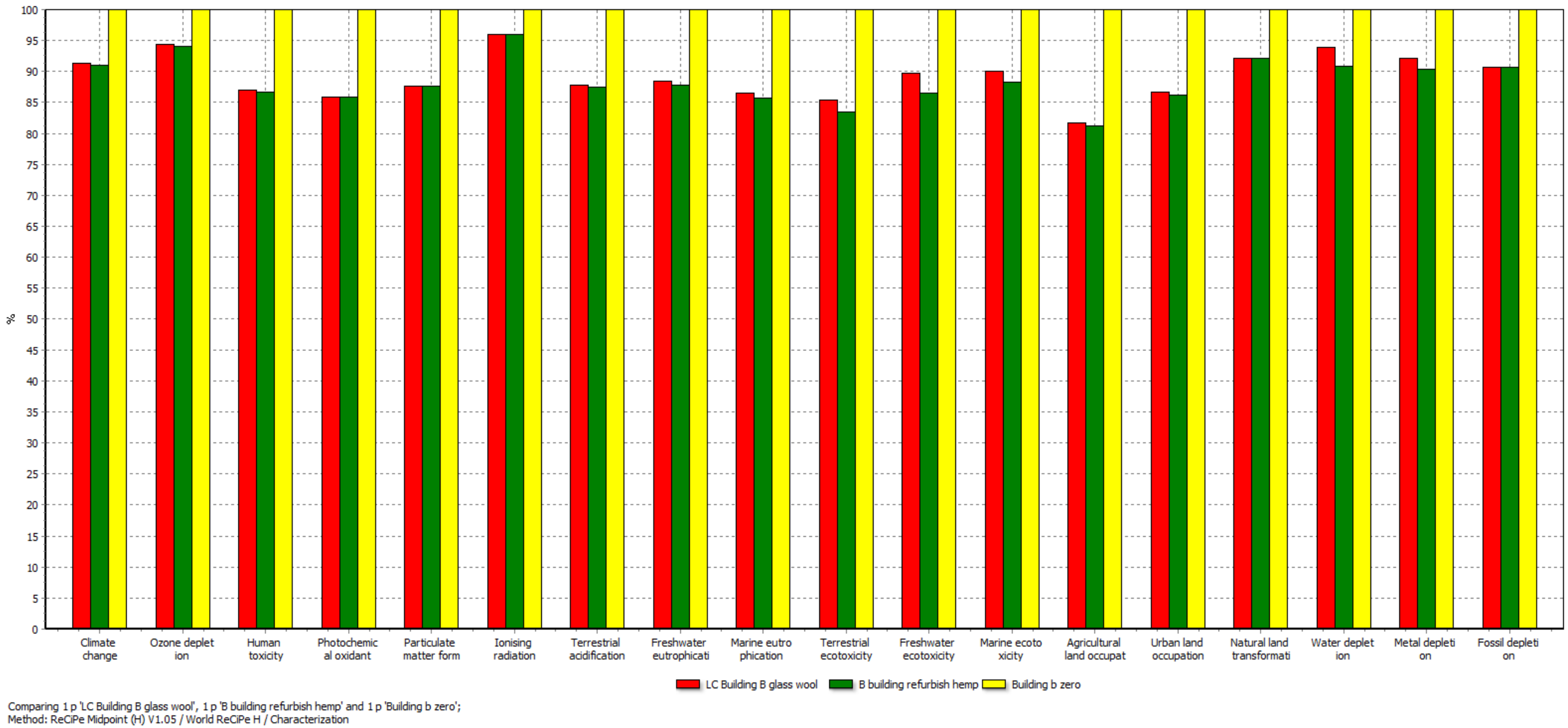
Input		amount (km)
Operation, lorry >32t, EURO5/RER S	wooden studs	$50km/10830m^2/50years = 0,00009$
Operation, lorry 3.5-7.5t, EURO5/RER S	(plastic film	$50km/10830m^2/50years = 0,00009$
Operation, lorry 3.5-7.5t, EURO5/RER S	plaster	$50km/10830m^2/50years = 0,00009$
Operation, lorry >32t, EURO5/RER S	hemp insulation	$5*1731km/10830m^2/50years = 0,016$
Transport, barge/RER S	hemp insulation	$6,7km/10830m^2/50years = 0,0000124$
Operation, lorry >32t, EURO3/RER S	gypsum board	$50km/10830m^2/50years = 0,00009$
Operation, lorry >32t, EURO3/RER S	gypsum board	$50km/10830m^2/50years = 0,00009$
Operation, van < 3,5t/RER S	paint	$50km/10830m^2/10 years = 0,0005$

Appendix 3.Input data for transportation of refurbishment materials in case with hemp insulation

No	Component name	amount	Material output	Weight (kg)
1	Hemcore hemp fibre production (29%)	1	Plastic waste	0,000173
2	Isonat production at Buitex, France	1	Steel waste	0,008463
3	Isonat production at Buitex, France	1	Packaging waste, paper and board	0,00001
		1	Plastic waste	0,00084
		1	Plastic waste	0,028571

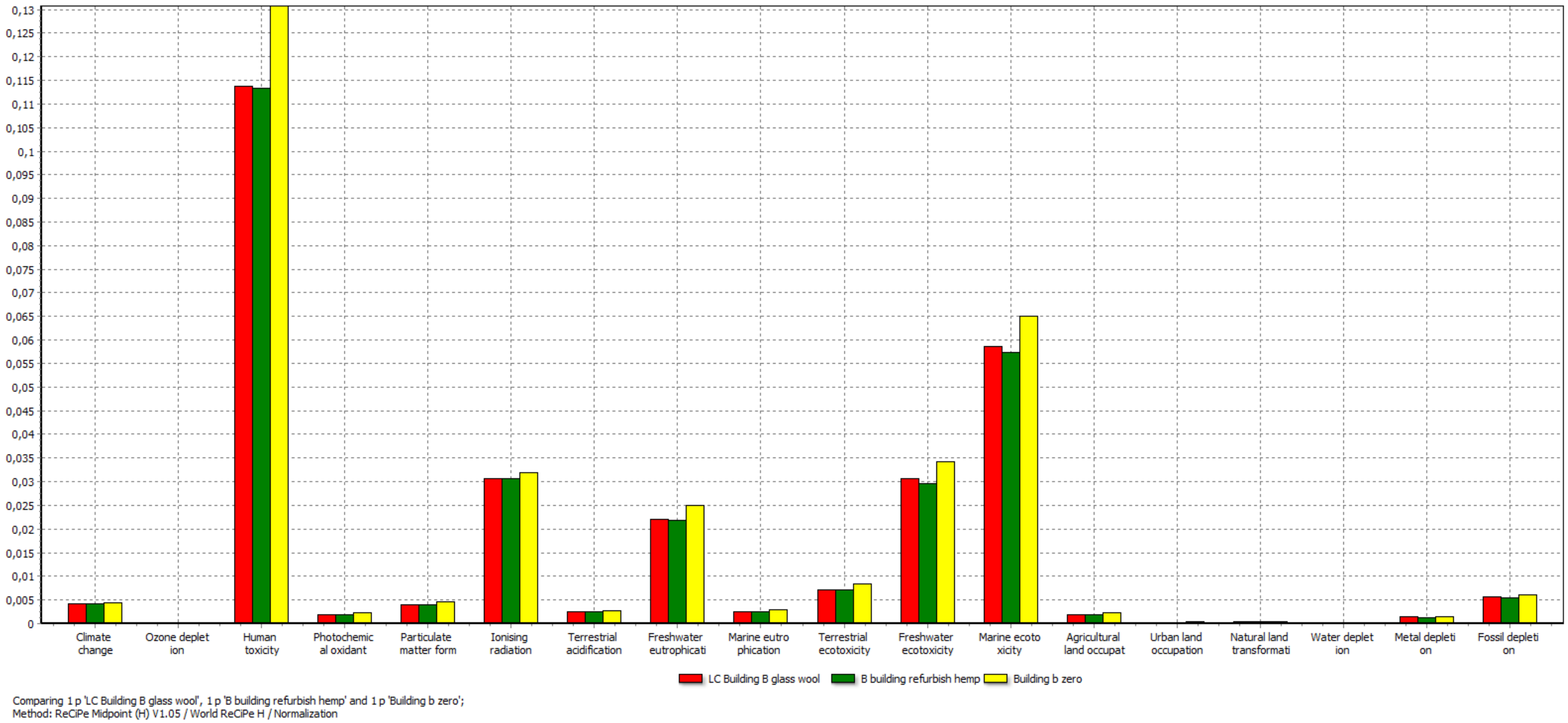
Appendix 4.Output data of refurbishment materials

5.5 Characterization



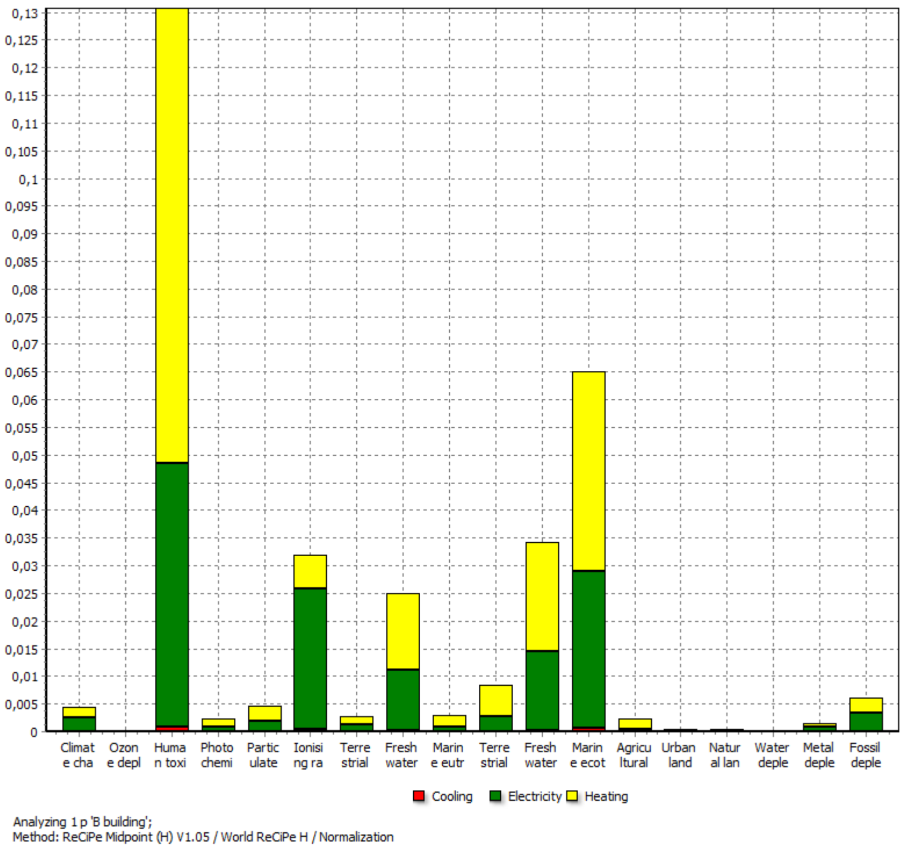
Appendix 5. Characterization

5.6 Normalization

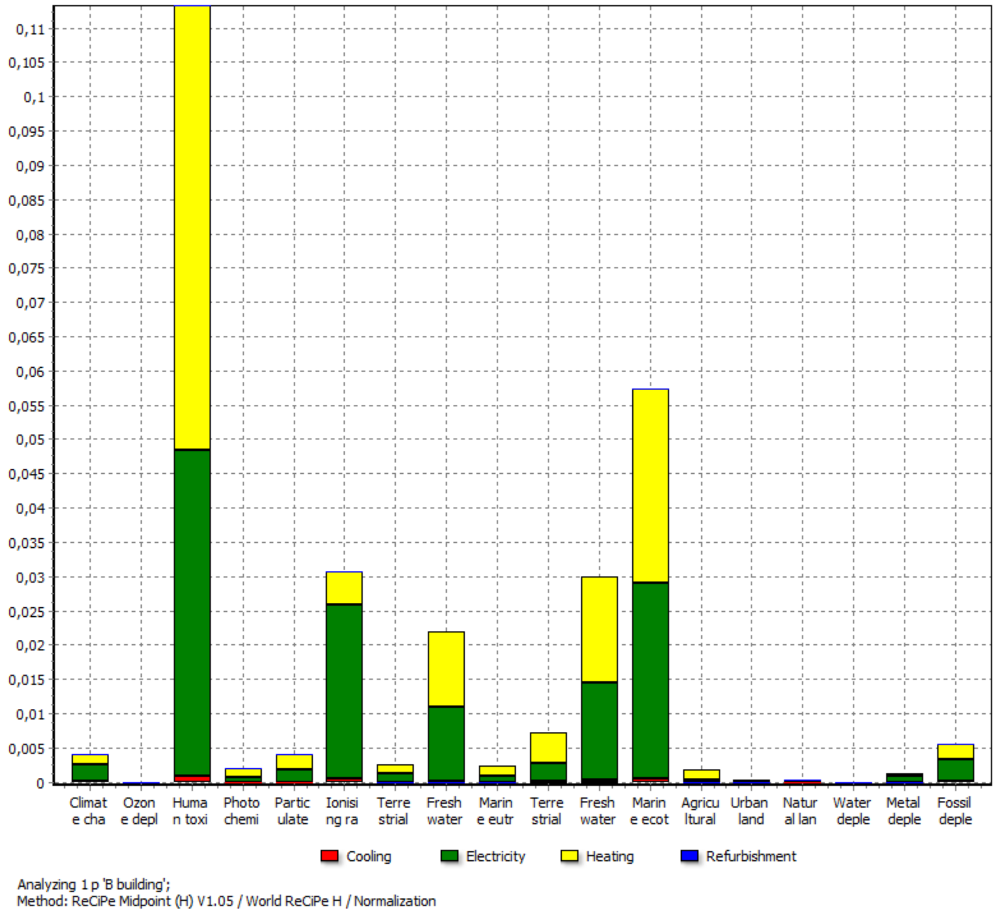


Appendix 6. Normalization

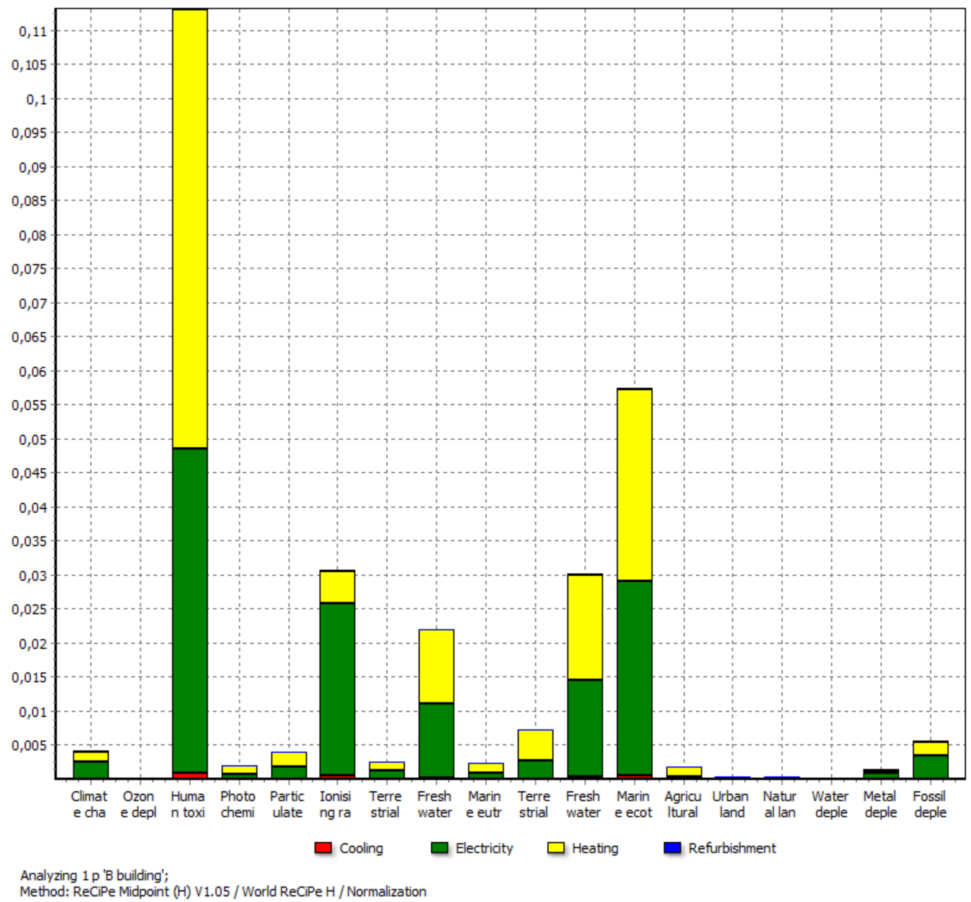
5.7 Stand-alone normalization



Appendix 7.Zero alternative



Appendix 8. Hemp insulation



Appendix 9. Mineral wool insulation

6 References

6.1 List of tables

6.2 List of figures

6.3 Sources

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