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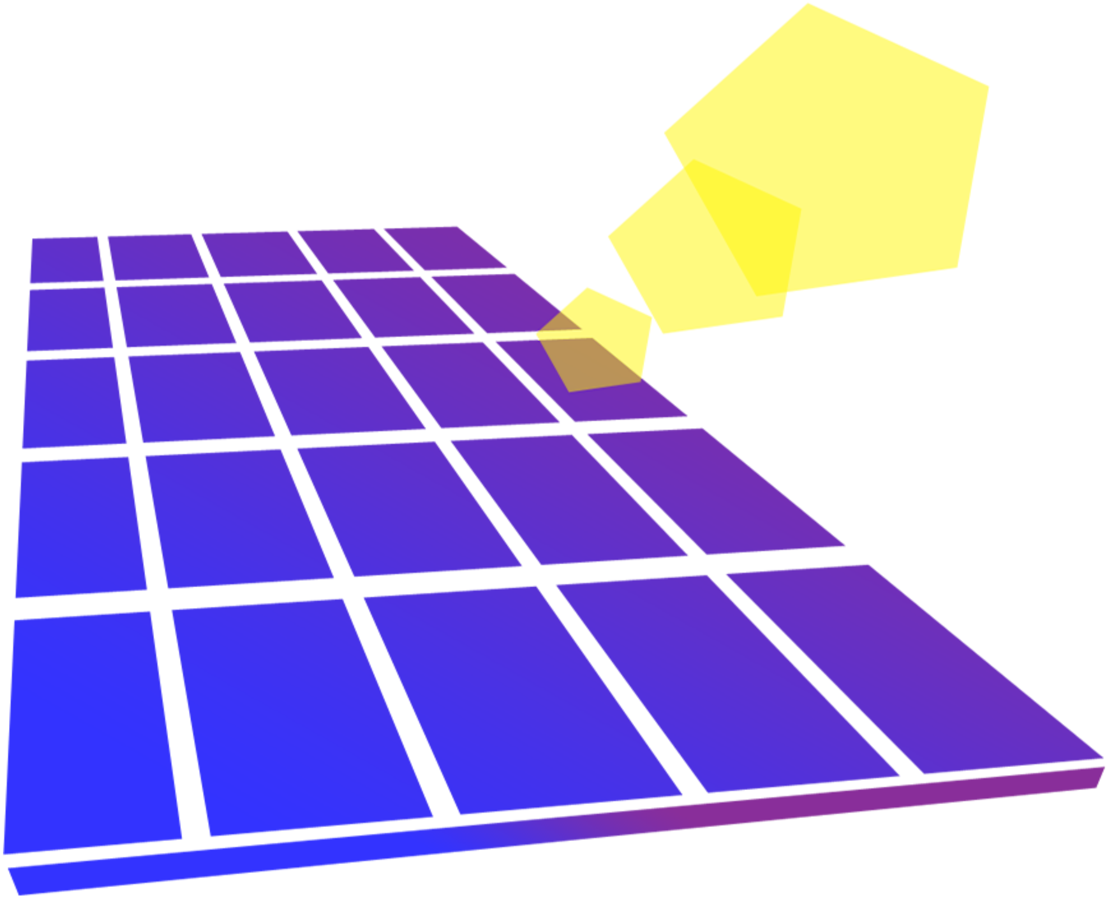

Life cycle assessment of a building-integrated solar technology

Master's Thesis in Industrial Ecology

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Göteborg, Sweden 2014

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Cover:
The cover picture is created by Erik Einebrant and shows a stylized solar panel.

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Abstract

Solar energy is a field that has grown immensely during the last decade, along with the increased public awareness of environmental challenges and sustainable development. While roof-installed solar cells have conventionally been mounted on aluminium panels, the idea of solar cells that are more integrated in the building design are gaining more and more interest. One innovation in this field is the solar sandwich, developed by SOLEV Entreprenad, which combines the functions of a roof with insulation and a surface where solar cells can be installed, without any conventional solar panels.

This thesis consists of a life cycle assessment of this solar sandwich as well as life cycle assessments of two typical roofs with conventional solar panels. Four sensitivity analyses were conducted in order to investigate some of the methodological and modelling choices that were made. The results of these sensitivity analyses did not alter the final results significantly. This suggests that the model used for the calculations is robust.

The results of the impact assessment show that the environmental impact of the solar sandwich is similar to that of a conventional wooden roof with solar panels. In four out of five impact categories – global warming potential, acidification potential, human toxicity potential and land use – the solar sandwich was found to perform better than the conventional roofs. The impact category where the solar sandwich performed the worst, by far, was stratospheric ozone depletion potential.

Keywords: solar energy, solar cells, renewable energy, sustainable building, sandwich, LCA, environmental impact, climate change

Sammanfattning

Solenergi är ett område som har vuxit väldigt snabbt under det senaste decenniet i samband med en ökad medvetenhet om miljöproblem och hållbar utveckling. Vanligtvis installeras solceller på paneler i aluminium som i sin tur monteras på ett existerande tak men det blir mer och mer vanligt att solceller istället integreras i byggnadsdesignen istället för att monteras ovanpå ett färdigt tak. Solar sandwich har utvecklats av SOLEV Entreprenad och är en innovation inom detta område; en enda produkt fungerar som tak, isolering och som en solpanel där solceller kan fästas direkt på takytan.

Denna uppsats består av en livscykelanalys av solar sandwich samt ytterligare livscykelanalyser på två typiska tak med konventionella solpaneler. Fyra känslighetsanalyser utfördes för att granska några av de metodikval och antaganden som gjordes. Dessa känslighetsanalyser visade att den använda modellen var robust och att slutresultatet inte påverkades signifikant av ändrade parametrar. Detta visar på att den modell som beräkningarna är baserade på är robust.

Livscykelanalysens resultat visar att miljöpåverkan från solar sandwich liknar den från konventionella trätak med solpaneler. I fyra av fem studerade miljöpåverkanskategorier – global uppvärmning, försurning, humantoxicitet och landanvändning – hade solar sandwich bättre resultat än de konventionella taken. Den kategori där solar sandwich presterade markant sämre än konventionella tak var ozonförstöring.

Nyckelord: solenergi, solceller, förnybar energi, hållbart byggande, sandwich, LCA, miljöpåverkan, klimatförändringar

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Jonathan Alvebratt & Martin Blidmark, Göteborg, June 4th 2014

Contents

1 Introduction

With an increased public interest in renewable energy technologies as well as a growing awareness regarding environmental problems such as global warming, solar energy technology has evolved and grown rapidly in the last decade. Apart from fossil fuels and nuclear power, solar energy is a viable alternative energy source with sufficient technical potential to provide a major share of a future energy system [1, 2]. In comparison with fossil fuels and nuclear power, solar energy is arguably a more sustainable energy source although there are some concerns regarding rare metals being used in today's solar technology, e.g. indium, gallium and tellurium [3].

Another issue is the life cycle impact of building-applied photovoltaics (BAPVs), which use solar panel mounting systems which typically consist of large amounts of different metals, aluminium in particular, and glass. These constructions are then retro-fitted, i.e. mounted on top of existing roofs. Previous life cycle assessments (LCAs) suggest that the production and installation of these mounting systems contribute to about 10-30 % of a solar power module's total carbon emissions [4–6].

In order for solar energy to become competitive on the market, it has to be cost effective, reliable and aesthetically appealing [7]. Instead of retro-fitting solar panels, the idea of integrating them in the building design has gained a lot of interest in recent years [8]. Building-integrated photovoltaic (BIPV) systems make for more aesthetically pleasing solutions and for instance enable the use of solar panels as an outer roof or as a house façade. This also reduces monetary and environmental costs, as the solar panels will replace materials that otherwise would have been used for roofing, panels or insulation [9].

This principle of substituting a roof with solar panels, working as both outer roof and as insulation, is the basis of the solar sandwich panel developed by SOLEV Entreprenad. Figure 1 shows a prototype of the solar sandwich. As opposed to floors, windows and internal walls which in some cases have negligible impact, ceilings and roofs almost always have a large contribution to a building's environmental impact [10]. Therefore, improvements in roof manufacturing processes and material choices are important to consider in sustainable building.

Sustainability is becoming an increasingly important factor when constructing buildings. Today, in developed countries, buildings account for 20-40 % of the total energy consumption and this number is steadily increasing due to people spending more time inside buildings along with higher requirements on services [11]. A resulting factor of this is that building efficiency is of significant importance when it comes to reducing energy consumption and thereby environmental impacts. One large contributor to energy consumption in buildings is space heating – according to the U.S Department of Energy, space heating accounted for 37 % of a building's energy consumption in 2010 [12]. A method to decrease the amount of space heating needed is to have better insulation [13]. A promising material for insulation is expanded polystyrene foam (EPS). It has the advantages of having good creep resistance, being water resistant and it is also strong [14].

Figure 1: A prototype of the solar sandwich developed by SOLEV Entreprenad.

1.1 Life cycle assessment

The methodology of LCA is described schematically in Figure 2. The first step of an LCA is determining a goal and scope, in other words to clearly define why the study is conducted, for whom the study is conducted, what is studied, which environmental impact categories are assessed, which assumptions are made, which limitations are used and what the system boundaries are. Furthermore, a functional unit and a reference flow are defined. The functional unit is a measure of a system's function that allows comparison between the studied options in a fair way. The reference flow is the amount of materials needed to perform the function described in the functional unit. Different choices might drastically alter the results, so it is important to have a relevant and useful functional unit [15].

The next step is to conduct a life cycle inventory analysis, which is the mapping of all different processes in detail along with relevant data regarding material use, energy consumption etc. With a complete inventory analysis, the environmental impact assessment of the life cycle can be conducted. In this step all different flows and processes described in the inventory analysis are assessed in terms of environmental impact per functional unit. After this is done an interpretation of the results is necessary to provide clear conclusions. Lastly, the results may be normalized or weighted into a single environmental performance score, although this is generally not recommended. This is because weighting methods are not generally considered scientifically accurate and subjective – a weighting method that gives high importance to certain impact categories may be relevant to some stakeholders but not to others [16–19].

As Figure 2 suggests, there are ongoing feedback processes between the different steps while conducting an LCA. For instance, different choices and discoveries during the inventory anal-

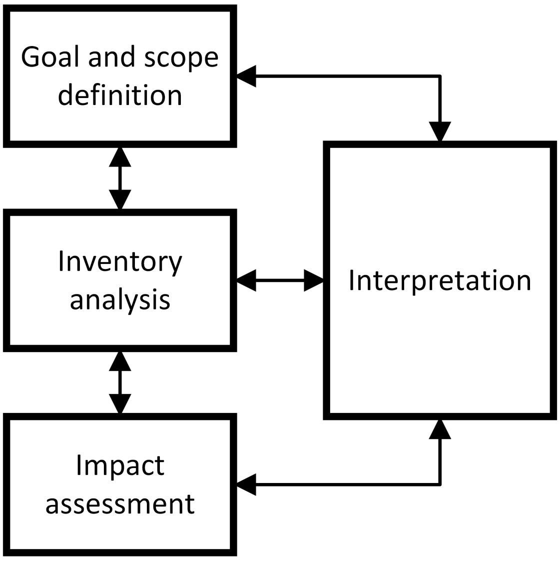

Figure 2: A schematic image describing the different steps in the LCA methodology and the ongoing feedback processes between these steps.

ysis might entail an alteration of the goal and scope in order to get a cohesive and relevant study.

There are different ways of allocating environmental impact from multi-output processes. In physical allocation the impact is distributed among the outputs based on some sort of physical property such as weight or energy content. The impact can also be distributed according to economic properties, i.e. allocated in proportion to the products' value. An alternative to allocation is using system expansion. This means that the studied system is expanded in order to account for how the byproducts replace the production of an equivalent product elsewhere.

1.2 Previous studies

There are no previous studies conducted on sandwich solar panels, as it is a new innovation that has not reached a broad market yet. There are, however, many studies that have assessed the environmental benefits of BIPVs in general, as opposed to retrofitted solar panel constructions.

In a British study a cradle-to-site LCA was performed on a 2.1 kW_p BIPV system in southern England [20]. The results showed a global warming potential of 94.5 g $CO_{2,eq}$ per kWh after subtracting the avoided emissions from concrete roof tiles that were replaced by the BIPV system, but without considering avoided emissions that otherwise would have been produced by other energy systems. The avoided emissions from the roof tiles were about 5% of those from the production of the BIPV system but it was not stated what materials were included in the solar panel frame construction, which contributed to 20% of the total global warming potential.

Another study compared a retrofitted solar panel with two different types of integrated solar panels [21]. No specific data on $CO_{2,eq}$ per kWh was given but compared with a retrofitted solar panel, the two integrated constructions studied reduced the $CO_{2,eq}$ return time with 15-22%, even though the integrated constructions had significant amounts of steel, aluminium and lead albeit not as much as the retrofitted construction. The CO_2 return time is the time it takes for the solar panels to reach net zero emissions, i.e. how long the PV system has to operate to avoid the amount of total emissions of CO_2 equivalents associated with the production of the system.

In a review article by Zhang et al. the CO_2 return times for 21 different solar panels were assessed [22]. The results varied between 0.8 and 3.5 years, with a median CO_2 return time of 1.7 years. In a study conducted by Cucchiella & D'Adamo the CO_2 return times were assessed for building-integrated monocrystalline silicon solar modules in three different locations in Italy [23]. The resulting CO_2 return times for the three cases were 2.5, 2.7 and 3.0 years. In another study from 2010, by Lu & Yang, the CO_2 return time for a 22 kW_p roof-mounted PV array in Hong Kong was estimated to 5.2 years [24]. The authors pointed out that the marginal electricity system considered was relatively clean and that a coal-based system as comparison would have resulted in a much lower value.

Depending on which electricity mix is chosen for the energy consumption in an LCA, the results of the impact assessment will vary a great deal. A sensitivity analysis on electricity mixes was conducted by Blom et al. [25]. The conclusion reached was that the environmental impact from electricity consumption was higher than the proportion of electricity used, in relation to the total energy content, for all studied scenarios. Therefore, the choice of electricity mix used in studies such as this thesis has a significant effect on the environmental impact. A direct implication of this has been shown in a recent study by Yue et. al, where the production of solar cells in China is estimated to have roughly twice as high CO_2 emissions as solar cells manufactured in Europe [26].

Previous LCAs of photovoltaics consider different impact categories. Stoppato published a study in 2008, where only two impact categories were studied: global warming potential and gross energy requirement [6]. The functional unit in this study was a 0.65 m^2 solar panel. In a working paper from 2008 by Jungbluth et al. the impact categories studied were global warming potential, fossil fuel use, acidification, ecotoxicity, land use, mineral extraction, carcinogenics emissions, ionising radiation, ozone layer depletion and respiratory effects. The functional unit was a 3 kW_p photovoltaic power plant [27].

The same ten impact categories were studied in a LCA by Zhong et al., with the only difference being that respiratory effects were assessed in two separate categories, organic and inorganic emissions. The functional unit of this study was a photovoltaic module of unspecified capacity [28]. The International Energy Agency conducted a study on life cycle inventories and life cycle assessments of photovoltaics where the main impact categories discussed were global warming potential, acidification and heavy metal emissions [29].

Table 1: Different values for amounts of emissions of CO_2-equivalents from a number of LCAs on solar energy production.

Study	Year	Estimated CO_{2-eq}/kWh	Comment
Stoppato [6]	2006	148-187 g	Two estimates.
NREL [30]	2013	20-218 g	Compilation of 17 studies with a total of 43 estimates. Median value of 57 g CO_{2-eq}/kWh.
Turconi et al. [31]	2013	13-130 g	Compilation of 22 studies.
Fthenakis & Kim [32]	2011	45 g	One estimate.
Tripanagnos-topoules et al. [33]	2005	104 g	–
Laleman et al. [34]	2011	80 g	Estimated value for a region with low solar irradiation, such as northern Europe.
Shervani et al. [35]	2010	44-280 g	Compilation of seven studies conducted between 1990 and 2006. Median value of 91 g CO_{2-eq}/kWh.

In general terms, attributional LCAs on solar power have a functional unit based on a certain panel size or capacity. In contrast, produced electricity in kWh is usually the functional unit in consequential LCAs where different energy systems are compared.

Table 1 shows results from a number of LCAs that have calculated g CO_2-equivalents per kWh of solar energy. The values in the table differ between 13 and 280 g CO_{2-eq}/kWh and the reason for the high variance is that the results are very dependent on the scope of the LCA but above all on the geographical boundaries of the study. For instance, a solar module installed in southern India will produce a lot more electricity during the course of its lifetime, compared with a solar module installed in northern Europe where the solar irradiation is much lower.

In a study by Turconi et al., the acidification potential from solar energy was found to be in the interval of $1.2*10^{-1}$ to $2.9*10^{-1}$ kg of SO_2-equivalents per kWh of electricity produced [31].

2 Goal and scope

The goal of this study is to do a cradle-to-grave LCA on a new type of building-integrated photovoltaic (BIPV) panel, developed by SOLEV Entreprenad. Since it is in the interest of SOLEV Entreprenad to have a complete accounting of their product's total environmental impact, the conducted LCAs will be attributional rather than consequential. Additional LCAs will be conducted on retrofitted solar panels on two different types of roofing widely used in Sweden, i.e. clay and concrete tiles on two different roof constructions mainly based on wood and concrete. The reason for studying these alternative scenarios is that they are commonly used in residential buildings in Sweden today. It will give a good indication about the sandwich panel's environmental performance compared to the major alternatives.

All cases will be assessed under equal insulation parameters as the sandwich panel, which means that the roofs need to be insulated to have a heat transport constant of approximately $0.16 W m^{-2} K^{-1}$. Ultimately, the main question that will be answered by this study is which type of solar panel and roof construction is environmentally preferable. The study will also show which processes contribute the most to the solar panels' environmental impact, suggesting where the greatest improvements can be made. In general, the highest environmental impact from solar energy systems comes from the production of the solar cells and more specifically from the purification of the silicon used in the wafers.

The target audience for the thesis is SOLEV Entreprenad who has commissioned the study, as well as other companies working towards sustainable building in Sweden. openLCA 1.3.4 is the software used in this study, the database for material data is EcoInvent 2.2 and CML 2001 is the designated method of impact assessment.

2.1 Functional unit

The functional unit of this study is the electricity production capacity of 1 kW_p – which means 1 kW of peak production under ideal conditions – from a south-aligned solar panel on a slanted roof on a residential apartment building in Sweden. The reference flow is 1 kW_p as well. Depending on the type of roof studied, different amounts of roof area will be needed to install a 1 kW panel. This is because of the more efficient solar cell fitting that the sandwich panel offers compared with a retro-fitted solution. Furthermore, since a slanted-roof construction is studied, the south-facing half of the roof is assumed to be filled with solar cells while the north-facing half will be empty. However, since this study assesses the function of the solar cells as well as the function of the roof – i.e. insulation, weather protection etc. – both parts of the roof will be taken into account in the calculations, meaning that twice the roof area that is needed for 1 kW_p of solar power is included in the functional unit.

The reference flows of the three scenarios studied, see Table 2, are based on the electric production capacities of the solar cells used and on how much roof area is needed to provide 1 kW_p. Since this study not only takes the function of solar electricity production into account

Table 2: The reference flows for the three different cases studied.

	Reference flow
Sandwich	10.7 m^2 roof area, of which 5.33 m^2 is used for solar cells
Clay	13.9 m^2 roof area, of which 6.93 m^2 is used for solar cells
Concrete	13.9 m^2 roof area, of which 6.93 m^2 is used for solar cells

but also the different functions of the roof, the total reference flows include both the south-aligned half of the roof, which is used for solar cells, as well as the north-aligned half, which is not used for solar cells. The same type of roof is used on both halves of the roofs in all cases.

2.2 System description

The BIPV panel developed by SOLEV Entreprenad is a multifunctional product which serves as both roof, insulation and as a solar panel. It consist of a sandwich material, i.e. a core material which is covered by two protective layers [36]. The function of the core material is to distribute the weight widely over the construction while the protective layers provide stability and protection from outer strain and climate effects. The advantages of a sandwich construction are that it is easy to implement, very flexible and has a high strength and low weight [37]. More specific for this study, the sandwich material consists of 200 mm expanded polystyrene (EPS) as core material, protected by two layers of 3 mm glass fibre-reinforced polyester that are glued to the EPS with a polyurethane adhesive. The PV modules are glued to the surface of the panel with the same polyurethane adhesive. Figure 3 shows a schematic image of the cross-section of the sandwich solar panel construction. The 200 mm panel has a total weight of 13.2 kg/m^2 and a heat transport constant of $U = 0.162 W m^{-2} K^{-1}$.

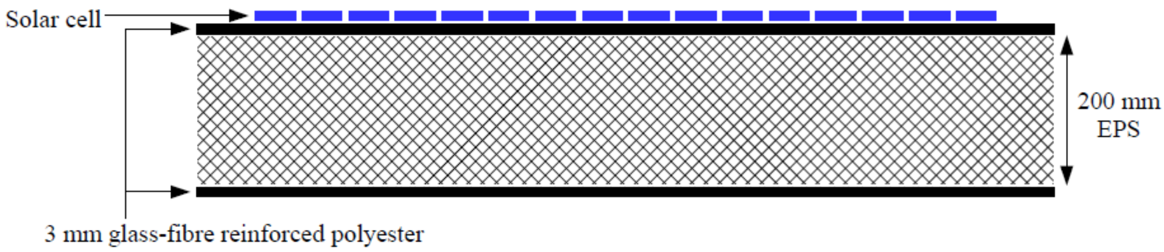

Figure 3: A schematic image of the cross-section of the sandwich panel with solar cells attached.

Figure 4 shows a basic flowchart of the different processes involved in the life cycle of a retro-fitted solar panel, as well as the roof it is mounted on. The same processes, except the ones with dashed lines, are involved in the life cycle of a solar sandwich. For more detailed flowcharts of the different roofs, see Figure 5, Figure 7 and Figure 9.

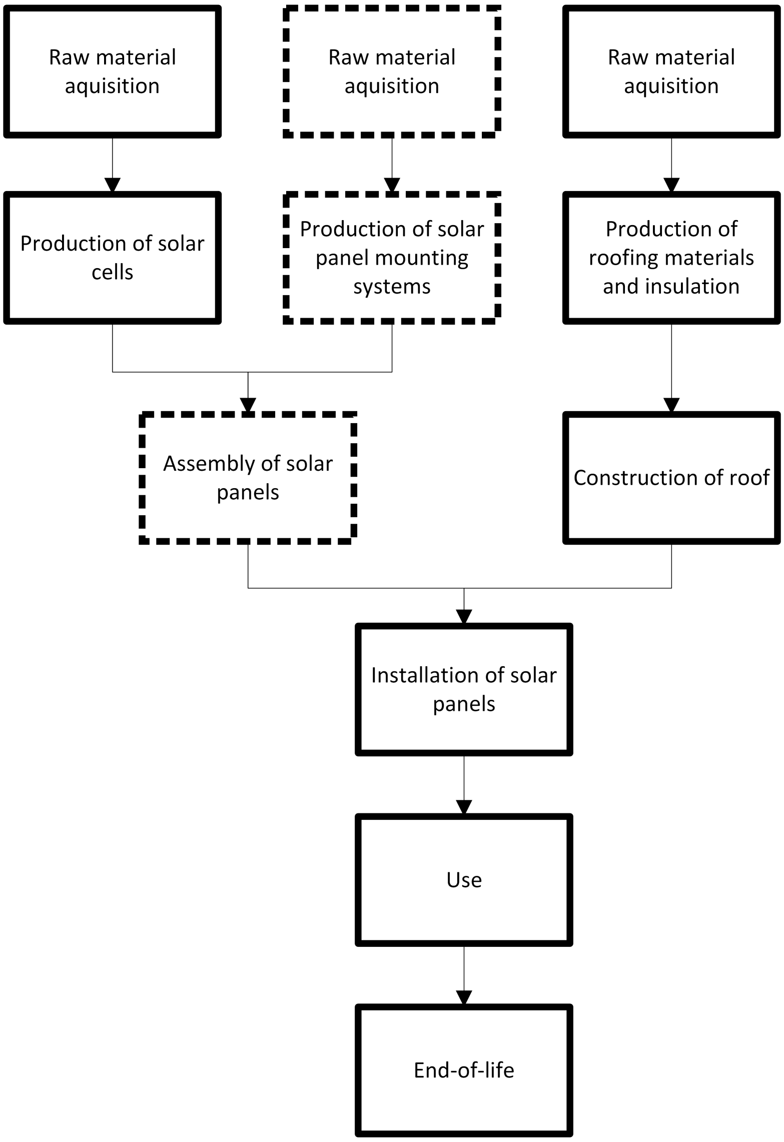

Figure 4: Flowchart describing the different processes involved in the life cycle of a solar panel and the roof it is mounted on. The processes with dashed lines are only present in the case of retro-fitted solar panels.

The reference roofs studied are taken from a Swiss study conducted by John in 2012 [10]. Since Switzerland and southern Sweden are in the same climate zone, the same amounts and types of building materials are needed for the same utility. In the study by John, LCAs are conducted on twelve different residential apartment buildings in Switzerland. Out of these twelve buildings, two of them have relatively small roofs – 114 m^2 and 145 m^2, respectively – and they were therefore chosen as references for this study, with one as a reference for a clay tile roof on a wooden construction and the other as a reference for a concrete tile roof on a concrete construction.

The reason for studying the smaller roofs is that the current sandwich panel thickness can support itself without any underlying structure at span widths up to six meters, so a much larger roof than those studied here might warrant another sandwich construction. The reason for studying two different buildings is to get a more general idea of the sandwich material's environmental performance, beyond one single case. Table 3 shows an overview of the different characteristics of the three roof types studied.

Table 3: Table of characteristics of the three roofs studied.

	Sandwich	Clay	Concrete
Outer roof material	Glass-fibre reinforced polyester	Clay tiles	Concrete tiles
Insulation	EPS	Cellulose fibre & rock wool	Polyurethane
Slanted roof	Yes	Yes	Yes
Solar panel installation	Building-integrated	Retro-fitted	Retro-fitted
Solar cell type	Helis (Sunplugged)	Reference cell	Reference cell

The original heat transport constant of the roof from the clay roof reference building is 0.13 $Wm^{-2}K^{-1}$ [10]. This is more insulated than the sandwich panel which has a heat transport constant of 0.162 $Wm^{-2}K^{-1}$. In order to get a similar heat transport constant for this reference roof, the amount of cellulose fibre was reduced. The insulation consists of both cellulose fibre and rock wool and in order to calculate a heat transport constant from several different insulation components, Equation 1 is used [38].

$$U = \frac{d_1}{k_1} + \frac{d_2}{k_2} + \ldots + \frac{d_n}{k_n} \tag{1}$$

In Equation 1, d denotes the thickness (m) of the different insulating materials and k denotes the thermal conductivities ($Wm^{-1}K^{-1}$) of the materials. In this case, with U set to 0.16 $Wm^{-2}K^{-1}$, the thickness of the cellulose fibre from the literature was reduced by 29.4%. Table 3 in Appendix A.2 lists all materials used for this type of construction.

The amount of insulation in the concrete roof was recalculated in the same manner. The original heat transport constant of the roof from the reference building *mfh09* is 0.19 $Wm^{-2}K^{-1}$ which is less insulated than the sandwich panel. In order to get a similar heat transport constant for this reference roof, the amount of polyurethane foam insulation – with $k = 0.03 Wm^{-1}K^{-1}$ – was increased. Equation 1 was used to calculate that 34.0% extra polyurethane foam was needed. Table 5 in Appendix A.3 lists all materials used for this type of construction.

Two different types of photovoltaic modules are assessed in this study, both consisting of monocrystalline silicon. For the retrofitted panel constructions, a reference solar cell from the EcoInvent database is used and it is assumed to be manufactured in Germany. Material data for the solar panel comes from a 2009 report by Stoppato [6]. The aluminium used in the panels is assumed to be 25% virgin material and 75% recycled aluminium, which is the ratio of primary production of aluminium and the total use of aluminium in the EU [39].

For the sandwich panel, another type of solar cell is studied. The reason for this is that there is no need for a covering glass on top of the sandwich panel, so instead another type of solar cell may be used, with an additional top layer of ethylene tetrafluoroethylene and ethylene vinyl acetate in order to protect the solar cells from outer climate strain. The PV module studied in the sandwich case is the Helis model manufactured by the Austrian company Sunplugged. Specific material data for the Helis model, see Table 2 in Appendix A.1, is therefore used in the sandwich case.

2.3 System boundaries and assumptions

2.3.1 Geographical boundaries

The geographical boundary of the study is limited to Sweden but will also include the production of some components in other countries and the transport of these components to the building site in Sweden.

Since this is an attributional LCA, an average electricity mix is going to be used rather than a marginal one. The manufacturer of the solar sandwich is Swedish and the results are mainly to be applied in southern Sweden. As a result of this, the current Swedish electricity mix is going to be used in the calculations – unless for the case of components or materials produced in other countries and imported to Sweden.

2.3.2 Technical boundaries

Environmental impacts for producing capital goods, such as production facilities, and also transport vehicles are excluded. Electrical components in the solar panels, such as cables and inverters, are also excluded. Environmental impact from construction labour is excluded.

2.3.3 Time horizon

The time horizon of this LCA is set to 50 years, since many researchers have used the same time horizon in other building-related LCAs [40–42].

2.3.4 Assumptions

The lifetime of a solar cell is usually 25 years, which means replacement of them will be included in all cases [43]. The waste management of solar cells is outside the scope of this study. There is some small-scale recycling going on, i.e. PV Cycle who are accepting all commercially available PV technologies, both silicon and non-silicon [44]. However, the recycling of PV modules is a young industry and currently there is no environmental data available. The situation will likely be entirely different in 25 years, when the amounts of PV waste will be many times greater than today, and assumptions on how these procedures will work would only weaken the validity of this study.

There is no data available on the lifetime of the sandwich panel but in this study it is assumed to have a lifetime longer than the time horizon, which is 50 years. Theoretically, as it is a structure totally encapsulated in solid reinforced polyester, this should be a valid assumption and as long as there is no serious mechanical damage to the roof it should not have to be replaced. However, a sensitivity analysis will be performed for a scenario where the entire roof has to be replaced once during the time horizon of the study. In the calculations, the polyurethane glue used in the sandwich construction is replaced with a rigid polyurethane foam. The same assumption has been made in other LCAs [45].

Apart from the aluminium in the retro-fitted solar panels, no recycling of any material has been taken into account in this study. Combustible materials are assumed to be incinerated at the end of their lifespan and non-combustible materials are assumed to be deposited at landfill sites. The reasoning behind this is that while roofing tiles in Sweden sometimes are collected and reused, most often they are deposited into landfills. This goes for both clay and concrete tiles. All waste flows are assumed to be transported 100 km by lorry.

The clay tile and concrete tile are assumed to have a life time of 65 years and 40 years, respectively, meaning that the concrete tiles will have to be replaced during the time scope of this study [46–48]. In both cases, 5% of the tiles are assumed to be replaced in ten-year intervals due to maintenance and replacement of damaged tiles [49].

For the solar panels, an ideal fitting scenario is assumed. This means that the maximal theoretical solar cell coverage per roof area is used in the calculations. In a real scenario, this would not be possible due to limitations in the dimensions of the roof compared to the size of the solar modules. This is true especially for the retro-fitted solutions which consist of panels of a certain given size that would have limited fitting options. With the integrated sandwich panel it would be easier to utilize as much of the roof as possible since the fitting would depend on the size of the individual solar cells.

2.4 Impact categories and method of impact assessment

This section describes the impact categories to be investigated in this study. These impact categories are global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), land use and stratospheric ozone depletion potential (SODP). These impacts were chosen because they represent a broad range of important impacts and they were also used by other authors, see section 1.2. The different impacts are calculated using the life cycle impact assessment method CML 2001 in openLCA. No normalization or weighting will be performed on the results of the impact analysis. Below follows brief descriptions of the impact categories considered in this study, as well as reasons for considering them.

- Global warming potential, GWP, is a global impact category which describes the total effect on climate change during the life cycle. Since different substances have different effects on global warming, GWP is measured in total amounts of CO_2 equivalents emitted. Climate change is usually considered to be one of the most important – if not the single most important – environmental impacts.
- Acidification potential, AP, is a site-specific impact category which quantifies the total acid air emissions in SO_2 equivalents. It is an important impact category to consider along with GWP, as life cycles with similar GWP impact may have drastically different effects on acidification [31].
- Human toxicity potential, HTP, is a site-specific impact category that shows the air emissions of toxic substances to human environments. Heavy metal air emissions are especially large contributors to this impact category. HTP is usually considered in LCAs on energy systems as materials and fuels involved in energy production systems often have toxic residuary products associated with them.
- Land use shows the occupation of land in an area under a certain period of time. As decribed in Section 1.2, previous studies on solar energy have studied this impact category but it is far more relevant and important when conducting LCAs on agricultural products or wood, which is commonly used as a building material in Sweden.
- Stratospheric ozone depletion potential, SODP, is a global impact category which described the potential depletion of the ozone layer. Other studies on solar energy has included this impact category and it is especially relevant in this study as potent fluorocarbons are used in the coating of the solar cells used in the sandwich panel.

2.5 Allocation

In contrast to physical allocation, economic allocation is universally applicable and always relevant [50]. The reason for choosing allocation over system expansion is that this is a comparative attributional LCA that aims to account for all environmental impacts as completely as possible. While system expansion is sometimes used in attributional LCAs, it is more relevant when conducting consequential LCAs, i.e. studying the consequences of changes in a process or a product [15].

There was no need of allocation in the solar sandwich scenario since no processes are producing more than one output, except for processes in EcoInvent 2.2, where the standard allocation settings for each process were used.

2.6 CO_2 return time

In order to link the results of this study to similar studies, a CO_2 return time is calculated. The CO_2 return time is a common way of estimating a so called environmental payback time and a good way of putting the results of an LCA of an energy system into context. Environmental payback times may be calculated on different bases, e.g. cumulative energy use or a certain emission type during a product's lifetime, in this case CO_2 emissions. The CO_2 return time is the time it takes for the existing electricity production system to produce the amount of greenhouse gases emitted during the entire lifetime of the energy system studied [4, 21, 32]. A system expansion is applied in order to estimate the CO_2 return time – this means that the renewable electricity production from the different cases in this study is assumed to substitute the marginal electricity production. Marginal electricity production in Sweden is assumed to come from coal-fired power plants [51].

The deterioration of electric production capacity of the solar cells is considered in the calculations of the CO_2 return time. In these calculations an assumption is made that the electrical production capacity of the solar cells will decline linearly to 80% after 25 years, after which they are decommissioned and replaced. This assumption is based on the fact that solar cell manufacturers usually guarantee 80% of the original capacity after using the solar cells for 25 years. This is a common assumption in LCAs on photovoltaics [5, 52]. Different types of monocrystalline silicon solar cells might have slightly different decline rates but no data on this is available, so the same assumption has been made for both types of solar cells studied.

2.7 Sensitivity analyses

A number of sensitivity analyses will be performed in order to see how some different scenarios would alter the results. In the first sensitivity analysis the entire sandwich roof is replaced, due to mechanical damages or some other reason, which means that the amount of materials needed to fulfil the sandwich panel's function will be doubled.

The second sensitivity analysis examines the impact from a 10% larger roof area in the clay and concrete cases. The amount of solar panels and solar cells are still the same, however. This is done because an ideal fitting scenario is assumed, i.e. the maximal amount of solar panels possible are assumed to be mounted on the roofs with no regard to limitations in panel fitting due to their size, which is 1.63 m^2. The reason for not increasing the roof area in the sandwich case is because the fitting of solar modules is limited by the solar cell size, which is $1.56*10^{-2}m^2$ for the Helis module, and not by the solar panel size.

The third sensitivity analysis examines the impact from double electricity use in the production of the Helis solar cells, which are used in the sandwich case. This production phase consists of the combination of the monocrystalline solar cells with the other materials used.

The current electricity use is based on a generic lamination process and this sensitivity analysis is intended to give an idea of the effects of a higher electricity use.

The fourth sensitivity analysis is conducted in order to study the effects of longer lifetime for the solar cells, more specifically how it affects the amount of CO_2-equivalents per kWh. As described in Section 2.3.4, the lifetime for the solar cells is assumed to be 25 years which is a common warranty time provided by manufacturers. The practical lifetime might be longer, however, so it is relevant to know how the results are affected by a solar cell lifetime of 30 years. As assumed earlier the decline of solar cell efficiency is considered linear, decreasing from 100% to 80% in 25 years and continuing to decline with the same rate until being replaced after 30 years of use.

3 Inventory analysis

This section describes the different life cycle inventories that are the basis of the calculation of environmental impact.

3.1 Solar sandwich

This section contains the components and processes included in the solar sandwich. There are two main components – the sandwich panel and the solar cells.

3.1.1 Sandwich panel

This section contains the different processes and materials involved in the life cycle of the sandwich construction, which consists of an EPS core with outer layers of glass fibre-reinforced polyester. The raw materials for polystyrene are crude oil and natural gas. The crude oil is refined to naphtha which is processed with natural gas into ethylene in a steam cracking facility. Benzene – which is produced from naphtha and some steam cracking products – and ethylene are synthesized into ethylbenzene. Styrene is then produced by catalytic dehydrogenation of the ethylbenzene, and polymerized into polystyrene. In order to get a foam structure, a blowing agent is added.

For this type of sandwich roof with a span of six meters and an angle of 40-50 °, no underlying supporting structure or roof truss is needed. Figure 5 shows the different processes involved in the production of a sandwich roof.

Data on electricity use in the production comes from the manufacturer, Kenpo Sandwich AB. Their yearly energy consumption is 176 MWh from burning natural gas and 332 MWh from the electric grid [53]. The energy use divided on the 91 500 m^2 of different sandwich panels they produce each year gives an average of 1.92 kWh from natural gas and 3.63 kWh from the electric grid per m^2 of panel. Table 1 in Appendix A.1 lists the materials included in the complete sandwich roof construction. This inventory includes the changing of the solar cells twice during the time horizon of this study.

3.1.2 Solar cell production

Two different types of photovoltaic modules are assessed in this study, both consisting of monocrystalline silicon. Figure 6 shows the different processes involved in the production of a monocrystalline solar cell. Quartz is mined and purified into high-quality silicon (>99.9999% purity) which is then cast into ingots, processed into wafers and assembled into solar cells [29].

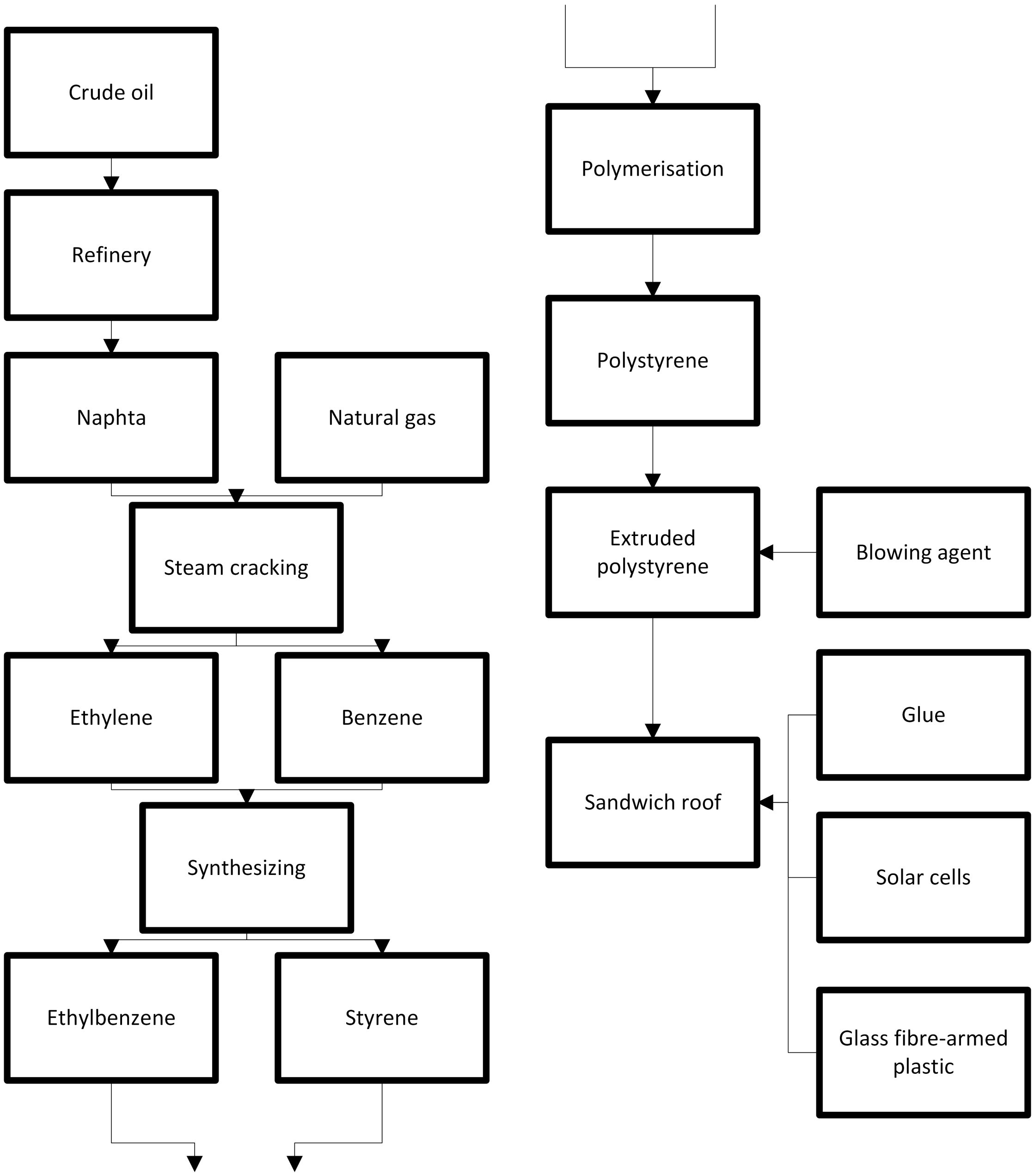

Figure 5: Flowchart of sandwich roof production.

For the sandwich panel, the Helis model manufactured by the Austrian company Sunplugged is used as the PV module. The reason for this is that there is no need for a covering glass on top of the sandwich panel. It has an additional top layer of ethylene tetrafluoroethylene and ethylene vinyl acetate in order to protect the solar cells from the outer climate. The energy use in this coating process has been approximated to 27.3 kWh/kW, based on other

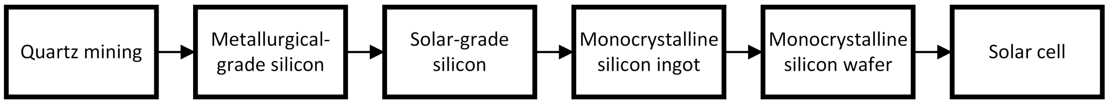

Figure 6: Flowchart of solar cell production.

lamination processes in photovoltaics [29].

The solar cells are glued on to the sandwich material with a 5 mm separation between them in sections of up to 20 m^2. There is also an additional 5 mm separation in between these sections. Since the Helis solar cell is 125x125 mm, $16.9 * 10^{-3}$ m^2 is needed per cell on the sandwich material with the 5 mm separation space added. When also including the separation between sections a total area of $17 * 10^{-3}$ m^2 is needed per cell. In total, this means a 92% of the roof surface is covered by solar cells in this case.

Table 2 in Appendix A shows the materials that are included in a 125x125 mm Helis module. The total thickness of the module is 2.5 mm, leading to less material use in comparison with conventional modules which usually are thicker. The peak capacity of one cell is 3.19 W [54]. In the case of the sandwich panel, the solar cells are glued on top of the panel surface which acts as a supporting structure, eliminating the need for aluminium panels with tempered glass.

The solar wafers are assumed to weigh 7 grams per 100 cm^2 [55]. This gives a total wafer weight of 3.42 kg per kW and a total solar cell weight of 27 kg per kW for the Helis modules. This amount is assumed to be transported 2000 km by freight train, from Austria to Gothenburg, and 100 km by lorry to the construction site.

3.2 Clay tile roof

This section contains the components and processes included in the clay tile roof. The main components are the roof, the solar panels and the solar cells. The roof comprises of an underlying construction, insulation and roof tiles.

3.2.1 Roof

In this scenario, the outer roof consists of clay tiles mounted on a wood structure. Stone wool and cellulose fibre are used as insulation. To create clay tiles, the first step is extraction of clay. It is then put into a storage where it is also mixed. The mixing is occuring when new clay is added as well as when clay is taken out to be used in the stone crushing, which is the next process. The stone crushing gets rid of eventual remaining stones in the clay. After the crushing the clay is pressed and then dried for two days. The final step for the clay is to be put in a tunnel kiln, which is divided into three zones: preheating, heating and cooling [47]. Figure 7 shows the different processes involved in the production of clay tiles.

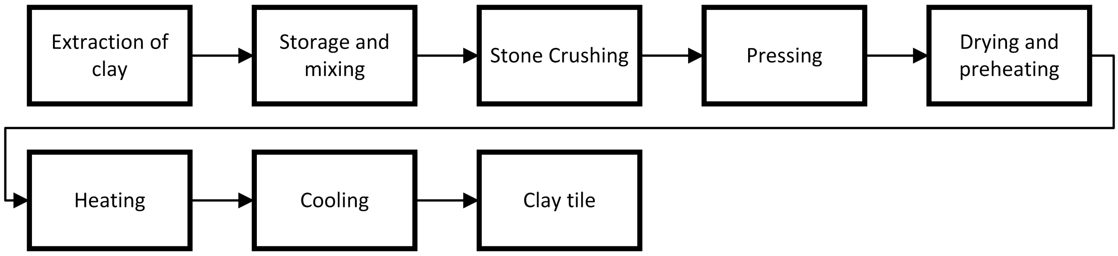

Figure 7: Flowchart of clay tile production.

In the literature, the reference building *mfh09* has fibre cement roof tiles which in this study were changed to clay tiles, which are more common in Sweden. No other alteration of the data was done, as the changing of roof tiling was assumed to have no effect on the underlying construction.

Typically, one square meter of clay tiles on a roof weighs 30 kg [56]. Table 3 in Appendix A.2 lists all material used in this type of construction. In the replacement phase, all materials except the roof tiles are replaced after 30 years [10]. The roof tiles have a longer lifetime but every ten years, 5% of the tiles are assumed to be replaced due to damages [49].

3.2.2 Solar panel production

A typical solar panel consists of assembled solar cells mounted on a supporting structure. Figure 8 shows the different processes involved in the production of a solar panel. To assemble solar cells onto solar panels, the first step is to solder solar cells with the same characteristics in series [57]. A five layered sandwich structure is then put together. It is made of interconnected solar cells in the middle, covered by layers of ethylene vinyl acetate (EVA) on the top and bottom, a top layer of tempered low iron glass and a back sheet at the bottom. It is finally laminated for protective measures of the solar cells against moisture and mechanical damage. In order for long-term stability, the EVA seals the module through a process called curing, where they are preheated, heated and cooled. The final step is corrosion-resistant framing, usually made of aluminium.

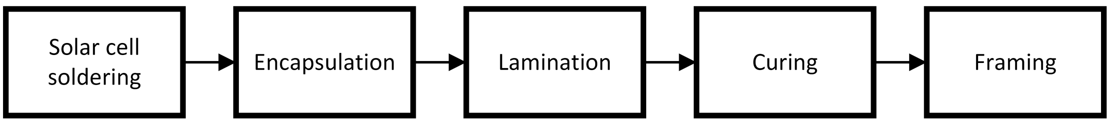

Figure 8: Flowchart of solar panel production.

In an article by Stoppato, the materials used in the production of a typical retrofitted solar panel is described [6]. Table 4 in Appendix A shows this data scaled up to 1 kW.

The most sold solar panel in the world is the Sharp NU-U235F1 [58, 59]. It is used as a reference when it comes to how much space the solar cells need in the retro-fitted scenario. It has a total area of 1.63 m^2. The panel includes 60 solar cells, which means each cell is using an area of $27 * 10^{-3}$ m^2. Each solar cell is 150x150 mm, which means that the extra space needed per solar cell is $4.7 * 10^{-3}$ m^2. The conclusion of this is that 83% of the roof surface may be filled with solar cells in the ideal case. The panel's total capacity is 235 W_p and divided by its 60 solar cells that means a capacity of 3.9 W_p per cell. As each cell uses $27 * 10^{-3}$ m^2 this means that one kW_p of solar panel uses 6.9 m^2 of roof area, compared to the 5.3 m^2 per kW_p in the sandwich case.

3.2.3 Solar cell production

For the retrofitted panel constructions, a reference solar cell from the EcoInvent database is used. It is assumed to be manufactured in Germany and transported 1000 km via freight train to Gothenburg, and 100 km by lorry to the construction site. See Figure 6 for a flowchart of the solar cell production.

3.3 Concrete tile roof

This section contains the components and processes included in the concrete tile roof. The main components are the roof, the solar panels and the solar cells. The roof comprises of an underlying construction, insulation and roof tiles.

3.3.1 Roof

In this scenario, the outer roof consists of concrete tiles mounted on an underlying concrete structure. Polyurethane foam is used as insulation. Figure 9 shows the different processes involved in the production of concrete tiles. Concrete is mainly made out of about 75% sand, 20% cement and 5% iron oxide [47]. To create the cement which acts as a binder in concrete, limestone is mined, heated up and then ground with about 5% gypsum. The cement is mixed with sand, water and iron oxide to create concrete. The iron oxide is used to give the concrete its color and can be made either from virgin iron ore or by oxidizing scrap iron with high enough quality. The concrete is finally poured into shapes made of aluminium to make concrete tiles. One square meter of concrete tiles placed on a roof typically weighs 41 kg [60]. Table 5 in Appendix A.3 lists all material used in this type of construction.

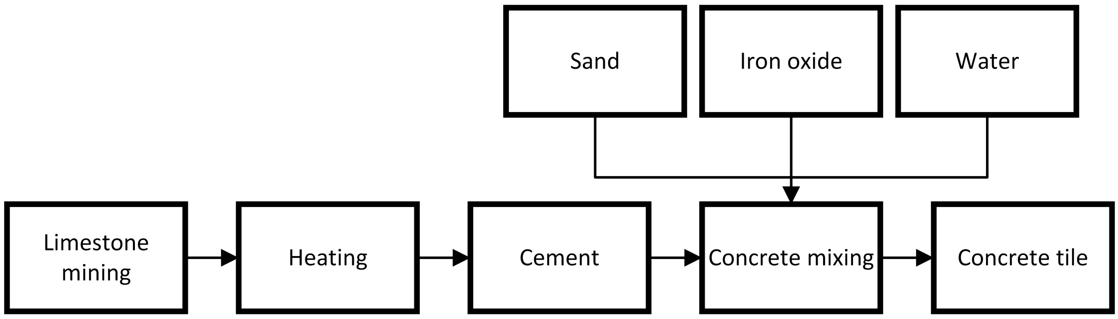

Figure 9: Flowchart of concrete tile production.

3.3.2 Solar panel production

This scenario uses the same solar panels as the clay tile roof. For a detailed description, see Section 3.2.2.

3.3.3 Solar cell production

This scenario uses the same solar cells as the clay tile roof. For a detailed description, see Section 3.2.3.

3.4 CO_2 return time

A monocrystalline silicon solar cell typically has an sunlight-to-electricity conversion efficiency of 14 % [32]. Furthermore, a roof-mounted 1 kW_p solar panel in Sweden, aligned to the south with a 30-50° angle towards the sun will produce about 950 kWh per year at its peak capacity [61]. This corresponds to a total capacity factor of 10.85%, i.e. a solar panel under the described conditions will produce 10.85% of its peak production capacity. In other words, a 1 kW_p panel will produce an average of 108.5 W over the course of a year. With a capacity loss of 20% in 25 years, the total amount of energy produced from a panel is 21375 kWh, assuming that the capacity loss is linear. The process *electricity, hard coal, at power plant (NORDEL)* in EcoInvent 2.2 yields a total of 965 g $CO_{2,eq}/kWh$.

3.5 Total energy output

As estimated in Section 3.4, the total energy output of 1 kW of solar cells in southern Sweden is 21375 kWh during 25 years. The total energy output of this system with respect to the time boundaries is therefore 42750 kWh, as two sets of solar cells will produce their maximal lifetime energy output and the third set of solar cells are installed at the end of the time horizon and will not produce any energy within this system. This amount of energy is used in the calculations of amount of CO_2-equivalents per kWh in the impact assessment. For the sensitivity analysis on longer solar cell lifetime the total energy output was calculated in the same manner to 42560 kWh, which is only 0.5% less than in the original scenario.

4 Results and discussion

In this section the emissions associated with the different processes in the inventory analysis are assessed and aggregated into impact categories. The results are then discussed and where similar literature is available they are also compared with the literature values in order to put the results in context. The impact categories studied are GWP, AP, HTP, land use and SODP. Each subsection describes one environmental impact category. The three scenarios studied – the solar sandwich construction, the clay tile roof with retro-fitted solar panels and the concrete tile roof with retro-fitted solar panels – are denoted *sandwich*, *clay* and *concrete* in the figures. Furthermore, the results from the sensitivity analyses are presented, as well as the CO_2 return times for all cases.

4.1 Global warming potential

The results from the calculations of total global warming potential from the three scenarios studied are shown in Figure 10.

Figure 10 shows that the GWP is lowest for the sandwich panel – although the clay tile roof has a mere 6.7% higher GWP – and highest for the concrete tile roof by a wide margin. The biggest contributors to the GWP are the solar cells, as well as the roof in the concrete case. In the sandwich case and the clay case, the roofs have impacts of roughly 640 and 720 kg of CO_2 equivalents per kW_p, respectively. In comparison with the solar cells, this is relatively small number although still significant and with room for improvement. As expected, the impacts from transports are low in comparison with the other parts of the inventory.

The Helis solar cells have a higher electricity output per cell than the solar cells used in the other two cases, leading to a smaller amount of solar cells per kW. In spite of this, the global warming potential impact is larger from the solar cells in the sandwich case than in the other two cases and the reason for this is the additional environmental impact from the extra materials used in the coating of the Helis modules.

The EPS core of the sandwich panel stands for 141 kg CO_2 equivalents, or roughly 4% of the solar sandwich's total GWP. This is less than anticipated but the glass-fibre armed plastic stands for 11% of the GWP, on the other hand. Ideally, as much of the sandwich panel as possible should be produced with recycled materials in order to lower the GWP.

Dividing the total GWP impacts from Figure 10 with the total energy output of 42750 kWh, as described in Section 3.4, gives average emissions of 94 g CO_2/kWh for the entire system in the sandwich case. The corresponding values from the clay and concrete cases are 100 and 161 CO_2/kWh, respectively. Comparing these values to the results of other studies, see Table 1, they are within the same interval. Important to note is that there are some differences in scope, regarding both physical system boundaries such as roof inclusion and time boundaries between this study and the comparative studies.

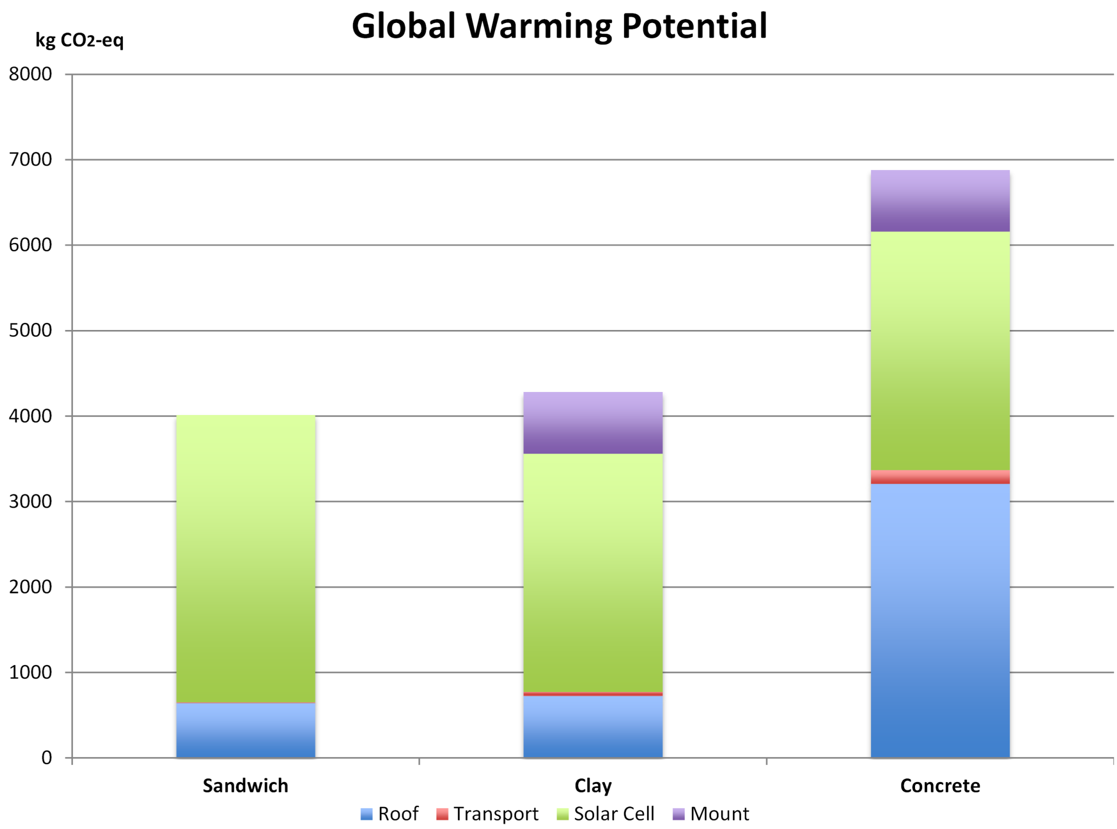

Figure 10: The total global warming potential, in kg CO_2-equivalents, per 1 kW_p for the three scenarios.

4.2 Acidification potential

The results from the calculations of total acidification potential from the three scenarios studied are shown in Figure 11.

As shown in Figure 11, the sandwich case has the lowest AP with 11.6 kg of SO_2 equivalents per kW_p. It is followed by the clay tile roof which has 17.9 kg of SO_2 equivalents per kW_p, meaning an increase of 54%. The solar cells have the biggest impact on AP in all cases. In contrast to GWP, the Helis solar cells now have about the same impact as the other two cases, meaning the extra materials included are not as potent to AP as GWP.

There are also significant impacts from the roofs, especially in the concrete case, as well as the solar mounts. The contribution from the transport is almost negligible in all cases except the concrete tile roof where it accounts for 3.6%, since there are many heavy loads to be transported. However, it is hard to quantify the actual effects from this impact category, since the effects are local and perhaps not in the vicinity of rural regions or sensitive ecosystems.

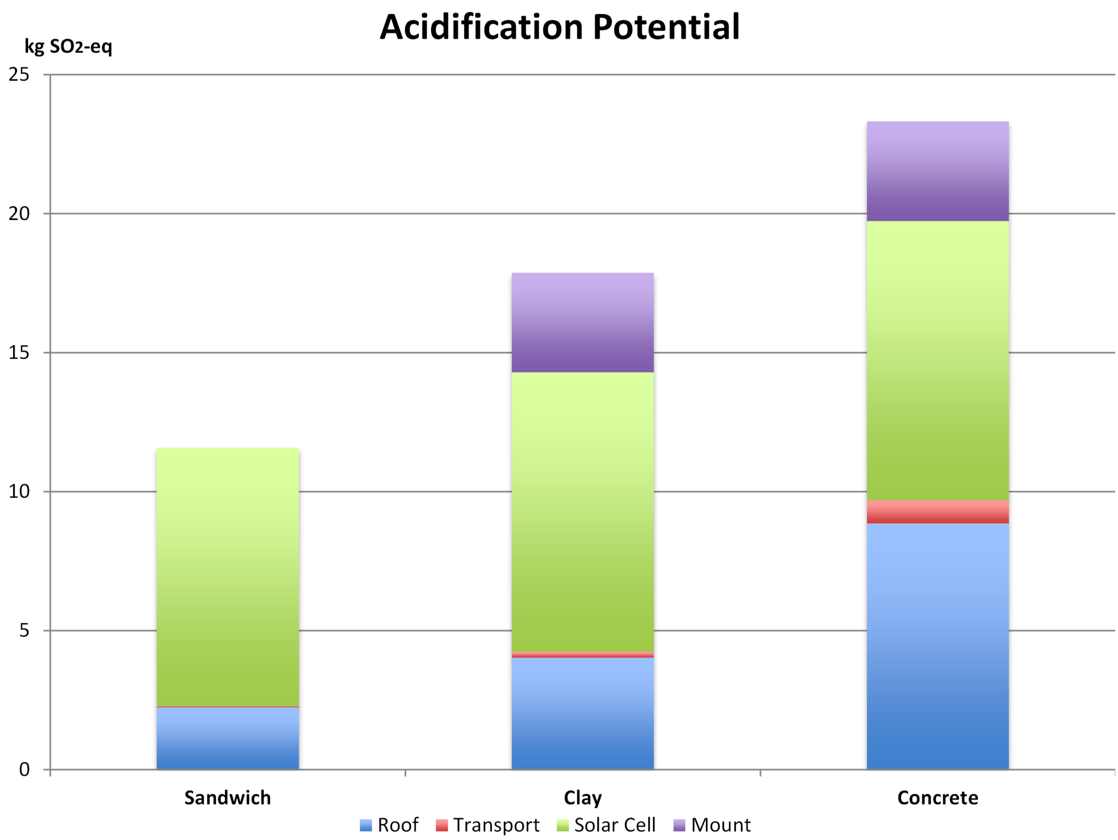

Figure 11: The total acidification potential per 1 kW_p for the three scenarios.

Dividing the total AP impacts from Figure 11 with the total energy output of 42750 kWh, gives average emissions of $2.7 * 10^{-1}$, $4.2 * 10^{-1}$ and $5.5 * 10^{-1}$ g of SO_2-equivalents for the sandwich, clay and concrete case, respectively. These values are reasonable when compared to the values estimated by Turconi et al. which were in the interval of $2.2*10^{-1}$ to $5.7*10^{-1}$ kg of SO_2 equivalents per kWh [31]. The values from this study are in the high end of that interval, but this is expected as all three sets of solar cells do not produce their entire lifetime energy output during the time horizon of this study. Furthermore, the AP impacts from the roofs have significant contributions to the total impact in all three cases.

4.3 Human toxicity potential

The results from the calculations of total human toxicity potential from the three scenarios studied are shown in Figure 12.

Figure 12 shows that once again the sandwich case has the lowest impact to HTP. Apart from

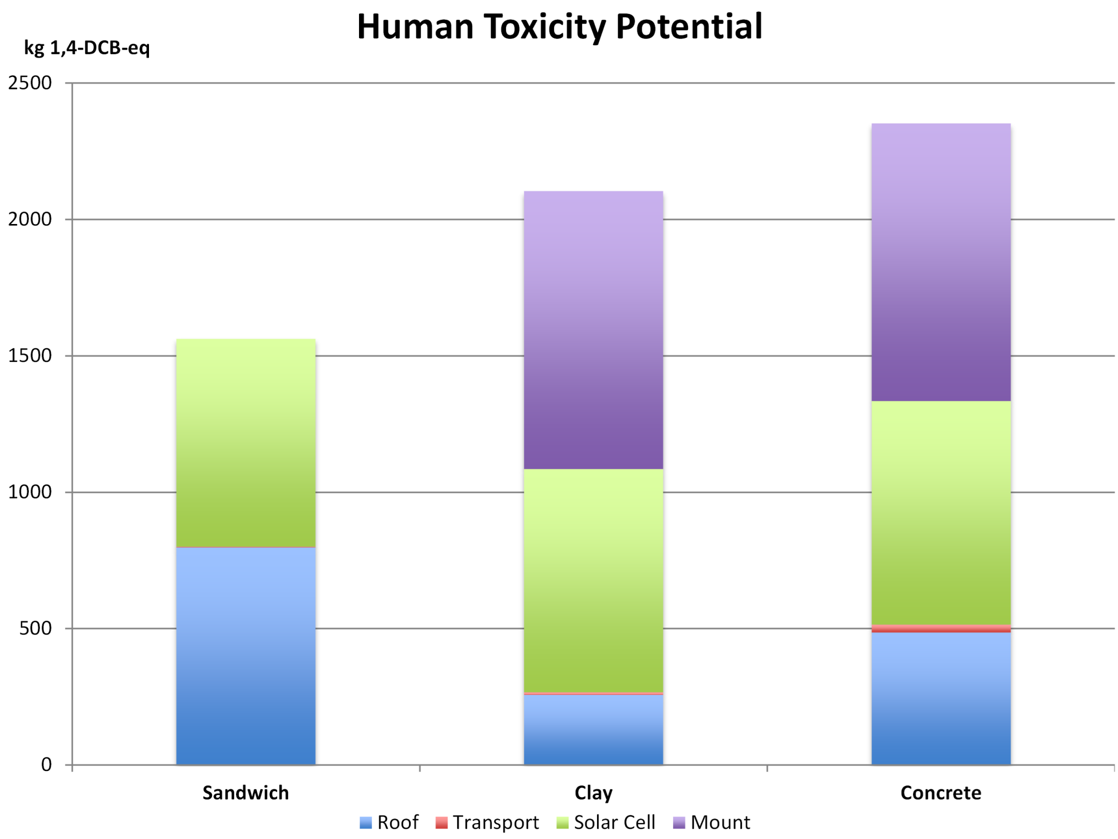

Figure 12: The total human toxicity potential per 1 kW_p for the three scenarios.

large contribution from the solar cells, there are also significant contributions to HTP from the sandwich roof and from the solar mounts. For the solar cells, most of the impact comes from Chromium VI. In the sandwich roof, which accounts for 51% of the total impact, the largest contributing process is the glass fibre reinforced plastic, which stands for 98.1% of the roof's total impact.

Lastly, the solar mounts stand for 48.4% and 43.3% of the total impact to HTP in the clay tile roof and concrete tile roof respectively. This is mostly due to the primary aluminium and the aluminium product manufacturing which together account for 82.2% of the solar mounts total impact.

Looking at Figure 10, Figure 11 and Figure 12, there is a pattern in the proportions of the impacts of the three cases in GWP, AP and HTP. The reason for this is the linkage between energy use and these impact categories. There are some differences in proportions between the different cases – for instance the solar mounts as well as the sandwich panel have large contributions to HTP, as discussed earlier, but there is a clear connection between energy use, GWP, AP and HTP in contrast to the impacts from land use and SODP which show no such correlation.

4.4 Land use

The results from the calculations of total land use from the three scenarios studied are shown in Figure 13.

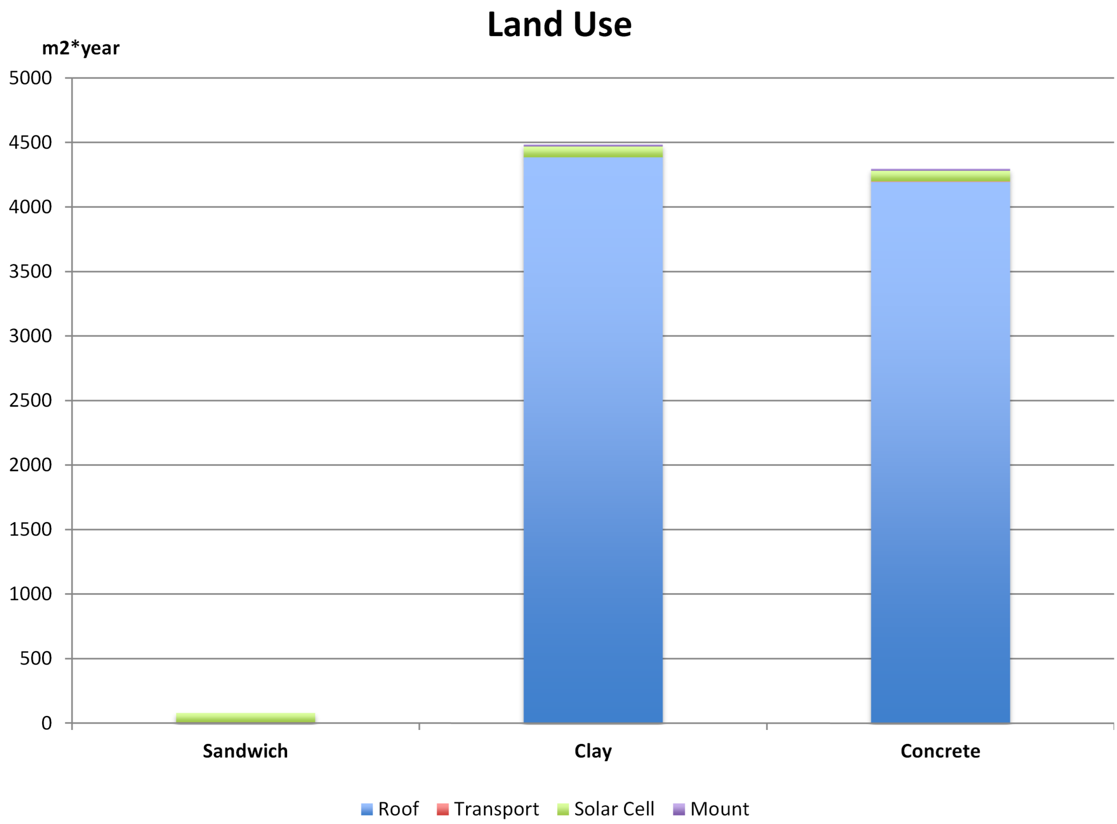

Figure 13: The total land use, in $m^2 * year$, per 1 kW_p for the three scenarios.

As shown in Figure 13, the clay and concrete cases have much larger land use impact than the sandwich case. This high impact comes almost entirely from the roof and it is an expected result, as the roof constructions in the clay and concrete cases contain large amounts of wood. In spite of the large differences between the sandwich case and the clay and concrete cases, this is not considered a problematic outcome as wood is a renewable resource which is abundant in Sweden. If the geographical boundary was to change to another country with less area and forests than Sweden, this difference in land use could become important and the sandwich case may be proven to be a better choice.

4.5 Stratospheric ozone depletion potential

The results from the calculations of total stratospheric ozone depletion potential from the three scenarios studied are shown in Figure 14.

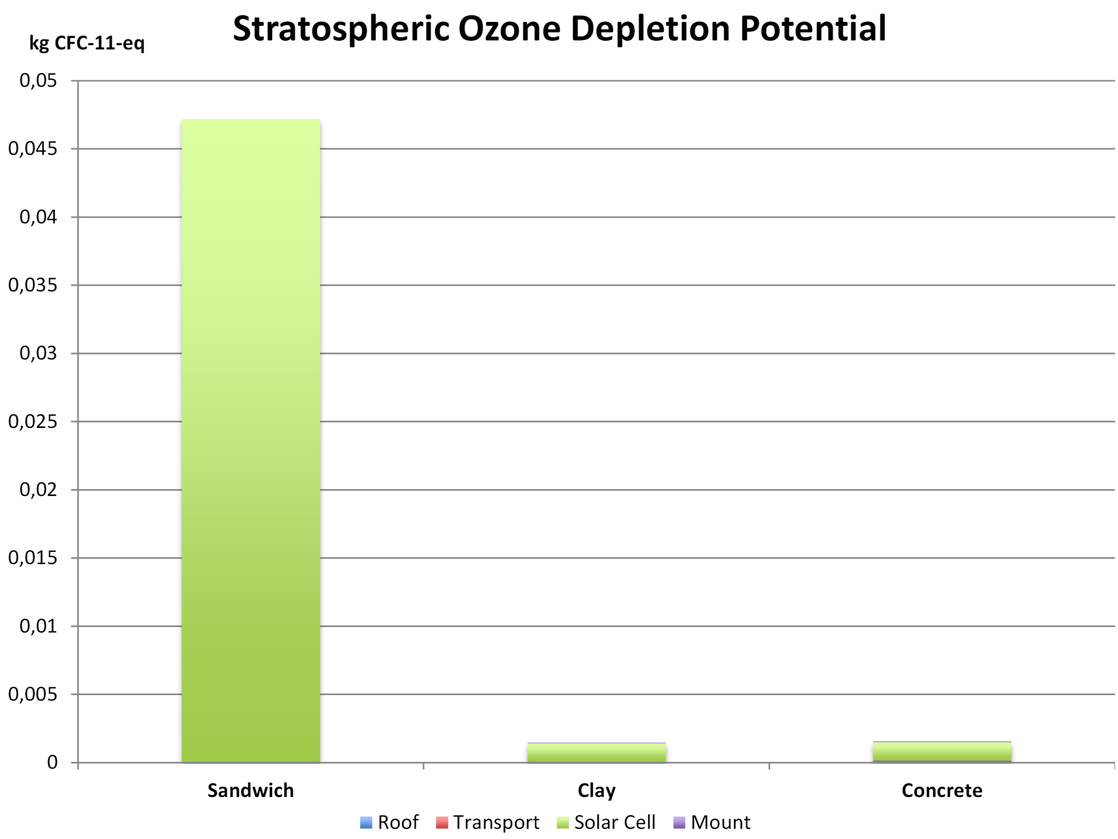

Figure 14: The total stratospheric ozone depletion potential, in kg of CFC-11 equivalents, per 1 kW_p for the three scenarios.

It is clear from Figure 14 that the solar cell is the only contributor to the SODP in all scenarios. The reason for the sandwich case having the significantly largest impact, around 47 mg CFC-11-eq per kW_p, compared to 1.3 mg in the other cases is because the Helis model uses a tetrafluoroethylene film as the front coating on its module. This material accounts for 97.6% of the impact to SODP. If the Helis solar cell could substitute its front coating material with another substance, this impact could reduce drastically.

4.6 Sensitivity analyses

The results presented in this section are limited to global warming potential. However, the results for all impact categories is available in Appendix B.

4.6.1 Sandwich replacement

As mentioned in section 2.7, the first sensitivity analysis is made on replacing the sandwich panel materials once during the full life cycle. The new scenario included is denoted *sandwich replacement*.

The results from the calculations of total global warming potential from the sensitivity analysis are shown in Figure 15.

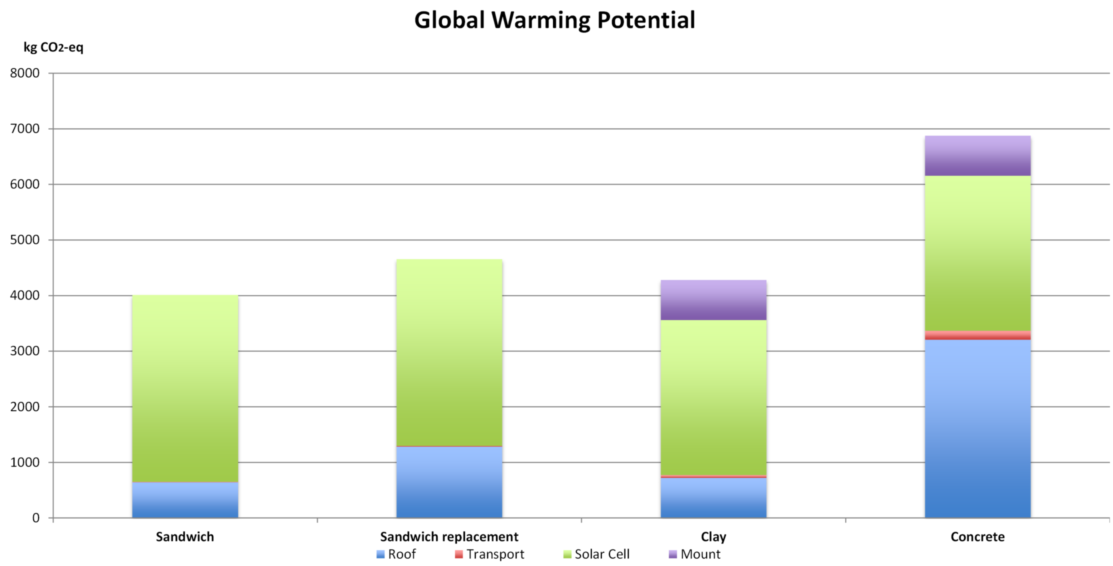

Figure 15: The total global warming potential, in kg CO_2-equivalents, per 1 kW_p for the four scenarios.

Figure 15 shows the impacts from replacing the entire sandwich roof once during the time scope of this study. The sandwich roof did not have a very large impact on GWP compared to the solar cells in the original scenario, and the effect is, that the GWP impact from the roof is doubled during the life time of this study in this analysis. This results in the sandwich replacement scenario having about 8.7% more impact on GWP than the clay tile roof but still has less impact than the concrete tile roof.

4.6.2 Imperfect panel fitting

In this sensitivity analysis, the clay roof and concrete roof use 10% more materials due to imperfect panel fitting.

The results from the calculations of total global warming potential from the sensitivity analysis are shown in Figure 16.

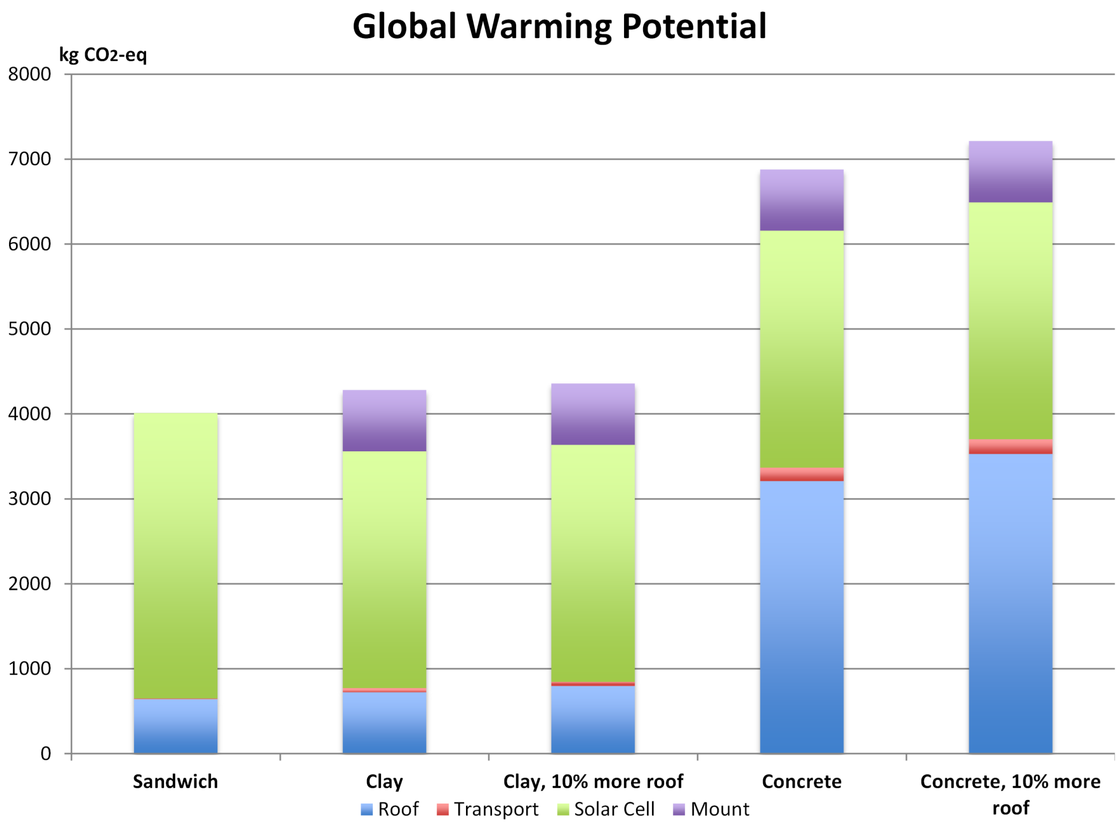

Figure 16: The total global warming potential, in kg CO_2-equivalents, per 1 kW_p for the five scenarios in the imperfect panel fitting analysis.

The effects from the imperfect panel fitting scenario is illustrated in Figure 16. Using 10% more roof area for the solar panels increases the impact from the roofs with 10%. In the big perspective, meaning looking at the total environmental impact of the clay scenario, this does not have a large impact where the total GWP is increased by 1.8%. The impact is significantly higher in the concrete case where the roof is a major part of the total impact. In this case the imperfect panel fitting contributed to a total GWP increase of 4.9%.

4.6.3 Different lamination technique

This sensitivity analysis examines the effect of doubling the electricity use during the coating of Helis solar cells.

The results from the calculations of total global warming potential from the sensitivity analysis are shown in Figure 17.

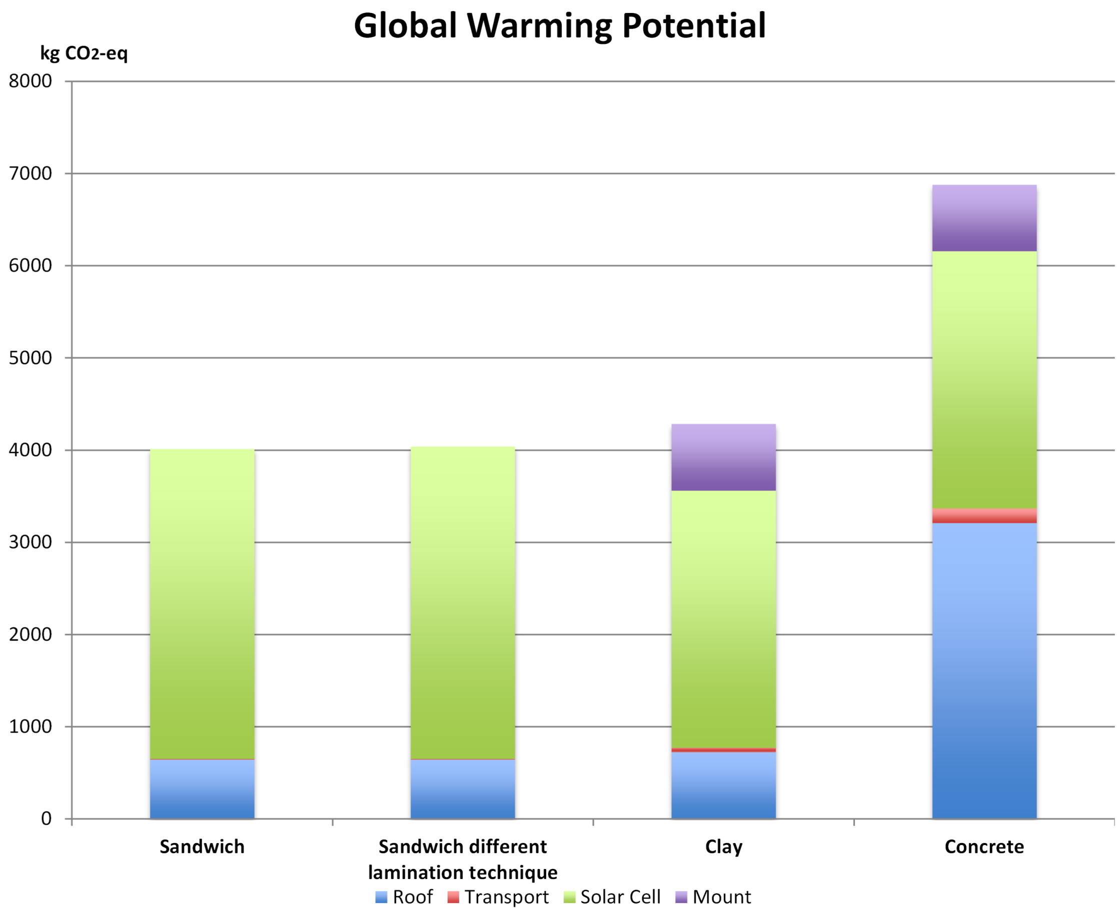

Figure 17: The total global warming potential, in kg CO_2-equivalents, per 1 kW_p for the four scenarios in the different lamination technique analysis.

As shown in Figure 17, the effect from doubling the electricity use in the coating of the Helis solar cells was an increase in GWP with 0.7%. In comparison with the entire system, this is a very small increase that does not affect the results. The result of this is that if there is a need for changing the coating technique, this impact can possibly be regarded as negligible.

4.6.4 Longer PV lifetime

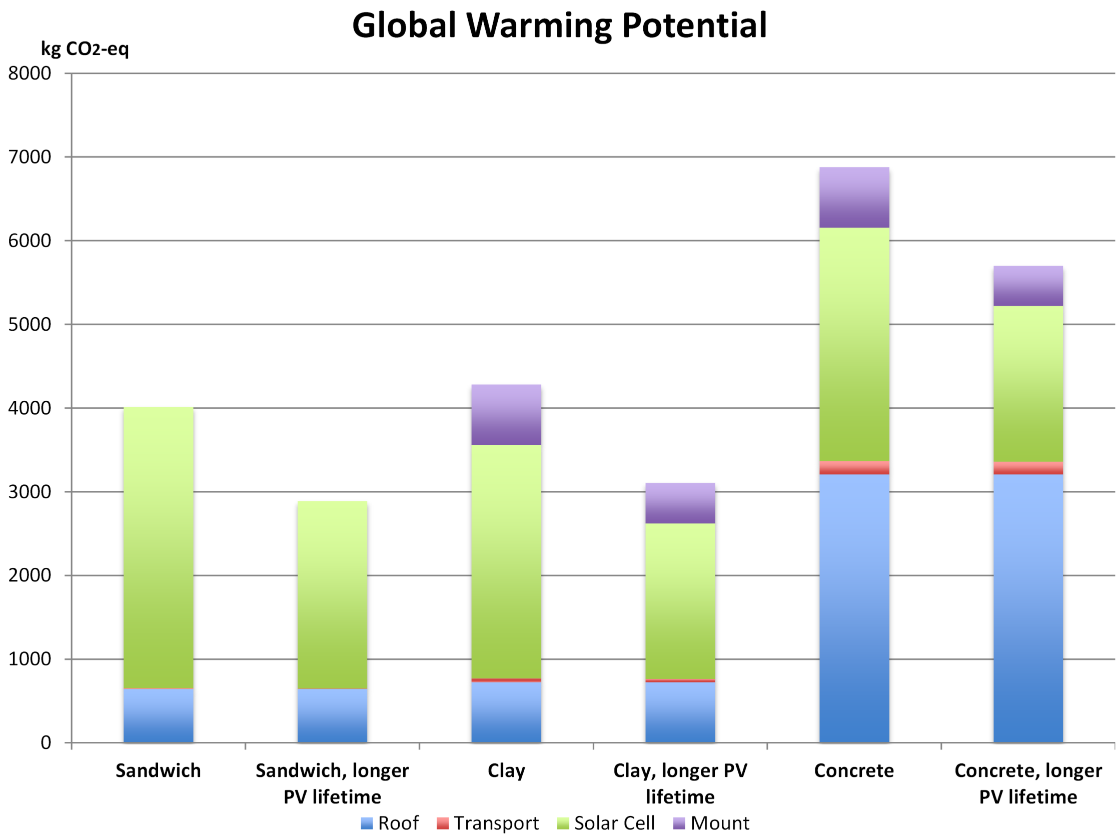

Figure 18: The total global warming potential, in kg CO_2-equivalents, per 1 kW_p for the six scenarios in the longer PV lifetime analysis.

This would also lead to less total electricity output when the electrical production capacity continues to decline after 25 years. The effects of this would be higher emission values per kWh produced but since the system's total environmental impact would be significantly lower, due to less solar cells being involved, the final results would likely be lower than the values shown in Section 4.1. On the other hand, if the time horizon was set to 60 years, which is not uncommon in building-related LCAs, there would still be three sets of solar cells involved. This shows a drawback in doing an LCA on two components with significantly different lifetimes, as small alterations in scope might.

4.7 CO_2 return time

The calculated CO_2 return times for the original scenario as well as the four sensitivity analyses are shown in Table 4.

Table 4: The CO_2 return times, in years, calculated for the original scenario as well as the four sensitivity analyses.

Scenario	Sandwich	Clay	Concrete
Original	4.9	5.2	8.3
Sandwich replacement	5.6	–	–
Imperfect panel fitting	–	5.3	8.7
Different lamination technique	4.9	–	–
Longer PV lifetime	3.5	3.8	6.9

The values in Table 4 show that the sandwich panel has the shortest CO_2 return time, which is in line with the GWP results presented in Figure 10. For the sandwich case, doubling the electricity for the lamination phase results in no increase in return time. Having to replace the sandwich material once results in an increase of 0.7 years in return time. The difference in return time between the sandwich case and the clay tile roof in the original scenario is only 0.3 years, which is an almost negligible difference. The concrete tile roof takes about 3 years longer to pay back its CO_2-emissions than the two other cases, however. The increase in return time for the imperfect panel fitting scenario is only significant for the concrete tile roof, where it is a 0.4 years increase. Considering the time horizon of this study being 50 years, this time is not substantial.

5 Conclusions

This study shows that the solar sandwich has the best environmental performance in four out of five impact categories studied, namely global warming potential, acidification potential, human toxicity potential and land use. It is also shown that the solar sandwich panel has a global warming potential impact similar to that of retrofitted solar panels on a conventional wooden roof with clay roof tiles. However, if ozone depletion is of specific interest, SOLEV Entreprenad should perhaps consider using another PV module for the solar sandwich. Another alternative would be to use the Helis module but with a different material as front coating, since the tetrafluoroethylene currently used has a very high SODP impact. Taking other factors of the solar sandwich into account – such as quicker construction, less need for maintenance work and easier replacement of solar cells – it has many benefits over conventional roofs.

As the biggest contributor to GWP is the production of solar cells, by a wide margin, it is crucial to consider what type of solar cells are used as well as how and where they are produced. As mentioned earlier, a recent study suggest that solar cells produced in China have double CO_2 emissions compared to solar cells produced in Europe [26]. Furthermore, unless a drastic drop in cell efficiency occurs, the solar cells should be used for at least 30 years. This has environmental as well as economic benefits. Additionally, the GWP impact from the sandwich panel without the solar cells is slightly lower than that of the wooden roof with clay tiles but could be lowered further if recycled plastics were used in the panel.

6 Further studies

Due to the high environmental impact from the monocrystalline silicon solar cells used, it might be worthwhile to evaluate other types of solar cells such as polycrystalline silicon cells, cadmium telluride (CdTe) cells, dye-sensitized cells, thin-film cells etcetera. A lot of research is being conducted in the field and future solar cells will likely perform better both in terms of environmental impacts during production and in terms of solar light-to-electricity efficiency. As mentioned earlier, a recent study suggest that solar cells produced in China have double CO_2 emissions compared to solar cells produced in Europe [26]. Further studies are needed in order to determine the difference in environmental impact from solar cells produced in different parts of the world. Further studies on recycling of solar cells will also be important in terms of sustainability.

Most of the data in this report is general data from the EcoInvent database which provides a basic idea of a sandwich panel's environmental performance. If a more precise environmental assessment of this specific solar sandwich is desirable, further studies should be performed with more exact data from all manufacturers involved in the production. Additionally, since installing a sandwich roof is simpler and quicker than constructing a conventional roof, further studies should also assess the environmental impact associated with the construction process.

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Appendix A.1: Inventory analysis tables, sandwich case

Table 1: The complete inventory data for the sandwich case.

Input	Unit	Amount
Initial construction phase		
Polystyrene, expandable, at plant	kg	41.57
Glass fibre reinforced plastic, polyester resin, hand lay up, at plant	kg	92.74
Polyurethane, rigid foam, at plant	kg	7.87
Electricity, medium voltage, production SE, at grid	kWh	38.73
Natural gas, high pressure, at consumer	kWh	20.49
Solar cell (Helis module)	m^2	4.91
Transport, freight, rail	ton*km	50.55
Transport, lorry, >16t, fleet average	ton*km	16.75
Replacement phase 1		
Solar cell, Helis module, see Table 2	m^2	4.91
Polyurethane, rigid foam, at plant	kg	1.47
Transport, freight, rail	ton*km	50.55
Transport, lorry, >16t, fleet average	ton*km	2.53
Replacement phase 2		
Solar cell, Helis module, see Table 2	m^2	4.91
Polyurethane, rigid foam, at plant	kg	1.47
Transport, freight, rail	ton*km	50.555
Transport, lorry, >16t, fleet average	ton*km	2.53
Waste		
Disposal, building, polyurethane foam, to final disposal	kg	2.94
Disposal, solar cell, Helis module, to final disposal	m^2	9.82
Transport, lorry, >16t, fleet average	ton*km	5.06

Table 2: Materials and energy included in 1 kW of 2.83 W 125x125 mm Helis solar cells produced by Sunplugged.

Input	Unit	Quantity
Tetrafluoroethylene film, on glass	kg	0.83
Ethylene vinyl acetate	kg	5.51
Monocrystalline solar cell	m^2	4.91
Polyethylene terephthalate, granulate, amorphous, at plant	kg	1.12
Glass fibre reinforced plastic, polyamide, injection moulding, at plant	kg	1.12
Sheet rolling, aluminium	kg	13.26
Electricity, medium voltage, production AT, at grid	kWh	27.30

Appendix A.2: Inventory analysis tables, clay case

Table 3: The complete inventory data for the clay case.

Input	Unit	Amount
Initial construction phase		
Three layered laminated board, at plant	m^3	0.263
Rock wool, at plant	kg	83.16
Cellulose fibre, inclusive blowing, at plant	kg	156.76
Fibreboard soft, at plant	m^3	0.42
Sawn timber, softwood, raw, kiln dried, u=10%	m^3	0.45
Roof tile, at plant	kg	415.82
Photovoltaic cell, single-Si, at plant	m^2	5.74
Solar mount, see Table 4	m^2	5.74
Transport, freight, rail	ton*km	80.02
Transport, lorry, >16t, fleet average	ton*km	113.24
Replacement phase 1		
Three layered laminated board, at plant	m^3	0.263
Rock wool, at plant	kg	83.16
Cellulose fibre, inclusive blowing, at plant	kg	156.76
Fibreboard soft, at plant	m^3	0.42
Sawn timber, softwood, raw, kiln dried, u=10%	m^3	0.067
Roof tile, at plant (*the total of 5% repairs every tenth year*)	kg	103.96
Photovoltaic cell, single-Si, at plant	m^2	5.74
Solar mount, see Table 4	m^2	5.74
Transport, freight, rail	ton*km	80.02
Transport, lorry, >16t, fleet average	ton*km	64.04
Replacement phase 2		
Photovoltaic cell, single-Si, at plant	m^2	5.74
Solar mount, see Table 4	m^2	5.74
Transport, freight, rail	ton*km	80.02
Transport, lorry, >16t, fleet average	ton*km	8
Continued on the next page...		

Input	Unit	Amount
Continued from the previous page...		
Waste		
Disposal, building, brick, to final disposal	kg	103.96
Disposal, building, mineral wool, to final disposal	kg	83.16
Disposal, building, waste wood, untreated, to final disposal	kg	216.53
Disposal, paper, 11.2% water, to municipal incineration	kg	156.76
Disposal, solar mount, to final disposal	m^2	11.48
Disposal, photovoltaic cell, to final disposal	m^2	11.48
Transport, lorry, >16t, fleet average	ton*km	72.04

Table 4: Materials and energy included in 5.74 m^2 of retrofitted solar mounts, equivalent to 1 kW.

Input	Unit	Quantity
Aluminium, primary, at plant	kg	3.2
Aluminium, secondary, from new scrap, at plant	kg	9.6
Aluminium product manufacturing, average metal working	kg	12.8
Sheet rolling, copper	kg	0.19
Solar glass, low-iron, at regional storage	kg	50.1
Polyvinylfluoride film, at plant	kg	0.97
Polyester resin, unsaturated, at plant	kg	4.7
Silicon product, at plant	kg	0.41
Ethylene vinyl acetate copolymer, at plant	kg	6.83
Electricity, medium voltage	kWh	40.9

Appendix A.3: Inventory analysis tables, concrete case

Table 5: The complete inventory data for the concrete case.

Input	Unit	Amount
Initial construction phase		
Stucco, at plant	kg	117.81
Concrete, normal, at plant	m^3	2.91
Reinforcing steel, at plant	kg	232.86
Bitumen sealing, V60, at plant	kg	48.23
Polyurethane, rigid foam, at plant	kg	77.97
Fleece, polyethylene, at plant	kg	65.14
Sawn timber, softwood, raw, kiln dried, u=10%, at plant	m^3	0.08
Three layered laminated board, at plant	m^3	0.33
Concrete roof tile, at plant	kg	568.2
Photovoltaic cell, single-Si, at plant	m^2	5.74
Solar mount, see Table 4	m^2	5.74
Transport, freight, rail	ton*km	80.02
Transport, lorry, >16t, fleet average	ton*km	831.20
Replacement phase 1		
Stucco, at plant	kg	117.81
Bitumen sealing, V60, at plant	kg	48.23
Polyurethane, rigid foam, at plant	kg	77.97
Fleece, polyethylene, at plant	kg	65.14
Sawn timber, softwood, raw, kiln dried, u=10%, at plant	m^3	0.08
Three layered laminated board, at plant	m^3	0.33
Concrete roof tile, at plant	kg	113.64
Photovoltaic cell, single-Si, at plant	m^2	5.74
Solar mount, see Table 4	m^2	5.74
Transport, freight, rail	ton*km	80.02
Transport, lorry, >16t, fleet average	ton*km	69.88
Continued on the next page...		

Input	Unit	Amount
Continued from the previous page...		
Replacement phase 2		
Concrete roof tile, at plant	kg	568.2
Photovoltaic cell, single-Si, at plant	m^2	5.74
Solar mount, see Table 4	m^2	5.74
Transport, freight, rail	ton*km	80.02
Transport, lorry, >16t, fleet average	ton*km	64.82
Waste		
Disposal, building, bitumen sheet, to final disposal	kg	48.2
Disposal, building, concrete, not reinforced, to final disposal	kg	681.84
Disposal, building, plaster board, gypsum plaster, to final disposal	kg	117.8
Disposal, building, polyethylene/polypropylene products, to final disposal	kg	65.2
Disposal, building, polyurethane foam, to final disposal	kg	78.0
Disposal, building, waste wood, untreated, to final disposal	kg	100.40
Disposal, solar mount, to final disposal	m^2	11.48
Disposal, photovoltaic cell, to final disposal	m^2	11.48
Transport, lorry, >16t, fleet average	ton*km	125.15

Table 6: Materials and energy included in 5.74 m^2 of retrofitted solar mounts, equivalent to 1 kW.

Input	Unit	Quantity
Aluminium, primary, at plant	kg	3.2
Aluminium, secondary, from new scrap, at plant	kg	9.6
Aluminium product manufacturing, average metal working	kg	12.8
Sheet rolling, copper	kg	0.19
Solar glass, low-iron, at regional storage	kg	50.1
Polyvinylfluoride film, at plant	kg	0.97
Polyester resin, unsaturated, at plant	kg	4.7
Silicon product, at plant	kg	0.41
Ethylene vinyl acetate copolymer, at plant	kg	6.83
Electricity, medium voltage	kWh	40.9

Appendix B.1 Sensitivity analysis, sandwich replacement

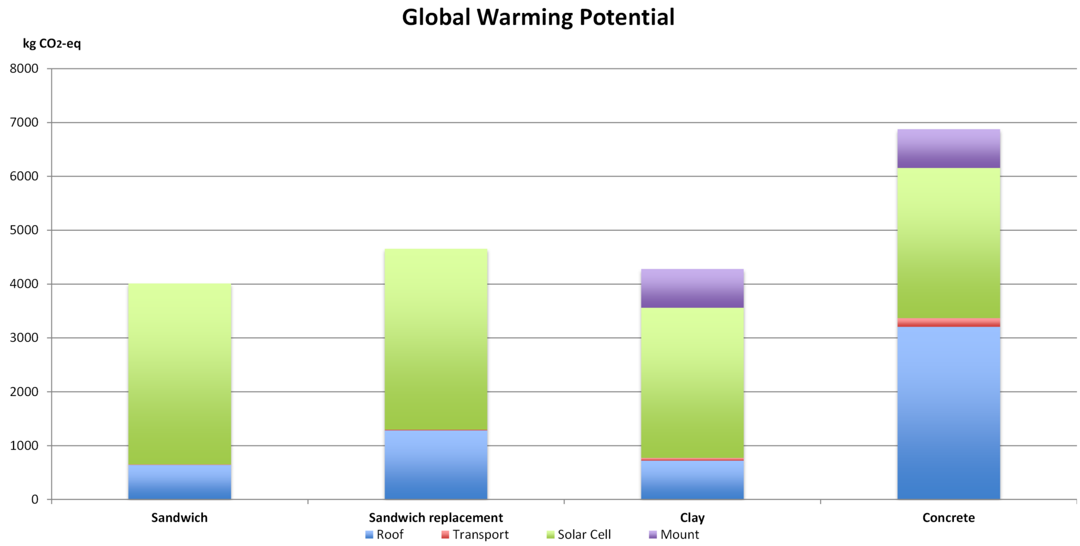

Figure 1: The total global warming potential, in kg CO_2 equivalents, per 1 kW_p for the four scenarios.

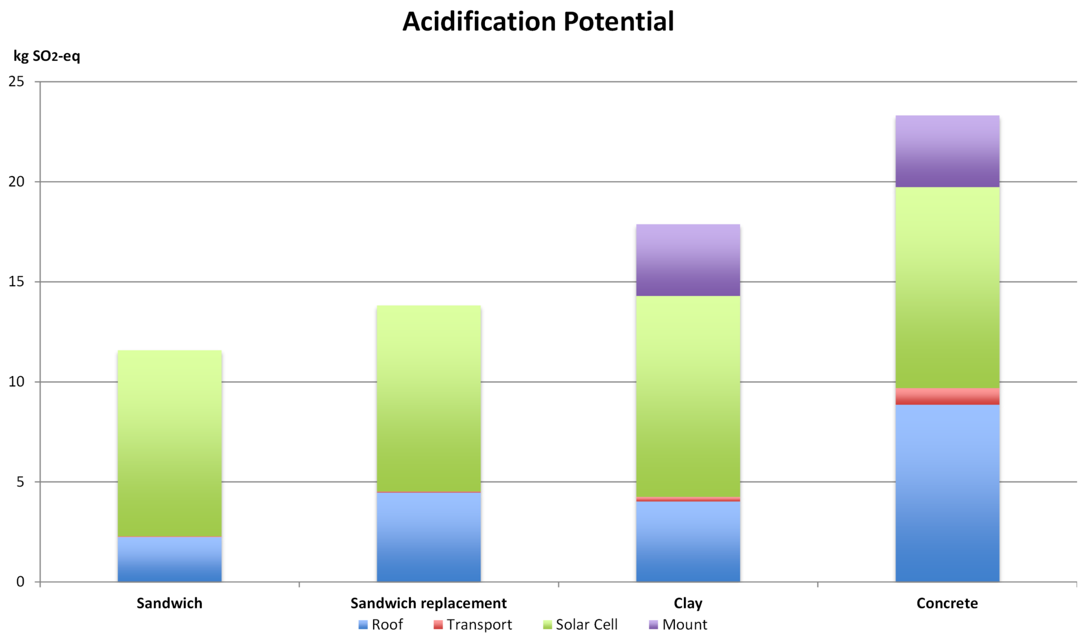

Figure 2: The total acidification potential, in kg SO_2 equivalents, per 1 kW_p for the four scenarios.

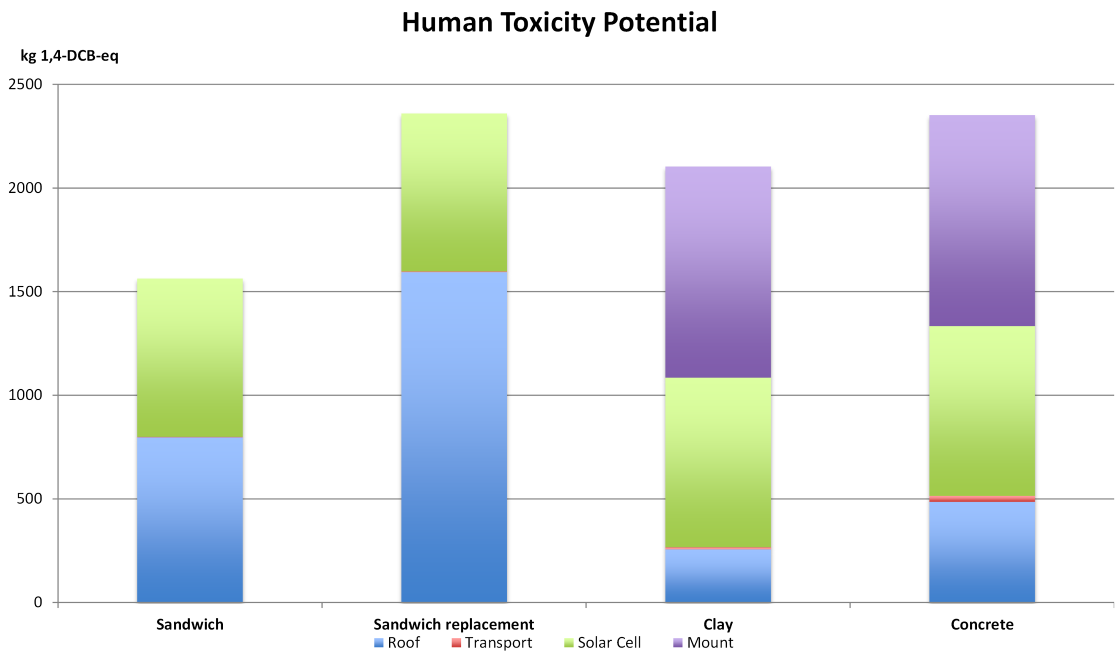

Figure 3: The total human toxicity potential per 1 kW_p for the four scenarios.

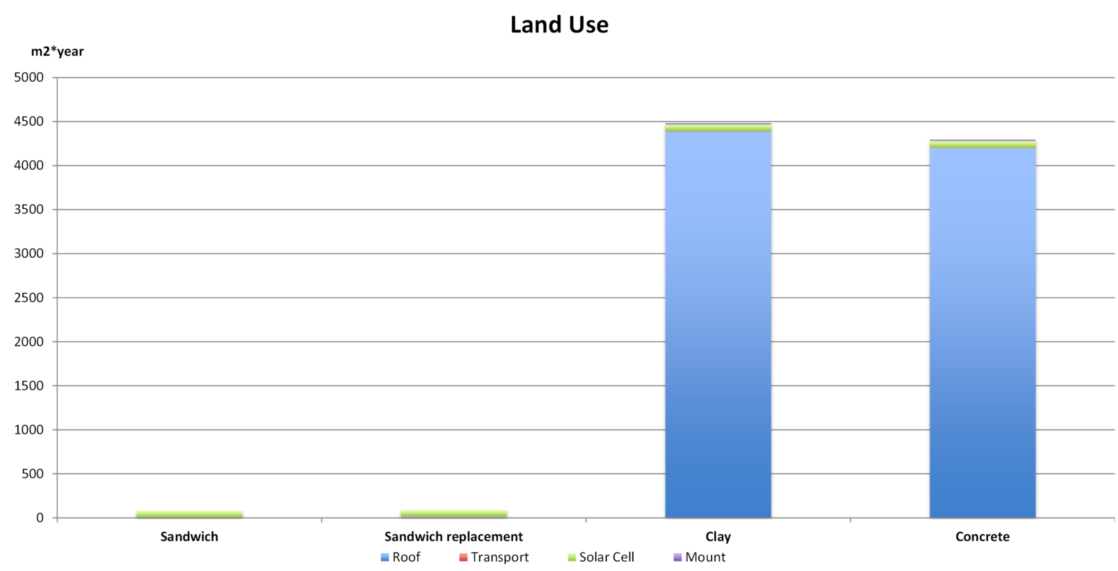

Figure 4: The total land use, in $m^2 * year$, per 1 kW_p for the four scenarios.

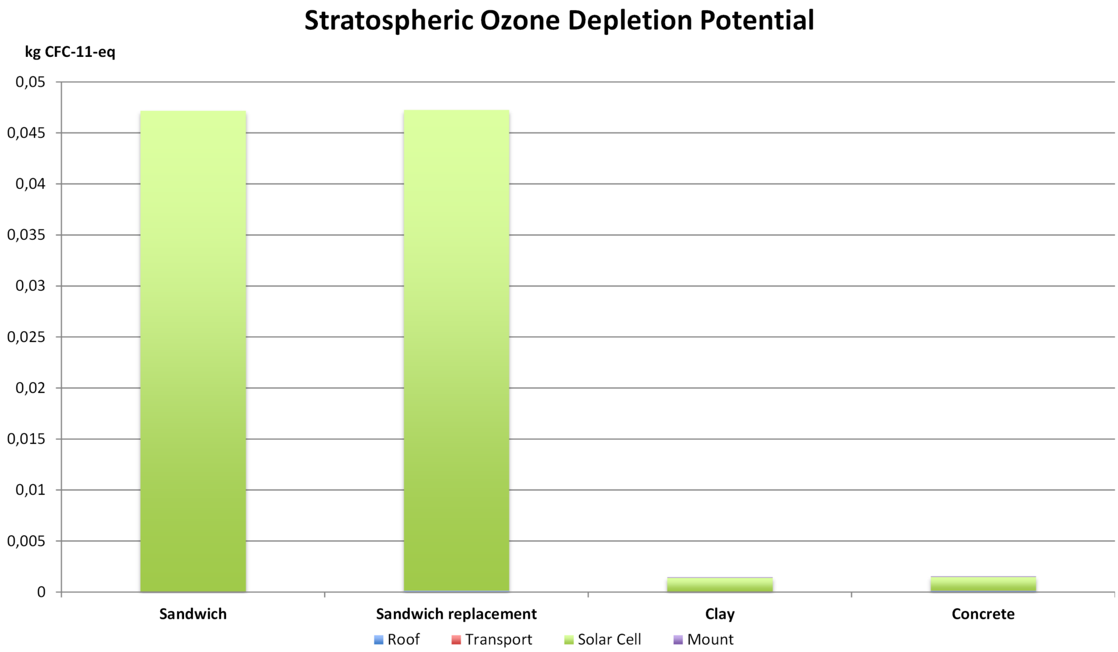

Figure 5: The total stratospheric ozone depletion potential, in kg of CFC-11 equivalents, per 1 kW_p for the four scenarios.

Appendix B.2: Sensitivity analysis, imperfect panel fitting

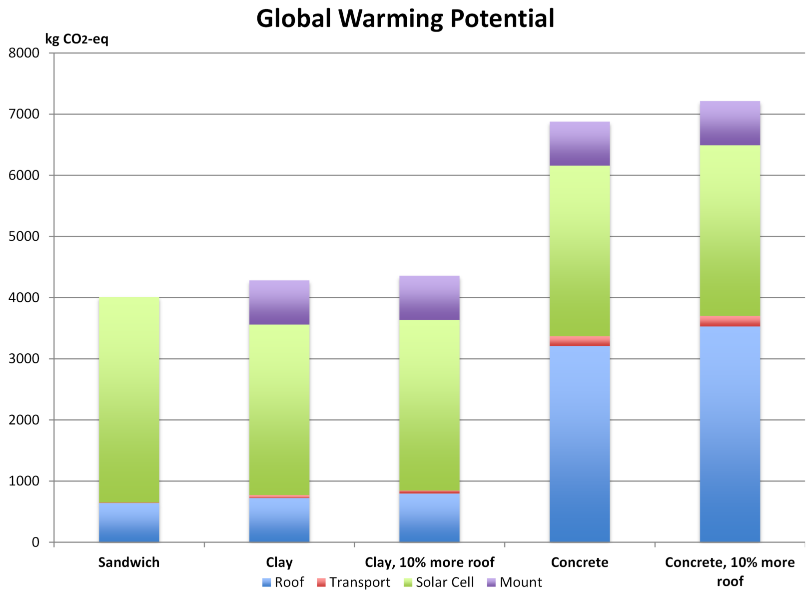

Figure 6: The total global warming potential, in kg CO_2 equivalents, per 1 kW_p for the imperfect panel fitting analysis.

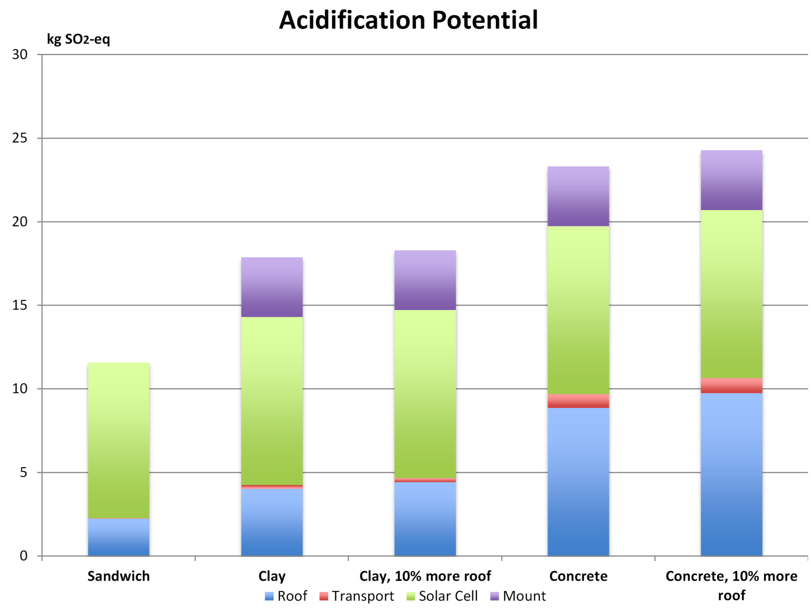

Figure 7: The total acidification potential, in kg SO_2 equivalents, per 1 kW_p for the imperfect panel fitting analysis.

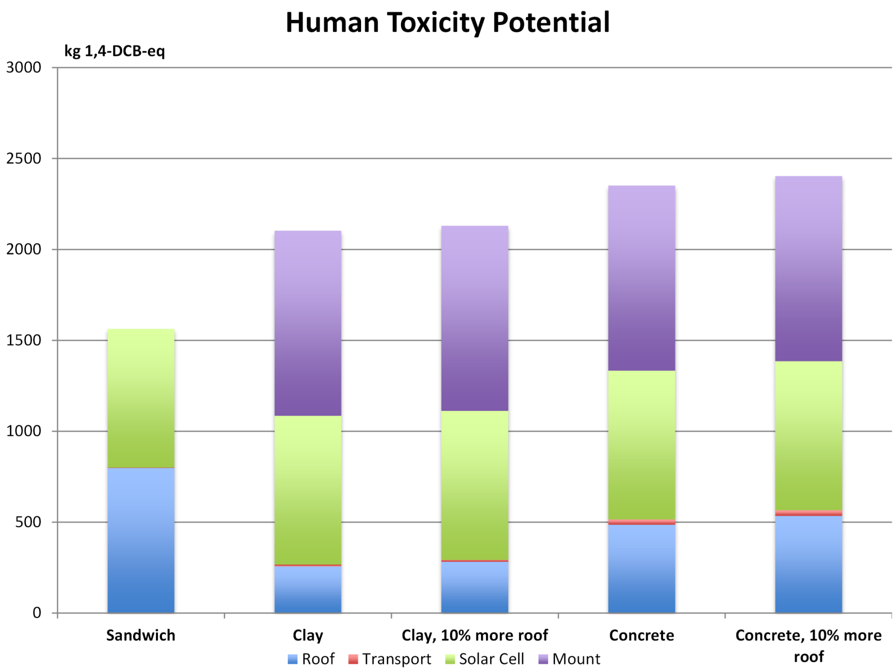

Figure 8: The total human toxicity potential per 1 kW_p for the imperfect panel fitting analysis.

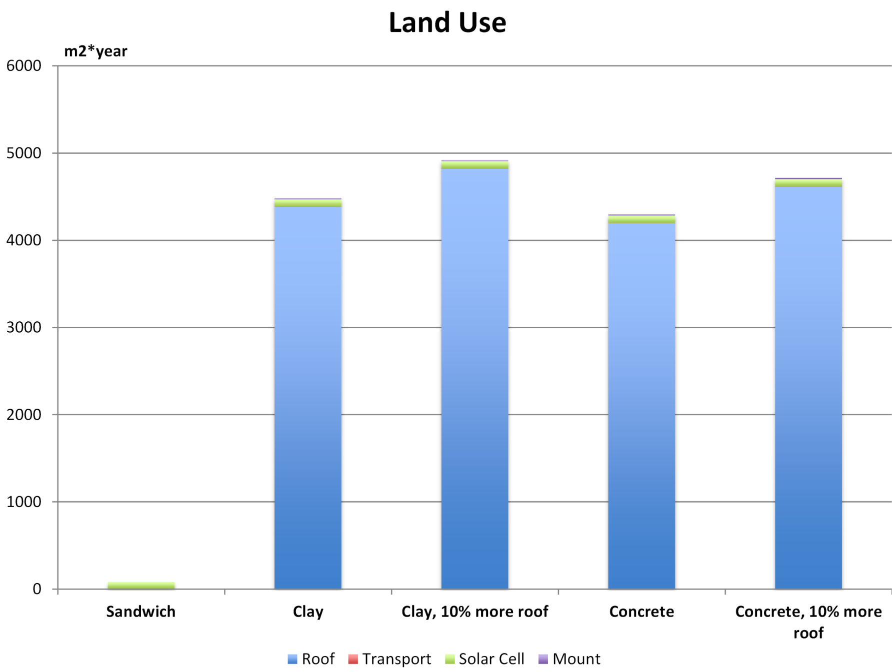

Figure 9: The total land use, in $m^2 * year$, per 1 kW_p for the imperfect panel fitting analysis.

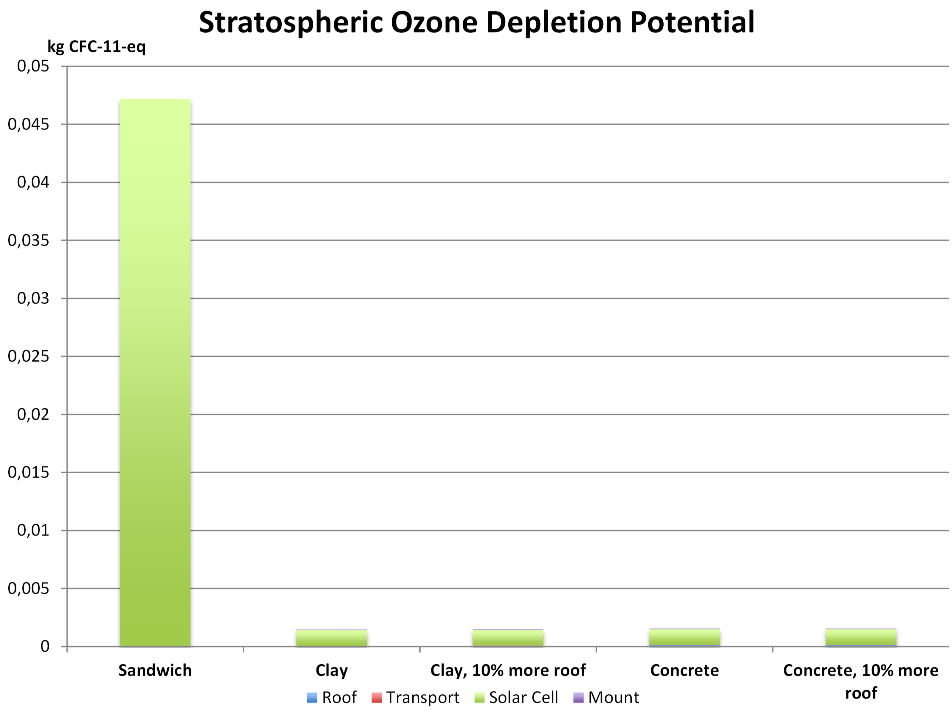

Figure 10: The total stratospheric ozone depletion potential, in kg of CFC-11 equivalents, per 1 kW_p for the imperfect panel fitting analysis.

Appendix B.3: Sensitivity analysis, different lamination technique

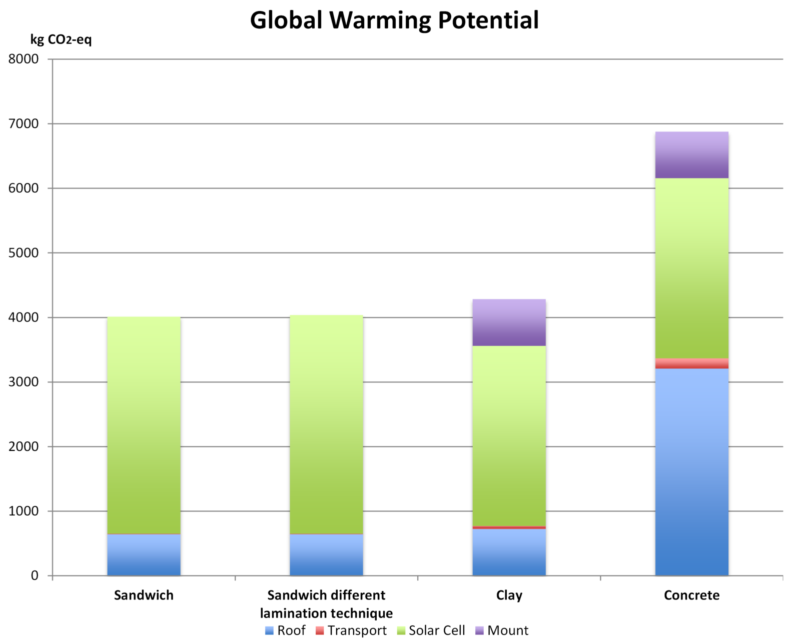

Figure 11: The total global warming potential, in kg CO_2 equivalents, per 1 kW_p for the different lamination technique analysis.

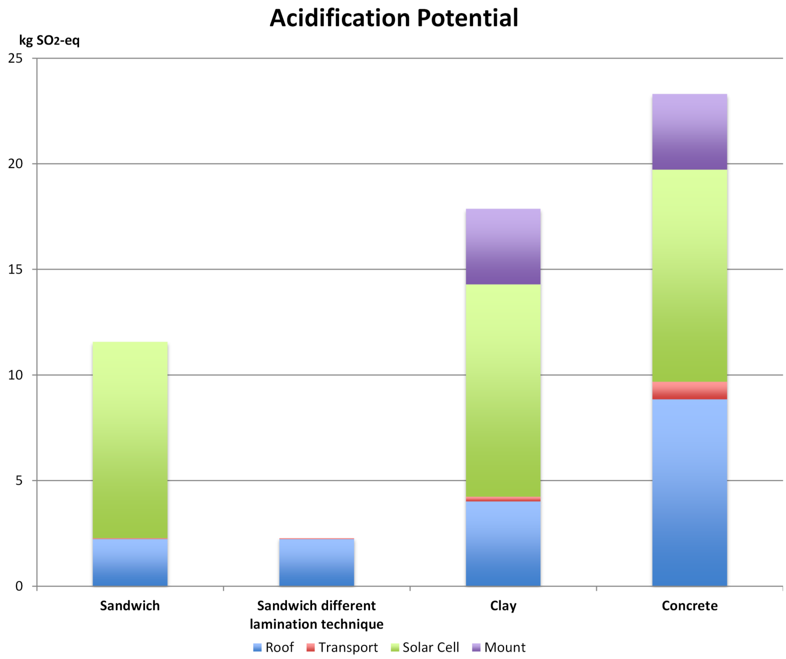

Figure 12: The total acidification potential, in kg SO_2 equivalents, per 1 kW_p for the different lamination technique analysis.

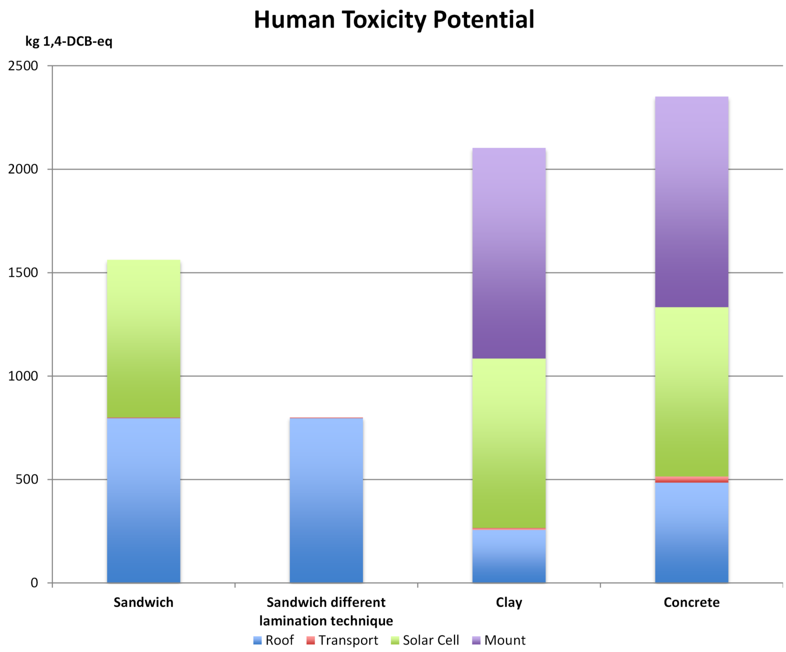

Figure 13: The total human toxicity potential per 1 kW_p for the different lamination technique analysis.

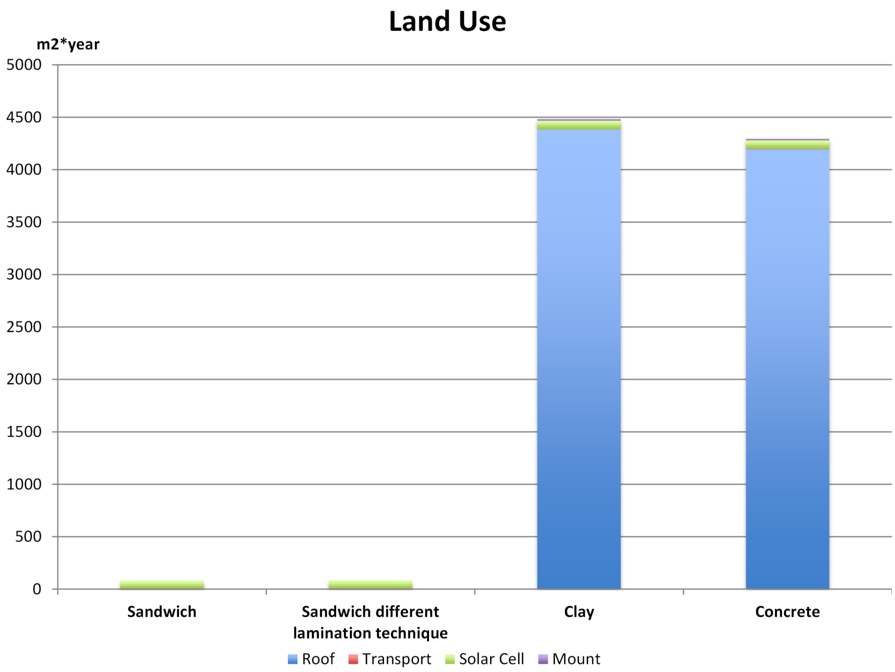

Figure 14: The total land use, in $m^2 * year$, per 1 kW$_p$ for the different lamination technique analysis.

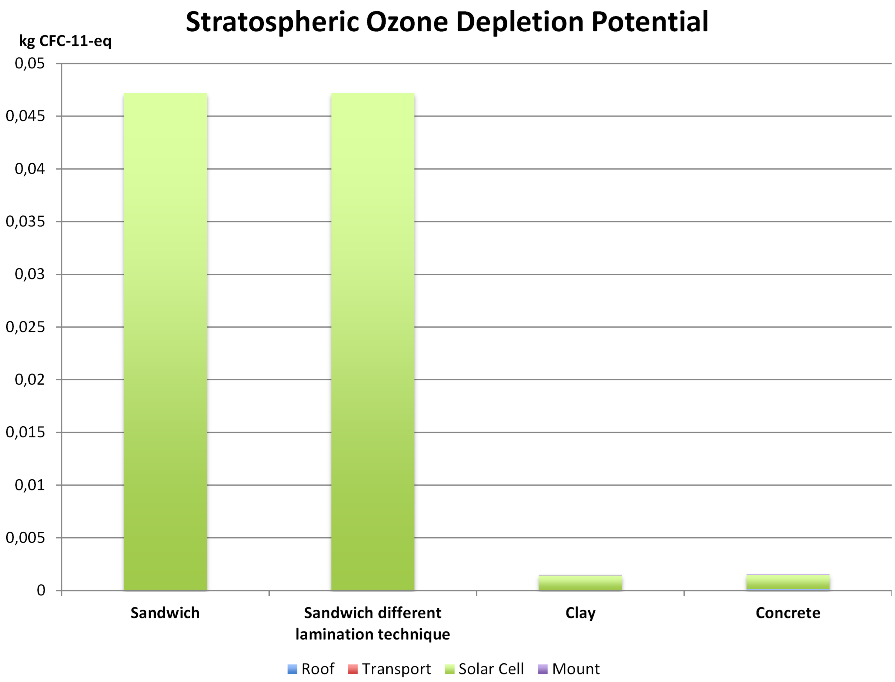

Figure 15: The total stratospheric ozone depletion potential, in kg of CFC-11 equivalents, per 1 kW_p for the different lamination technique analysis.

Appendix B.4: Sensitivity analysis, longer PV lifetime

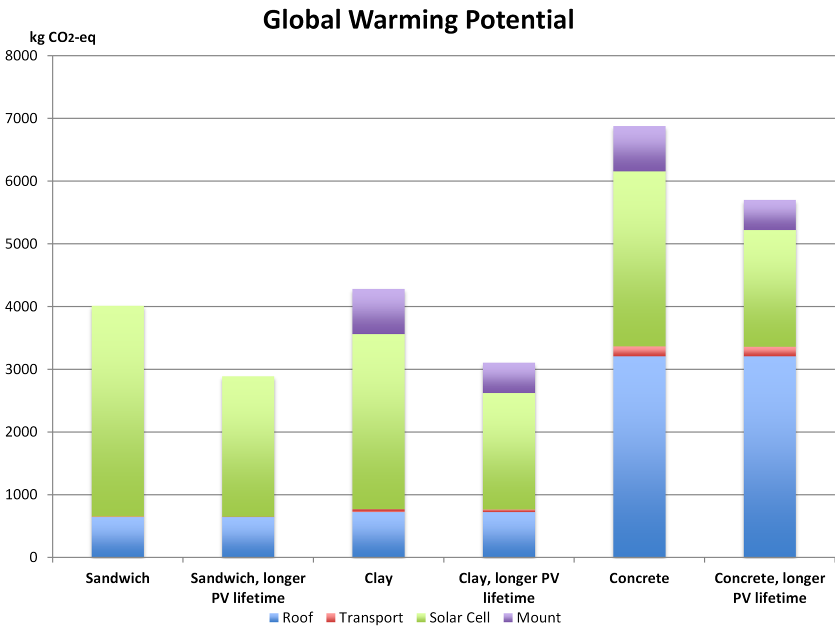

Figure 16: The total global warming potential, in kg CO_2 equivalents, per 1 kW_p for the longer PV lifetime analysis.

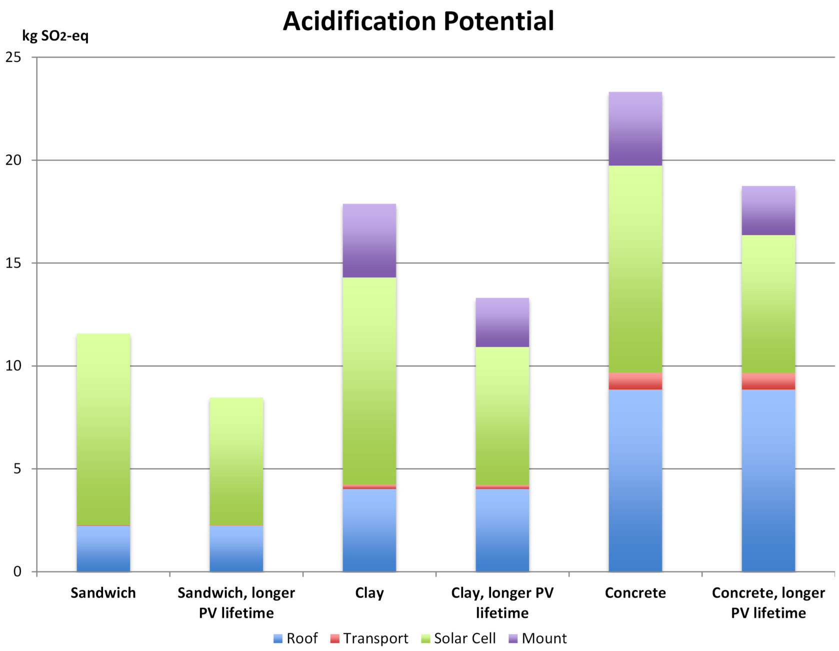

Figure 17: The total acidification potential, in kg SO_2 equivalents, per 1 kW_p for the longer PV lifetime analysis.

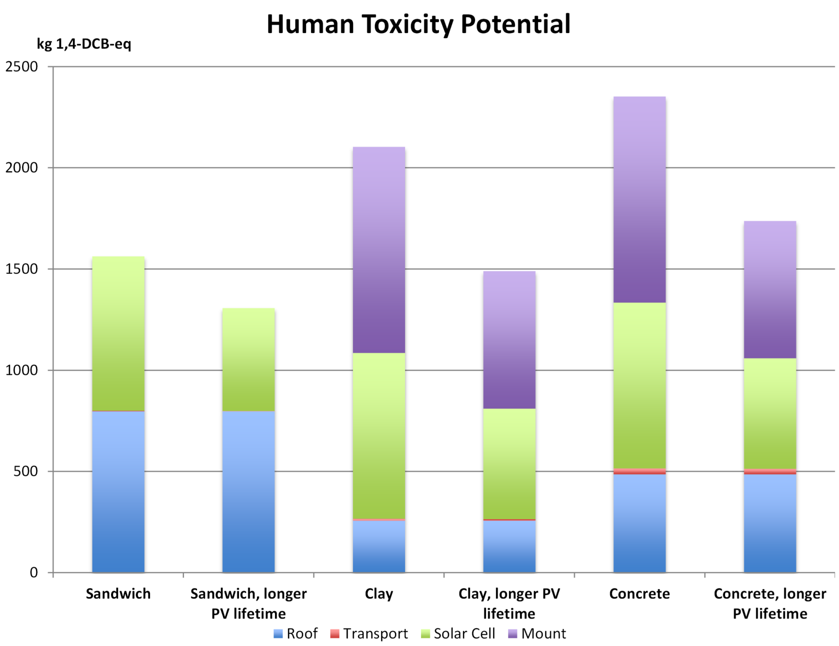

Figure 18: The total human toxicity potential per 1 kW_p for the longer PV lifetime analysis.

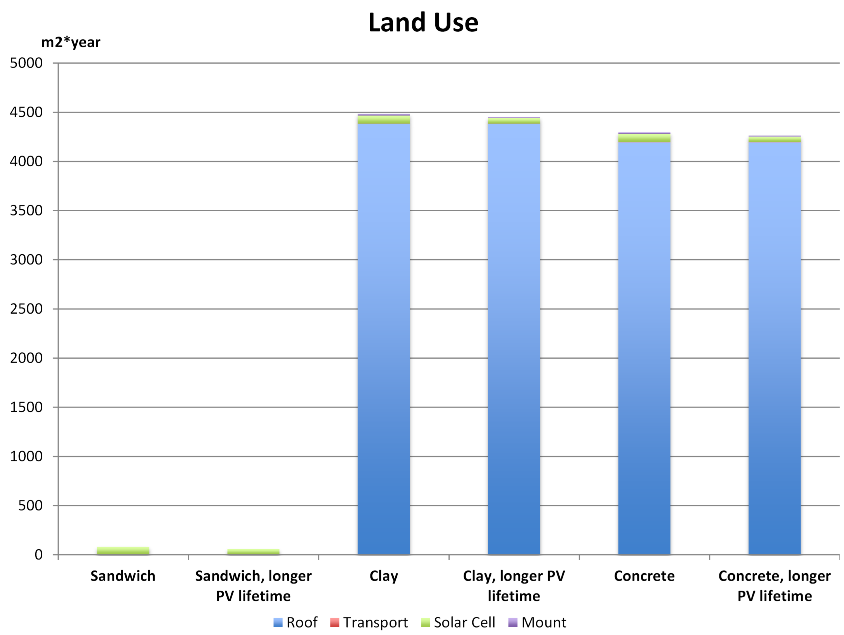

Figure 19: The total land use, in $m^2 * year$, per 1 kW_p for the longer PV lifetime analysis.

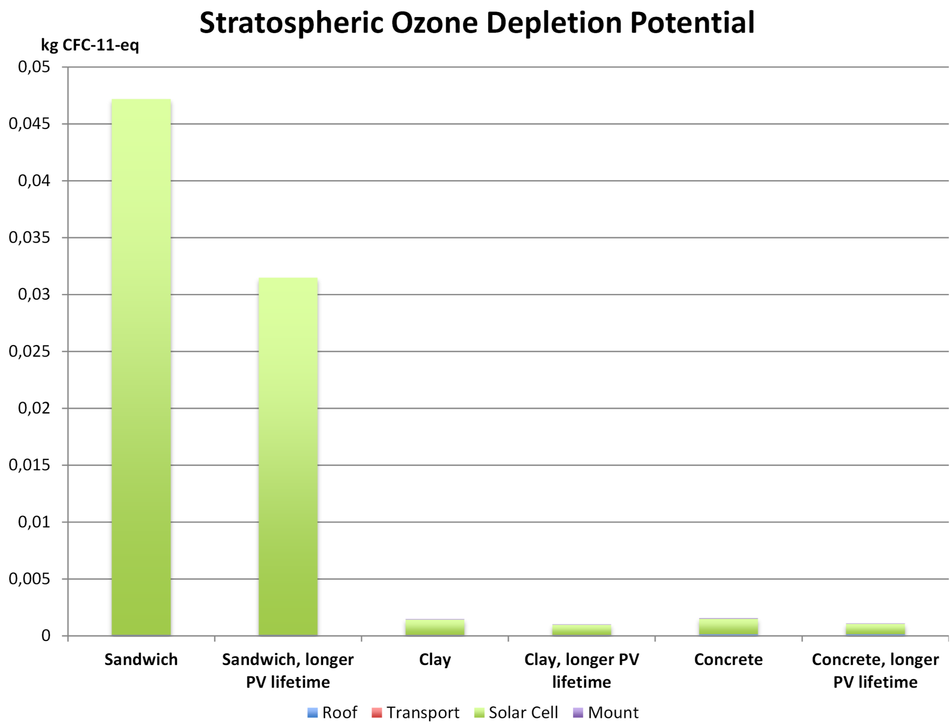

Figure 20: The total stratospheric ozone depletion potential, in kg of CFC-11 equivalents, per 1 kW_p for the longer PV lifetime analysis.